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TECHNICAL REPORT BRL-TR-2843

REGENERATIVE ELECTRICAL  
IGNITER FOR A LIQUID  
PROPELLANT GUN

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AUGUST 1987

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<p>A novel igniter for a regenerative liquid propellant gun (RLPG) is described, which utilizes only the liquid gun propellant (LGP). The liquid which is sealed in the igniter is ignited by an arc discharge causing a rise in pressure. At a predetermined pressure the igniter opens and gas products and unreacted liquid are injected to mix and react externally. The liquid jet derives its injection pressure hydraulically from the constantly generated internal gas pressure. The igniter is self-regulating to operate below a certain internal pressure. Two exploratory configurations of the injector were used, both containing 4.5 cc of LGP 1845 or LGP 1846. The injectors were fired into open air as well as into a 500 cc windowed closed chamber (simulating a gun chamber). Their discharge was photographed and the pressure rise in the chamber was measured. The LGP was electrically ignited using less than 50 J, and with as little as 300 V on the electrodes.</p>					
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19. ABSTRACT (Con't)

Three electrode configurations were tested. Successful operations of the injectors were achieved with opening pressures above 18 MPa resulting in complete injection of the LGP and products in less than 6 msec. In tests when the LGP burnt to completion, the pressure rise in the combustion chamber was rather steep, ranging from tens to hundreds of MPa per msec. Although the igniters need much refinement to reach true practicality, they are nevertheless deemed highly promising.

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## I. INTRODUCTION

### 1. BACKGROUND

Despite recent progress toward a practical large caliber RLPG, igniter development for the gun is still in its infancy. Only solid propellant gas generators have been used effectively as igniters for the RLPG in small and medium caliber guns and are expected to perform as well in large calibers. Various igniter concepts, which are not based on solid propellants, have been suggested<sup>1</sup> but none has yet reached maturity. From the logistical point of view, the ideal igniter would be based solely on the LGP itself. However, considering the requirements for an igniter, the development of such an igniter is not an easy task. An igniter has to provide about 18 MPa pressure in the RLPG combustion chamber in about 5 msec. For a large caliber gun (having a 5000 cc combustion chamber) an LGP charge in excess of 200 g is required. A practical method to ignite and burn rapidly in a controlled manner such charges is the subject of this paper.

### 2. IGNITER CONCEPTS

Two basic approaches for combusting a large mass of LGP in a short duration are plausible. In the first, the LGP is ignited to combust in a bulk loaded external chamber. A vent can then be opened to discharge the gas into the RLPG combustion chamber. In the second approach, the LGP is introduced directly into the gun chamber and is ignited there. Both approaches have drawbacks and neither has been successfully proven.

Concerning the ignition of the LGP, it is rather straight forward in the first approach. Electrical ignition of bulk loaded LGP's have long been demonstrated.<sup>2-5</sup> It is best accomplished by arc discharge and involves energy deposition of tens of joules (an easy task). However, controlling the combustion, and the timely venting of the hot gas, strain the practicality of the approach. The risk is that the combustion may proceed too rapidly to extreme pressures resulting in the mechanical failure of the igniter. An operation with an externally loaded igniter has been recently demonstrated by DeSpirito et al.<sup>5</sup> but it involved only 2 cc of LGP 1846 and a 1.6 mm vent

orifice permanently open. Such an igniter is not practical in a large caliber weapon for two reasons. Firstly, since the LGP is not sealed, it can leak prior to firing; and, secondly, large masses of LGP would require much larger vents. Successful ignition to a complete combustion of bulk loaded LGP having a large permanent vent is very difficult to achieve with reasonable electrical energy.

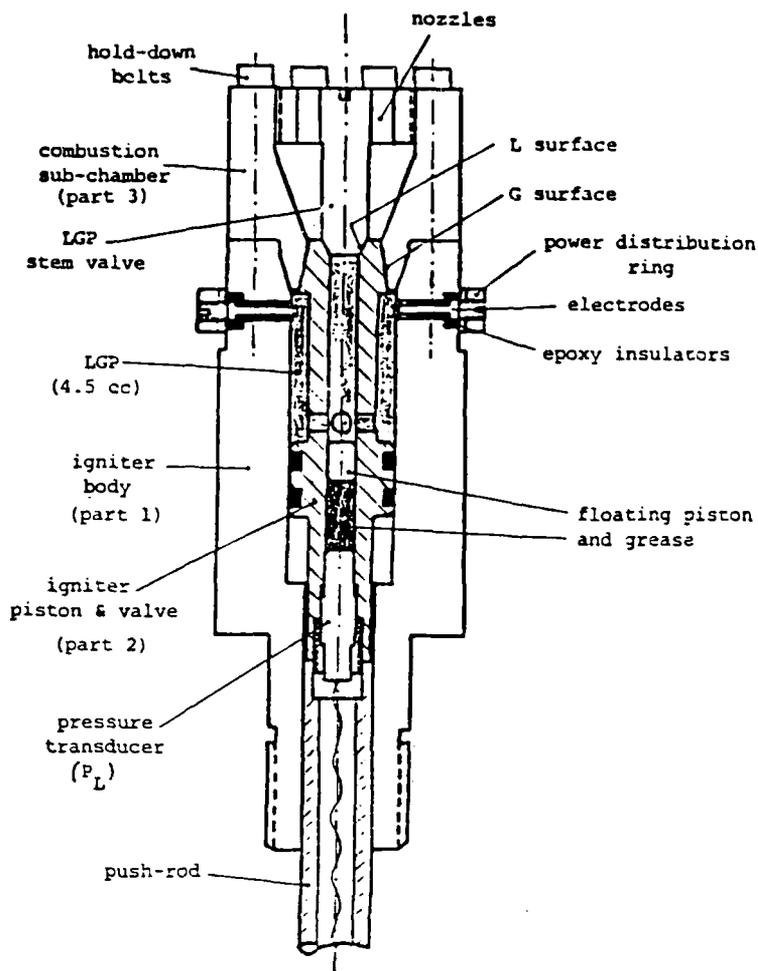
The second approach does not require operation at very high pressures but its practicality is also questionable. A large mass of LGP has to be injected rapidly into the gun chamber in the form of a fine spray. This is essential, since the atmospheric pressure ignition of low loading density LGP is very difficult. Only a fine uniformly distributed spray may be ignited, possibly by a stream of hot gas. The prompt atomization of the LGP in the low density chamber gas environment can be practically obtained by blasting the LGP with high velocity gas (which is the principle of air blast atomizers), perhaps with hot gas which would also serve to ignite the LGP. Thus, the approach is based on the availability of auxiliary high pressure and temperature gas, which is an undesirable system complication.

A third approach, discussed in the paper, is a synergistic hybrid of the first two approaches and it is considered practical. The LGP is sealed in the igniter and is ignited there electrically. Thereafter, no auxiliary gas supply is required for the igniter's operation. An exploratory igniter, called "Regenerative Electrical Igniter", has been constructed and operated to demonstrate the viability of the approach. Successful operation has been achieved with 6 g of LGP and it is believed that the igniter can be scaled to work with over 200 g.

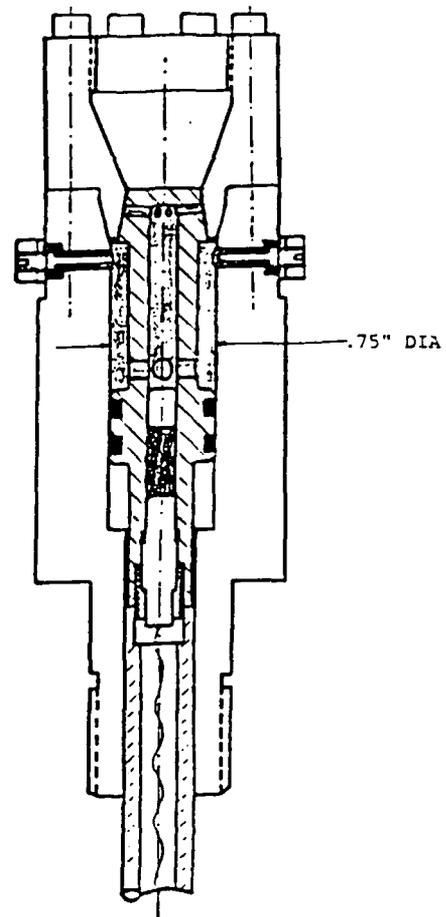
## II. EXPERIMENTAL

### 1. IGNITER DESIGN

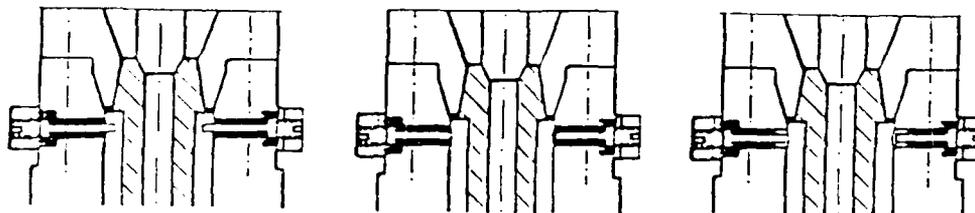
The igniter assembly is shown in Figure 1. Two igniter concepts and three electrode configurations were tried. Being exploratory in nature, the igniters were rudimentarily constructed to fit into existing hardware. Each



a. Igniter Concept 1



b. Igniter Concept 2



Configuration A

Configuration B

Configuration C

c. Electrode Configurations

Figure 1. Igniter Assemblies

igniter consists of three major parts: the igniter body (part 1), the igniter piston and valve (part 2), and the combustion sub-chamber (part 3). In concept 2, the last part is degenerate. LGP is sealed between the first two parts avoiding any ullage. In concept 1, there are two sealing conical surfaces (metal to metal), designated "L surface" and "G surface". In concept 2, only the G surface exists. The G surface is between part 2 and part 1. The L surface is between part 2 and the LGP stem valve which is anchored to part 3. In concept 1, the LGP stem valve contains six venting nozzles for the combustion sub-chamber. Four pin electrodes (1/16" DIA) are provided to ignite the LGP close to the G surface. They are insulated and held in place by epoxy moldings. A power distribution ring provides electrical continuity between the electrodes. Part 2 contains a Kistler 601B pressure transducer to measure the LGP pressure ( $P_L$ ) via a teflon floating piston and a silicone grease column. A differential area push-rod (Fig. 2) applies force on part 2 and holds it tight against parts 1 and 3. A pressure ( $P_L$ ) 13 times greater than the holding pressure ( $P$  in the pressure chamber) of the push-rod is required in order to unseat part 2.

a. Principle of Operation. The principle of operation is as follows. In both concepts, the sealed LGP is ignited by arc discharge (using the electrical circuit outlined in Fig. 2). Gaseous products are generated near the G surface. The pressure rises to overcome the push-rod force. The igniter piston & valve (part 2) then retreats and an annular vent along the G surface opens to vent the gas into the combustion sub-chamber (part 3). Coincidentally, in concept 1, a vent is opened along the L surface to inject the LGP into part 3. In concept 2 the LGP is injected into the vent along the G surface through the holes in the tip of part 2. In both concepts, the liquid injection is due to the gas products pressure transmitted hydraulically throughout the LGP via the connecting passages in part 2. The hot, high velocity combustion products promptly mix with the injected LGP to finely atomize the liquid and ignite it. Fine atomization is achieved by the impingement, and shearing action on the liquid, of the high velocity gas. Sonic pressure waves emanating from the vent exit aid in the atomization process. Ignition occurs because of the promptness and fineness of the mixing between the hot gas and the liquid. The resulting homogeneous two phase mixture has a rather uniform temperature distribution in accordance with the

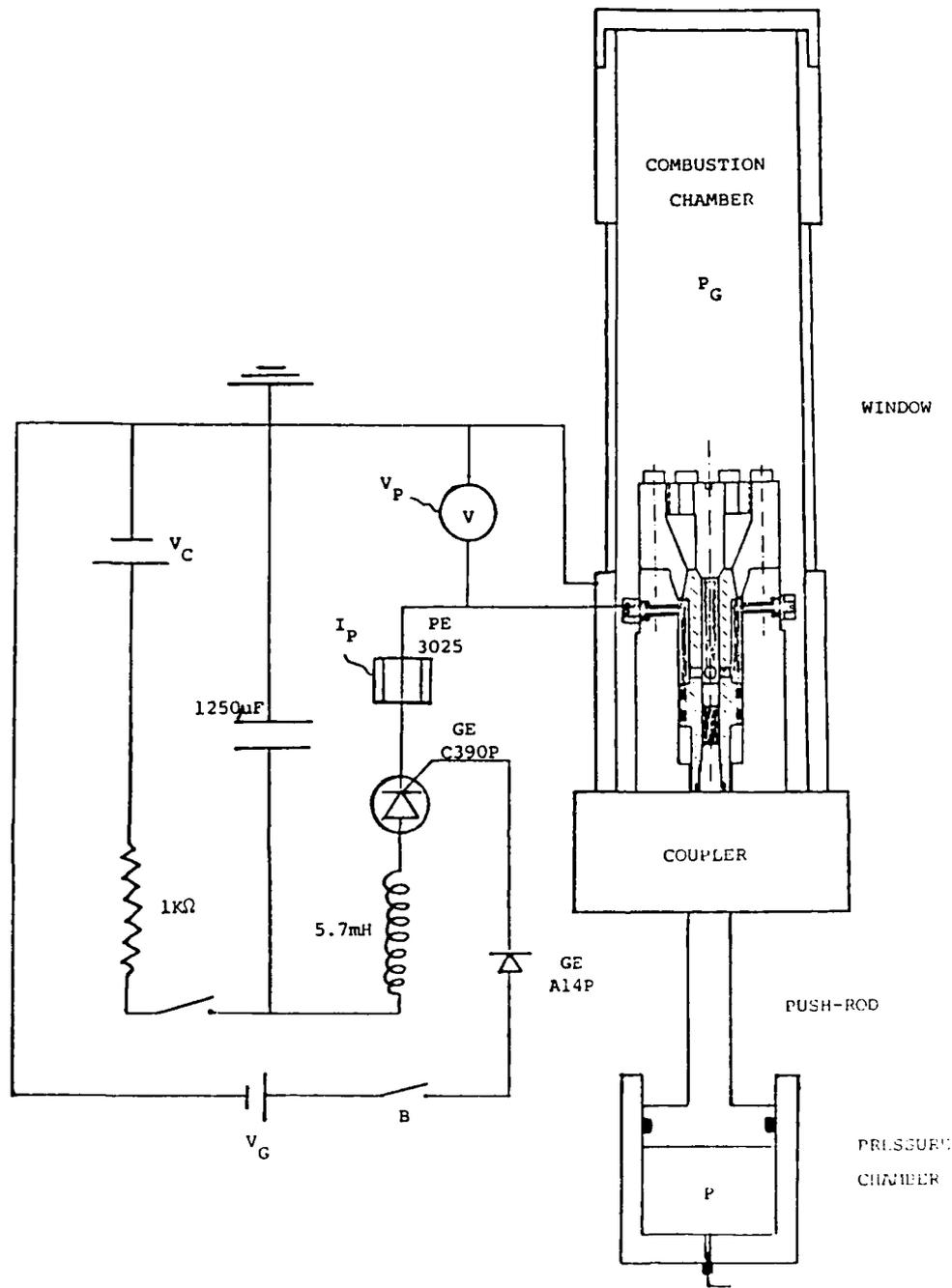


Figure 2. Experimental Set-up

mass flow rates of the separate phases and their temperatures. Even if the gas mass flow rate is only one tenth of the liquid flow rate, due to the high temperature of the gas (over 2000 K), the final mixture will attain a temperature above 200 C which is enough for initiation of propellant decomposition. Transition to combustion follows after the pressure has arisen above 5 MPa.<sup>6</sup> Complete combustion of the LGP may then proceed either in part 3 or in the bigger combustion chamber in which the igniter may be mounted (Fig. 2). The odds for complete combustion are better with the concept 1 igniter which has a nozzled combustion sub-chamber. This is due to enhanced mixing and flame holding in the sub-chamber. The mechanisms of gas/liquid mixing and their flow rates are different in the two concepts and are discussed next.

In concept 1, the gas and liquid are injected separately. The gas is injected through a converging annular nozzle to reach sonic velocity at its exit. The mass flow rates dependence on  $P_L$  can roughly be estimated as follows:

Assuming that the gas does not contain liquid particles, the mass flow rate per unit area is found using choked flow relations. For LGP 1846 one gets:

$$\dot{m}_G/A_G \text{ [kg/sec cm}^2\text{]} = 8.05 P_L \text{ [MPa]}$$

(where the 8.05 constant has the proper dimension)

The liquid flow obeys the Bernoulli equation, and for LGP 1846, assuming a typical discharge coefficient of 0.7, one gets:

$$\dot{m}_L/A_L \text{ [kg/sec cm}^2\text{]} = 155.8 P_L^{1/2} \text{ [MPa]}$$

From the above expressions, it is apparent that although the gas flow rate rises faster with pressure than the liquid flow rate, only at  $P_L=374$  MPa (for  $A_G=A_L$  and neglecting compressibility and non-ideal flow effects) equal

mass flow rates would be achieved. At the lower pressures, the liquid mass flow rate per unit area greatly exceeds that of the gas, but, as explained before, ignition of the entire liquid is still possible due to the prompt and fine mixing of the phases. This is the key to the ability of the igniter to consume rapidly large masses of LGP at moderate pressures and vent openings.

The geometries of the sealing surfaces of the concept 1 igniter tested in this work were such that  $A_L=2.32 X [\text{cm}^2]$  and  $A_G=1.68 X [\text{cm}^2]$ , where  $X$  is the part 2 displacement upon vent opening (for  $X < 0.1 \text{ cm}$ ). The igniter would inject 4.5 cc of LGP 1846 in 5 msec under  $P_L=18 \text{ MPa}$  when  $X=0.76 \text{ mm}$ . The calculated ratio of liquid to gas mass flow rates at  $P_L=18 \text{ MPa}$  was about 6.3 which was enough to assure ignition. Thus, in principle, the concept 1 igniter should have been capable of discharging its contents and ignite them in less than 5 msec.

The flows in concept 2 igniter are more complex than in concept 1 and no attempt is made here to estimate the mass flow rates. Mixing between the phases occurs while within the G surface vent. The gas shears perpendicularly the liquid emanating from the vent nozzle wall. The resulting two phase flow has a much lower sonic velocity than the individual constituents and therefore there is a large pressure drop at the vent exit. As a result, the liquid particles' surfaces disrupt due to pressure imbalances between the particles interiors and exteriors and the liquid is promptly atomized. (A commercial atomizer<sup>7</sup> is based on a similar principle.) The attractiveness of concept 2 is in the need for only a single sealing surface which eliminates the combustion sub-chamber as an integral part of the device. The concept 2 igniter tested had a degenerate sub-chamber (lacking a downstream wall) which was less functional in mixing and flame holding. Thus, the successful operation of concept 2 igniter was less certain.

An unknown factor in the design of the igniter was the combustion rate of the LGP in its reservoir. As discussed before, for a successful operation of the igniter, the gas generation had to be no less than a tenth of the injected liquid mass flow rate. This required liquid regression rates (due to gas generation) higher than 50 cm/sec. The only published data available concerning regression rates were obtained by McBratney<sup>8</sup> with a gelled LGP 1845

in an open tube. His data indicated weak dependence on pressure (to the 0.103 power for pressures below 60 MPa) and regression rates an order of magnitude lower than required for the igniter. These data were considered irrelevant for the igniter geometry and operating conditions. Therefore, the geometry and dimensions of the igniter vent openings were designed intuitively. It was hoped that  $P_L$  could be stabilized below 30 MPa as the igniter could not (for practical reasons) be constructed robust enough.

b. Electrical Discharge Circuit. Shown in Fig. 2, the circuit is basically an LRC circuit. The capacitors were charged to  $V_C < 500$  V and discharged by the activation of the SCR (Silicon Controlled Rectifier). The activation was achieved by the remote closure of the contact B which applied a gate voltage ( $V_G = 5$  V) to the SCR. The current  $I_p$  and voltage  $V_p$  on the electrodes were monitored. The current was measured using a Pearson Electronics Pulse Current Transformer model 3025. The circuit was underdamped (i.e.,  $R^2 < 4L/C$ , oscillatory decaying) since the LGP offered little resistance during arcing. Inherently, the SCR passed only half cycles.

c. Electrode Configurations. Three electrode configurations (Fig. 1c) were chosen on the basis of practicality. The exposure lengths of the electrode pins in configurations A and C was 1/16" (equal to their diameter). Configurations similar to B and C were used successfully in Ref. 2 which reported that C was more effective due to the steep electrical field perpendicular to the pins' curved surfaces between the pins' edges and the adjacent stepped walls. Configuration A is more effective than B due to the shorter discharge distance. On the other hand, configurations A and C are more prone than B to erosion due to their more concentrated electrical fields. Also, C is more prone to electrode shielding by large gas bubbles around the pins during LGP loading which may impede arcing.

## 2. TEST RESULTS

a. General. The summary of successful tests with igniter opening pressures above 18 MPa is given in Table 1. The tests with the best recorded data are depicted in Figures 3 to 8. (Data were recorded on a Nicolet 4094 wave recorder.) Table 1 represents only a third of the tests actually

conducted. A number of tests yielded erratic results which were traced (based on current and voltage measurements) to bad contacts in the electrical circuit. In other tests, with opening pressures below 18 MPa or when voltages were too low, ignition never occurred. The igniters' main parts had to be refabricated twice as two tests resulted in catastrophic failure of the igniters. The test results will be discussed chronologically by test groups as given in Table 1.

TABLE 1. Summary of Tests\*

Test** Group	No. of Tests	LGP	V <sub>C</sub> (Volt)	Results
1/A/N	4	1846	300	Prompt*** ignition and complete combustion of LGP. The igniter was destroyed in the last test.
2/A/N	4	1846	300 to 400	Prompt ignition but incomplete combustion.
1/B/Y	4	1846	400	Two prompt ignitions and one delayed ignition but incomplete combustion. Delayed ignition in last test followed by complete combustion and destruction of the igniter. In the last test, the opening pressure of the igniter was set at 27 MPa.
1/C/Y	2	1846	400	Prompt ignition in the first test but incomplete combustion. In the second test, prompt ignition and slightly delayed complete combustion (Fig. 3). The combustion sub-chamber of the igniter was damaged.
2/C/Y	4	1845	400 to 500	Various degrees of ignition and combustion depicted in Figures 5 to 8.

\* Opening pressure of the igniter was set to 18 MPa.

\*\* Igniter concept (Fig. 1) / Electrode configuration / Y for igniter injecting into combustion chamber, N for injection into open air.

\*\*\* Less than 5 msec delay.

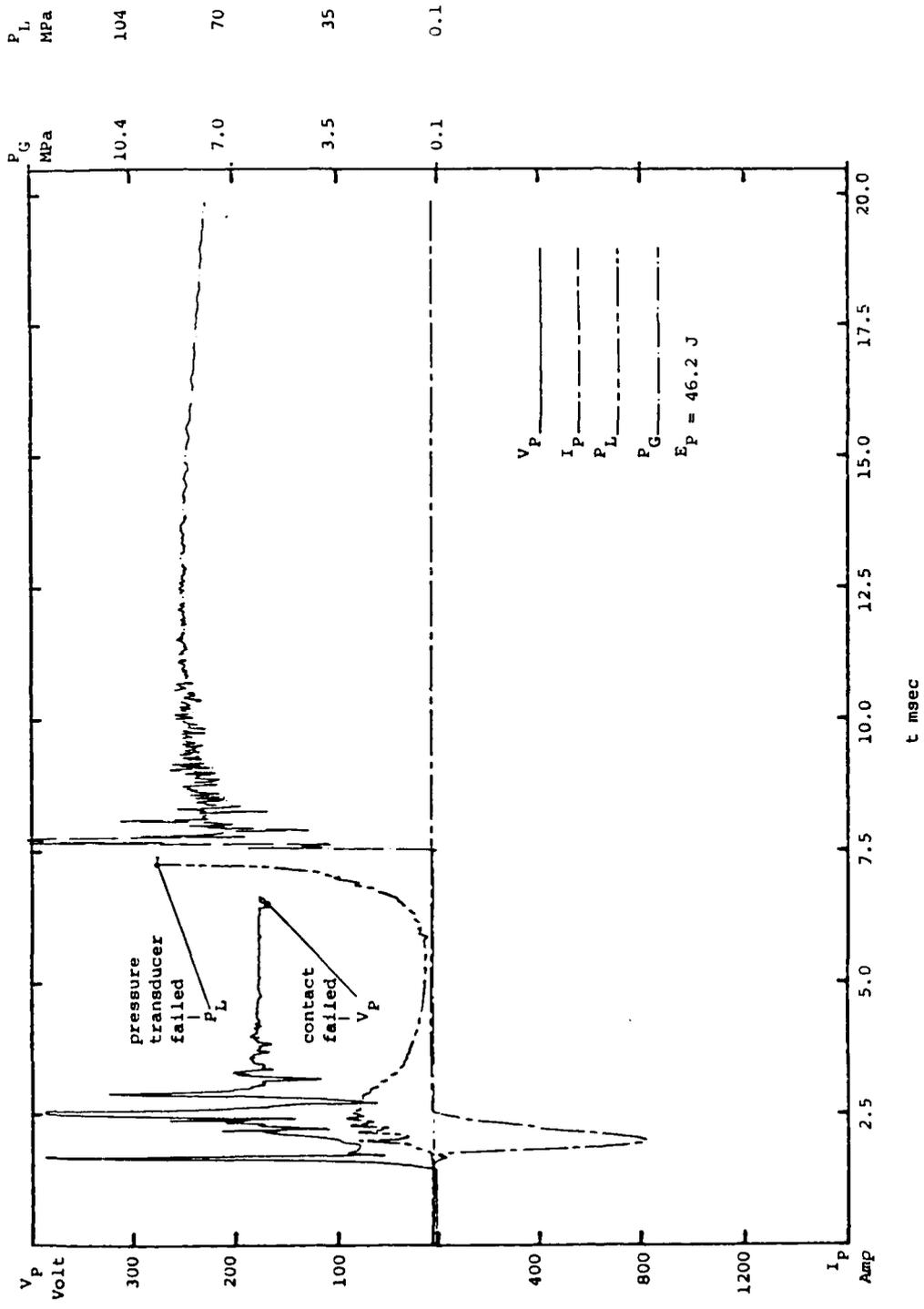


Figure 3. Complete combustion of LGP after short delay.

(test group 1/C/Y)

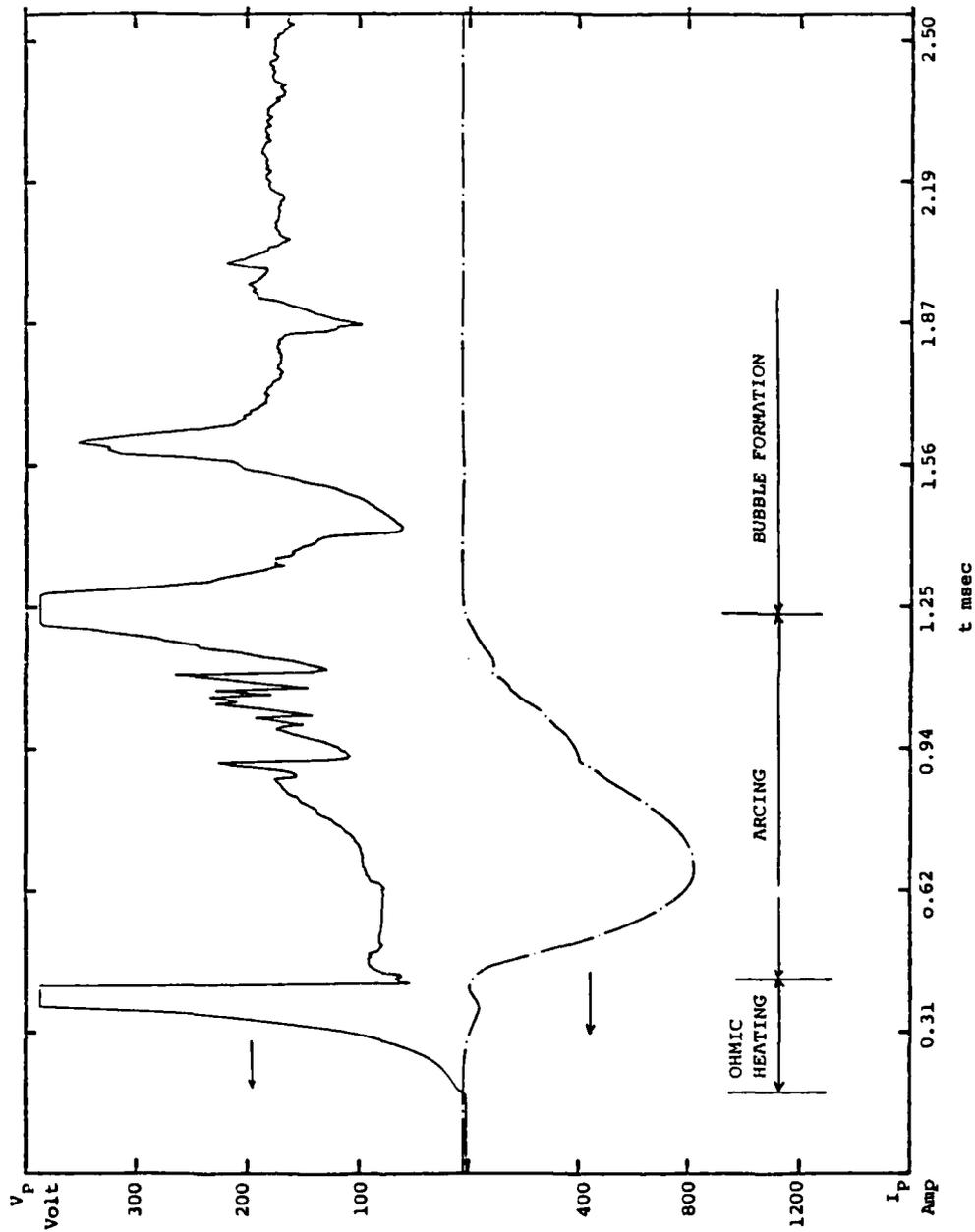


Figure 4. Details of electrical discharge of Fig. 3 test.

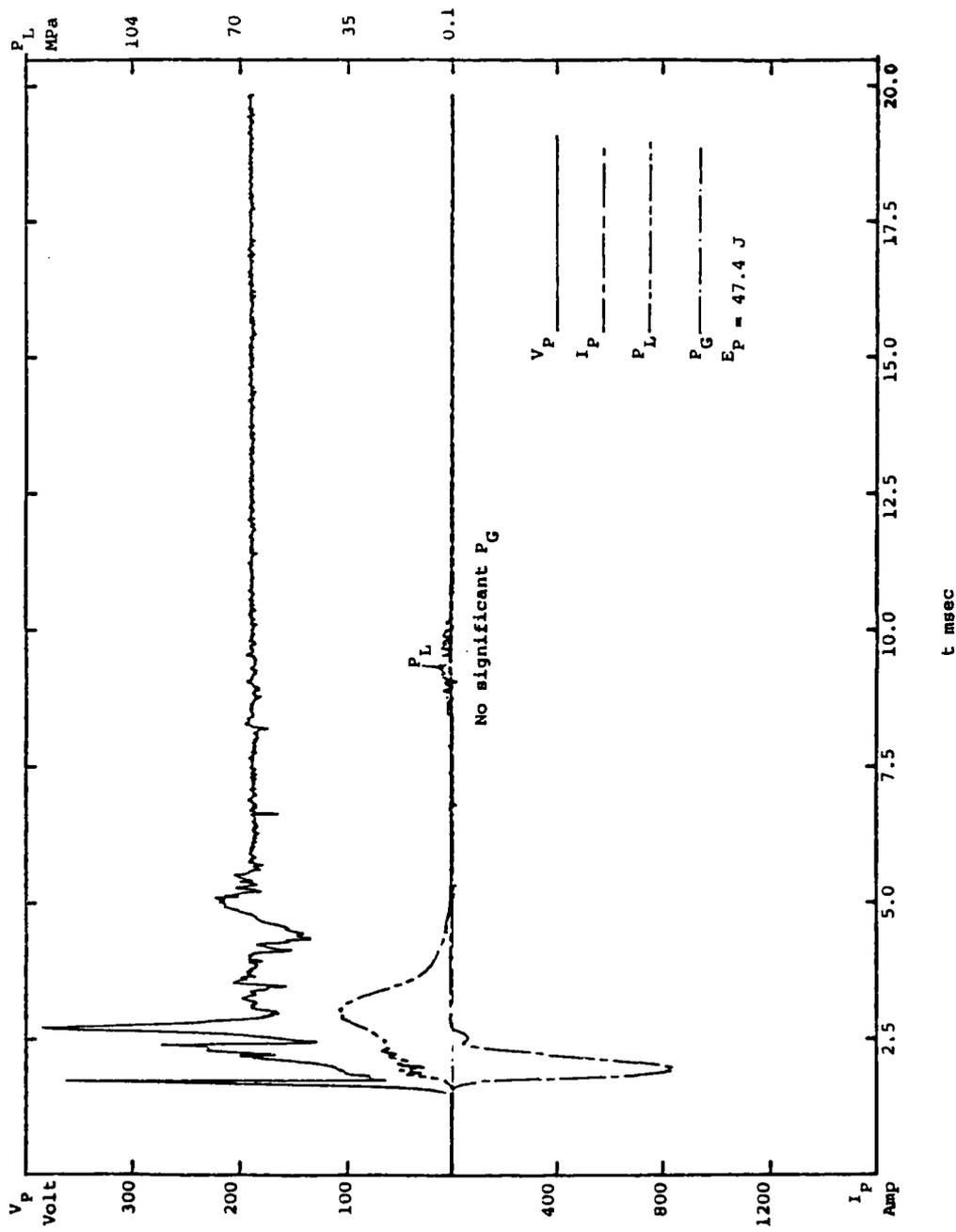


Figure 5. Prompt injection of LGP, but no combustion in combustion chamber.

(test group 2/C/Y,  $V_C = 400$  volt)

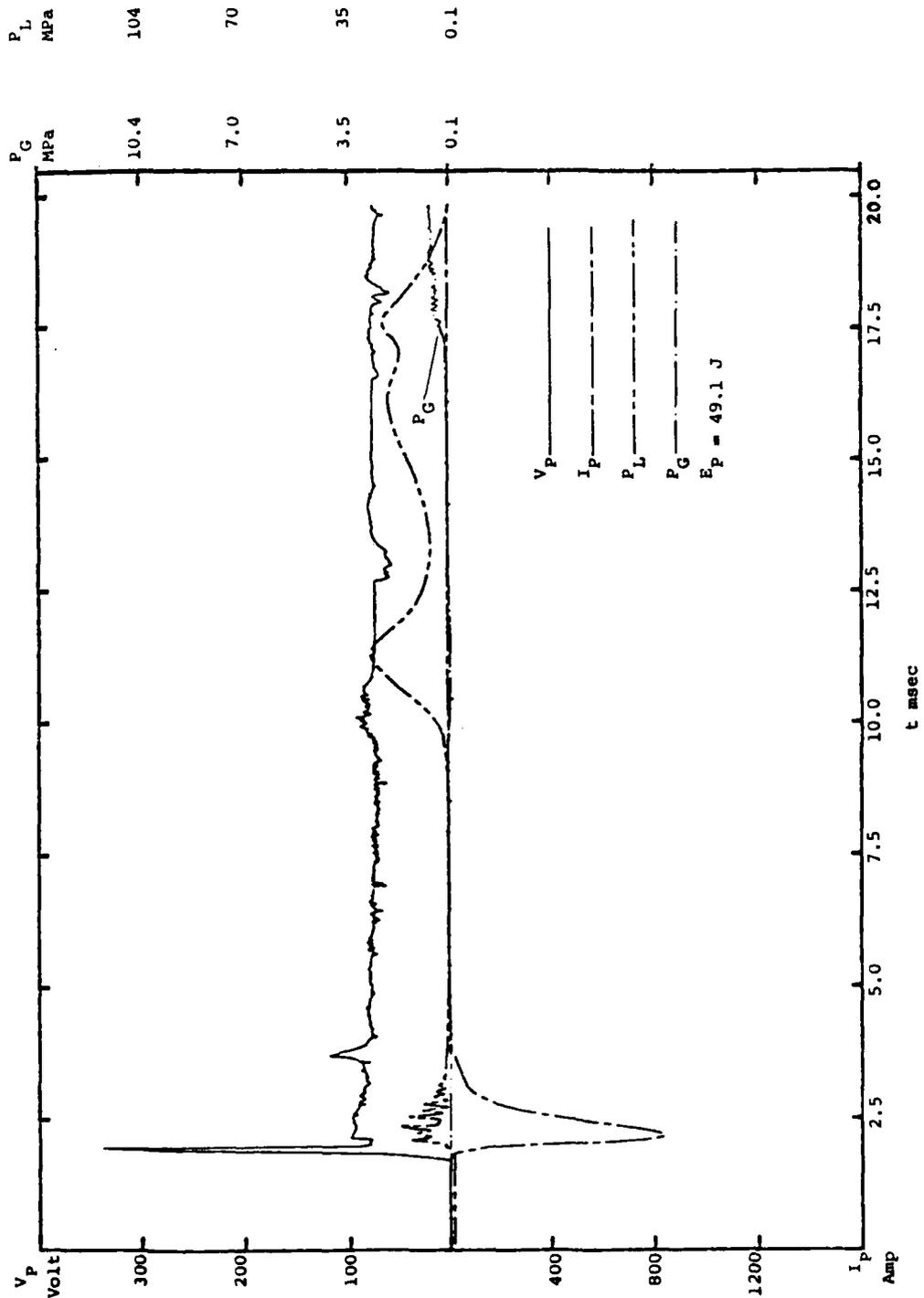


Figure 6. Delayed injection of LPG and partial combustion in combustion chamber.

(test group 2/C/Y,  $V_C = 400$  volt)

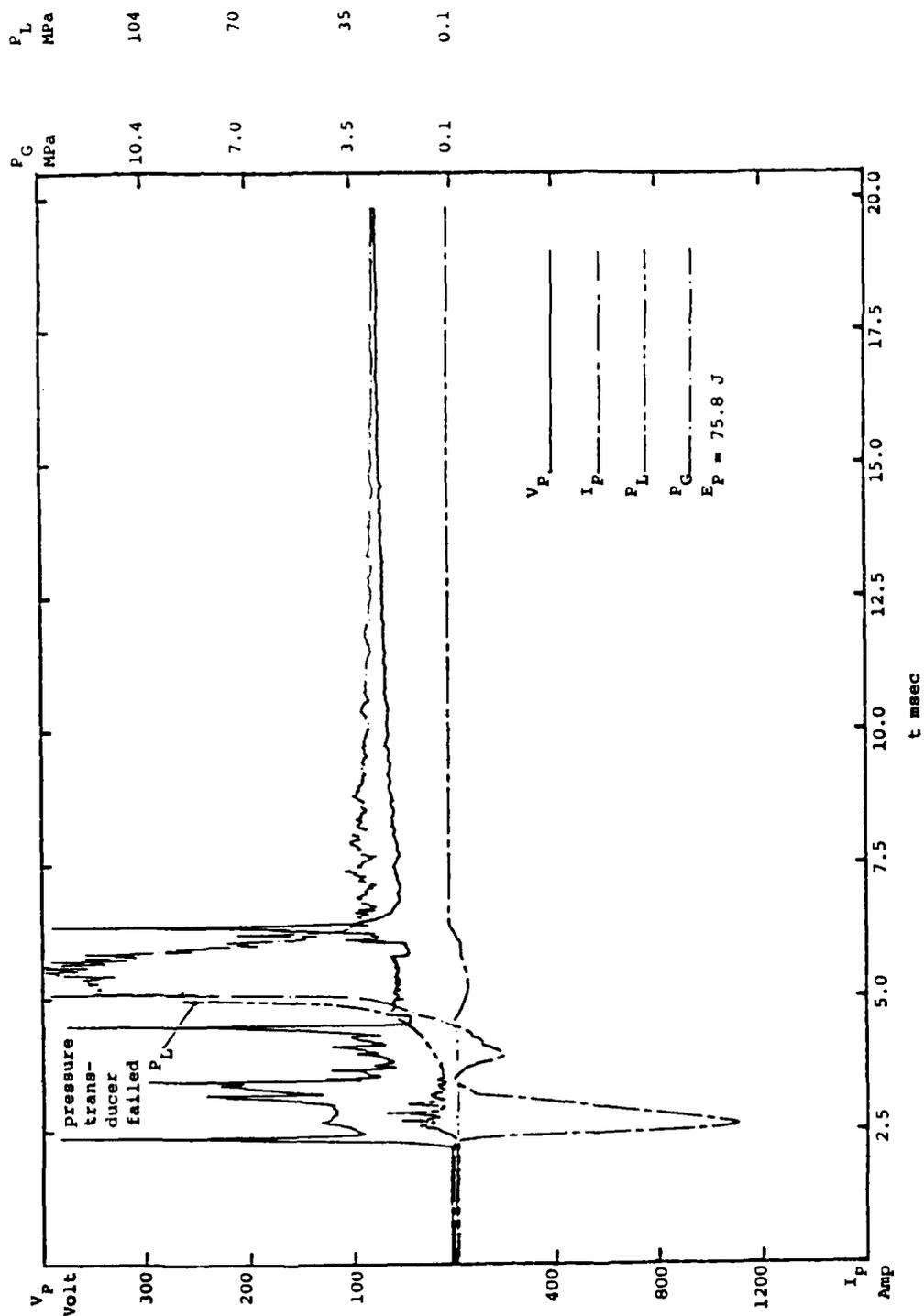


Figure 7. Prompt injection and combustion of LGP

(test group 2/C/Y,  $V_C=500$  volt, 3 electrodes)

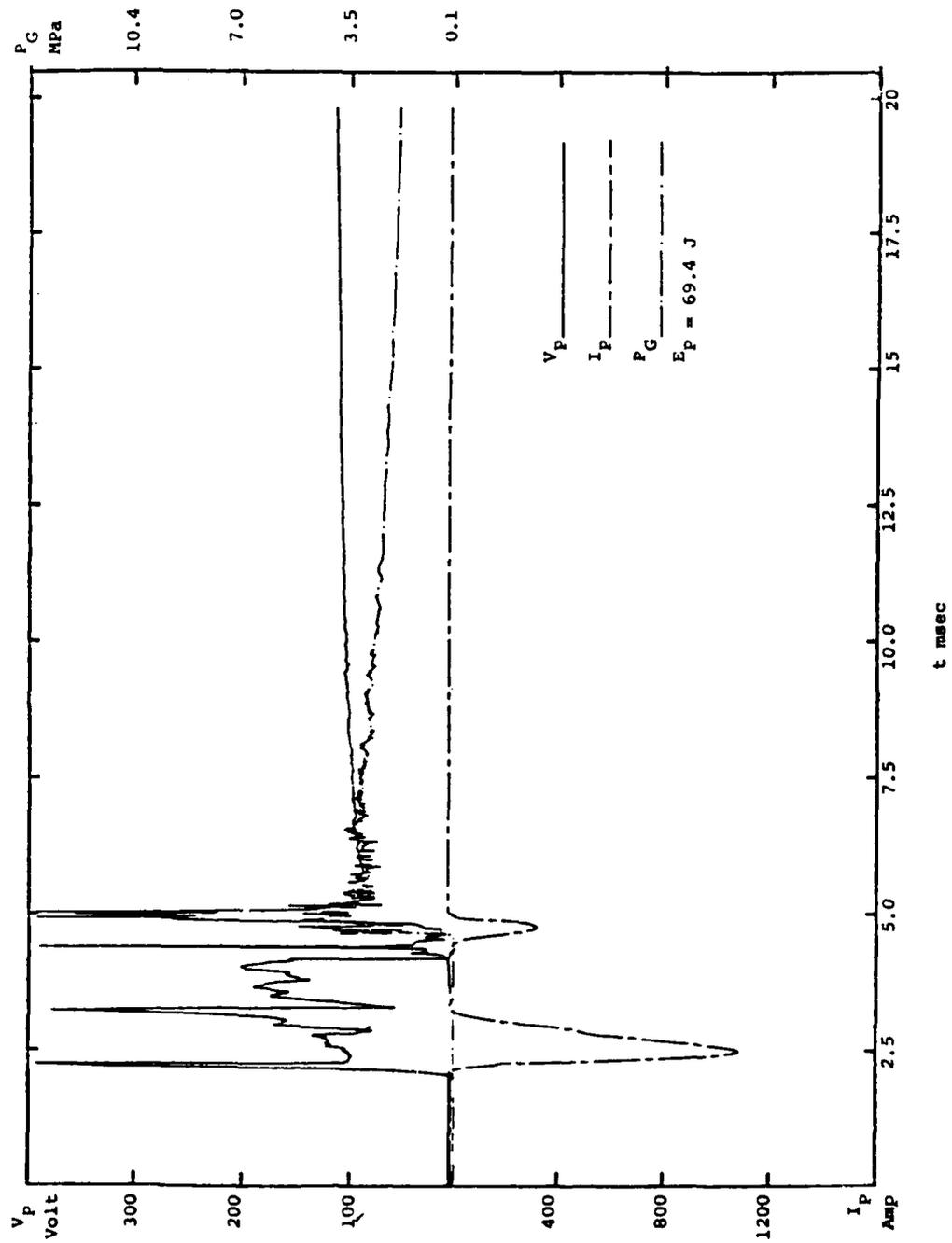


Figure 8. Prompt injection and combustion of LGP  
 (test group 2/C/Y,  $V_c=500$  volt, 2 electrodes)

b. Injection into Open Air. The original igniter was fabricated from stainless steel 316 to prevent corrosion. Only the igniter piston was made from heat treated stainless steel 17-4PH which is much harder than the 316. This prevented galling and locking of the sealing surfaces upon impact as the vents reclosed under pressure after the LGP exhaustion. The combustion sub-chamber was screwed onto the igniter body and a Buna-N rubber O-ring seal was placed between them. In the first test group (1/A/N), concept 1 with configuration A proved its effectiveness in achieving prompt ignition and combustion of the LGP. The ignition was manifested by a loud sound, by a sudden rise in  $P_L$ , and by the ejection of fluid from the igniter. No traces of liquid were found after the test inside the igniter and on witness plates outside, which was an indication of complete combustion (exclusively to gaseous products). In the last test, the igniter's sub-chamber and body were sheared apart violently due to failure of the threads and bulging of both parts. The bulging indicated yielding of the material which meant the achievement of pressures above 200 MPa in both the LGP reservoir and in the combustion sub-chamber. Such high pressures occurred in later tests, a clear indication of very high LGP regression in the reservoir well above the values given by Reference 8. It is possible that the liquid surface was highly agitated resulting in a much increased surface area.

New igniter parts were fabricated in order to continue with the 2/A/N (concept 2) test group. The parts were made from the much stronger stainless steel 17-4PH. Although prompt ignition and LGP injection were obtained, the combustion was incomplete as evidenced from the post test recovery of most of the LGP.

c. Injection into the Closed Combustion Chamber. To simulate operation in a gun, the next series of tests was conducted with the igniter mounted in the combustion chamber (Fig. 2). The degree of LGP combustion was judged from the pressure level obtained in the combustion chamber.

In the test groups discussed before (electrode configuration A), the igniter piston material across the electrode gap was found eroded. It was suspected that the spalled hot metal fragments aided in the ignition by enhanced heat transfer. Therefore, configuration B was chosen for the next

test group (1/B/Y). This configuration was found less effective than A and the voltage had to be raised to 400 V. The test results were peculiar. Although the arc discharges were nominal, the ignitions were delayed for over a second in two tests. In an attempt to achieve prompt ignition and complete combustion, in the last test the opening pressure of the igniter was increased to 27 MPa. Although complete combustion was achieved, the ignition was delayed by almost a second. As in a previous case, the igniter threads failed, resulting in the abrupt separation of the igniter sub-chamber from its body, albeit without bulging of the parts. Apparently, LGP was trapped in the threads and ignited there causing concentrated thermal stresses. (The 17-4PH material is notorious for failure under high thermal stresses.) New igniter parts were fabricated from 17-4PH but this time the sub-chamber was bolted to the igniter body (Fig. 1). This construction proved more durable.

Trying to achieve better results, electrode configuration C was used in the remaining tests. Indeed, the configuration C tests were more successful than the B configuration tests and electrodes erosion was far lower than of the A configuration (due to more diffused electrical field in configuration C).

In the second test of group 1/C/Y, complete combustion was obtained within approximately 5 msec from arc discharge. The combustion in the sub-chamber was so intense that the LGP stem valve shattered. Therefore, the last four tests were conducted with the concept 2 igniter (group 2/C/Y) which did not require the stem valve. To investigate the effects of the ignition source distribution, two of the tests were conducted with only three and two active electrodes.

The last five tests are depicted in Figures 3 to 8. The figures reveal many aspects of the operation and performance of the igniters. The voltage and current measurements revealed the dynamics of the arcing and the amount of electrical energy actually deposited in the LGP. The liquid pressure measurements indicated the outcome of the electrical discharge. A pressure ( $P_L$ ) above 18 MPa indicated the ignition of the LGP, and the opening of the igniter and ejection of fluid. A steep rise of  $P_L$  to values well above 18 MPa indicated runaway combustion within the igniter (Figures 3 and 7). A

measurable gas pressure in the large combustion chamber indicated significant combustion of the LGP. The interpretations of the various measurements are discussed next.

(1) Electrical discharge in the LGP and ignition. In the present work, the electrode pins were used as the anodes and the chamber walls as the cathode. Operation with electrode pins as the cathodes was demonstrated to work as well.<sup>5</sup> The first millisecond of the electrical discharge exhibited the same characteristics in all of the tests. The details are shown in Figure 4. The voltage and current traces are very similar to the ones obtained in Reference 4. (The reader is referred to Ref. 4 for a comprehensive discussion about the characteristics of arcing in liquids.) In the first stage of the electrical discharge no arcing occurs but ohmic heating of the liquid. The voltage across the electrode gap ( $V_p$ ) will rise to a value that is commensurate with the circuit inductance and LGP conductance with a corresponding increase in current. Local vaporization may commence at the electrode minimum-area surface and in particular at sharp corners where the current density is high. Gas may also be generated near the surface by electrolysis. The electrical field near the electrode surface will be altered by both ion migration and the generation of tiny gas bubbles. Eventually, a local breakdown of the field takes place followed by arcing and the formation of a continuous plasma channel across the electrodes gap. Associated with the arcing is a rapidly dissipating shockwave in the liquid. Thermal and chemical ignition of the LGP may ensue (due to radicals in the plasma), with further gas generation, leading to pressure rise and reaction propagation. It was found<sup>9</sup> that with LGP 1846, the ignition always occurred near the anode surface even in an electrode configuration where the anode and cathode were indistinguishable (in a trapezoidal geometry).

The duration and strength of the arcing depend on the electrical circuit capacitance and inductance. The initial arc may not discharge all of the circuit energy and a second arcing, albeit much weaker, is possible. A second arcing may aid in ignition (Figures 7 and 8). Multiple arcing is less likely, if the electrodes become inhibited by large gas bubbles and when the liquid becomes agitated, which is the case when significant liquid reactivity commences after the first arcing. The current ( $I_p$ ) will then stay very low

but  $v_p$  may fluctuate widely commensurately with the electrode gap resistance. Eventually, the electrodes are shielded with a thick layer of gas and all electrical activity ceases. If most of the liquid is injected immediately after the first arcing, no further combustion in the reservoir is likely (Fig. 5). Otherwise, chemical reactions in the liquid may continue and a runaway reaction is possible if the decomposition products and pressure reach some threshold (Figures 3 and 6).

The electrical energy deposited in the LGP,  $E_p$ , is simply the product  $V_p I_p t$ . Typically, less than 50 joules were sufficient for ignition (Fig. 3). Despite operating with fewer electrodes, prompt ignition and more complete combustion were obtained with higher capacitor voltage and with multiple arcing (Figures 7 and 8). It may be due to the higher deposition of energy per electrode.

(2) Combustion chamber pressures and flow phenomena. The theoretical adiabatic equilibrium pressure in the 500 cc combustion chamber upon the complete combustion of the igniter's LGP (4.5 cc) is about 11.5 MPa. Judged from the pressure measurements ( $P_G$ ), the most effective igniter was the concept 1 igniter (Fig. 3). Nevertheless, concept 2 igniter also proved its viability (Figures 7 and 8). In most cases,  $P_G$  rose very steeply, in the order of hundreds of MPa per msec. These rates may be too high for a practical igniter. Overshoots in the pressure values above the 11.5 MPa level (Figures 3 and 7) indicated nonequilibrium processes of localized concentrated combustion in the chamber. These steep pressure rises were preceded by runaway pressure rises in the LGP reservoir. A very gentle  $P_G$  rise was recorded in conjunction with a much delayed moderate  $P_L$  (Fig. 6). This latter case did not fulfill the performance requirements of a practical igniter with respect to operating time.

The cases depicted in Figures 5 and 8 (concept 2 igniter) were photographed at 5000 fr/sec (with a Photec camera and using back lighting). In the Fig. 5 case, in which no measurable  $P_G$  was obtained, the photography revealed the ejection into the chamber of a finely dispersed fluid at a velocity exceeding 200 m/sec. In Figure 8's case, the dispersed fluid was observed to be consumed rapidly by faint flame fronts bouncing back and forth

in the chamber. The first test of group 1/C/Y (concept 1 igniter) was also photographed, indicating an ejection velocity higher than 300 m/sec. In the latter case, the gas phase attains a much higher sonic velocity than the two phase mixture in the concept 2 igniters, because, in the concept 1 igniter, the mixing with the liquid occurs outside the igniter vent openings. The pressure measurements and the photography validated the operation principles of the igniter.

### III. CONCLUSIONS AND RECOMMENDATIONS

The viability of regenerative electrical igniters based on LGP has been proven. Of the two igniter concepts tested, concept 1 igniter was more effective in combusting its LGP load. However, the concept 2 igniter is less complex, more compact and is therefore more practical. The igniters' design need much refinement in order to become truly practical. The igniters should be designed to operate at peak gun pressures. They failed to operate satisfactorily at internal pressures below 100 MPa. It is recommended that future work concentrates on concept 2 igniter.

The present work did not address the effects of the electrodes polarities on ignition as well as the effects of prepressurizing the LGP. Future work should address these issues.

Although successful operation was demonstrated with 400 to 500 V electrode voltage (and electrical energy depositions below 50 joules), it is recommended to operate with higher voltages in order to achieve good repeatability. Also, a design for multiple arcings should be given consideration as they promoted ignition.

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## NOMENCLATURE

A - Vent area  
C - Capacitance  
 $E_p$  - Electrical discharge energy  
I - Current  
L - Inductance  
 $\dot{m}$  - Mass flow rate  
P - Pressure  
R - Resistance  
t - Time  
V - Voltage  
 $V_C$  - Capacitor voltage  
 $V_G$  - Gate voltage  
X - Injector piston displacement

### Subscripts

G - Gas  
L - Liquid  
P - Propellant

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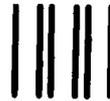
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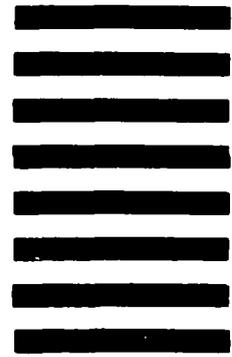


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