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TECHNICAL REPORT BRL-TR-2855

REGENERATIVE LIQUID PROPELLANT GUN IGNITER CONCEPTS

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OCTOBER 1987

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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-2855	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)

REGENERATIVE LIQUID PROPELLANT GUN IGNITER CONCEPTS

12. PERSONAL AUTHOR(S)

Knapton, John D., Birk, Avi, DeSpirito, James and Watson, Cris

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
TR	FROM 10/85 TO 9/86		

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)

Three ignition concepts are reviewed for use in medium and large caliber regenerative liquid propellant (LP) guns. The concepts are based on the use of hydrogen and air, fuel and air, and compression. Data was only obtained for the hydrogen and air concept. The feasibility of the two other concepts are based on system studies. The ignition goals were the generation of a pressure of about 18 MPa in 5 msec. The liquid propellant selected for the study was the hydroxylammonium nitrate (HAN) based monopropellants designated 1845 and 1846.

Two types of igniters using hydrogen were examined. For the first type, hydrogen and air was considered which was ignited by either a spark or a volume type of ignition source. The second type consisted of hydrogen and oxygen diluted with argon and

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL John D. Knapton	22b. TELEPHONE (Include Area Code) (301) 278-6170 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

19. ABSTRACT (Con't)

supplemented with liquid propellant. Ignition was achieved by a discharge of electrical current through the propellant jet during the initial injection. The second type has the advantage of reducing the hydrogen requirement. Using the first type of igniter and a commercially available metal hydride storage device with a capacity of 2500 liters of hydrogen, approximately 6000 tests could be performed in a 50 cm^3 chamber. Scaling to larger chambers would result in a corresponding linear decrease in the number of tests. Due to lack of data, an uncertainty exists in the time to reach maximum pressure. Using the second type of igniter, tests demonstrated that the desired pressure could be reached by reducing the volume of hydrogen by a factor of 2.4, however the time to maximum pressure was much too fast. Further decreasing the initial volume of hydrogen resulted in more acceptable pressure rise times, however the maximum pressures failed to satisfy the design goal of 18 MPa.

The use of fuel and air for an igniter is based on an earlier study at the BRL. In this study, reported at the 9th JANNAF Combustion Meeting, JP-4 and air were burned at high pressure for use as a gun propellant. The results of the earlier study are directly applicable for an igniter design, if the fuel and air can be burned outside of the gun chamber at high pressure with the combustion gases allowed to vent into the gun chamber. For the present study, the igniter design goals for a small or medium caliber gun (with chamber volumes up to 500 cm^3) could be satisfied by spark igniting a mixture of fuel and air in an external chamber at an initial pressure of 24 MPa, assuming sufficient turbulence in the chamber. Concerns for larger chambers are the time requirement to reach maximum pressure in 5 msec, which might require the use of a multi ignition source such as a plasma plug, and the power requirements for supplying the air.

The last igniter concept is based on compression ignition. Two approaches can be considered. In the first approach, the liquid propellant is compressed in a bulk loaded chamber. In the second, which is the recommended approach, the liquid propellant is injected into a chamber, as in a diesel engine, in which the gas has been heated to a high pressure and temperature. For the present study, initial conditions of 400° C and 10 MPa should be adequate to ignite a spray of the LP.

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I. INTRODUCTION

1. BACKGROUND

Typical ignition systems used in regenerative liquid propellant guns (RLPGs) have consisted of an electrical primer followed by various types of solid pro-pellant booster charges. The igniters are discharged in the gun chamber and result in sufficient gas generation to initiate displacement of the regenerative piston, start the propellant injection, and ignite the injected propellant. Although this approach has been very successful, it is recognized that significant system advantages could be achieved if the solid propellant igniter charge were replaced with an igniter that would have no impact on the resupply logistics. The system which this paper addresses is the igniter for a 155-mm self propelled howitzer. A chamber volume of 5000 cm^3 is assumed, although final designs for the 155-mm chamber have not been completed. The use of the same liquid propellant which is used for the main charge is an ideal energy source for an igniter. However, the HAN-based liquid propellants are difficult to ignite and for this reason other igniter concepts are being examined. A survey of various igniter concepts was reported at the 22nd JANNAF Combustion Meeting.[1] As a result of this survey, four concepts were selected for further study. One of the concepts, electrical ignition, was selected as the primary concept and is being addressed in two separate papers.[2,3] The concepts that were selected for further study, and are reviewed in this paper, include (A) a hydrogen and oxygen igniter supplemented with liquid propellant, (B) a fuel air igniter, and (C) a compression type igniter.

2. PROPELLANT

The type of HAN monopropellant which is being studied uses triethanol-ammonium nitrate (TEAN) for the fuel component. Two propellants are being considered for use in the RLPG and are designated 1845 and 1846. Ignition of the propellants when starting at atmospheric conditions is often difficult. The mechanism for transferring energy has to be done properly, if not, the propellant will not be ignited. This difficulty helps to make the propellants attractive from a safety viewpoint, but not when considering the design of an igniter for a gun. One method for increasing the possibility of ignition, and to reach sustained combustion, is to increase the confinement of the liquid propellant. This approach, however, can lead to unacceptably high pressures. Indeed, the inherent instability of the surface area of an all liquid propellant igniter results in a condition highly suspect for any practical application, especially if the igniter is initially loaded at a high loading density (e.g., greater than 0.5 g/cm^3).

3. IGNITION ENERGY

The conditions required in the gun chamber for the initiation of the RLPG process may be rather restrictive. Mandzy[4] stated that a solid propellant igniter for a RLPG works satisfactorily in various caliber guns when an igniter pressure (in the gun chamber) of 18 MPa is achieved in about 5 msec, although it is possible that other pressure and time conditions may be acceptable. The total energy content of the solid propellant igniters are typically about 3 to 5 kJ for 30-mm size weapons.

The energy to ignite the LP, and to achieve sustained combustion at pressures up to 18 MPa, depends on the physical state of the LP, such as the type of confinement, and the fuel component. For example, difficulty in achieving acceptable ignition was encountered in some types of RLPG tests when using the HAN-based LP containing isopropylammonium nitrate (IPAN) for the fuel component.[5] In one type of RLPG test, which resulted in poor ignition, the LP at the start of injection was in the form of relatively large droplets. In a second type of RLPG test, where no ignition problems were encountered, the LP at the start of injection was in the form of a fine spray. Although not part of this study, it is interesting to note that the fuel component can also influence the ignition characteristics. Using the same type of initial spray and the same type of pyrotechnic igniter, Watson[6] found that the HAN-based LPs containing TEAN can be ignited more readily than similar LPs containing IPAN. More recently, Birk and Reeves[7] found that LGP 1846 ignited readily when injected into pressures and temperatures above 10 MPa and 1800 K obtained from the combustion of a hydrogen-oxygen-argon mixture.

In bulk loading, the actual ignition of the LPs can be achieved with relatively little energy. For example, Klein,[8] using small plasma plugs containing 35 microliters of LP, found that the HAN propellants can be ignited with less than 0.1 J. Hot wire ignition tests[9,10] of bulk loaded LPs (including 1845 and 1846) confined in a 25-mm chamber showed that the LPs can be ignited with less than a few tenths of a Joule of electrical energy. The resulting gas generation rate, however, even under conditions of a full charge of LP (maximum loading density) was sufficiently slow (tens of milliseconds) to preclude the use of such a device as a practical igniter for a bulk loaded gun. More practical electrical igniter systems for medium caliber bulk loaded gun systems have been tested[11,12] in which the energy delivered to an electrode configuration was of the order of tens of Joules. Recently, DeSpirito et al.[2] found that 2 ml of 1846, with confinement limited to a 1.6 mm vent orifice, could be ignited with energies greater than 60 J.

II. HYDROGEN AND AIR IGNITER

1. BACKGROUND

Two methods are reviewed in this paper using hydrogen and oxygen as the basis for an ignition system. The two methods are (1) ignition of a hydrogen-air mixture using an electrical igniter and (2) a current discharge through an LP jet as the jet is injected into a gaseous mixture of hydrogen and oxygen diluted with argon.

Hydrogen and oxygen diluted with argon provide a convenient method for obtaining the conditions of a well mixed reactor. The approach, therefore, is suitable for evaluating a system for generating the pressure and temperature conditions in a chamber necessary for igniting the liquid propellant. A possible more practical system for generating the desired chamber conditions would be the use of the vehicle fuel and air. However, a system using the vehicle fuel would require a well designed injector to achieve acceptable mixing of the fuel and air. The fuel air system is discussed later.

The interest in the use of hydrogen for the fuel component in a propellant for use in a possible igniter is based on the metal hydride systems which have been commercially developed for the storage of hydrogen.[13] Metal hydride storage devices are commercially available with dimensions of 24x12x3 inches and can hold up to 2500 liters of hydrogen. Vulnerability firing tests with small arms, which resulted in rupturing the storage devices, did not produced a flame or explosion.[14] Despite the safety precautions developed by the manufacturer, it is recognized that the use of hydrogen in a practical igniter could present safety problems which could limit development. Because of the potential safety problems, the use of hydrogen in an igniter may only be limited to laboratory tests in a well controlled environment. Nevertheless, it could find application as an interim igniter for rapid testing of weapon components pending the development of a more practical all LP igniter or, as an igniter for generating sufficient pressure in an abnormally large initial volume (i.e., a solution to the projectile "sticker" problem). It is for these possible applicatio that this section addresses.

2. APPROACH

a. Igniter (1): Hydrogen and Air. The first igniter is based on an analytical study in which compressed air is stoichiometrically mixed with hydrogen. The second igniter is based on experimental tests in which mixtures of hydrogen and oxygen, diluted with argon, are ignited during the injection of a jet of LP.

(1) Thermochemistry. The combustion of hydrogen and air to give the required chamber pressure is based on a NASA-Lewis thermochemical calculation.[15] The conditions around stoichiometry are summarized in Table 1.

TABLE 1. Thermodynamic Properties of Hydrogen and Air to Give a Final Pressure between 17.2 MPa and 20.7 MPa (Ref.15).

Equivalence Ratio	O/F	Percent Fuel %	Pressure MPa	Temperature K	Loading Density g/cm^3
0.98	34.59	2.810	17.2	2474	0.02058
0.98	34.59	2.810	20.7	2476	0.02469
1.00	33.89	2.866	17.2	2494	0.02033
1.00	33.89	2.866	20.7	2496	0.02439
1.02	33.23	2.922	17.2	2501	0.02018
1.02	33.23	2.922	20.7	2503	0.02420

For a given equivalence ratio, the volume of required hydrogen and air may be determined from the loading density and the percent fuel. The results are summarized in Table 2 (see also Ref.1) for the case of equivalence ratio 1. Three different chamber volumes are examined.

Table 2 shows that the volume of hydrogen required for the three chamber volumes could be obtained from a single metal hydride device. For the three chamber volumes listed in the table, assuming a final pressure of 20.7 MPa and a storage device with 2500 liters of hydrogen, it would be possible to obtain about 6000, 600 and 60 tests, respectively, for the three chambers.

TABLE 2. Required Hydrogen and Air at STP to Give Final Pressures of 17.2 MPa and 20.7 MPa for Three Different Chambers.

Chamber Volume	Pressure			Required Volume of Hydrogen	Required Volume of Air
	initial		final		
	total	H_2			
cm^3	MPa	MPa	MPa	liter	liter
50	2.43	0.724	17.2	0.324	0.845
50	2.92	.862	20.7	0.388	1.013
500	2.43	.724	17.2	3.24	8.45
500	2.92	.862	20.7	3.88	10.13
5000	2.43	.724	17.2	32.4	84.5
5000	2.92	.862	20.7	38.8	101.3

(2) Combustion Rate. Also of concern is the time required for complete combustion. A review of the literature did not disclose any consistent burning rate information at the pressures of interest for constant volume combustion. For a point ignition source and laminar burning at constant pressure, a flame speed of several hundred cm/sec would be expected. With this burning rate, the time for complete combustion would be too long, even for the 50 cm^3 size chamber. However, tests in this study demonstrate that for turbulent burning under constant volume conditions, the burning rate could be increased significantly, possibly as much as a factor of ten. For such an increased burning rate, the time for complete combustion would be acceptable for the three chambers. For example, in Ref. 16, transition to a detonation was obtained for atmospheric hydrogen/air mixtures, 15 cm away from a spark plug in a 5 cm diameter tube. The ignition location and intensity, and the chamber configuration are factors in a detonation onset. The risk of detonation exists only for the larger 5000 cm^3 chamber. Therefore, if hydrogen/air combustion is considered for an igniter, then a plan should be considered for obtaining burning rate data under the conditions envisioned for the actual chamber configuration. To further augment the combustion process, consideration should also be given to a volume type of ignition source, as opposed to a point source (e.g., a spark).

b. Igniter (2): Hydrogen and Air Supplemented with LP. Because of the limited number of tests that could be performed in a large chamber volume, assuming only one hydrogen storage device, it was decided to perform some additional tests in which the hydrogen would be supplemented with the LP. Additionally, there was a concern that a point source type of igniter could result in a combustion process that would not yield the maximum pressure in the required time. A point source igniter produces at constant pressure a spherical flame surface with flame speeds of the order of a hundred cm/sec. As stated above, these flame speeds could be significantly increased by turbulent burning at constant volume. The increase, however, is not known and would require testing in a chamber planned for the actual gun tests. An additional method for increasing the early mass decomposition rate would be a multi ignition source. A plasma jet ignition is such a method.[17,18] A variation on the plasma method is considered in this section: current is discharged through the orifice during injection producing a plasma which atomizes the LP jet and ignites both the ambient gas and the LP.

(1) Experimental. A circular sheet jet was injected into a chamber using the equipment described in Reference 19. Two chamber volumes were used, approximately 500 cm^3 and 1000 cm^3. The smaller chamber was 20.3 cm long with a diameter of 5.72 cm. The larger chamber consisted of a second 500 cm^3 chamber mounted on top of the first chamber. Overall length of the two chambers was 40.6 cm. The chambers were prepressurized with hydrogen and oxygen diluted with argon (in stoichiometric ratios of two moles of hydrogen, one mole of oxygen, and seven moles of argon). The LP used was LGP 1845 and the volume of the injected LP was about 3 cm^3. The thickness of the injected LP sheet was constant for each test and varied between tests from 0.05 mm to 0.15 mm. During injection a current was discharged through the orifice from a capacitance circuit of 5000 microFarad. The injector head and electrical circuit is shown in Figure 1. A typical charging voltage of 300 V stores 225 J on the capacitors.

(2) Spark Ignition Results. A high energy discharge of about 3.5 J was more than sufficient to ignite the $O_2/2H_2/7Ar$ mixture in the two chamber configurations discussed earlier. These tests preceded the LP plasma tests and were conducted both for demonstration of the first igniter approach discussed before (i.e., ignition of a reactive gas), and for comparison with the second approach (i.e., ignition of a reactive gas by supplemental LP plasma). As a demonstration of the first approach, the pressure traces from the tests clearly indicate the importance of chamber configuration on performance. Performance was better in the longer (and larger) chamber, particularly for the higher initial mixture pressures. Faster pressure rise times from ignition (i.e., from sparking) and to higher peak pressures were obtained in the longer chamber. Both photography and pressure data indicate flame velocites in excess of 25 m/s in the longer chamber. Indeed, photography revealed turbulent flame propagation. A penalty of turbulence is high heat losses which lowers the pressure from its peak value, but on a time scale which is of little importance for actual igniter applications (i.e., tens of milliseconds). The maximum pressure obtained is dependent on its rise time. Shorter rise times mean less heat loss during flame reactions and pressure peaks closer to the calculated adiabatic values.

The pressure traces for the short chamber are peculiar. They indicate a prolonged induction time (10 msec) between spark discharge and significant pressure rise. The actual pressure rise is as steep as in the long chamber but (unlike the long chamber) once the peak pressures are reached, the pressure levels are sustained with little heat loss, an indication of lesser turbulence. Possibly the reason for the long induction times in the short chamber is its high surface area per unit volume, which results in reaction quenching on the walls by heat loss and species recombination. In the longer and larger chamber, quenching is less significant and the length of the chamber enables turbulent flame acceleration (as the unburnt gas is being heated by the pressure waves generated by the flame) and therefore achievement of higher peak pressures.

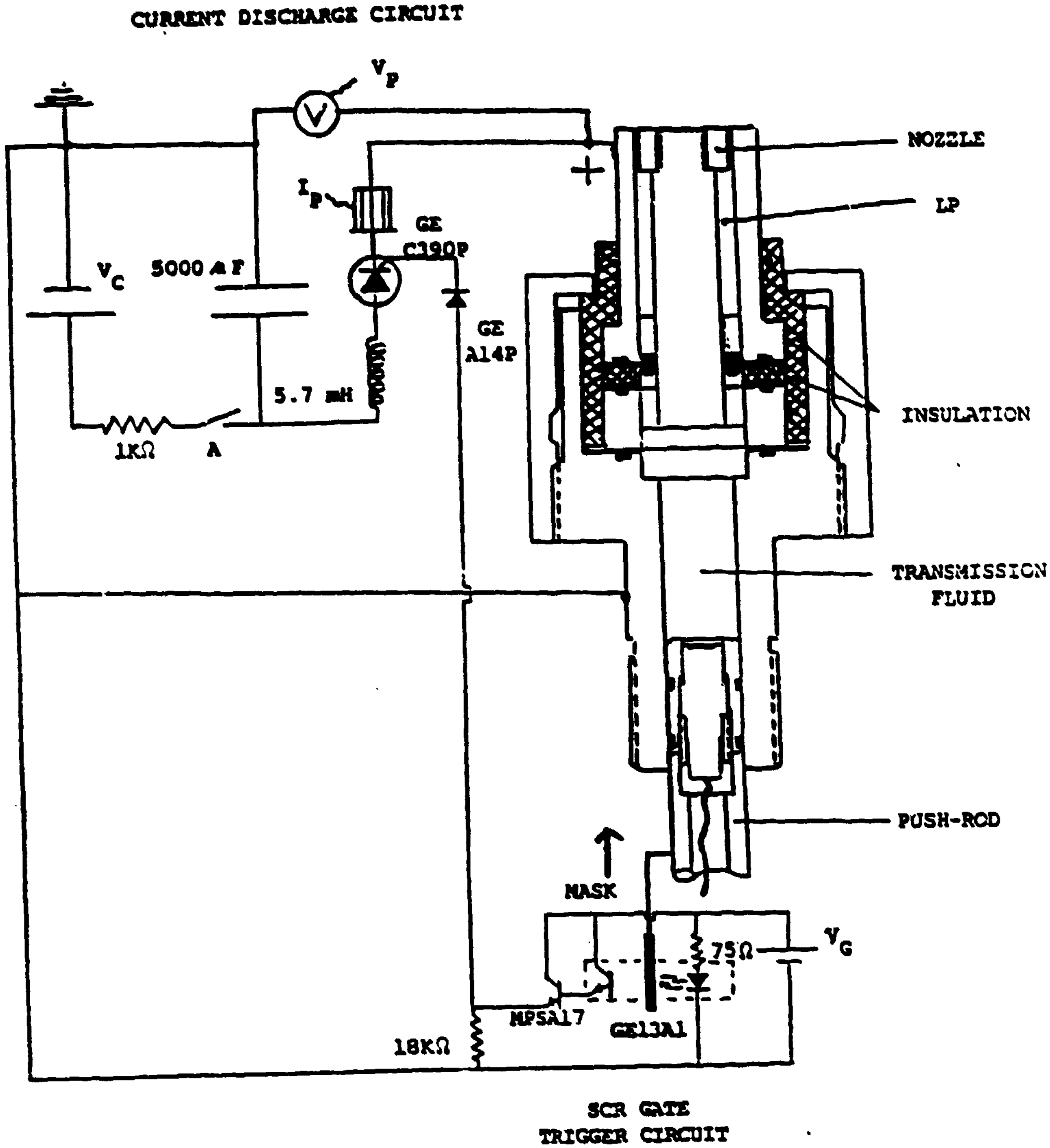

Figure 1. Injector head and current discharge circuit

The location of the spark plug also has a bearing on performance. It is not apparent from this work, but, for example, in tests conducted in Ref. 20 with hydrogen and air mixtures ignited at the center of a 16 cm diameter spherical bomb, flame velocities were less than 10 m/s (i.e., laminar). It should be noted that faster rise times would be achieved with less diluted mixtures than the ones used in the current work. However, in practice, the long induction times for pressure rise (particularly in small chambers) by spark ignition may not be acceptable for an RLPG igniter; hence, the use of a plasma jet ignition is recommended.

(3) Thermochemistry. The partial pressures obtained from the combustion of the hydrogen, oxygen, argon mixture and from the burning[13] of the LGP 1845 were estimated from the NASA-Lewis thermochemical code. The results for the conditions of the tests are summarized in Table 3.

(4) Results for Igniter (2) Using Hydrogen and Air Supplemented with LP. The conditions of the tests and the results are summarized in Table 4. As evidenced from tests 1 and 7, it is very difficult to ignite the LP jet itself in the absence of a supporting reactive environment. Only if injection takes place into pressures well over 10 MPa, may the LP ignite, even in inert gas.

TABLE 3. Partial Pressures and Total Final Pressures Expected from the Stoichiometric Combustion of Hydrogen, Oxygen in Argon and also from the Complete Combustion of the LGP 1845 (Ref.13). The mixture of hydrogen, oxygen and argon in the ratios of one mole of hydrogen, two moles of oxygen and seven moles of argon. Heat loss is not included.

Chamber Volume	Initial Gas Pressure	Initial Vol of Hydrogen (STP)	Final Partial Pressures		Total Final Pressure
			H_2O	1845	
cm^3	MPa	liter	MPa	MPa	MPa
1000	1.38	2.72	12.5	3.95	16.4
500	0.345	0.34	3.05	7.90	11.0
500	0.690	0.68	6.08	7.90	14.0

TABLE 4. Summary of Plasma Jet Injection Tests. Three grams of LGP 1845 was injected into the chamber. Approximately 100 V was applied across the orifice. The maximum current measured during the injection was 1200 A and the pulse width at half maximum was about 0.8 msec.

Test No.	Chamber Volume cm^3	Chamber Gas atm	Initial Pressure MPa	Orifice Gap mm	Injection Velocity m/s	Results
1	1000	O_2,4Ar	1.4	0.050	30	No ignition
2	1000	$2H_2$,O_2,7Ar	1.4	0.050	30	Violent ignition, complete combustion of LP. P_{max} > 14 MPa.
3	500	$2H_2$,O_2,7Ar	0.69	0.050	25	Ignition and complete combustion of LP P_{max} = 9.0 MPa, rupture disc pressure.
4	500	$2H_2$,O_2,7Ar	0.34	0.050	25	Ignition, but incomplete combustion of LP P_{max} = 7.2 MPa.
5				0.050	35	
6				0.15	20	
7	500	Ar	8.3	0.050	20	Partial decomposition of LP. 8.3 < P_{max} < 9.7 MPa.

The energy deposited in the LP jet during the tests, as measured from the current and voltage, was about 48 J. The volume occupied between the electrodes contained (for the smaller gap in Table 4) 19 microliters of liquid. Even if assuming no liquid flowed during the current discharge, heat transfer calculation shows that the liquid temperature (if not reacting) will rise by only 288 K, which is not enough to produce a plasma. A positive confirmation for plasma generation was obtained from photography. Apparently, arcing does not fill the entire volume. The sudden gas generation and its expansion replaces the liquid and provides a much smaller mass between the electrode for heating to plasma temperatures.

The first test with the propellant and plasma injected into an inert atmosphere at 1.4 MPa did not result in ignition.

The second test with an expected final pressure of about 16.4 MPa resulted in a violent combustion of the reactants. The maximum pressure saturated the recording channel at 14.0 MPa. The rate of pressure rise was over 100 MPa/msec and suggested that the maximum pressure was localized and would have exceeded the expected thermodynamic equilibrium pressure.

Test 3, with an initial pressure in the smaller chamber of 0.69 MPa, resulted in complete combustion, but the maximum pressure was 9.0 MPa when a rupture disc burst. From Table 3 the expected pressure would have been about 14 MPa for complete combustion. The present data showed a more gradual rate of pressure rise when compared with the data from the previous test. An initial pressure rise to a sustained level of 6 MPa took about 4 msec. After an additional 15 msec the pressure resumed a slow, accelerated rise to the burst pressure of 9.0 MPa. The time from current discharge to burst pressure was about 30 msec, which is slow for a practical igniter. Possibly, only a portion of the LP burned during the first 4 msec.

The remaining tests with the hydrogen, oxygen and argon atmosphere were performed at lower initial gas pressures. Tests 4, 5 and 6 were performed with an initial pressure of 0.34 MPa and resulted in partial combustion of the LP. Test 4 showed an initial pressure rise which was much faster than for the cases where spark ignition was used and, also, the peak pressure was higher. However, the pressure was not sufficient to sustain complete combustion of the LP. In test 5 the injection velocity was higher than in test 4 and the ignition performance was marginally better. In practice, higher injection velocities mean shorter injection times for a given LP mass, which is desired. Test 6 was similar to tests 4 and 5. The thicker jet did not make much difference.

The last test was performed with only argon and despite the high initial pressure of 8.3 MPa, the LP did not burn completely. Photography and pressure data revealed that it only partially decomposed.

III. FUEL AIR IGNITER

1. BACKGROUND

An earlier study[21-23] at the BRL is used as a basis for examining the feasibility of using fuel and air as an igniter. In that study, aviation grade JP4 was injected into a chamber prepressurized with air with the objective of evaluating fuel and air as a gun propellant. The results of that study are directly applicable to an igniter for a regenerative LP gun. If the igniter is mounted external to the gun chamber, the combustion takes place at high pressure, and the reaction products are allowed to vent into the gun chamber. Maximum pressures obtained during these earlier tests were of the order of 138 MPa (20 kpsi). The chamber volume was 56 cm^3. If the gas from the igniter is allowed to vent into a gun chamber, then the maximum gun chamber volume, for the conditions of the earlier tests, would be limited to about 500 cm^3. This volume is about a factor of ten less than the desired goal. Nevertheless, it was considered instructive to examine the experimental parameters effecting combustion.

2. EXPERIMENTAL

The experimental set-up is described elsewhere[21-23] and is only briefly summarized here. The same fast response valve, as used in the above study on the hydrogen-air mixture for an igniter, was used as a means for injecting the fuel into a chamber prepressurized with air. The chamber was prepressurized, depending on the test, between 13.8 and 27.6 MPa. The volume of the chamber was 56 cm^3. Tests were conducted for equivalence ratios varying from about 0.6 to 2.4 (fuel rich). The fuel was injected into the chamber using various nozzles. The nozzle which gave the best results in terms of maximum pressure and maximum rate of pressure rise consisted of six holes of 0.343 mm diameter and a length to diameter ratio of 5.9. Five of the holes were equally spaced on a radius of 4.76 mm, the sixth hole was placed in the center. Injection velocities varied from 65 m/s to 210 m/s. The fuel-air mixture was ignited by a discharge of 40 kV across a 0.43 mm gap. Total energy stored in a capacitor in the discharge circuit was 32 J.

IV. RESULTS (PARAMETERS AFFECTING COMBUSTION FOR FUEL INJECTED INTO A CHAMBER PRE-PRESSURIZED WITH AIR)

The test conditions and results are given for three tests, as an example of the study, in Table 5. The parameters that were found to be important in optimizing both the maximum pressure and the maximum rate of pressure rise were the injector design, equivalence ratio and a mixing time. Several injector designs were tested. Only the results from the injector which yielded the best performance (i.e., maximum pressure and maximum rate of pressure rise) are given here. The mixing time is defined as the time between injection of one-half of the fuel and ignition by the spark. The effect of the equivalence ratio and the mixing time are described in detail in Refs. 21 and 22. The mixing time is related to the level of turbulence in the chamber and the degree of mixing between the components. Initially, when the turbulence is high, the reaction is more complete resulting in a relatively high final pressure. Later, as the level of turbulence decreases, the final pressure also decreases. With further increase in time the final pressure increases and is likely due to the improved mixing of the components. It was found in the study that the maximum pressure increased with equivalence ratio, reaching a maximum around 2.0. Also, it was found that the maximum rate of pressure rise could be approximated by a linear dependence of the log of the equivalence ratio, up to a value of about 1.6 and when the mixing time was about 18 msec.

TABLE 5. Test Results for Three Runs Illustrating the Effect of Equivalence Ratio and Mixing Time on the Maximum Pressure and the Maximum Rate of Pressure Rise.

Test No.	Loading Density g/cm^3	Equivalence Ratio	Pressure Initial MPa	Pressure Final MPa	Injection Velocity m/s	Mixing Time ms	dP/dt (max) MPa/ms
16	0.180	1.0	13.8	88	131	17.7	7.6
109	.309	1.7	20.7	243	133	11.5	59
133	.221	2.4	15.9	154	210	26.9	63

V. POWER REQUIREMENTS (FOR EITHER THE FUEL AIR OR THE HYDROGEN AIR IGNITER)

Based on our earlier review,[1] two problems were identified that required additional study. First, the power requirement for supplying the air should not place an undue burden on the available power source. Second, the volume of air must be sufficiently large so that the final ignition pressure (18 MPa) in the combustion chamber is adequate to start the regenerative process. From Ref. 1, it was estimated that 86 liters of air (STP) would be required for a fuel-air igniter, assuming stoichiometric combustion, to achieve a final equilibrium pressure of 20.6 MPa in a 5000 cm^3 chamber. Since this calculation did not include heat losses, it is used here as a basis for estimating the power requirement. For comparison, the volume of air required for a hydrogen-air igniter would also be comparable (from Table 2, 85 and 101 liters of air were estimated to achieve a final pressure of 17.2 MPa and 20.7 MPa, respectively). For purposes of estimating the power requirements, a value of 86 liters (STP) is assumed as being sufficient to achieve the required chamber pressure.

The power required for operating an air compressor, assuming 50% efficiency, was estimated based on an ideal gas and the adiabatic power required to generate a required air flow. The required air flow is based on two firing rate cases. First, the firing rate of the present 155-mm M109A2/A3 system, which is four rounds per minute, followed by three rounds in one minute, followed by a sustained rate of one round per minute. Second, a firing rate of a proposed 155-mm Advance Field Artillery System with a firing rate of four rounds in 15 seconds, followed by a sustained rate of six rounds per minute. For purposes of these calculations, the sustained rate is taken as an equilibrium condition, that is, the compressor should be capable of delivering sufficient air to maintain a constant output pressure during the sustained firing rate. In order to accomodate the initial higher firing rates, a reservoir storage tank is required. Additional assumptions for the calculations are:

Volume of storage tank: 0.02831 m^3 (1 ft^3)
Input pressure to compressor: 1 atm (air)
Output pressure from compressor: 13.8 MPa (for cases 1 and 2, 6.90 MPa for case 3, summarized below)
Compressor efficiency: 50%

The adiabatic power required for operating a compressor may be expressed as:

$$\text{Power} = (Q\ P1\ Z\ /(1 - k)$$

where Q = flow rate
P1 = input pressure
k = specific heat ratio (for air = 1.4)
Z = (P2/P1) exp (-1/k)
P2 = output pressure

From Ref. 1, the assumed required air flow rate, for the two equilibrium cases, is 1.43 and 8.6 liter/sec (0.0086 m^3/s). Assuming a compressor operates at 13.8 MPa output pressure and at a sufficient capacity to maintain a constant air supply for the steady state firing conditions described above, then the required power for the two firing rate cases are 3.0 and 17.9 hp. The results are given in Table 6 and are compared with a third less restrictive case where the output pressure of the compressor was reduced to 6.9 MPa.

TABLE 6. Air Compressor Requirements for Firing a 155-mm RLPG Using an Igniter Operating on Air and JP4. 86 liters of air is assumed for firing cases 1-3.

Firing Case	Firing Rate Conditions	Assumed Flow Rate liter/sec	Pump Output Pressure MPa	Tank Equilibrium Pressure MPa	Pump Power hp
1	4 rds 1st 15 sec,	1.43	13.8	12.6	3.0
	6 rds/min for 3 min,			8.0	
	1 rd/min (equilibrium case)			8.0	
2	4 rds 1st 15 sec	8.6	13.8	13.0	17.9
	6 rds/min (equilibrium case)			13.0	
3	(same as case 2)	8.6	6.9	6.1	13.7

The critical problem shown in Table 6 is the flow rate. For example, firing case 2 and 3 require 8.6 liter/sec of air at STP. The size of a compressor to deliver this flow rate, summarized in Table 7, requires a displacement of 600 cm^3, sufficiently large to raise questions on systems integration. On the other hand, if LP can be used to supplement the fuel and air, as in case 4, then the size of the compressor could be significantly reduced. A solution, therefore, seems to be one where the fuel air requirement is reduced by supplementing the fuel and air with the LP.

TABLE 7. Size of Various Compressors to Satisfy the Required Flow Rate for a Fuel Air Type of Igniter for a 155-mm RLPG.

Firing Case (Table 6)	Flow Rate liter/sec	Displacement cm^3	rpm
1	1.43	100	1720
2, 3	8.6	600	1720
4	0.86	60	1720

VI. COMPRESSION TYPE OF IGNITER

A compression initiation system is the only ignition concept under study which is completely mechanical. The concept does not rely on pyrotechnic primers or high voltage electrical power sources. The system can be activated remotely or via a conventional lanyard.[24] Compression ignition has been proven in a liquid propellant gun system[24] and the concept has been employed in the modern Diesel internal combustion engine for many years. The concept uses a piston to adiabatically compress a gas, usually air, thus raising the temperature and pressure of the gas. A fuel or monopropellant is introduced into the high temperature gas where it then ignites and combusts.

Two compression ignition techniques exist. The first technique injects the propellant prior to compression of the gas. The propellant initially is in the chamber and is then compressed with the gas as the piston completes its stroke. This type of approach requires high compression ratios due to heat losses to the propellant. Also, one cannot control the burning surface of the liquid propellant. Regardless of the problems, this concept was successfully employed in a bulk-loaded, small caliber liquid propellant gun system.[24] To combat the higher heat losses, moderately high compression ratios of 50-75, were used in the study to achieve reliable ignition. The propellant used was an alkyl nitrate-based propellant. This propellant has a higher shock sensitivity than the present hydroxylammonium nitrate based propellants. The higher sensitivity may have improved the reliability of the system in igniting the propellant. Also, the total amount of propellant ignited was fairly small, less than 5 cm^3. The igniter for the 155-mm RLPG will require greater than 150 cm^3 of liquid propellant in order to achieve the desired pressure in the combustion chamber. While this concept was proven in small caliber and in propellant characterization studies at Princeton Combustion Research Laboratory,[25] the concept does not appear attractive for igniting larger quantities of liquid propellant because of the large initial volume needed for high compression ratios and the erratic combustion behavior of a large bulk-loaded charge.

The second concept injects the propellant after compression of the gas. The concept is similar to the Diesel engine. The technique has lower heat losses and provides greater control over the injection process. The system is more complex since some type of high pressure injection system must be devised. The propellant may be injected using an outside injector pump or a regenerative injector within the combustion chamber. Due to the high combustion pressures (up to 100 MPa in the igniter), outside injection pumps may not be feasible. A simple regenerative injector similar to the main combustor of the gun would be better suited to perform the job of pumping the liquid propellant into the igniter combustion chamber. In a Diesel engine, a piston compresses air to pressures between 4 and 8 MPa and temperatures between 800-1000 K.[26] Compression ratios between 15 and 22 are typical. These conditions should be sufficient to ignite the HAN-based monopropellants.

VII. DISCUSSION AND CONCLUSIONS

1. HYDROGEN AND AIR IGNITER

It appears that hydrogen mixed with air could be used as an igniter for achieving the required pressure of about 18 MPa within 5 msec. The primary uncertainty is the time to reach the required pressure. Enhancement of the reported flame speeds at constant pressure conditions could be expected when burned at constant volume. Increasing the early gas generation rate could also be achieved by a multi source type of igniter or a plasma plug type of igniter. Because of the uncertainty in the time to reach maximum pressure, it would be necessary to perform actual tests in chambers with the desired geometry before this approach could be considered viable.

It may also be possible to reduce the initial volume of hydrogen by augmenting the hydrogen and oxygen with LP. One approach was examined in this study, however the conditions of the one test, which had sufficient hydrogen and oxygen and LP to reach the desired pressure, generated a very rapid pressure rise. The pressure rise was much less than the required time of 5 msec. In addition, the maximum pressure based on the NASA-Lewis model would have been about 5% too low, not including heat losses which would further reduce the pressure. Extrapolating the volume of hydrogen required for a 1000 cm^3 chamber (from Table 2) and comparing with the conditions for the 1000 cm^3 case in Table 3, shows that the volume of hydrogen could be reduced per test by a factor of 2.4 by augmenting the hydrogen with LP.

One test with LP augmentation (No. 3, where maximum pressure was not reached due to rupture of a safety disc) resulted in complete combustion, however the pressure rise rate was much too slow. The maximum predicted pressure for this test was 14.0 MPa, neglecting heat losses. Although this pressure is only 22% too low from the igniter design goal of 18 MPa, it is interesting to note that the volume of hydrogen was a factor of 4.7 less than the corresponding case in Table 2.

Based on the above studies, we conclude that for large caliber weapons requiring chamber volumes of several thousand cubic centimeters, the required volume of hydrogen would require several of the commercially available storage devices in order to reduce the logistical impact of resupply during extended firing missions. For smaller caliber weapons mounted in a vehicle or for laboratory testing, the hydrogen storage devices could be considered. Because of the uncertainty in the rate of combustion for the igniters that were examined, we further conclude that additional tests should be performed before guidelines can be offered for the design of an igniter for regenerative injection liquid propellant guns. However, if the required maximum pressure of 18 MPa can be relaxed, then some preliminary guidelines for an igniter could be formulated based on the present study and using either hydrogen plus air or hydrogen plus air augmented with LP.

The important issue of safety in the use of hydrogen was not addressed in this paper.

2. FUEL AIR IGNITER

Experimental parameters that can have a significant effect on the combustion and hence maximum pressure and rate of pressure rise are the type of injector, the degree of mixing of the fuel and air, and the equivalence ratio. Conditions were summarized which would likely provide an acceptable igniter for gun chambers less than 500 cm^3. For larger chambers the problem becomes one of supplying the required air flow rate from a system which does not impose burdens on the available space and power supply. For a 155-mm weapon system, and when firing at rates envisioned for the 1990 time frame, the size of the compressor would likely be prohibitively large. For this reason, if further studies are conducted with this approach, it is recommended that the fuel and air be supplemented with the liquid propellant.

3. COMPRESSION TYPE OF IGNITER

The major parameters which affect the performance of a compression type of igniter are the compression ratio, the initial temperature of the gas, the heat transfer to the propellant, and the physical state of the injected propellant (i.e., the velocity and size density distributions). Of the two types of compression type igniter concepts examined, the regenerative injection ignition technique appears more feasible for use in a large caliber gun. The large propellant quantities that are necessary preclude using the pre-injection igniter since very large compression ratios would be required. Lower compression ratios can be used in the regenerative system. The pressure and temperature generated by the compressed gas at compression ratios of 15 to 22 should be sufficient to achieve ignition and sustained combustion.

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