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The Application of Electrothermal-Chemical (ETC) Propulsion Concepts to Reduce Propelling Charge Temperature Sensitivity

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ARL-TR-1509 September 1997

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ARL-TR-1509 **September 1997**

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Abstract

The concept of the propelling charge temperature coefficient and its impact on gun performance is explored. Ballistic factors, in addition to the propellant burn rate dependence on initial temperature, that often increases the magnitude of the propelling charge temperature coefficient, are identified and discussed. Techniques for moderating the effects of the propelling charge temperature coefficient are presented, with special emphasis on the utilization of electrothermal-chemical (ETC) concepts.

Acknowledgments

The authors would like to thank Messrs. Ron Anderson and Andy Brant for their time and effort in reviewing the manuscript.

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1. Introduction

In designing propelling charge configurations for gun applications, a wide range of factors must be considered in optimizing performance. An especially complicating factor in the development of charge configurations for Army applications is the operational requirement that the charge functions over a wide temperature range, typically $-32°$ C to $52°$ C. Unfortunately, the ballistic performance of gun propelling charges, as measured by maximum breech pressure or projectile velocity, is dependent upon the initial temperature of the charge, generally decreasing as the initial charge temperature drops. The effect on ballistic performance associated with the initial temperature of the propelling charge is a function of a wide range of ballistic parameters. For example, one of the more important parameters is the burn rate of the propellant utilized in the charge. The dependence of the propellant burn rate on initial propellant temperature is illustrated in Figure 1 for experimental closed-chamber firings using the double base propellant JA2 and clearly shows the decrease in propellant burn rate as the initial propellant temperature drops. The burn rates were computed using the closed-chamber data reduction code BRLCB (Oberle and Kooker 1993). Thus, a propelling charge configuration optimized assuming an ambient propellant temperature, $21°$ C, could well exceed one of the system design parameters, usually maximum pressure, when the initial propellant temperature increases. As a consequence, charge optimization and design for Army applications are generally established with the initial propellant temperature at the maximum of the required operational temperature range, $52°$ C. The nominal or ambient temperature performance of the charge is the performance that results when the charge configuration established at the hot temperature is fired with an initial propellant temperature of $21°$ C.

To illustrate the impact that propelling charge sensitivity to initial temperature can have on performance, consider the M829A1 tank round fired in the standard M256 tank cannon. Details of the M829A1/M256 configuration are given in Table 1. Propellant burn rates are based upon the computed values in Figure 1, with an adjustment in the burn rate for the conditioned hot temperature case, since the upper operational temperature for this round is $52°$ C, not $65°$ C. Values for the burn rates are given in Table 2.

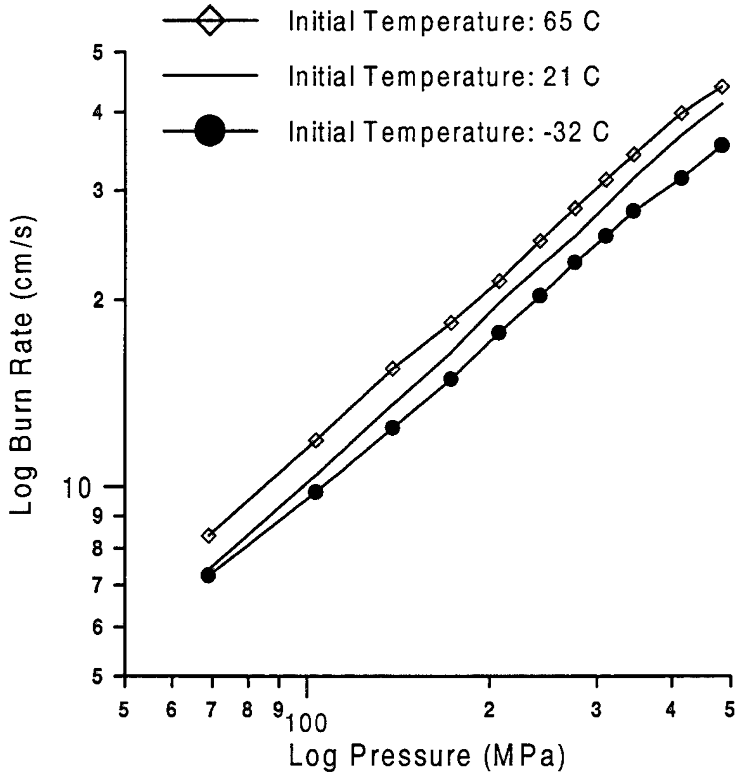

Figure 1. Temperature Dependence of the Propellant Burn Rate for JA2.

Breech pressure versus time histories, assuming initial propelling charge temperatures of 52° C and 21° C for the M829A1/M256 configuration, are shown in Figure 2. Although the curves in Figure 2 result from interior ballistic calculations using the interior ballistic code IBHVG2 (Anderson and Fickie 1987), the results match fielded performance. At the higher initial temperature, the maximum breech pressure is 669 MPa with a corresponding velocity of 1,623 m/s. For the ambient initial temperature simulation, the corresponding values are 558 MPa and 1,568 m/s. This represents a decrease of 17% in maximum breech pressure and a 3.4% drop in velocity, due entirely to the propelling charge dependence on initial temperature. Similar calculations, assuming an initial propelling charge temperature of −32° C, results in a maximum pressure of 482 MPa, and a velocity of 1,508 m/s. Figure 3 summarizes the temperature sensitivity results for this specific gun and charge configuration.

If the decrease in maximum breech pressure, and the corresponding drop in muzzle velocity associated with the decrease in initial propelling charge temperature could be minimized, then a

Table 1. M829A1/M256 Configuration

Parameter	Value
Tube Type	M256, Smooth Bore
Bore Diameter	120 mm
Free Chamber Volume	9.5536 liters
Projectile Travel	474.98 cm
Expansion Ratio	6.612
Projectile Mass	8.98 kg
Propelling Charge: Primer	0.0155 kg, Benite
Propelling Charge: Case	0.655 kg, Combustible
Inert Cap	0.088 kg
Main Charge: Type	JA2
Main Charge: Geometry	19-perf hex
Main Charge: Mass	7.9 kg

Table 2. Burn Rates of JA2 Based Upon the Data of Figure 1

Temperature Condition (cm/s)	Burn Rate Law and Pressure Range (MPa)
Burn Rate at −32° C	$0.33305 * P^{0.7162}$; $P < 70$
Burn Rate at −32° C	$0.17013 * P^{0.8796}$; $P > 70$
Burn Rate at 21° C	$0.35890 * P^{0.7162}$; $P < 70$
Burn Rate at 21° C	$0.18333 * P^{0.8796}$; $P > 70$
Burn Rate at 52° C	$0.39827 * P^{0.7162}$; $P < 70$
Burn Rate at 52° C	$0.19953 * P^{0.8796}$; $P > 70$

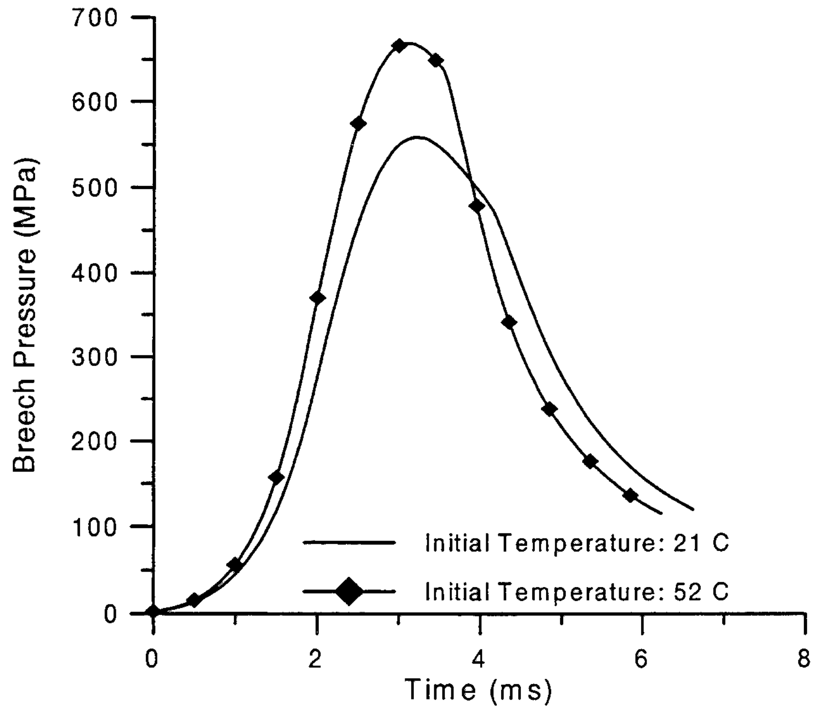

Figure 2. Breech Pressure Versus Time for the M829A1/M256 Configuration With Initial Propellant Temperature 21° C and 52° C.

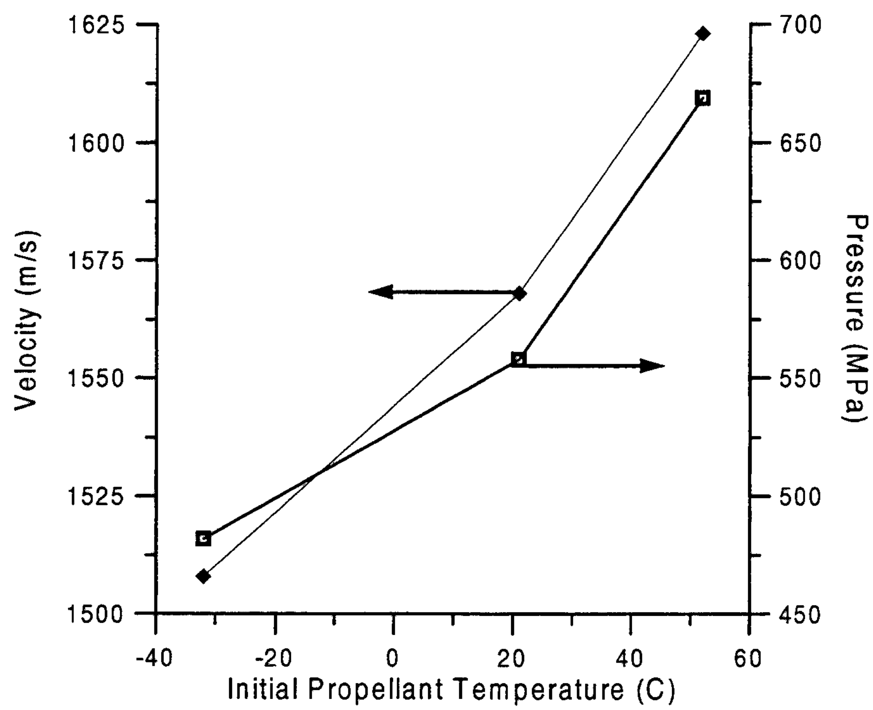

Figure 3. Summary of Temperature Sensitivity for M829A1/M256 Configuration.

significant increase in velocity, +3.4% for the ambient temperature case and +7.6% for the cold temperature case for the M829A1/M256, could be realized.

The objective of this report is to explore potential mechanisms or techniques for moderating or eliminating decreases in ballistic performance resulting from the initial propelling charge temperature. This has been a goal of interior ballisticians for over 50 yr, and an extensive amount of effort has been devoted to this end. In this work, the focus is on the potential use of electrothermal-chemical (ETC) propulsion concepts to achieve this goal. However, to provide a perspective on the difficulties and efforts associated with this problem, other techniques besides those associated with ETC are discussed. The remainder of the report is organized as follows: first, the concepts of the propellant temperature coefficient and propelling charge temperature sensitivity are introduced; next, interior ballistic factors that have a tendency to exacerbate the drop in maximum pressure and velocity (i.e., factors affecting the propelling charge temperature sensitivity) are discussed; and, finally, techniques for minimizing the pressure/velocity drop are presented. Included is a brief discussion of traditional approaches in addition to newer mechanisms being proposed, which are associated with ETC propulsion concepts.

2. Propellant Temperature Coefficient and Propelling Charge Temperature Sensitivity

The response of the solid propellant combustion rate (i.e., burn rate) to changes in the initial propellant bulk temperature is termed "propellant temperature coefficient". The concept has been studied extensively by both the rocket and gun research communities. Within the rocket community, the propellant temperature coefficient is typically expressed as a normalized change in propellant burn rate due to a change in propellant temperature at a constant pressure (Cohen and Flanigan 1983). However, due to the much higher pressures associated with gun ballistics (hundreds of megapascals for guns versus tens of megapascals for rockets) and the greater dynamic pressures observed in guns, the temperature coefficient measurements utilized by the rocket community become substantially less accurate when applied to the gun environment (Cohen and Flanigan 1983). As a consequence, for gun applications, the propellant temperature coefficient is often defined as the percent change in deduced closed-chamber burn rates for different initial propellant temperatures. In computing the percent change in the burn rates, it is often assumed that the exponent, n, in the traditional $r = bP^n$ burn rate law remains fixed, with all the change occurring in the coefficient b. Physically, this corresponds to assuming that the slope of the burn rate curves for different initial propellant temperatures on the log of burn rate versus log of pressure graph remains constant. As illustrated in Figure 1, this assumption does not appear to be unreasonable for JA2 propellant. However, it should be noted that this is not always the case (e.g., M30 propellant [Hall 1990]). Referring to the burn rates shown in Figure 1, the percent change in burn rate for the propellant with initial temperature 65° C is +11.2%, compared to the propellant with initial temperature 21° C. For the propellant with initial temperature −32° C, the percent change in burn rate with respect to the ambient burn rate is −7.2%. Table 3 summarizes the values for the $r = bP^n$ burn rate law at each temperature for the data shown in Figure 1, assuming that the exponent remains constant.

Table 3. Coefficient and Exponent for the $r = bP^n$ Burn Rate Laws For the Double Base Propellant JA2 Shown in Figure 1

Initial Propellant Temperature	Coefficient ($cm/s\text{-}MPa^n$)	Exponent (-)
65° C	0.20386 (+11.2%)	0.8796
21° C	0.18333	0.8796
-32° C	0.17013 (-7.2%)	0.8796

Since more than just the propellant temperature coefficient determines the drop in ballistic performance as initial charge temperature deceases, the most common approach to quantifying the dependence of ballistic performance on initial charge temperature in guns is to measure the change in maximum breech pressure per unit change in initial charge temperature. This parameter is referred to as the propelling charge temperature sensitivity. For example, for the M829A1/M256 system used in the introduction, the propelling charge temperature sensitivity associated with an initial propellant change from 52° C to 21° C is

$$\text{Propellant Charge Temperature Sensitivity} = \frac{669 - 558}{52 - 21} = 3.58\ \text{MPa/°C}.$$

It should be noted that the propelling charge temperature sensitivity is not a measure of the propellant burn rate dependence on temperature (i.e., propellant temperature coefficient). The propellant temperature coefficient is just one component contributing to the propelling charge temperature sensitivity.

3. Factors Impacting the Propelling Charge Temperature Sensitivity

Ballistic parameters affecting the propelling charge temperature sensitivity include, but are not limited to: (1) propellant temperature coefficient; (2) propellant grain geometry; (3) the exponent of the burn rate law; (4) deterrent layers coating the outside of the propellant grain; (5) ignition delays and flamespread in the propelling charge; (6) propellant loading density (ratio of charge mass to free chamber volume); (7) grain breakup, especially at cold temperatures; (8) grain softening at high temperatures; (9) projectile mass; and (10) projectile travel and expansion ratio.

The impact of the propellant temperature coefficient on ballistic performance was illustrated in the introduction. In this section, the next five parameters (2) – (6), previously listed, are discussed. Grain breakup (7) and grain softening at high temperatures (8) deal more with the mechanical properties of the propellant and is outside the scope of this paper. Projectile mass (9) and projectile travel and expansion ratio (10) are generally fixed parameters for a gun system and cannot be modified. For additional details reference is made to Kopicz, Kuo, and Thynell (1995) and Kruczynski and Hewitt (1991) and the references therein. Extensive information is also available in Anderson and Puhalla (1991).

3.1 Effect of Propellant Grain Geometry. Propellant grains are classified as having either a progressive, neutral or degressive (regressive) geometry, depending on whether the reacting surface of the grain increases, remains constant, or decreases as the depth burn of the grain increases. In general, the more progressive the grain geometry, the greater the ballistic performance (i.e., muzzle velocity) for a given initial grain temperature and gun/charge configuration. The reason for this is that as the projectile moves down-bore, the volume in which the propellant is burning increases. For maximum velocity, the pressure should remain constant at the highest permissible breech pressure. To accomplish this, the mass generation rate should also increase. An increasing propellant surface area is one approach to achieve the required increased mass generation rate. Figure 4 illustrates the geometric progressivity for various grain geometries utilized for gun propellants.

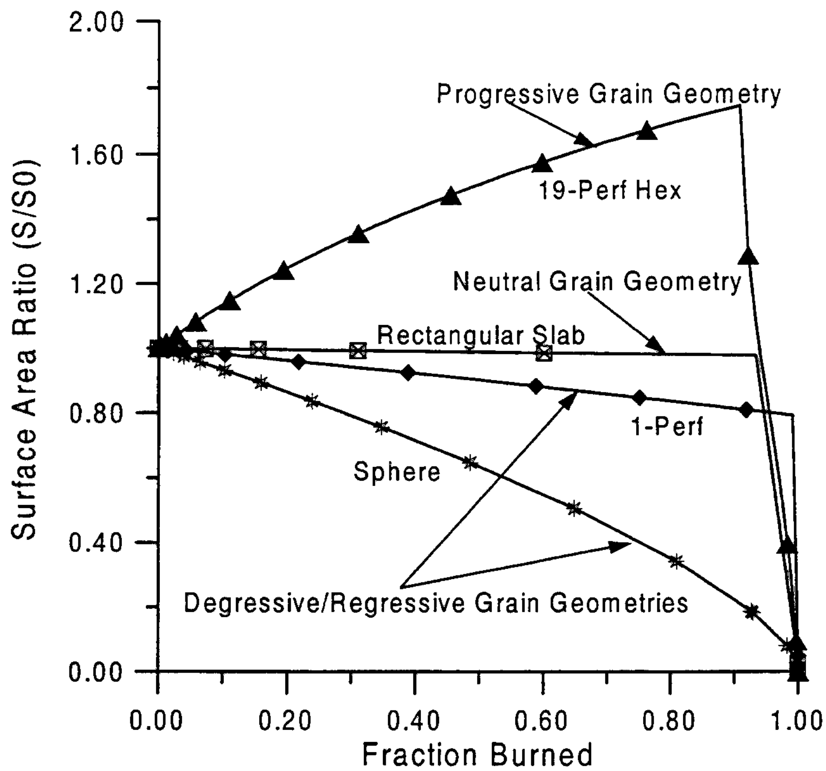

Figure 4. Surface Area Ratio for Typical Gun Propellant Geometries as a Function of Depth Burned.

Since the progressivity of the grain impacts the mass generation rate and ultimately the maximum breech pressure, it would be expected that the grain geometry would also affect the propelling charge temperature sensitivity (Anderson and Puhalla 1991). To determine the possible impact of grain progressivity, IBHVG2 calculations for three different geometries representing each of the different geometric progressivities (19-Perf Hex, Slab, and Sphere) were performed. For each of the grain geometries, the M829A1/M256 configuration was used, and the burn rates for the calculations were those given in Table 2, roughly a 9% difference between the hot temperature and ambient temperature burn rates. Finally, for each geometry, the charge mass and web were varied to produce the maximum velocity with the hot temperature pressure constraint of 669 MPa. The charge mass and web were then held fixed for the ambient temperature simulations. This is the typical charge establishment process utilized in large-caliber gun firing programs. Results of the simulations are given in Table 4. For this configuration from Table 4, there is a 61% increase (2.23 to 3.58) in the propelling charge temperature sensitivity in going from the regressive sphere geometry to the much more progressive 19-perf hex geometry.

Table 4. Propelling Charge Temperature Sensitivity for Various Grain Geometries With Charge Mass and Web Chosen to Meet the Pmax Constraint at Hot Temperature

Grain Geometry	Pmax/Velocity at 21° C (MPa - m/s)	Pmax/Velocity at 52° C (MPa - m/s)	Propelling Charge Temperature Sensitivity (MPa/° C)
Sphere	600/1417	669/1472	2.23
Slab	585/1547	669/1605	2.71
19-perf hex	558/1568	669/1623	3.58

Anderson and Puhalla (1991) also explored the impact of grain geometry on the propelling charge temperature coefficient, using different approaches for the charge establishment process, and obtained results similar to those in Table 4. First, they investigated, also using IBHVG2 simulations, the impact of grain geometry with energy held constant (i.e., the charge mass was held fixed with grain dimensions [e.g., webs, adjusted to obtain 500 MPa at ambient temperature]). Table 5 summarizes these data and clearly shows the increase in propelling charge temperature sensitivity as the grain progressivity increases.

However, as mentioned earlier, the maximum gun pressure constraint is the determining factor in fixing charge mass and grain dimensions. Since the maximum pressure generally occurs when the propellant is conditioned to the hot temperature, the charge establishment process must take into

Table 5. Constant-Energy Propelling Charge Temperature Sensitivity Results From Anderson and Puhalla (1991).

Grain Geometry	Pmax/Velocity at 21° C (MPa)	Pmax/Velocity at 49° C (MPa)	Propelling Charge Temperature Sensitivity (MPa/° C)
Sphere	500	588	3.14
Rolled-Ball	500	594	3.36
1-Perf	500	614	4.07
7-Perf	500	682	6.50
19-Perf	500	724	8.00

account performance with the propellant conditioned to the hot temperature. Two approaches to achieve this goal are possible. The first approach is to optimize charge mass and grain dimensions to meet the pressure constraints at the hot temperature, accepting the resulting performance for the ambient temperature. This approach was used in producing the results in Table 4. The second approach used by Anderson and Puhalla (1991) is as follows.

(1) Choose a maximum breech pressure for ambient conditions.

(2) Determine the charge mass-web configuration yielding the highest velocity, assuming the initial temperature is ambient. (Note: This approach does not lead to a constant energy calculation as in Table 5.)

(3) Try the combination from step 2, assuming the hot burn rate for the propellant.

(4) Iterate with higher/lower pressures in step (1) until the maximum breech pressure at the hot temperature condition in step (3) is consistent with the maximum gun pressure.

Results are shown in Table 6 for the same configuration used to produce the data in Table 5. The difference between the ambient and hot burn rates was approximately 7%, and all of the calculations were performed with IBHVG2.

Table 6. Results From Anderson and Puhalla (1991) Using the Second Approach for Charge Establishment

Grain Geometry	Pmax/Velocity at 21° C (Mpa - m/s)	Pmax/Velocity at 49° C (Mpa - m/s)	Propelling Charge Temperature Sensitivity (MPa/° C)
Sphere	565/1383	663/1449	3.46
Rolled-Ball	555/1437	662/1497	3.80
1-Perf	529/1489	661/1577	4.72
7-Perf	487/1518	663/1629	6.28
19-Perf	461/1516	662/1644	7.18

As can be seen in Tables 4–6, no matter which approach is utilized for charge optimization, the propelling charge temperature sensitivity increases as the geometric progressivity of the grain geometry increases. However, grain geometry is just one of many parameters affecting the propelling charge temperature sensitivity, and the possible impact that other parameters have had on these calculations is unknown.

The interesting question is, "Why should the propellant with the more progressive geometry exhibit a higher propelling charge temperature sensitivity?" Essentially, the answer is the maximum pressure constraint at maximum temperature. In order to satisfy the maximum pressure constraint, a certain mass generation rate/profile is needed. The more progressive the grain geometry, the smaller the initial surface area must be when compared to a less progressive grain geometry, if both geometries are to reach the same maximum pressure. In effect, this means that the more progressive grain is forced to be further away from the optimized ambient grain geometry than the less progressive grain. This results in the larger decrease in pressure for the more progressive grain geometry. This does not necessarily mean, however, that the muzzle velocity of a less progressive grain will be higher at ambient temperature than the velocity of a more geometrically progressive grain. To illustrate, consider the results in Table 4; the spherical grain geometry resulted in a decrease of 69 MPa, while the 19-Perf hex grain dropped by 111 MPa, yet the velocity of the 19-perf hex grain decreased by 3.4% compared to the 3.7% for the spherical grain.

3.2 Effect of the Exponent of the Burn Rate Law. The parameter of interest here is the exponent in the standard $r = bP^n$ burn rate law, which is traditionally utilized in gun interior ballistics to describe the propellant reaction rate. To determine the impact of the burn rate exponent, computations were performed using IBHVG2 with a 19-perf hex grain for various values of the exponent in the burn rate law. The specific values selected for the exponent were 0.9, 1.0, and 1.15. In an attempt to isolate only the impact of the exponent, the burn rate coefficients were normalized. The process was to first choose the coefficient for the case in which the exponent was 0.9. Based on the JA2 burn rate data in Figure 1, the coefficient was chosen to be 0.18. Next, for the ambient temperature 1.0 and 1.15 exponent cases, the coefficient was chosen so that the average burn rate (integral of bP^n from 0 to 700) would be the same as for the 0.9 exponent case. The burn rate at hot was assumed to increase by 9%, which was achieved by multiplying the coefficient of the burn rate law by 1.09. Results are based on calculations with the M829A1/M256 configuration and are given in Table 7 and graphically in Figure 5.

Table 7. Impact of the Exponent in the Burn Rate Law on the Propelling Charge Temperature Sensitivity for a 19-perf hex Geometry

Exponent (-)	Coeff. at Amb. (cm/s/P^n)	Coeff. at Hot (cm/s/P^n)	Pmax at Amb (MPa)	Pmax at Hot (MPa)	Propelling Charge Temperature Sensitivity (MPa/° C)
0.9	0.18	0.1962	563	669	3.42
1.0	0.0984	0.1073	547	669	3.94
1.15	0.0396	0.0432	505	669	5.29

As can be seen from Table 4 and Table 7 the propelling charge temperature sensitivity with the exponent 0.8796 and 0.9 are approximately the same, 3.58 versus 3.42, as expected. However, as the magnitude of the burn rate exponent increases, the propelling charge temperature sensitivity increases by up to 55%, 3.42 versus 5.29. Similar trends are observed for other grain geometries. For example, for the degressive ball geometry, the computations indicate a 34% increase in the propelling charge temperature sensitivity, as the exponent in the burn rate law increases from 0.9 to

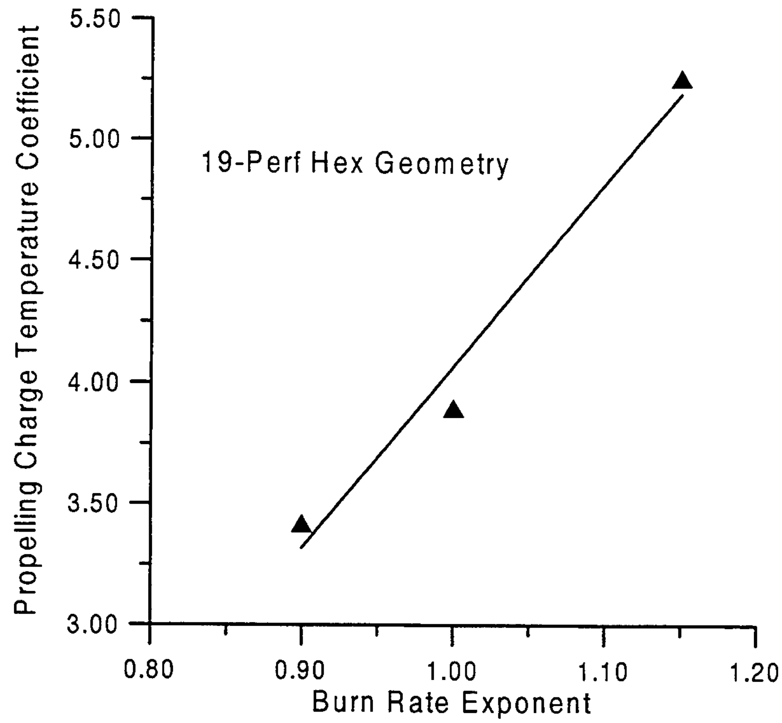

Figure 5. Propelling Charge Temperature Sensitivity Versus Burn Rate Exponent: LS Fit = 7.5 * x - 3.43.

1.15, 2.26 versus 3.032. This lower increase in the propelling charge temperature sensitivity for the spherical geometry, again, illustrates the impact of grain geometry progressivity.

The higher the exponent in the burn rate law, the higher the burn rate gets as the pressure increases. This has an effect similar to making the grain geometry more progressive, since the quantity that matters is the mass generation rate that involves the product of the burn rate and reacting propellant surface area. Thus, the propelling charge temperature sensitivity increases as the burn rate exponent increases for essentially the same reasons given previously for the progressivity of the grain geometry.

3.3 Effect of Deterrent Layers. One method for inhibiting or reducing the propellant burn rate during the early portion of the ballistic cycle is through the use of deterrents. The effect is to create a propellant with a continuously varying burn rate on the outer shell of the propellant grain. In general, the burn rate of the outer layer containing the deterrent is slower than the burn rate of the inner layer or base grain that contains little or no deterrent. By lowering the burning rate on the outer layer, the grain at the beginning of the combustion cycle has a lower mass generation rate, which may allow for an increase in charge mass, while still meeting the maximum pressure constraint. Besides the potential for increasing the charge mass, deterrents also permit the choice of burn rates for the inner layer that could be tailored to provide a more desirable mass generation progressivity after maximum pressure.

Anderson and Puhalla (1991) investigated the impact on the propelling charge temperature sensitivity and muzzle velocity for rolled-ball geometry with different concentrations of deterrent. Their calculations showed that as the amount of deterrent increased, the muzzle velocity increased and the propelling charge temperature sensitivity also increased. Table 8 summarizes their results for the case where the charge mass and grain dimensions are selected to achieve maximum breech pressure at the hot temperature. As before, results are from calculations using IBHVG2 with essentially the gun configuration in Table 1. The increase in muzzle velocity results from the fact that as the amount of deterrent increased the charge mass to obtain the same maximum pressure also increased due to the reduced gas generation rate early in the ballistic cycle.

Table 8. Results of the Deterrent Concentration Study on Propelling Charge Temperature Sensitivity From Anderson and Puhalla (1991)

Deterrent (%)	Charge Mass (kg)	Pmax at Hot (MPa)	Velocity at Hot (m/s)	Pmax at Ambient (MPa)	Velocity at Ambient (m/s)	Propelling Charge Temperature Sensitivity (MPa/C)
0	5.049	662	1338	591	1321	2.55
10	5.148	662	1347	588	1329	2.64
20	5.266	662	1358	583	1338	2.82
40	5.596	662	1388	571	1363	3.25

3.4 Effect of Ignition Delays and Flamespread. Anderson and Puhalla (1991) studied the impact of delaying ignition (i.e., time between primer discharge and initiation of propellant combustion for a portion of the total charge). As expected, the ignition delay results in a delay of the time of maximum pressure, which results in an increased charge mass to achieve the same maximum pressure and an increased muzzle velocity. Unlike the case of deterrents that showed an increase in the propelling charge temperature sensitivity, Anderson and Puhalla's calculations for this situation indicated a decrease in the propelling charge temperature sensitivity. Again, additional details are available in Anderson and Puhalla (1991).

3.5 Effect of Propellant Loading Density. Loading density (ld) is defined to be the ratio of the charge mass to the free chamber volume. The effect on the propelling charge temperature sensitivity resulting from changing the propellant loading density is a competition between two opposing factors. As loading density increases, ullage decreases, and the web must be increased in order to meet the maximum pressure constraint. Thus, one would expect the propelling charge temperature sensitivity to increase, since the surface area progressivity is becoming increasingly more unoptimized for the ambient temperature case. However, the increased loading density and decreased ullage means that higher pressures can be obtained with fewer combustion gases, impacting the grain geometry. Will this be sufficient to reduce the propelling charge temperature sensitivity?

To determine the impact of loading density on the propelling charge temperature sensitivity, simulations with IBHVG2 for the M829A1/M256 system were performed with the loading density varied. Results are shown in Figure 6. As shown in the figure, for this particular system the propelling charge temperature sensitivity is reduced as the loading density increases. However, it is not clear that the drop in the propelling charge temperature sensitivity is totally a result of the loading density change, since the grain geometry changes for each loading density in order to meet the maximum pressure constraint. Also, these results should not be generalized to other systems. A complete analysis for a given system should be performed to determine the impact of increased loading density; different results would not be surprising.

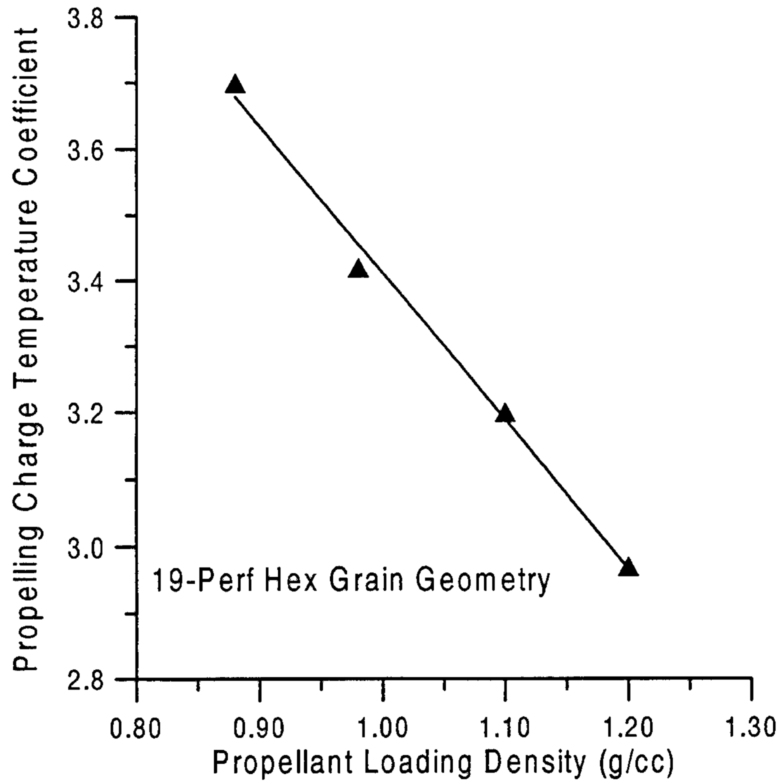

Figure 6. Propelling Charge Temperature Sensitivity Versus Loading Density: LS Fit = −2.23 * ld + 5.64.

4. Techniques for Moderation of the Propelling Charge Temperature Sensitivity

Techniques for moderation of the propelling charge temperature sensitivity fall into basically four categories: (1) chemical modifications to the propellant, (2) chamber volume modifications, (3) propellant temperature modifications, and (4) chamber pressure history modifications. It is believed that ETC propulsion concepts can be applied in conjunction with the last two techniques, heating the propelling charge and altering the chamber pressure history. However, before focusing on the possible use of ETC concepts, several comments on the status of other non-ETC concepts are felt to be worthwhile.

Kruczynski and Hewitt (1991) provide an overview of concepts that have been suggested for the first two techniques. A brief summary of their results is provided.

Chemical modifications generally entail the use of additives, such as, lead, copper, iron oxide, aluminum, and deterrents, to control the propellant burn rate and/or reduce the propellant temperature coefficient. Some positive experimental results have been obtained at low pressure, less than 20 MPa. Unfortunately, these results have not translated to the higher gun pressures.

Chamber volume modification basically entails changing the chamber volume as a function of the propellant temperature. They discuss two approaches: (1) a control tube that pushes the projectile further down the gun tube as propellant temperature increases before the main charge is ignited and (2) chamber inserts that change the volume of the chamber as a function of the propellant temperature. Again, mixed results with these approaches have been experimentally obtained.

4.1 Propellant Temperature Modifications. Of course the most obvious method for reducing the propelling charge temperature sensitivity would be to eliminate the problem altogether by maintaining a constant propelling charge temperature (i.e., propellant temperature modifications), as is done for Navy rounds. Since, in general, maximum performance is achieved when the propelling charge is conditioned to the hot temperature, the objective would be to maintain the propellant at the hot temperature. At the present time, the authors are aware of three possible approaches for maintaining a constant temperature with the tank mission in mind: (1) heat the bustle containing the rounds, (2) use microwaves to heat the propelling charge in the chamber (Howard et al. 1945; Minor and Horst 1996), and (3) use ETC concepts, especially radiative heating, to heat the propelling charge in the gun chamber prior to firing.

Heating the propellant in the bustle would appear to be the most reliable approach. However, this approach does not appear to be attractive to the user community, perhaps due to the additional heat generated within the tank, which could potentially increase the thermal signature of the vehicle or for other reasons, stated by Kruczynski and Hewitt (1991) as follows.

> There are of course some readily foreseeable problems with this technique. First, the propellant might change performance levels after long periods of high temperature soaking or cycling due to the release of volatiles. Second, without the main power plant of the vehicle operating, a

possible scenario for dug-in or concealed operations, there is not likely to be enough power to continue heating the propellant. Finally, many non-powered systems simply may not have the ability for propellant conditioning.

If heating of the propelling charge through the use of ETC concepts is to be employed, then an important question is, "How much of the propellant has to be heated?" In other words, "Is it sufficient to heat only a portion of the propellant?" To address this question, IBHVG2 simulations were performed using the M829A1/M256 configuration, which has been used throughout this report. The approach was to assume that a certain depth of the propellant was heated uniformly by an ETC plasma to the hot temperature, with the remainder of the grain assumed to be at the ambient temperature. An important assumption for these calculations is that all surfaces, including inside the perforations, were heated to the proper depth. Results are shown in Figure 7. It should be noted that nonuniform heating of the propellant could result in unacceptable ballistic performance.

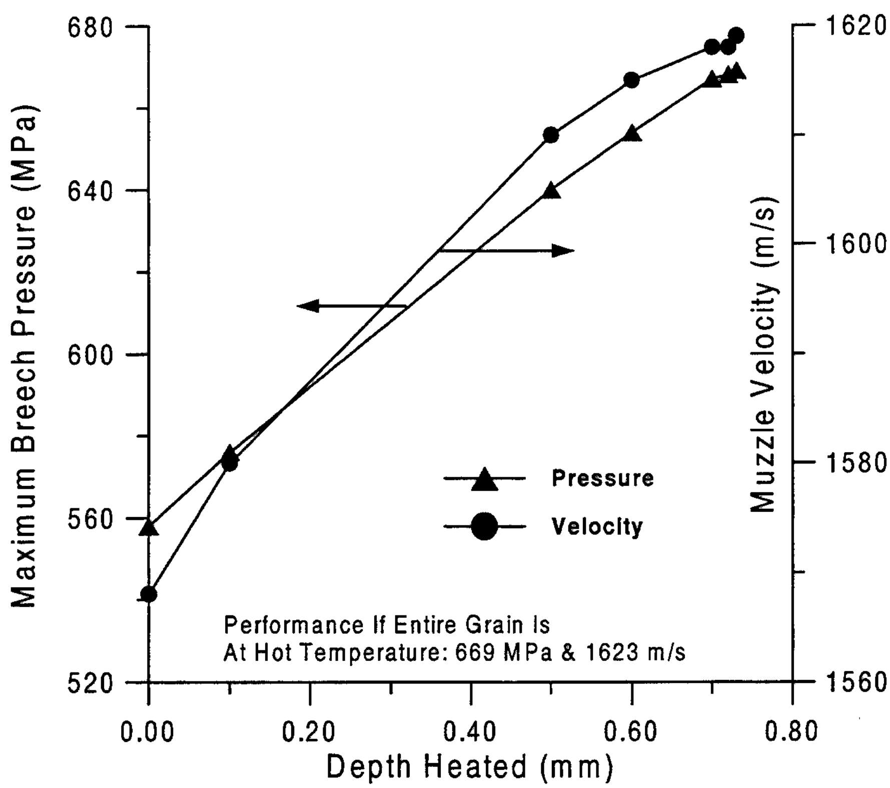

Figure 7. Pressure and Velocity Dependence on Depth Heated.

As can be seen from Figure 7, at a heated depth of 0.73 mm (maximum possible depth is 1.003 mm), the results are nearly equivalent to those that would be obtained if the entire grain were heated to the hot temperature. The pressure in both cases is 669 MPa. However, the velocity for the partially heated grain is 1,619 m/s versus the 1,623 m/s, which would be obtained if the entire grain were heated to the hot temperature condition. The slight drop in muzzle velocity is a result of the ambient temperature of the unheated portion of the grain that has a lower burn rate. For the geometry of the grain utilized in the computation in order to heat the grain to a depth of 0.73 mm, about 62% of the total mass would have to be heated. Based upon heat capacity values in Miller (1994), the total energy that would be required to heat this percent of the charge is approximately 200 kJ. Studies by White (1996) indicated that radiation from an electrically generated plasma could achieve this level of heating within the ballistic time frame, depending on the optical properties of the propellant. The reference by Howard et al. (1995) contains similar details for the case of microwave heating.

It is important to remember that the aforementioned calculation assumed that the entire grain surface was heated. This included the interior of the perforations. If the perforation surfaces are not heated, then calculations indicate that the hot pressure and velocity cannot be achieved.

4.2 Chamber Pressure History Modifications. One approach for modification of the chamber pressure history involves the use of the ETC plasma to supply sufficient energy to heat the chamber gases up to the hot temperature maximum pressure. No modification to the burn rate of the propellant is assumed (i.e., ambient burn rates are assumed). This represents the most conservative case for the use of the plasma energy in terms of the total amount of electrical energy required to achieve the maximum hot temperature pressure. If the plasma actually enhances the burn rate of the propellant through radiative heating or some other mechanism, then additional chemical energy would be entering the system, and the amount of electrical energy would be reduced. It should be noted that this approach is similar to the chamber modification techniques discussed earlier, in that both approaches attempt to alter the pressure rise rate to force the system to reach the maximum hot temperature pressure. Figure 8 shows IBHVG2 calculations for the M829A1/M256 system. The two curves with open symbols are identical to the curves in Figure 2 and show the impact of the

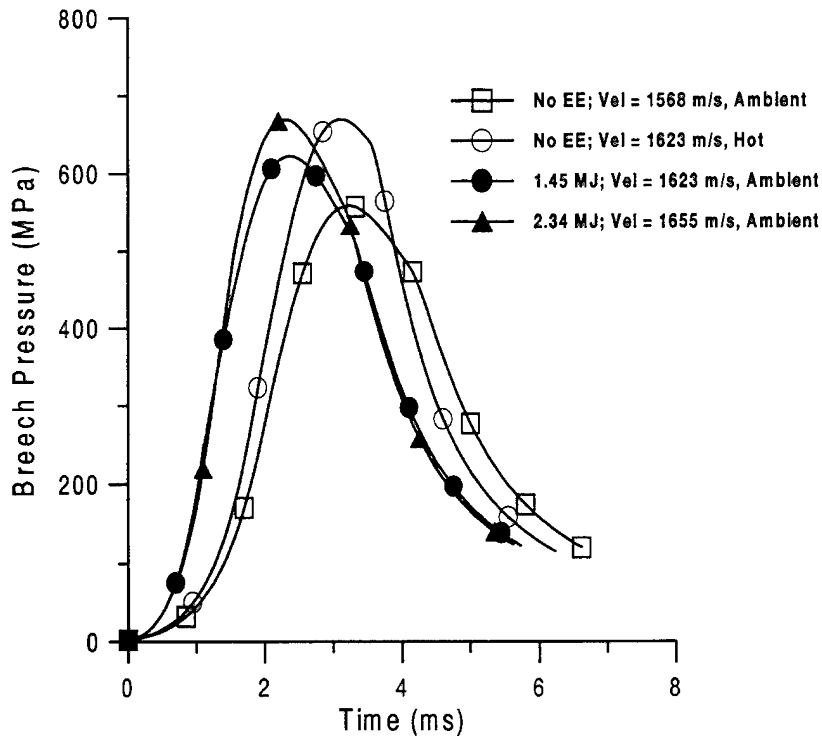

Figure 8. Results of the Direct Addition of Electrical Energy to Moderate the Propelling Charge Temperature Coefficient.

propelling charge temperature sensitivity for the system. The two curves with solid symbols are the results with adding electrical energy to reach the hot pressure (closed triangles) or the hot velocity (closed circles) when the round is initially at the ambient temperature condition. As indicated in Figure 8, 2.34 MJ and 1.45 MJ, respectively, of electrical energy are required in order to achieve these results.

Although these electrical energy requirements may not permit integration into a tank system given the current state-of-the-art for pulsed-power systems, it would be expected that the electrical energy requirements would decrease as the loading density of the propellant increased and the ullage decreased. The decreased ullage would mean less energy would be required to reach a specified pressure. The loading density for the M829A1/M256 system studied is approximately 0.9 g/cm^3. For ETC gun propulsion systems, loading densities up to 1.3 g/cm^3 are envisioned. Figure 9 shows estimates on electrical energy requirements to meet hot temperature pressure or velocity (assuming

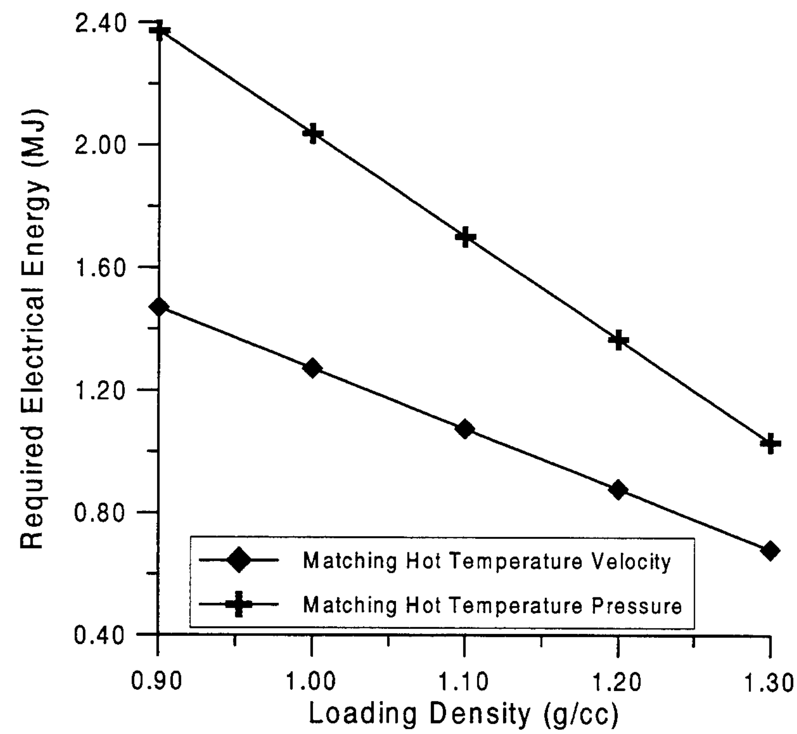

Figure 9. Electrical Energy Requirements as Loading Density Increases.

that the propellant is initially at the ambient temperature) as the propellant loading density increases. IBHVG2 simulations were used to produce the results. As can be seen from the figure, substantial reductions in required electrical energy occur as the loading density increases.

To determine if the concept of adding electrical energy simply to bring the chamber pressure up to the hot temperature is viable, a series of gun firings using DM13 120-mm tactical rounds in the M256 cannon was performed by United Defense, Limited Partnership (UDLP) under contract to the Army. Results are shown in Figure 10 and clearly indicate the ability to use ETC concepts to eliminate the propelling charge temperature sensitivity. The conventional ignition baseline points represent the average of three firings. Although, not shown, pressures for all the firings remained below the 605-MPa pressure of the round conditioned to the hot temperature and ignited conventionally. The results for the 10-round repeatability series, which was performed with the rounds conditioned to 0° C, are (1) average velocity, 1,790.9 m/s; (2) average maximum breech pressure, 591 MPa; (3) velocity coefficient of variation, 0.49%; and (4) standard deviation in muzzle exit time, 0.049 ms. Electrical energy utilized for the repeatability firings was approximately 700 kJ.

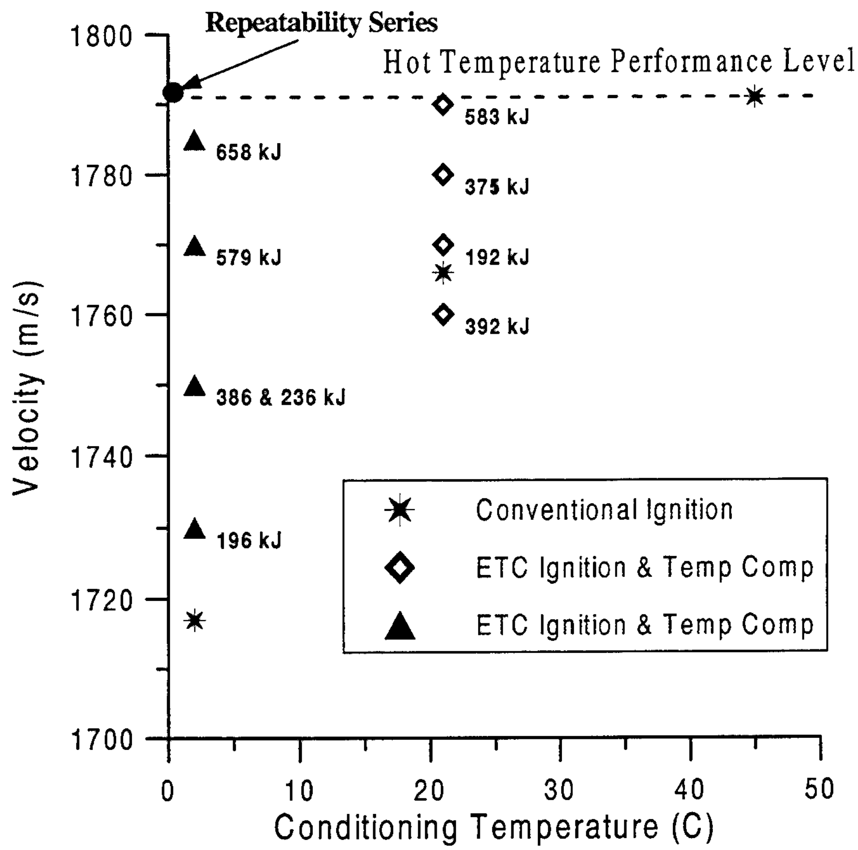

Figure 10. UDLP 120-mm ETC Results Demonstrating the Ability to Modify the Propelling Charge Temperature Sensitivity.

The most surprising result of this firing series was the amount of electrical energy required to match the hot temperature velocity with the initial propelling charge temperature 21° C, ~ 600 kJ, and initial propelling charge temperature 0° C, ~ 700 kJ. Calculations prior to the firing series, similar to those shown in Figure 8, predicted that 1.13 MJ and 2.45 MJ would be required to match the hot temperature velocity with the initial propelling charge temperatures of 21° C and 0° C respectively. Thus, the actual electrical energy requirements from the experimental firings are 47% and 71% below the predicted values, depending on propelling charge initial temperature. This indicates that other processes between the plasma and propellant are occurring, which result in an increase of the mass generation rate. Possible mechanisms are burn rate augmentation, erosive burning, or radiative heating of the propellant by the plasma as discussed earlier. Calculations performed after the firings that utilized the actual electrical energy input required an average burn rate increase for the JA2 propellant of 4.4% above the measured ambient burn rate when the initial propelling charge temperature was 21° C and 14.5% above measured 0° C burn rates when the initial propelling charge temperature was 0° C. Based on closed-chamber firings, the burn rate dependence of JA2 propellant on temperature is approximately 0.3% per degree Celsius. Thus, the computed increases in burn rate of 4.4% and 14.5% would require a 15° C to 50° C bulk heating of the propellant bed, which is not felt to be unrealistic. Supporting the radiative heating hypothesis is the fact that about 430 kJ of energy would be required to heat the entire 7.345 kg of propellant in the DM13 round from 0° C to 45° C. It is also noted that for these results, the required electrical energy is not linear as a function of the initial grain temperature.

The following is a proposed model of the plasma heating of the propellant bed that could lead to the aformentioned results. Recent measurements of the absorption coefficients of propellants indicate that the actual absorption coefficients may be relatively low in the visible region where plasma radiant energy is large. As a consequence, the radiant heating of the propellant would be somewhat uniform throughout the grains. It has also been observed that the propellant has significant radiative scattering properties. Thus, as the radiation from the plasma passes through one grain, a small percentage is absorbed, but a large percentage is scattered to adjacent grains. These, in turn, absorb some radiation and scatter the remainder of the radiation, some of it back to the original grain resulting in multiple radiation passes through a grain and further absorption with an accompanying increase in temperature. The radiation propagation part of this process occurs at the speed of light although the accompanying temperature rise is dictated somewhat by the propellant thermal properties as well as optical properties. The convective heating of the propellant bed may occur later and would be controlled by hydrodynamic properties of the bed, temperature, density, and velocity of the plasma convective flow. Thus, this convective flow might proceed into an already radiatively heated propellant bed, resulting in an ignition and combustion of a heated, faster burning propellant.

This hypothesis will be tested with both experiments and analysis in future work. Radiative and convective heat flux measurements will be made in the propellant bed during action of the plasma. Radiation propagation calculations will be carried out via Monte Carlo ray tracing techniques using measured propellant optical properties and known plasma radiative characteristics. The objective will be to determine the radiant energy deposition profile and subsequent heating in a propellant bed by the plasma radiation. In parallel with this, two-dimensional interior ballistic calculations (NGEN) will be carried out to determine the convective energy deposition profile, subsequent heating, ignition, and combustion of the propellant bed due to the plasma convective heating. The objective of the two calculations described is to evaluate the thermal history from the two heating sources (radiation and convection) to see how they compliment each other leading to ignition. Will the models show if there is the possibility of radiant heating prior to the ignition and combustion event, initiated and driven by the convective flow? As was mentioned, experimental measurements in a gun simulator will accompany these calculations.

Note: Similar results have been obtained in a 105-mm tank cannon (Perelmutter et al. 1996). ETC firings by UDLP have demonstrated moderation of the propelling charge temperature sensitivity in a 30-mm configuration (Marinos 1995).

5. Conclusions

This report has investigated the phenomena associated with the propelling charge temperature sensitivity. The impact of various ballistic parameters on the propelling charge temperature sensitivity, such as the propellant temperature coefficient, grain geometry, burn rate exponent, deterrents, ignition delays, loading density, etc., were discussed. In addition, approaches for modifying the propelling charge temperature sensitivity were explored. Major conclusions from the study include the following.

(1) Progressive grain geometries increase the propelling charge temperature sensitivity.

(2) Increasing burn rate exponents will lead to larger propelling charge temperature sensitivity.

(3) Chemical and mechanical (e.g., chamber inserts) approaches for modifying the propelling charge temperature sensitivity have had mixed results to date (Kruczynski and Hewitt 1991).

(a) Chemical modifications have been the most successful. However, the use of deterrents reduces propellant specific energy and has not in general been successfully applied to perforated propellants. This has resulted in little or no demonstrated enhancement in performance.

(b) The control tube device has shown positive results in moderation of the propelling charge temperature sensitivity, but has suffered in implementation since it is not "fail safe."

(c) Chamber inserts to alter chamber volume have shown some promise in reducing the propelling charge temperature sensitivity, but have been difficult to implement in practical systems.

(4) Hot temperature performance can be achieved in theory if a sufficiently thick layer of the grain can be heated uniformly to the hot temperature. Microwave heating or plasma radiation heating are two approaches showing some promise in achieving this result. However, for perforated grains, calculations for plasma heating indicate that the perforation surfaces must also be heated.

(5) In theory, heating through plasma radiation should be sufficient to achieve significant reductions in the propelling charge temperature coefficient. Both the radiation levels and time scales for heating a portion of the propelling charge are compatible with the ballistic cycle.

(6) Elimination of the propelling charge temperature sensitivity using an ETC plasma has been demonstrated at full scale in the temperature range of 0° C to 45° C for the DM13 kinetic energy round. Electrical energy requirements were over 50% lower than predicted, indicating that other processes besides simply heating the chamber gases were occurring. It is noted that the electrical energy required experimentally is consistent with that required to heat the propellant via plasma radiation. Calculations indicate that to match the

experimental data, the propellant gas generation rate must be increased between 5% and 15% with the addition of the electrically generated plasma energy.

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1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1997	Final, Jun 96-Jun 97

4. TITLE AND SUBTITLE
The Application of Electrothermal-Chemical (ETC) Propulsion Concepts to Reduce Propelling Charge Temperature Sensitivity

5. FUNDING NUMBERS
PR: 1L162618AH75

6. AUTHOR(S)
William Oberle and Kevin White

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-WM-PA
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-1509

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
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13. ABSTRACT ***(Maximum 200 words)***

The concept of the propelling charge temperature coefficient and its impact on gun performance is explored. Ballistic factors, in addition to the propellant burn rate dependence on initial temperature that often increases the magnitude of the propelling charge temperature coefficient, are identified and discussed. Techniques for moderating the effects of the propelling charge temperature coefficient are presented, with special emphasis on the utilization of electrothermal-chemical (ETC) concepts.

14. SUBJECT TERMS
propulsion, electrothermal-chemical, loading density, temperature sensitivity

15. NUMBER OF PAGES
42

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
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5. 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. ____________

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

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