ARMY RESEARCH LABORATORY

Summary of Experimental Efforts to Determine Plasma-Augmented Burn Rates for Solid Propellants

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This report summarizes results of plasma/propellant combustion studies performed on M5 and JA2 solid propellants. Both static (fixed pressure) and dynamic (variable pressure) closed chamber firings are analyzed to provide insight into the plasma/propellant combustion process. Results indicate that the plasma may influence propellant combustion (as measured by propellant burn rate) early in the combustion cycle, but appears to have little or no impact once full propellant burning begins.

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1. INTRODUCTION

An electrothermal-chemical (ETC) gun is a propulsion concept that utilizes a low-mass, high-energy, electrically generated plasma to initiate and, hopefully, control the combustion of an energetic material (propellant). The electrical and chemical energy of the plasma and propellant combine to produce expanding gases. These gases propel the projectile in a similar gas dynamic manner, although at increased performance levels, as equivalent caliber conventional powder guns. Thus, similar to conventional gun systems, optimization and detailed modeling of the ETC gun system require an accurate knowledge of both the thermochemical properties of the plasma/propellant gases as well as the burning or gas generation rate of the propellant with and without plasma augmentation. In fact, for ETC concepts utilizing solid propellants (SPETC), calculations (White et al. 1994) indicate that burn rate enhancements, due to the plasma (or other factors), of at least 100% over the standard (non-augmented) burn rate are required to achieve significant improvement in gun performance when using high-loading density charges with conventional propellant granulations. Consequently, knowledge of the burn rate (with and without plasma augmentation) is needed not only for optimization and modeling purposes, but also to determine the viability of proposed solid propellant compositions and geometries to provide the performance enhancements possible with ETC gun propulsion.

To date, four mechanisms have been proposed to explain how a plasma could modify the propellant gas generation rate:

(1) Erosion of the solid propellant surface (Harris et al. 1993) by the hot plasma, resulting in the removal of additional propellant material beyond the amount due to non-augmented combustion

(2) Creation of "worm holes" in the propellant (Lieb and Gillich 1994), due to imperfections in the grain, which create additional burning surface area that would be reflected as an increase in burn rate

(3) In-depth radiative heating of the propellant grain (White et al. 1994)

Radiative heating of the propellant is feasible since calculations have shown that a 200-K in-depth temperature increase may be possible in the ballistic time frame (1–2 ms) due to radiation from the plasma. (Details can be found in White et al. [1994]). In addition, as measured from closed chamber experiments, propellant burn rate is a function of the propellant grain temperature exhibiting increases of 0.3–0.8% in burn rate per degree rise in temperature.

(4) The plasma simply increases the gas temperature, causing an increase in pressure.

The objective of this report is to summarize experimentally obtained burn rate results for the solid propellants M5 and JA-2 with and without plasma augmentation. To address the erosion mechanism, results from experiments performed at North Carolina State University (NCSU), under contract to the U.S. Army, which involved the direct impingement (felt to be a necessity for erosion) of the plasma on a single JA2 propellant grain are presented. Radiative heating is addressed via ETC closed chamber experiments at various electrical-energy input levels (15–60 kJ) and electrical pulse lengths (1.2–2.4 ms) performed at the U.S. Army Research Laboratory (ARL). Burn rate results from these experiments are provided. The effect on burn rate due to "worm holes" is not addressed in this report since no experiments to quantify this effect have been performed. Using plasma as a source to increase pressure and, hence, the gas generation rate, does not affect burn rate and is not discussed. Also not addressed in this report are possible interrelationships of the four proposed mechanisms affecting propellant burn rate. This remains an open research area.

2. PROPELLANT CHARACTERISTICS

As mentioned in section 1, this report focuses on the plasma/propellant combustion behavior of two standard solid propellants, M5 and JA2. Both M5 and JA2 are high-energy propellants. JA2 propellant is currently being used in certain U.S. Army tank rounds, and, like M5, has been proposed for use in several ETC charge configurations. Thus, attempting to fully characterize the combustion behavior of both propellants seems appropriate. Thermochemical and physical properties for both propellants that were utilized in performing the various analyses are given in Table 1.

3. NORTH CAROLINA STATE UNIVERSITY (NCSU) RESULTS

As mentioned in the introduction, the NCSU experiments involved the direct impingement of plasma on the propellant. It was hoped that this experiment would provide information on burn rate augmentation due to erosive effects. However, it is possible that other mechanisms such as radiative heating are also influencing the measured results.

Table 1. Thermochemical and Physical Properties of M5 and JA2

Property	M5	JA2
Impetus (J/g)	1,093	1,144
Flame temperature (K)	3,397	3,424
Molecular weight	25.70266	24.886
Ratio-of-specific heats (gamma)	1.2258	1.2254
Covolume (cm^3/g)	0.984	0.991
Density (g/cm^3)	1.65	1.58
Standard BR Law[a]: (Experimentally measured without plasma)		
r (cm/s)	$0.3131\ P^{0.7999}$	$0.17969\ P^{0.8796}$

[a] P represents pressure in MPa.

The solid granular propellant JA2 was tested in the experimental electrothermal plasma-propellant test facility (PIPE) at NCSU to determine its burn rate with plasma injection perpendicular and parallel to the surface of the propellant (Edwards 1993). Burn rates have been determined at pressures between 55 and 90 MPa (8,000 and 13,000 psi, respectively) over 400-µs pulse length. This pressure is provided by the electrothermal plasma source that injects a high-density, low-temperature plasma onto the surface of the propellant (Bourham et al. 1992). The experimental facility provides controlled external heat flux to ignite propellants at preselected pressures. The electrothermal plasma source is connected to a pulse power system, which consists of a 340-µF Maxwell capacitor, parallel transmission line, spark-gap switch, charging power supply, and necessary interlocking circuits. The capacitor can be charged up to 10 kV (17 kJ stored energy), and provides up to 100 kA discharge current over 400 µs. The plasma source is a typical capillary discharge, which forms a high-density, low-temperature plasma by the ablation of the source insulator. The source is attached to a combustion chamber (15.24 cm, six-way stainless steel cube) that contains two test stands for the propellant and material samples. Positioning is necessary so that the heat flux can be varied easily from high (close to the plasma) to low (farther away). Figure 1 shows a schematic drawing of the experiment (left), and details of the propellant sample test stand diagnostics (right).

The experiment is equipped with various standard and special diagnostics. Standard diagnostics include a Rogowski coil and a potential divider for the discharge parameters (current and voltage), and an absolute pressure transducer for the chamber pressure. Special diagnostics include strain gauges for pressure and stress distribution, fast thermocouples for heat flux calorimetry, fiber optics-to-photodiodes

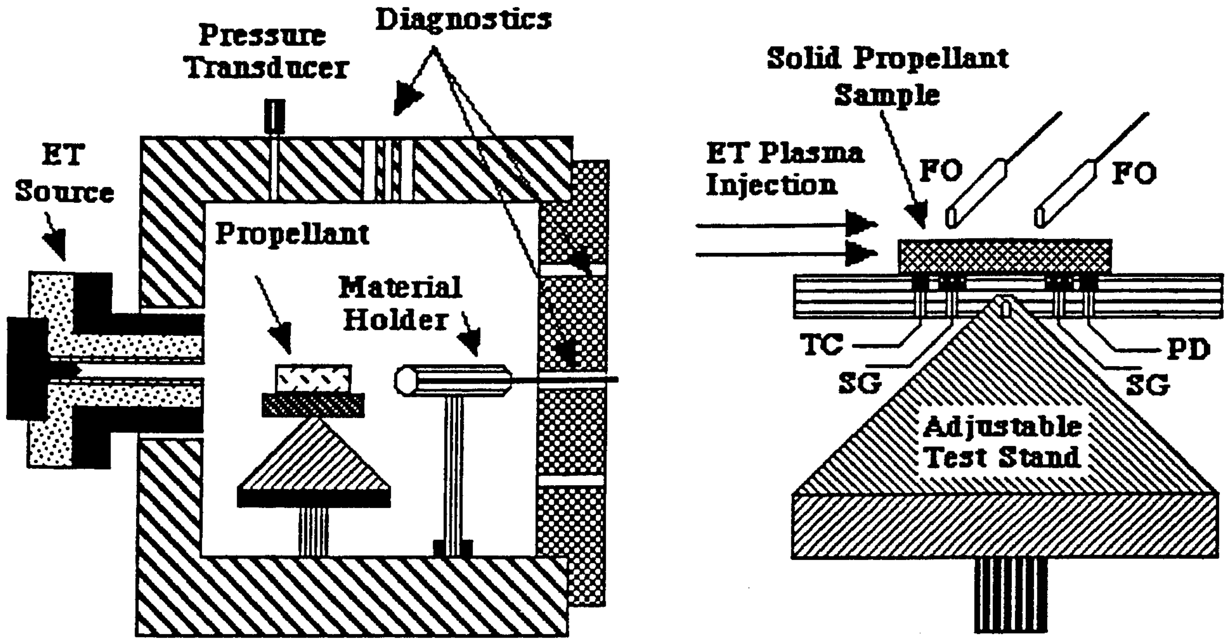

Figure 1. Schematic drawing of the experiment (left) and details of the propellant test stand (right). (FO = fiber optics, TC = thermocouple, PD = photodiode, and SG = strain gauge).

for burn rate measurements, and fiber optic-to-infrared detectors for surface and flame temperature monitoring. The test stand allows for plasma injection normal or parallel to the surface of the propellant, or at any desired angle of injection. The plasma is injected over a discharge period of 400 µs to provide external heat flux and pressure sufficient to ignite the propellant and maintain burning during the injection time.

Evaluation of JA-2 burn rate has been conducted in the PIPE experiment for two modes of plasma injection, perpendicular and parallel to the surface of the propellant (Figure 2). The experiments have been conducted at 3–5.6 kJ input energy levels. This input energy range provides power fluxes from 15 to 38 GW/m^2 at surface pressures between 55 and 90 MPa. The evaluation of the burn rate is based on the incomplete burn method, which can be used to evaluate the burn rate from the mass loss. This direct, or static, method is useful when electrothermal plasmas are generated under vacuum by the ablation of the source liner. This method is different from the closed chamber experiment where the plasma can be at atmospheric or higher pressure by exploding a fuse inside of the electrothermal source. When electrothermal plasma is injected into the propellant under vacuum, the burn process continues only during the discharge time. This is because the pressure at the propellant's surface is high enough for increased

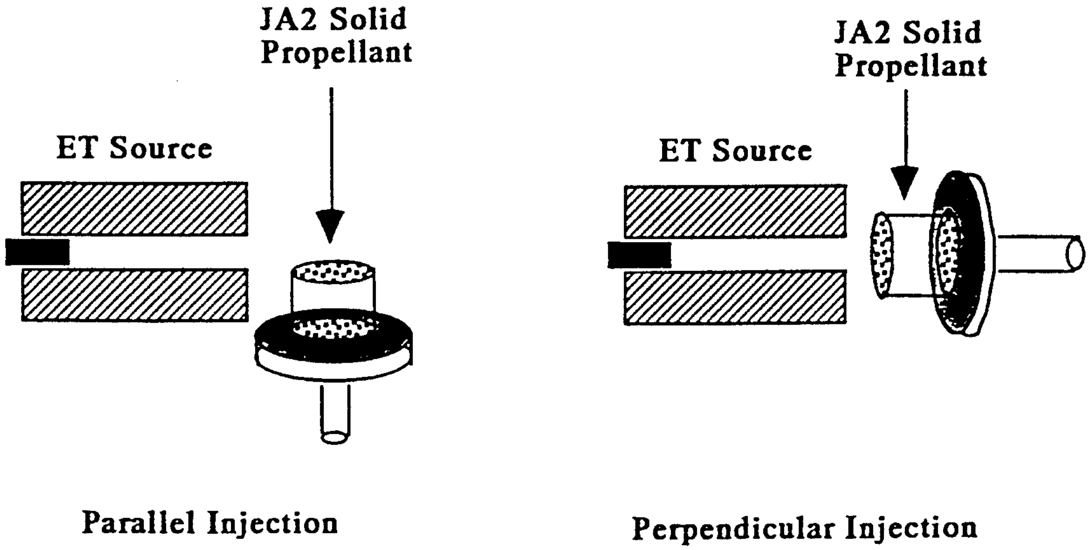

Figure 2. Schematic drawing showing the position of the plasma source and the propellant test stand for two different test scenarios, parallel and perpendicular injection to the surface. (The propellant is 3.5 cm from the source exit).

burn rate, and the burn extinguishes after the plasma discharge is terminated as the pressure rapidly decreases. In such a case, the burn will be incomplete and mass loss of the propellant can be measured to evaluate the burn depth per unit time.

The burn rate results obtained for plasma injection perpendicular and parallel to the surface of the propellant are compared to known conventional burn rate results for the same propellant. Conventional burn rate data have been provided by the U.S. Army Research Laboratory for solid JA2 propellant. Figure 3 shows the burn rate of JA2 solid propellant with plasma injection compared to the burn rate for conventional ignition. The burn rate has been calculated from the evolved mass (mass loss transferred to ablation thickness) over the discharge period of 400 μs, assuming that the burn process takes place during that time, which represents an average estimate of the burn rate. The conventional burn rate data is shown in Figure 3 by the solid line for the burn rate equation BR (in/s) = $80 \times 10^{-5}\ P^{0.889}$, where P is the pressure in psi. The measured values are shown by the squares and circles for perpendicular and parallel injection, respectively. The dotted curve represents the best curve fit for the data obtained for perpendicular injection (BR = $3.49 \times 10^{-5}\ P^{1.3755}$). Plasma injection parallel to the surface shows an enhancement in the burn rate between 20–40%, compared to conventional burn rate data. These results are within reported data for various bulk-loaded JA2 tests. The set of measurements with plasma injected perpendicular to the surface shows an increase in the burn rate by a factor of 3, and greater, at a surface

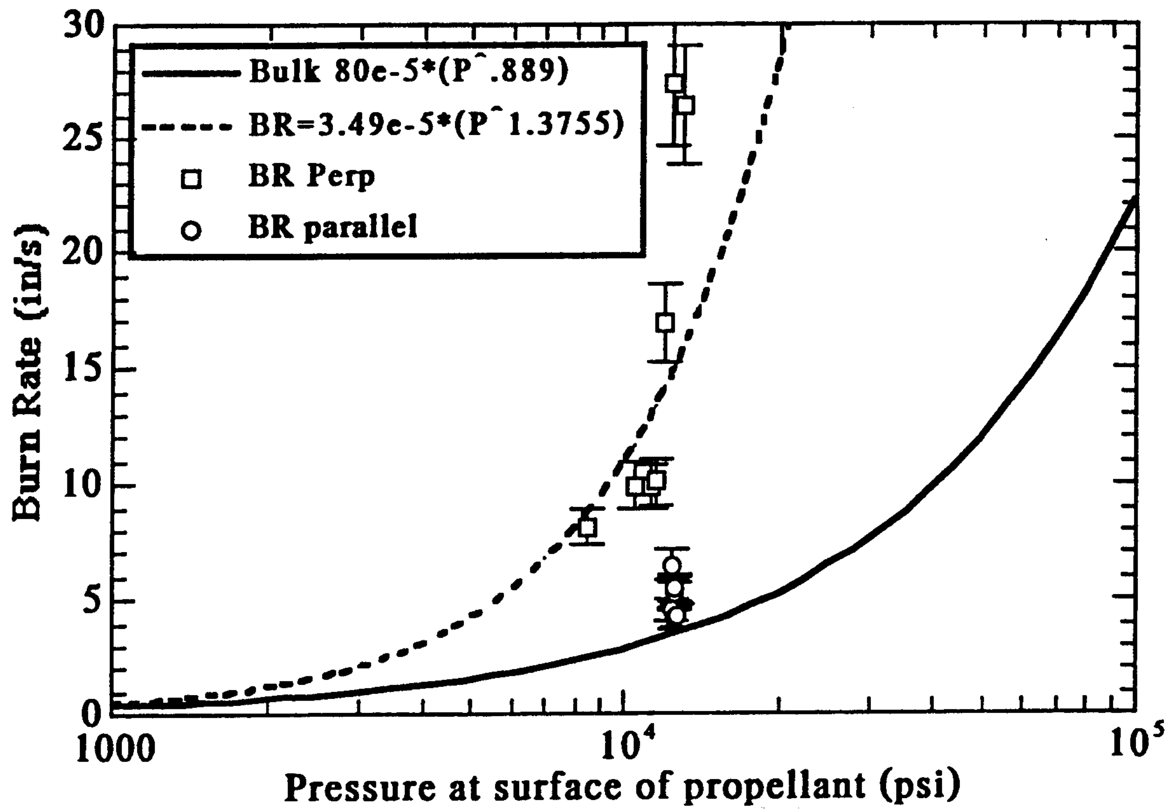

Figure 3. Measured burn rate of JA2 solid propellant for plasma injection perpendicular and parallel to the surface as a function of the pressure at the propellant's surface, compared to the burn rate of the same propellant with conventional ignition.

pressure between 69 and 83 MPa (10,000 to 12,000 psi). These results suggest that the angle of injection, with respect to the direction of the grains, is important in burn rate augmentation. It appears that possible plasma augmentation to burn rates is not only dependent on the pressure, but also on the geometry.

These results have been obtained at various energy input levels to the plasma source (i.e., different average plasma temperatures from 1 to 3 eV), which results in power fluxes between 15 and 38 GW/m^2 over the entire pulse length. The actual heat flux received at the surface of the propellant will be dominated by the effectiveness of the vapor shield (Gilligan et al. 1992). This means that the vapor layer at the surface of the propellant absorbs a large fraction of the incoming energy. This fraction may change depending upon the effectiveness of the flame vapor shield at the plasma-propellant interface. The coupled effect of both plasma pressure and temperature is still unknown, which suggests more research is needed to decouple plasma temperature and pressure effects. However, possible plasma augmentation to JA2 solid propellant burning rates is evident from these results and is dependent on the angle of injection, which shows higher burn rates when the electrothermal plasma is injected perpendicular to the surface (normal to grains) of the propellant.

4. U.S. ARMY RESEARCH LABORATORY RESULTS

Experimental firings at ARL involved the use of a closed chamber modified to accommodate plasma injection. A schematic of the ETC closed chamber and associated pulse power system are shown in Figure 4. Specific details concerning the fixture, instrumentation, data acquisition, and propellant geometry can be found in two separate papers (Del Guercio et al. 1994; Stobie, Del Guercio, and Oberle 1994). For future reference, two pressure gauges are used with the fixture: gauge 1 in the end closure plug, right-hand wall of combustion chamber on center line, and gauge 2 located on the side wall.

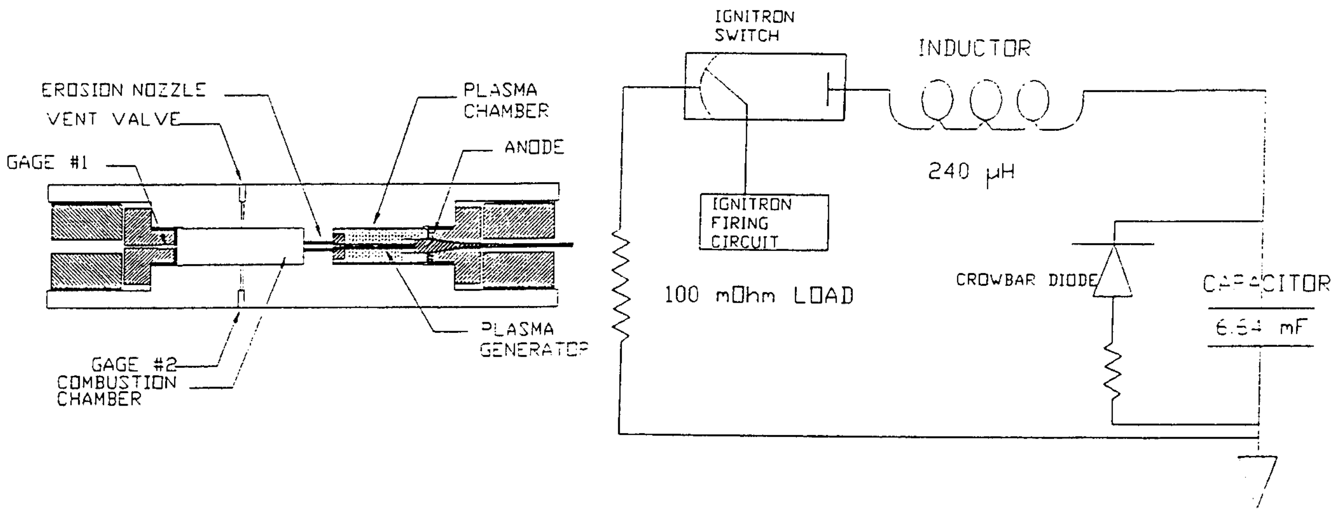

Figure 4. Schematic of ARL ETC closed chamber and power supply.

The objective of the ARL firings was to determine the impact of the electrically generated plasma on the burn rate for bulk-loaded propellants as opposed to the single grains used in the NCSU experiments. As previously discussed, it was hoped that a significant increase (at least 100%) in burn rate would be observed with the most likely explanation being radiative heat transfer since direct impingement of the plasma on the bulk of the propellant was unlikely. Evidence strongly supporting the plasma radiative heating hypothesis would be elevated (greater than the standard burn rate) burn rates after the electrical energy input was terminated.

4.1 Conventional Closed Chamber Firings. However, to ensure that burn rate results were not being influenced by the geometry of the closed chamber, two conventionally (using black powder without electrical energy) ignited firings were performed in which the plasma generator cavity was sealed off from the combustion chamber. Deduced burn rates from the pressure data using the BRLCB closed-chamber data analysis code (Oberle and Kooker 1993) and the standard JA2 burn rate are shown in Figure 5 on the normal log burn rate vs. log of pressure plot. The propellant loading density was 0.23 g/cm^3.

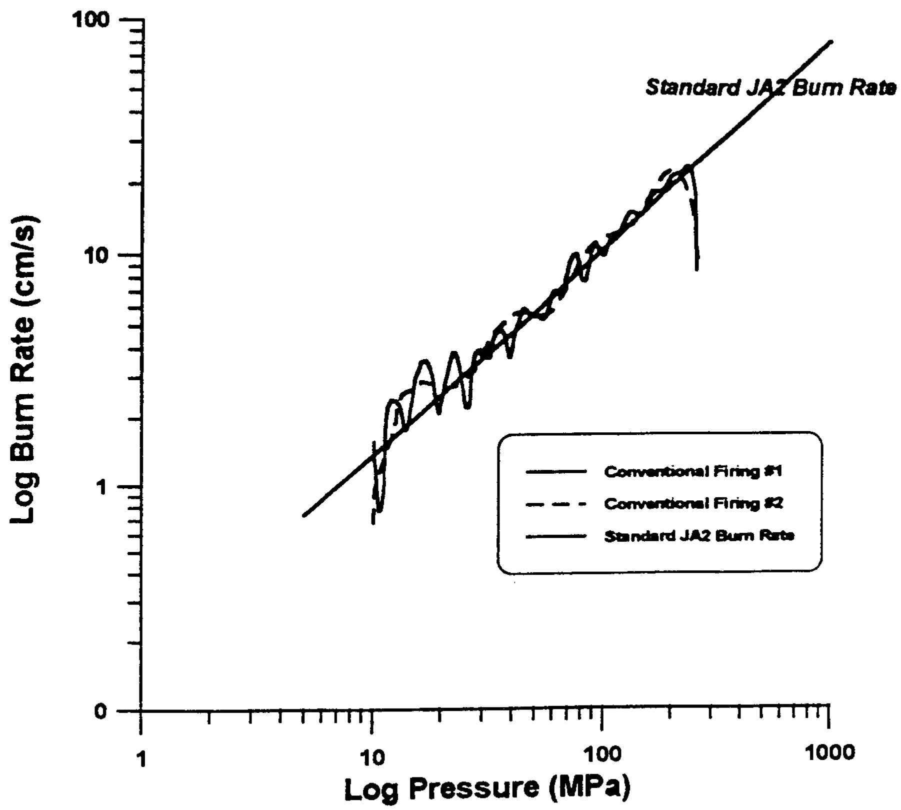

Figure 5. Comparison of standard JA2 burn rate with those deduced from ETC closed chamber firings using convention ignition.

As can be observed in the figure, the burn rates for the two conventionally ignited firings are virtually identical to the standard JA2 burn rate, especially in the 20–80% of maximum pressure (40–180 MPa) range. Due to the uncertainties in propellant ignition and variability in grain geometry, closed chamber data are generally considered most accurate in the 20–80% of maximum pressure range. Details concerning the loading density (ratio of propellant mass to chamber volume) and deduced burn rate laws in the tradition $r = bP^n$ representation are provided in Table 2.

Table 2. Results of Conventionally Ignited JA2 Closed-Chamber Firings

Firing ID	Loading Density (g/cm^3)	Burn Rate Coefficient ($cm/MPa^n - s$)	Law Exponent (–)
12103S1	0.23	0.164011	0.9079
12103S2	0.21	0.130195	0.9618

4.2 Plasma-Augmented Closed Chamber Firing Results. With confidence in the ETC closed chamber design due to the excellent match of deduced burn rates for the conventionally ignited JA2 firings and the standard JA2 burn rate, plasma-augmented closed chamber firings were performed using M5 and JA2 solid propellant.

4.2.1 M5 Burn Rate Results. Typical burn rate results for two of the M5 propellant firings are shown in Figure 6. Both curves display the same type of behavior. First, there appears to be substantial wave structure to the curves. This is most likely due to the vigorous and often nonuniform ignition provided by the plasma and the large ullage associated with closed chamber firings where loading densities are well below those associated with gun charges (0.2–0.35 g/cm^3 in closed chamber vs. 0.8–0.95 g/cm^3 for typical gun loading densities). Second, at low pressures (below 70 MPa for these firings), both curves exhibit enhanced burn rates compared to the standard M5 burn rate (solid straight line). This is consistent with the NCSU results, since at the early stages of combustion, many of the grains could be directly impacted by the plasma. Finally, above 70 MPa, both curves appear to oscillate about the standard burn rate curve. This indicates little or no impact on the propellant burn rate by the plasma, even though for firing 021594S1, the electrical energy level input continues well past 200 MPa (dashed vertical line). At this point in the combustion cycle, above 70 MPa, the chamber would be filled with a substantial amount of combustion gases than could form a vapor shield, isolating any unburnt propellant grains from the plasma. As will be seen in the JA2 firings, this behavior is typical for almost all solid propellant ETC closed chamber firings investigated under this study.

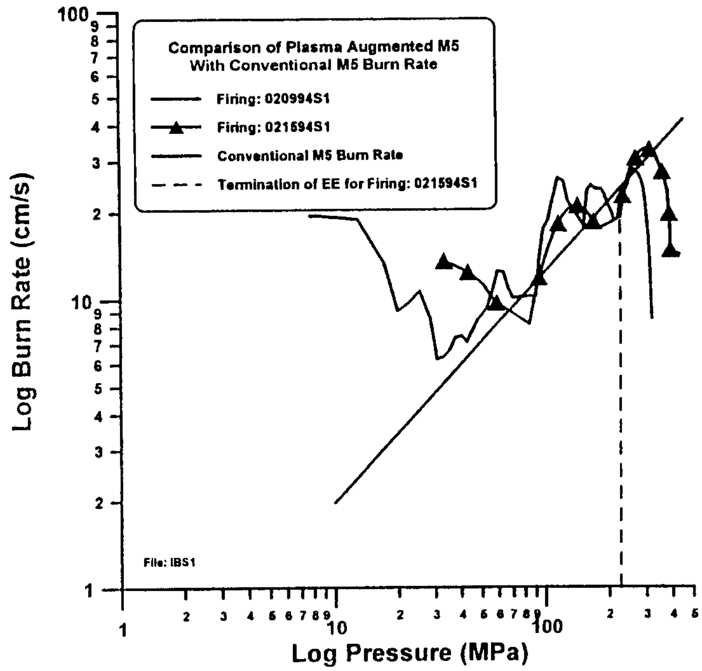

Figure 6. M5 BR results with plasma augmentation.

Since the oscillatory nature of the burn rate cures makes it difficult to quantitatively compare the deduced burn rate with the standard propellant burn rate, the following procedure is employed. First, using the 20–80% of maximum pressure range, a least-squares linear fit for the data is determined. Basically, this provides a typical $r = bP^n$ burn rate law for the specific pressure range (see Table 3). This will also mitigate the impact of the oscillations on the burn rate curve. Second, using this burn rate law and the conventional burn rate law for the propellant (see Table 1), the average burn rate difference over the 20–80% maximum pressure range is determined. The average burn rate difference is computed as the integral of the difference of the two burn rate laws with limits of integration 20% of maximum pressure and 80% of maximum pressure. The integral is then divided by the length of the 20–80% of maximum pressure range. Third, in a similar manner, the average burn rate over the same pressure range using the conventional burn rate law is computed. Finally, the average percent difference is computed by dividing the results of step two by the integral computed in step three. For the firing 020994S1, the average difference was 8.6%, while for firing 021594S1, the corresponding value was 4.8%. Thus, using this metric, for M5 propellant, there appears to be little burn rate enhancement attributable to the introduction of the plasma, at least in the 20–80% of maximum pressure range. Detailed information on the two M5 firings is provided in Table 3.

Table 3. Details of the M5 Closed Chamber Firings and Results

ID No.	Loading Density (g/cm^3)	EE (kJ)	EE Density (kJ/g)	Pmax (MPa)	20–80% Pmax (MPa)	BR Law (20–80% Pmax) (cm/s)	Average Difference (%)
020994S1	0.225	17.1	0.587	323	65–258	2.05393 $P^{0.446}$	8.6
021594S1	0.272	16.4	0.466	431	86–345	0.484887 $P^{0.7277}$	4.8

It should be noted that the electrical energy densities (EE Den.) for the two firings are typical for ETC gun firings. Thus, these closed chamber results should provide pertinent data at least in terms of plasma/propellant characteristics for actual gun firings.

4.2.2 JA2 Burn Rate Results. Closed chamber firings utilizing JA2 propellant were performed over a wide range of electrical energy densities and pulse duration, as shown in Table 4. However, in all instances, once the electrical energy density approached 1.0 kJ/g, unacceptable pressure data were obtained. The most likely explanation is radiative heat of the pressure transducers by the plasma, causing the gauge to read low (Stobie and White 1994). Other possibilities will be discussed later in this report.

4.2.2.1 Short Pulse Length Firings. As can be seen in Table 4, the firings for the short pulse length can be subdivided into three groups based on electrical energy density: (1) low electrical energy density, firings 01245S1 and 01305S1; (2) high electrical energy density, firings 04084S1, 04194S1, 02105S1; and (3) typical gun firing electrical energy densities, firings 03154S1, 03154S2, 03184S1, and 02095S1. Deduced burn rates for these firings are given in Figures 7–9. (Note: Deduced burn rates are not provided for firings 04084S1 and 04194S1 due to unacceptable pressure data being recorded.)

As can be observed from the figures, except for firing 03154S2 (Figure 9), the behavior for the burn rate curves is similar. It matches that observed for the M5 firings, namely, significant wave structure and elevated burn rates at low pressures with essentially no burn rate augmentation at higher pressures, regardless of the timing of the electrical energy input. The average percent difference in burn rate, (Table 5) is consistent with these observations, indicating no substantial burn rate augmentation except for firing 03154S2, which is considered an outlier.

Table 4. JA2 Plasma-Augmented Firing Matrix[a]

Pulse Length		Low Input (3 kV, ~ 17 kJ) ID	LD[b] (g/cm^3)	EE Density[c] (kJ/g)	High Input (5 kV, 25–60 kJ) ID	LD (g/cm^3)	EE Density (kJ/g)
Pulse Length	Short Pulse (1.2 ms)	03154S1	0.21	0.645	04084S1	0.22	1.27
		03154S2	0.21	0.586	04194S1	0.21	0.96
		03184S1	0.27	0.492	02105S1	0.21	0.91
		01245S1	0.21	0.295			
		01305S1	0.21	0.231			
		02095S1	0.21	0.639			
	Long Pulse (2.4 ms)	None			08314S1	0.18	2.44
					09164S1	0.18	2.66

[a] Chamber volume = 129.4 cm^3
[b] Propellant loading density
[c] Electrical energy (EE) (ratio of total electrical input energy to charge mass)

4.2.2.2 High Input Energy Firings. Since one of the primary objectives of the closed chamber experiments was to investigate the possibility of radiative heating by the plasma, it was felt that increasing the electrical energy input would only enhance this effect. Thus, the high electrical energy input firings (short and long pulse lengths) were performed, even though the resulting electrical energy densities exceed those expected in actual ETC gun applications (1–3 kJ/g vs. 0.5 kJ/g, see Table 3). All the high electrical energy firings (except 02105S1) will be discussed at the same time, since similar and unacceptable results from the firings were obtained.

The recorded pressure data for firings 08314S1 and 09164S1 are shown in Figures 10 and 11. For both firings, not only do the two gauges record substantially different pressure profiles, but the maximum pressure recorded is still 30–40% below the theoretically calculated maximum pressure. These discrepancies render the data unacceptable.

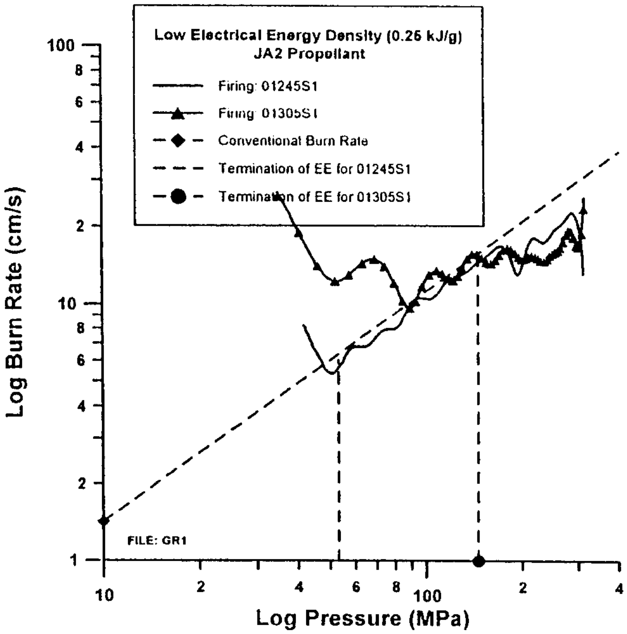

Figure 7. JA2 burn rate for low EE density.

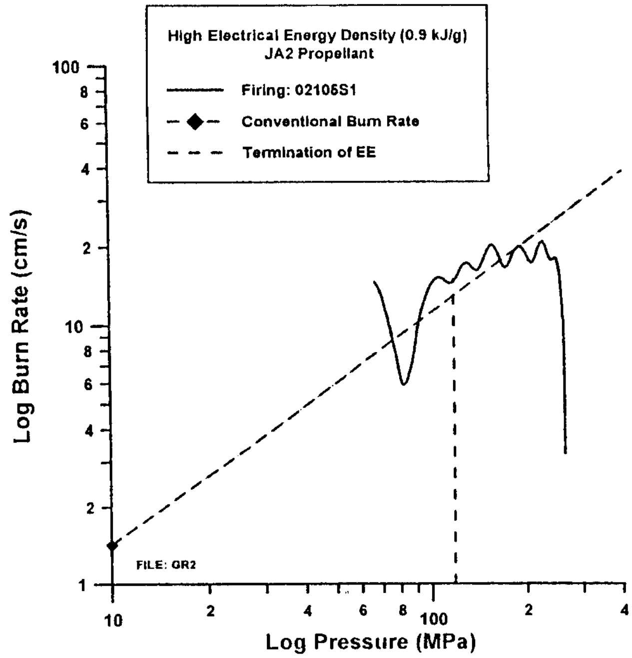

Figure 8. JA2 burn rate for high EE density.

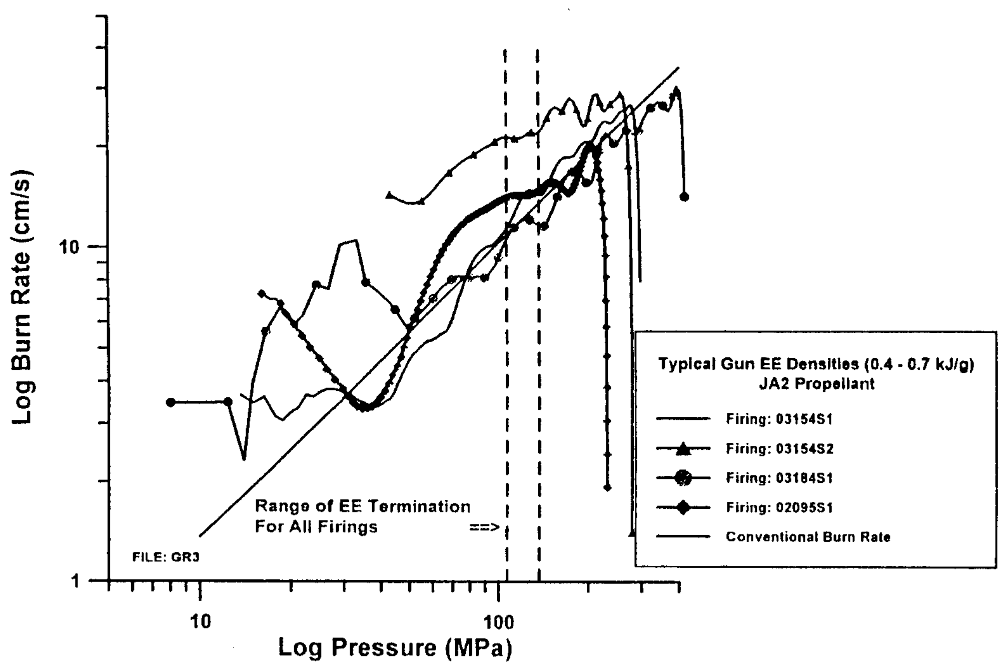

Figure 9. JA2 burn rate for typical gun electrical energy densities.

Table 5. Details of the JA2 Closed Chamber Firings and Results

ID No.	Loading Density (g/cm^3)	EE (kJ)	EE Density (kJ/g)	Pmax (MPa)	20–80% Pmax (MPa)	BR Law (20–80% Pmax) (cm/s)	Average Difference (%)
03154S1	0.21	16	0.645	344	69-275	$0.125702\ P^{0.9656}$	–0.36
03154S1	0.21	17.8	0.586	351	70-281	$4.06992\ P^{0.3523}$	34.0
03184S1	0.27	17	0.492	416	83-333	$0.181633\ P^{0.8591}$	–17.8
01245S1	0.21	8	0.295	311	62-249	$0.385633\ P^{0.7104}$	–17.2
01305S1	0.21	6.3	0.231	313	62-249	$4.41329\ P^{0.234}$	–14.0
02095S1	0.21	17.4	0.639	239	48-191	$0.779128\ P^{0.5982}$	2.5
02105S1	0.21	24.6	0.907	266	53-213	$0.339886\ P^{0.7752}$	3.4

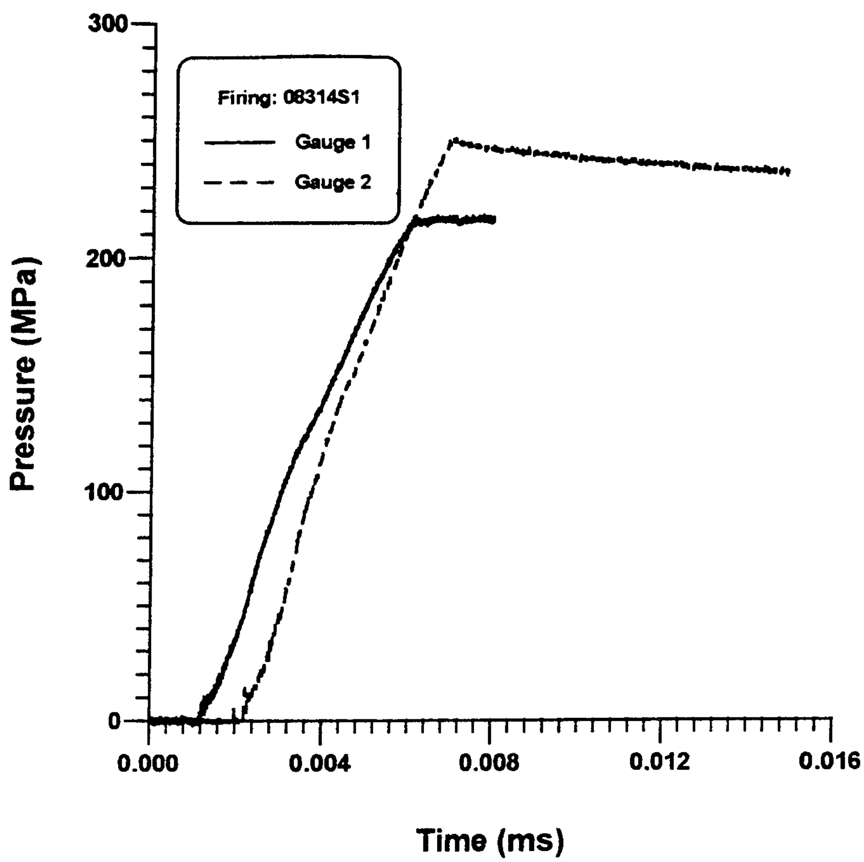

Figure 10. Firing 08314S1 gauge 1 and 2 pressure histories.

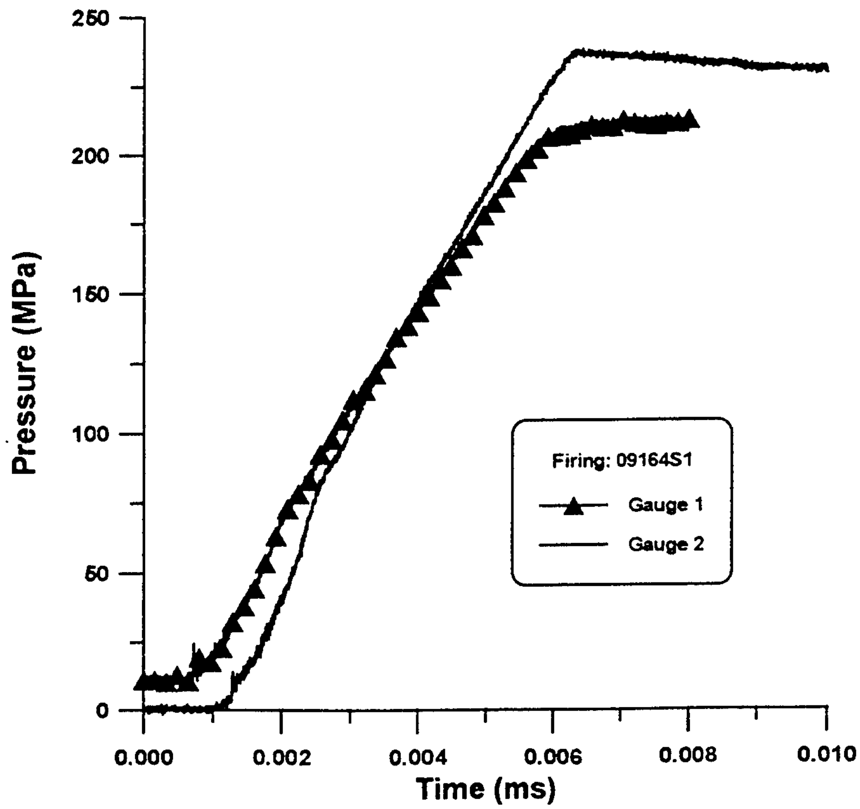

Figure 11. Firing 09164S1 gauge 1 and 2 pressure histories.

Several explanations to explain these high electrical energy results have been proposed:

• The tests were conducted at low loading densities (0.18–0.22 g/cm^3) compared with most ETC gun firings (>0.9 g/cm^3). Additionally, these tests were conducted at higher than normal electrical energy densities. As a consequence, the pressure gauges may have received large quantities of radiant energy from the plasma, which is at a much higher temperature than the propellant combustion gases. If the gauge were heated by the plasma, it would cause a reduction in the apparent measured pressure since heat is known to cause a negative effect on the gauge (Stobie and White 1994). As discussed earlier, the closed chamber had two gauges, one in the side wall and one in the end closure plug of the combustion chamber. The end gauge (gauge 1) would be subjected to the entire output from the plasma since the plasma is delivered along the center axis directly in line with the gauge. However, the side gauge (gauge 2) would receive a lesser amount of heat due to, among other things, the presence of the propellant. As can be observed in Figures 10 and 11, the end gauge (gauge 1) measured over 20% lower in maximum pressure for both firings.

• An assumption is made in all ETC firings (closed chamber and gun firings) that the electrical power and energy measured as an input to the plasma is all converted into heating either the propellant or combustion products, which then can be used for delivering energy to the projectile. Unfortunately, this may not be entirely true. There are at least two mechanisms, both of which could occur at the same time, in which some part of the plasma energy would not interact with the propellant or combustion products. First, a significant portion of the plasma energy is in the form of radiation. Since the propellant is not totally opaque in the visible region, not all the radiative energy will be absorbed immediately. Some radiative energy could be lost to the bomb walls. Second, as the pressure rises in the combustion chamber, it may exceed that in the plasma chamber, causing the plasma energy to be trapped in the plasma generator. There is some experimental evidence for this hypothesis. From post firing analysis of the high-energy firings, it was observed that metal melted from the steel electrode was confined primarily to the plasma generator region of the fixture. Very little of the metal reached the combustion chamber, as would be expected (Del Guercio et al. 1994). This could indicate that some portion of the electrical energy is lost to heating in the plasma generator chamber and never reaches the propellant or combustion products. This would manifest itself as a lowering of the measured chamber pressure compared to the expected pressure.

5. CONCLUSIONS

This report has attempted to summarize efforts directed at determining the burn rate of M5 and JA2 solid propellant subjected to an electrically generated plasma. Four different mechanisms—erosive burning, creation of "worm holes," radiative heating, and combustion product heating to maintain high pressure—have been proposed to explain mechanisms by which a plasma may affect or enhance propellant burn rate. This report addresses the first and third of these mechanisms since no specific experiments have been performed to address "worm holes" and the fourth mechanism affects pressurization rates, not burn rate.

Based upon the results presented in this report, it appears that plasma augmentation has no significant impact on propellant combustion behavior as measured by propellant burn rate, except possibly at the beginning of the combustion cycle. It is important to note that these results may only be valid for the two propellants studied or propellants similar in composition. Sustained elevated burn rates due to plasma augmentation for LOVA propellants containing nitramine have been reported (Phillips 1995). Specific observations concerning the experiments documented in this report are:

(1) Direct impingement of plasma on propellant grains at distances of 1–2 cm appears to cause enhanced burn rates, but is highly dependent on the angle of injection of the plasma onto the propellant surface.

(2) For closed chamber firings, plasma ignition of the solid propellants studied produced low-magnitude pressure waves that were exhibited on the burn rate curves.

(3) Closed chamber burn rates indicate no burn rate enhancement due to plasma injection except at low pressures where direct plasma on propellant grains may be occurring. At high pressures, the combustion gases may be acting as a vapor shield, preventing the plasma from having any influence on the unburnt solid propellant.

(4) All the high electrical energy input firings, except one, generated unacceptable pressure histories with 30–40% discrepancies in observed and theoretical maximum pressure. In addition, 20% differences in maximum recorded pressure between gauges in the closed chamber were observed for these firings. Several possible explanations for the high electrical energy input firing results are radiative heating of the gauges and/or excessive heat loss in either the combustion or plasma generator chamber walls.

Finally, if significant heat/energy losses are occurring in either the combustion chamber (to the wall) or the plasma generator chamber (melting of electrical components, etc.), then this could be at least a partial answer to why ETC gun firings have historically not demonstrated the efficiency or ballistic ratio of solid propellant guns (Oberle and White 1991).

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