AD

TECHNICAL REPORT BRL-TR-2853

LIQUID PROPELLANT GUNS

WALTER F. MORRISON
JOHN D. KNAPTON
MELVIN J. BULMAN

OCTOBER 1987

US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188
Exp Date: Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) BRL-TR-2853	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION US Army Ballistic Rsch Lab	6b. OFFICE SYMBOL (If applicable) SLCBR-IB
7a. NAME OF MONITORING ORGANIZATION	
6c. ADDRESS (City, State, and ZIP Code) Aberdeen Proving Ground, MD 21005-5066	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING / SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

LIQUID PROPELLANT GUNS

12. PERSONAL AUTHOR(S)

Morrison, Walter F., Knapton, John D., and Bulman, Melvin J.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
TR	FROM ______ TO ______		

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Liquid propellants have been the focus of periodic research efforts since just after the Second World War. Early efforts centered on the mechanically simple bulk loaded liquid propellant gun. A large number of experimental gun firings were conducted, and semi-quantitative models of the bulk loaded interior ballistic process were developed. However, the ballistic control required of a practical gun system has never been achieved. In contrast, the regenerative liquid propellant gun has demonstrated the required ballistic control, but at the expense of mechanical complexity heretofore unknown in gun systems. Nevertheless, the regenerative liquid propellant gun may provide the mechanism for the development of a practical weapon system based on a liquid gun propellant.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Walter F. Morrison	22b. TELEPHONE (Include Area Code) 301-278-6189	22c. OFFICE SYMBOL SLCBR-IB-B

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

TABLE OF CONTENTS

TABLE OF CONTENTS (CON'T)

LIST OF FIGURES

LIST OF FIGURES (CON'T)

LIST OF TABLES

I. INTRODUCTION

The objective of this paper is to summarize liquid propellant gun research in the United States, and thus to provide a guide to further study. It is not possible to address all LP gun research efforts over the past forty years. We have, therefore, severely limited discussion of these efforts in many cases. However, we have attempted to provide a comprehensive bibliography, which we hope will provide access to the large body of literature related to this subject.(i)

Liquid propellants have been the focus of periodic research efforts since just after the Second World War.[1,2] While progress in propellant[2,3] and gun[4] development have only recently made such weapons appear practical for military application, the pervasive system advantages of a fluid propellant[5-8] have helped to maintain interest in LP guns for nearly forty years. In the past, the potential for very high propellant energy content has been viewed as a primary advantage of liquid propellants.[9] However, the results of recent system studies point to the fluid nature of the propellant as the dominant factor in determining the military value of liquid propellants.[8]

The interior ballistic process of conventional guns is based on the rapid generation of gas by the combustion of a solid propellant charge. The mass generation rate of the charge is controlled through the linear burning rate and total burning surface area of the propellant grains,[10] which are functions of propellant formulation and grain geometry respectively. While a fixed initial grain geometry provides a simple, effective method for controlling the ballistic process, it also represents a constraint on the system as a whole. The requirement for a fixed initial grain geometry directly impacts propellant formulation and processing techniques. The art of charge design is based on the packaging of propellant grains to insure efficient and reliable ignition and combustion of the charge. In turn, propelling charge design influences the packaging, storage, and logistics of ammunition, as well as the design of guns, autoloaders, and combat vehicles.

In contrast, liquid propellant charges are formed at the gun(ii) by metering the propellant into the gun chamber. The surface area required

---

(i) The BDM Corporation, under contract to DARPA, has generated a bibliography on Liquid Propellant Gun Technology, which resides at the Chemical Propulsion Information Agency, Columbia, MD.

(ii) The exception is the cased LP charge. This approach was investigated in the 1950's as a means to field an LPG system rapidly.[9] However, individually packaged charges negate many of the advantages of liquid propellants. Recent LP research efforts have not considered cased LP charges.

for combustion of the propellant harge on the time-scale of the ballistic cycle is generated as the charge burns. The result is an increase in complexity of the gun itself, but significant advantages for the system as a whole. Propellant formulation and processing will be simpler, less costly, and less hazardous. Propellant packaging can be designed to improve efficiency in the logistics chain. Autoloader design will be simplified, and reduction of personnel through automation will be more easily achieved. The flexibility permitted in the vehicle design will result in weapon systems with increased combat capability, and reduced vulnerability, both through increased flexibility in ammunition stowage and reduced vulnerability of the propellant itself. Improvements in gun performance are also possible. Thus, liquid propellant guns offer improvements throughout the military system.[7,8]

There are three basic design approaches to the liquid propellant gun; bulk-loading, externally powered injection, and regenerative injection.

In the bulk loaded gun, propellant initially fills the chamber behind the projectile. The majority of bulk-loaded investigations have utilized either nonhypergolic bipropellants (the fuel and an oxidizer are separated until introduced into the combustion chamber, but do not react upon mixing), or monopropellants (either a single component liquid, or a mixture of components to form a homogeneous liquid). Both nonhypergolic bipropellants and monopropellants require an external ignition source to initiate combustion. The surface area required for propellant combustion is then generated by the breakup of the gas-liquid interface separating the bulk of the liquid and the combustion products. Although hypergolic bipropellants (the fuel and oxidizer are separated until introduced into the combustion chamber where they react upon mixing) are not practical for bulk-loaded LP guns, some early small caliber firings were conducted with encapsulated materials.[11]

In both injection concepts, the propellant is pumped from a reservoir into the combustion chamber during the combustion cycle. The combustion process in injection type guns is similar to that in liquid propellant rocket engines. In both monopropellant and bipropellant systems, the rate of gas generation is controlled primarily by the injection process. If a bipropellant (either hypergolic or nonhypergolic) is used, the injection process provides breakup and mixing of the fuel and oxidizer. Vaporization of the droplets and diffusion of fuel and oxidizer vapor then control the combustion process. If a monopropellant is used, breakup of the liquid jet in the combustion chamber provides the surface area required to burn the propellant. The externally powered gun requires a source of high pressure external to the combustion chamber to inject the propellant. The regenerative injection system utilizes the combustion chamber pressure, which is amplified and applied to the propellant in a reservoir by a differential area piston to inject the propellant into the combustion chamber against the high gun pressure. The externally powered injection system has not played a major role in LPG research, since the injection energy requirements are "excessive for ultimate service use".[12]

A summary of early liquid propellant gun research in the United States, through 1970, has been provided by Haukland.[1] This summary provides an excellent overview of early LPG research, and contains a comprehensive bibliography from this period.

The initial post war studies were conducted between 1946 and 1950 in 0.50 caliber using a hydrazine-hydrogen peroxide, hypergolic bipropellant.[11-13] The three basic LPG approaches were investigated. Velocities up to 7000 ft/s were achieved with the externally powered injection device,[13] but, as noted previously, the requirement for external power makes this device impractical for military application. Bulk-loaded tests were conducted with encapsulated propellants. The hypergolic mixture was initially separated by encapsulating one component. The system was ignited by a squib which ruptured the capulse, mixing the hypergolic components. Velocities of about 11,300 ft/s were reported.[11] However, excessive variation in muzzle velocity and chamber pressure were also noted. The regenerative injection study[12,14] was completed successfully, and an effort to develop a 37-mm RLPG test fixture was initiated.[15,16] Another important accomplishment of this period was the introduction of monopropellants (a mixture of hydrazine, hydrazine nitrate, and water) for use in liquid propellant guns.[17]

In the period from 1950 to 1957, numerous investigations of both liquid propellants and gun concepts were undertaken.[1] With the introduction of monopropellants, bulk-loaded research efforts rapidly increased.[18-22] Several 90-mm tank guns were eventually tested in two separate programs with hydrazine monopropellants. Muzzle velocities near 5,000 ft/s were achieved at a charge-to-mass ratio of 1.06,[21] and gun firings were successfully conducted at -62°F.[21] However, ballistic variability in bulk-loaded firings exceeded that of conventional guns. Although some investigations of regenerative injection guns using a monopropellant were made, the main research interest was hypergolic bipropellants, due to the very high energy content of such systems.[22-26] A 127-mm regenerative injection gun was built and tested.[24-26] The device was designed to operate with twelve radial injection pistons housed in three separate injection blocks of four pistons each, but the complexity of this device and the nature of the propellant severely limited testing. Following the end of the Korean Conflict, interest in LPG research began to diminish, and by 1957, with the increasing emphasis on rockets and missiles, both tactical and strategic, nearly all research had stopped.

LPG research continued through the 1960's at a relatively low level, and only in bulk-loaded configurations. At the BRL, monopropellants, primarily hydrazine-hydrazine nitrate-water mixtures, were fired in 37-mm and 120-mm guns.[27-30] The 37-mm tests were conducted over a wide range of ballistic parameters, but the primary interest was the high velocity regime. Muzzle velocities of about 7200 ft/s were achieved at a charge-to-mass ratio of approximately 3.5 in the 120-mm fixture using the hydrazine monopropellant. However, ballistic variability, in both 37mm and 120mm, was high. Additional efforts at Frankford Arsenal focused on the electrical ignition and cook-off of a variety of liquid propellants.[31]

By the late 1960s, the Vietnam War experience had demonstrated the continued need for gun systems in all applications; air-to-air, air defense, fire support, etc. The Naval Weapons Center, China Lake, began development of a rapid fire, bulk-loaded medium caliber cannon for aircraft application.[32,33] A nonhypergolic bipropellant, red fuming nitric acid and a hydrocarbon fuel, was used in this effort. In parallel, the Naval Ordnance Station, Indian Head, began development of a new class of liquid monopropellants based on hydroxyl ammonium nitrate.[2] These efforts formed the basis for a sharp resurgence of LPG activity in the 1970s.

LPG research since 1970 can be separated into two distinct periods; the period prior to 1976 in which bulk-loading was the primary focus of development efforts, and the period since 1978, in which the focus has shifted almost exclusively to regenerative injection.

In the 1970-76 period, efforts to develop a rapid fire 25-mm bulk-loaded gun using a nonhypergolic bipropellant continued,[32,33] and development of both medium and large caliber, bulk-loaded guns[2] using a monopropellant was initiated. Twenty-five round bursts were fired at a rate of 350 rounds per minute using the 25-mm nonhypergolic bipropellant gun. While the ballistic control required for safe, high rate fire was achieved, ballistic variability was still large compared to conventional guns.

The BRL continued ballistic investigations in 37-mm guns, using the new hydroxyl ammonium nitrate (HAN) monopropellants[3] developed by the Naval Ordnance Station, Indian Head. This work was done in support of the development of large caliber cannons for Naval application. However, no large caliber firings were ever conducted in conjunction with this program, due to problems in controlling very high chamber pressures, and unacceptable ballistic variability in 37-mm test data.

A separate effort was initiated by the Advanced Research Projects Agency (ARPA, now DARPA), to develop a high velocity 75-mm LPG cannon for application in light armored vehicles. The technical results of all three efforts remain classified. However, in 1976, two successive firings in the DARPA 75-mm program resulted in catastrophic failures. The causes of these failures were never fully determined. In one case, the failure appears to have been linked to an error in the fill procedure. In the other, the propellant, which had been changed for the second firing, was implicated. In any case, these failures quickly lead to the temporary termination of nearly all Government supported LPG research.

The first investigations of regenerative monopropellant systems since the 1950s were initiated by Graham and Bulman in 1974, in 0.30 caliber and 25-mm fixtures.[34,4] This work lead to renewed Government involvement by 1978. Bulman has subsequently developed and tested a rapid fire 30-mm RLPG.[4] In a separate, Government supported effort, a 105-mm RLPG has also been successfully tested, achieving a muzzle velocity of 810 m/s at a charge-to-mass ratio of 0.28.[35] The significant accomplishments in these efforts have been the high degree of ballistic control and the excellent reproducibility in pressure and muzzle velocity. An effort, based on these results, is now underway to develop and test a 155-mm RLPG (howitzer) monopropellant system.

II. BULK LOADED LIQUID PROPELLANT GUNS

1. GENERAL

In the bulk loaded system the propellant initially fills the chamber behind the projectile. Therefore, high loading densities can be achieved, usually between 1 g/cm^3 and about 1.45 g/cm^3 depending on the density of the LP and the amount of ullage. Ignition sources for most experimental studies have been either pyrotechnic or submerged electrical spark.

This review of the BLPG will concentrate on the monopropellant case due to the availability of unclassified literature. Although the mixing of immiscible fuel and oxidizer components of a bipropellant produces a quasi-stable suspension in the gun chamber, the basic hydrodynamic mechanisms controlling the ballistic process are the same for both monopropellant and bipropellant.

III. INTERIOR BALLISTICS OF THE BLPG

While the BLPG is mechanically the simplest implementation of the liquid propellant gun, the interior ballistic process is more complex, and ultimately the most difficult to control. Many studies have shown that the energy and geometry of the igniter influence the shape of the chamber pressure-time curve. Although many exceptions have been noted, the most common chamber pressure-time trace is double peaked, the magnitude of the first peak being influenced by the igniter output. Factors controlling the second peak pressure, besides the igniter, are the complex velocity and acceleration dependent charge break-up mechanisms inherent in the bulk-loaded process.

If the charge is ignited at the projectile base, the mathematical description of the interior ballistic process is simplified somewhat, since combustion takes place in a more or less cigarette fashion. However, ballistic efficiency is low due to the low mass consumption rate in this configuration. It has been shown experimentally[20] that breech ignition results in increased ballistic efficiency in the BLPG apparently due to the large propellant surface area generated hydrodynamically, which enhances the propellant consumption rate. In the following description of the BLPG interior ballistic process in this section, only breech ignition is considered.

Ullage is another factor which can complicate the BLPG process. If the ullage is localized, the system is asymmetric and nonhomogeneous, making mathematical description more difficult. This is also a highly undesirable configuration due to the potential for secondary ignition, from the adiabatic compression of the ullage, leading to large pressure excursions. These problems are circumvented if the ullage is assumed to be uniformly distributed throughout the system and the bubbles are very small. In this case, the mathematical formulation reduces to the zero ullage case, however, the physical characteristics of the liquid become a function of the amount and distribution of the ullage. Only the zero ullage configuration is treated here, for simplicity.

Comer et al[27-30,36] developed the first phenomenological interior ballistic model of the bulk loaded gun based on detailed experimental data. In the analysis of gun firing data, it was noted that calculated projectile acceleration, based on chamber pressure measurements, and projectile acceleration obtained from interferometer data, varied by as much as 50%. This discrepancy was attributed to a portion of the LP charge moving with the projectile.

Information on the motion of the LP charge was obtained,[27] using a radioactive tracer method. A Cobalt-60 source was encapsulated in polyethylene, approximating the density of the LP. It was assumed that the motion of the Cobalt-60 would closely follow that of the LP. A plot summarizing the test results is presented in Figure 1. When the source is initially located forward in the chamber, the source moves with the projectile. When the source is initially located near the center of the chamber, the source lags behind the projectile, and when the source is initially located at the rear of the chamber, the source moves relatively little. These results indicated that, in fact, a portion of the charge moves with the projectile.

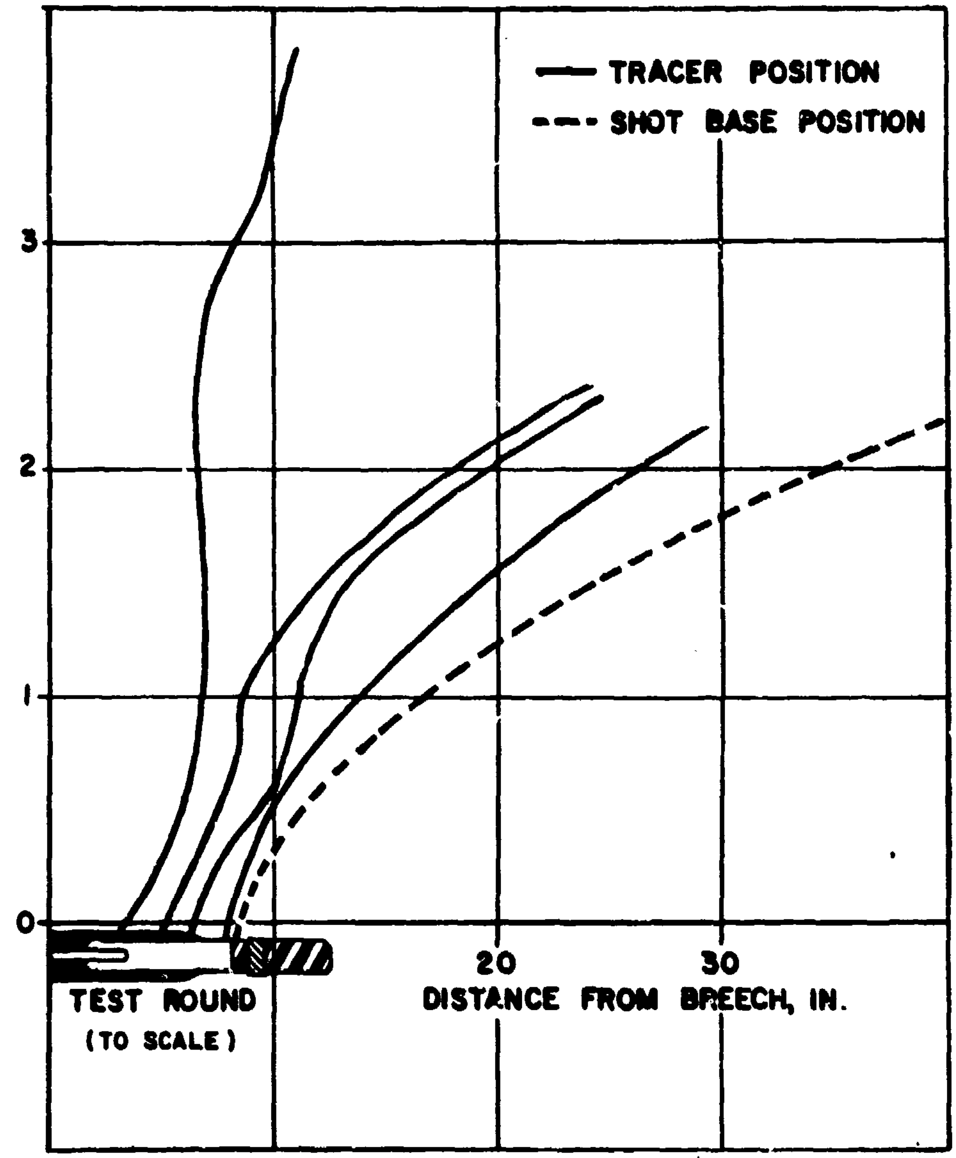


Figure 1. Trajectories of Projectile Base and Radioactive Source as a Function of Initial Source Location

The radioactive tracer data were also used to estimate the amount of charge traveling with the projectile by comparing the source displacement with that of the LP initially located forward of the source. It was assumed that the "LP slug" forward of the source moved with the projectile. Representative data are presented in Figures 2 and 3. The dotted line is the trajectory of the projectile while the solid line is the source trajectory. Figure 2, with the source initially at the forward end of the chamber, shows that the source moved with the "LP

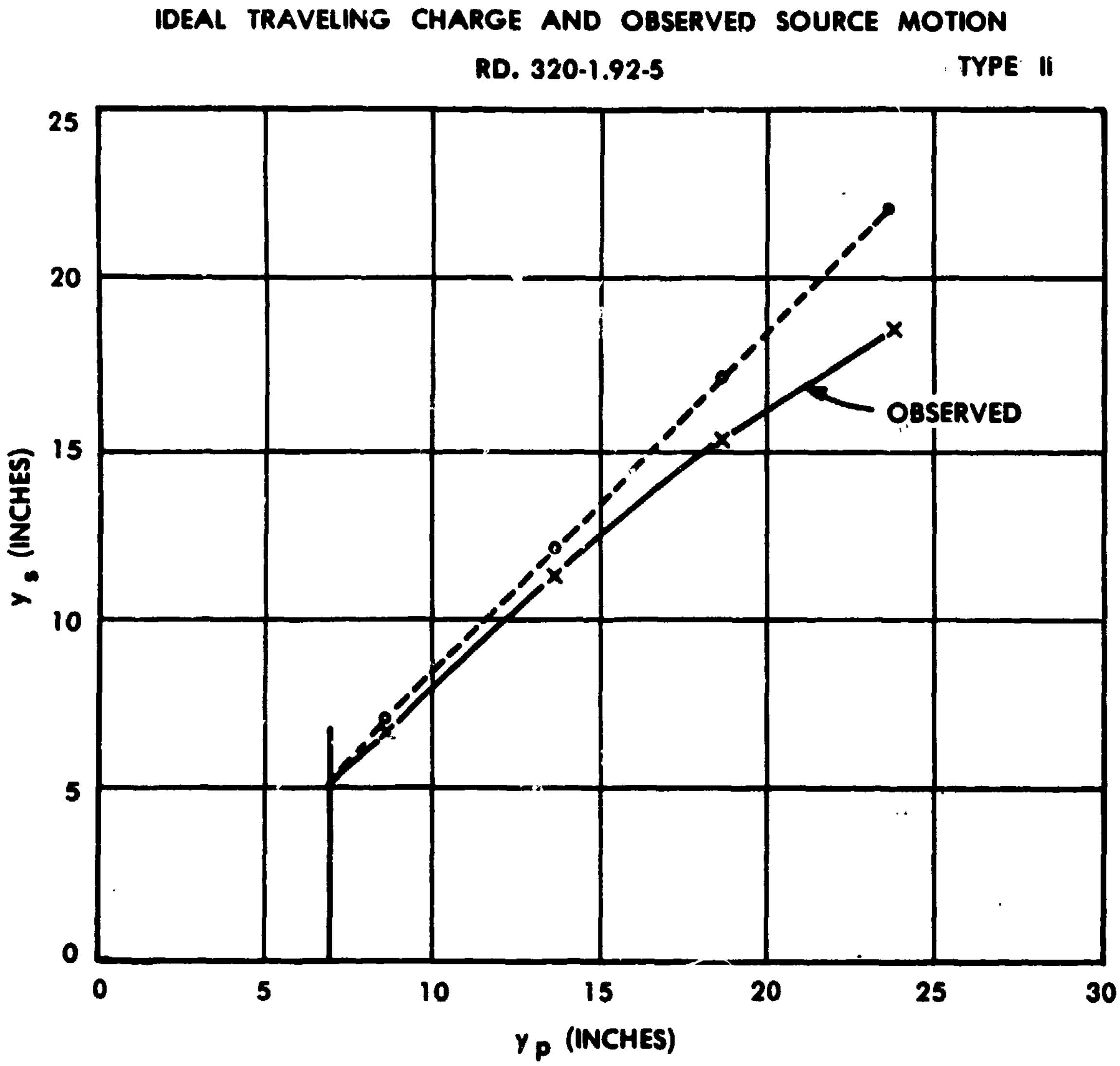


Figure 2. Projectile Base and Radioactive Source Trajectories: Source Initially Located at Forward End of Chamber

slug" for about 380 mm (15 in.). Figure 3, with the source initially near the center of the chamber, shows that the source lagged well behind the "LP slug". Hence, only that portion of the LP charge initially located in the forward section of the chamber moves with the projectile for any significant distance.

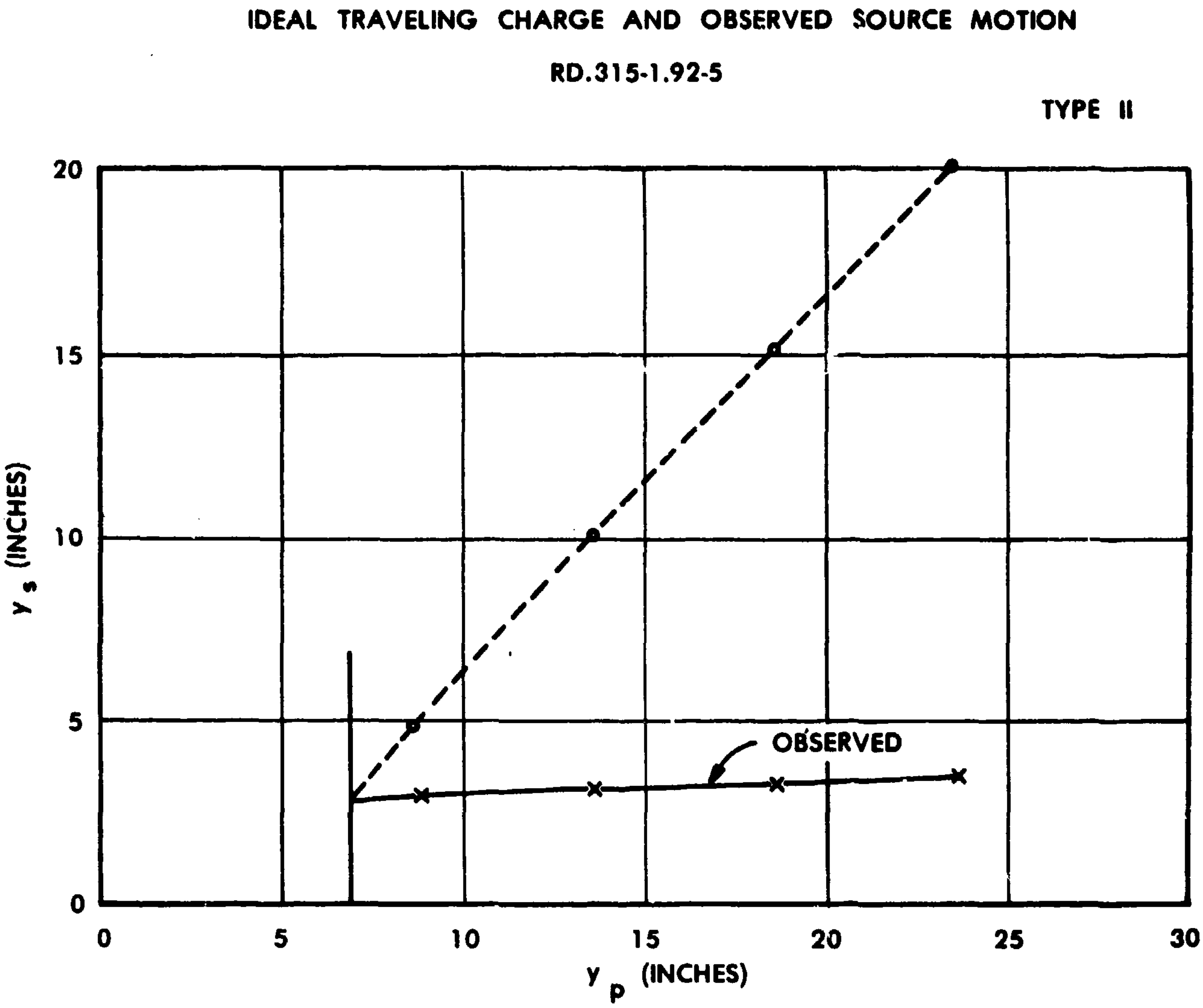


Figure 3. Projectile Base and Radioactive Source Trajectories: Source Initially Located Near the Center of Chamber

In developing a description of the BLPG interior ballistic process, it was necessary to pose a model which was consistent both with the physical situation, and with the experimental data. The model proposed by Comer et al[27] is summarized in Figure 4. The ignition process is essentially a small explosion in the liquid, as treated by Cole,[37] which creates a bubble, or cavity, of hot combustion products near the breech. A complex pattern of pressure waves develops in the liquid column as a result of multiple reflections of the initial pressure pulse generated by the ignition event. These pressure waves tend to cause the liquid-gas interface at the cavity to spall, increasing the rate of mixing of propellant with the hot combustion products. Analyses of experimental data indicate that the first peak in chamber pressure occurs prior to significant projectile travel. Therefore, combustion of only a small protion (<5%) of the propellant charge is required to produce the observed chamber pressure. After shot start, the high pressure gases in the cavity at the breech accelerate both the projectile and the "liquid slug" between the projectile and the cavity. This situation is physically equivalent to that posed by Taylor in his analysis of the instability of accelerated liquid surfaces.[38,39] The growth of the instability at the gas-liquid interface leads to the development of a "Taylor" cavity which penetrates the liquid column, eventually overtaking the projectile.

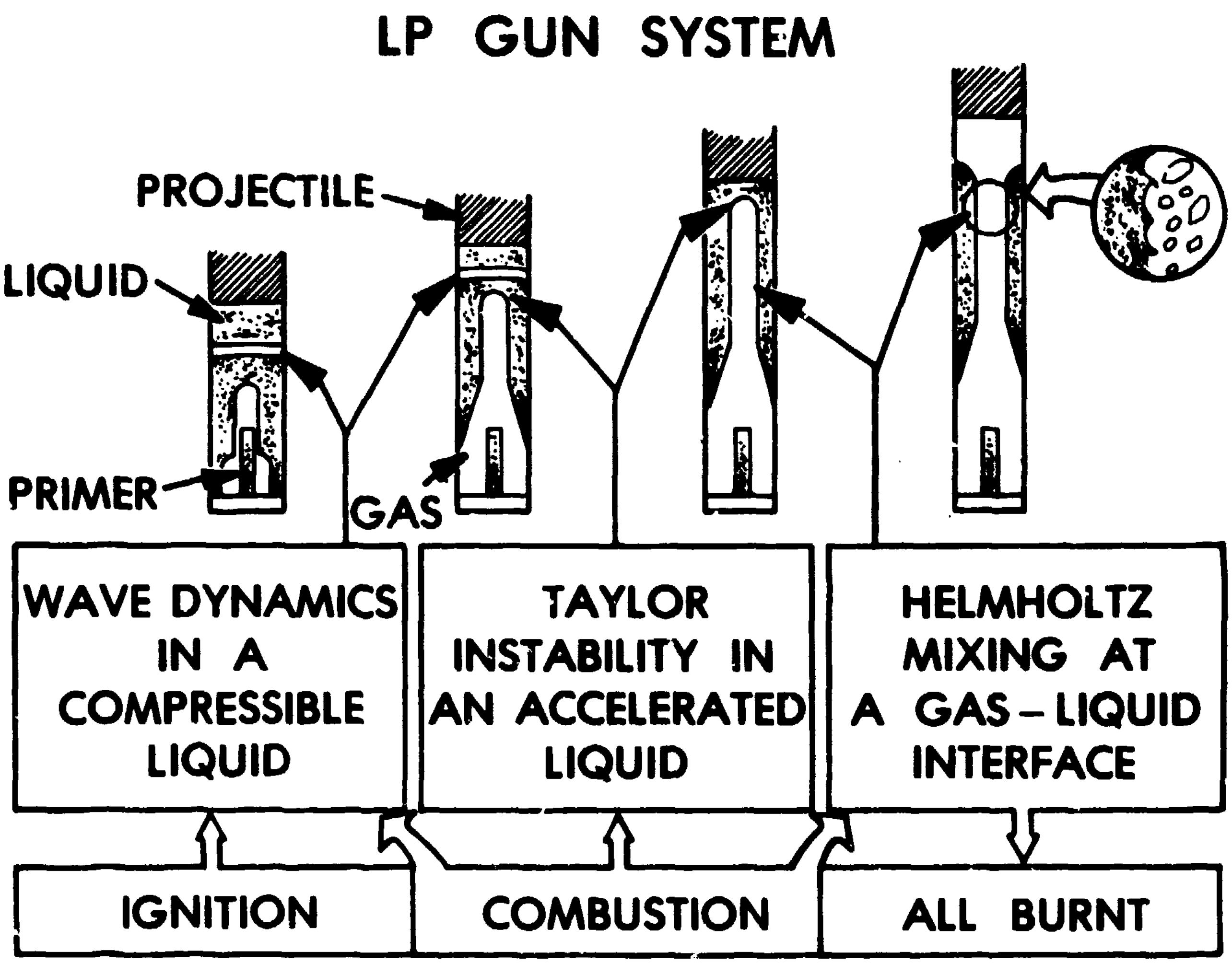


Figure 4. Bulk Loaded LP Gun System

A similar hypothesis, suggesting the formation of a gas core during the early combustion process had been developed previously by Giedt and Rall[40] at Detroit Controls. Their conclusions were based on the interpretation of data from thermocouples located in the chamber and a few inches down tube of the forcing cone of a 40-mm fixture.

The experimental studies of Lewis[42] show that the velocity at which the cavity tip penetrates the liquid column is proportional to the square root of the product of the acceleration of the liquid surface and the cavity radius. Comer et al proposed a modified relation based on the linear analysis of the Taylor instability,

$$v_c = C_1 \left\{ r_c \, a \left(\frac{\rho_1 - \rho_g}{\rho_1 + \rho_g} \right) \right\}^{1/2} \qquad (1)$$

where v_c is the cavity tip velocity, r_c the cavity radius, a the acceleration, and ρ_1 and ρ_g the liquid and gas densities respectively. C_1 is a constant depending on liquid properties and chamber geometry, which is determined from experimental data. After the cavity reaches the projectile base, an annulus of liquid will remain on the chamber walls. Combustion gases flowing at high velocity through this annulus will result in turbulent mixing of the liquid and gas at the inner surface of the liquid annulus, the Kelvin-Helmholtz instability.[42] The rate at which the liquid surface is eroded has been shown to be proportional to the velocity difference across the interface.[43]

$$\dot{r}_c = C_2 \left(v_g - v_1 \right) \qquad (2)$$

The constant C_2 was also determined from experimental data, and was found to be in reasonable agreement with theoretical estimates. This Helmholtz mixing mechanism produces the large burning surface area required to burn the bulk LP charge during the interior ballistic cycle. This description is highly idealized, and at the very least some superpositioning of the component processes is to be expected.

Comer et al[27] also estimated the fraction of the charge burnt, Φ, as a function of time during the ballistic cycle. They greatly simplified the analysis by assuming that the charge moves with the projectile until burnout, that the kinetic energy of the gas and therefore the pressure gradient in the gas can be neglected, and that the total energy loss at any point is equal to 10% of the projectile kinetic energy. They assumed a Nobel-Abel equation of state for the gas and the energy equation for the system. Eliminating the gas temperature, they obtained,

$$\Phi \left[\frac{C\lambda}{\gamma - 1} + \frac{1.1}{2} cv^2 - \frac{\bar{P}C}{\gamma - 1} (1/\rho_g - \eta) \right] =$$

$$\frac{\bar{P}}{\gamma - 1} [U_o + Ax] + \frac{1.2}{2} [M + C] v^2 \qquad (3)$$

The values of Φ were calculated using experimental data for pressure, displacement and velocity, beginning at the muzzle and working backward in time. At some point, Φ begins to decrease sharply, indicating propellant burnout. Estimates of fraction of charge burnt and fractional burning rate averaged over 10 test firings are presented in Figure 5.[27]

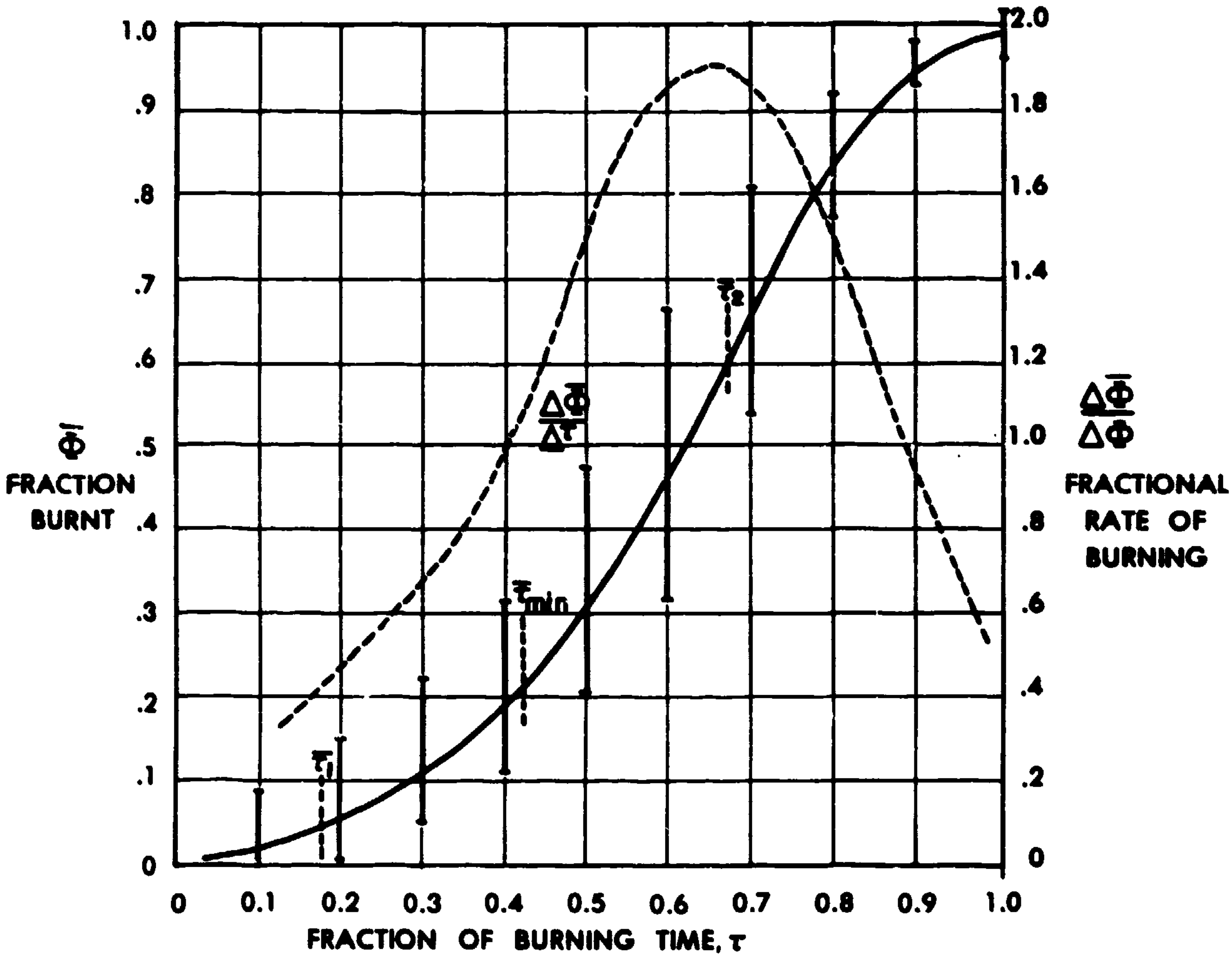


Figure 5. Estimated Fractional Burning Rates Based on Data from 10 Firings.

The subscripts 1,2, and min refer to the time of first peak pressure, second peak pressure, and the intermediate minimum. The time at which the Taylor cavity reached the projectile base was also estimated using equation (1). It was found that the cavity penetrated the liquid column near t_{min}, and correlated well with the rapid increase in fractional burning rate of the propellant. Comer et al[27] argued that the liquid column would be expected to undergo some breakup as the cavity reached the projectile base, which would account for a sharp rise in combustion rate. They also noted that the increase in fractional burning rate after cavity penetration support the Helmholtz mixing hypothesis. Equation (2) was utilized to estimate the amount of propellant "mixed" after cavity penetration. A composite plot of the various measured and estimated quantities addressed in this model is presented in Figure 6. The amount of propellant mixed, calculated from the Helmholtz relation, equation (2), and the amount burnt, calculated from the energy equation, equation (3), correlate well.

Additional experimental studies, conducted at much higher pressures than those of Lewis, have also shown the propagation of an accelerating gas into a denser liquid column. The air-water investigations of Howland et al[44,45] were limited to gas pressures of 14 MPa, and accelerations of 200 to 1100 g's. High speed photographs show the formation of a gas cavity which penetrated the water column as the gas-liquid-piston accelerated down a transparent tube. A comparison of the velocity of the gas cavity with a numerical simulation[45] indicated that the experimental cavity velocity was higher than the predicted velocity by about a factor of two. The authors speculated that the discrepancy was due to acceleration affects not included in the model, or to the growth of secondary instabilities superimposed on the primary cavity. Additional studies on the formation of a gas cavity under high pressure conditions were conducted by Irish[46] who used an X-ray system and a 37-mm fiber glass fixture. Photographs of well defined gas cavities were obtained, however problems with variations in igniter output and difficulties with propellant combustion limited progress on the project.

Subsequent interior ballistic models of the BLPG[47-51] have been based to some degree on the phenomenological model of Comer et al. These models vary in complexity from the simple, zero dimensional model of Burnett[47] to the two-dimensional solutions of the Navier-Stokes equations of Butler and O'Rourke[50] and Phillips et al.[51] However, none of the models have been utilized to any significant degree in the analysis of experimental data.

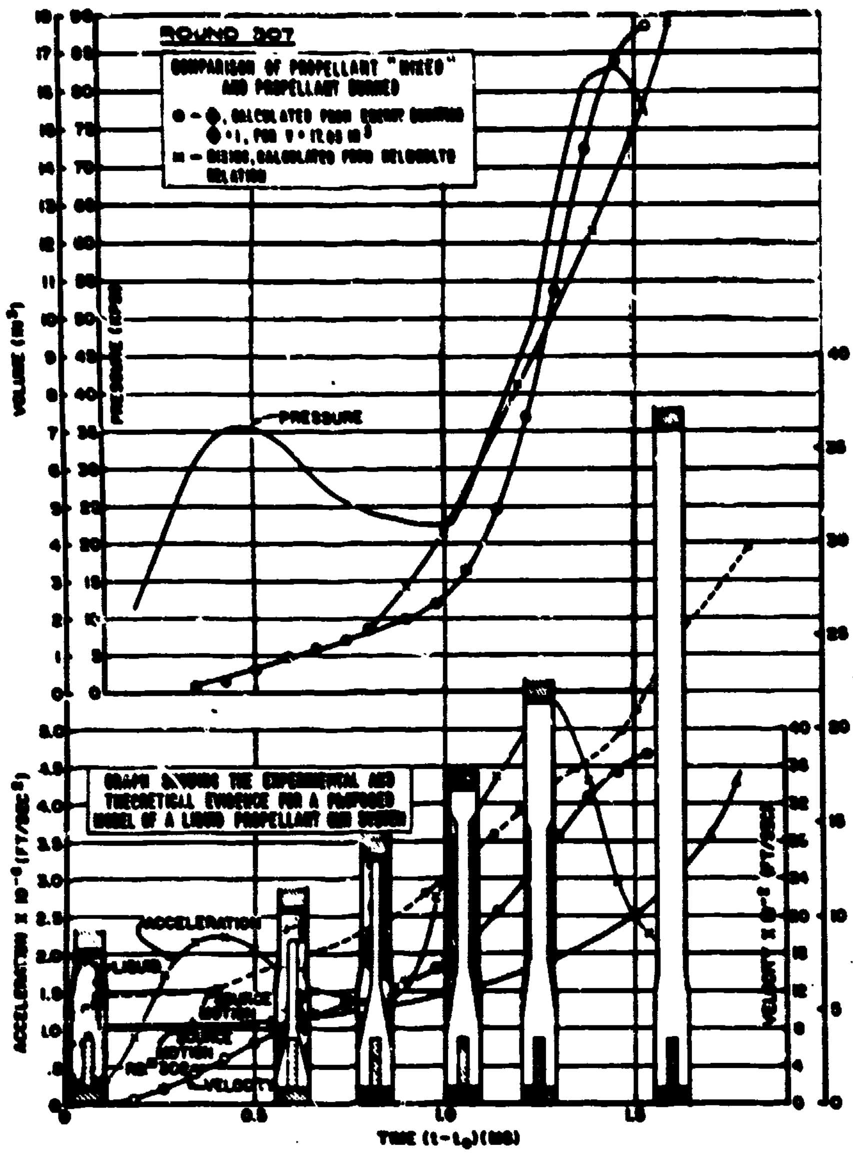


Figure 6. Composite Plot of Measured Estimated Parameters from a BLPG Firing

IV. PHENOMENOLOGICAL STUDIES

1. IGNITION LOCATION AND GEOMETRY

The ignition system of the BLPG, more so than in a solid propellant gun, is key to safe ballistic operation. The coupling (temporal and spatial) of igniter energy to the LP controls the subsequent evolution of the ballistic process; indeed, most gun overpressures have been attributed to improper ignition. Guidelines for development of BLPG igniters are largely empirical. Analytical guidelines are limited to the one-dimensional pressure wave models of Comer and McBratney,[36] and Erickson[52] which address the response of the combined gas-liquid system to the early pressure rise from the igniter.

Regan and Shambelan[53] used a hydrazine-based monopropellant[(iii)] and a 15.2-mm gun in a parametric study of pyrotechnic ignition. The parameters examined included the configuration of the igniter tube, location of the vent in the igniter tube, the number of vents, and the total vent area. General conclusions from their work include: (1) An increase in the number of ignition sites (based on the number of igniter hole vents) results in an increase in the minimum pressure between the first and second peaks; (2) The first peak pressure decreases as the vent of an axial igniter is moved forward in the charge, but increases as the vents of a radial igniter are moved forward in the charge (a similar finding was reported earlier by Griffin[54] in tests with anhydrous hydrazine in a 7.62-mm fixture); (3) The chamber pressure increases with increasing igniter vent area.

Extensive ignition and gun development work was conducted by Detroit Controls.[18] A pyrotechnic igniter mounted in the bore of the projectile was tested in a 30-mm fixture with a hydrazine-based monopropellant.[(iv)] This approach offers advantages for mechanical simplification during loading. Satisfactory performance in a five round group with a propellant charge to mass ratio (C/M) of 0.31 was reported. The mean chamber pressure and muzzle velocity were, respectively, 269 MPa with a maximum deviation of 28 MPa, and 968 m/s with a maximum deviation of 9.1 m/s.

Comer et al,[27] using a hydrazine-based monopropellant[(v)] in a 37-mm BLPG found, as in the earlier studies, that the shape of the chamber pressure-time trace is influenced by the igniter output characteristics.

(iii) 67.5% hydrazine, 21.5% hydrazine nitrate, 11.0% water.

(iv) 63% hydrazine, 32% hydrazine nitrate, 5% water.

(v) 65% hydrazine, 30% hydrazine nitrate, 5% water.

For example, if the igniter output is too vigorous, or too widely distributed in the charge, the first peak pressure becomes excessive. Knapton and Stobie using a HAN-based LP in both a 38.8mm and a 37mm, also concluded that the igniter output characteristics have a direct influence on the magnitude of the first chamber peak pressure. Elmore[55,56] using various HAN-based LPs in small caliber fixtures, also found that the output charateristics of a pyrotechnic igniter can be used to modify the shape of the chamber pressure-time records.

Messina et al[57] have emphasized the importance of controlling the rate of pressure rise in the bulk liquid. A special vented chamber was developed, along with a rapid fill system, to study the compression sensitivity of both statically and dynamically loaded liquid monopropellants, either neat or containing a measured volume of gas, to various pressure loading rates. It was shown that for sufficiently high pressure rise rates the propellant can be ignited. The initiation mechanism is assumed to be the adiabatic compression of ullage in the bulk liquid.[58,59] These data would tend to support arguments attributing some gun overpressures to the generation of secondary ignition sites by compression ignition of ullage bubbles distributed throughout the bulk of the LP charge.

2. IGNITION ENERGY

The energy required to initiate sustained combustion of a bulk loaded charge is strongly system dependent, i.e. the total amount of igniter energy required for sustained combustion depends not only on the LP but also on various system factors, such as igniter output characteristics and projectile shot start pressure.

In a comprehensive study on the electrical ignition of hydrazine propellants, Evans, Given and Doran[60] postulated that the energy transferred to the propellant by ohmic heating during the formative phase prior to breakdown may be more efficient for ignition than a similar quantity of energy delivered after breakdown, during the spark or arc phases. In a review of earlier work, Kirshner and Stiefel[31] concluded that the electrical conductivity of the liquid propellant has a significant effect on the electrical ignition requirements of the propellant. For example, an ignition energy of about 200 J was required for a 90-mm gun using mixtures of ethyl and n-propyl nitrate. In comparison, only 32 J was required for a 30-mm gun using a hydrazine monopropellant which had an electrical conductivity about six orders of magnitude higher than the ethyl and n-propyl nitrate propellant. Kirshner and Stiefel also performed open cup electrical igniter studies on alkyl nitrate and hydrazine type monopropellants. They concluded that the electrical energy could be transferred to the hydrazine propellants solely by formative phase heating, a finding similar to the earlier observations of Evans, Given, and Doran.[60] Formative phase energy transfer is desirable, since the energy can be transferred at lower voltages and with less pitting and wear of the electrodes. Kirshner and

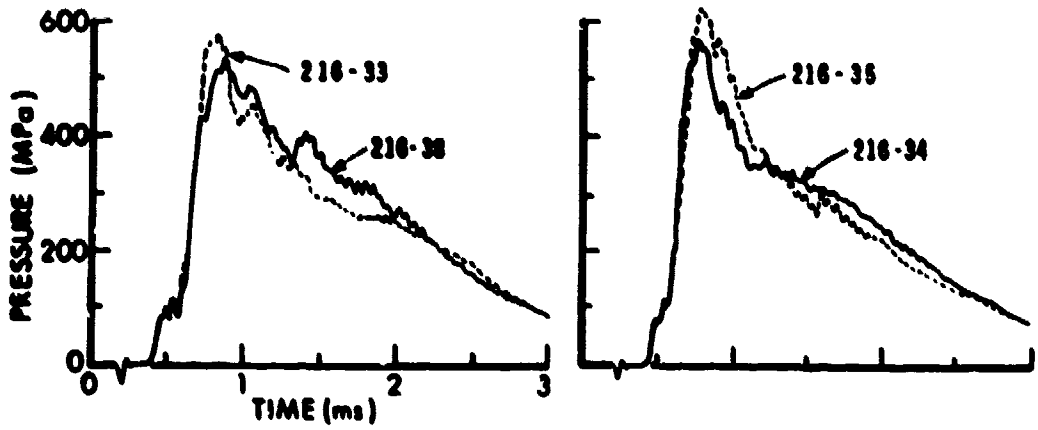
Stiefel[31] also concluded, based on tests using various additives to increase the conductivity of the alkyl nitrate propellants, as well as results of the hydrazine propellants studies, that a propellant with a high conductivity enhances formative phase energy transfer. They also concluded that increasing the rate of energy transfer (power transfer) increases the probability of igniting a liquid monopropellant with formative phase. Weinberg[61] has made a similar observation after a review of data on the electrical ignition of the hydroxyl ammonium nitrate type of propellants. Weinberg further postulated that the power density should be an important ignition criteria.

A hydrazine-based monopropellant has been successfully ignited in a 37-mm BLPG with 27 Joules of electrical energy delivered across a spark gap.[62] In a similar 37-mm gun, the hydrazine-based LP was ignited using either an M38B2 or T9E6 igniter (which is similar to an M52A3B1) plus a solid propellant booster charge of about 3.9 to 4.5 g of Eimite (40% nitrocellulose, 27.6% potassium nitrate, 16.7% magnesium, 9.8% sulfur, and 5.9% resorcinol, with an impetus of 511 J/g) for a loading density of 0.216 g/cm^3. The energy content of this ignition system was about 10.5 to 12.0 kJ.

HAN-based LPs have been ignited in gun fixtures by various methods including hot wire, spark, pyrotechnic and laser. Investigations involving these various ignition sources have been reviewed by Klingenberg, Knapton, and Morrison.[63] For NOS 365, electric spark energies are typically about 20 Joules in a 30-mm fixture.[64] Lower energies have produced inconsistent results. In one test, 12.6 Joules produced reasonable ignition, whereas 15.9 Joules resulted in an under-ignition in a separate test. Pyrotechnic igniters have been used successfully with the HAN-based LPs in 37-mm guns.[65] These igniters consisted of a T9E6 or M52A3B1 igniter and a solid propellant booster charge of 0.08 to 0.4 g of Unique Powder, giving an ignition energy of about 1.3 to 3.0 kJ. Hot wire ignition tests performed by Knapton et al,[66] in a 25-mm blow-out gun and by Klingenberg et al[67] in a closed chamber have demonstrated that a HAN-based LP can be ignited with a fraction of a Joule. However, the initial gas generation rate is too slow for a practical ignition system.

3. PRESSURIZATION RATE

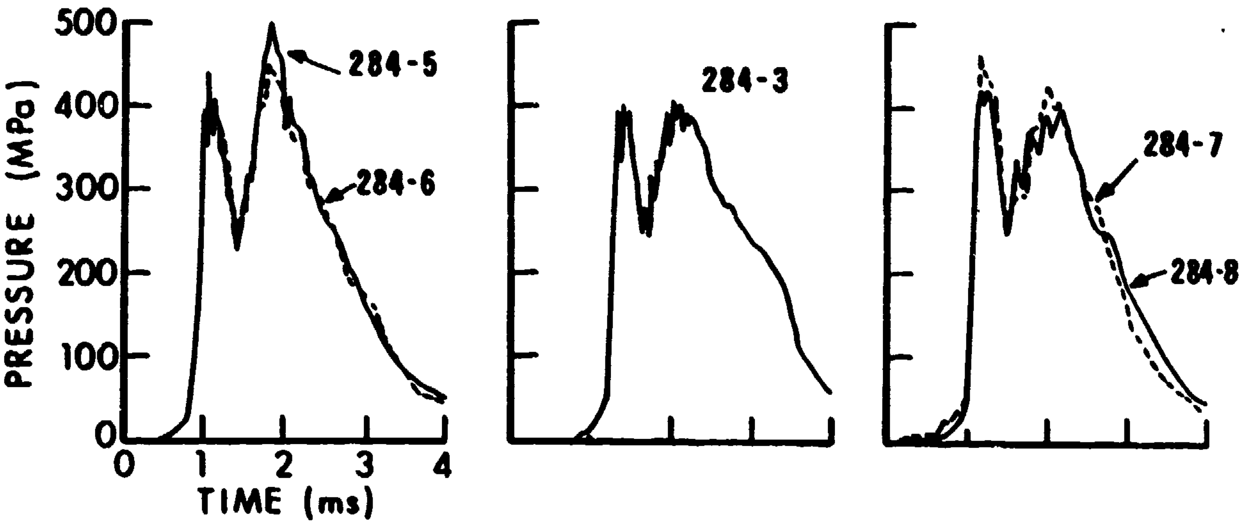
The early pressurization rate is an important parameter in a BLPG,[52-57] which can affect the gas generation rate during the ignition and combustion cycle. Figures 7 and 8 show the pressure-time curves for two separate series of 37-mm BLPG firings in which different pyrotechnic materials were used in the ignition systems. A piston radial primer was used in both series of tests, however, in one series a rapid burning pyrotechnic mixture was used (Figure 7) while a slower burning mixture was used in the other (Figure 8). In other respects, the test configurations were nearly the same. The resulting pressure-time curves are distinctly different in character.



GUN: 37 mm
IGNITER: PISTON RADIAL M1 WITH UNIQUE POWDER
PROPELLANT: NOS 365
CHARGE: 351g
EXPANSION RATIO: 12.9
PROJECTILE MASS: 318g

	P1 (MPa)	V1 (m/s)	LOT
216-33	594	1441	H44
216-34	606	1490	H44
216-35	679	1521	H45
216-38	537	1531	H44

Figure 7. BLPG Firing Using a Rapid Burning Pyrotechnic Primer



GUN: 37 mm
IGNITER: PISTON RADIAL WITH M30 AND EIMITE
PROPELLANT: NOS 365
CHARGE: 353g
EXPANSION RATIO: 18.6
NUMBER OF FIRINGS: 13

$\overline{P1}$ = 376 MPa (σ = 8.5%)
$\overline{P2}$ = 484 MPa (σ = 19%)
$\overline{V2}$ = 1634 m/s (σ = 2.4%)

Figure 8. Comparison Breech Pressure Plots for a Series of Firings with a Projectile Mass - 293g

The faster acting igniter results in a 25-50% higher first peak pressure in about the same elapsed time as the slower igniter. This implies a higher pressure rise rate in the gun chamber for the more vigorous igniter. As discussed earlier, the results of Comer et al[27] indicate that only a small portion (about 5%) of the total propellant charge is consumed in the rise to first peak pressure. Therefore, a more vigorous ignition system, interacting with a larger volume of the LP charge, would be expected to produce a higher pressure rise rate and a higher first peak pressure, consistent with the data in Figures 7 and 8.

The more vigorous igniter consistently produced a pressure-time trace with a single peak, Figure 7, whereas the less vigorous igniter produced a double peaked curve with the two peaks nearly equal. Current interior ballistic theories are not capable of explaining this result in detail.

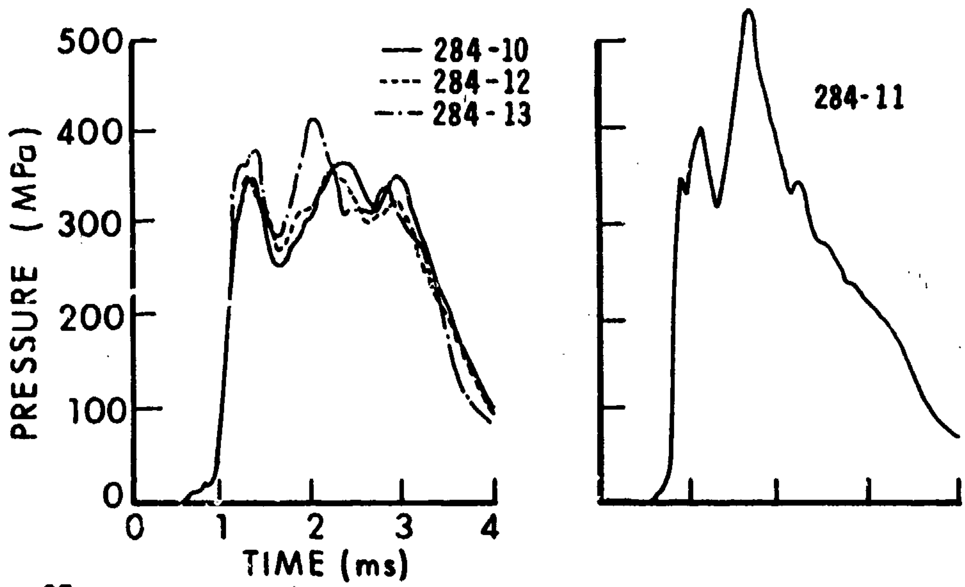
4. CHARGE CONFIGURATION

Regan and Shambelan[53] investigated the effect of chamber geometry on BLPG ballistics, by varying the breech configuration. It was found that the first peak chamber pressure is reduced when the shape of the breech is such that the volume of LP in the vicinity of the igniter is reduced. McBratney,[65] Knapton, and Stobie using HAN-based LPs in 37-mm and 38.8-mm guns found that the maximum chamber pressures could be reduced by using conically shaped inserts mounted in the breech, around the pyrotechnic igniter. These results again point to the sensitivity of the BLPG to the amount of propellant interacting with the igniter.

Most investigators have attempted to minimize the amount of ullage in the bulk propellant charge, to reduce the possibility of secondary ignition due to adiabatic compression of bubbles. Some investigators, however, found for the hydrazine-based LPs that a small amount of ullage, a few percent of the total charge, can be used to dampen pressure waves generated during the ignition event. Poudrier[68] has commented that some of the early US Navy tests intentionally involved a small amount of ullage for this purpose. Elmore[69] also studied the effects of ullage on ballistic performance. He used a spark igniter in a 30-mm gun with a dynamically loaded hydrazine-based LP. The ullage was varied from 2.2% to 4.0% without adverse effects on the ballistic performance.

5. PROJECTILE MASS

The effect of projectile mass on the BLPG process has been investigated by Knapton and Stobie using a HAN-based monopropellant in a 37-mm fixture. Results from this investigation are presented in Figures 8-10. The ignition system, charge configuration, and expansion ratio were kept constant throughout the investigation, and only the projectile mass was varied. Projectile masses of 293 grams (Figure 8), 627 grams (Figure 9), and 929 grams (Figure 10) were used, giving charge to mass ratios of 1.20, 0.56, and 0.38 respectively. The igniter used in these tests had a relatively low gas generation rate. It was found that the peak pressure did not vary significantly with C/M. However, the overall shape of the pressure-time curves did change with the change in projectile mass.



GUN: 37 mm
IGNITER: PISTON RADIAL WITH M30 AND EIMITE
PROPELLANT: NOS 365
CHARGE: 354 g
EXPANSION RATIO: 18.5
NUMBER OF FIRINGS: 4

$\overline{P1}$ = 365MPa (± 20MPa)
$\overline{P2}$ = 410MPa (+114,-56MPa)
$\overline{V2}$ = 1245m/s (+6,-15 m/s)

Figure 9. Comparison Breech Pressure Plots for a Series of Firings with a Projectile Mass - 627g

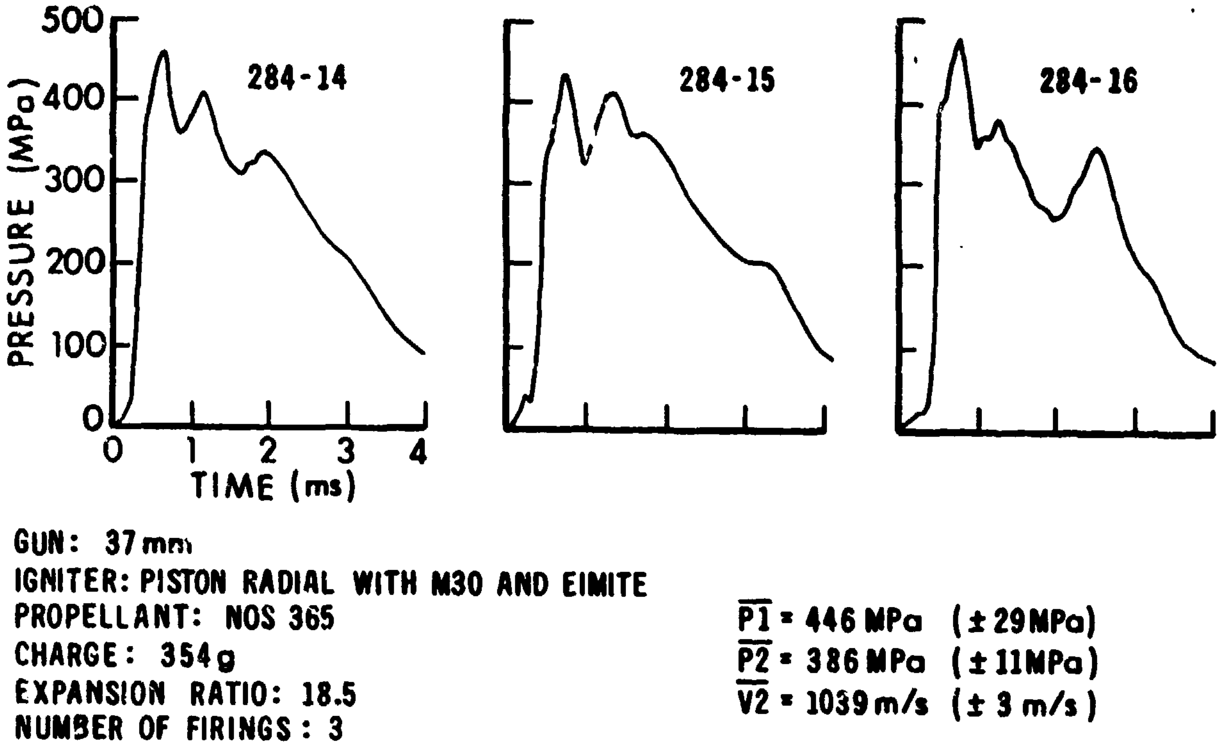


Figure 10. Comparison Breech Pressure Plots for a Series of Firings with a Projectile Mass = 929g

6. PRESSURE WAVE SUPPRESSION METHODS

Comer et al[27] found that the first peak chamber pressure could be influenced by a pressure wave damper located at the projectile base. Lucite disks were attached to the base of the projectile, and it was found that the thickness is an important variable. Other materials, such as Neoprene have also been used,[65] although no optimization studies were performed. The results of these studies indicate that suppression of pressure waves in the liquid column could be an important factor in controlling the maximum pressure in a bulk-loaded LPG.

7. VARIATION OF PROPELLANT PHYSICAL PROPERTIES

The physical properties of interest are the propellant viscosity and surface tension, since these influence the development of the Taylor and Helmholtz instabilities. There have been only limited experimental investigations of the effects of propellant physical properties in the past,[56] and these were severely limited in the range over which the viscosity and surface tension could be varied.

It can be shown theoretically that increased viscosity and surface tension will suppress the shorter wavelength Taylor and Helmhotz instabilities. It has been suggested[70] that by increasing the propellant viscosity and/or surface tension in order to suppress wavelengths below a desired minimum, say the diameter of the chamber or tube, the bulk-loaded process can be initiated in a more controlled fashion, possibly leading to improved repeatability. Under gun conditions, the increases in these properties must be very large (4-5 orders of magnitude) in order to have the desired effect; however, if the increase is too large, difficulty may be encountered in the generation of sufficient surface area to burn the charge.

V. SUMMARY OF BULK-LOADED MONOPROPELLANT TESTS

A summary of monopropellant BLPG investigations over the past 30 years is presented in Tables 1-3. Table 1 addresses investigations made using hydrazine-hydrazine nitrate-water monopropellants. Table 2 deals with investigations in which organic nitrate monopropellants were used, and Table 3 with investigations made with hydroxyl ammonium nitrate-based monopropellants. All gun firings were made at ambient temperature, except six tests with a HAN-based LP (Table 3) which were part of an investigation of the effect of temperature on BLPG ballistics. Calibers range from 6.2 mm to 120 mm; pyrotechnic, spark, and compression ignition systems are represented, and data obtained with four classes of monopropellants are included. The best muzzle velocity repeatability reported was about 1/2% - 2/3% in early 15.2-mm tests. Otherwise the variation in muzzle velocity is 1% or greater.

Figures 11 and 12, from Jones et al[71] illustrate the repeatability problem encountered with BLPG approach. The four pressure-time traces shown in Figure 11, recorded in the chamber of a 37-mm gun, represent the four extreme recordings of a 29 round reproducibility group. A hydrazine-based LP was used for the tests. Figure 12 shows four additional pressure-time traces from the same reproducibility group that exhibit completely different characteristics. The poor pressure-time reproducibility was attributed (based on an analysis of bore surface thermocouple data) to erratic ignition at the base of the projectile which occurred for some of the tests almost immediately after projectile start. The cases where projectile base ignition was believed to have occurred are shown in Figure 12, which contrasts with the significantly different pressure-time records shown in Figure 11. The cases in which ignition at the projectile base may have occurred gave reasonable pressure-time reproducibility, however the ballistic performance was lower than the cases represented in Figure 11. When no base ignition occurred, Jones et al[71] speculated (based on an analysis of pressure and projectile acceleration data) that a portion of the charge was accelerated with the projectile. It was later postulated by Knapton and Stobie[79] that the poor reproducibility evident in Figure 11 was associated with poor igniter reproducibility. This hypothesis, however, was never proven.

TABLE 1. Summary of Some of the Monopropellant BLPG Tests Using a Hydrazine-based LP.

Source	Ref	Year	Gun Cal (mm)	Ign[1]	Proj Mass (g)	C/M[2]	No.of Tests	P_{MAX} (MPa)	Muzzle Velocity (m/s)	Standard Deviation (m/s)	Standard Deviation (%)
Griffin	(54)	1952	15.2	p	73.7	0.54	10	359	963	8.8	0.91
Griffin	(54)	1952	15.2	p	73.7	0.54	11	352	964	6.4	0.66
Griffin	(54)	1952	15.2	p	73.7	0.54	10	324	961	6.1	0.63
Foster	(72)	1952	15.2	p	12.4	2.95	9	452	2068	61	2.9
Foster	(72)	1952	15.2	p	12.4	2.96	11	430	2201	42	1.9
Foster	(72)	1952	15.2	p	8.2	4.46	5	514	2299	103	4.4
Foster	(72)	1952	15.2	p	5.4	6.76	5	499	2796	122	4.4
Foster	(72)	1952	15.2	p	4.4	9.18	5	548	3115	130	4.2
Regan	(53)	1955	15.2	p	75.0	0.69	19	379	1118	5.8	0.52
Miksch	(18)	1956	30	p	207	0.31	5	269	968	9.1	0.94
Elmore	(73)	1956	90	s	5670	1.07	17	414	1496	30.0	2.0
Elmore	(73)	1956	90	s	5670	1.06	6	379	1423	12.2	0.86
Comer	(27)	1963	37	p	2549	0.065	1	421	424	--	--
Comer	(27)	1963	37	p	708	0.63	1	395	1076	--	--
Comer	(27)	1963	37	p	219	1.44	1	675	1679	--	--
Comer	(27)	1963	37	p	132	2.42	1	323	1853	--	--
Comer	(27)	1963	37	p	70.8	6.51	1	466	2572	--	--
Jones	(71)	1965	37	p	250	1.35	19	280	1505	55	3.7
McBratney	(63)	1967	120	p	3580	3.51	8	274	1960	130	6.6
McBratney	(62)	1968	37	s	356	0.928	2	285	1448	--	--
McBratney	(62)	1968	37	s	239	1.37	3	300	1748	--	--
McBratney	(62)	1968	37	s	147	2.24	7	292	2088	44	2.1
Elmore	(69)	1977	30	s	428	0.63	25	322	1075	16	1.5

NOTES:

1. Igniters: p - pyrotechnic
   s - electric spark

2. Propellant Formulations:

	N_2H_4	$N_2H_5NO_3$	H_2O
References (73)	60	35	5
References (18,69,73)	63	32	5
References (27,62,71)	65	30	5
Reference (53)	66.4	22.7	10.8
References (54,72)	76	16	8

Table 2. Summary of Some of the BLPG Tests Using Otto-II and Monopropellants Containing Ethyl Nitrate.

Source	Ref	Year	Gun Cal (mm)	Temp	Propellant[1]	Ign[2]	Proj Mass (g)	Charge[3]	C/M	No. of Tests	P_{max} (MPa)	Muzzle Velocity (m/s)	Standard Devaition (m/s)	(%)
Turner	(74)	1958	7.6	20	60/40 ep	c	6.5	(0.5ml)		5	--	445	14	3.1
Turner	(74)	1958	7.6	-78	60/40 ep	c	6.5	(0.5ml)		5	--	394	25	6.3
Turner	(74)	1958	7.6	ambient	60/40 ep	c	6.5	(1.0ml)		10	93	637	10	1.6
Turner	(74)	1958	7.6	ambient	20/80 ep	c	6.5	(1.0ml)		10	222	522	62	11.9
Turner	(74)	1958	7.6	ambient	80/20 eb	c	6.5	(1.0ml)		10	164	563	164	29.1
Comer	(27)	1963	37	ambient	60/40 ep	p	871		0.20	1	301	738	--	--
Comer	(27)	1963	37	ambient	OTTO II	p	182		2.98	1	362	1910	--	--
McBratney	(62)	1973	37	ambient	OTTO II	p	355		0.812	6	445	1341	17.7	1.3

NOTES:

1. Propellant Formulations: ep: ethylnitrate/n-propylnitrate
   eb: ethylnitrate/butylnitrate

2. Igniters: p - pyrotechnic
   c - compression

3. Only propellant volume provided in Reference 74; propellant densitity not available

Table 3. Summary of Some of the BLPG Tests Using HAN-Based LPs.

Source	Ref	Year	Gun Cal (mm)	Temperature (C)	Ign[1]	Proj Mass (g)	C/M[2]	No. of Tests	P_{max} (MPa)	Muzzle Velocity (m/s)	Standard Deviation (m/s)	(%)
Elmore	(55,75)	1972	6.2	ambient	p	3.89	1.31	7	408	1104	60	5.4
Elmore	(55,75)	1972	6.2	ambient	p	3.89	1.31	5	436	1115	35	3.1
Elmore	(55,76)	1972	6.2	ambient	p	3.89	1.31	9	396	1050	21	2.0
Elmore	(55,76)	1972	6.2	ambient	p	3.89	1.31	5	396	1049	18	1.7
Elmore	(55,77)	1972	6.2	ambient	p	3.89	1.31	5	366	1071	33	3.1
Elmore	(55,77)	1972	6.2	ambient	p	3.89	1.31	11	382	1066	11	1.0
Elmore	(78)	1972	6.2	25	p	3.89	1.29	2	431	1172	(±14)	(±1.2)
Elmore	(78)	1972	6.2	-20	p	3.89	1.29	2	372	1047	(±41)	(±3.9)
Elmore	(78)	1972	6.2	-30	p	3.89	1.29	2	390	966	(±27)	(±2.8)
Elmore	(78)	1972	6.2	-40	p	3.89	1.29	2	297	582	(±85)	(±14.6)
Knapton	(62)	1977	38.8	ambient	ev	329	1.10	5	524	1569	39	2.5
Knapton	(62)	1977	38.8	ambient	ev	329	1.105	5	490	1549	19	1.2
Knapton	(62)	1977	38.8	ambient	rv	328	1.10	7	491	1533	42	2.7
Knapton	(62)	1977	38.8	ambient	rv	323	1.13	13	507	1531	32	2.1
Knapton	(62)	1977	38.8	ambient	rv	190	1.82	1	666	1881	--	--
Knapton	(62)	1977	38.8	ambient	rv	194	2.06	1	598	1910	--	--
Knapton	(62)	1977	38.8	ambient	rv	191	2.26	3	535	1791	29.3	1.6
Knapton	(62)	1977	38.8	ambient	rv	191	2.32	3	562	1803	22.6	1.3

NOTES:

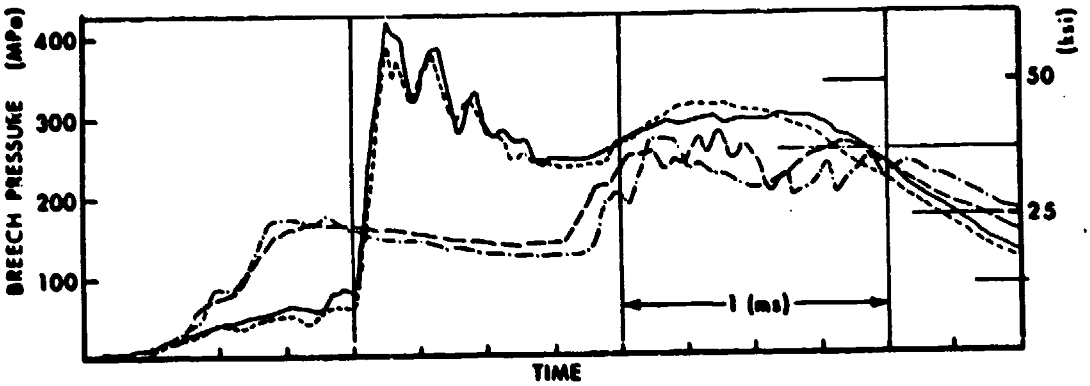
1. Igniters: All igniters pyrotechnic; end vent and radial vent configurations noted.

   p - pyrotechnic
   ev - end vent
   rv - radial vent

2. Propellants:

   References (55,75,76,77) NOS-283-8
   References (62,78) NOS-365

BREECH PRESSURE COMPARISON
FOR HIGHEST AND LOWEST PEAKS

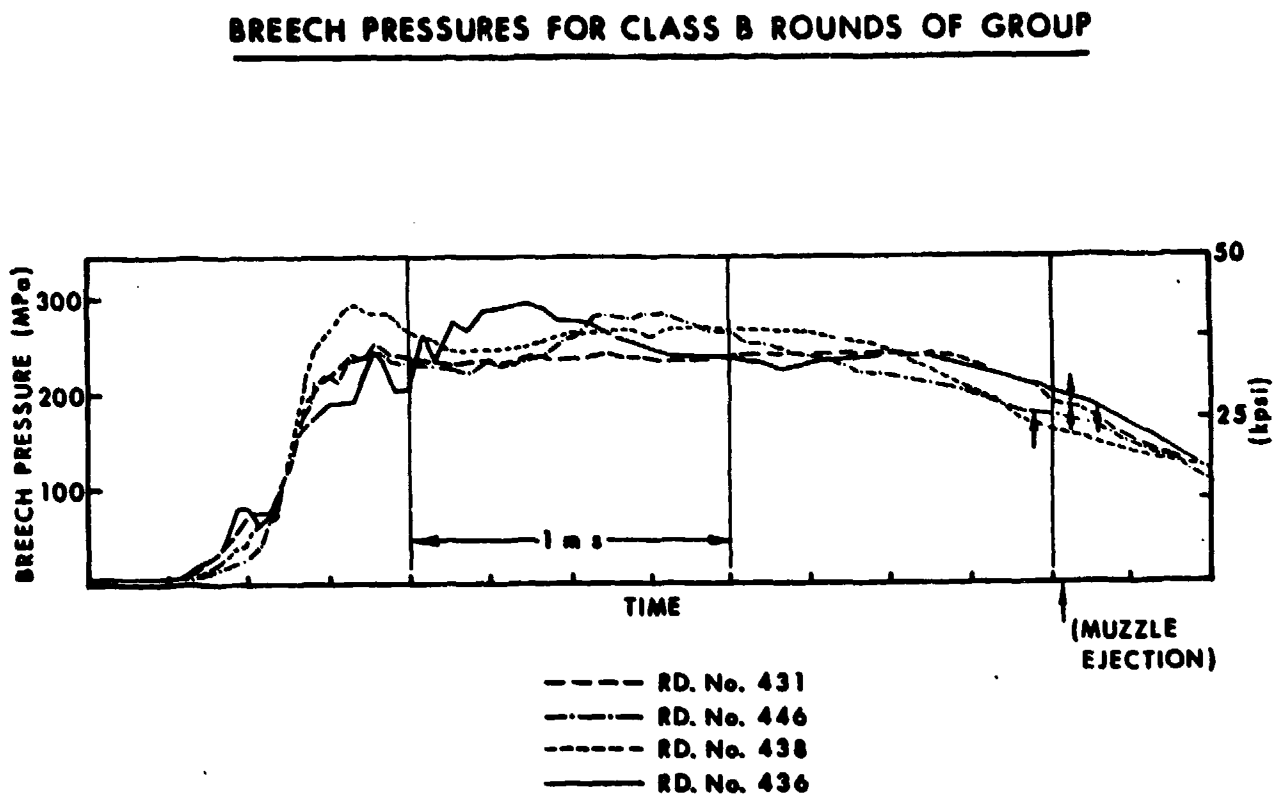


DATE 1965
GUN 37mm
PROPELLANT: HYDRAZINE (65%), HYDRAZINE NITRATE (30%), WATER (5%)
PRIMER 5 HOLE RADIAL VENT, M38B2 IGNITER ELEMENT WITH BOOSTER CHARGE IN BAYONET TYPE PRIMER.
SAMPLE SIZE 29
BREECH PRESSURE SUMMARY:
FIRST PEAK (P_1) = 247 MPa, σ = 76.4 MPa (31%)
SECOND PEAK (P_2) = 280 MPa, σ = 24.5 MPa (8.7%)

20 JAN 78

Figure 11. Breech Pressure Comparison Showing Typical Cases with Two Pressure Peaks

A number of investigations utilizing HAN-based LPs have focused on the development of an ignition system that was both reproducible and controllable. The ability to control the early rate of pressure rise is important in reducing problems associated with waves in the gas-liquid medium, and in eliminating ignition due to adiabatic compression.[58] In addition to the electric spark ignition studies of Elmore,[69] and the pyrotechnic ignition studies of Knapton and Stobie,[80] and McBratney;[65] Fisher and Sterbutzel,[64] and Liedtke[32 33] have investigated electical ignition, and Irish[46] has studied both pyrotechnic and electric ignition of HAN-based LPs.



REFERENCE BRL R 1288 (1965)

Figure 12. Breech Pressures for Firings when the Propellant was Likely Ignited at the Base of the Projectile.

McBratney[65] and Knapton and Stobie[80] designed various pyrotechnic igniters which offered some improvements in reproducibility. Performance data for two of their igniter configurations, an axial (or end) venting igniter and a radial venting igniter, are presented in Table 3, and in Figures 7-10 and 13. Figure 8 shows five breech pressure records and illustrates the variability associated with the radial type of igniter. For the end vent igniter (Figure 13), the pressure-time traces were typically either relatively flat, or the first peak was suppressed and much lower than the second peak. The sources of this variation are not known; however, it was observed in a separate study by Hartman et al[81] that the flow pattern from the end vent type of igniter was not consistent on a shot to shot basis. Also, measurements of the igniter pressure, using a separate closed chamber for recording the pressure output from the igniters, indicated poor reproducibility in the functioning of the igniter.[80] An additional study characterizing the igniter output was conducted by Klingenberg, et al.[82] In this study the igniter pressure was measured and an attempt was made to measure the igniter flame output. This study, however, did not lead to additional igniter optimization.

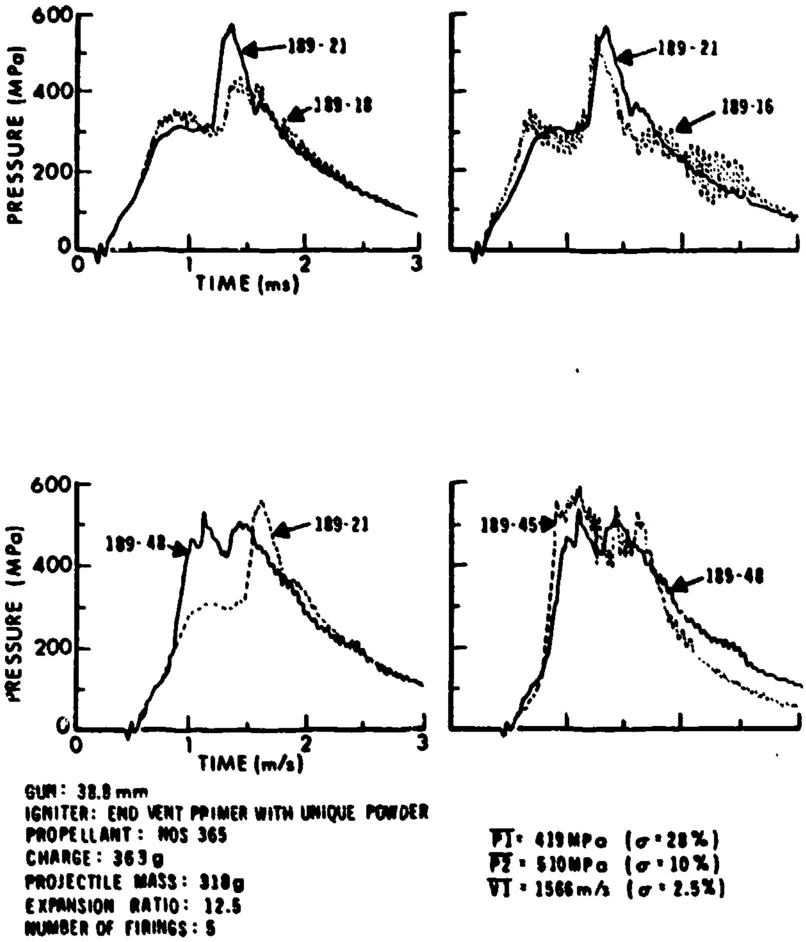
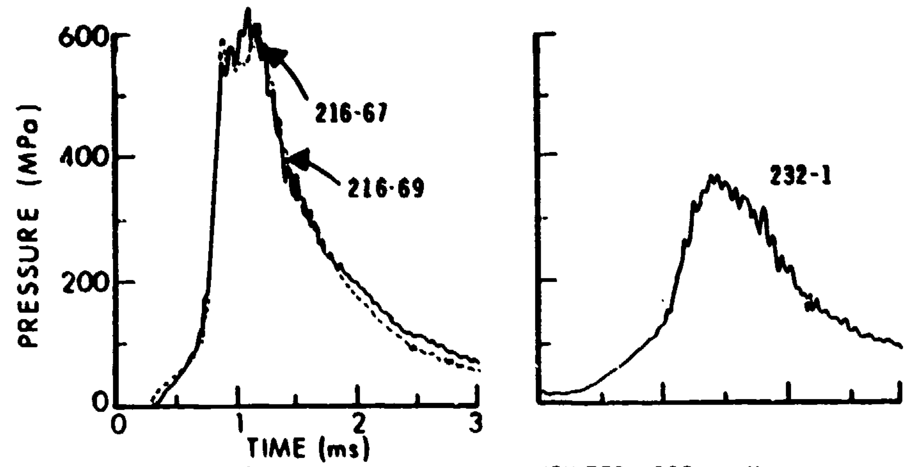


Figure 13. Variability in Pressure vs Time for the End Vent Type of Igniter

As noted earlier, the reproducibility in the pressure-time data from gun tests using the radial vent igniter was better than that with the end vent igniter.[79] An example of five breech pressure-time records from firings with a radial igniter and a booster charge with a low gas generation rate is shown in Figure 8. The variation in the the first peak pressure was 8.5% for a group of 13 tests, however the over-all shape of the pressure-time trace was generally the same with the first peak pressure less than the second peak pressure. In 53 tests with the radial igniter and a similar booster charge, there were only four tests in which the first peak pressure was either equal to the second peak pressure or slightly (~10%) exceeded it.[79] Changing the booster charge from a slow burning charge, which generated a lower first peak pressure, to a faster burning booster charge resulted in a much higher first peak pressure as shown in Figure 7. The faster burning booster charge also had the effect of eliminating the second peak pressure.

In order to achieve greater control of the start-up process, a combined solid and liquid propellant charge was also tested by Knapton et al.[79] The solid propellant booster charge was significantly increased from less than 1% of the total charge, which was used with the end vent and radial type of igniters, to 8.5% of the total charge. The increased booster charge was ignited first and, based on the few tests that were performed, there seemed to be some improved level of control in the generation of the breech pressure-time records. An example of the breech pressure-time record generated by the combined solid and liquid charge is shown in Figure 14.



IGNITER: 805 mg U
14.8 g M8

IGNITER: 330 mg U
24.5 g M8

GUN: 38.8 mm
PROPELLANT: NOS 365
PROJECTILE: 318g

IDENT NO	CHARGE (g)	EXPANSION RATIO	VELOCITY (m/s)
216-67	290	15.4	1514
216-69	272	16.4	1503
232-1	268	16.6	1453

Figure 14. Examples of Breech Pressure Using a Combined Solid-Liquid Propellant Charge.

VI. COMPARISON OF THE PERFORMANCE OF MONOPROPELLANTS BLPGS AND CONVENTIONAL SOLID PROPELLANT GUNS

It has often been suggested that the BLPG offers improved performance in comparison to the conventional solid propellant gun. This was based on the hypothesis that when ignited at the breech, the bulk of the propellant in a BLPG traveled with the projectile and burned as a classical traveling charge.[83]

Figure 15 is a plot of muzzle velocity vs charge to mass ratio for 105-mm solid propellant[84,85] and 37-mm and 90-mm BLPG[27,62,83] gun firings. The BLPG firings were conducted with a hydrazine-based monopropellant in 37 mm[27] and 90 mm,[83] and a HAN-based monopropellant in 37 mm.[62] The existing data would suggest that muzzle velocity is independent of the charge composition for the systems considered.[(vi)] Indeed, from a thermodynamic standpoint, the BLPG appears to be equivalent to the conventional solid propellant for the C/M range considered here. Therefore, the data would indicate that enchanced performance, i.e. increased ballistic efficiency, at very high velocity cannot be anticipated.

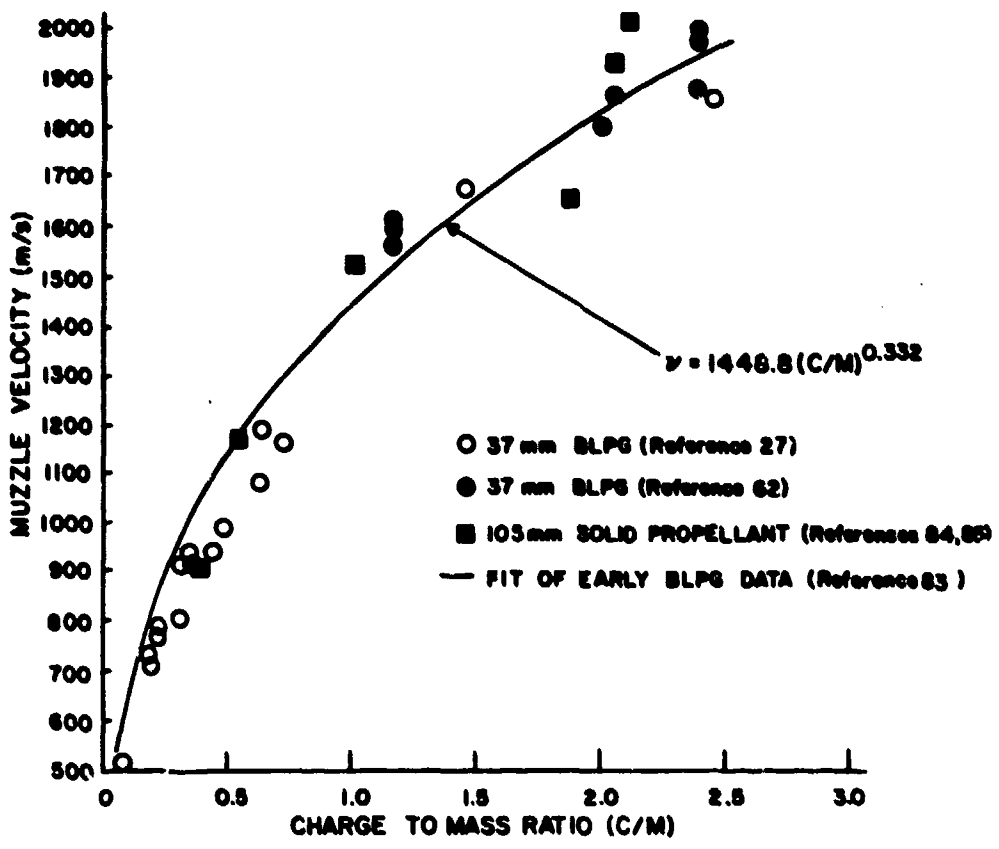


Figure 15. Muzzle Velocity vs Charge to Mass Ratio

VII. BIPROPELLANT BLPG TESTS

Early BLPG investigations[11] were conducted with hypergolic bipropellants. In order to initially separate the fuel and oxidizer, either one or both were encapsulated. Ignition was achieved by firing a pyrotechnic squib, which ruptured the capsule(s), allowing the components to mix. This technique eliminated many of the advantages of the LPG concept, was difficult to implement, and presented a safety hazard due to the potential for leakage. It was not until the introduction of nonhypergolic bipropellants in the late 1960's that significant progress was made in bipropellant BLPG research.

Mallory[32 33] has described work at the US Naval Weapons Center on a 25-mm nonhypergolic bipropellant BLPG in the only unclassified reports on this effort. A single shot, modular system designed for use with various injectors, chambers, and barrels was developed to permit variation of propellant formulation, injection parameters, and expansion ratio. A 25-mm dynamically loaded BLPG, designed to fire at rates up to 350 rounds/minute, was also developed. A mixture of red fuming nitric acid and a hydrocarbon fuel was used in these investigations. Tests were performed in the single shot gun under a variety of conditions. It was found that, by controlling the injection parameters, LP combustion could be varied from one extreme where ignition was difficult, to the other where detonation was approached. Tests were performed under various ullage conditions, and it was found that 5% initial ullage provided the best ballistics. Too much ullage, about 10%, resulted in erratic ignition.

Electric spark ignition was used in these tests, simplifying the gun mechanism. Duration of the discharge could be varied from 0.4 to 1.0 millisecond. Peak currents of up to 1400 amps (a 50 microfarad capacitor charged to 2000 volts) were used. Spark energy was varied from 25 to 150 Joules; 25 Joules was not reliable, whereas 150 Joules was excessive.

Firing tests were made with a standard 25-mm projectile weighing 194.4 g. The charge to mass ratio was varied from 0.48 to 2.85. In a total of 106 separate shots over a temperature range from +4 to +43° C, the mean muzzle velocity was 1186.9 m/s with a standard deviation of 25.9 m/s (2.2%).

(vi)If chamber pressures are considered, however, the HAN-based monopropellants typically generated higher chamber pressures than the hydrazine based monopropellants.

VIII. REGENERATIVE LIQUID PROPELLANT GUN

1. GENERAL

While the bulk-loaded interior ballistic process is based on complex, coupled hydrodynamic and combustion (physico-chemical-hydrodynamic) processes, the RLPG achieves performance equivalent to that of conventional solid propellant systems through mechanical control of the interior ballistic process. The introduction of the regenerative piston provides control necessary to generate repeatable ballistics, substituting engineering issues for the hydrodynamic problems of the BLPG.

This review concentrates on developmental results since the early 1970s, however, results of early RLPG investigations are also discussed. Following the post World War II period, no RLPG investigations were conducted until the early 1970s. Since 1976 the majority of LPG effort in the USA has been in the RLPG area, and since 1980, the RLPG has become the main thrust of LPG investigations in France, Germany, and the United Kingdom as well.

IX. INTERIOR BALLISTICS OF THE RLPG

It has been found that the RLPG interior ballistic process is controlled to a large extent by the injection of the liquid propellant, and thus the motion of the regenerative piston.[4,34,86] Therefore, a gross simulation of the RLPG reduces to a model of the hydraulic response of the regenerative piston and the liquid propellant reservoir. The details of propellant hydrodynamics and combustion appear to be of secondary, though certainly not negligible, importance.

A simple regenerative liquid monopropellant gun is depicted in Figure 16. It consists of a standard gun tube attached to a chamber which contains the regenerative piston. The head of the regenerative piston divides the chamber into two sections, a combustion chamber and a propellant reservoir. The length of the reservoir, and thus the reservoir volume and maximum piston travel, are defined by a breech element through which the piston shaft extends. Cylindrical injector orifices are located in the head of the piston. These orifices are initially sealed to prevent leakage of propellant into the combustion chamber prior to ignition. An ignition train, consisting of a primer, an ignition charge, and in some cases a booster charge complete the system.

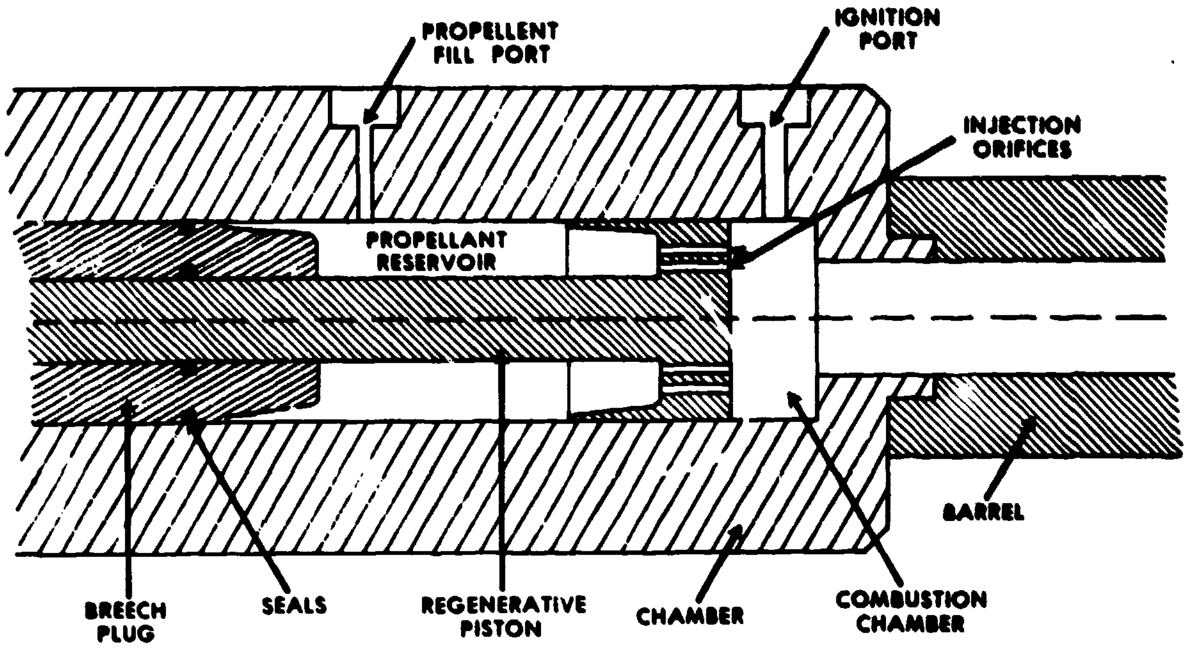


Figure 16. Schematic of a Simple Inline Regenerative Test Fixture

A characteristic regenerative combustion chamber pressure versus time plot showing the five main phases of the interior ballistic process is presented in Figure 17. The process is initiated by the ignition train, which pressurizes the combustion chamber and forces the piston to the rear, compressing the liquid propellant in the reservoir. The area of the chamber face of the piston is greater than that of the reservoir face, providing the differential pressure required for injection of the liquid propellant.

The second phase is an ignition delay. During this period, the piston continues to move to the rear, injecting liquid propellant which accumulates in the combustion chamber. When the cool liquid does ignite, the accumulated propellant burns rapidly, phase three, bringing the chamber to operating pressure and accelerating the regenerative piston to its maximum velocity. Phase four is usually characterized by a pressure plateau. This plateau is interpreted as a quasi-stable equilibrium in which the increase of gas in the chamber (to compensate for piston motion) and the flow of gas down the barrel are balanced by the combustion of freshly injected propellant. Phase four ends at the completion of piston travel and propellant burning. The final phase is the usual expansion of the combustion gasses after all-burnt.

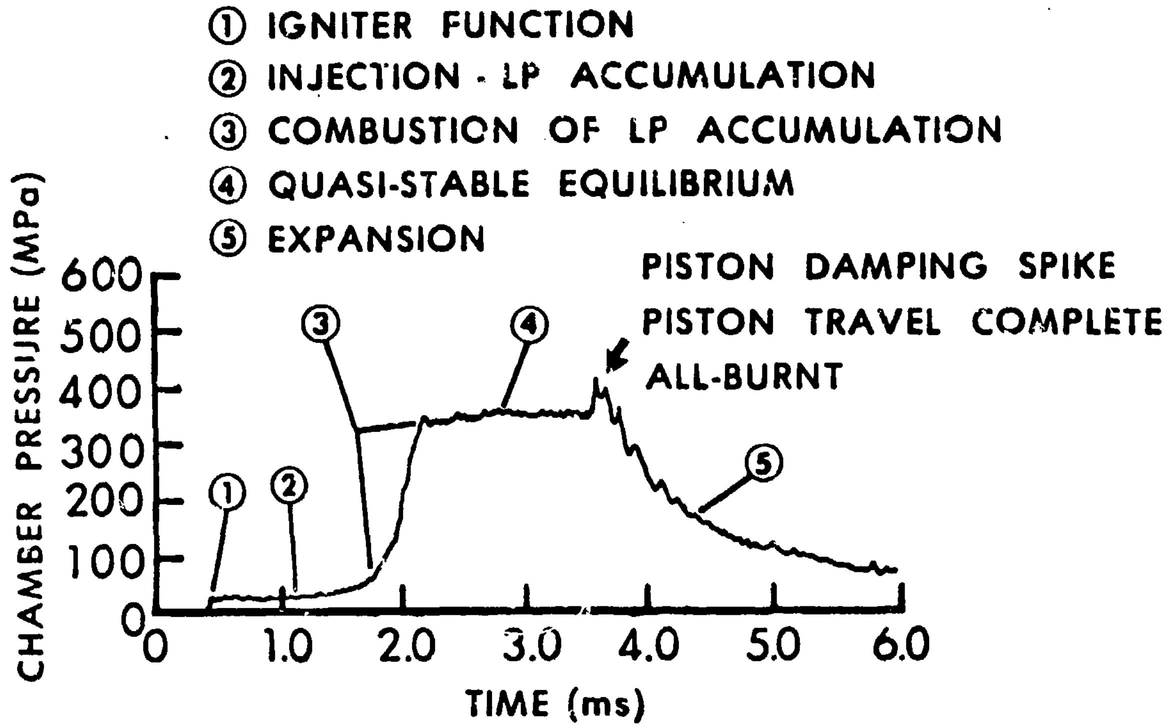


Figure 17. A Typical Regenerative Chamber Pressure vs Time Curve Showing The Five Phases of the IB Process.

In developing an interior ballistics model for the RLPG, one must consider the following;

(1) Piston Motion
(2) Propellant Injection
(3) Propellant Breakup and Droplet Formation
(4) Propellant Accumulation in the Chamber
(5) Propellant Ignition and Combustion
(6) Constituitive Equation for the LP in the Reservoir
(7) Constituitive Equation for the Two Phase Mixture of Propellant and Combustion Gases in the Chamber and Barrel
(8) Entrance Flow into the Barrel
(9) Barrel Flow or Pressure Gradient in the Barrel
(10) Projectile Motion

In general, the formulation of an interior ballistics model for the RLPG is straightforward. A set of equations describing these processes is presented by Morrison et al.[86] Other formulations have been developed by Gough,[87] Coffee,[88] Cushman,[89] Bulman,[90] and Pagen et al.[91] However, the complexity of the spray combustion process in the RLPG[92-95] has precluded detailed treatment of the interior ballistic process.

1. PISTON MOTION

In developing the equations of motion for the regenerative piston, only the pressure and friction forces are normally considered. However, it can be shown that the momentum of the liquid exiting the injection orifice, and the inertia of the liquid in the reservoir will also influence piston acceleration, and thus propellant injection.[96]

2. PROPELLANT INJECTION

Propellant injection is usually modeled by a steady state Bernoulli's equation. However, Coffee[92-93] and Edelman[97] have reported calculated discharge coefficients which exhibit an unexplained variation, over a wide range ($0.2 < C_D < 1.0$) during the interior ballistic cycle. Edelman utilized a two-dimensional, axisymmetric model to simulate orifice flow. The ratio of the computed mass flow rate through the orifice, and a calculated mass flow rate based on the square root of the computed pressure difference across the injector (i.e. a steady state Bernoulli formulation) provided an estimate of the discharge coeficient as a function of time. This estimated discharge coefficient was found to be a monotonically increasing function of time. In contrast, Coffee has developed an inverse simulation of the RLPG interior ballistic process, which utilizes experimental gun pressures, and piston and projectile displacements as input.[92-93] A steady state Bernoulli equation is utilized to describe propellant injection. The mass flow rate into the combustion chamber, discharge coefficient, gas generation rate in the combustion chamber, liquid accumulation in the combustion chamber, and Sauter mean diameter for the propellant in the combustion chamber are then computed. The calculated discharge coefficient rises rapidly to near the theoretical value, drops suddenly to a value of about 0.25, and then rises again to near the theoretical value. The sudden drop in the discharge coefficient coincides with a sharp change in the injection area. It has been postulated that this apparent variation of the discharge coefficient is due to the inertia of the liquid propellant in the reservoir, and that a time dependent formulation of the injection process is required to accurately describe propellant injection.[96]

3. PROPELLANT COMBUSTION

Breakup of the propellant jet entering the combustion chamber, accumulation, ignition, and combustion have been addressed in the majority of existing interior ballistic models; however, little is actually known about these processes in a gun environment. The treatment of these processes usually involves an assumption of a population of spherical droplets (defined either arbitrarily or through a Weber Number criteria) which decompose according to a pressure dependent, linear burning rate. Ignition, when included, is treated as a time delay. None of these assumptions are theoretically supportable for the RLPG process, however, accurate "gross simulations" of given experimental results are obtainable using these assumptions and appropriate input parameters.

4. CONSTITUITIVE EQUATIONS

Constituitive equations for the liquid propellant in the reservoir, and for the two-phase liquid and combustion products mixture in the combustion chamber are required for closure of the governing equations. For the HAN-based liquid monopropellants, a modified Tait equation of state, i.e. pressure is a power function of density, provides an excellent fit to experimental pressure versus density measurements.[98-99] A Nobel-Abel equation of state is normally used for the combustion products, as in standard solid propellant interior ballistic models.

5. ENTRANCE AND BARREL FLOW

The entrance flow to the barrel is treated in a variety of ways. Morrison et al[86] have suggested a Bernoulli's equation, with entrance loss and the assumption of isentropic flow from the chamber to the barrel. Gough[87] and Coffee[88] have implemented this model and demonstrated that it provides excellent agreement with the pressure drop, from the chamber to the barrel, observed in experimental data.

Similarly, a variety of barrel flow models, ranging from a simple Lagrange approximation to a one-dimensional, two-phase flow formulation, have been developed. In the case of the Lagrange approximation, it has been suggested by Morrison et al[86] that the non-zero gas velocity at the barrel entrance must be accounted for in the RLPG simulation. This results in a modified Lagrange approximation of the form,

$$P(y) = P_B + (m_g/2M)\,(P_B - P_f)\,[1 - (y/x)^2]$$

$$+ (m_g/2A)\,(\dot{v}_b + (v_b\,[(V - v_b)/x])\,[1 - (y/x)]^2 \qquad (4)$$

where the subscripts B and b refer to the projectile base and the barrel entrance respectively. Coffee[87] has implemented a form of this equation in his RLPG interior ballistic model, and has shown that it provides excellent agreement with both one-dimensional barrel flow simulations, and experimental data.

The assumption that all the liquid propellant burns in the breech, and the barrel contains only combustion products, leads to an interesting result at burnout. Using the one-dimensional model of Gough,[87] Morrison et al[4] have shown that at burnout a rarefaction wave moves from the breech, along the barrel to the projectile. In the case considered by Morrison et al,[4] the projectile exited the tube before being overtaken by the rarefaction wave. This result would indicate that there exists a maximum effective charge for the RLPG, and that propellant charge in excess of this maximum has no effect on the ballistic performance of the system.

6. SUMMARY

In summary, a variety of RLPG interior ballistic models exist. In general, the formulation of these models is straightforward, but the unique characteristics of the RLPG system must be accounted for in order to accurately simulate the interior ballistic process if lumped parameter models are used. The pressure drop from the chamber to the barrel, the non-zero gas velocity at the barrel entrance and the inertia of the liquid in the propellant reservoir are among the unique characteristics of the RLPG which must be considered.

The status of liquid propellant spray ignition and combustion models for the RLPG is quite poor. Little is known about these processes in the gun environment. While this has not proven a limitation in the simulation of the gross features of RLPG interior ballistics, detailed simulations are beyond the capability of existing models. The gross agreement with experimental data is apparently a result of the rapid ignition and combustion of the injected liquid propellant at gun operating pressures (>10 MPa). However, an accurate description of propellant ignition and combustion is important during the ignition phase, which can be accumulation driven, and may also prove important in the simulation of high frequency pressure oscillations observed in some RLPG firings.

X. PHENOMENOLOGICAL STUDIES

1. REGENERATIVE PISTON CONFIGURATIONS

Unlike the BLPG, in which the geometric configurations are limited, the RLPG offers a wide variety of design variations.[100] The so-called simple in-line piston, Figure 16, provides one of the simpler implementations of the RLPG concept.[4 34 101 102] Other piston configurations which have been implemented and tested in gun fixtures include; the in-line hollow piston[2 23-26] (Figure 18), the annular injection piston[22] (Figure 19), the in-line annular piston[4 35 103] (Figures 20 and 21), and the reverse annular piston. These piston configurations have been utilized in a variety of experimental gun systems.

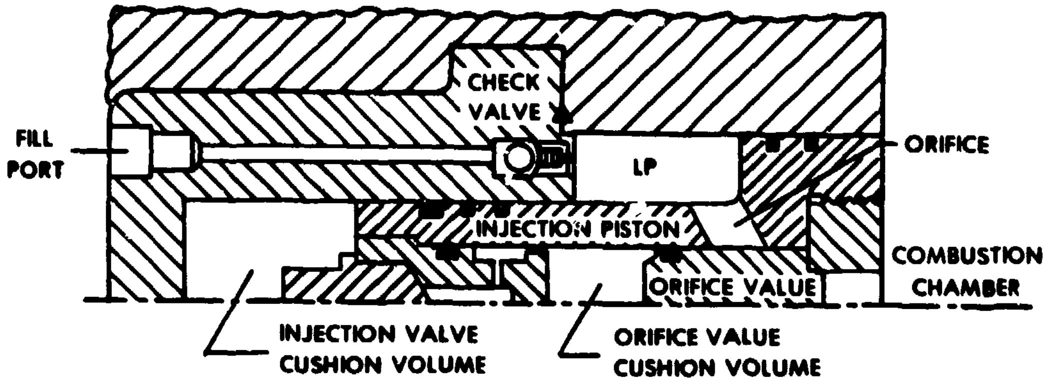


Figure 18. In-Line Hollow Piston

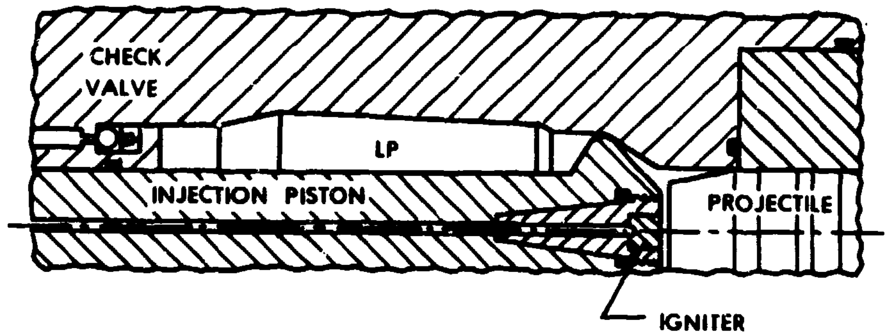


Figure 19. Annular Injection Piston

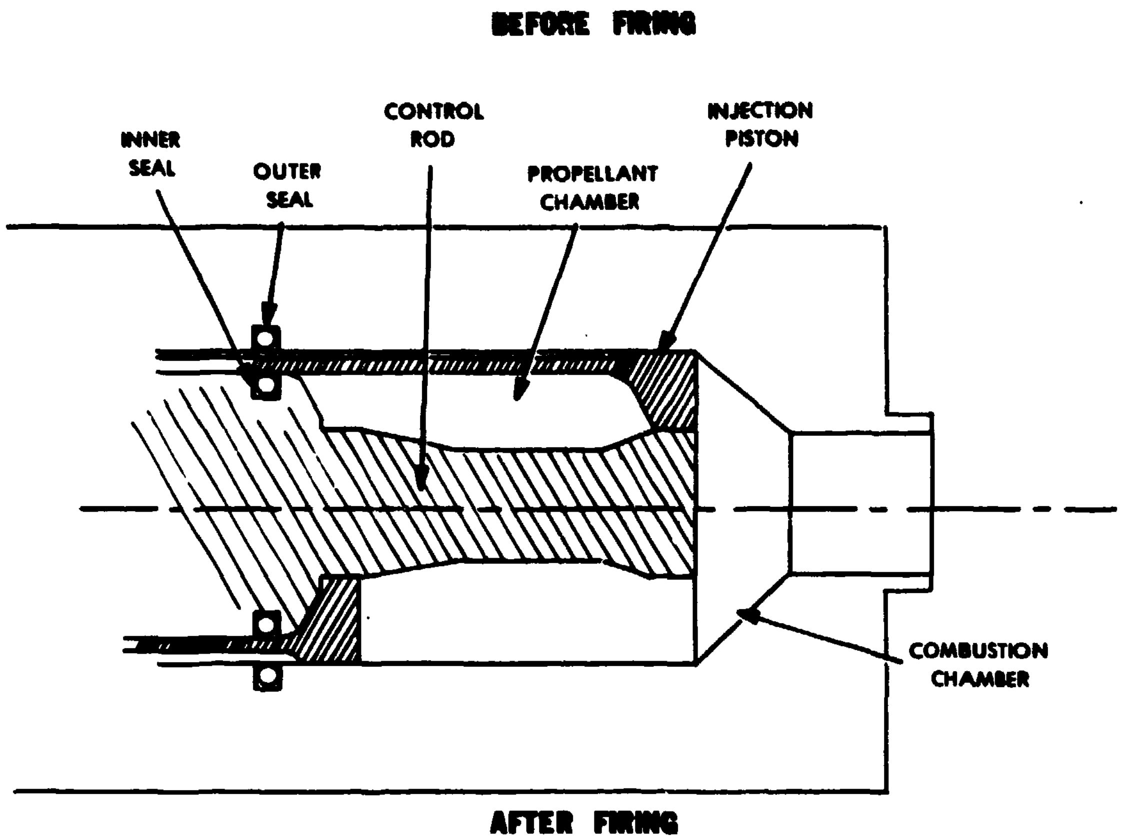


Figure 20. In-Line Annular Piston with Tapered Control Rod (GE Concept VI)

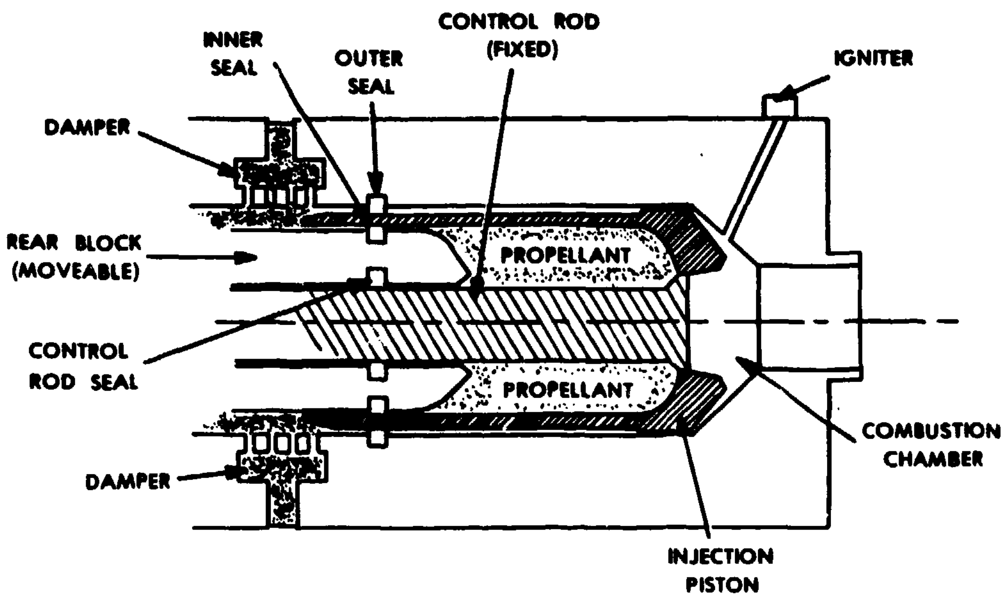


Figure 21. In-Line Annular Piston with Uniform Control Rod (GE Concept VIA)

Both Experiment Inc.[23-26] and General Electric[2] have investigated the in-line hollow piston. Experiment Inc. developed and tested 40-mm[23] and 127-mm[24-26] hypergolic bipropellant systems using opposing, simple in-line pistons (alternating oxidizer and fuel) at 90° intervals around the periphery of the chamber,[24-26] (Figure 22). In the 127-mm fixture, up to 3 "blocks" of pistons, i.e. a maximum of 12 pistons, were tested. The complexity of these multiple piston systems, as well as the difficulties involved in handling hypergolic bipropellants, hampered development and testing in this program. Little data is available from the Experiment Inc. effort, but General Electric found this design to be mechanically complex and subject to pressure oscillations, and ultimately abandoned it.

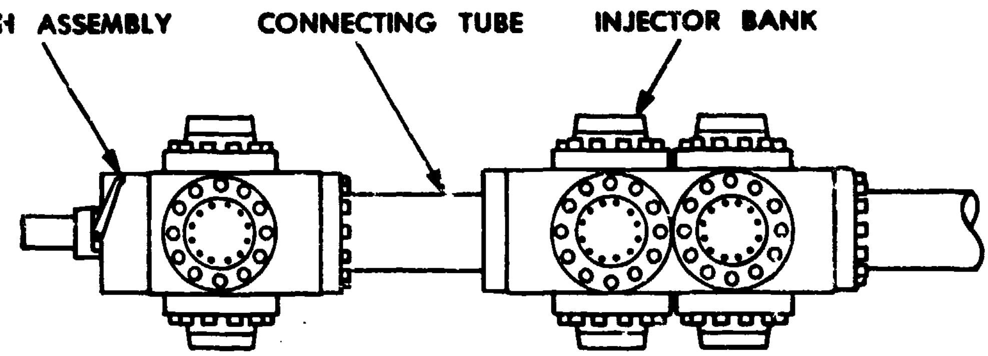


Figure 22. Opposing In-Line Pistons Used in a Bipropellant RLPG

The annular injection piston was investigated by Experiment Inc. in a 40-mm fixture using a hydrazine monopropellant.[22] Again, the available firing data is limited, but Experiment Inc. concluded that this particular RLPG configuration was very promising.

The in-line annular piston was also suggested by Experiment Inc.,[101] but there is no record of it ever having been tested in gun hardware. General Electric, however, has tested four variations of this concept in 25-mm, 30-mm, and 105-mm RLPG fixtures using a HAN-based liquid propellant.[4 35 104 105] The variants of this particular concept appear particularly suited for practicle mechanization (i.e. weaponization), and for controlled variation of the interior ballistic process. General Electric is currently under contract to the US Army to develop a 155-mm RLPG, utilizing a variation of the in-line annular piston.

General Electric has also investigated the reverse annular piston[4] for high rate of fire applications. A 30-mm regenerative fixture, capable of firing a 5 round burst at a rate of 500 rounds per minute, has been developed and tested.

Despite the wide variety of RLPG designs which have been tested, the majority of phenomenological investigations have been conducted with a simple in-line piston configuration. Therefore, we will concentrate on this configuration in the remainder of this section. The data is primarily the result of General Electric independent research, using 25-mm hardware and a nitrate ester liquid monopropellant, OTTO Fuel II.

2. INJECTION AREA

The effect of total injection area is shown in Figure 23.[4 34] As the total injection area is increased from 2.03 cm^2 to 3.17 cm^2 (56%), the maximum chamber pressure increases from 186.0 MPa to 338.0 MPa (32.5%) and the muzzle velocity increases from 1043 m/s to 1139 m/s (9.2%). In similar tests at a higher charge to mass ratio, muzzle velocities of 1258 m/s, 1346 m/s, 1417 m/s, and 1468 m/s were obtained for total injection areas of 2.84 cm^2, 3.85 cm^2, 4.40 cm^2, and 5.14 cm^2. The pressure curves obtained in these tests are similar to those shown in Figure 23. Therefore, the maximum chamber pressure is directly related to the total injection area, which is thus a basic design parameter. In other tests, it was found that with a given total injection area, smaller diameter injectors result in less initial propellant accumulation and less over-shoot in chamber pressure. The length of the injection orifice was also found to affect the ballistic process. Doubling the length of the injector was found to reduce the maximum chamber pressure, and thus reduce the muzzle velocity.

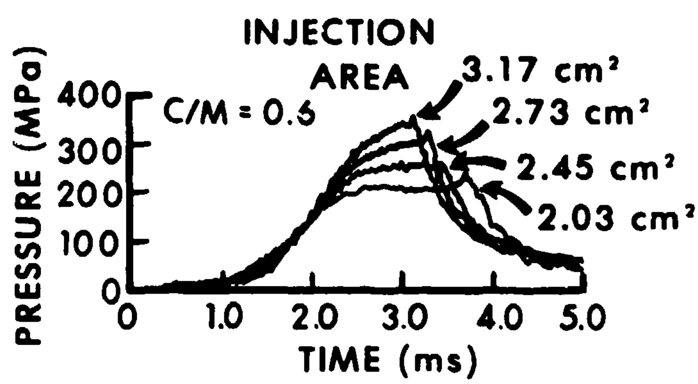


Figure 23. Effect of Injection Area on Chamber Pressure

3. PISTON TRAVEL

The effect of maximum piston travel, and thus the total charge is shown in Figure 24.[4 34] In the three tests, only the piston travel was varied. The maximum pressure is approximately the same for each test, however, the length of the plateau region increases with increasing reservoir length. Therefore, the quasi-stable combustion process, once established, is maintained for the duration of piston travel.

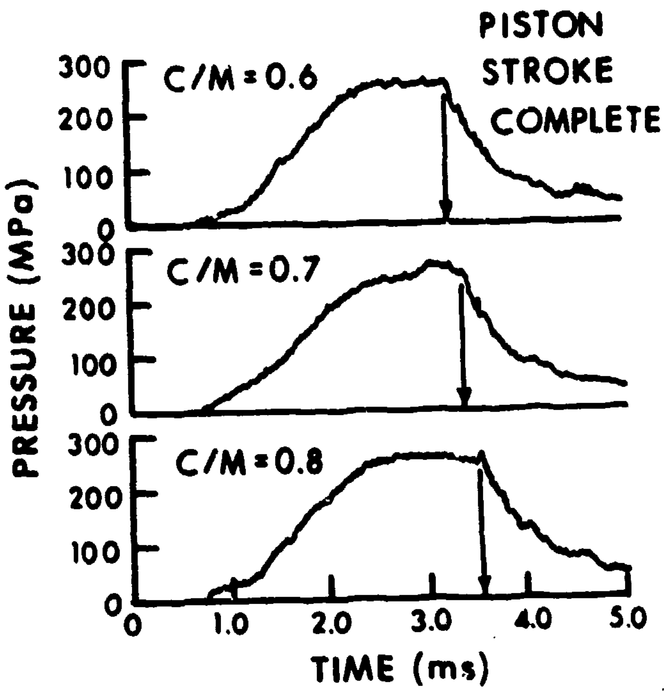


Figure 24. Effect of Charge to Mass Ratio on Chamber Pressure

4. CHARGE TO MASS RATIO

The results of tests investigating the influence of C/M and maximum chamber pressure on muzzle velocity are summarized in Figure 25.[4 34] The curves of velocity versus C/M for the three chamber pressures are similar in character to those for conventional guns. Figure 25 also serves to summarize the effects of total injection area and piston travel (C/M). For any given C/M, both pressure and velocity increase with increasing injection area, while for any given injection area (maximum pressure), velocity increases with increasing piston travel.

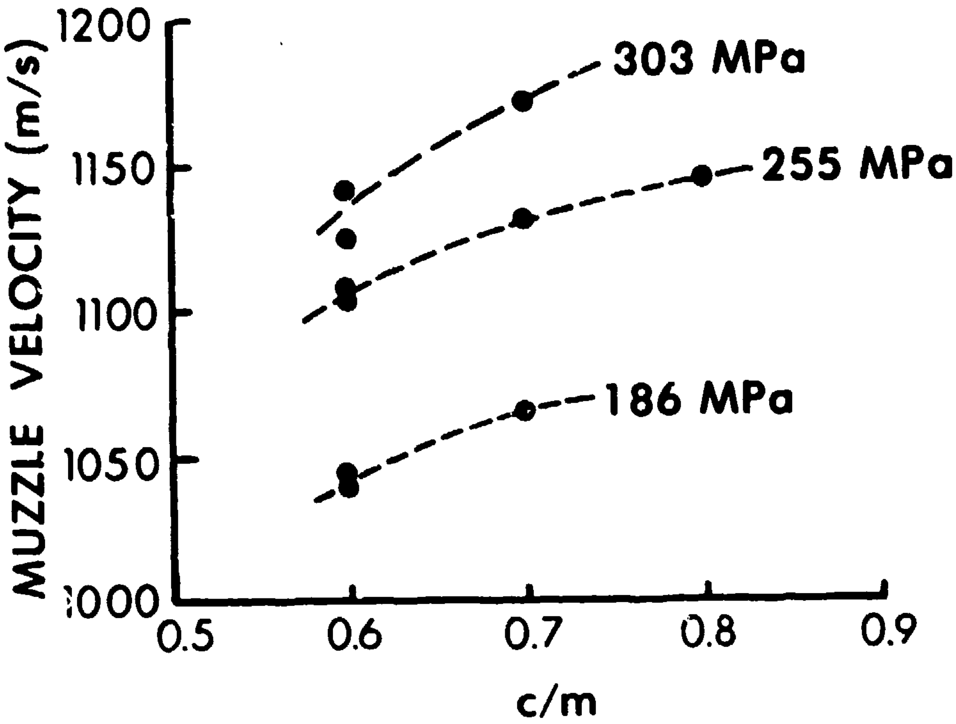


Figure 25. Summary of C/M Parametric Tests

5. PRESSURE PLATEAU

The plateau pressure phenomena was initially attributed to choking of the flow at the entrance to the barrel. However, in computer simulations of test firings, it was necessary to apply a 20-30% correction (reduction) to the barrel flow area in order to match the net gas accumulation in the chamber and the chamber pressure when using the sonic barrel flow assumption. This reduction in effective flow area could be accounted for by a vena contracta near the entrance to the bore, which would be favored by the sharp corner at the barrel entrance. However, many of the data obtained in the parametric test firings cannot be reconciled with a theoretical picture which incorporates the hypotheses of a stagnation condition in the chamber and sonic flow in the barrel entrance.

The barrel pressure gage nearest the chamber was mounted 0.7 cm from the bore entrance. The pressure measured at this location in Shot 143, along with the corresponding pressures in the combustion chamber and at other barrel locations are presented in Figure 26. If the flow entering the bore were choked, the ratio of throat pressure to chamber

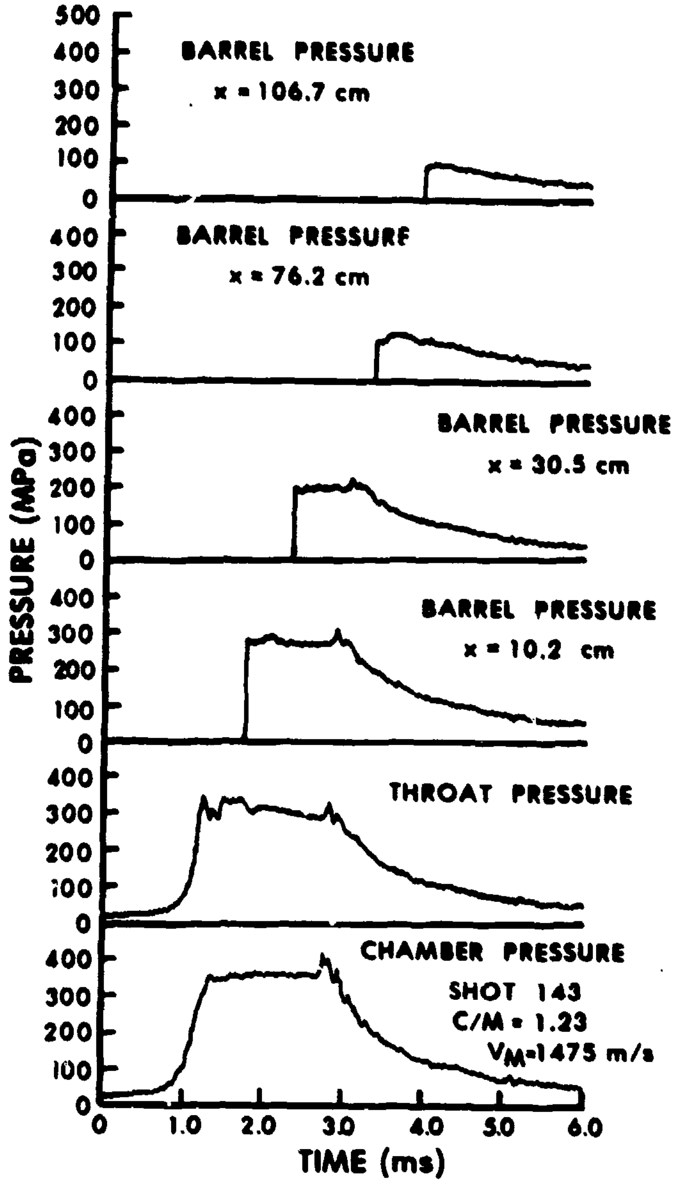


Figure 26. Pressure vs Time for Shot 143.

pressure would be about 0.55. The plateau in the chamber pressure occurs at 359 MPa, while the maximum pressure measured by the barrel gage is 324 MPa. Therefore, the ratio of barrel pressure to chamber pressure at the begining of the plateau is 0.9. This pressure ratio corresponds to a Mach Number of 0.4 at the barrel gage location, well below the choked condition. It is noted that the pressure measured at the barrel wall is not necessarily that in the core flow, and, more importantly, the pressure gage would probably not be located at the minimum area of the vena contracta if one were formed. However, the barrel pressure decreases steadily after the maximum, indicating an increasing Mach Number. This would imply that the flow is not choked at the beginning of the plateau. The Mach Number at the barrel gage location at the end of the plateau is 0.6, still well below the choked condition.

If choked flow at the barrel entrance were responsible for the plateau, choking must be established by the beginning of the flat top. Once choking occurs, the chamber is decoupled from the barrel since information from the bore cannot be propagated upstream through the sonic region. Therefore, the hypothesis of choked flow at the entrance to the bore would require that the chamber pressure be independent of the projectile mass.

As part of the parametric test series, projectile mass was varied to determine its effect on the regenerative process. Two projectile masses were used, 194.4 gm and 97.7 gm. Firings were made with the original chamber, diameter 4.445 cm, and a larger chamber with a diameter of 5.715 cm. Finally, two firings were made at each condition for a total of 8 tests in this portion of the study. In these tests, the chamber pressure was found to be a function of the projectile mass. With the lighter projectile and the original chamber diameter, the average chamber pressure dropped 24%. In tests with the larger chamber, the average chamber pressure dropped 23% when the lighter projectile was substituted. In both chambers, the muzzle velocity increased by about 11% when the lighter projectile was used.

Figure 27 shows the ratio of the pressure at the first barrel gage location to the chamber pressure, along with the corresponding Mach Number, as a function of time for Shot 42 (194.4 gm) and Shot 66 (97.7 gm). The time scale is relative to shot start, and the plateau region is indicated by a dashed line.

The insert shows the pressure curves for these firings. As in Shot 143, Figure 26, the Mach Number at the barrel gage location increases steadily after the plateau is reached. Note, however, that the Mach Number is significantly higher in the case of the light projectile. In both cases the Mach Number approaches unity by the end of the plateau, indicating a tendency toward choking near the end of the plateau region. This tendency could be increased in high velocity firings with large charges and light projectiles. However, choking of the entrance flow to the barrel would not appear to influence the establishment of the pressure plateau.

Examination of the barrel entrance Mach Number and the effects of projectile mass would appear to eliminate choked flow as the cause of the pressure plateau in regenerative gun firings. In order to explain the plateau, we consider the relative mass flow rate of an ideal gas through a constriction as a function of Mach Number. At a Mach Number of 0.5 the relative mass flow rate is 0.75, and at a Mach Number of 0.7 the relative mass flow rate is about 0.91. The mass flow rate is a weak function of Mach Number, and, thus, the pressure ratio, for Mach Numbers above 0.5. While the weak dependence of mass flow rate on Mach Number, and thus pressure ratio, would indicate a tendency toward a pressure plateau, it cannot explain the extreme flatness of the regenerative pressure curves.

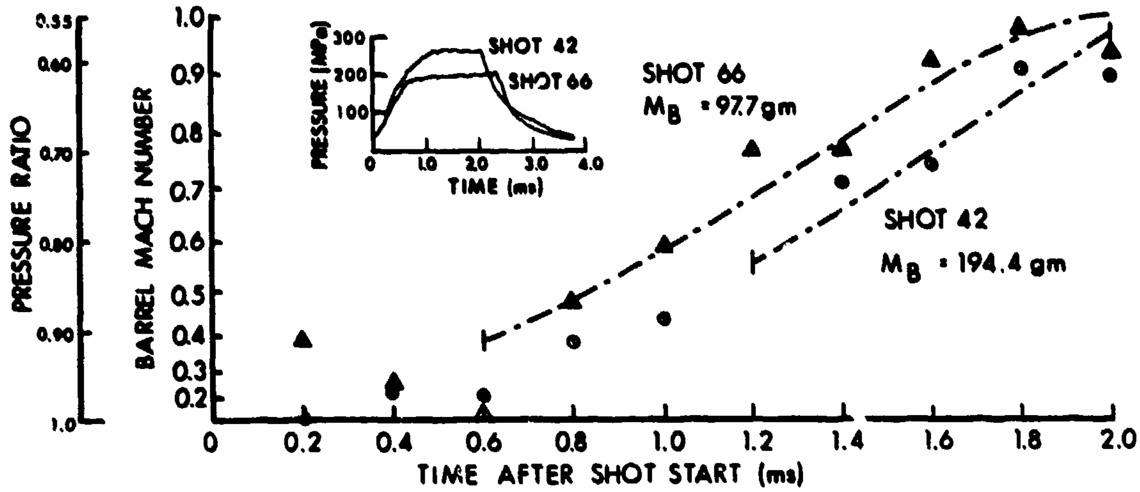


Figure 27. Ratio of Pressure at the First Barrel Gage Location to Chamber Pressure, and Corresponding Mach Number vs Time for General Electric Shots 42 and 66.

6. REGENERATIVE PRESSURE CURVE SHAPES

During the parametric test f..ings, it was found that regenerative pressure curves are not always flat topped. Figure 28 shows four types of regenerative pressure curves obtained in the parametric series. The first type, labeled "Natural", occurred most often. In this case, the pressure peaks early and then declines slowly up to the point of all burnt. The second type, labeled "Classic", is initially similar to the "Natural", however no decline in pressure occurs after the maximum pressure is reached, up to all burnt. The "Classic" curve occurred almost as often as the "Natural". The third type, labeled "Flat Top", was observed on several occasions. It differs from the previous two types in the sharpness of the rise to maximum pressure, and a noticeable break at the plateau. The final type, labeled "Ramp" occurred least often. It is similar to the "Flat Top" type up to the break at the beginning of the plateau, but the pressure continues to increase after the break in slope.

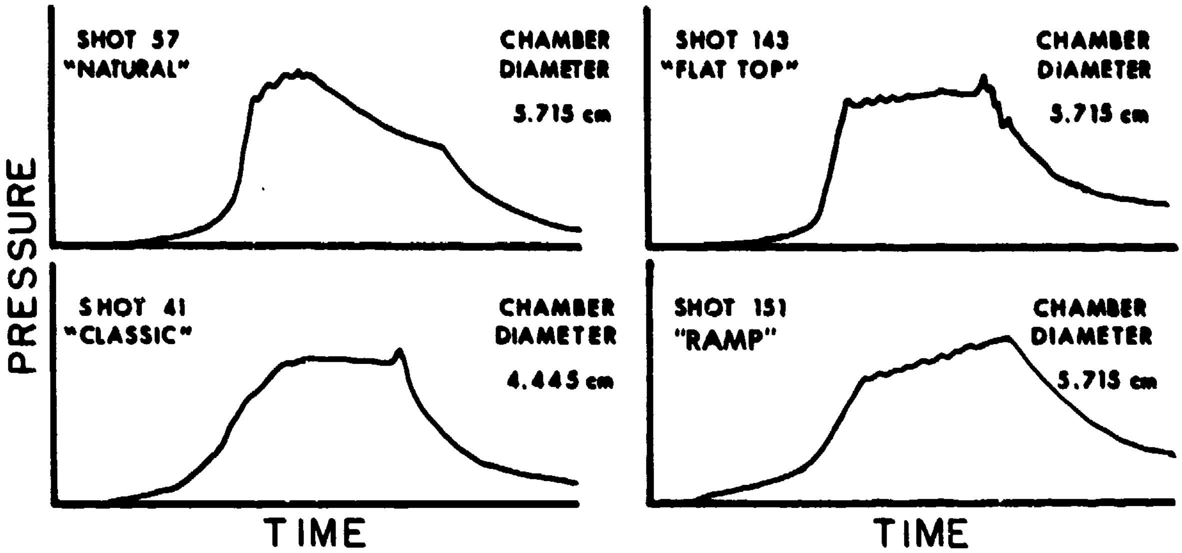


Figure 28. Regenerative Chamber Pressure Curve Types

The four types of regenerative pressure curves can be explained in terms of propellant accumulation and combustion in the chamber. It has been observed that at low pressure during the incubation phase, propellant is injected faster than it burns, leading to the accumulation of unburned propellant in the chamber. (The amount of propellant injected up to shot start is determined by the piston travel measurement, and the amount burned is calculated from the chamber volume and pressure.) As the pressure rises rapidly to a plateau value, the process accelerates, and the propellant mass consumption rate exceeds the injection rate. The plateau pressure is defined by the rates of propellant injection, propellant combustion and gas flow into the barrel, which depend on injection area, reservoir area, chamber area, piston mass, propellant characteristics, etc. It is noted that other processes are almost certainly involved in determining the shape of the regenerative pressure curve. However, based on the existing 25-mm data, accumulation appears to be a very important factor.

Other pressure curve shapes have been obtained in regenerative gun firings.[4] These non-flat-top curves are attributable to the design parameters of the specific regenerative fixture in question, and are usually related to the maximum injection area or completion of piston stroke before a quasi-steady equilibrium is achieved.

7. IGNITION CRITERIA

The ignition function in hypergolic bipropellant, and monopropellant or nonhypergolic bipropellant RLPGs (we are aware of no examples of the latter) are significantly different. In the hypergolic bipropellant case, the process is initiated by injecting some portion of the oxidizer and fuel into the chamber, where they react, providing the energy required to sustain the regenerative process. The mechanism for initiation of propellant injection can be quite simple in this case, often involving only pressurized air or nitrogen to initially displace the piston.

In the monopropellant RLPG, the igniter must perform two functions: (1) displacement of the regenerative piston to initiate propellant injection, and (2) generation of hot, high pressure gas to ignite the cold liquid propellant as it enters the combustion chamber. The parameters of interest are the rate of pressure rise (i.e. mass and energy fluxes), the maximum pressure, and the duration of the igniter. These parameters must be tailored to the hydraulic characteristics of the injection piston and the liquid propellant reservoir to insure that the reservoir pressure is greater than the chamber pressure when the injector opens. Since the propellant reservoir is normally prepressurized to reduce the chances of compression ignition of the propellant in the reservoir,[57-59] the initial pressure level in the reservoir must be considered in tailoring the igniter.

It is also necessary to tailor the injection area profile, to provide sufficient initial propellant injection to sustain the regenerative process, but also to avoid excess propellant injection which might result in long ignition delays or quenching of the regenerative process. In practice, it has been found that the development of igniters to meet these criteria is not difficult.

8. IGNITER DESIGN

Igniter designs for monopropellant RLPGs have historically been quite simple and robust. Experiment Inc. has tested an electrical spark ignition system in a bulk charge initially filling the combustion chamber between the regenerative piston and the projectile base.[22] More recently, investigators have utilized a solid propellant charge burning at high pressure in a chamber mounted external to the RLPG to vent hot gases into the combustion chamber.[34,35] Secondary booster charges, solid or liquid, have been used in some cases to augment the igniter. However, such systems would not be practical in a fully developed (weaponized) system. DeSpirito et al[106] have reported investigations of ignition systems utilizing electrically initiated liquid instead of solid propellant ignition charge. Such a system could be automated and made practical, thus simplifying igniter design and eliminating the need for separate igniters in the logistic system.

9. TEMPERATURE VARIATIONS

As a part of the effort to develop and demonstrate a brassboard 155-mm RLPG, General Electric has conducted test firings from -55° C to

+65° C, in a 30-mm, Concept VIA fixture, using a HAN-based liquid monopropellant.[103, 107, 108] These tests were conducted by cooling or heating the entire regenerative fixture to the desired temperature before firing. No mechanical changes were made in the hardware during the cold low and high temperature test series to compensate for temperature variation. However, the maximum injection area was reduced by about 15% for the high temperature test series.

In a series of 17 tests, a total of 12 firings were conducted between [illegible] C and 0° C.[107] The data from this test series is presented in Table 4. These data show only minor velocity variation from ambient to -47° C. Below this temperature, the muzzle velocity drops rapidly with decreasing temperature, but even at -55° C, there was no indication of any safety issues in the test results.

TABLE 4. Low Temperature Regenerative Gun Firings

Test Number	T (°C)	Muzzle Velocity (m/s)
1	16	968.6
2	16	966.8
3	16	950.1
4	16	975.1
5	0	944.9
6	-20	969.9
7	-37	960.1
8	-46	944.9
9	-50	879.9
10	-49	850.1
11	-47	947.3
12	-26	967.7
13	-10	961.6
14	-11	949.4
15	-50	904.9
16	-55	644.6
17	16	969.9

Subsequently, a series of 13 test firings were conducted at temperatures up to +65° C.[108] The data from this series of tests are presented in Table 5. The muzzle velocity was reasonably uniform over the temperature range, and again there were no indications of safety issues in the test data.

TABLE 5. High Temperature Regenerative Gun Firings

Test Number	T (°C)	Muzzle Velocity (m/s)
1	15	965.0
2	32	975.1
3	35	969.9
4	42	979.9
5	20	959.8
6	45	949.8
7	50	940.0
8	55	1000.0
9	60	960.1
10	64	960.1
11	65	985.1
12	65	975.1
13	65	965.0

In Table 6, a summary of average velocities and standard deviations for the cold and hot series are presented. Although the statistics are limited, tentative conclusions can be drawn from analysis of this data. The decrease in injection area in the hot series would be expected to produce a drop in muzzle velocity. Indeed, this appears to be the case; however, the

TABLE 6. Summary of Data from Low and High Temperature Test Firings.

Temperature Range	Number of Tests	Average Velocity (m/s)	Standard Deviation (m/s)	(%)
<u>Cold Series:</u>				
16° C	5	966.1	8.46	0.88
-47° C to 0° C	8	955.7	9.64	1.01
-47° C to 16° C	13	959.7	10.50	1.09
<u>Hot Series:</u>				
15° C to 20° C	2	962.4	2.60	0.27
32° C to 65° C	11	969.1	15.95	1.65
15° C to 65° C	13	968.1	14.90	1.54

number of tests at ambient temperature in the hot series is too limited to support such a conclusion. As one might expect, the average muzzle velocity in these tests does show a definite increase with increasing temperature. The increase in muzzle energy from -47° C to +65° C is about 6.2%, while the increase expected from the temperature change alone is about 4.2%. The difference would be attributable to variations in the mechanical systems and/or propellant ignition and combustion with temperature. However, the change in muzzle velocity from -47° C to +65° C is suprisingly small. Finally, the variation in muzzle velocity over the temperature range is reasonable. At ambient temperature, the standard deviation in the cold series was about 0.9%, comparable to previous values obtained in similar Concept VIA hardware. The standard deviation for the tests from -47° C to 0° C is not substantially different from that for the ambient tests, despite the wide temperature range. The hot tests do show an increased standard deviation, but again, the variation in muzzle velocity is not unreasonable given the variation in temperature.

10. PRESSURE OSCILLATIONS

Some early RLPG test data show indications of pressure oscillations above the noise level in the pressure-time records.[26] More recently, Hasenbein[102,109] has reported the investigation of high amplitude, high frequency pressure oscillations in a 40-mm simple in-line RLPG using OTTO Fuel II monopropellant. The oscillations were regular, with a frequency of about 10-12 kHz over the interior ballistic cycle. Hasenbein, therefore, concluded that the oscillation could not be a longitudinal mode. The observed frequency correlates well with the 1st tangential mode for the combustion chamber; therefore, it was identified as a combustion instability, analogous to that observed in liquid propellant rocket engines. The oscillation began when the piston had displaced to a point where the length of the combustion chamber was approximately equal to the chamber diameter. Baffles were introduced into the piston face, and the injectors were modified, similar to techniques developed to control combustion instabilities in rocket engines. The modifications significantly reduced the oscillations in this fixture, as can be seen in the before and after pressure-time curves in Figure 29.

General Electric, in testing of a 105-mm RLPG using Concept VI hardware (see Figure 20), has also encountered high amplitude, high frequency oscillations.[4,35,105,110] Typical pressure vs time data from these tests are presented in Figure 30, in which the pressure oscillations as measured in the combustion chamber at gages G0 and K0, in the liquid propellant reservoir, gage LP350, and in the grease column between the piston and the chamber wall, gage M60, which is separate from both the combustion chamber and the LP reservoir, can be seen. Fourier analyses to determine the frequency content of these data were conducted.[35,105] At gage K0, the primary frequencies are in the 17-20 kHz range, with secondary peaks at 10, 14, 26, 34-36, and 50 kHz, with numerous minor peaks over this range. Above 50 kHz, the relative amplitude falls off rapidly. At gage LP350, the power spectral density shows a broad, complex, almost continuous structure out to about 60 kHz, tapering off in intensity by 75 kHz. Similar oscillations have been reported by Watson et al[111] in a 30-mm, Concept VI RLPG fixture.

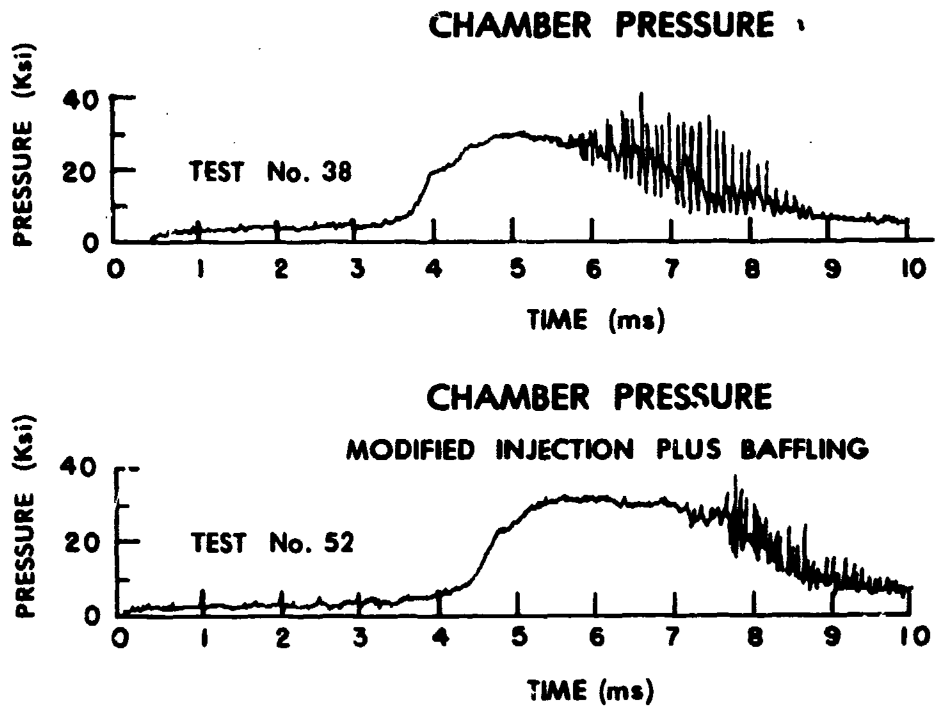


Figure 29. Combustion Chamber Pressure vs Time for a 40-mm Regenerative Liquid Propellant Gun.

These data do not exhibit the characteristics of a classical combustion instability, although it does appear that some acoustical modes in the chamber are being excited.[111] In addition, Watson et al[111] have found, in his 30-mm investigations, that the high frequency oscillations are transmitted through the chamber walls and the tube, and that the resulting stress waves in the steel are detected by the piezoelectric pressure gage, Figure 31, located at the muzzle. A similar observation had been made in the 105-mm investigations at General Electric.

More detailed study of the Concept VI design and the test set up yields other potential sources for the observed pressure oscillations.[109] These include;

1. Flow separation and reattachment in the injector
2. Mechanical oscillation of the regenerative piston

3. Coupling between 1 and 2
4. Acoustic oscillations in the chamber and reservoir
5. Excitation of stress waves in the chamber walls by interaction with the moving piston
6. Electronic noise

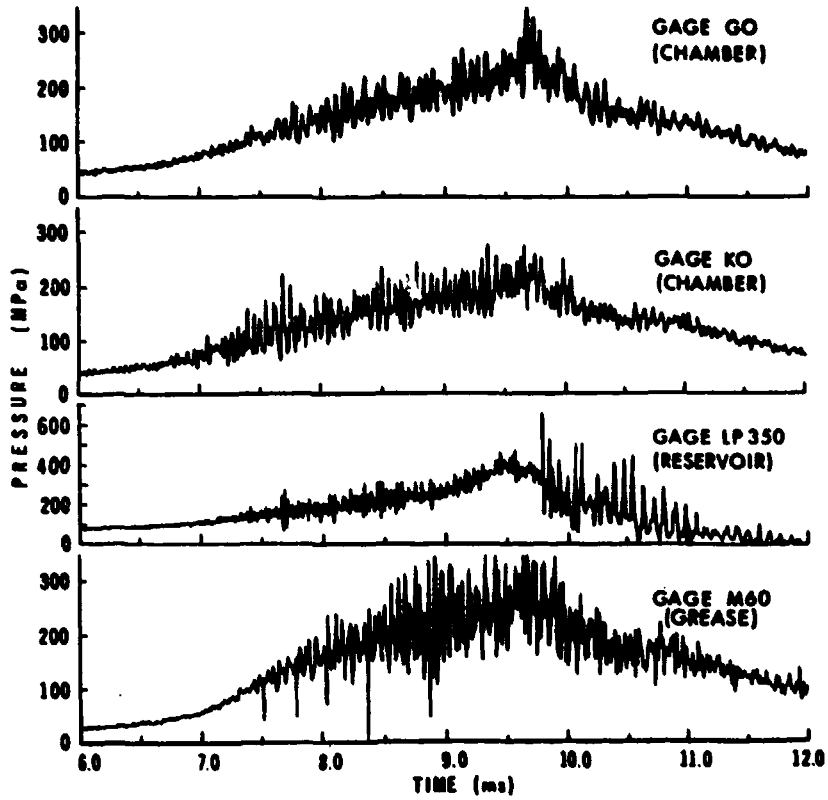


Figure 30. Concept VI. 105-mm Pressure vs Time for Shot Number 8.

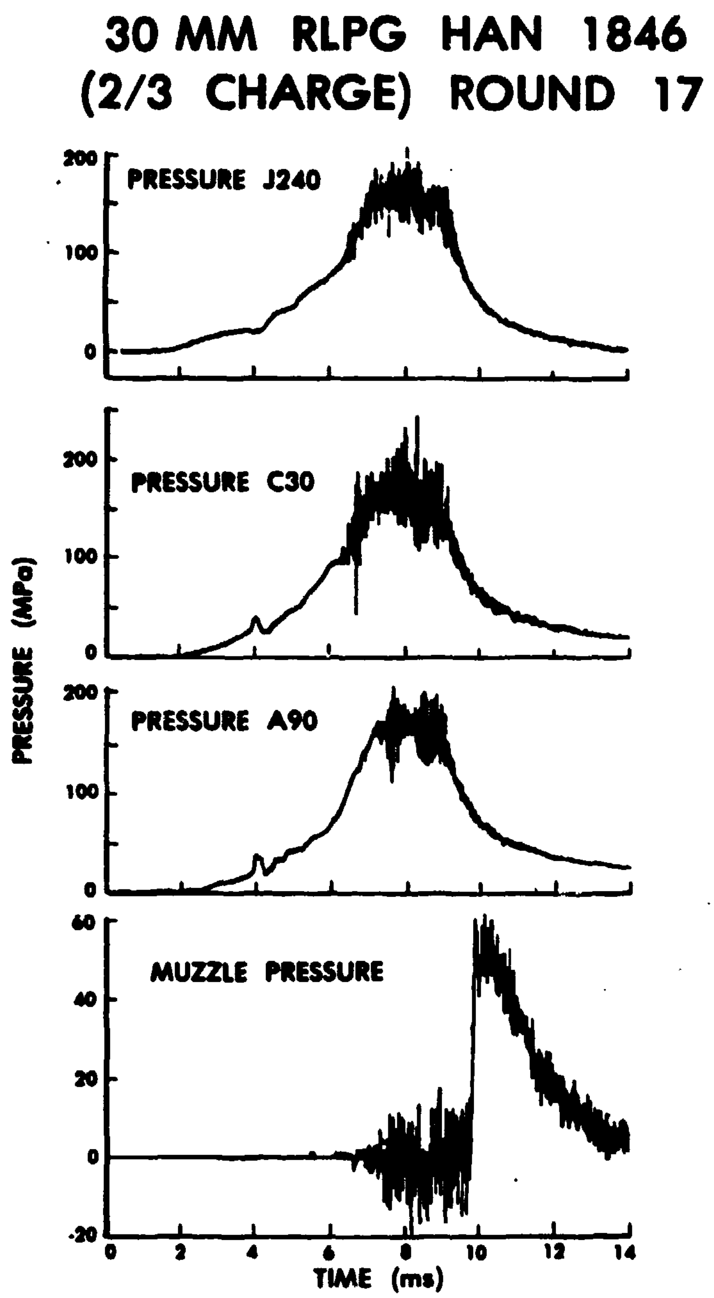


Figure 31. Concept VI. 30-mm RLPG Pressure vs Time Data Showing Oscillations at the Muzzle Gage Prior to Passage of the Projectile.

The first three potential sources of the pressure oscillations are depicted in Figure 32. If either of the first two oscillations occur, the coupled mode could be excited. For example, as the pressure increases in the propellant reservoir the regenerative piston is forced outward toward the chamber wall. This would increase the pressure in the grease dike, and also reduce the area for flow of grease into the chamber. This increase in pressure in the grease column would then force the piston wall inward, increasing the flow area of the grease. Such a mechanical vibration is applied directly to the injector, i.e. the vibration of the piston would result in a time dependent radial boundary condition on the flow in the orifice, potentially generating separation if the flow cannot follow the motion of the boundary. Similarly, it can be argued that a hydraulic instability in the injection orifice would excite the vibrational modes of the regenerative piston.

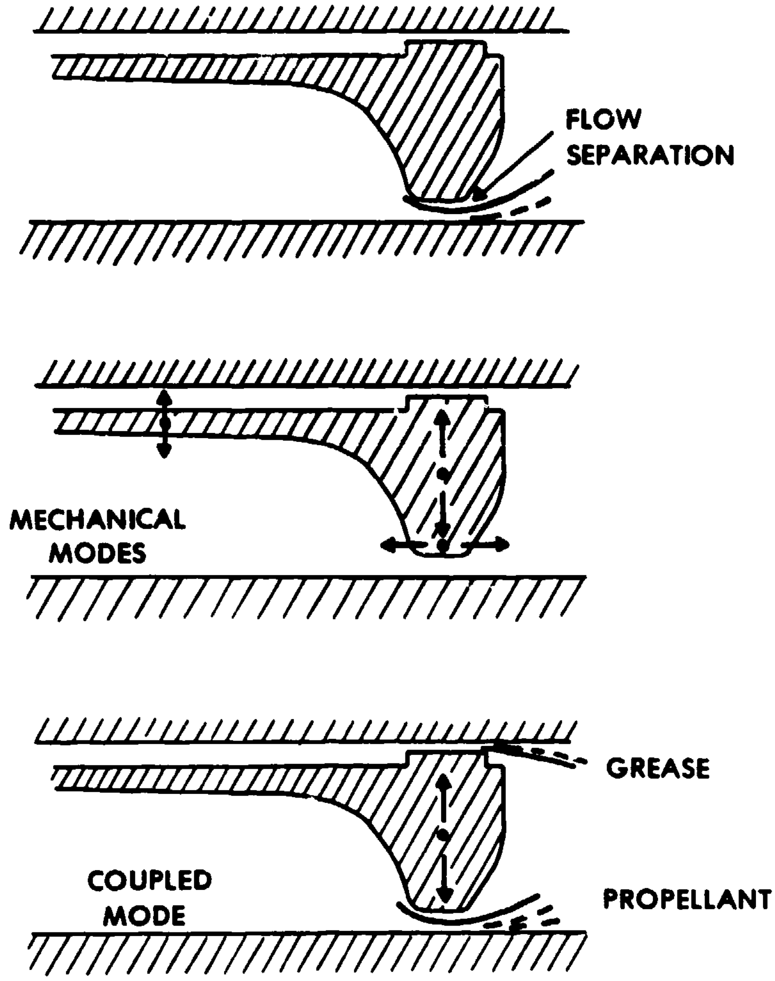


Figure 32. Potential Oscillatory Modes for a Concept VI RLPG

Recent ballistic investigations by General Electric have focused attention on the design of the injection orifice and the chamber wall boundary condition on the piston. It has been found that elimination of the grease dike, reduction of the radial clearance between the piston and the chamber wall, and redesign of the injector to suppress flow separation result in a significant reduction in pressure oscillations. The combination of these factors has been utilized to eliminate pressure oscillations in three 30-mm Concept VI variants, and to significantly reduce oscillations in a 105-mm Concept VIA test fixture.

An adequate understanding of these pressure oscillations has not been developed, and the oscillations have not been eliminated in the 105-mm RLPG. Although the oscillations have not been linked to any structural or ballistic problems in the RLPG, the severity of the oscillations does increase in scaling from 30 mm to 105 mm. It would seem reasonable to expect a similar effect in scaling to 155 mm. However, current experimental evidence suggests that the pressure oscillations are not completely a classical combustion instability, and that RLPG hardware designs can be modified to control or eliminate the oscillations.

11. HIGH VELOCITY RLPG FIRINGS

A limited series of high velocity RLPG firings have been conducted by Bulman using a 25-mm simple in-line fixture and OTTO Fuel II. Approximately 11 tests were conducted in this series, 3 tests yielding velocities in excess of 1500 m/s. The maximum velocity for this series was about 1700 m/s at a charge to mass ratio of 2.2. A 25-mm fixture similar to that used in other ballistic investigations was modified to provide increased propellant injection area, i.e. increased chamber pressure, and a lighter projectile was used to increase the charge to mass ratio. Based on the RLPG ballistic parameters, the calculated muzzle velocity for a comparable solid propellant gun, using a Mayer-Hart simulation, is 1735 m/s. The excellent agreement between the experimental and Mayer Hart velocities would tend to indicate that the efficiency of the regenerative process at high velocities, at least up to 1700 m/s, is comparable to that of conventional solid propellant guns.

XI. SUMMARY OF REGENERATIVE MONOPROPELLANT TESTS

1. 25-MM TEST RESULTS

Initial testing of Concept VI was conducted in a 25-mm fixture.[104,105] Chamber pressure and velocity, for an eight round reproducibility series, are summarized in Table 7. The rear and forward chamber pressure gages are located, respectively, 3.72 cm to the rear and 1.33 cm forward of the initial position of the piston face, or 5.05

cm apart. The propellant used for the tests was Otto-II.

TABLE 7. Summary of Reproducibility Tests for 25-mm, Concept VI.

Test No.	Chamber Pressure Rear (MPa)	Chamber Pressure Forward (MPa)	Velocity (m/s)
202093912	190	157	950.3
202132204	188	166	963.7
202162833	177	161	935.4
203091315	185	159	948.2
203120125	176	161	940.6
203155953	177	154	945.4
204085344	190	162	941.8
204132842	-	-	941.8
Mean	183	160	945.9
Std Deviation	(3.5%)	(2.4%)	(0.91%)

The mean charge weight was 115.7 g with a standard deviation of 0.29 g (0.25%), and the charge to mass ratio was 0.634. The velocity was obtained using a 15 GHz radar, and the accuracy of the data reduction technique is estimated to be no better than 0.5 - 1.0%.

In the 25-mm firings, there was no evidence of oscillations below a pressure of 130-140 MPa. The maximum amplitude of the oscillations in the forward section of the chamber is about 6-12% of the maximum pressure, while the maximum amplitude of the oscillations in the rear of the chamber is about twice as large. The dominant frequency of the pressure oscillations in the chamber is in the 50 to 60 kHz range.

Additional 25-mm tests were performed to investigate the effect of increasing sheet thickness.[105] For these tests the total injection area was the same as that for the preceding reproducibility test series, however, the sheet thickness was no longer uniform. The non-uniform sheet thickness was achieved by scalloping the center bolt. The amplitude of the pressure oscillations in these tests is larger than observed in the reproducibility group. One test group was particularly interesting, and involved the firing of a projectile with twice the nominal projectile mass. During the decay of the pressure after completion of piston motion, there is an apparent excitation of the acoustical modes in the chamber, as suggested by the occurrence of the higher order harmonics. The first peak in the frequency spectrum occurs at 23.5 kHz and the approximate interval between the peaks is also about 23 kHz. The first radial mode in the chamber, assuming a uniform center bolt and a sound speed of 701 m/s, would be 23.9 kHz. The second radial mode would occur at 44.7 kHz, compared with an observed doublet at 41-44 kHz. Assuming a somewhat lower sound speed, of course, would improve the agreement. The observed frequencies occuring during the pressure decay suggests that some energy is released in the system beyond completion of the piston motion, or that the damping mechanisms in the chamber are negligible.

2. 30-MM TEST RESULTS

Test firings were conducted in a 30-mm Concept VI fixture with Otto II, LGP 1845, and LGP 1846.[104-111] The results of these tests are summarized in Tables 8a, 8b, and 8c. The projectile mass was nominally 287 g for these tests, all of which were fired at 2/3 the maximum propellant charge or 160 cc. The initial free volume in the combustion chamber was approximately 95 cc. The maximum pressure at three chamber locations and in the liquid reservoir is presented. The rear most gages, A90 and C30, are located 3.6 cm and 2.1 cm to the rear of the initial position of the piston face, while gage J120 is located 1.2 cm forward of the piston face. As in the 25-mm firings, the data would indicate a pressure gradient between the face of the piston and the forward end of the chamber.

TABLE 8a. Summary of Reproducibility Tests for 30-mm, Concept VI with Otto II.

Test No.	LP	Pressure A90 (MPa)	C30 (MPa)	J120 (MPa)	LP (MPa)	Velocity (m/s)
335:14	Otto-II	174	192	164		939
336:15	Otto-II	-	-	-	-	950
342:13	Otto-II	179	180	144		930
343:12	Otto-II	168	197	179		965
Mean		174	190	162		946
Standard Deviation		(2.6%)	(3.8%)	(8.8%)		(1.6%)

In the test firings with Otto II, Table 8a, the technique for seating the projectile and the initial projectile position at the origin of rifling was varied. This variation might contribute to the poor repeatability in this test series. However, the reproducibility obtained in the LGP 1845 series, Table 8b, was about the same. In this series, the projectile was seated in nominally the same position in each firing. If the apparent outlier (Test No. 364-046) is omitted, the standard deviation in muzzle velocity becomes 0.80%. Furthermore, inspection of the data suggests that it may be divided into two distinct groups with mean velocities of 1005 m/s and 1019 m/s, for which the standard deviations are 0.05% and 0.24% respectively. Currently, there is no satisfactory explanation for this apparent grouping of data.

LGP 1846 testing is still underway, and the number of firings is limited as indicated in Table 8c. Although the statistics are not significant, there would appear to be an improvement in reproducibility.

TABLE 8b. Summary of Reproducibility Tests for 30-mm, Concept VI with LGP 1845.

Test No.	LP	Pressure A90 (MPa)	C30 (MPa)	J120 (MPa)	LP (MPa)	Velocity (m/s)
364-032	1845	197	190	177	-	1020
364-033	1845	181	181	167	-	1005
364-034	1845	191	190	177	-	1005
364-035	1845	194	186	182	-	1020
364-041	1845	192	189	171	227	1018
364-042	1845	195	181	182	202	1021
364-043	1845	184	177	166	-	1005
364-044	1845	-	-	-	-	1004
364-046	1845	186	178	169	-	973.5
Mean		190	184	174	215	1008
Standard Deviation		(3.0%)	(2.9%)	(3.7%)	-	(1.5%)

TABLE 8c. Summary of Reproducibility Tests for 30-mm, Concept VI with LGP 1846.

Test No.	LP	Pressure A90 (MPa)	C30 (MPa)	J120 (MPa)	LP (MPa)	Velocity (m/s)
364-16	1846	205	195	190	-	1023
364-17	1846	190	184	184	285	1009
364-31	1846	231	205	213	-	1011
Mean		209	195	196	-	1014
Standard Deviation		(8.1%)	(4.4%)	(6.4%)		(0.6%)

The mean velocity for the eight tests with LGP 1845 (omitting the apparent outlier) and the three tests with LGP 1846 are, respectively, 1012 m/s and 1014 m/s. This close agreement is initially surprising in view of the differences in impetus of the two propellants. The impetuses for LGP 1845 and LGP 1846 are, respectively, 934 and 898 J/g.

Despite the 4% difference in impetus, the test firings yield approximately the same performance. It is significant, however, that the maximum chamber pressures for the LGP 1846 series are uniformly higher than those for the LGP 1845 series. LGP 1846 contains approximately 3% more water than LGP 1845, and closed bomb tests have shown that the decomposition rate of LGP 1846 is somewhat slower than that of LGP 1845, particularly at low pressure. Thus it may be hypothesized that during the ignition portion of the ballistic cycle, more propellant accumulates in the combustion chamber in the case of LGP 1846 (due to its lower decomposition rate), leading to a higher maximum pressure and, therefore, a slightly higher muzzle velocity despite its lower energy content.

The pressure data contains high frequency oscillations for all three propellants. The amplitude of the oscillations is larger than in the case of the 25-mm reproducibility series. The dominant frequencies occur around 34-35 kHz; however, spectral analysis of this data shows a broad band of frequencies between 32 and 42 kHz. In general, there are no significant differences in these frequencies for Otto-II, LGP 1845, or LGP 1846. The frequency components in the 34-35 kHz range suggest the excitation of the second radial mode in the combustion chamber. The calculated frequency for the second radial mode is between 32.2 kHz and 42.1 kHz for sound speeds between 701 m/s and 914 m/s. However, the data does not contain frequency components corresponding to the first radial mode of the chamber. The amplitude of the oscillations was about 12% of the maximum chamber pressure in the forward section of the chamber and about 20% towards the rear of the chamber. The oscillations began when the chamber pressure reached approximately 90 MPa.

3. 105-MM TEST RESULTS

Test results for the 105-mm Concept VI firings have been previously reported.[4,35,104,105] A summary of these results is presented in Table 9. Tests were initially conducted at 1/3 charge, about 900 cc of propellant, using a thinner than normal annular liquid sheet, i.e. a thinner injection gap. The reduced injection area was used to test the combustion efficiency of the annular liquid sheet. The results were satisfactory, and the injection area was increased for subsequent tests. A similar procedure was utilized in 5/8 charge and full charge firings. As indicated in Table 9, the projectile mass varied slightly during the test series. The last 8 full charge firings were conducted under nominally the same conditions. These tests resulted in a mean velocity of 810.5 m/s with a standard deviation of 0.33%, which is comparable to the muzzle velocity repeatability obtained in the 105-mm howitzer.

TABLE 9. Summary of Test Firings 105-mm, Concept VI with Otto II.

Test No.	Charge	Projectile Mass (kg)	C/M	Chamber Pressure (MPa)	Muzzle Velocity (m/s)
1*	1/3	11.2	0.092	117	502.9
2*	1/3	11.2	0.092	103	499.0
3*	1/3	11.2	0.092	110	-
4	1/3	11.2	0.096	103	504.7
5	1/3	11.2	0.096	124	517.2
6*	5/8	12.5	0.157	193	665.1
7*	5/8	12.5	0.157	200	659.9
8	5/8	12.5	0.161	262	662.6
9	5/8	12.5	0.161	269	658.4
10*	Full	12.5	0.250	221	762.6
11*	Full	12.5	0.250	172	747.7
12**	Full	11.2	0.292	124	660.0
13	Full	11.6	0.278	234	808.9
14	Full	11.6	0.278	221	805.0
15	Full	11.6	0.278	255	807.7
16	Full	11.6	0.278	248	810.1
17	Full	11.6	0.278	255	814.1
18	Full	11.6	0.278	255	811.4
19	Full	11.6	0.278	248	811.0
20	Full	11.6	0.278	241	810.0

* Thin Sheet Injection
** Projectile Failed Inbore

XII. RLPG BALLISTIC PERFORMANCE

The Concept VI test firing results are summarized in Table 10, along with the ballistic efficiencies for the various test series. The energy of the igniter has been included in the calculation of the efficiencies, but represents only a small correction to the ballistic efficiencies, 1-3% for the 105 mm and less than 1% for the 25 mm and 30 mm.

TABLE 10. Summary of Test Results 25-mm, 30-mm and 105-mm, Concept VI.

Fixture	LP	No. of Tests	Charge Mass (kg)	C/M	Proj Travel (m)	Expansion Ratio	Velocity (m/s)	Pressure (MPa)	Ballistic Efficiency Experiment (%)	Ballistic Efficiency Calculated (%)
25mm	Otto II	8	0.116	0.634	2.13	7.65	946	183	21.1	24.0
30mm	Otto II	4	0.197	0.683	2.44	8.50	946	119	19.6	23.9
	LGP 1845	4	0.234	0.812	2.44	8.50	1019	195	13.9	17.5
	LGP 1846	3	0.227	0.787	2.44	8.50	1014	196	15.0	18.0
105mm	Otto II	3	1.03	0.092	5.18	15.90	501	110	36.2	39.8
	Otto II	[illegible]	1.08	0.096	5.18	15.90	511	114	37.7	41.5
	Otto II	2	1.96	0.157	5.18	12.80	662	196	40.4	41.9
	Otto II	2	2.01	0.161	5.18	12.80	661	266	39.5	45.1
	Otto II	2	3.13	0.250	5.18	10.40	755	196	33.9	38.3
	Otto II	8	3.22	0.278	5.18	10.40	810	245	35.0	37.7

The low ballistic efficiencies for the 25-mm and 30-mm test series are due primarily to the small injection gap used with the annular piston. The small injection gap corresponds to a large web for a solid propellant, i.e. the larger the web, the smaller the solid propellant burning surface area. Thus, even for a relatively high charge mass ratios, 0.63-0.81, the propellant injection area remains relatively small, and the rate of pressure rise and the maximum pressure in the chamber are correspondingly low. In the case of the 105 mm, however, the expansion ratios are greater than for the smaller calibers. The greater expansion ratio results in increased ballistic efficiencies, despite the low maximum chamber pressures.

These data also illustrate one of the ballistic characteristics of the regenerative gun, variable chamber volume. In a conventional solid propellant gun, the chamber volume, and thus the expansion ratio, is fixed. This can lead to difficulties when designing artillery charges for shorter ranges, particularly for long range cannons with large chambers. In the 105-mm RLPG, the initial free volume in the combustion chamber was fixed, and only the volume of the propellant reservoir changed with the charge. The ignition characteristics of the system were, therefore, independent of the charge. Also, as the charge decreased, the expansion ratio of the system increased, maintaining the ballistic efficiency of the system.

Finally, the calculated ballistic efficiencies for analogous solid propellant systems are provided in Table 10 for comparison. A simple

Mayer Hart simulation was used, with the assumption of optimum initial free volume in the combustion chamber. Since no attempt was made to optimize the various RLPGs, it is not suprising that the experimental ballistic efficiency always falls below the calculated value. However, the differences in the ballistic efficiencies is for the most part small, 1.5% to 5.6%.

XIII. SUMMARY

Since 1946, various liquid propellant gun systems involving both bulk-loaded and regenerative hardware, using both monopropellants and bipropellants, have been investigated. However, over the past 15 years, the primary focus of research efforts has been the regenerative gun concept utilizing a hydroxl ammonium nitrate based liquid monopropellant.

It has been demonstrated repeatedly that the RLPG provides the ballistic control necessary for a practical weapon system, and that hydraulic and combustion issues which arise in testing are readily amenable to correction through mechanical design changes to the regenerative hardware. The key technical issue associated with the RLPG is not ballistic in nature, but involves the reliability and durability of the regenerative system in the field environment. This issue is related to the reliability of the high pressure seals inherent in the regenerative concept, and to the lifetime of the regenerative piston, seals, and other internal components which are exposed to the regenerative gun environment.

In contrast, the bulk-loaded LPG is mechanically simple, but lacks the ballistic control necessary for practical implementation. Under controlled laboratory conditions, the best repeatability in muzzle velocity which has been reported is about a 1% standard deviation. This performance would be acceptable in direct fire applications, however, the repeated occurrence of very high pressure and catastrophic gun failures has severely limited the investigation of the BLPG. The concern over the catastrophic failures in the BLPG is not simply that they have occurred; catastrophic failures occur regularly in solid propellant development programs and even occur on occasion in fielded systems. The primary concern is the inability of existing theories to adequately explain the cause such that corrective actions can be taken to prevent future failures.

With the rapid development of regenerative gun technology over the past several years, general interest in liquid propellant gun technology has increased significantly.

In addition to the investigation of new regenerative gun designs, a variety of related efforts have been initiated. These include renewed investigations of the bulk-loaded concept and a liquid propellant traveling charge, as well as alternate propellant formulations. These efforts represent only the initial wave of innovative research projects which will continue to emerge, if liquid propellant guns indeed prove practical for military application.

REFERENCES

1. Haukland, A.C., "State-of-the-Art Survey of Liquid Propellant Gun Systems," Indian Head Technical Report 350, 30 December 1971.

2. Morrison, W.F., Knapton, J.D., and Klingenberg, G., "Liquid Propellants for Gun Application," Proceedings of the Seventh International Symposium on Ballistics, April 1983.

3. Klein, N., "Liquid Propellants For Use In Guns - A Review," BRL Technical Report 2641, February 1985.

4. Morrison, W.F., Baer, P.G., Bulman, M.J., and Mandzy, J., "The Interior Ballistics of Regenerative Liquid Propellant Guns," Proceedings of the Eighth International Symposium on Ballistics, October 1984.

5. Scandland, T., "A Study of the Liquid Propellant Gun Applied to a New Medium Tank," Addendum to BRL Report 890 June 1954.

6. Wells, W.W., "Liquid Versus Solid Propellant - A Synthesis of Tank Weapon Systems Circa 1990," Rock Island Technical Report RE-TR-71-86, June 1972.

7. Morrison, W.F., "The Application of Liquid Propellant Gun Technology to Field Artillery," Proceedings of the 1983 JANNAF Propulsion Meeting.

8. Brooks, J., "A Systems Analysis of Liquid Propellants in a 155mm SP Artillery Weapon System," Systems Analysis Branch Information Report SA-61, Large Caliber Weapon Systems Laboratory, September 1984.

9. Hudson, C.M., "Army Ordnance LPG Program," Proceedings of the Third Annual Conference on the Application of Liquid Propellants to Guns," June 1952.

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

11. Barr, W.J. and Wilson, E.J., "Liquid Fuel Catapult, III; Caliber 0.50 Systems for Launching Projectiles at Hypervelocities," Experiment, Inc. TP 37, December 1949.

12. Niemeier, B.A., et al, "Liquid Fuel Catapults with Regenerative Injection, I; Design and Test of Preliminary Caliber 0.50 Models," Experiment, Inc. TP 38, December 1949.

13. Barr, W.J., et al, "Liquid Fuel Catapult, II; Further Investigations at Caliber 0.50 Scale," Experiment, Inc. TP 33, August 1948.

14. Dewey, E.A., et al, "Liquid Fuel Catapult, IV; Miscellaneous Studies with Caliber 0.50 Systems," Experiment, Inc. TP 40, September 1950.

15. Niemeier, B.A., et al, "Liquid Fuel Catapults with Regenerative Injection, II; The Design of a 37mm Launcher," Experiment, Inc. TP 39, December 1949.

16. Dorsey, E.C., et al, "Liquid Fuel Catapults with Regenerative Injection, III; Design Improvements and 37mm Test Results," Experiment, Inc. TP 41, 1950.

17. Johnson, E.S., et al, "Summary of Research and Development of Liquid Propellant Guns," Proceedings of the Symposium on Liquid Propellants for Guns, Frankford Arsenal, December 1950.

18. Miksch, R.S., "Liquid Propellant Gun Systems," Detroit Controls Corp. RC-190, April 1956.

19. Griffin, D.N., "Development of Monopropellant Hydrazine as a Liquid Propellant for Guns," Olin Mathieson Chemical Corp. Report NF-3087, June 1954.

20. Elmore, L.C., "Liquid Propellant Gun Systems," Detroit Controls Corp. RC-226, September 1957.

21. Miksch, R.S., "Investigation of Liquid Propellant Gun Systems for 90mm Tank Guns," Detroit Controls Corp. RC-224, Contract No. DA-04-200-ORD-341, 1957.

22. Fleischauer, E.T., "Application of Liquid Propellants to Guns and Launchers, III; New Injection Systems," Experiment Inc. TP 95, November 1955.

23. Swanson, D.L., "The Design and Construction of a 40mm Liquid Propellant Regenerative Injection Gun," Experiment Inc. TP 92, October 1955.

24. Dorsey, E.G., et al, "Liquid Fuel Catapults with Regeneratie Injection, V; Design of an Experimental 127mm Launcher," Experiment Inc. TP 56, August 1952.

25. Dorsey, E.G., et al, "Liquid Fuel Catapults with Regenerative Injection, VII; Construction and Preliminary Test of an Experimental 127mm Launcher," Experiment Inc. TP 81, July 1954.

26. Dorsey, E.G., et al, "Liquid Fuel Catapults with Regenerative Injection, VIII; Engineering Evaluation of a 127mm Regenerative Launcher," Experiment Inc. TP 81, May 1955.

27. Comer, R.H., Shearer, R.B., and Jones, R.N., "Interior Ballistics of Liquid Propellant Guns," Ballistic Research Laboratories Report 1205, May 1963.

28. Comer, R.H., Jones, R.N., and Shearer, R.B., "Predicted Performance of a High Pressure, High Velocity Liquid Propellant Gun," Ballistic Research Laboratories MR 1573, July 1964.

29. Comer, R.H., "Fluid Dynamics of Bulk-Loaded Liquid Propellant Guns," AGARD-CP No. 10, 1966.

30. Comer, R.H., "Ignition and Combustion of Liquid Monopropellants at High Pressure," 16th International Symposium on Combustion, pp 1211-1219, 1976.

31. Kirshner, H.A. and Stiefel, L., "Spark Initiation of Aklyl Nitrate Monopropellants," Frankford Arsenal Report R-1882, 1968.

32. Mallory, H.D., "A Dynamically Loaded 25mm Liquid Propellant Gun," Journal of Ballistics, Vol 3, 1979.

33. Mallory, H.D., "The NAVAIRSYSCOM Liquid Bipropellant Gun," National Defense, October 1984.

34. Graham, A. and Bulman, M.J., "General Electric 25mm Regenerative Liquid Propellant Gun Program," Proceedings of the Twelfth JANNAF Combustion Meeting, CPIA Publication 273, Vol. 1, pp 391-404, 1975.

35. Mandzy, J., Magoon, I., Morrison, W.F., and Knapton, J.D., "Preliminary Report on Test Firings of a 105mm Regenerative Fixture," Proceedings of the 20th JANNAF Combustion Meeting, 1983.

36. Comer, R.H. and McBratney, W.F., "Transient Combustion Modeling in Bulk-Loaded Liquid Propellant Guns," 9th JANNAF Combustion Meeting, CPIA Publication 231, Vol. III, pp 71-100, 1972.

37. Cole, R.H., "Underwater Explosions," Princeton University Press, 1950.

38. Davies, K.M., and Taylor, G.I., "The Mechanics of Large Bubbles Rising Through Extended Liquids and Then Through Liquid in Tubes," Proc. Roy. Soc. A200, 1950.

39. Taylor, G.I., "The Instability of Liquid Surfaces When Accelerated in a Direction Perpendicular to Their Planes, I," Proc. Roy. Soc. A201, 1950.

40. Giedt, W.H. and Rall, D.H., "Heat Transfer in Liquid Propellant Guns," Detroit Controls Final Report, RC-207, Contract No. ORD 16217, Task 2, December 1956.

41. Lewis, D.J., "The Instability of Liquid Surfaces When Accelerated in a Direction Perpendicular to Their Planes, II," Proc. Roy. Soc. A202, 1950.

42. Helmholtz, H., Monatsber. Berlin Acad., 1868, Reprinted in Phil. Mag. 36, 1868.

43. Ingraham, R.L. and Wheeler, J.A., LASL Report LA-1593, 1953.

44. Howland, J.S., Guzdar, A.R., and Rhee, S.S., "A Study of the Hydrodynamic Aspects of the Physical Processes in Liquid Propellant Guns," Phase II, Final Report Contract No. DA-18-001-AMC-1115(X), Foster-Miller Associates, Inc., 1967.

45. Howland, J.S., Rhee, S.S., Erickson, A.J., and Guzdar, A.R., "A Study of the Hydrodynamic Aspects of the Physical Processes in Liquid Propellant Guns," Phase III, Final Report Contract No. DAAD05-68-C-0047(X), Foster-Miller Associates, Inc., 1968.

46. Irish, C., US Naval Ordnance Station, Indian Head, Maryland, private communication.

47. Burnett, W.M., "An Interior Ballistics Model For Liquid Propellant Guns," US Naval Ordnance Station Indian Head TR-444, 1973.

48. Edelman, R.B., "The Interior Ballistics of Liquid Propellant Guns," R&D Associates TR-4400-010, August 1974.

49. Edelman, R.B. and Hogge, H.D., "A Transient Quasi-One Dimensional Model of the Interior Ballistics Process for Non-Hypergolic Liquid Bi-Propellant Guns," R&D Associates TR 8700-001, September 1976.

50. Butler, T.D. and O'Rourke, P.J., "A Numerical Method For Two Dimensional Unsteady Reacting Flows," Proceedings of the 16th International Symposium on Combustion, 1976.

51. Phillips, G., Murty, S., Traci, R., and Edelman, R.B., "Analysis of the Interior Ballistics Processes of Bulk Loaded Liquid Propellant Guns," Proceedings of the 17th JANNAF Combustion Meeting, CPIA Publication 329, pp 403-448, 1980.

52. Erickson, A., "Generalized Wave Dynamics and Cavity Penetration Analysis of Liquid Propellant Guns," Foster-Miller Associates, Inc., BRL Contract Report No. 88, 1973.

53. Regan, J.E. and Shambelan, C., "Ignition Studies of Liquid Monopropellants," Frankford Arsenal Report No. R-1288, 1955.

54. Griffin, D.N., "Development and Experimental Evaluation of Monopropellant Gun and 20-mm Machine Gun," Report No. 17-1, Jet Propulsion Laboratory, 1952.

55. Elmore, L.C., "Small Caliber, Multipurpose, Automatic Liquid Propellant Gun," Pulsepower Systems, Inc. TR-65, Contract No. DAAD05-72-C-0087, 1972.

56. Elmore, L.C., "Small Caliber, Multipurpose, Automatic Liquid Propellant Gun," Pulsepower Systems, Inc. TR-94, Contract No. DAAD05-72-C-0317, BRL Contract Report No. 319, 1976.

57. Messina, N.A., Leyzorek, J., and Summerfield, M., "Compression Ignition Sensitivity Studies of Liquid Monopropellants," 15th JANNAF Combustion Meeting, CPIA Publication No. 297, Vol. I, pp 335-358, 1978.

58. Messina, N.A., Ingram, L.S., and Summerfield, M., "Sensitivity of Liquid Monopropellants to Compression Ignition," 18th JANNAF Combustion Meeting, CPIA Publication No. 347, Vol. II, 1981.

59. Messina, N.A., Ingram, L.S., and Summerfield, M., "Sensitivity of Liquid Monopropellants to Compression Ignition," Contract No. DAAK11-81-C-0012, ARBRL-CR-00482, 1982.

60. Evans, M.W., Given, F.I., and Doran, D.G., "Ignition and Combustion Properties of Liquid Monopropellants," Stanford Research Institute Final Report, SRI Project No. GU-1123, (Contract No. DA-04-200-ORD-320), 1956.

61. Weinberg, F., private communication at Workshop on Ignition of Hydroxylammonium Nitrate Based Liquid Propellants, held at Ballistic Research Laboratory, April 1986.

62. Knapton, J.D., Stobie, I.C., Comer, R.H., McBratney, W.F., and Stansbury, L., "Survey of Ballistic Data from High Velocity Liquid Propellant Gun Firings," BRL Report No. 2005, 1977.

63. Klingenberg, G., Knapton, J.D., Morrison, W.F., "Review on Liquid Gun Propellant Ignition Studies," Ernst-Mach-Institut Report V7/83, Fraunhofer-Gesellschaft, August 1983.

64. Fisher, E.B. and Sterbutzel, G.A., "Investigation of Ignition/Combustion Phenomena in a 30mm Liquid Monopropellant Gun," Calspan Report No. KB-6002-X-1, Contract No. N00123-75-C-1520, 1976.

65. McBratney, W.F., "Mid-Caliber Ballistic Test of NOS 365," ARBRL-TR-02337, 1981.

66. Knapton, J.D., Stobie, I.C., and Travis, K.E., "Liquid Propellant Characterization Tests at Maximum Loading Densities," 16th JANNAF Combustion Meeting, CPIA Publication No. 300, Vol. I, pp 393-404, 1979.

67. Klingenberg, G., Knapton, J.D., and Travis, K.E., "Studies of the Decomposition of the Liquid Monopropellant NOS 365," ARBRL-TR-02328, 1981.

68. Poudrier, G., US Naval Ordnance Station, Indian Head, Maryland, private communication.

69. Elmore, L.C., Pulsepower Systems, Inc., private communication, to B. Dunetz, BRL, 1977.

70. Fishburn, B., US Army Armaments Research and Development Center, Dover, New Jersey, private communication.

71. Jones, R.N., Comer, R.H., Shearer, R.B., and Stansbury, L., "A Source of Variability in the Interior Ballistics of Liquid Propellant Guns," BRL Report No. 1288, 1965.

72. Foster, C.R. and Cowles, F.B., "High Velocity Firings with Liquid Propellants in a Caliber 0.60 Gun," Jet Propulsion Laboratory Progress Report No. 17-9, 1952.

73. Elmore, L.C., "Liquid Monopropellant Gun Interia Ballistics Data Review," Pulsepower Systems Incorporated, TD-610.115, September 1975.

74. Turner, C.F., "Development of a Liquid Propellant Compression Ignition System for Weapons Application," Olin Mathieson Chemical Corporation Document No. NH-1182, Contract No. DA-19-059-ORD-2659, 1958.

75. Elmore, L.C., "Small Caliber, Multipurpose, Automatic Liquid Propellant Gun," Pulsepower Systems, Inc. TR-49, Contract No. DAAD05-72-C-0087, 1972.

76. Elmore, L.C., "Small Caliber, Multipurpose, Automatic Liquid Propellant Gun," Pulsepower Systems, Inc. TR-50, Contract No. DAAD05-72-C-0087, 1972.

77. Elmore, L.C., "Small Caliber, Multipurpose, Automatic Liquid Propellant Gun," Pulsepower Systems, Inc. TR-52, Contract No. DAAD05-72-C-0087, 1972.

78. Elmore, L.C., "Small Caliber, Multipurpose, Automatic Liquid Propellant Gun," Pulsepower Systems, Inc. TR-56, Contract No. DAAD05-72-C-0087, 1972.

79. Knapton, J.D., and Stobie, I.C., "Bulk-Loaded Liquid Propellant Guns: What Can Be Expected in Terms of Pressure Reproducibility?," J. Ballistics, Vol. 3, 1979.

80. Knapton, J.D., Stobie, I.C., and Comer, R.H., "Pyrotechnic Primer Design for Liquid Propellant Guns," 13th JANNAF Combustion Meeting, CPIA Publication No. 281, Vol. I, pp 187-198, 1976.

81. Hartman, R.A., Knapton, J.D., Stobie, I.C., and Comer, R.H., "A Study on the Establishment of Pyrotechnic Ignition Criteria for Liquid Propellant Guns," BRL Report No. M2606, 1976.

82. Klingenberg, G., Knapton, J.D., Taylor, D., and Stobie, I.C., "Flame Temperatures and Internal Pressures of Pyrotechnic Igniters Used in Liquid Propellant Gun Firings," ARRADCOM Report ARBRL-TR-02398, July 1982.

83. Miksch, R.S., "Investigation of Liquid Propellant Gun Systems for 90mm Tank Guns," Detroit Controls Corp. RC-236, Contract No. DA-04-200-ORD-341, 1957.

84. Frankle, J.M., "Interior Ballistics of High Velocity Guns, Experimental Program - Phase 1," BRL Report No. M1879, 1967.

85. Heppner, L.D., "Special Study of Setback and Spin for Artillery, Mortar, Recoilles Rifle, and Tank Ammunition," US Army Test and Evaluation Command Project No. 9-7-0023-27, 1968.

86. Morrison, W.F., Bulman, M.J., Baer, P.G., and Banz, C.F., "The Interior Ballistics of Regenerative Liquid Propellant Guns," Proceedings of the 1984 JANNAF Propulsion Meeting.

87. Gough, P.S., "A Model of the Interior Ballistics of Hybrid Liquid Propellant Guns," USABRL Contract Report in Preparation.

88. Coffee, T.P., "A Lumped Parameter Code for Regenerative Liquid Propellant Guns," USABRL Technical Report No. BRL-TR-2703, December 1985.

89. Cushman, P., General Electric Ordnance Systems Division, private communication.

90. Bulman, M.J., General Electric Ordnance Systems Division, private communication.

91. Pagen, G., Harvey, A., and Izod, D.C.A., "Regenerative Liquid Propellant Gun," Proceedings of the Seventh International Symposium on Ballistics, 1983.

92. Coffee, T.P., "The Analysis of Experimental Measurements on Liquid Regenerative Guns," Proceedings of the 22nd JANNAF Combustion Meeting, October 1985.

93. Coffee, T.P., "The Analysis of Experimental Measurements on Liquid Propellant Guns," USABRL Technical Report No. BRL-TR-2731, May 1986.

94. Birk, A. and Reeves, P., "Gun Type Liquid Propellant Spray," Proceedings of the 22nd JANNAF Combustion Meeting, CPIA Publication No. 432, Vol. II, pp 351-363, October 1985.

95. Birk, A. and Reeves, P., "Annular Liquid Propellant Jets - Injection, Atomization and Ignition," USABRL Technical Report BRL-TR-2780, March 1980.

96. Morrison, W.F. and Wren, G., "A Lumped Parameter Description of Liquid Injection in a Regenerative Liquid Propellant Gun," Proceedings of the 23rd JANNAF Combustion Meeting, October 1986.

97. Edelman, R., Science Applications, Inc., private communication.

98. Johnson, R.T., "Determination of Equation of State for Liquid Monopropellant (NOS-365)," Naval Ordnance Station Technical Report No. IHTR 459, March 1977.

99. Constantino, M., Lawrence Livermore National Laboratory, private communication.

100. Morrison, W.F., Knapton, J.D., and Klingenberg, G., "Regenerative Injection Liquid Guns," Journal of Ballistics.

101. Smith, E.H. and Dorsey, E.G., "Liquid Fuel Catapults with Regenerative Injection VI; Interior Ballistics, A Theory of Pressure Variation During Burning of the Propellant," Experiment, Inc. TP 62, September 1953.

102. Hasenbein, R.G., "Regenerative Liquid Propellant Gun Technology," USAARADCOM Technical Report No. ARLCB-TR-81026, June 1981.

103. Pate, R.A. and Schlerman, C.P., "Flow Properties of LGP 1846 At Reduced Temperatures," Proceedings of the 22nd JANNAF Combustion Meeting, CPIA Publication No. 432, Vol. II, pp 319-332, October 1985.

104. Morrison, W.F., Knapton, J.D., and Baer, P.G., "Liquid Propellant Gun Technology," AGARD Conference Proceedings No. 392; Interior Ballistics of Guns, September 1985.

105. Mandzy, J., Cushman, P.G., and Magoon, I., "Liquid Propellant Technology Final Report," USABRL Contract Report No. BRL-CR-546, October 1985.

106. DeSpirito, J., Klein, N., and Knapton, J.D., "Progress Report on Ignition Methods for a 155mm Regenerative Injection Liquid Propellant Gun," Proceedings of the 22nd JANNAF Combustion Meeting, CPIA Publication No. 432, Vol. II, pp 307-318, October 1985.

107. Schlerman, C.P., Pate, R.A., and Walter, B., "Ignition and Combustion of LGP 1846 at Reduced Temperatures," Proceedings of the 23rd JANNAF Combustion Meeting, CPIA Publication No. 457, Vol. II, pp 519-527, October 1986.

108. Pate, R., DiOrio, S., and Banks, J., "Ballistic Performance of LGP 1846 Propellant at Elevated Temperatures," Proceedings of the 23rd JANNAF Combustion Meeting, CPIA Publication No. 457, Vol. II, pp 529-537, October 1986.

109. Graham, A.R., "The Regenerative Liquid Propellant Gun," USAARADCOM Technical Report No. ARLCB-TR-82022, November 1982.

110. Baer, P.G. and Morrison, W.F., "Modeling of High Frequency Pressure Oscillations in the 105mm Regenerative Liquid Propellant Gun," Proceedings of the 20th JANNAF Combustion Meeting, October 1983.

111. Watson, C.A., Knapton, J.D., DeSpirito, J., and Boyer, N., "A Study on High Frequency Pressure Oscillations Observed in a 30mm Regenerative Liquid Propellant Gun," Proceedings of the 22nd JANNAF Combustion Meeting, CPIA Publication No. 432, Vol. II, pp 239-254, October 1985.

NOMENCLATURE

A	Cross-sectional area of tube
a	Acceleration
C	Mass of propelling charge
C_1	Taylor cavity constant
C_2	Kelvin-Helmholtz constant
M	Mass of projective
m_g	Mass of gas in the barrel
P	Pressure
$\bar{P}$	Space mean pressure
P_B	Breech pressure
P_f	Bore resistance pressure
r_c	Radius of Taylor cavity
U_o	Initial chamber volume
v	Projectile velocity
v_b	Gas velocity at barrel entrance
v_c	Taylor cavity tip velocity
v_g	Gas velocity parallel to gas - liquid interface
v_l	Liquid velocity parallel to gas - liquid interface
x	Projectile travel
γ	Ratio of specific heats
λ	Propellant force constant
η	Propellant co-volume
ϕ	Fraction of charge burnt
ρ_g	Gas density
ρ_l	Liquid density

DISTRIBUTION LIST

No. of Copies	Organization
12	Commander Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145
1	Director Defense Advanced Research Projects Agency ATTN: H. Fair 1400 Wilson Boulevard Arlington, VA 22209
7	HQDA DAMA-ART-M DAMO-FDE DAMA-WSW DAMO-FDR DAMA-CSM DALO-SMA DALO-PLA Washington, DC 20310
1	Commander US Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333-0001
1	Headquarters Laboratory Command ATTN: AMSLC-TP-PL, Dr. Ian Bartky 2800 Powder Mill Rd Aldephi, MD 20783-1145
1	Commander US Army Armament, Munitions and Chemical Command ATTN: SMCAR-ESP-L Rock Island, IL 61299-7300

No. of Copies	Organization
1	Commander US Army Aviation Research and Development Command ATTN: AMSAV-E 4300 Goodfellow Blvd St Louis, MO 63120
20	Commander Armament RDE Center US Army AMCCOM ATTN: SMCAR-TSS SMCAR-TDC SMCAR-FSS-DA, C. Daly SMCAR-CCH, R. Price SMCAR-FSS-DA, J. Irizarry SMCAR-FSA-S, H. Liberman R. Kopmann SMCAR-AEE-B, J. Lannon D. Downs A. Bracuti A. Beardell W. Seals B. Fishburn Pai Lu SMCAR-FSS-A, L. Frauen SMCAR-FSS-E, J. Brooks SMCAR-FSS-A, B. Brodman L. Stieffel T. Davidson W. Quine Picatinny Arsenal, NJ 07806-5000
1	Office of Program Manager Ammunition Logistics ATTN: AMCPM-AL Bldg 455 Picatinny Arsenal, NJ 07806-5000

DISTRIBUTION LIST

No. of Copies	Organization
8	Director Benet Weapons Laboratory Armament R&D Center US Army AMCCOM ATTN: SMCAR-LCB-TL, E. Conroy A. Graham D. Jones J. Zweig F. Heiser J. Kapp S. Tauscher P. Thornton Watervliet, NY 121[illegible]
1	Program Manager Cannon Artillery Weapons Systems ATTN: AMCPM-CAWS Picatinny Arsenal, NJ 07806-5000
1	Commandant US Army Quartermaster School ATTN: ATSM-CDM Ft Lee, VA 23801
1	Commandant USA Ord Missile & Munitions Sch ATTN: ATSK-Z Redstone Arsenal, AL 35897-6095
1	Commandant USA Transportation School ATTN: ATST-CDM Ft Eustis, VA 23604-5361
1	Commander USA Logistics Center ATTN: ATCL-MGM Ft Lee, VA 23801
1	Commander USA LABCOM ATTN: AMSLC-TP-AL 2800 Powder Mill Rd Adelphi, MD 20783-1145
1	Commander USACACDA ATTN: ATZL-CAM-O-I Ft Leavenworth, KS 66027-5300
1	Commander Materials Technology Lab US Army Laboratory Cmd ATTN: SLCMT-MCM-SB, M. Levy Watertown, MA 02172-0001
1	Director US Army Air Mobility Rsch and Development Lab Ames Research Center Moffett Field, CA 94035
1	Commander US Army Communications Electronics Command ATTN: AMSEL-ED Fort Monmouth, NJ 07703
1	Commander ERADCOM Technical Library ATTN: STET-L Ft Monmouth, NJ 07703-5301
1	Commander US Army Harry Diamond Labs ATTN: SLCHD-TA-L 2800 Powder Mill Rd Adelphi, MD 20783

DISTRIBUTION LIST

No. of Copies	Organization
1	Commander US Army Missile Command Rsch. Dev, & Engr Ctr ATTN: AMSMI-RD Redstone Arsenal, AL 35898-5500
1	President USA Field Artillery Board ATTN: ATXBR-BDP Ft Sill, OK 73503
1	Commander US Army Missile & Space Intelligence Center ATTN: AIAMS-YDL Redstone Arsenal, AL 35898-5500
2	Commander US Army Belvoir R&D Ctr ATTN: STRBE-WC, Tech Library (Vault) B-315 STRBE-VU Ft Belvoir, VA 22060-5606
2	Commander US Army Tank Automotive Cmd ATTN: AMSTA-TSL AMSTA-ZDM Warren, MI 48397-5000
6	Commander US Army Research Office ATTN: Tech Library R. Weigle D. Mann R. Ghiardelli R. Singleton F. Oertle PO Box 12211 Rsch Triangle Park, NC 27709-2211
1	Director US Army TRADOC Systems Analysis Activity ATTN: ATAA-SL White Sands Missile Range, NM 88002
6	Headquarters US Army Trng & Doctrine Cmd ATTN: Tech Library M. Pastel (ATCD-G) ATCD-M ATCD-F ATCD-SL ATEN-S Ft Monroe, VA 23651-5000
2	Commandant US Army Infantry School ATTN: ATSH-CD-CSO-OR ATSA-CD Ft Benning, GA 31905
2	Commandant US Army Field Artillery School ATTN: ATSF-CMW ATSF-WN, J. Spicer Ft Sill, OK 73503
2	Commandant US Army Armor Center ATTN: ATSB-CD-MLD Ft Knox, KY 40121
1	Commander US Army Development and Employment Agency ATTN: MODE-TED-SAB Ft Lewis, WA 98433
1	Commander Naval Surface Weapons Center ATTN: D.A. Wilson, Code G31 Dahlgren, VA 22448-5000

DISTRIBUTION LIST

No. of Copies	Organization
2	Commander US Naval Surface Weapons Ctr ATTN: O. Dengel K. Thorsted Silver Spring, MD 20902-5000
1	Commander Naval Weapons Center China Lake, CA 93555-6001
1	Superintendent Naval Postgraduate School Dept of Mechanical Engr ATTN: Code 1424, Library Monterey, CA 93943
1	AFWL/SUL Kirtland AFB, NM 87117
1	Air Force Armament Lab ATTN: AFATL/DLODL Eglin AFB, FL 32542-5000
1	AFOSR/NA (L. Caveny) Bldg 410 Bolling AFB, DC 20332
1	Commandant USAFAS ATTN: ATSF-TSM-CN Ft Sill, OK 73503-5600
1	US Bureau of Mines ATTN: R.A. Watson 4800 Forbes Street Pittsburgh, PA 15213
3	Director Jet Propulsion Lab ATTN: Tech Library J. Kelly E. Lawton 4800 Oak Grove Drive Pasadena, CA 91109

No. of Copies	Organization
2	Director National Aeronautics and Space Administration ATTN: MS-603, Tech Library MS-86, Dr. Povinelli 21000 Brookpark Road Lewis Research Center Cleveland, OH 44135
1	Director National Aeronautics and Space Administration Manned Spacecraft Center Houston, TX 77058
10	Central Intelligence Agency Office of Central Reference Dissemination Branch Room GE-47 HQS Washington, DC 20502
1	Central Intelligence Agency ATTN: Joseph E. Backofen HQ Room 5F22 Washington, DC 20505
2	Bell Aerospace Textron ATTN: F. Boorady A.J. Friona PO Box One Buffalo, NY 14240
1	Calspan Corporation ATTN: Tech Library PO Box 400 Buffalo, NY 14225
1	General Electric Company Armament Systems Department ATTN: D. Maher Burlington, VT 05401

DISTRIBUTION LIST

No. of Copies	Organization
12	General Electric Ord Sys Dpt ATTN: OP43-220, J. Mandzy R.E. Mayer H. West M. Bulman R. Pate I. Magoon J. Scudiere J. McCaleb J. Lenehan J. Lacatell G. Bair J. DeFreitas A. Giovanetti 100 Plastics Ave Pittsfield, MA 01201-3698
1	IITRI ATTN: Library 10 W. 35th St Chicago, IL 60616
1	Olin Chemicals Research ATTN: David Gavin PO Box 586 Chesire, CT 06410-0586
1	FMC Corporation Northern Ordnance Division ATTN: Ron Ricci 4800 East River Road Minneapolis, MN 55421
2	Olin Corporation ATTN: Victor A. Corso Dr Ronald L. Dotson PO Box 30-9644 New Haven, CT 06536
1	Paul Gough Associates ATTN: Paul Gough PO Box 1614 Portsmouth, NH 03801

No. of Copies	Organization
1	Safety Consulting Engr ATTN: Mr C. James Dahn 5240 Pearl St Rosemont, IL 60018
1	Science Applications, Inc. ATTN: R. Edelman 23146 Cumorah Crest Woodland Hills, CA 91364
1	Sunstrand Aviation Operations ATTN: Dr. Owen Briles PO Box 7002 Rockford, IL 61125
1	Veritay Technology, Inc. ATTN: E.B. Fisher 4845 Millersport Highway PO Box 305 East Amherst, NY 14051-0305
1	Director Applied Physics Laboratory The Johns Hopkins University Johns Hopkins Road Laurel, MD 20707
2	Director Chemical Propulsion Info Agency The Johns Hopkins Univ ATTN: T. Christian Tech Library Johns Hopkins Road Laurel, MD 20707
2	University of Delaware Department of Chemistry ATTN: Mr. James Cronin Professor Thomas Brill Newark, DE 19711

DISTRIBUTION LIST

No. of Copies	Organization
1	U. of Illinois at Chicago ATTN: Professor Sohail Murad Dept of Chemical Engr Box 4348 Chicago, IL 60680
1	U. of Maryland at College Park ATTN: Professor Franz Kasler Department of Chemistry College Park, MD 20742
1	U. of Missouri at Columbia ATTN: Professor R. Thompson Department of Chemistry Columbia, MO 65211
1	U. of Michigan ATTN: Prof Gerard M. Faeth Department of Aerospace Engr Ann Arbor, MI 48109-3796
1	U. of Missouri at Columbia ATTN: Professor F.K. Ross Research Reactor Columbia, MO 65211
1	U. of Missouri at Kansas City Department of Physics ATTN: Prof R.D. Murphy 1110 East 48th Street Kansas City, MO 64110-2499
1	Pennsylvania State University Dept of Mechanical Engr ATTN: K. Kuo University Park, PA 16802
1	Yale University ATTN: Professor Richard Chang Applied Physics PO Box 2157 Yale Station New Haven, CT 06520

No. of Copies	Organization
2	Princeton Combustion Rsch Laboratories, Inc. ATTN: N.A. Messina M. Summerfield 475 US Highway One North Monmouth Junction, NJ 08852
1	University of Arkansas Department of Chemical Engr ATTN: J. Havens 227 Engineering Building Fayetteville, AR 72701

Aberdeen Proving Ground

Dir, USAMSAAA
ATTN: AMXSY-D
AMXSY-MP, H. Cohen
AMXSY-LX
AMXSY-RA

Cdr, USATECOM
ATTN: AMSTE-TO-F
AMSTE-CM

Cdr, CRDEC, AMCCOM
ATTN: SMCCR-RSP-A
SMCCR-MU
SMCCR-SPS-IL

Commandant
USA OC&S
ATTN: ATSL-CD-MS
ATSL-TD-NSS

USER EVALUATION SHEET/CHANGE OF ADDRESS

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

1. BRL Report Number____________________Date of Report__________

2. Date Report Received______________________________

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

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

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.)

CURRENT ADDRESS

Name

Organization

Address

City, State, Zip

7. If indicating a Change of Address or Address Correction, please provide the New or Correct Address in Block 6 above and the Old or Incorrect address below.

OLD ADDRESS

Name

Organization

Address

City, State, Zip

(Remove this sheet, fold as indicated, staple or tape closed, and mail.)