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EXPERIMENTS WITH LIQUID GUN PROPELLANTS

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U.S. ARMY LABORATORY COMMAND

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Closed chamber and gun firing tests on various liquid monopropellants were performed at the Fraunhofer-Institute (EMI-AFB) and the Ballistic Research Laboratory (BRL). The objectives of the study were twofold: (1) to investigate the ignition requirements of the propellants in both a closed chamber and a gun and (2) to investigate the combustion characteristics of the propellants, also in both a closed chamber and a gun. Pyrotechnic igniters were used in both the closed chamber and gun tests. The propellants tested at EMI-AFB were isopropyl nitrate, nitromethane, and three hydroxylammonium nitrate (HAN) based liquid monopropellants, NOS-365, LP 1845 and LP 1846, a variation of LP 1845. The gun tests at EMI-AFB were performed in a 28-mm regenerative liquid propellant gun (RLPG). The propellants tested at the BRL were NOS-365, LP 1845 and LP 1846. The gun tests at the

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I. INTRODUCTION

The concept of liquid propellant gun systems using regenerative propulsion technology is presently being investigated in the United States and in several European countries.[1,2] The regenerative liquid propellant propulsion concept is, for example, being tested in the United States in a 105-mm test fixture to provide a data base for scaling to a 155 mm. Tank gun studies are also underway in both countries. The regenerative system is being considered because it offers a viable means to control ignition and combustion of liquid propellants in guns.[1]

Monopropellants are used in the United States, while both non-hypergolic bipropellants and monopropellants are investigated in the Federal Republic of Germany. A monopropellant is a stable homogeneous liquid containing both fuel and oxidizer. It may be composed of a single component such as isopropyl nitrate, or of a combination of miscible fluids such as nitromethane and methanol. A second example of miscible fluids are the monopropellants based on hydroxylammonium nitrate (HAN) and a water soluble organic fuel.[1]

A bipropellant is characterized by the separation of fuel and oxidizer outside the gun environment. Bipropellant research has focused on nitric acid and H_2O_2 as candidate oxidizers. Fuel components range from hydrazine to hydrocarbons.[1] Also, a gelled propellant concept has been studied in the United States.[3] In this concept, energetic solid oxidizers are suspended in an energetic liquid carrier and diluted with an inert liquid.

The original HAN-based liquid propellants (e.g., NOS-365) were developed by the US Navy as a candidate torpedo fuel. NOS-365 propellant has been replaced by alternate formulations such as LP 1845 and LP 1846,[1,4] which contain the fuel triethanol ammonium nitrate. The company Rheinmetall in the Federal Republic of Germany has tested a series of liquid monopropellants such as isopropylnitrate (IPN), and mixtures of nitromethane (NM) with isopropylnitrate or methanol.[1]

The present paper describes research efforts directed toward the study of various liquid monopropellants. Closed bomb studies and gun firing tests were performed in both the Fraunhofer-Institute EMI-AFB and the Ballistic Research Laboratory (BRL). The ignitability of the monopropellants as well as the combustion characteristics were investigated. The objective of these studies is to support the large caliber regenerative liquid propellant gun development.

The monopropellants tested in this study offer many desirable properties, such as energy content, stability, low cost, and relatively safe in handling properties. Besides the propellant properties just mentioned, an appropriate monopropellant should also offer suitable ignition characteristics. However, it is recognized that continued research in propellant development may result in improved monopropellants. For a regenerative gun, the igniter system, such as a pyrotechnic igniter or an electric igniter system, has two functions; namely, (a) to start the piston motion and (b) to ignite the initially injected monopropellant. Monopropellants that offer safe handling properties such as high ignition pressures may require relatively large amounts of energy to ignite and hence sustain the regenerative process. Therefore, as part of our studies, we evaluated the energy output of the igniter systems.

II. EXPERIMENTAL

1. TEST EQUIPMENT

a. Igniter Systems: For the studies performed at EMI-AFB, the igniter consisted of either 1.0 or 2.8 g of black powder. The igniter used at the BRL consisted of a M52A3B1 initiator and either 3.0 g or 3.5 g of IMR 4350. The principal ingredient in the M52A3B1 is lead styphnate. IMR 4350 is a single base extruded propellant normally used in small arms. The volume of the igniter cavity was 6.8 cm^3 and the limiting vent orifice diameter into the larger closed chamber, or the gun fixture, was 3.81 mm.

b. Closed Chambers: Three different chambers were used in the tests. The EMI-AFB chamber had a rectangular cross section with a volume of about 41.5 cm^3 and a length to width ratio of about 1.5.[4] A schematic of this chamber is shown in Figure 1. The monopropellants were ignited using an electrically heated nichrome wire immersed in the liquid.[4]

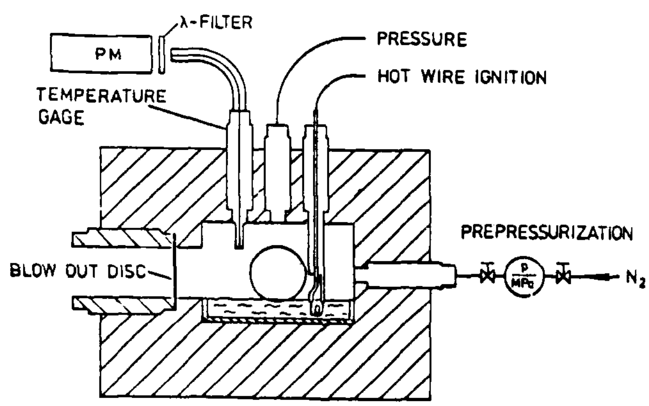

Figure 1. Schematic of the EMI-AFB Closed Chamber

In the BRL tests the ignition and combustion of the igniter were studied using two different closed chambers. Pressures were measured in both chambers and temperature was measured in the second chamber using the invasive optical probe method developed by Klingenberg.[5,6] Both chambers had a volume of 106 cm^3. Importantly, the length to diameter ratio (l/d) of the first chamber was 1.5 and therefore heat losses were probably not important (<10%). The second chamber consisted of the 30-mm gun chamber. In this chamber the l/d was about 0.3 and resulted in significant heat losses. As a result, the maximum pressures were considerably lower than the pressures recorded in the first chamber. The 6.8 cm^3 igniter was used for both chambers.

c. Gun Fixtures: The EMI-AFB 28-mm experimental test gun fixture[7] used various regenerative pistons with 24 cylindrical injection orifices, see Figure 2. The diameter of the injector holes was varied from 1.2 mm to 3.5 mm. The pressure in the propellant reservoir prior to firing was one atmosphere.

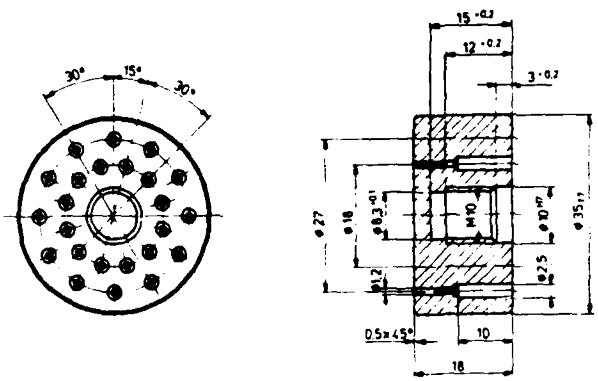

Figure 2. Schematic of the EMI-AFB Injector Piston

The fixture, shown in Figure 3, had a rather short barrel of approximately 0.5 m so that the in-bore combustion of the monopropellant was incomplete in some cases. Both the chamber and tube of the test fixture were made from one piece of steel. Therefore, the tube could not be conveniently replaced.

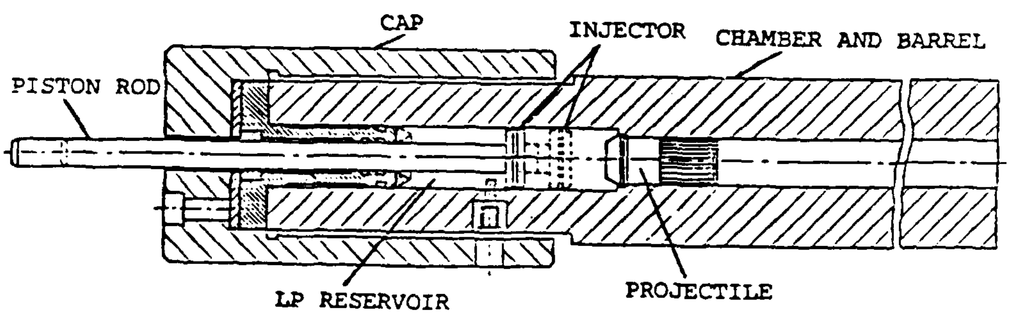

Figure 3. Schematic of Caliber 28-mm Regenerative Test Fixture

The BRL 30-mm test fixture was based on a concept for injecting the LP into the combustion chamber in the form of a circular sheet. An illustration of the basic concept, showing the chamber and LP reservoir sections, is shown in Figure 4. The basic concept has been referred to as Concept VI. The injection piston is shown in the upper half of Figure 4 in the forward position prior to firing and in the lower half of Figure 4 in the rear position at the end of firing. The injection piston is a thin shell cylinder supported from deformation by a lubricant film and the chamber wall. At ignition, the pressure developed in the chamber forces the injection piston to the rear. The higher pressure developed in the propellant reservoir, due to the differential area of the injection piston, forces the LP around the annulus on the outside of the control rod, or center bolt, and into the combustion chamber. The contour shown on the control rod provides a means for varying the instantaneous injection area. Initially, the injection area is zero preventing leakage of LP into the chamber during the LP fill and during prepressurization. For all tests reported here, the initial prepressurization of the LP was 6.9 MPa. As the injection piston is displaced to the rear, the injection area rapidly increases permitting an increase in the mass injection rate. Maximum injection area is reached when the starting taper on the control rod ends. Motion of the injection piston is retarded toward the end of its stroke by the rear taper on the control rod.

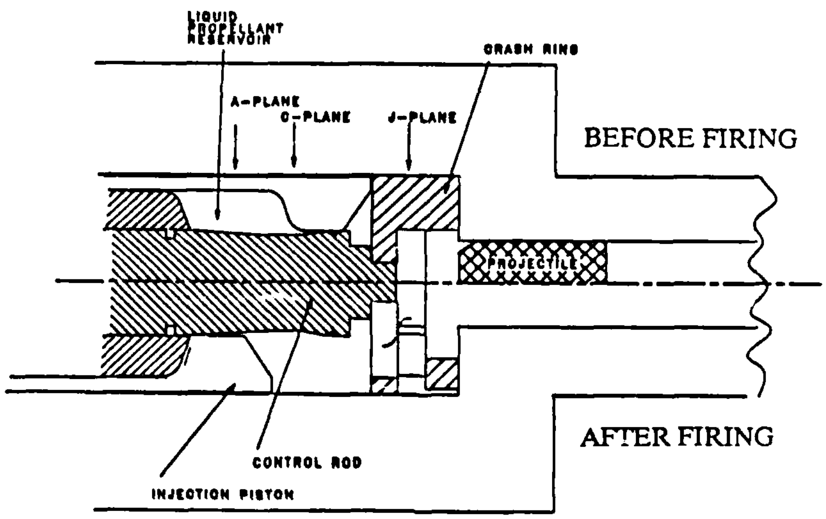

Figure 4. Concept IV. Inline Annular Piston

d. Instrumentation: Pressures were measured using commercial high pressure piezoelectric gages. Temperatures were measured[5,6] using an emission gage technique which measures the brightness temperature. In radiating opaque combustion gases, estimates of the gas temperature may be made if the spectral emission or radiance is measured. The spectral emission of the combustion gases may be conveniently characterized by the brightness temperature, defined as the temperature of a blackbody that has, at a given wave length, the same radiance. The accuracy and calibration procedures are described in References 5 and 6.

2. THERMOCHEMISTRY

a. Igniter: The thermochemistry of the igniter components are summarized in Table 1.

TABLE 1. Summary of the Thermochemistry of the Igniter Used in the Closed Chamber and Gun Tests[7-10] at Specified Loading Densities

Component	Loading Density g/cm^3	Flame Temperature K	Impetus J/g	Pressure MPa
Black Powder	0.1	2382	318	33.4
IMR4350	0.0280	2875	1003	28.8
M52 and 3.0g IMR	0.4663	2884	974	777

b. Propellants: A summary of the thermochemical properties of the propellants is given in Table 2. The propellants 1845 and 1846 use HAN as the oxidizer component (which is actually a weak monopropellant) and triethanol ammonium nitrate (TEAN), (also a weak monopropellant).

TABLE 2. Properties of the Liquid Propellants Used in the Gun Fixtures[1 2 7 10]

LP	Fuel Name	Fuel Wt.%	HAN Wt.%	Water Wt.%	Density g/cm^3	Impetus J/g	Flame Temp K	Gamma
1845	TEAN	20.0	63.2	16.8	1.45	934	2592	1.218
1846	TEAN	19.2	60.8	20.0	1.43	898	2469	1.223
Nitromethane (NM)					1.13	1244	3044	-
80% NM + 20% Methanol					1.07	986	2349	1.446
Isopropylnitrate (IPN)					1.036	831	1776	1.445

III. RESULTS

1. IGNITER CHARACTERISTICS

The igniter used in the EMI-AFB studies consisted of either 1 g or 2.8 g of black powder, which was filled into a 3.58cm^3, 7.62-mm case. The igniter was ignited by a percussion device and was tested by firing into a closed chamber with a volume of 41.5cm^3, i.e., the chamber of the 28-mm test fixture gun. To evaluate the igniter discharge, both the pressure and temperature were measured. Table 3 summarizes the results.

TABLE 3. Igniter Data of EMI-AFB Tests.

Igniter	Maximum Pressure MPa	Maximum Temperature K
1.0 g Black Powder	3.8 - 4.2	2250 - 2350
2.8 g Black Powder	11.8 - 11.9	2350 - 2420

The BRL 6.8-cm^3 igniter was tested in both the 106-cm^3 closed chambers. The results are summarized in Tables 4 and 5. In these tables, the A, B and C under Igniter refer to the type of confinement of the IMR powder used in the 6.8-cm^3 igniter. In the A configuration, a portion of the powder adjacent to the M52A3B1 is confined in a paper straw. In the B and C configurations, the straw was replaced with a slightly larger diameter plastic straw and there was more propellant directly in-line with the M52A3B1. As shown in Table 4, the B configuration yielded improved reproducibility for the recorded maximum pressure in the igniter. The maximum chamber pressure in the larger chamber, however, was degraded, a problem which may only be due to the limited number of tests.

Despite the increased charge used in the second chamber (Table 5), the recorded maximum pressures were significantly lower than the maximum pressures recorded in the first chamber, a result, as postulated earlier, of the low l/d of the chamber and the high heat loss.

TABLE 4. Summary of Experimental Results for the 106-cm^3 Closed Chamber. The loading densities, neglecting the M52A3B1 and assuming all of the propellant is displaced into the larger chamber, were 0.0266 and 0.0310 g/cm^3 respectively for, the igniter configurations A or B, and C.

Igniter	No. of Tests	Mean Maximum Pressure Igniter Chamber MPa	Std Dev (%)	106 cm^3 Chamber MPa	Std Dev (%)	10 to 90% Rise Time Mean ms	Std Dev (%)
M52	1	10.6	-	1.1	-	-	-
A. M52 and 3.0 g IMR	6	181	15.2	16.8	3.1	1.37	14.4
B. M52 and 3.0 g IMR	9	142	9.1	17.3	7.8	1.60	23.1
C. M52 and 3.5 g IMR	2	(not measured)		21.5			

TABLE 5. Summary of Experimental Results for the 106 cm^3 30-mm Closed Chamber. The loading density was 0.0325 g/cm^3.

Igniter	No. of Tests	Maximum Pressure MPa	Standard Deviation (%)	Maximum Temperature K	Standard Deviation (%)
C. M52 and 3.5 g IMR	6	13.3	3.0	2527	5.8

Based on the maximum pressure data summarized in Table 4, an estimate of the igniter charge burned in the small igniter chamber may be made and, by comparison with the pressure-time data, an estimate of the unburned mass flux into the larger chamber may be obtained. Assuming that no gas is vented from the igniter chamber during the rise to maximum pressure and that there were no heat losses, then the mass of propellant burned in the igniter chamber is approximately proportional to the ratio of the measured pressure and the theoretical pressure. Using the theoretical pressure from Table 1, based on a loading density of 0.466 g/cm^3, indicates that about 0.55 g of solid propellant for the B igniter configuration burns in the igniter chamber with the remainder venting into the larger chamber (Table 6). Examining the pressure-time data, Figure 5, or simply taking the 10 to 90% rise time given in Table 4, gives the approximate unburned mean mass flux into the larger chamber of $2.45/(0.0016 \times 3.14 \times 3.86^2/4) = 131$ g/mm^2/sec.

TABLE 6. Estimate of propellant burned in the igniter chamber and unburned propellant which vents into the gun chamber. The experimental pressure is taken from Table 4 and the theoretical pressure is extrapolated linearly from Table 1.

Igniter	Loading Density of IMR	Pressure		Estimate of SP	
		Expt.	Theoret.	Burned in 6.8 cm^3 Chamber	Vented in to 106 cm^3 Chamber
	g/cm^3	MPa	MPa	g	g
B.M52 and 3.0 g IMR	0.441	142	777	0.55	2.45
A.M52 and 3.0 g IMR	0.441	181	777	0.70	2.30

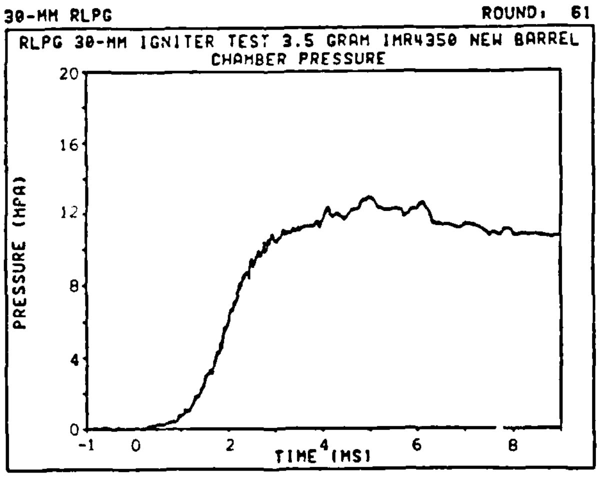

Figure 5. Pressure vs. Time for 3.5 g Igniter

Additionally, an estimate of the total heat loss may be determined by comparing the experimentally measured pressures with the theoretical pressures. The results are summarized in Table 7.

TABLE 7. Estimate of Heat Loss from the Burning of the Propellant in the Igniter and the Larger Chambers.

Igniter Config.	Loading Density	Mass of IMR Charge	Pressure Expt.	Pressure Theoret.	Estimate of Heat Loss during the Combustion in the Two Chambers
	g/cm^3	g	MPa	MPa	(%)
			Chamber No. 1		
B	0.0281	3.0	17.3	28.8	39.9
A	0.0281	3.0	16.8	28.8	41.7
C	0.0325	3.5	21.5	32.9	34.6
			Chamber No. 2		
C	0.0325	3.5	13.3	32.9	59.6

The recorded maximum chamber temperature (Table 5) of 2527 K is 12% lower than the theoretical value (Table 1). A comparison of the maximum chamber pressure (Table 4) with the theoretical pressure would suggest a much lower value for the measured temperature. The ratio of the measured pressure and the theoretical pressure (taken from Table 6) suggests a heat loss of over 30% for Chamber No. 1 for a much larger heat loss for chamber No. 2.

A plot of the brightness temperature vs. time due to the igniter is shown in Figure 6 for the same test illustrated in Figure 5. The data shows a rapid rise to about 1855 K followed by a second increase to about 2095 K. This temperature is about 73% of the flame temperature (Table 1).

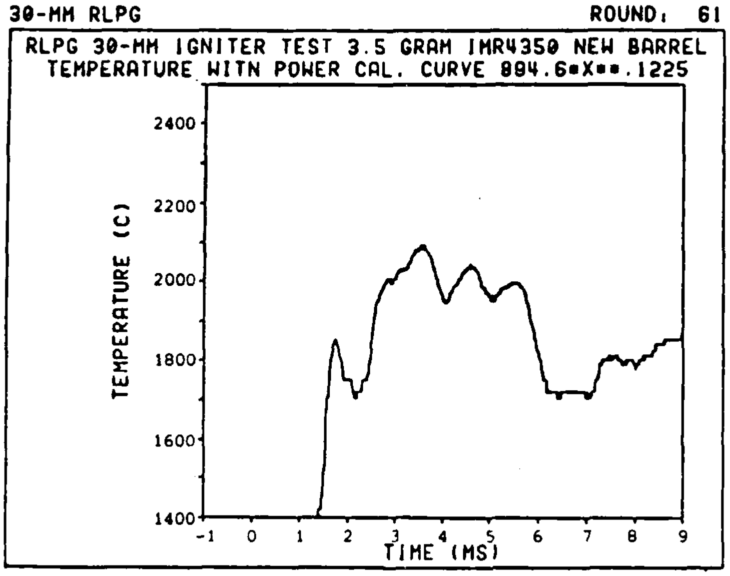

Figure 6. Temperature vs. Time of Igniter Discharge into the Chamber of the Caliber 30-mm Test Fixture.

2. IGNITABILITY TESTS OF THE PROPELLANTS

The ignitability of the monopropellants was investigated using the EMI-AFB closed chamber and the 28-mm gun test fixture. The energy delivered to the hot wire was determined at the time when a self-sustained reaction started. The results of the closed chamber tests are summarized in Table 8. In these tests, the prepressure in the closed chamber was varied. Rather high igniter energies of the order of 165 to 324 J were required to ignite the NOS-365 at atmospheric pressures. Similar ignition behavior was observed with the monopropellants LPG 1845 and 1846.[4]

At a prepressure of 3 MPa, all three HAN-based monopropellants could be ignited at an igniter energy of about 0.6 to 0.7 J. Comparatively, both the NM/methanol mixture and the IPN could not be ignited in the closed chamber even if the prepressure was increased to 7 MPa and igniter energies of about 2.6 to 16 kJ were applied. These results show that the HAN-based monopropellants are easier to ignite than the NM or IPN propellants.

TABLE 8. Results of Ignitability Tests.

Monopropellant	Prepressure	Hot Wire Power	Hot Wire Energy	Result + Ignition - No Ignition
	MPa	W	J	
NOS-365	0.1	21.0	165	+
	0.1	25.0	324	+
	0.1	19.5	260	+
	0.5	20.4	41	+
	1.0	20.2	1.6	+
	1.5	20.2	1.07	+
	3.0	20.4	0.51	+
	3.0	20.4	0.61	+
	3.0	20.4	0.63	+
	3.0	20.2	0.58	+
LP 1845	3.0	20.4	0.69	+
LP 1846	3.0	20.4	0.69	+
Isopropyl-nitrate	6.0	41.0	2648	-
(IPN)	7.0	47.0	1628	-
80% Nitro-Methane/20%	7.0	60.2	5715	-
Methanol	7.0	91.2	15960	-

The ignitability characteristics of the monopropellants were also evaluated in the 28-mm test fixture gun. The results are shown in Table 9. The 28-mm tests also showed that the HAN-based monopropellants were easier to ignite in the gun chamber. However, the NM mixture could be ignited in the gun when a black powder charge of 2.8 g was used. No ignition was obtained for IPN. A high propellant ignition energy may be a concern in some regenerative systems, depending on the initial chamber volume and the level of prepressurization that may be used.

TABLE 9. Results of 28-mm Gun Firings.

Monopropellant	Igniter Black Powder g	Result + Ignition - No Ignition
LGP 1845/1846	1	+
80% NM, 20% Methanol	1	-
IPN	1	-
LP 1845/1846	2.8	+
80% NM, 20% Methanol	2.8	+
IPN	2.8	-

3. GUN FIRINGS

Several diagnostic methods were used during the testing of the monopropellants in the 28-mm fixture. For each test various parameters were measured including the pressure and temperature histories in the combustion part of the chamber (location M2), the pressure in the reservoir (M1), the piston travel (optical EMNEG 100), and the in-bore projectile velocity (laser Doppler velocimeter).[11,12] The free flight projectile velocity was determined by means of laser light barriers mounted at an axial distance from the muzzle of 1 m. Figure 7 shows the diagnostic set-up used in the gun tests.

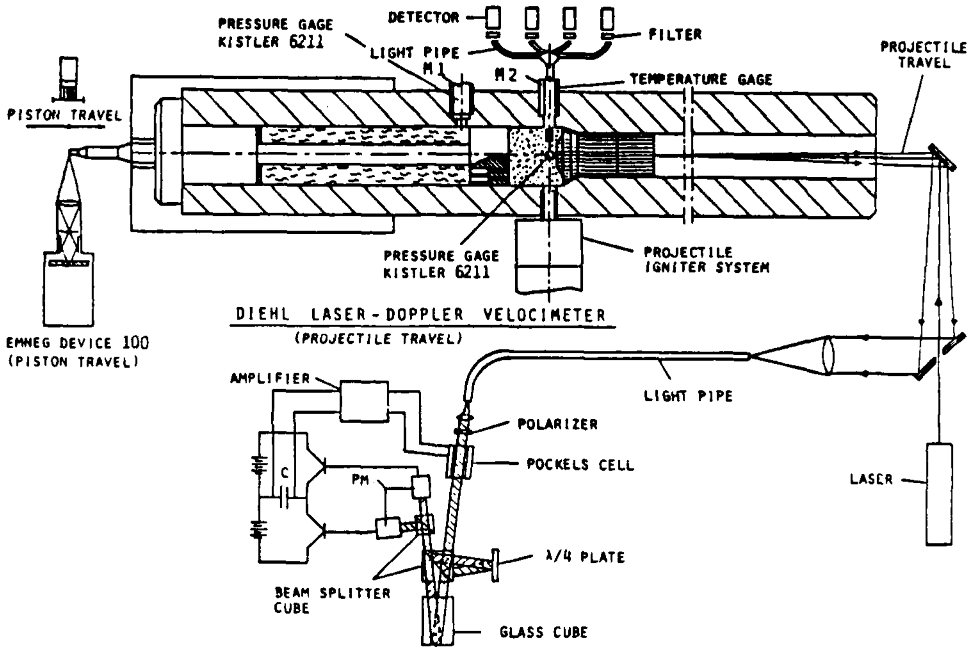

Figure 7. Schematic of Diagnostic Set-up Used in the 28-mm Regenerative Gun Test Fixture.

By measuring the above parameters, the combustion characteristics of the monopropellants could be investigated under various conditions. For example, variations were made to the dimensions of the piston thereby altering the force on the piston, the igniter energy released into the combustion chamber, the diameter of the injector orifice, the engraving force of the projectile, and the friction of the piston. A parametric study on these parameters provided data for calibrating and improving model predictions[13,14] as well as to provide guidelines for optimizing the gun performance.

a. Flashback. During the early studies flashback was encountered. This was attributed to a low differential area of the piston. The piston motion was sometimes stopped due to high friction and flashback occurred in the liquid propellant reservoir. For example, Figure 8 shows the measured piston travel vs. time for such a case. LP 1846 was used in this firing. For t $\leq$ 5.5 ms the piston moves in the correct direction towards the breech (positive travel in Figure 8). At 5.5 ms the piston motion reverses due to flashback to the reservoir. For 5.5 < t < 11 ms the piston continues in the forward direction towards the gun tube until it is stopped at the forward section of the gun chamber. The problem was avoided by using a piston with a larger differential area.[7 15]

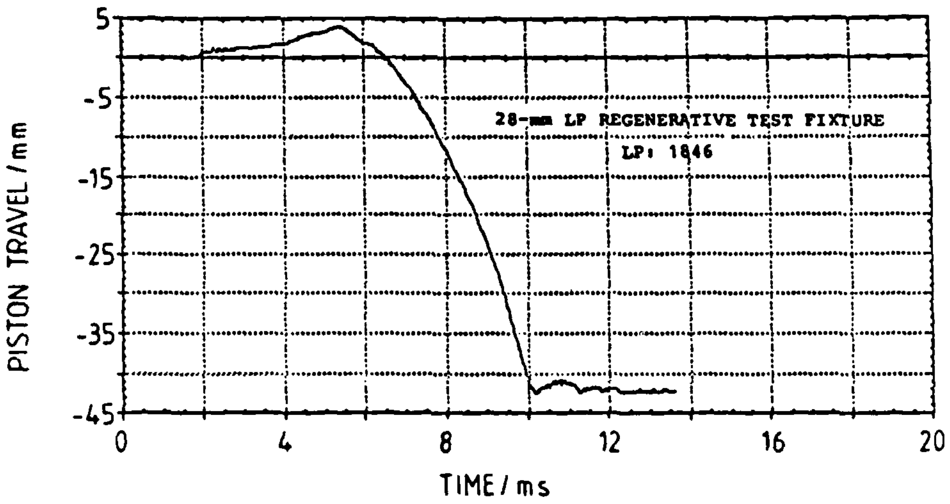

Figure 8. Example of Piston Reversal (LP 1846)

b. Temperature. The temperature was measured inside the gun chamber at M2 using the emission gage technique[5 6] described above. After injection, the combusting liquid monopropellant forms a dense, opaque mixture of droplets and gases so that blackbody condition can be assumed inside the combustion part of the gun chamber.[15] Also, the opaque mixture of the particle-laden flow, stemming from the discharge of the pyrotechnic igniter, yields a good estimate of gas temperature.[16 17] Therefore, the measured brightness temperature approaches the actual gas temperature, permitting an approach for estimating the temperature history in the chamber.

An illustration of the results of a test with a monopropellant mixture of 80% NM and 20% methanol and an injector orifice of 1.2 mm are shown in Figure 9. The temperature of the igniter gases, vented from the pyrotechnic igniter into the combustion part of the gun chamber, is much higher than than the temperature developed during the combustion of the liquid propellant.

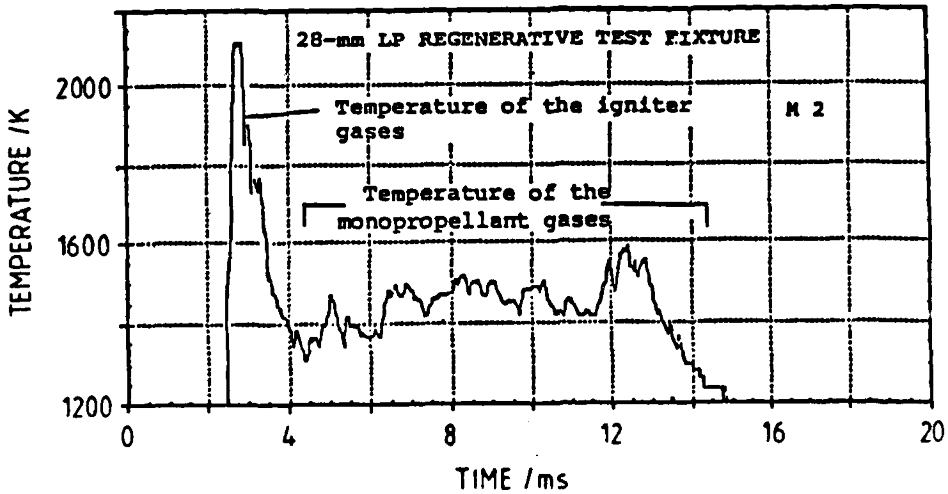

Figure 9. Chamber Temperature vs. Time (80% NM and 20% Methanol)

c. Pressure Oscillations: Severe pressure oscillations were encountered as the diameter of the injector orifices was increased from 1.2 mm to 2.0 mm and larger.[15] As an example, a test (No.45) using 80% NM and 20% Methanol is illustrated. For this test, the diameters of the injector orifices were 2.0 mm and the chamber volume was 20.4 cm^3. For the short barrel gun tube, the measured velocity at 1 m from the muzzle was 450 m/s. Figures 10 and 11, based on a data sampling rate of 2 microsec, show the pressures measured in the reservoir (M1) and in the chamber (M2). Figure 12 shows the differential pressure between the reservoir and chamber. Evidence of negative pressures as shown in this type of plot is a potential source of problems and may result in a flashback to the reservoir. The pressure oscillations start at $t > 3.5$ ms. For $t > 4.0$ ms the oscillations are quite severe and occur just when the projectile leaves the short barrel.

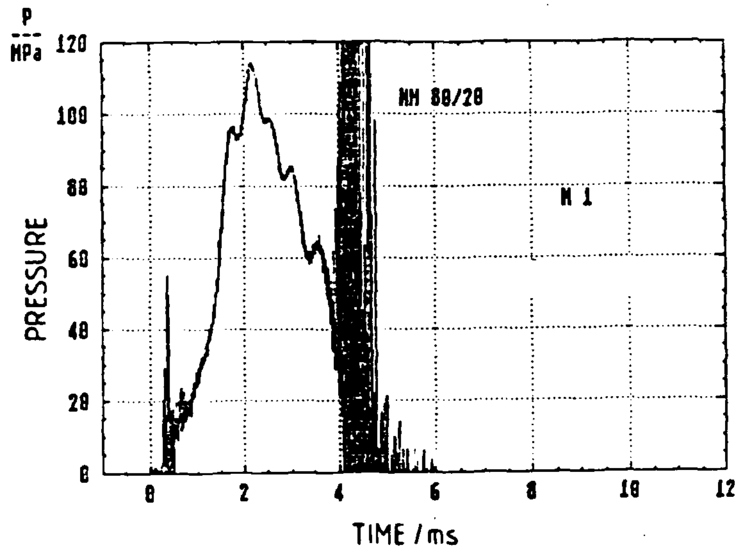

Figure 10. Reservoir Pressure (M1) vs. Time (Test No. 45).

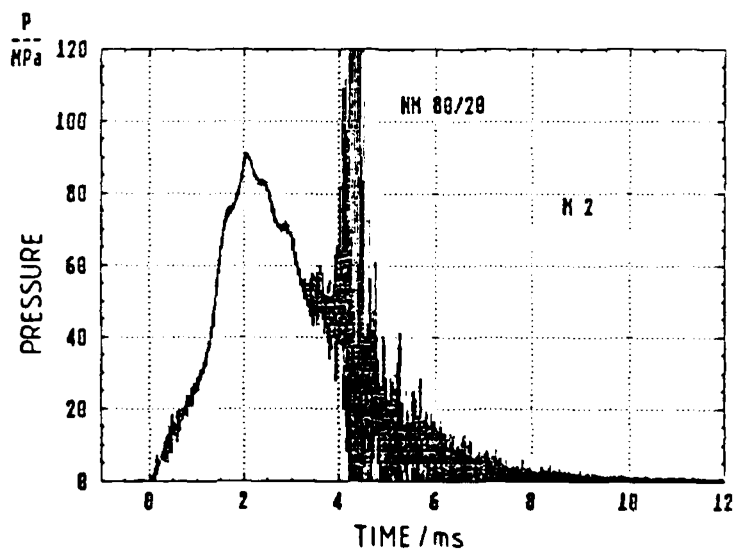

Figure 11. Chamber Pressure (M2) vs. Time (Test No. 45).

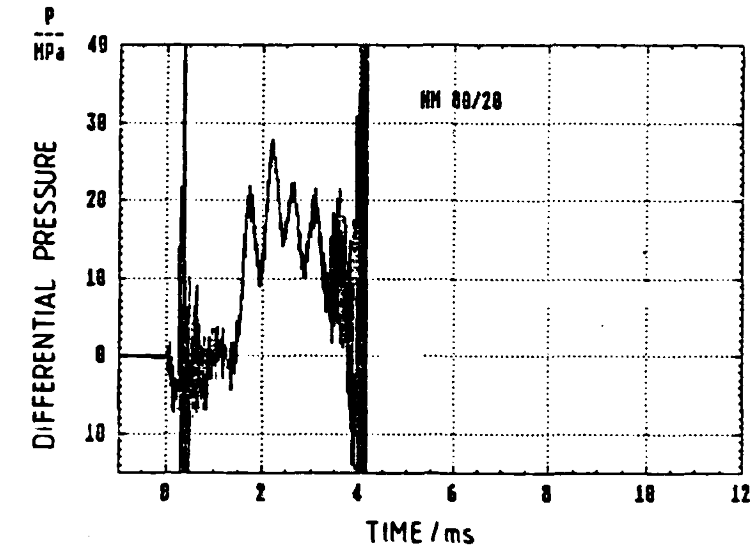

Figure 12. Differential Pressure between the Reservoir and Chamber vs. Time (Test No. 45).

The corresponding chamber temperature vs. time, for the same test shown in Figures 10 - 12, is given in Figure 13.

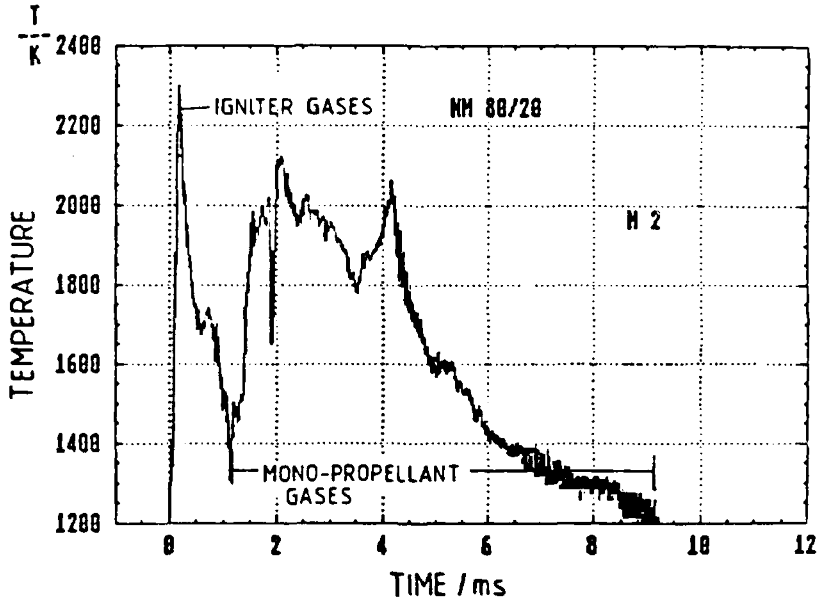

Figure 13. Chamber Temperature vs. Time (Test No. 45).

The piston and projectile travel curves for Test No. 45 are shown in Appendix A. Recording a complete set of data, as illustrated in Figures 10 - 13 and Appendix A, is important for proper model validation.

The chamber pressure record illustrated in Figure 11 was examined by passing the data through a low pass filter with a cut-off frequency of 10 kHz. The resulting data is shown in Figure 14 on an expanded time scale which show a rather smooth frequency between $3 < t < 4$ ms and again between $5 < t < 6$ ms. The larger amplitude frequencies occur after the projectile has left the gun and may therefore be associated

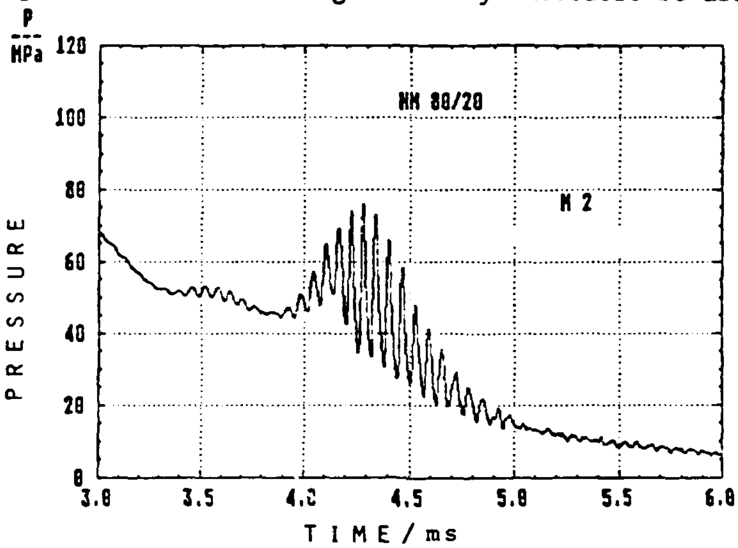

Figure 14. Pressure vs. Time on an Expanded Time Scale for Test No. 45 Using a Cut-off Frequency of 10 kHz.

with instabilities caused by the interaction between the injected propellant and an expansion wave due to the projectile displacement. The expansion wave travels upstream towards the combustion chamber as the projectile leaves the barrel.[15] The frequency with the smaller amplitudes may be due to acoustical modes.

The oscillations were further studied by increasing the injection orifice diameter to 2.5 mm. A test (No. 63) was performed with 80% NM and 20% Methanol. The resulting chamber pressure is shown in Figure 15. The volume of the combustion chamber for this test was 20.4 cm^3. A Fourier analysis of this record is shown in Figure 16. The two dominant peaks occur at 15-16 kHz and 130 kHz. The lower frequencies are assumed to be due to combustion instabilities, possibly triggered by the expansion wave. The higher frequency is the resonance frequency of the pressure gage.

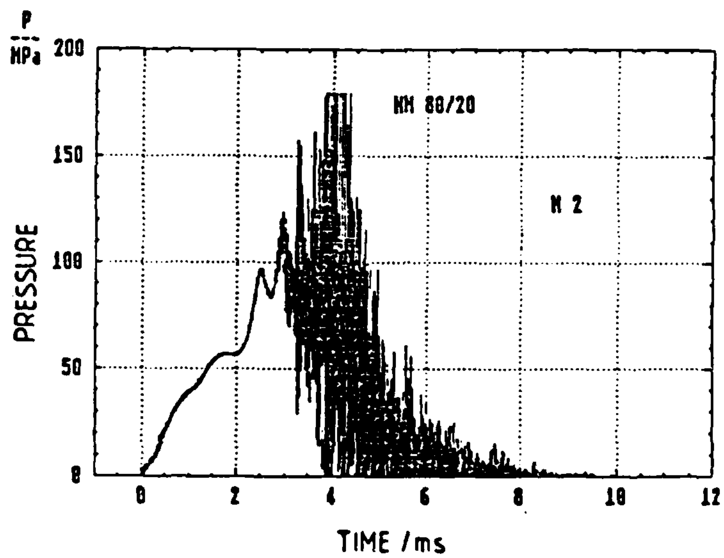

Figure 15. Chamber Pressure vs. Time, Test No. 63.

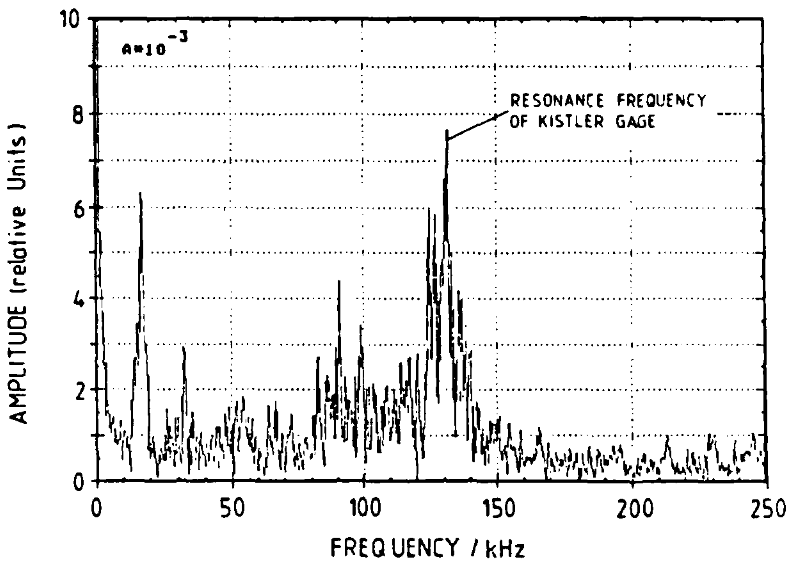

Figure 16. Fourier Analysis of Data Shown in Figure 15

d. Parametric Studies. Additional parametric studies were conducted at EMI-AFB. The parameters studied included the projectile engraving force and the chamber diameter. The results of these studies are given in Appendix B.

Parametric studies have also been performed in the US. The first group of parametric studies were investigated at the General Electric Co. and were reported by Morrison et al.[18] Parameters studied included the injection area, charge to mass ratio, and piston length. Importantly, these studies did not identify mechanisms which might lead to potential failure modes due to the development of uncontrolled high pressures.

4. 30-mm REGENERATIVE LIQUID PROPELLANT GUN

a. Reproducibility Groups: The 30-mm was tested using the HAN-based LPs NOS-365, 1845, and 1846. The results, all fired with a reduced charge and a relatively thin injection sheet, are summarized in Table 10. The velocity reproducibility of the tests with LP 1845 gives a variation in the standard deviation of 1.5%. If the apparent outlier (Ident. No. 364-046) is omitted, then the variation in the standard deviation becomes 0.80%. Furthermore, an inspection of the data suggests that the data may be divided into two groups with mean velocities of 1005 m/s and 1019 m/s. The respective variations in the standard deviation of the two groups without the outlier are 0.05% and 0.12%. The reason for such a grouping of the data has not been identified.

TABLE 10. Summary of Reproducibility Tests with the 30-mm, Concept VI (Igniter: 3.0g, IMR 4350, 2/3 LP charge tests).

Ident. No.	LP	Pressure* J120 MPa	C30 MPa	A90 MPa	LP MPa	Velocity m/s
364-032	1845	177	190	197	-	1020
364-033	1845	167	181	181	-	1005
364-034	1845	177	190	191	-	1005
364-035	1845	182	186	194	-	1020
364-C41	1845	171	189	192	227	1018
364-042	1845	182	181	195	202	1021
364-043	1845	166	177	184	-	1005
364-044	1845	-	-	-	-	1004
364-046	1845	169	178	186		973.5
mean	1845	174	184	190		1008
std dev/ mean		3.7	2.9	3.0		1.5
364-016	1846	190	195	209	-	1014
364-018	1846	184	184	190	285	1009
364-031	1846	213	205	231	-	1011
mean	1846	196	195	210	-	1011

*120 gage located 12mm forward of the initial position of the piston face and gages C30 and A90 gages located, respectively, 21 mm and 36 mm to the rear of the initial position of the piston face. The error in the pressure readings, especially for the gages in the C and A plane, may be as high as ± 10%.

b. Pressure Oscillations: The pressure data, somewhat similar to the results obtained with the 28 mm, were characterized by the presence of high frequency oscillations. An example from a test with LP 1845 is shown in Figure 17. Also shown in Figure 17 is the piston displacement data. The dominant frequencies occur around 34 to 35 kHz as illustrated in Figure 18 for a test with 1846. A frequency analysis plot of this same data shows, Figure 19, the existence of a frequency band between 32 to 42 kHz. In general, there were no significant differences in the frequencies when tested with either LP 1845 or LP 1846. The presence of a frequency in the 34 to 35 kHz range suggest the excitation of a second radial mode or a combined second radial and first tangential mode type of instability. The calculated frequency for the second radial mode is between 32.2 kHz and 42.1 kHz and the calculated frequency for the combined second radial and first tangential mode is between 32.6 kHz and 42.4 kHz for a spread in sound speed between 701 and 913 m/s.

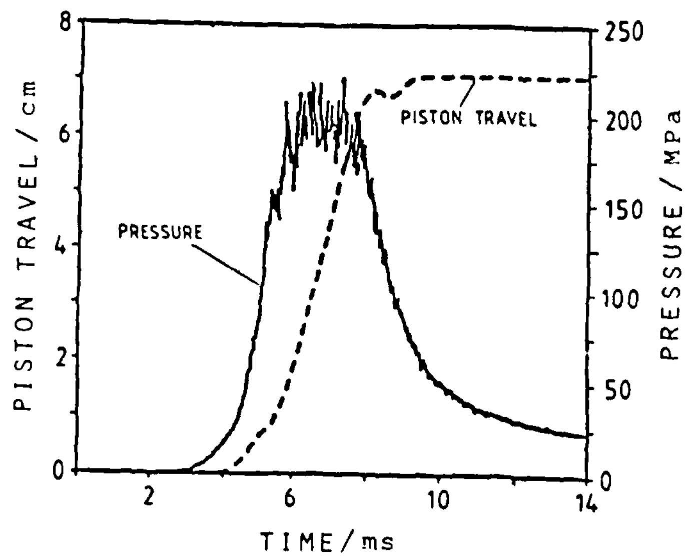

Figure 17. Pressure and Piston Displacement vs. Time.

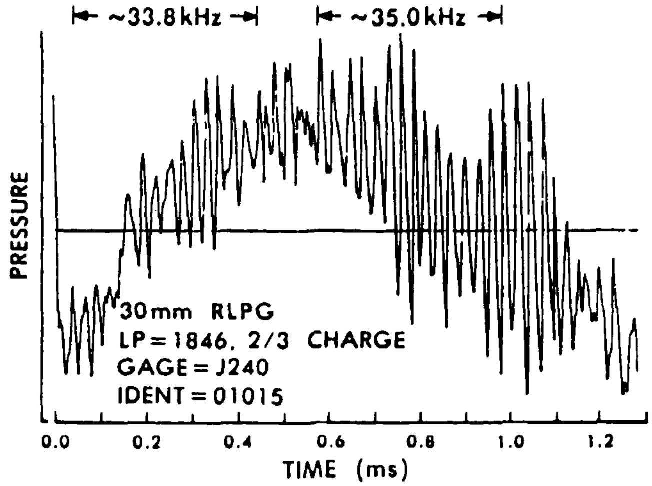

Figure 18. Example of Pressure vs. Time on an Expanded Time Scale (Digitized at 400 kHz).

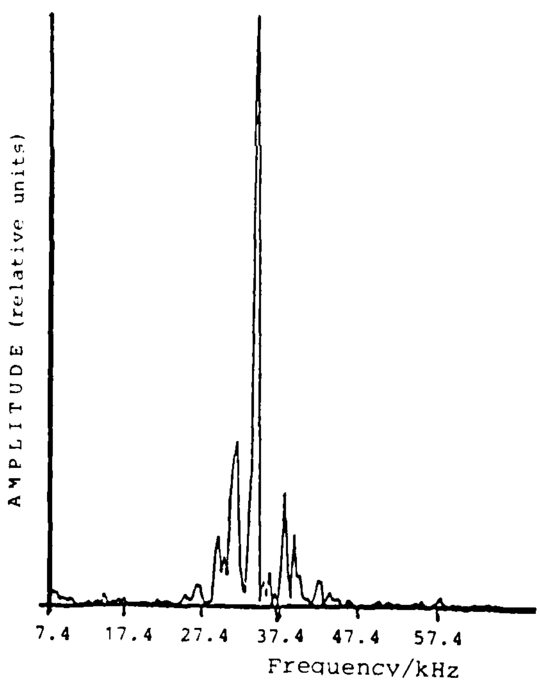

Figure 19. Frequency Analysis of the Data Illustrated in Figure 18.

Some tests, interestingly, resulted in exciting many more frequencies. The reason for the different frequency content may be associated with the orientation of the crash ring shown in Figure 4.

The origin of the oscillations are believed to be related to combustion noise, which excites various acoustical modes in the chamber.

The amplitude of the pressure oscillations was about 12% of the maximum pressure in the forward section of the chamber and about 20% toward the rear of the chamber. The oscillations started around 90 MPa.

c. Performance Comparison Between 1845 and 1846: The mean velocity between the eight tests with 1845 (omitting the apparent outlier) and the three tests with 1846 are, respectively, 1012 m/s and 1011/ms. This close agreement is rather surprising in view of the differences in the impetus (or the chemical energy defined as impetus divided by gamma minus one) between the two propellants (Table 2). The impetuses for 1845 and 1846 are, respectively, 934 and 898 J/g. Despite the 4% difference in impetus, the test firings yielded approximately the same performance.

d. Comparison with NOS-365: Two tests with NOS-365 were conducted. The fuel component of NOS-365 is isopropylammonium nitrate. Closed chamber tests with this propellant revealed a gradual release of energy followed by a sharp pressure transition.[19] The slow release of energy occurring at low pressures is believed to be associated with the formation of relatively stable intermediate reaction products. This initial slow release of energy in a closed chamber contrasts with similar tests with 1845 and 1846 which revealed a more gradual rate of pressure change.

The two tests with NOS-365 fired in the 30-mm RLPG used the same igniter as used with the tests with 1845 and 1846. Interestingly these tests yielded an excessively slow pressure increase in one test and in the second test there was a hang fire. Importantly, the two tests with NOS-365 show that the igniter output characteristics are not as well optimized for NOS-365 when compared with 1845 and 1846.

e. Combustion Chamber Temperature for a 30-mm RLPG Test with 1845: The plot of the brightness temperature for a test with 1845 is shown in Figure 20. The maximum temperature during the combustion of the LP is about 2300 K, or about 90% of the theoretical flame temperature (Table 2). The temperature time data reveals some structure, but generally have significantly lower frequency content when compared with the pressure data. This is not surprising since the emission gage responds to the integrated radiation from a wide field of view, unlike the pressure gage which responds to the sum of the localized pressure waves incident on the gage.

IV. SUMMARY AND CONCLUSIONS

The present study has shown that the ignitability of the five different monopropellants varies substantially. The HAN-based monopropellants have a much lower ignition level than the nitromethane and isopropylnitrate monopropellants. However, the ignitability

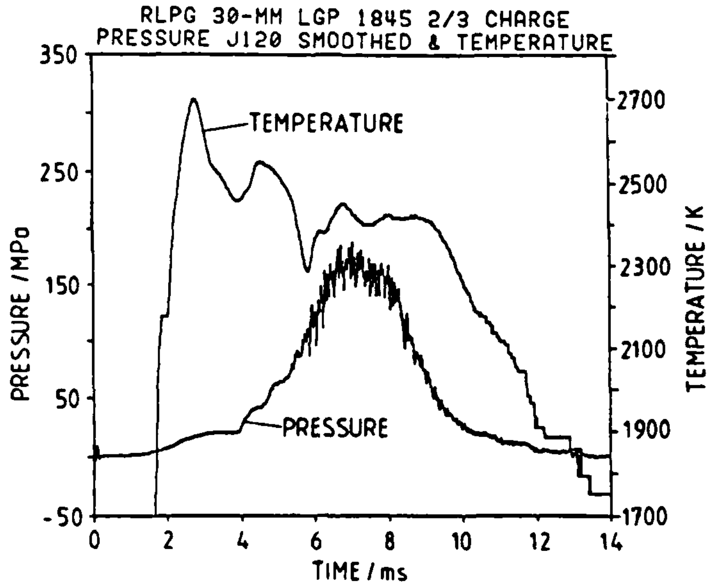

Figure 20. 30-mm RLPG Test Showing Temperature and Pressure vs. Time (LP 1845).

studies can only provide the initial guidelines in the design of an igniter for a regenerative gun fixture. The ignitability studies revealed little or no difference in the energy required to ignite NOS-365 and LPG 1845 and 1846. The 30-mm tests, however, suggested that a more energetic igniter would be required when testing with NOS-365.

The nitromethane ignitability tests showed that significantly more energy, when compared with the HAN-based monopropellants, may be necessary to achieve sustained combustion when tested in a regenerative gun fixture. Aside from possible design implications, an igniter requiring a high energy output is not necessarily undesirable. If the igniter generates a high gas pressure, then the piston should be displaced sufficiently early in the ignition phase to avoid the potential problem of flash back through the injection orifice. On the other hand, an igniter with a lower energy output, such as the igniter used for the ignition of HAN-based monopropellant, typically generates gas pressures of 15 to 20 MPa, sufficient to displace the piston and to start the regenerative process.

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APPENDIX A.

Piston and Projectile Displacement Data for Test No. 45, 28-mm RLPG.

Figure A1 shows the measured piston travel vs. time. Piston moves 63 mm during 0_< t_< 12 ms.

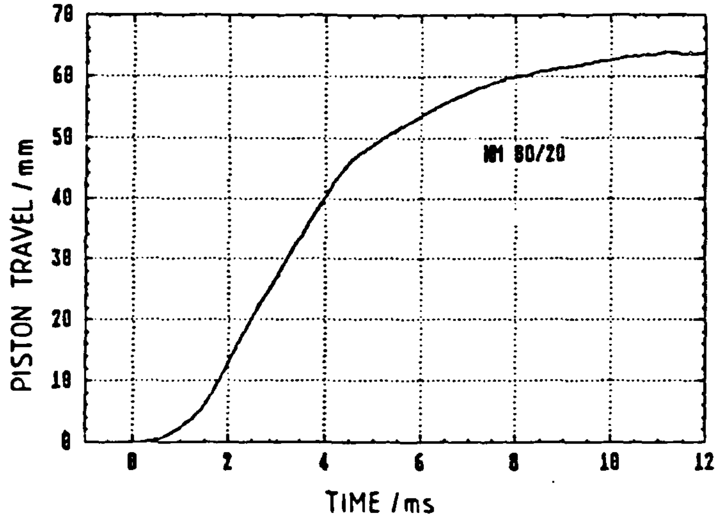

Figure A1. Piston Displacement vs. Time (Test No. 45).

Figure A2 shows the measured projectile velocity vs. time.

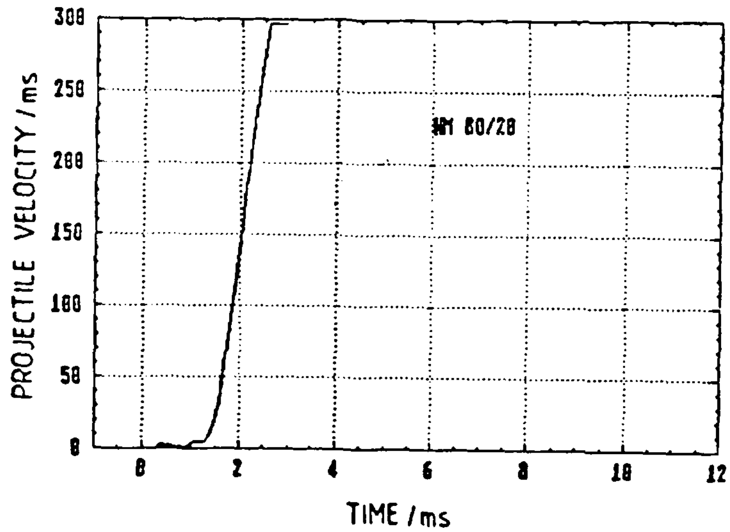

Figure A2. In-bore Projectile Velocity vs. Time (Test No. 45).

APPENDIX B

Parametric Studies, 28-mm RLPG.

The effect of variations of the engraving force of the projectile is summarized in Table B1. In order to obtain different engraving forces, the shape and material of the projectile was altered. The projectile is shown in Figure B1.

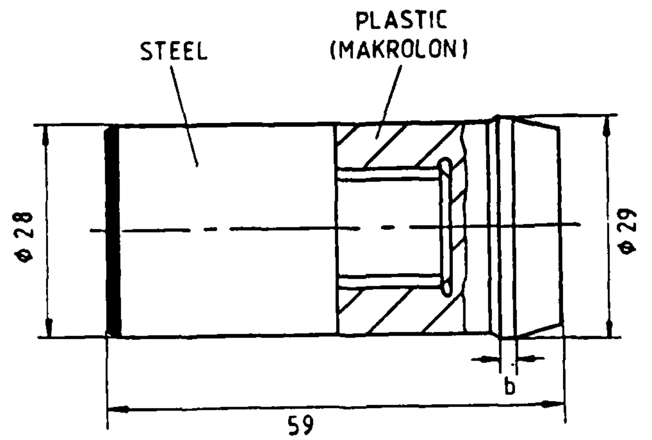

Figure B1. Projectile Used in the 28-mm RLPG.

The first group of tests were performed using plastic (Makrolon) on the base of the projectile.[15] For some tests the plastic was reinforced with glass fibers. Higher engraving forces were obtained by using aluminum and two different widths "b" of the projectile band. The engraving force was determined statically by pushing the projectile slowly into the gun tube and measuring the applied force. For a given injector diameter, the data suggests that higher velocities are obtained as the engraving force of the projectile increases.

Other parameters that were varied were the diameter of the injector orifice and the chamber volume. The results are summarized in Table B2. The influence of the injector orifice is illustrated in Figure B2 which shows the increase in maximum pressure in the combustion chamber when the diameter of the injector orifice increases from 1.2 mm to 3.0 mm. The maximum chamber pressure increases with increasing LP mass injected per unit time into the gun chamber.

TABLE B1. Influence of Engraving Forces Using Different Materials for the Base of the Projectile.

Test	Material	Engraving Force	Proj Mass	Injector Orifice	Pressure maximum M1	Pressure maximum M2	Velocity
		kN	g	mm	MPa	MPa	m/s
47	Makrolon, with glass fiber	18	180	2.5	110	102	506
51	Aluminum, AlMgSi, 0.5	28*	199	2.5	108	110	495
50	Makrolon, no glass fiber	14	177	3.0	32	37	235
33	Makrolon, with glass fiber	18	180	3.0	172	140	569
52	Aluminum AlMgSi 0.5	40**	199	3.0	140	150	601

Igniter. 2.8 g Black Powder.
Volume of Combustion Chamber = 20.4 cm^3.
M1: Gage located in Reservoir. M2: Gage located in Chamber.
* b = 1.0 mm. ** b = 1.7 mm.
Velocity measured at 1 m from muzzle.

TABLE B2. Results of Test Firings with the 28-mm Fixture.

Injector Orifice	Volume of Combustion Chamber	Injected Volume	Piston Travel at Proj Launch	Pressure maximum M1	Pressure maximum M2	Temp	Velocity
mm	cm	cm	mm	MPa	MPa	K	m/s
1.2	20.4	7.607	10	74	53	1850	282
	43.3	-	-	42	34	1870	232
2.0	20.4	23.587	31	100	84	2065	431
	43.3	-	-	87	74	2050	423
2.5	20.4	34.991	46	113	108	2095	506
	43.3	-	-	90	100	2170	489
3.0	20.4	54.768	72	172	140	-	564
	43.3	-	-	-	-	-	-

Igniter: 2.8 g Black Powder.
Projectile Engraving Force: 18 kN.
M1 and M2 and Velocity described in Table B1.

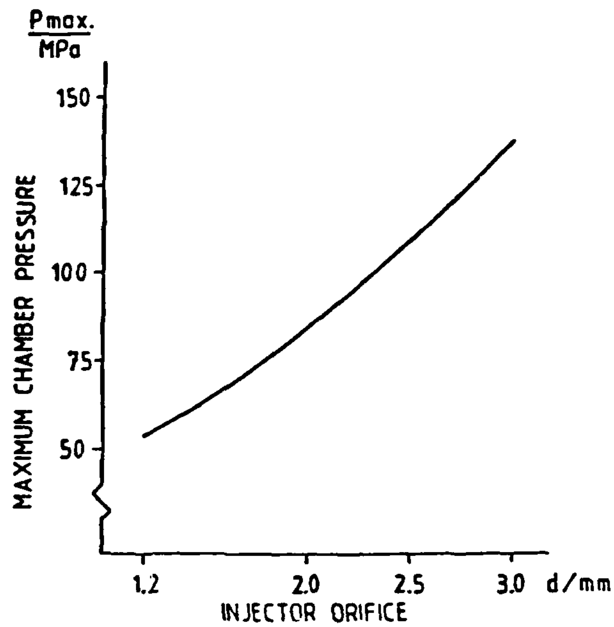

Figure B2. Maximum Chamber Pressure vs. Diameter of Injector Orifice.

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