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MEMORANDUM REPORT ARBRL-MR-03171

ON THE EROSIVITY OF STICK AND GRANULAR PROPELLANT

J. R. Ward

May 1982

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
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An interior ballistic scheme devised by Nordheim during World War II claimed the distribution of unburned propellant would significantly affect heat transfer to a gun in the commencement of rifling region where were is most severe. Heat transfer would be greatest when the unburned propellant stayed in the chamber; heat transfer would be least when the unburned propellant was evenly distributed throughout the gun. Such a hypothesis implies stick propellant, which is likely to stay in the chamber, will be more

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erosive than granular propellant which is likely to be spread throughout the chamber.

Nordheim's hypothesis was tested with the zone 85 charge for the 155 mm M199 towed howitzer. Heat inputs were computed assuming the stick propellant (XM208) remained in the chamber while granular propellant (XM203E2) was distributed throughout the gun. The stick propellant proved to cause eighteen percent higher heat input.

Experimental values of heat input in the absence of additives were obtained by combining heat transfer data collected by Calspan Corporation and BRL during an investigation of the XM201E2 propelling charge. The experimental heat input for the XM208 charge without additive was thirteen percent higher than the XM203E2. The heat transfer calculations also were done with a zone 3 charge for the FH70 which uses stick cordite NQ which is more erosive than granular M30A1; the stick propellant flame temperature must be reduced 300K to get equivalent heat input with granular M30A1. Such results imply the distribution of unburned propellant can have as dramatic effect on heat transfer as a wear-reducing liner. The results also suggest substituting cool, stick propellant such as M31E1 for M30A1 propellant in the M203 charge will increase wear unless a wear-reducing additive is used with the M31E1 propellant.

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I. INTRODUCTION

An extensive investigation of gun barrel wear in hypervelocity guns was sponsored by the National Defense Research Committee during World War II.[1] A key problem was how to compute heat transfer to gun barrels. Nordheim and coworkers at Duke University[2] devised an interior ballistics scheme to compute heat flux from combustion gases using Reynolds analogy between energy and momentum transfer for the convective heat transfer coefficient.

Nordheim observed that the assumption as to the distribution of unburned powder significantly changed heat transfer. The heat transfer at the commencement of rifling was least when the propellant was evenly distributed behind the projectile; the heat transfer was greatest when the unburned propellant remained in the chamber, since all the combustion gases had to pass the commencement of rifling. The difference in heat transfer diminished down the barrel to the point where all the propellant was consumed. Nordheim provided results for both assumptions; he felt the short, granular propellants conformed to the assumption of evenly distributed grains.

Nordheim's work implied that propelling charges made with stick propellants would be more erosive than propelling charges with equivalent interior ballistics made with granular propellants, since the unburned stick propellant would remain in the chamber. A Swedish investigator, Jacobsson, recently claimed confirmation of Nordheim's hypothesis[3].

Jacobsson used seven-perforated granular propellant and stick propellant in an M138 37-mm anti-aircraft gun to monitor movement of the unburned powder. Jacobsson concluded that seven-perforated, granular powder follows the projectile, while stick propellant remains in the chamber until the projectile leaves the muzzle. Jacobsson further observed that: "discrepancies in powder behavior may explain the great differences in bore wear which are observed in conjunction with firing using these types of powder, regardless of whether measures were taken to prevent wear."

During the course of investigations to discern the unusual wear produced by the 155-mm XM201E2 charge, heat transfer and erosion sensor measurements were done with a series of 155-mm propelling charges in which the wear-reducing

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[1] *"Hypervelocity Guns and the Control of Gun Erosion," Summary Technical Report of Division 1, National Defense Research Committee, Wash, DC, 1946.*

[2] *L.W. Nordheim, H. Soodak, and G. Nordheim, "Thermal Effects of Propellant Gases in Erosion Vents and Guns," NDRC Armor and Ordnance Report No. A-262, March 1944.*

[3] *D. Jacobsson, "Movement of Powder in Bore During Firing," Forsvarets Forskningsanstalt, A1589-D9, D2, June 1974, pp 1-35.*

additives were removed.[4,5] Among the charges tested were a stick propellant version, XM208, of the XM203E2 charge with granular propellant. Since heat transfer data had been collected in separate laboratories, and the use of the heat transfer technique and erosion sensors was in its infancy, the larger wear and heat input for the XM208 charge stirred little interest. In this report Nordheim's hypothesis about the distribution of unburned propellant is tested by computing heat inputs for the XM203E2 and XM208 charges assuming the granular propellant in the XM203E2 is evenly distributed while the stick propellant in the XM208 charge stays in the chamber. These heat inputs will be compared to heat inputs measured in the absence of the TiO_2-wax liner.

The gun barrel wear community in the US apparently was unaware of Nordheim's implication for the erosivity of stick propellant as evidenced by the failure to mention the topic during tri-service symposia on gun barrel wear in 1970[6] and 1977[7]. A technical forecast for extending the wear life of Army guns even included stick propellant as an option.[8] The US community during this period was preoccupied with understanding the many subtle features influencing the wear-reducing additives with which the US had experience. Stick propellant had limited trials, and on rare occasions where wear data surfaced with stick in place of granular propellant, the difference was attributed to interaction with the TiO_2-wax additive.[4,8,9] The need to understand whether stick propellant is more erosive than granular propellant grows acute in the US, since stick propellant is being evaluated for the 120-mm HEAT round,[10] 155-mm propelling charges,[11] and an automatic anti-armor cannon.[12]

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

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

[6] *Proceedings of the Tri-Service Symposium on Gun Barrel Wear and Erosion, Watervliet Arsenal, Watervliet, NY, February 1970.*

[7] *Proceedings of the Tri-Service Gun Tube Wear and Erosion Symposium, ADPA, Dover, NJ, March 1977.*

[8] *J.R. Ward, "A New Initiative in Gun Barrel Wear and Erosion," Proceedings of the Tri-Service Gun Tube Wear and Erosion Symposium, ADPA, Dover, NJ, March 1977.*

[9] *A. Yermal and E. Wurzel, "Comparison of Wear Characteristics of the 152-mm XM150 Gun Tubes Using XM578 Cartridge Model-Six Slug Rounds with Wear-Reducing Additives (TiO_2 vs Talc)," Picatinny Arsenal Technical Memorandum, October 1970.*

[10] *A. Albright, "Overview of 120-mm Tank Main Armament System," 1980 JANNAF Propulsion Meeting, CPIA Publication 325, March 1980.*

[11] *H.D. Fair, R.S. Westley, and B. Howard, "Propulsion Technology for the Enhanced Self-Propelled Artillery Weapons System," 1980 JANNAF Propulsion Meeting, CPIA Publication 315, March 1980.*

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

II. HEAT TRANSFER AND WEAR DATA

Table 1 lists characteristics of the XM203E2 charge and two stick propellant analogs, the XM208 and the FH70 Zone 3. The zone 3 charge is one version of the top-zone charge for the 155-mm FH70 howitzer.

Calspan Corporation measured total heat input at three axial locations on the M185 barrel with thermocouples imbedded in the barrel wall. The thermocouples were placed so they were directly over a groove. One thermocouple was placed forward of the commencement of rifling where remaining tube life is estimated from the bore enlargement.[13] Another thermocouple was mounted one-third the distance between the commencement of rifling and the muzzle, while the third thermocouple was mounted at the muzzle. Wear sensors were placed on the bore surface in the commencement of rifling region. The sensors were made of steel or inconel. Bore surface temperatures at the commencement of rifling were computed from the total heat input and interior ballistic trajectories.[14] At BRL the total heat input was measured at the commencement of rifling with four thermocouples imbedded at different distances from the bore surface.[15] In order to obtain equivalent units of energy per unit area, the BRL measurements are divided by the bore perimeter (613.7 mm).

Table 2 summarizes which zone 8S charges were tested. The goal of the tests was to reduce the wear of the XM201E2 charge, so no systematic testing of zone 8S charges was planned.

Table 3 summarizes the results obtained by Calspan with the zone 8S charges, the BRL results are summarized in Table 4.

One should note first that the Calspan and BRL data for the XM203E2 charge cannot be compared directly since the BRL heat input represents heat input with a "clean-out" round after each shot. The Calspan heat input is the average of five consecutive XM203E2 shots. In order to see how well heat inputs agree between the two sets of measurements, charges without wear-reducing additives are compared in Table 5. One sees the Calspan measurements are three percent greater. Using 1.034 as a correction factor the BRL heat inputs corrected to be consistent with Calspan are 1.336 J/mm^2 and 1.183 J/mm^2 for the XM203E2 charge minus its additive and XM203E2 charge, single-shot respectively.

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[13] *"Evaluation of Cannon Tubes", Dept of the Army Technical Manual TM-9-1000-202-14, November 1976.*

[14] *F.A. Vassallo, "Mathematical Models and Computer Routines Used in Evaluation of Caseless Ammunition Heat Transfer," Calspan Report No. GM-2948-Z-1, June 1971.*

[15] *T.L. Brosseau, "An Experimental Method for Accurately Determining the Temperature Distribution and Heat Transferred in Gun Barrels," BRL Report No. 1740, September 1974. (AD B000171L)*

TABLE 1. CHARACTERISTICS OF 155-mm ZONE 8S CHARGES EVALUATED

Charge	Additive	Propellant	Type	Flame Temp, K	Charge Mass, kg	Peak Chamber[a] Pressure, MPa	Muzzle Vel,[a] m/s
XM203E2	TiO_2-wax	M30A1	7-perf	3,000	11.8	318	830.0
XM208	TiO_2-wax	M30A1	Stick	3,000	11.3	308	817.2
FH70 Zone 3	Polyurethane Foam	Cordite NQ	Stick	2,860	12.3	316	813.5

[a]Inert-loaded M549 RA Projectiles

TABLE 2. ZONE 8S CHARGES EVALUATED FOR HEAT TRANSFER

Propelling Charge	Additive	Calspan	BRL
XM203E2	TiO_2-wax	X	X
XM203E2	None	-	X
XM208	TiO_2-wax	X	-
XM208	None	X	-
Zone 3	Polyurethane Foam	X	-
Zone 3	None	-	-

TABLE 3. CALSPAN HEAT INPUT AND WEAR DATA FOR ZONE 8S CHARGES[a]

Charge	No. Shots	Heat Input, J/mm^2			Wear, μ	Peak Temp, K[b]
		1.006m	2.108m	6.007m	1.006m	1.006m
XM203E2	5	1.119	0.863	0.673	0.1-0.2	1.001
Zone 3 UK	5	c	.892	.554	c	c
XM208	3	c	.971	.610	2.0-3.0[d]	c
XM208 (no additive)	2	1.518	1.106	.666	4.0-5.0[d]	1.306

[a] *Axial distances measured from rear face of tube (RFT).*

[b] *Calculated from measured total heat input.*

[c] *Data unavailable*

[d] *Wear extrapolated to five rounds*

TABLE 4. HEAT INPUTS FOR XM203E2 CHARGE MEASURED AT BRL

Charge	Heat Input, 1.006mRFT, J/mm^2
XM203E2(no additive)	1.292
XM203E2	1.144

TABLE 5. HEAT INPUTS MEASURED BY BOTH CALSPAN AND BRL

Charge	Heat Input, J/mm^2		Ratio, Calspan/BRL
	Calspan	BRL	
M119	1.138	1.103	1.032
XM119E4(minus liner)	1.290	1.245	1.036

Figure 1 summarizes the heat inputs from Table 3 and the modified BRL heat inputs. Interpretation of some of the data is confounded by the wear-reducing additives and missing values in the commencement of rifling region. Nonetheless, one sees the XM208 charge produces greater heat input than the XM203E2 even when the wear-reducing additive is taken from both charges. The difference between the stick and granular propellant decreases downtube as expected from Nordheim's hypothesis that the distribution of unburned propellant accounts for the greater heat input near the commencement of rifling. At the muzzle the zone 3 charge with cordite NQ has the smallest heat input. The trend from the muzzle to 2.108m RFT, suggests the stick cordite NQ propellant is more erosive than the granular M30A1 propellant at the commencement of rifling. More firings minus additives are required to separate propellant type from the wear-reducing additives effect on heat transfer.

III. HEAT TRANSFER COMPUTED WITH NORDHEIM'S METHOD

The procedure Nordheim outlined in Chapter VI of his report will be used here to compute heat input at the commencement of rifling region for the XM203E2, XM208, and the European Zone 3 charges, each minus wear-reducing additives. The equations will be taken directly from Nordheim; the report should be consulted directly for more detail or explanation.

Propellant properties were determined with the BLAKE thermochemical code;[16] other interior ballistic parameters were taken from Heppner's report.[17] Nordheim's values for the physical properties of gun steel are also used here.

The basic relation for starting the computation of heat transfer in guns with Nordheim's method is the so called heating parameter, L, defined as follows:

$$L = 43.1 \left(\frac{\lambda C_p}{(kc\rho_s)^{\frac{1}{2}}}\right) \left(\frac{C^{3/4}}{m^{\frac{1}{4}}A^{\frac{1}{2}}F}\right) \left(\frac{1-\Delta/\rho_p}{\Delta}\right)^{3/4} \left(P_{max}\right)^{5/4} , \quad (1)$$

where λ = friction factor,
C_p = specific heat of propellant gases,
k = thermal conductivity of steel,
c = specific heat of steel,
ρ_s = density of steel,
C = charge weight,
m = reduced projectile mass,
A = cross-section area of barrel,
F = impetus of propellant,
Δ = loading density,
ρ_p = propellant density, and
P_{max} = maximum chamber pressure,

[16] *E. Freedman, "BLAKE-A Ballistic Thermodynamic Code Based on TIGER," Proceedings of the International Symposium on Gun Propellants, Picatinny Arsenal, Dover, NJ, October 1973.*

[17] *L.D. Heppner, "Setback and Spin for Artillery, Mortar, Recoilless Rifle and Tank Ammunition," Report No. APG-MT-4503, September 1974.*

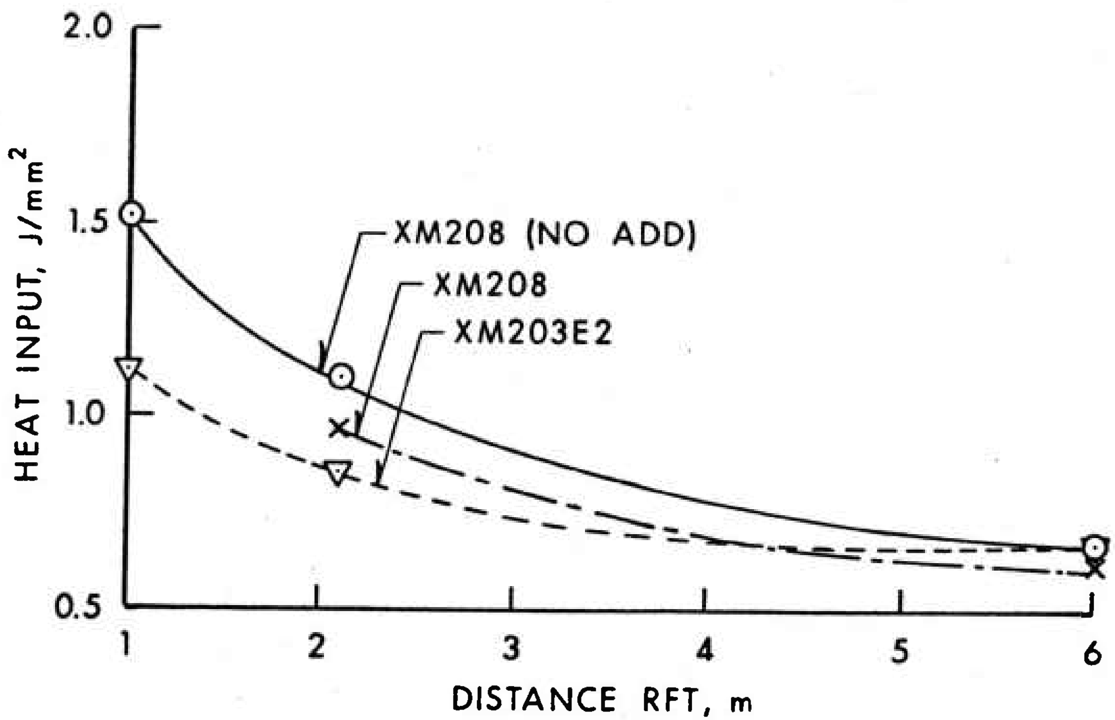

Figure 1. Heat Input for 155-mm Propelling Charges at Various Distances Along the M185 Cannon

All quantities are defined by the interior ballistic inputs except λ and m. These quantities are defined below

$$\lambda = (14.2 + 4 \log_{10} D)^{-2} \quad , \tag{2}$$

where D = bore diameter, cm.

The reduced projectile mass, m, is defined by

$$m = 1.04 \ (m_o + C/3) \quad , \tag{3}$$

where m_o = projectile mass. Another relation needed to compute the heat transfer is the reduced time coefficient, α, given below

$$\alpha = \frac{\left[\frac{C(1-\Delta/\rho_p)}{m} \quad 3.45 \ P_{max}\right]^{\frac{1}{2}} \cdot A}{0.18 \ U_o(1-\Delta/\rho_p)} \quad , \tag{4}$$

where U_o = chamber volume. The heat transfer at a specific location is then

$$Q = \left(\frac{2\rho_s ck}{\alpha}\right)^{\frac{1}{2}} \cdot I_1 \ , \tag{5}$$

where I_1 = a function of L.

The appropriate functional dependence for the zone 8S charges with a propellant with initial temperature of 27°C (300K) and 2,500 K flame temperature is illustrated in Figure 2. If the flame temperature or initial temperature of propellant is different from the nominal values of 2,500 K and 27°C, then I_k in Eq. (5) is replaced by I_∞ defined below

$$I_\infty = \frac{T_o}{2,500} \ I_1 - \left[\theta_o - 300 \ (1 - \frac{T_o}{2,500})\right] S \ , \tag{6}$$

where T_o = flame temperature

θ_o = initial temperature relative to 27°C, and

S = function of L.

Figure 3 illustrates the functional dependence of S with L; in all calculations here the initial propellant temperature is 27°C, so $\theta_o = 0$.

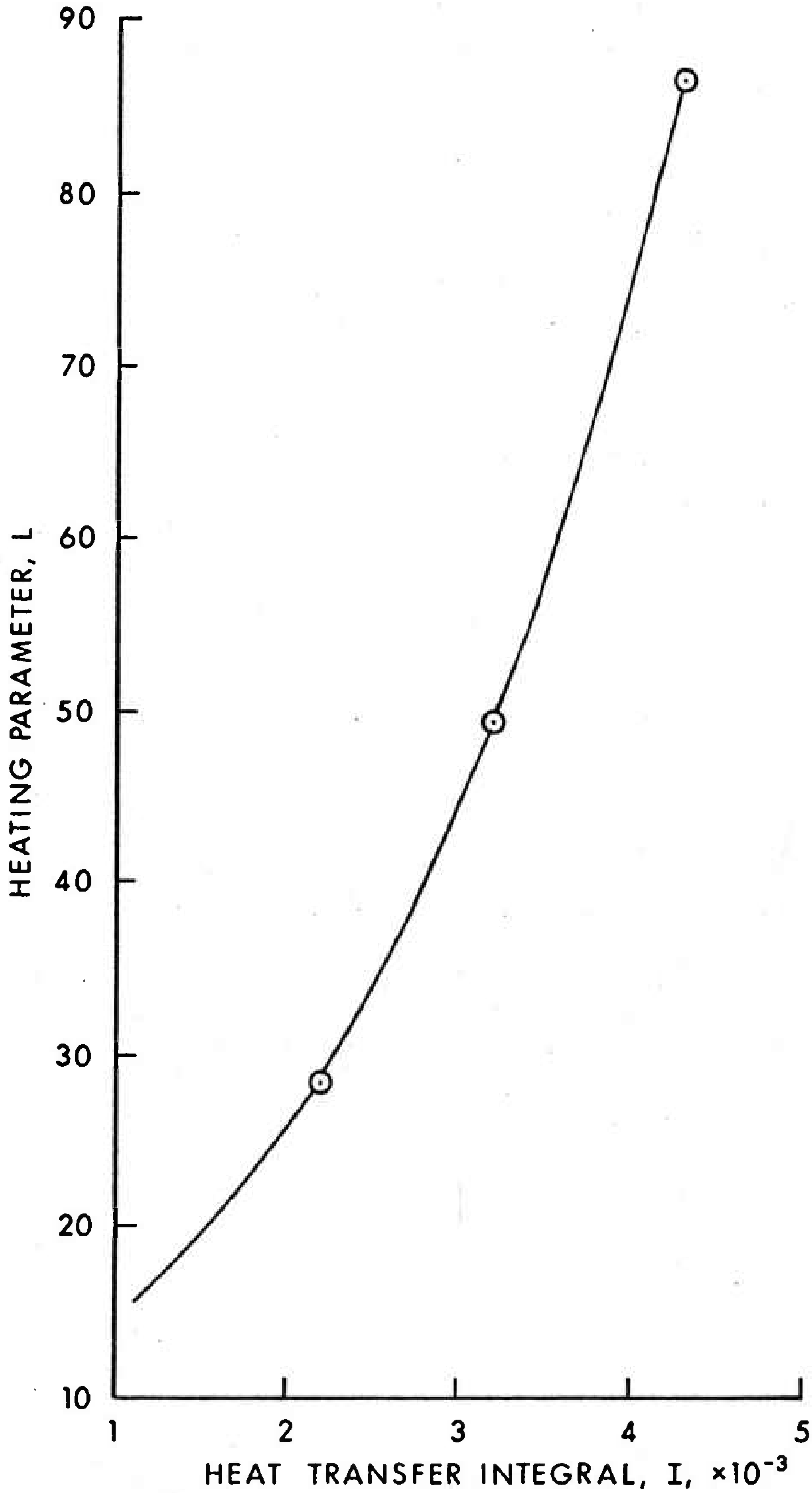

Figure 2. L vs I_1 for Unburned Powder Evenly Distributed

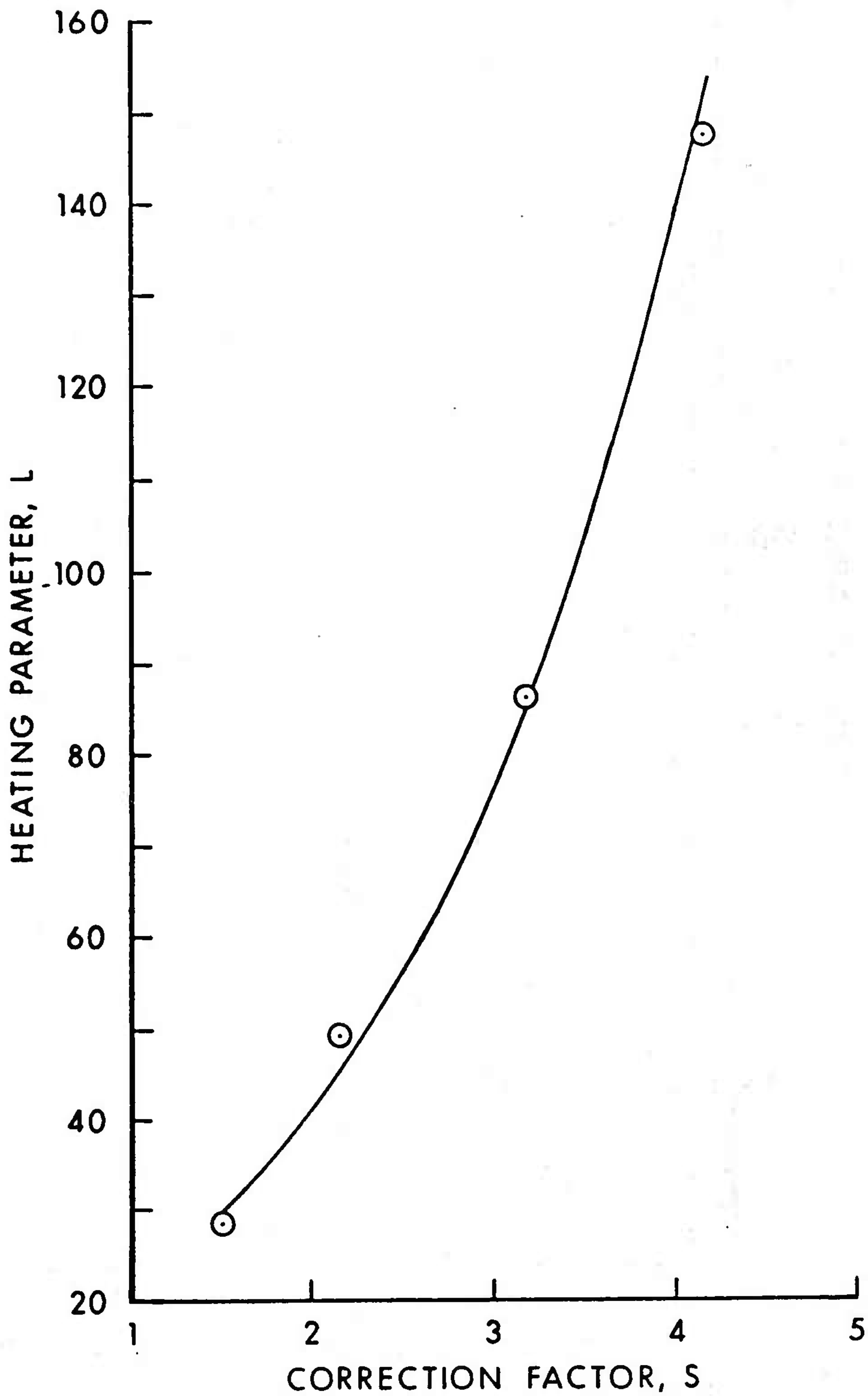

Figure 3. L vs S

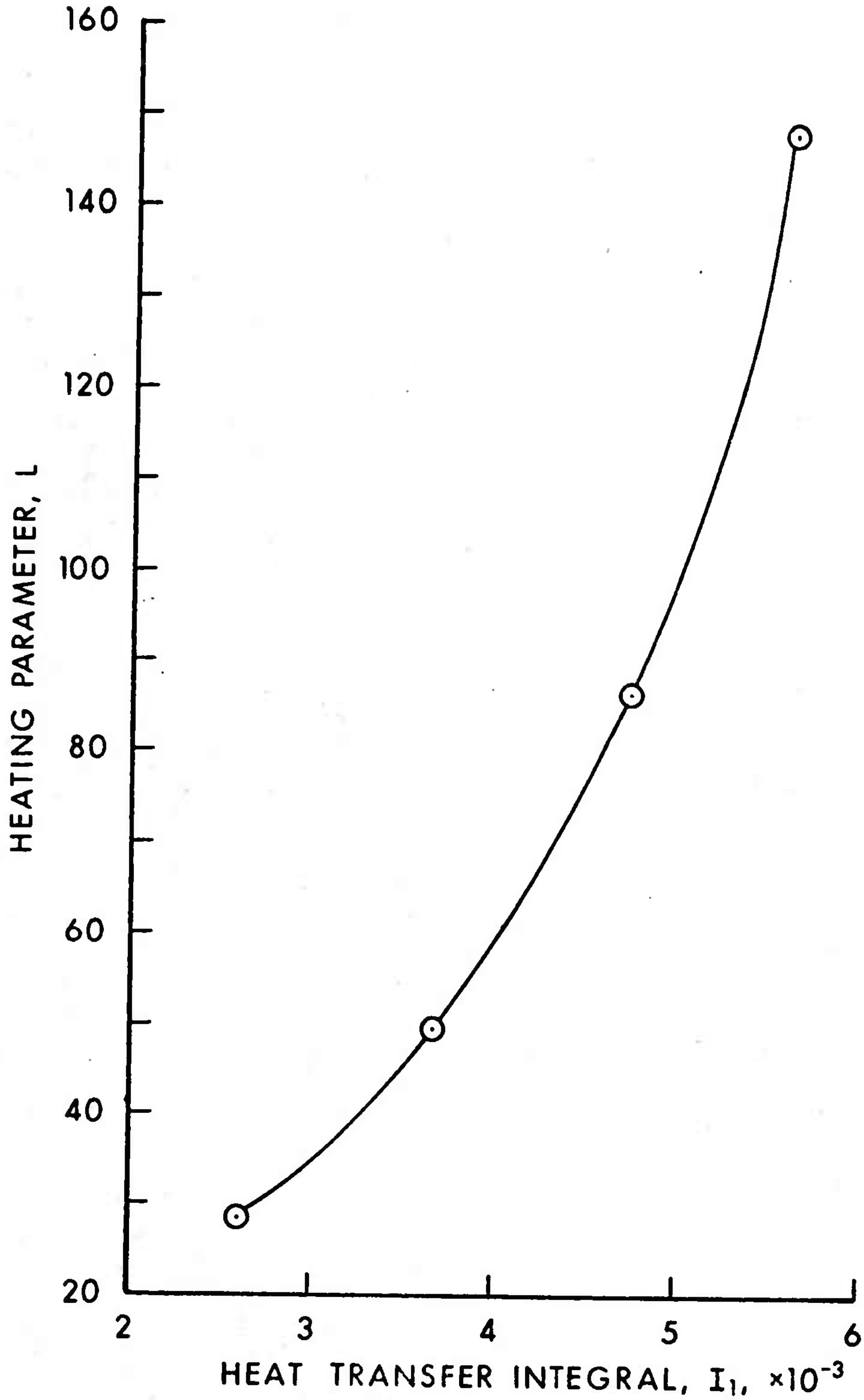

Figure 4. L vs I_1 for Powder Remaining in Chamber

TABLE 6. PROPELLANT PROPERTIES FOR HEAT TRANSFER CALCULATIONS

	M30A1	Cordite NQ
T_o, K, x 10^{-3}	3.00	2.86
C_p, J/kg-K, x 10^{-3}	1.88	1.88
F_1, J/kg, x 10^{-6}	1.065	1.085
ρ_p, kg/m^3, x 10^{-3}	1.67	1.67

TABLE 7. INTERIOR BALLISTIC PARAMETERS

	XM203E2	XM208	Zone 3
Gun	M185	M185	M185
Propellant	M30A1	M30A1	Cordite NQ
Projectile	M549	M549	M549
U_o, m^3, x10^2	1.88	1.88	1.88
C, kg	11.9	11.3	12.3
m_o, kg	43.5	43.5	43.5
m, kg	49.4	49.2	49.5
A, m^2, x 10^2	1.92	1.92	1.92
P_{max}, Pa, x 10^{-8}	3.28	3.08	3.16
α, s^{-1}, x 10^{-3}	4.75	4.52	4.68
Δ, kg/m^3, x 10^{-2}	6.3	6.0	6.5

The above procedure applies to the assumption the unburned propellant is evenly distributed. Some modifications must be made to compute heat transfer with the unburned propellant left in the chamber. The friction factor is defined as

$$\frac{1}{\lambda_b} = (17.7 + 4 \log_{10} D)^2 \tag{7}$$

where the subscript, b, refers to the assumption of unburned powder in the chamber. Eq. (1) is used with λ_b to obtain a value of L_b. This heating parameter is related to L at the commencement of rifling region by

$$L = L_b(I_1 + 0.55). \tag{8}$$

Figure 4 depicts the dependence of I_1 and L under the assumption unburned powder stays in the chamber.

The appropriate propellant properties and interior ballistic parameters are given in Tables 6 and 7. Nordheim gives the physical properties for gun steel as

$$(\rho ck)^{-\frac{1}{2}} = 2.8 \frac{cm^2 \, s^{\frac{1}{2}}}{cal}, \text{ or} \tag{9}$$

$$(\rho ck)^{-\frac{1}{2}} = 6.7 \times 10^{-7} \frac{m^2 s^{\frac{1}{2}}}{J}. \tag{10}$$

Table 8 summarizes the heat inputs computed with Nordheim's scheme. One sees the heat input computed for the XM208 charge is eighteen percent higher than the heat input computed for the XM203E2 charge which reflects how the unburned propellant distribution affects heat transfer. The experimental heat input for the XM208 charge is thirteen percent higher than the XM203E2 charge, so the greater heat input for the XM208 charge can be accounted for solely by the unburned propellant distribution. The zone 3 charge's heat input further illustrates the strong influence the propellant distribution has on the heat transfer. The zone 3 charge has cordite NQ, a propellant with a flame temperature of 2,800K, yet the heat input for the zone 3 charge is greater than the XM203E2 with a 3,000K flame temperature propellant, M30A1.

In order to see how much lower the flame temperature of stick propellant must fall in order to match the heat input from the XM203E2 charge, the following calculation was performed. First, the friction factor for the stick propellant calculation was varied until the computed heat input matched the experimental heat input.

TABLE 8. HEAT INPUTS COMPUTED WITH NORDHEIM'S METHOD[a]

	XM203E2	XM208	Zone 3
$1/\lambda$	360	504	504
L_b	-	40.9	39.7
L	60.6	63.4	61.6
I_1	3,590	4,140	4,080
S	2.62	2.70	2.66
I_∞	4,465	5,130	4,790
Q, J/mm^2	1.37	1.61	1.48
Q, J/mm^2, expt.	1.34	1.52	--

[a]*All charges minus wear-reducing additives.*

A value of 550 for $1/\lambda$ gave a computed heat input of 1.52 J/mm^2. Heat inputs for the XM208 were then computed with various flame temperatures. Figure 5 illustrates the results showing the flame temperature must be reduced to 2,700K to match the XM203E2. To appreciate how significant is the effect of the unburned powder distribution on heat transfer, one should note Smith-O'Brasky's empirical wear formula accounts for the effect of the wear-reducing additive by reducing the flame temperature by 300K.[18]

A contemplated product-improvement for the zone 8S charge envisions replacing M30A1 propellant with M31E1 stick propellant which has a flame temperature of approximately 2,600K. Figure 4 suggests that a wear-reducing additive should be used with the M31E1 propellant, since heat input for the XM203E2 fired repeatedly is 1.12 J/mm^2.

[18]*C.S. Smith and J.S. O'Brasky, "A Procedure for Gun Barrel Erosion Life Estimation," Proceedings of the Tri-Service Symposium on Gun Tube Wear and Erosion, ADPA, Dover, March 1977.*

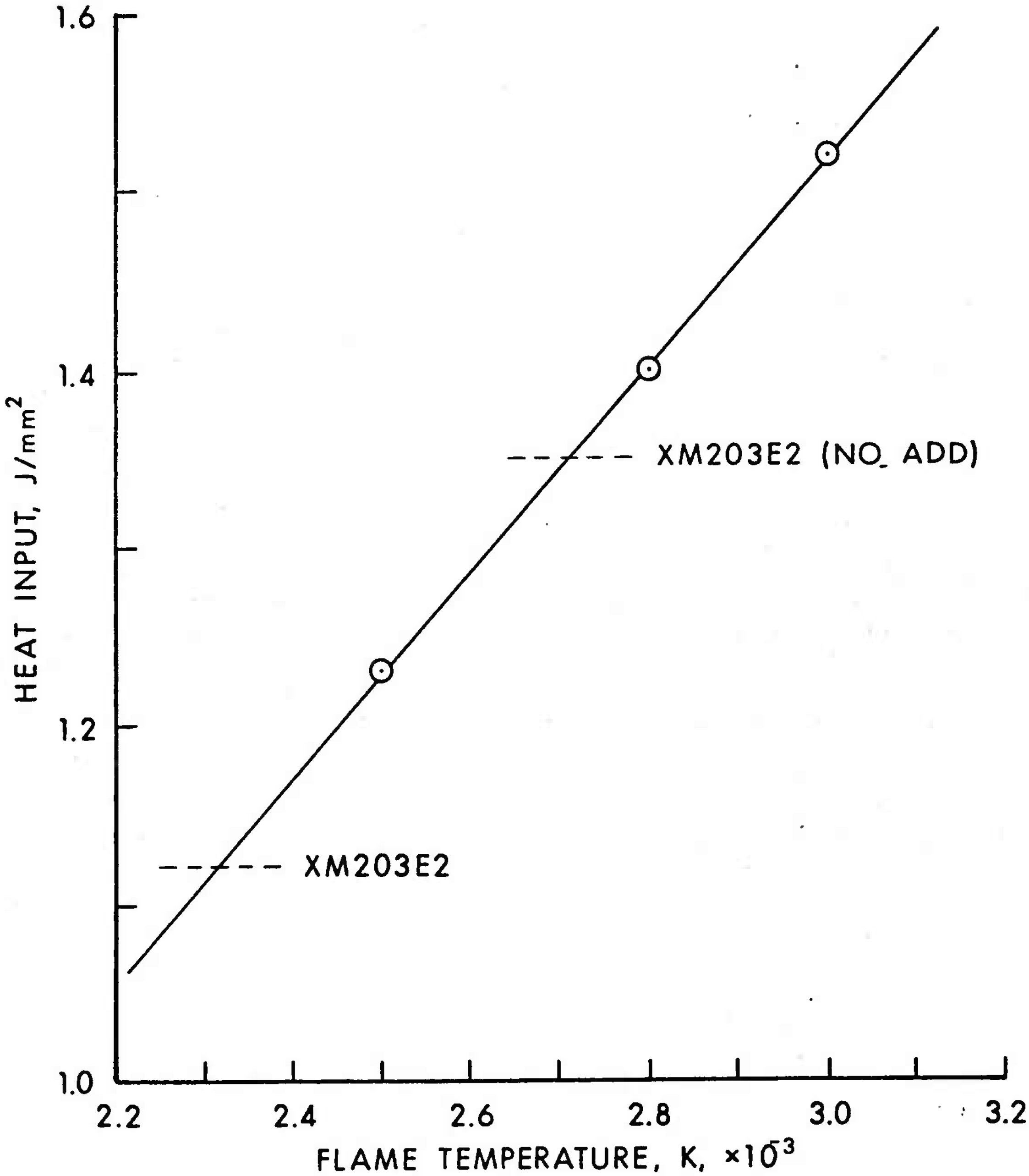

Figure 5. Heat Input vs Flame Temperature for XM208 Charge Minus Additive

IV. CONCLUSIONS

1. Examination of heat transfer data collected by Calspan and BRL shows the heat input from the XM208 charge without additive is thirteen percent greater than the XM203E2 charge without additive in the commencement of rifling region.

2. Heat inputs were computed for these two charges with Nordheim's interior ballistic scheme. The unburned, granular propellant in the XM203E2 charge was assumed to be evenly distributed throughout the gun while the unburned stick propellant in the XM208 charge stayed in the chamber. The computed heat transfer was eighteen percent higher for the stick propellant suggesting stick propellant is more erosive than granular propellant because the unburned propellant stays in the chamber.

3. Heat transfer calculations with the zone 3 charge for the FH70 which uses stick, cordite NQ propellant predict the zone 3 charge will be more erosive than the M203 charge despite the use of a propellant with a 200K lower flame temperature.

4. Heat transfer results show the flame temperature of the propellant in the XM208 charge must be reduced 300K to obtain equivalent heat input for granular, M30A1 propellant. The results also suggest that if the granular M30A1 propellant in the M203 charge is replaced with stick M31E1 propellant, a wear reducing additive will still be needed to maintain current wear life.

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