AD-A241 552

TECHNICAL REPORT BRL-TR-3264

BRL

ELECTROTHERMAL-CHEMICAL PROPULSION AND PERFORMANCE LIMITS FOR THE 120-MM, M256 CANNON

WILLIAM F. OBERLE
KEVIN J. WHITE

SEPTEMBER 1991

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

UNCLASSIFIED

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1991	Final, January 1991 - April 1991

4. TITLE AND SUBTITLE

Electrothermal-Chemical Propulsion and Performance Limits for the 120-mm, M256 Cannon

5. FUNDING NUMBERS

1F2Z9W9X
DGS3
DA31880

6. AUTHOR(S)

William F. Oberle and Kevin J. White

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING MONITORING AGENCY REPORT NUMBER

BRL-TR-3264

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Electrothermal-chemical (ETC) propulsion and potential performance for the M256, 120-mm cannon are examined. The upper performance limit for this cannon is about 15 MJ of projectile muzzle energy. The study also indicates that the most effective use of electrical energy in ETC propulsion is pressure profile control. The addition of electrical energy simply to augment the total energy results in a low (<20%) transfer of energy to the projectile.

14. SUBJECT TERMS

electrothermal-chemical; ETC; capillary; electric guns; hybrid propulsion, working fluids

15. NUMBER OF PAGES

24

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

UNCLASSIFIED

Standard Form 298 (Rev. 2-89)

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

INTENTIONALLY LEFT BLANK.

LIST OF FIGURES

INTENTIONALLY LEFT BLANK.

1. INTRODUCTION

The 120-mm, M256 cannon has been the focus of attention of the tank community as an armament which, hopefully, could be upgraded to meet future armor threats. Although a larger caliber (bore diameter and/or travel) weapon could be used for this purpose, significant logistical and system problems inherent with such a selection could be introduced. However, over the past several years, proponents of electrothermal-chemical (ETC) propulsion have claimed that significant enhancements in muzzle kinetic energy (KE) (increased projectile mass and/or velocity) could be obtained in the current 120-mm, M256 cannon, by tailoring gun pressure profiles to the elastic strength profile for the cannon.

Thus, the objective of this report is to examine the upper practical limits of performance that can be achieved within the 120-mm, M256 gun envelope using the ETC propulsion concept. For this report, a launch mass of 11.4 kg is utilized. Penetrator studies (Giglio-Tos 1989) have indicated that such a launch mass with muzzle KEs on the order of 17 MJ may be required to defeat projected armor threats.

2. PROCEDURE

To assess the potential M256 performance with this launch mass, interior ballistic (IB) calculations are performed to determine bounds on maximum projectile muzzle KE within the current M256 gun envelope. These calculations are not meant to be predictive, but rather to set upper limits on performance consistent with certain assumptions. Constant breech pressure calculations (Oberle and White 1991) are performed in which the maximum breech pressure selected was the maximum pressure that can be used in the gun, consistent with temperature sensitivity.* The calculations assume that the energetic material in the chamber upon ignition instantaneously produces the maximum allowable chamber pressure and maintains this pressure as the projectile is accelerated down bore until all the energetic material is consumed. At this point, a lossless adiabatic expansion is assumed as the projectile moves to the muzzle. These calculations assume that the combustion process is under complete control and can generate sufficient chemical energy in such a manner that,

*Associated with currently fielded rounds.

together with the electrical energy, a constant breech pressure is maintained until burnout of the propellant.

Specifically, the calculation process proceeds as follows:

(1) The maximum chamber pressure is chosen to be 574 MPa, a pressure consistent with the system temperature sensitivity associated with the M829A1 round.

(2) The loading density (charge mass/chamber volume, g/cm^3) is chosen equal to the density of the material; i.e., there was no ullage in the chamber.

(3) A given electrical energy density (EED) (electrical energy/mass propellant, kJ/g) is selected. The electrical energy density is varied from zero up to 3 kJ/g.

(4) A BLAKE (Freedman 1982) thermochemical calculation is performed on each propellant/electrical mixture to determine impetus, covolume, and the ratio-of-specific heats, γ, required for the IB calculation.

(5) The propellant mass and, hence, the chamber volume is varied to achieve maximum muzzle velocity. However, the chamber volume is not allowed to exceed 9.75 liters, the chamber volume of the M256.

(6) No friction or heat losses are considered.

(7) The Lagrange ballistic assumption (Corner 1950) is used; i.e., the gas density between the breech and the projectile is assumed constant. It has been shown that traditional pressure gradient models are applicable to low molecular weight products which may be encountered in ETC propellants (Morrison et al. 1991). Using the Lagrange assumption, the relationship between the pressure on the base of the projectile and the breech pressure is

$$P(\text{breech}) = \left(1 + \frac{c}{2m}\right) P(\text{base}), \tag{1}$$

where c is the charge mass and m is the projectile mass.

(8) A Nobel-Abel covolume equation of state is assumed; i.e.,

$$\bar{P}(V-b) = RT/M, \tag{2}$$

where $\bar{P}$ is the space mean pressure V the free volume, b is the covolume correction to the volume, M the gaseous molecular weight of the combustion products, R the universal gas constant, and T the average gas temperature.*

(i) The gun/projectile envelope is:

Chamber volume (max)	=	9.75 l
Projectile mass	=	11.4 kg
Projectile travel	=	4.75 m
Maximum pressure	=	574 MPa

(j) The impetus, I, is defined as,

$$I = RT/M. \tag{3}$$

3. THERMOCHEMICAL AND INTERIOR BALLISTIC SIMULATION RESULTS

Results for the thermochemical calculations for the various electrical energy density inputs are given in Table 1. The propellant (working fluid) consists of a H202 (70%)/octane mixture in a mass ratio to maximize the impetus. The density of the mixture is 1.26 g/cm^3.

*The right-hand side of this equation must be multiplied by the mass ratio, mass gas products/mass of propellant, if a significant amount of condensed phase products are produced. The assumption here is that condensed phase products do not give rise to pressure and, hence, contribute nothing to the acceleration of the projectile. This factor will account for this. For most propellants, this factor is nearly equal to 1.

Table 1. Thermochemical Properties of H_2O_2/Octane for Various EED and JA2

EED (kJ/g)	Impetus (J/g)	gamma	covolume (cm^3/g)	T(flame) (K)
0	1,019	1.2[illegible]	0.539	2,646
1/2	1,098	1.2[illegible]	0.576	2,846
1	1,174	1.2033	0.607	3,030
3	1,449	1.1942	0.705	3,654
JA2 (Reference Solid Propellant)				
0	1,144	1.2254	0.991	3,424

Results for the gun calculations for the four EEDs given in Table 1 are given in Table 2 together with results using the solid propellant JA2. Column 5 through 7 represent the partitioning of the total energy (column 4) between projectile kinetic energy, gas kinetic energy, and gas internal energy. The values are determined using the equation,

$$\frac{Ic}{\gamma - 1} = \frac{1}{2} mv^2 \left(1 + \frac{c}{3m}\right) + \frac{\bar{P}V}{\gamma - 1}, \tag{4}$$

where I is the propellant impetus, m the projectile mass, v projectile velocity, c charge mass, $\bar{P}$ space mean pressure, V total chamber and tube volume, and γ the ratio-of-specific heats.

Several observations can be made from Tables 1 and 2.

(1) Introducing electrical energy is equivalent to producing a propellant with increased impetus (column 2, Table 1). However, for this formulation, the flame temperature for an EED of 3 kJ/g, 3,654 K, is considerably higher than for JA2, 3,424 K, (column 5, Table 1).

(2) Increased projectile KE is obtained as the amount of electrical energy is increased (columns 2 and 5, Table 2).

(3) Adding 37 MJ of electrical energy (column 2, Table 2) results in only a modest increase in projectile KE of 3.5 MJ (column 5, Table 2), when compared to the case where no

Table 2. Ballistic Calculation Results

EED (kJ/g)	EE (MJ)	Impetus (J/g)	Total Energy (MJ)	Projectile KE (MJ)	Gas KE (MJ)	Internal Energy (MJ)	Charge Mass (kg)	Burnout Distance (m)	Ballistic Effic. (%)	EE Converted to Projectile KE (%)
0	0.0	1,019	58.5	13.6	4.9	40.0	12.3	1.57	23	—
1/2	6.2	1,098	65.0	14.4	5.2	45.4	12.3	1.76	22	13
1	12.4	1,174	71.7	15.1	5.5	51.1	12.3	1.94	21	12
3	37.0	1,449	92.1	17.1	6.2	68.8	12.3	2.54	19	9
JA2										
0	0.0	1,144	51.3	14.3	4.2	32.8	10.1	1.64	28	—

electrical energy was added. This represents a conversion efficiency of 9% (column 11, Table 2). The majority of the added electrical energy goes into the internal energy of the gas, 28.8 MJ of the 37 MJ (column 7, Table 2).

(4) Thus, for the system under consideration, the primary role of the electrical energy in the interior ballistic cycle should be to control the chemical energy release, and hence, the pressure profile, rather than supplementing the propellant energy. Control of the gas generation rate is required if the advantages offered by high volumetric energy density propellants which can be utilized with ETC are to be exploited.

(5) The optimized charge mass (column 8, Table 2) is the same for all electrical energy inputs. It is equal to the maximum possible loading density. If the chamber volume is allowed to vary beyond 9.75 liters, the optimum charge mass would have increased. Thus, an additional performance enhancement could be achieved by increasing the chamber volume. For JA2, a charge mass of 10.1 kg is used. This represents a solid propellant maximum c' arge which can be loaded in the 9.75 liter chamber.

(6) The total energy (column 4, Table 2) is not the sum of the chemical energy (58.5 MJ in each firing) and electrical energy (column 2, Table 2). This is a result of the thermochemical calculation and the physical factors are under investigation.

4. PHYSICAL INTERPRETATION

To illustrate the interior ballistic process with and without the addition of electrical energy pressure vs. displacement graphs are shown for EE = 0.0 MJ (Figure 1) and EE = 37 MJ (Figure 2). In addition, projectile position at various times is shown below the graph in Figure 2. Each curve on the figures illustrate the pressure profile at a different time. The corresponding projectile base pressures are shown in Figure 3 and 4.

In Figures 1 and 2, at

t0, the projectile has not moved (it is located at 0.87 m, the end of the chamber).* The pressure is 574 MPa.

t1, the projectile has moved a small distance and the Lagrange gradient has been immediately established.

t2, the projectile has moved to the propellant burnout position.

t3, the adiabatic expansion has started with corresponding drop in pressure, and the projectile has moved down bore.

t4, the projectile has moved to muzzle exit.

The pressure profile between the breech (displacement = 0) and the projectile base (Figures 1–2) is not actually linear. However, the curves do qualitatively illustrate the pressure profile.

5. DISCUSSION

(1) In Figure 2, EE = 37 MJ, it is clear that the burnout position, t2, is moved further down bore and that the muzzle pressure is considerably higher than for EE = 0.0 (Figure 1 and column 9, Table 2). Moreover, the average pressure when the projectile is at muzzle exit, t4, is substantially higher in Figure 2 than in Figure 1. The projectile base pressures for both

*In these calculations, the chamber has the same diameter as the tube, 120 mm. Consequently, to give the correct chamber volume, the chamber must be 0.87 m in length. In the actual M256 cannon, the chamber is 0.55 m in length (see Figure 5).

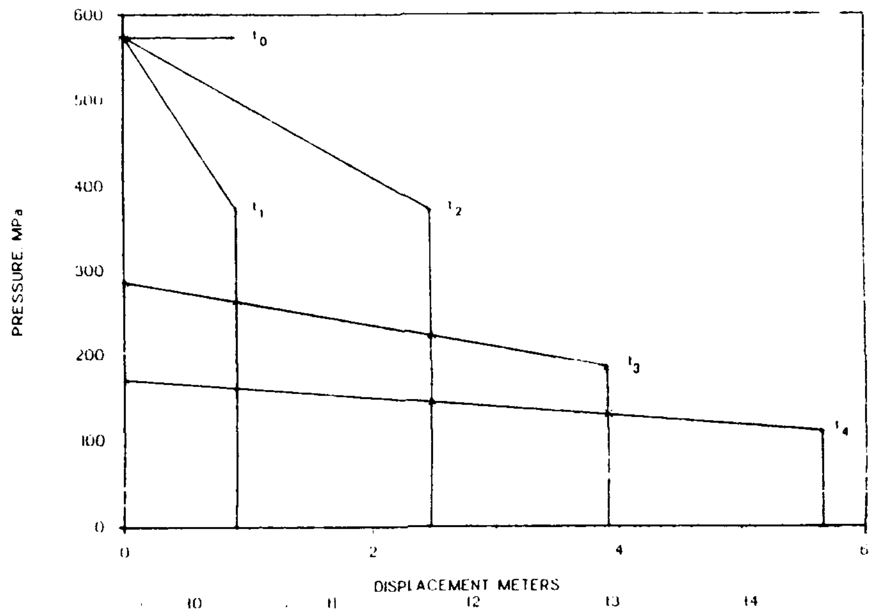

Figure 1. Pressure-Displacement Profiles at Selected Times t0...t4, EE = 0.0 MJ.

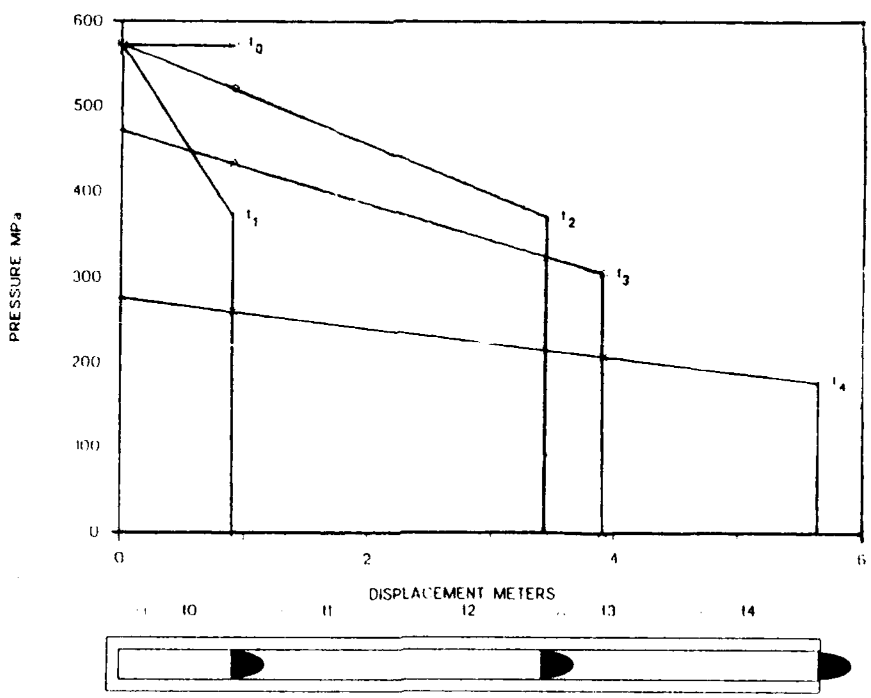

Figure 2. Pressure-Displacement, EE = 37 MJ.

Figures 1 and 2 are shown in Figures 3 and 4. The respective areas (Figures 3 and 4) represent the work done on the projectile and, hence, the projectile energies. The residual energy in the gas when the projectile reaches muzzle exit is $P_aV/(\gamma-1)$, where P_a is the average pressure at t4 and V the chamber plus tube volume. Since γ-1 is on the order of 0.2, the gas internal energy (column 7, Table 2) is approximately $5P_aV$.

(2) The energy added by the electrical input to the system is partitioned among the various degrees of freedom (gas velocities v_x, v_y, v_z) as well as the internal degrees of freedom. However, only the gas velocity associated with the projectile motion, v_x, is useful for projectile energy. Thus, the electrical energy is partitioned between many degrees of freedom, which leads to reduced efficiency when considering only projectile KE.

(3) The limiting factor in performance for gas-driven guns is the existence of a pressure gradient which lowers the projectile base pressure relative to the chamber pressure. This lower base pressure results from the fact that energy is required to accelerate the propellant gases down the tube. The relation between the breech and base pressure is given by,

$$P(\text{base}) = \frac{P(\text{breech})}{1 + \frac{c}{2m}} \tag{4}$$

if the Lagrange ballistic assumption is utilized. As shown in Equation 4, to increase the base pressure, the following three approaches are available: (1) increase the breech pressure, (2) increase the projectile mass (m) while fixing the charge mass, and (3) decrease the charge mass (c) while fixing the projectile mass. Since maximum breech pressure and projectile mass are fixed by system requirements, the only approach for increasing base pressure and, thus, performance within a given gun system for which the Lagrange assumption is valid is by reducing the charge mass. If the same or more chemical energy is to be provided, then a propellant, either liquid or solid, with substantially higher volumetric energy density is required. *It is exactly this potential to utilize higher volumetric energy density propellants which is the major benefit, in terms of performance, offered by ETC.*

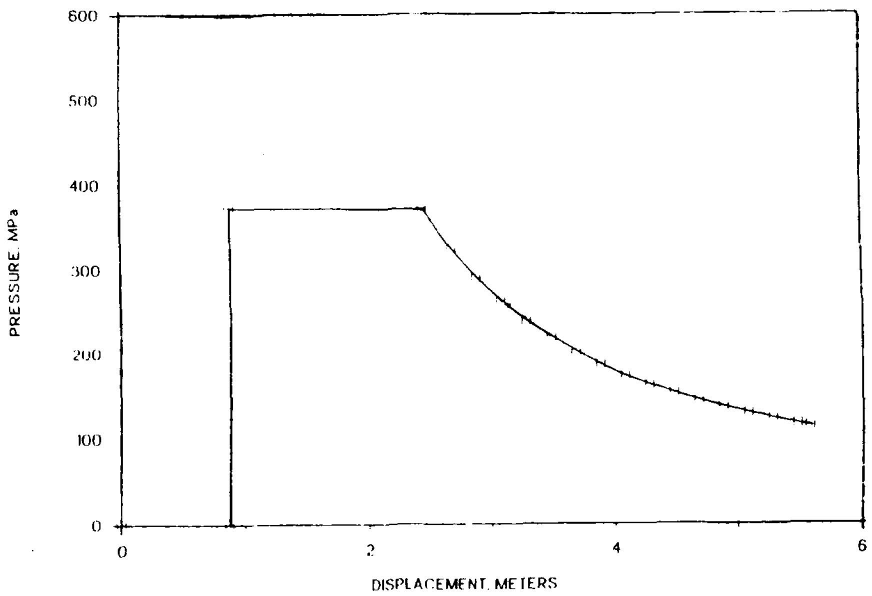

Figure 3. Projectile Base Pressure, EE = 0.0 MJ.

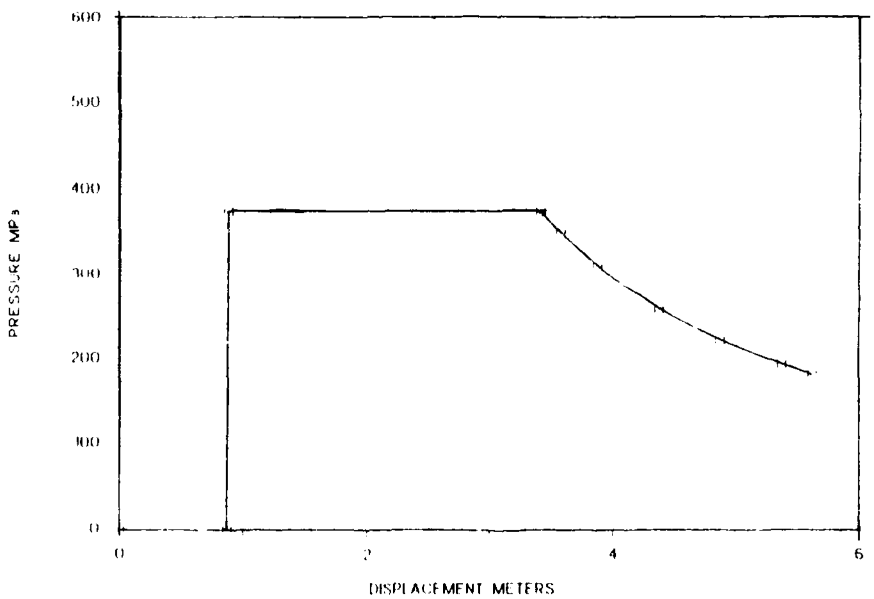

Figure 4. Projectile Base Pressure, EE = 37 MJ.

(4) Besides reducing the pressure gradient, another approach to increasing projectile KE is to reduce the gas internal energy. One method of extracting a greater percentage of the internal energy of the gases is to lengthen the gun tube, allowing gas expansion to lower the residual gas pressure. The calculations of Table 3 are identical to Table 2 except that the gun tube is lengthened to 47.5 m (obviously unrealistic). It is seen that the ballistic efficiency has nearly doubled to 43% and that 28%, ([35.2 - 24.9]/37) of the 37 MJ of electrical energy has been converted into muzzle energy.

Table 3. Ballistic Calculation Results, Travel = 47.5 m

EED (kJ/g)	EE (MJ)	Total Energy (MJ)	Projectile KE (MJ)	Gas KE (MJ)	Internal Energy (MJ)	Charge Mass(c) (kg)	Burnout Distance (m)	Ballistic Effic. (%)
0	0.0	58.5	24.9	9.0	24.6	12.3	1.57	43
3	37.0	92.1	35.2	12.7	44.2	12.3	2.54	38

(5) Figures 6 and 7 show the base pressure profiles for the calculations for EE = 0.0 MJ and EE = 37 MJ. Superimposed on those curves is the elastic strength pressure (ESP) profile for the M256 gun tube shown in the horizontal axis (Hasenbein 1991). Distance is measured from the rear face of the M256 gun tube (see Figure 5). A substantial drop in tube strength is observed at 2.41 m (1.86 m of projectile travel). The autofrettage of the barrel ends at this point which is just short of the bore evacuator (Hasenbein 1991). It is clear that the gas pressure in Figure 7 exceeds the allowable ESP for the gun tube. Examination of column 9, Table 2, indicates that to ensure that burnout occurs before 1.86 m of travel, muzzle energy will be limited to somewhere between 14.5 and 15 MJ, for the M256 cannon, even under the ideal conditions described in this report.

(6) The pressure profiles for EE = 0.0 MJ and 37 MJ (Figures 1 and 2), along with the ESP curve, are plotted in Figures 8 and 9. As discussed earlier, the drop in pressure from the chamber (574 MPa) to the projectile base (373 MPa) is due to the Lagrange pressure gradient which depends on the propellant charge to projectile mass ratio. If the charge mass could be

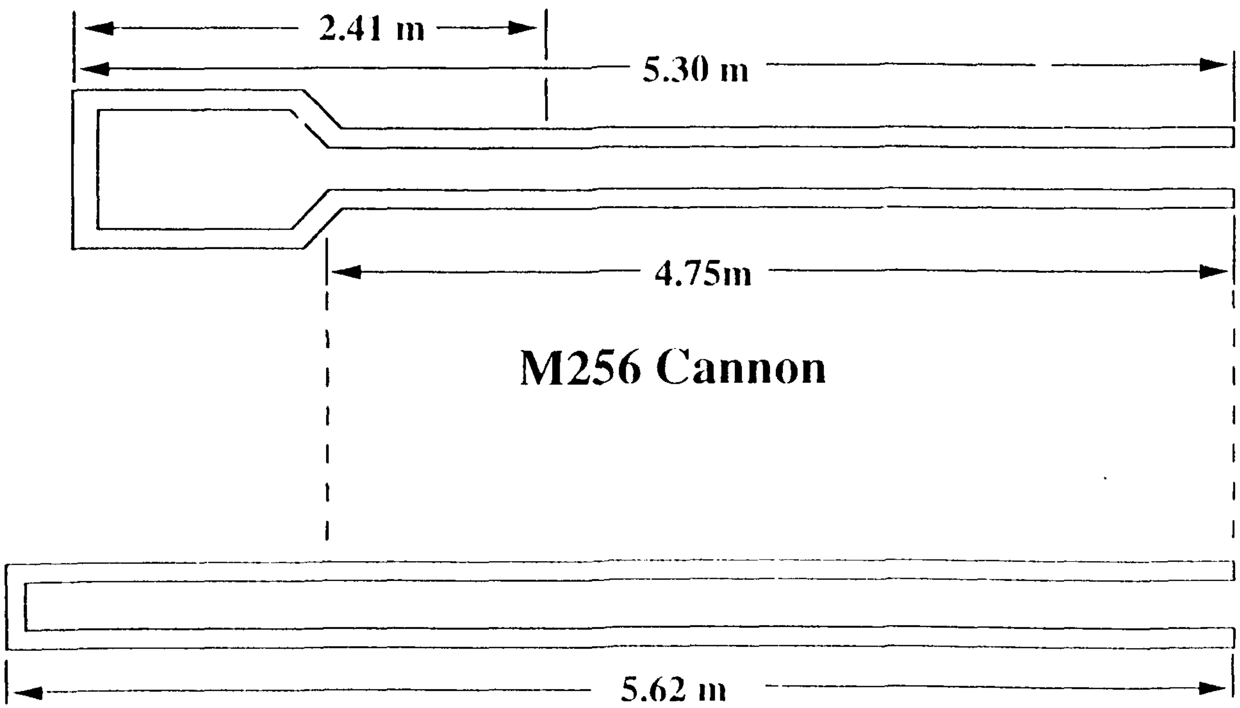

Figure 5. M256 Cannon and One-Dimensional Equivalent. End of Autofrettage, 2.41 m.

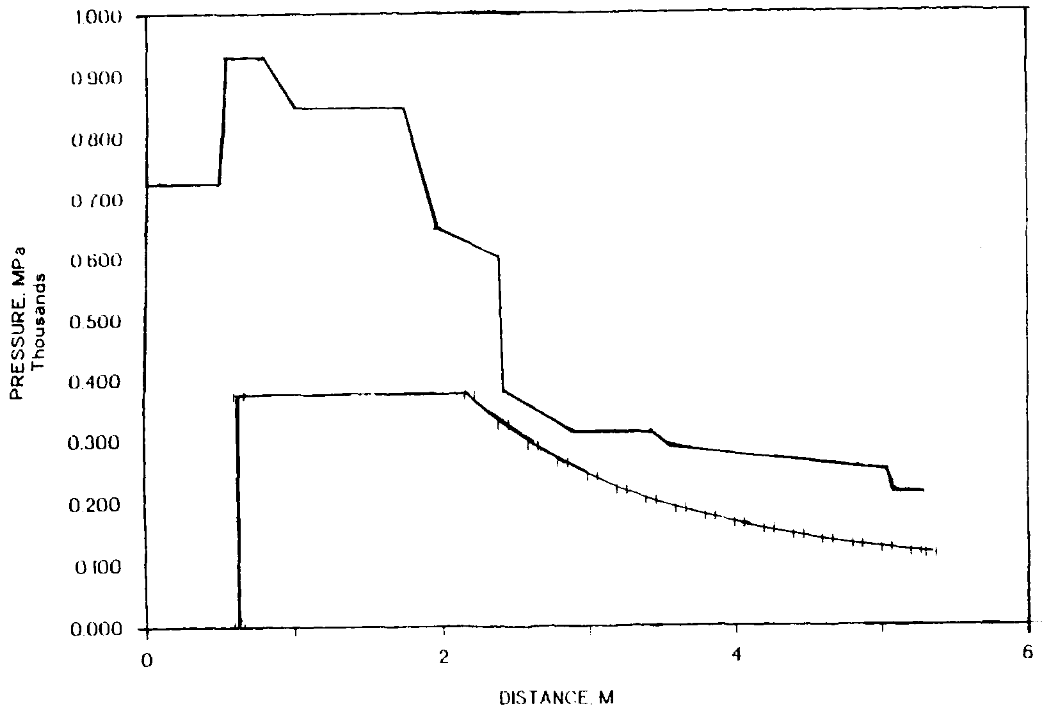

Figure 6. Base Pressure, EE = 0.0 MJ, and M256 Cannon Elastic Strength Pressure (ESP).

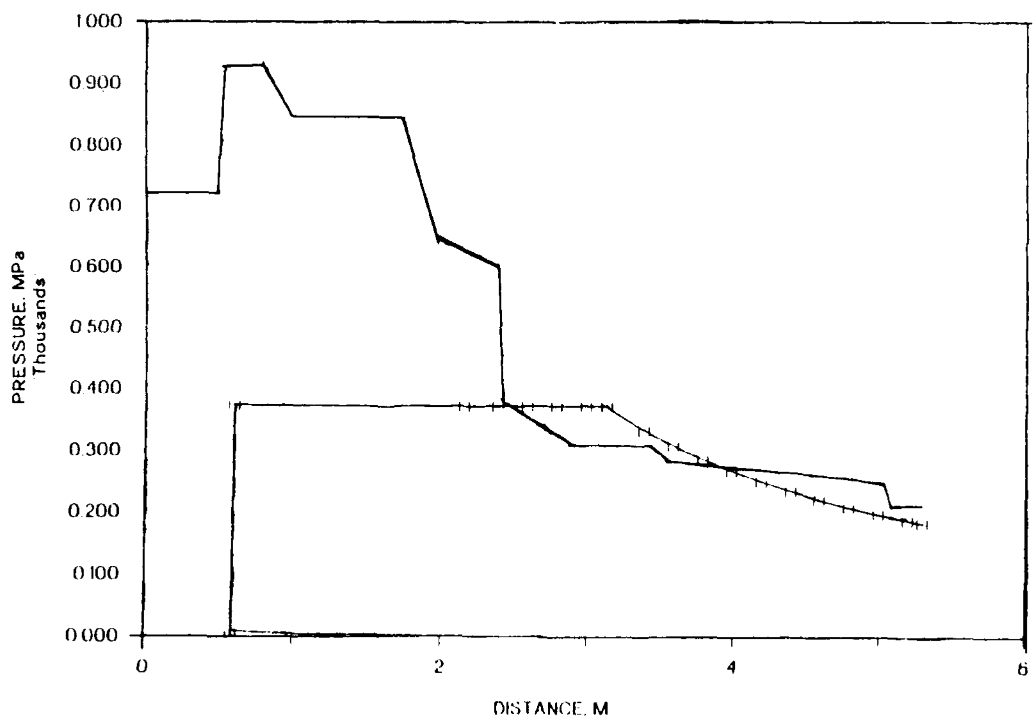

Figure 7. Base Pressure, EE = 37 MJ, and M256 Cannon Elastic Strength Pressure (ESP).

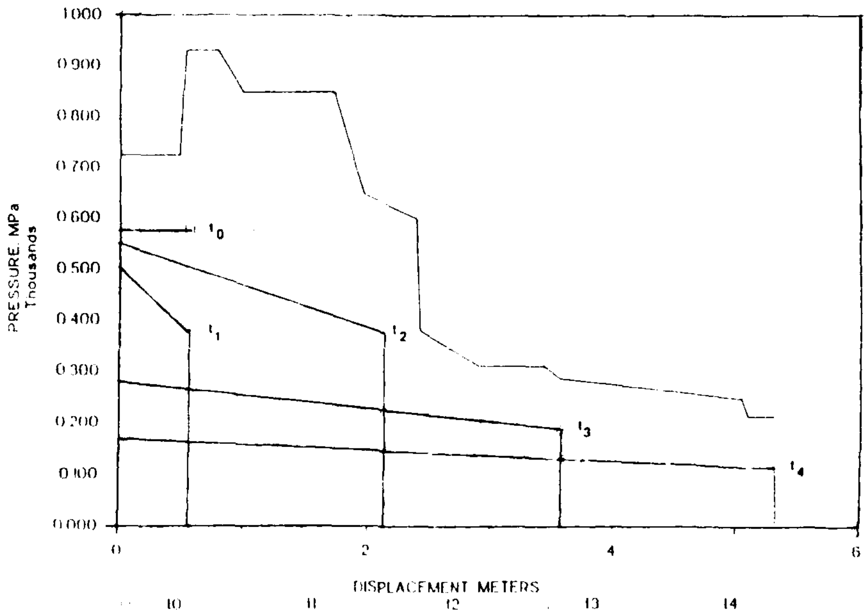

Figure 8. Pressure Profiles, EE = 0.0 MJ, and M256 Cannon Elastic Strength Pressure (ESP).

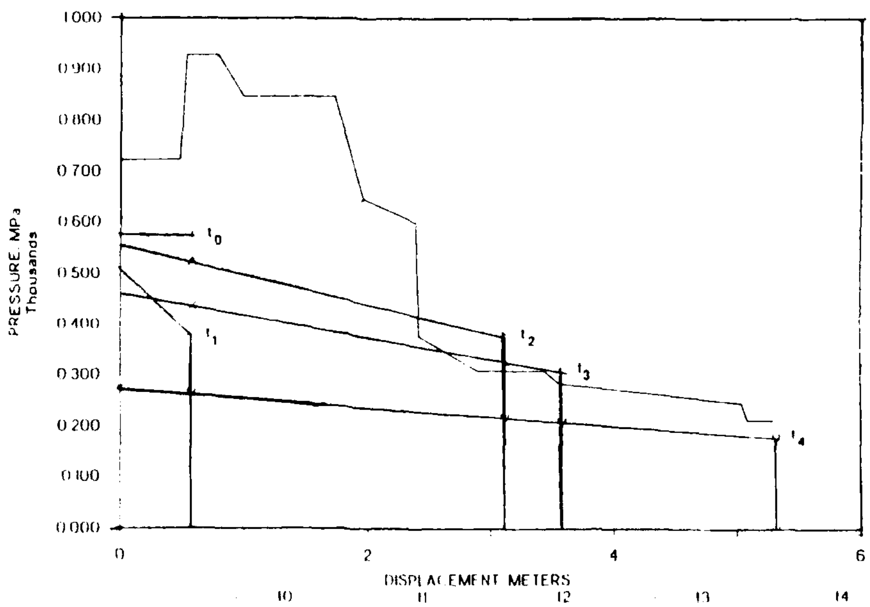

Figure 9. Pressure Profiles, EE = 37 MJ, and M256 Cannon Elastic Strength Pressure (ESP).

reduced by using a much more energetic propellant, it would be possible to increase the base pressure at t1 and t2 to take advantage of the gun tube strength in that region. Other techniques, such as a traveling charge, could also be employed to increase base pressure in that critical region.

(7) *It is clear from these calculations that it is not possible to generate a pressure profile within the M256 cannon, assuming a constant breech pressure profile, to take full advantage of the gun tube strength. It is not possible, assuming a Lagrange gradient and adiabatic expansion, to arbitrarily generate a pressure profile that would mimic the elastic strength pressure profile of the gun tube.*

(8) It should be further noted that the base pressure curve must be substantially less than the ESP curve since this is the upper limit of the pressure for a single shot. Allowance must be made for multiple shots, fatigue life, and for increases in operating pressures due to increased operating temperatures.

6. CONCLUSIONS

It is clear from an examination of Table 2 that the potential for increased performance from ETC propulsion compared with conventional solid propellant charges comes from the potential to utilize propellant materials with increased energy density. Consequently, the primary role of the electrical energy input should be to control the chemical energy release for reproducible ballistics at weapon level performance.

To take advantage of the gun tube strength, it is necessary to decrease the Lagrange gradient either by a smaller charge mass or by bringing about a traveling charge effect.

Arbitrary ballistic pressure profiles cannot be generated to conform to the elastic strength profile of a gun tube, given traditional interior ballistic pressure gradients.

The maximum muzzle energy for the M256 cannon is between 14.5 and 15 MJ. An important reason for this limitation is the termination of the autofrettage procedure at the bore evacuator. A modification to the M256 ESP could result in increased performance potential.

7. REFERENCES

Corner, J. "Theory of the Interior Ballistics of Guns." New York: John Wiley & Sons, Inc., 1950.

Freedman, E. "BLAKE - A Thermodynamics Code Based on TIGER: User's Guide and Manual." BRL-TR-02411, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1982.

Giglio-Tos, L. Private communication. U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1989.

Hasenbein, R. Private communication. Watervliet Arsenal, NY, 1991.

Morrison, W. F., G. P. Wren, W. F. Oberle, and R. Richardson. "The Application of Lagrange and Pidduck-Kent Gradient Models to Guns Using Low Molecular Weight Gases." U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD (to be published).

Oberle, W. F., and K. J. White. "Electrothermal Gun Technology and Performance: An Analysis of Small and Large Caliber Ballistic Data." BRL-TR-3238, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1991.

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers below will aid us in our efforts.

1. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ______________________________

2. How, specifically, is the report being used? (Information source, design data, procedure, source of ideas, etc.) ______________________________

3. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ______________________________

4. General Comments. What do you think should be changed to improve future reports? (indicate changes to organization, technical content, format, etc.) ______________________________

BRL Report Number BRL-TR-3264 Division Symbol ____________

Check here if desire to be removed from distribution list. ____

Check here for address change. ____

Current address: Organization ______________________

Address ______________________

DEPARTMENT OF THE ARMY
Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

OFFICIAL BUSINESS

NO POSTAGE NECESSARY IF MAILED IN THE UNITED STATES

BUSINESS REPLY MAIL
FIRST CLASS PERMIT No 0001, APG, MD

Postage will be paid by addressee

Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066