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Investigation of Ignition of Liquid Propellant in Reservoir in Regenerative Liquid Propellant Gun Trials

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ABSTRACT

It is important to understand the internal ballistic processes for the development of regenerative liquid propellant guns (RLPGs). A 30 mm RLPG test fixture was developed and firing trials were conducted to study the performance of the gun. During the trials, sometimes, combustion ignition in the reservoir took place resulting in substantial damage to the injection piston. This paper highlights the possible causes of this combustion and offers suggestions regarding improvement in the design. An elaborate instrumentation set-up which could pinpoint the specific conditions leading to failures is suggested.

NOMENCLATURE

$P_{bub}(t)$	Pressure of bubble at time t
$P_{bub}(t-\tau)$	Pressure of bubble at earlier time
$P_r(t)$	Pressure in reservoir at time t
$T_{bub}(t)$	Temperature of bubble at time t
$T_{bub}(t-\tau)$	Temperature of bubble at earlier time
$U_{lp}(t)$	Volume of liquid propellant at time t
$U_a(t)$	Volume of air entrained in liquid at time t
$U_{lp}(t) + U_a(t)$	Total volume of reservoir at time t
$\beta_{eff}(t)$	Effective bulk modulus at time t
$\beta_a(t)$	Bulk modulus of air at time t
	Bulk modulus of liquid at time t
	Ratio of specific heat of gases in bubble
	Time delay between liquid propellant injection and combustion.

1. INTRODUCTION

Extensive research is being carried out in several countries on liquid propellant guns, including 30, 105 and 155 mm caliber guns with the aim of developing an artillery weapon[1-4]. Liquid propellant guns offer a variety of advantages over the conventional solid propellant guns, viz., caseless and insensitive ammunition, simpler logistics, cheaper propellant, and multiple round and simultaneous impact (MRSI) capability. A couple of accidents with the liquid propellant during the loading process have been reported in literature[5]. These failures were attributed to the increase in temperature of air bubble during compression. These bubbles are inadvertantly introduced into the liquid propellant during the loading process. In addition, oscillations in the reservoir due to turbulence in the vent which cause a flashover, have also been reported[6].

Development of a 30 mm regenerative liquid propellant gun (RLPG) test fixture with a simple in-line piston was taken up with the aim of understanding ignition, injection and combustion processes in liquid propellant gun as a ground work for the futuristic gun. Initial pressurisation of the

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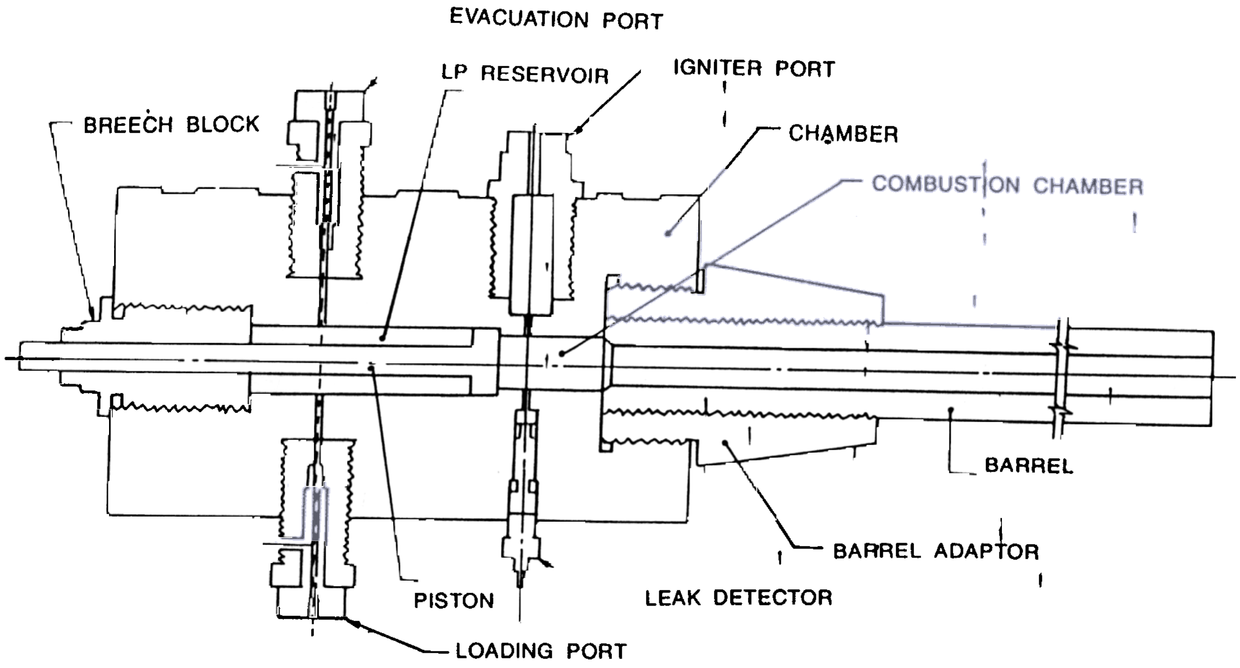

Figure 1. Experimental set-up of regenerative liquid propellant gun fixture

combustion chamber was done with a pyrotechnic igniter. This allowed the piston to move rearward, causing the liquid propellant in the reservoir to be pressurised. Once the reservoir pressure increases above the chamber pressure, injection of the liquid propellant into the chamber starts. The injected liquid propellant combusts in the combustion chamber, increasing the chamber pressure, which in turn sustains the injection. The difference in area between the reservoir and chamber side of the piston ensures that even when the reservoir pressure is more, the piston can move rearward causing further injection of the liquid propellant. The chamber pressure also causes the projectile to move forward.

2. EXPERIMENTAL DETAILS

The test fixture consisting of a 50 mm diameter reservoir and a 40 mm diameter combustion chamber separated by a simple in-line piston was designed and developed (Fig. 1). The fixture incorporates two ports each for chamber, reservoir and barrel pressure, liquid propellant loading and evacuation, and one port for housing an igniter. The pressure ports are offset at right angles to the loading ports; hence they are not visible in the figure. A 30 mm smooth bore barrel of 1 m length was fixed to the front of the chamber. Projectiles used were aluminium slugs with an embedded steel bolt having a total weight of about 360 g. Gravity loading of the liquid propellant was done and efforts were made to keep the ullage minimum. A pyrotechnic igniter (primer 1A electric modified) was used to initiate regenerative injection and combustion of the liquid propellant. A 5.5 g liquid propellant bag was kept in the combustion chamber to enhance the pressure. The reservoir was filled with 100 ml of LP1846 (HAN:60.8 %, TEAN: 19.2 %, Water :20 %). The initial volume of the combustion chamber was about 200 cc. Pressure measurements were conducted with the help of piezoelectric pressure transducers and data acquisition was done on digital storage oscilloscopes.

3. OBSERVATIONS

Figures 2 and 4 show the reservoir and chamber pressures in two trials, where the initiation of liquid propellant in the reservoir took place. Figures 3

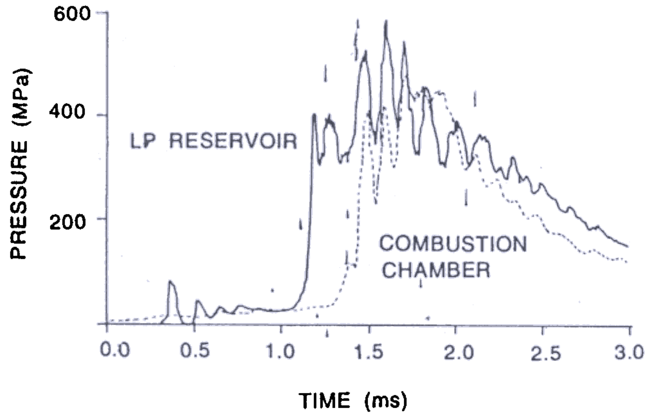

Figure 2. Pressure-time curve of chamber and reservoir-trial 1

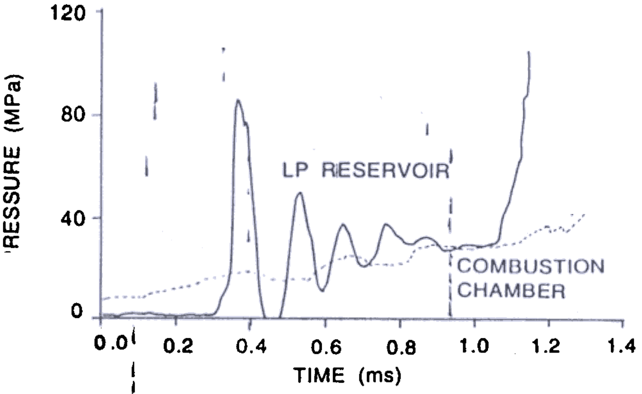

Figure 3. Expanded view of early portion of pressure-time curve of chamber and reservoir-trial 1.

and 5 show the same curves with the early portion of the pressure curve expanded in time and amplitude. The changes in dimensions of the piston shaft starting from the base of the piston head are shown in Tables 1 & 2 for trials 1 & 2, respectively. In one of the trials, where a threaded piston shaft was used, it was observed that due to this narrowing of the shaft, there was a separation from the piston head.

3.1 Trial 1

In trial 1, a sudden rise in reservoir pressure was observed at about 1.3 ms to over 500 MPa . At this time, pressure in the chamber was around 30 MPa, indicating a clear case of initiation in the reservoir. Subsequent rise in chamber pressure (around 1.9 ms) could be attributed to the gases in the reservoir entering through the vents to reach the

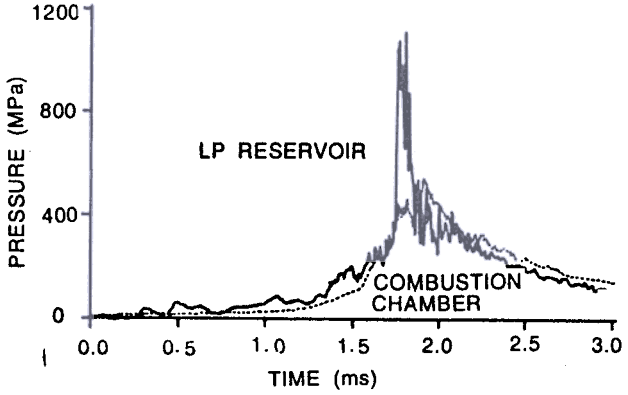

Figure 4. Pressure-time curve of chamber and reservoir-trial 2.

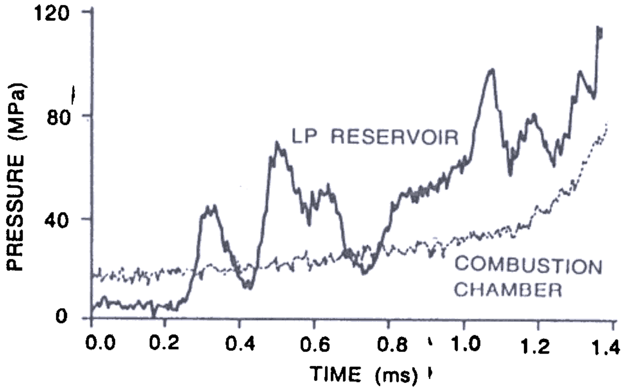

Figure 5. Expanded view of early portion of pressure-time curve of chamber and reservoir-trial 2.

Table 1. Changes in dimensions of the piston after trial 1

Distance from shaft base (mm)	Original Diameter (mm)	Final Diameter (mm)
1.5	20	20.00
5.0	20	19.50
10.0	20	19.00
15.0	20	18.00
20.0	20	18.30
25.0	20	19.20
30.0	20	19.50
35.0	20	19.50
40.0	20	19.70
50.0	20	19.70
60.0	20	19.85
70.0	20	19.90
80.0	20	20.00
100.0	20	20.00

Table 2. Changes in dimensions of the piston after trial 2

Distance from shaft base (mm)	Original diameter (mm)	Final diameter (mm)
1.5	20	19.65
5.0	20	18.60
10.0	20	18.10
15.0	20	17.30
20.0	20	17.80
25.0	20	18.20
30.0	20	18.50
35.0	20	18.70
40.0	20	19.05
50 .0	20	18.55
60.0	20	18.75
70.0	20	19.25
80.0	20	20.00
100.0	20	20.00

combustion chamber. It is seen from Fig. 3, where the early portion of Fig. 1 is expanded in both amplitude and time, that there were oscillations in the reservoir pressure curve with the reservoir pressure becoming less than the chamber pressure in some regions of the curve.

3.2 Trial 2

In trial 2, the reservoir and chamber pressures were now observed to closely follow each other up to 1.75 ms, indicating proper injection. At about 1.75 ms, there was a sudden rise in the reservoir pressure to over 900 MPa. This is the case where the injection could be considered to have taken place for some time and initiation in reservoir at 1.75 ms. Subsequently, there was a sudden rise in chamber pressure at 1.9 ms, which could be attributed to the gases in the reservoir escaping from vents to reach the chamber. It is seen from Fig. 4 where the early portion of Fig. 3 is expanded in both amplitude and time, that there were oscillations in the reservoir pressure curve. In this case, however, the oscillations are of less amplitude and the excursions in reservoir pressure below the chamber pressure are also less.

The above phenomena observed in several firings could be attributed to the ignition of the liquid propellant in the reservoir. This resulted in the liquid propellant combusting in the bulk mode in the reservoir contributing to large overpressure. The regenerative piston, instead of travelling rearward, stayed in front and damage to the front portion of the piston shaft was noticed with change in dimensions. This change in dimensions probably took place due to overpressures in the reservoir.

4. POSSIBLE CAUSES OF IGNITION

(a) If for some reason, smooth movement of the piston is arrested and pressurisation of the liquid propellant is stopped, it is a matter of time before the chamber pressure causes flashover into the reservoir.

(b) Adiabatic heating of the ullage as it gets compressed may cause the ignition[5].

(c) The ullage in the reservoir may give rise to pressure oscillations. The reason for this is that as the liquid gets compressed, the effective bulk modulus of the liquid and the gas combination changes. This oscillation could cause the pressure in the reservoir to fall below the level of the chamber, resulting in a flashover and ignition of the liquid propellant in the reservoir.

(d) Pressure measurements are taken at ports at a substantial distance from the nozzles. The actual pressure near the vent which can also promote flashover may be higher[6].

(e) A sharp orifice at the exit of the vent may give rise to local vortices that can drive flame front in the reservoir[6].

Observations of the chamber indicated that there was some damage to the reservoir in the front portion and jamming of the piston. To overcome this problem, the piston was withdrawn slightly, so that the damaged portion of the chamber was avoided and free motion of the piston was assured. Even after this, there was ignition and combustion of the liquid propellant in the reservoir probably due to any of the causes specified at (b) to (e) above or some combination of those.

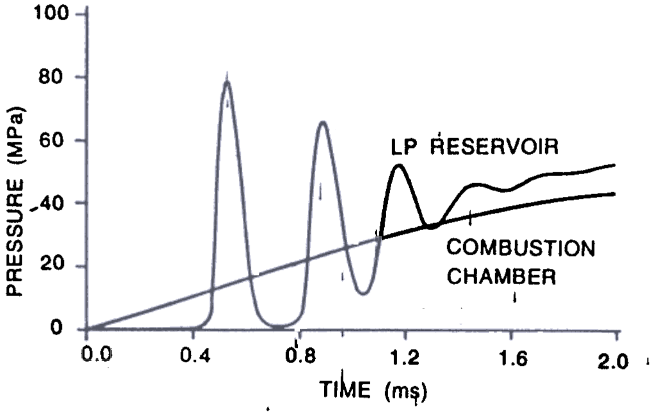

Figure 6. Theoretically estimated early portion of pressure-time curve of chamber and reservoir with 1 per cent ullage.

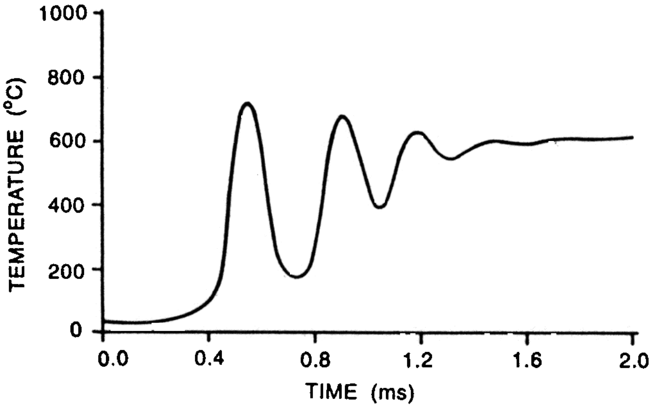

Figure 7. Theoretically estimated early portion of temperature of bubble in reservoir with 1 per cent ullage.

5. THEORETICAL ESTIMATES OF TEMPERATURE & PRESSURE

A model[7] was used to simulate the liquid propellant gun performance to theoretically ascertain if either cause (b) or cause (c) was responsible. The bulk modulus of the liquid propellant in the reservoir changes drastically with pressure and can be given as[5]

$$\beta_{lp}(t) = A + B\,P_r(t) \tag{1}$$

A and B are user input parameters which need to be estimated experimentally. As experimental data were not available, the reported data[8] were used. The model[7] was modified to incorporate the ullage. Ullage results in a varying bulk modulus because of greater compressibility of air. For effective bulk modulus, the standard formula of hydraulic fluids with air entrainment is used[9].

$$\frac{1}{\beta_{eff}(t)} = \frac{U_a(t)}{U_a(t) + U_{lp}(t)}\,\frac{1}{\beta_a} + \frac{U_a(t)}{U_a(t) + U_{lp}(t)}\,\frac{1}{\beta_{lp}(t)} \tag{2}$$

The bulk modulus of the liquid propellant is given by Eqn 1 and that of air is given by $\nu_{bub} P_{bub}(t)$. As the pressure of the reservoir increases, the air gets compressed. The compression is assumed to be adiabatic and follows the equation:

$$P_{bub}(t)\; U_a(t)^{\nu_{bub}} = \text{constant} \tag{3}$$

The temperature of the bubble can be estimated as[5]

$$T_{bub}(t) = \left[P_{bub}(t)/P_{bub}(t-\tau)\right]^{(\nu_{bub}-1)/\nu_{bub}} * \; T_{bub}(t-\tau) \tag{4}$$

After incorporating the above modifications, simulation was done for various values of ullage and the *P-T* curve and temperature profile of the bubble were observed. Figure 6 shows an expanded view of the early portion of the theoretically expected pressure profiles in the chamber and reservoir for 1 per cent ullage. It is seen that the reservoir shows pressure oscillations similar to those in the experimental curves. The excursion of the reservoir pressure below the chamber pressure could be the region where flashover takes place. The simulation temperature curves in the early portion of the firing cycle with 1 per cent ullage are shown in Fig. 7. It is observed that with 1 per cent ullage, temperature can go up to 700 °C, which is enough to ignite the liquid propellant. With higher ullage, the modeling indicates a higher temperature. It is seen that the frequency of the oscillations does not match with the experimental curve. This deviation in frequency may be due to the wrong bulk modulus of the liquid used. A more accurate value of bulk modulus experimentally determined may give a more accurate result.

6. DEDUCTIONS & SUGGESTIONS FOR FUTURE WORK

The experimental results supported by theoretical work suggest that causes (b) or (c) could be responsible for combustion ignition of liquid propellant in the reservoir. At present, a theoretical model for checking if cause (d) or cause (e) could be responsible for the failure is not available. Future work needs to be directed towards pinpointing and isolating the causes of failure. The present lumped parameter model could be replaced by a two-dimensional model to get insight into the causes of pressure variations and turbulence in the combustion chamber. Basic experiments in the form of injection studies also need be done to obtain data on droplet formation and combustion. It is evident from Section 5 that ullage could be the major cause of the ignition of liquid propellant in the reservoir. Proper measurement of ullage and loading with minimum ullage will give more insight into the causes (b) and (c). Consideration may also be given to the replacement of simple in-line piston concept with an annular piston for ullage-free loading[5]. Pre-pressurising the liquid, which decreases ullage, could also be considered. The number of pressure measurement ports will also have to be increased to see at which point the combustion ignition in the reservoir starts. If failure is due to flashover, it will start near the piston head. If it is due to pressurisation and temperature increase in the bubble, it will start anywhere in the reservoir volume. Displacement and acceleration of the injection piston should also be monitored accurately by appropriate techniques. Pinpointing the cause of failure is necessary for making further progress in the field.

7. CONCLUSIONS

In the present work, the major problems that the liquid propellant gun designers are likely to face have been identified. The work further indicates that minimisation of ullage and appropriate pre-pressurisation will reduce the chance of combustion ignition. The effort highlights how proper instrumentation set-up and initiation of injection studies are essential to analyse the problems encountered. Possible remedies are also suggested.

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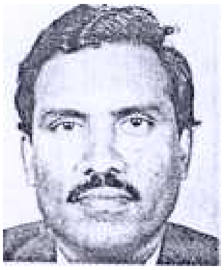

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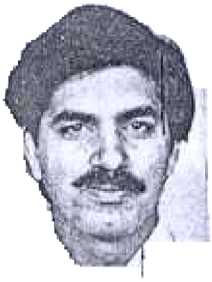

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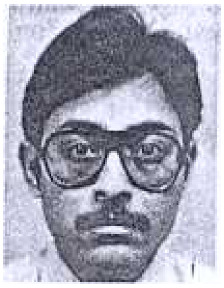

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