AD

AD-E402 642

Technical Report ARAED-TR-94023

ADVANCED PROPULSION CONCEPT: STEP CHAMBER FOR BULK-LOADED GUN

A. J. Bracuti
D. S. Chiu
A. K. MacPherson

June 1995

COMMITTED TO EXCELLENCE
US ARMY
TANK AUTOMOTIVE AND
ARMAMENTS COMMAND
ARMAMENT RDE CENTER

U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Armament Engineering Directorate

Picatinny Arsenal, New Jersey

Approved for public release; distribution is unlimited.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE June 1995	3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE ADVANCED PROPULSION CONCEPT: STEP CHAMBER FOR BULK-LOADED GUN	5. FUNDING NUMBERS
6. AUTHOR(S) A. J. Bracuti, D. S. Chiu, and A. K. MacPherson	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSES(S) ARDEC, AED Energetics Warheads Division (AMSTA-AR-AEE-BR) Picatinny Arsenal, NJ 21005-5001	8. PERFORMING ORGANIZATION REPORT NUMBER
9.SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(S) ARDEC, IMD STINFO Br. (AMSTA-AR-IMC) Picatinny Arsenal, NJ 07806-5000	10. SPONSORING/MONITORING AGENCY REPORT NUMBER Technical Report ARAED-TR-94023
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The military gun community throughout the world has tried to develop bulk-loaded liquid propellant (LP) gun systems because they offer conceptually a great advantage over solid propellant guns.

Until now, bulk-loaded guns have not been fielded because of ballistic problems attributed to a combination of combustion instabilities and fluid dynamics. A new chamber concept, step chamber, was developed at ARDEC to control the combustion instabilities and fluid dynamics.

This report describes the design of the step chamber and also presents comparative ballistic data obtained from both normal straight chambers and step chambers. The step chambers tested include 1, 2, and 3-step configurations. The data suggest that the incorporation of steps in the combustion chamber wall does, indeed, correct the ballistic problems associated with bulk-loaded LP guns. An explanation is proffered for the efficacy of the step chamber.

SUBJECT TERMS Bulk-loaded liquid propellant gun Combustion chamber Combustion	15. NUMBER OF PAGES 20
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01 280-5500
Prescribed by ANSI Std. Z39-18
298-102

Standard Form 298 (Rev. 2-89)

CONTENTS

Accesion For	
NTIS CRA&I	☑
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and / or Special
A-1	

INTRODUCTION

For many years the gun community has tried to develop a reliable bulk-loaded liquid propellant gun (BLPG) system. This system employs a combustion chamber or cartridge filled with liquid propellant (LP) as a monolithic propelling charge. Motivation for this interest was based on BLPG's potential advantages over current solid propellant (SP) and regenerative LP gun systems. These advantages are:

- Superior performance - The highest possible loading density can be achieved in a BLPG. This results in an extremely high energy/density propelling charge which will deliver superior performance.

- Design simplicity - The BLPG is much less complicated than the regenerative liquid propellant gun. There are no seals or moving hardware parts which are sources of mechanical failure. Also, the elimination of these hardware parts reduces the weight of the gun itself.

- Low cost - Cost of BLPG fabrication is comparable to that of a solid propellant gun. Guns in the field could also be directly converted to bulk-loaded LP guns. This represents a potentially huge cost savings for upgrading present capabilities to meet future requirements.

Despite these advantages, the BLPG has never emerged beyond the exploratory development stage because of its apparent lack of ballistic reliability. Historically, small to medium caliber BLPG tests have yielded nonreproducible pressure-time profiles that exhibited pressure spikes and oscillations with accompanying erratic muzzle velocities. Large caliber efforts have resulted in similar histories with the added problems of occasional breech blows and explosions. Soon, consensus opinion was that a BLPG was not feasible because its combustion and ballistics were not controllable. As a result of this opinion, all government BLPG research and development (R&D) was stopped by congressional order in the late 1970's.

In 1983, a Defense Advance Research Projects Agency (DARPA) sponsored LP workshop (ref 1) concluded that the BLPG concept in its present form was not a practical system, but suggested substitution of viscous non-Newtonian LPs for normal low viscosity LPs as a possible remedy to the problem. The workshop's rationale was that higher viscosity would beneficially affect the fluid dynamics which in turn would dominate or better control the combustion and ballistics.

Subsequent U.S. Army Armament Research, Development and Engineering Center (ARDEC) investigations (ref 2) have shown that viscosity does, indeed, affect LP combustion, but apparently not enough to control the interior ballistic cycle. These studies also demonstrated that igniter configuration can affect LP combustion. These two observations suggested that the BLPG ballistic problem is not intractable and it was concluded that combustion might be controlled by some physical mechanism or combustion chamber design alteration. This led to the hypothesis of a step combustion chamber configuration to control bulk-loaded LP ignition and combustion and the resulting ballistics.

This paper summarizes a comparison study of the performance of the standard M55 20-mm round (ball powder propelling charge) with a similar round using a BLPG step chamber containing Otto Fuel II LP.

EXPERIMENTAL

A single-shot 20 mm test fixture was fabricated (ref 3) from a standard 20-mm gun by boring out its combustion chamber so that it could accept step-forming inserts without sacrificing required combustion chamber volume. The chamber and barrel were instrumented with pressure gages. A schematic of this fixture is presented in figure 1.

All LP shots in the tests were made with zero ullage using Otto Fuel and baseline SP shots were made with ball powder. Liquid propellant charges were increased by enlarging the diameter of a fixed-length chamber with cylindrical inserts with appropriate diameters.

RESULTS AND DISCUSSION

Traditional BLPG Model

In this model (ref 4), a spherical bubble is initially formed upon ignition. Burning inside the bubble produces lower density gases which accelerate toward liquid interface. This results in the formation of an expanding burning cavity with a concave leading surface penetrating the LP. This cavity is known as the Taylor cavity.

The column of liquid behind the projectile is compressed slightly as the Taylor cavity penetrates deeper, until the projectile starts to move. As the projectile moves, the Taylor cavity penetrates more rapidly, and its leading surface detaches from the chamber wall and forms a tunnel-like cavity that traverses the entire length of the propelling charge (maximum length/diameter).

In addition to Taylor instability burning, there is another burning mechanism. Inside the Taylor cavity, gases moving over the liquid cause turbulent surface interactions (Helmholtz instabilities), much like white caps on the ocean, which strip droplets from the liquid surface that burn extremely fast. Helmholtz instabilities produce mass generation rates which accelerate burning uncontrollably and cause the observed chamber overpressures and erratic pressure oscillations. This problem can be exacerbated by multiple Taylor cavity formation.

Based on this model, the rationale used to control burning is to permit formation of only one Taylor cavity and to minimize the Helmholtz instabilities within it by maintaining a limited Taylor cavity depth during the combustion cycle. In theory, this should be achieved by increasing Taylor cavity diameter faster than it can penetrate the liquid column. As the diameter increases, the area of leading surface of the Taylor cavity increases and the curvature gets flatter. The mass generation and associated pressure now primarily depends on increasing the surface area of the moving Taylor cavity front. In this way, LP combustion is better controlled.

New Step Chamber Design

The combustion chamber design used to control Taylor cavity growth has a discontinuous surface (steps) and a volume smaller at the breech-end than at the projectile end. Specifically, the chamber consists of a coaxial series of cylindrical chambers with appropriately selected exceedingly larger diameters. To ensure the formation of only one Taylor cavity, the diameter of the first chamber is quite small.

One proposed mechanism for step chamber efficacy is that after ignition the burning Taylor cavity expands isotropically until it contacts the chamber wall. Then it expands preferentially in the axial direction until it reaches first step where it detaches from the wall. After this, the cross-section of the Taylor cavity becomes larger with a flatter but larger leading surface and reattaches to the wall. The larger surface area increases the mass generation rate and the Taylor cavity is accelerated to the next step where this process is repeated. Thus, in a step chamber, the Taylor cavity is constrained to expand in a controlled step-wise manner to ensure proper mass generation with resulting smooth reproducible pressure-time histories.

The critical feature of this concept is that the chamber diameter must be increased stepwise rather than by a smooth gradual increase in chamber diameter. A conical chamber without these discrete steps <u>does</u> <u>not</u> improve bulk-liquid combustion. The steps are necessary for controlled burning .

Test Results

Table 1 contains data from a series of test firings which address the effects of various step configurations on ballistic performance of Otto fuel and ball powder. An illustration of the excellent performance of the BLPG and its potential problems can be appreciated by comparing the ballistics of LP charges with SP charges with comparable impetus. Shot 1 (impetus, 31,696 J) has a velocity of 981 m/s and a maximum peak pressure of 427 MPa. In contrast, shot 2 using a SP charge with a slightly higher impetus (32,696 J) has a lower muzzle velocity of 875 m/s and a lower maximum peak pressure of 247 MPa. These data suggest that performance optimization of this 20-mm system with Otto fuel LP in a straight chamber would yield significantly higher velocity than could be attained with SP, but possibly at the risk of an unacceptable if not disastrous overpressure.

The problem is how to extract performance from the LP charge without paying a pressure penalty. The LP charge impetus in shot 3 was reduced to 20,697 J which resulted in a muzzle velocity of 730 m/s which is lower than the velocity observed with the SP and a peak pressure of 358 MPa which is higher than the peak pressure observed with the SP. It was concluded that simply reducing the LP charge size is not the answer to this problem.

Shot 4, a 32.7 g LP charge fired in a 1-step chamber, delivered a 925 m/s muzzle velocity with a peak pressure of 346 MPa. Although the impetus of this LP charge is less than that of shot 2 SP charge, its muzzle velocity is significantly greater than the velocity of shot 2 and its peak pressure is significantly less than obtained with LP shot 1.

To resolve the influence of charge size on these results, shot 5, which is only 6% larger than shot 3 (straight chamber shot), was fired in a two-step chamber. Shot 5 yielded a velocity of 781 m/s and a peak pressure of 231 MPa compared to a shot 3 velocity of 730 m/s and a peak pressure of 385 MPa. It was concluded that it is possible to reduce peak pressure without sacrificing muzzle velocity by incorporating a surface discontinuity or step in the chamber.

Two shots were fired in a three step chamber to determine if better performance without a pressure penalty could be attained. The target velocity was a value greater than 981 m/s and the target pressure maximum was less than 427 MPa. To avoid any potential problems, the initial LP charge fired (shot 6, 24,507 J) in a 3-step chamber had an impetus that approximated the average impetus of the two LP charges previously fired in step chambers. In this case, shot 6 yielded a muzzle velocity of 866 m/s and a peak pressure of 272 MPa. These values fall midway between the respective velocity and peak pressure values for shot 4 and shot 5. The velocity and peak pressure values in shot 6 (1,069 m/s and 408 MPa) met these targets.

Another major problem with the BLPG is that it is not as ballistically controllable as the SP system. This lack of controllability manifests itself in erratic muzzle velocities and nonreproducible pressure-time profiles. A series of four shots were fired to see if reproducible ballistics could be achieved with a 3-step chamber configuration. The ballistic targets were a reproducible muzzle velocity greater than 981 m/s and a reproducible maximum peak pressure of less than 427 MPa. Data for equivalent LP charges fired in this 3-step chamber configuration are shown in table 2. The average velocity for these shots is 1,078 m/s with a standard deviation of 9 m/s which indicates that reproducible ballistics are possible in a step chamber BLPG.

Although the initial 3-step chamber ballistics compared quite well with the ballistics observed in laboratory SP shots, an attempt was made to match or exceed the velocity of the standard 20-mm gun by modifying the 3-step design to accept a larger LP charge. The standard 20-mm M55 A2 round was found by this laboratory to have a muzzle velocity of 1,030 m/s with a standard deviation of 15 m/s and a peak pressure of 415 MPa. The data in table 3 reveal that the larger LP charge in the modified chamber resulted in a higher muzzle velocity of 1,166 m/s with a standard deviation of 10 m/s and an average higher peak pressure of 520 MPa.

An overlay of the pressure-time traces for these LP shots (fig. 2) reveals four curves which for the most part superpose each other. At the outset of ignition, each shot is similar with ignition starting between 0.2 to 0.3 ms with small but equal pressure spikes due to the igniter. Each pressure-time curve has a double peak with pressure oscillations on the first peak. The combustion pressure rise for each shot is virtually identical with the peak occurring at 0.8 ms with an average value 520 MPa. The second peak occurs at 1.1 ms, but its peak pressure differs slightly from shot to shot. The downside curves of this peak almost superpose. These data illustrate that better combustion reproducibility are possible with a step chamber.

It is quite possible that the oscillations exhibited by the first peak can be reduced or minimized by optimizing the 3-step configuration in this system. It also may be possible to change the general shape of the pressure-time profile by using a different step configuration. An effort is now underway to scale-up to 40 mm.

Finally, a new model was proposed that uses fluid supercriticality, a dark pyrolytic zone, a luminous flame zone, and thermal transport prederties to explain the BLPG combustion and ballistics mechanism.

CONCLUSIONS

Liquid propellant burning in the bulk-loaded liquid propellant gun can be modified with the use of a step combustion chamber. In addition, with the correct step chamber configuration controlled, reproducible ballistics can be obtained.

Table 1
Effect of chamber configuration on otto fuel and ball powder ballistics

Shot	Steps	Prop	Mass, G	Impetus, J	Velocity, m/s	Pressure, MPa
1	0	LP	36.6	31696	981	427
2	0	SP	30.7	32696	875	247
3	0	LP	23.9	20697	730	358
4	1	LP	32.7	28318	925	346
5	2	LP	25.4	21996	781	231
6	3	LP	28.3	24507	866	272
7	3	LP	43.6	37758	1069	408

Table 2
20-mm BLPG repro shot data using Otto fuel for initial 3-step chamber configuration

Mass, G	Impetus J	Velocity, m/s	Pressure, MPa
47.0	40702	1080	401
47.0	40702	1085	406
45.6	39489	1067	385
46.0	39836	1082	400

Table 3
20-mm BLPG repro shot data using Otto fuel with enhanced 3-step chamber configuration

Charge mass, g	Projectile, mass, g	Impetus J	Temp, °C	Velocity, m/s
56.7	99.1	49102	15	1156
56.8	98.9	49188	15	1153
56.9	98.8	49275	18	1166
56.5	98.1	49929	18	1173
56.8	99.1	49188	18	1174

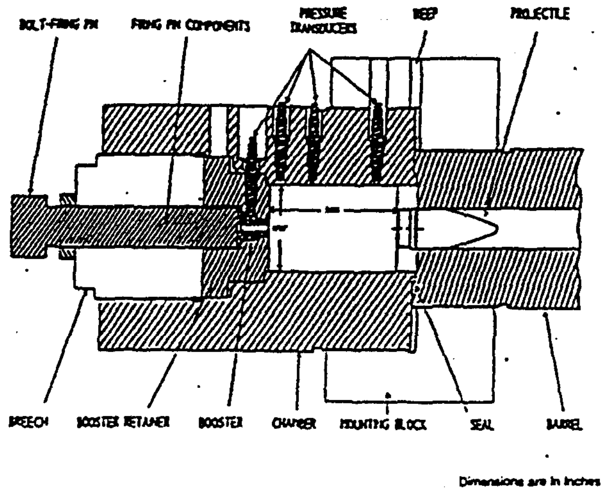

Figure 1
20-mm single-shot firing fixture

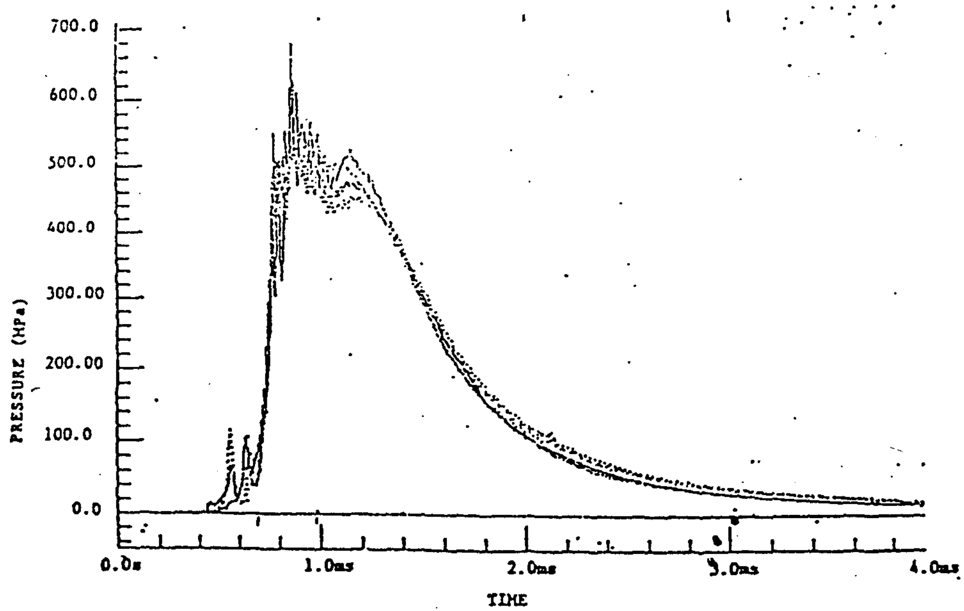

Figure 2
Pressure-time traces of five shots in same 3-step chamber

REFERENCES

1. Goddard, T.P., "DARPA Advanced Cannon Propellant (ACP) Workshop on Diagnostics Proceedings", Report BDM/M-TR-TR-0017-81, The BDM Corp, Monterey, CA, November 1981.

2. Chiu, D.S., Bracuti, A.J., Hui, P., and Sterbutzel, G., Bulk Mode Testing of Non-Newtonian Liquid Propellants, Proceedings of 1987 Propulsion Meeting, CPIA Publication No. 480, Vol. 1, pp. 347-358, San Diego California, December 1987.

3. Talley, Robert L. and Owczarczak, John A., Veritay Report C90-001, Veritay Technology, Inc., East Amherst, NY, September 1991.

4. Burnett, W., "An Interior Ballistics Model for Liquid Propellant Guns", Indian Head Technical Report 444, Naval Ordnance Station, Indian Head, MD, September 1976.

DISTRIBUTION LIST

Commander
Armament Research, Development and Engineering Center
U.S. Army Armament, Munitions and Chemical Command
ATTN: AMSTA-AR-IMC (3)
AMSTA-AR-GCL
AMSTA-AR-AEE (4)
AMSTA-AR-AEE-B, A. Bracuti (10)
Picatinny Arsenal, NJ 07806-5000

Administrator
Defense Technical Information Center
ATTN: Accessions Division (12)
Cameron Station
Alexandria, VA 22304-6145

Director
U.S. Army Material Systems Analysis Activity
ATTN: AMXSY-MP
Aberdeen Proving Ground, MD 21005-5066

Commander
Chemical/Biological Defense Agency
U.S. Army Armament, Munitions and Chemical Command
ATTN: AMSCB-CII, Library
Aberdeen Proving Ground, MD 21010-5423

Director
U.S. Army Edgewood Research, Development and Engineering Center
ATTN: SCBRD-RTT (Aerodynamics Technical Team)
Aberdeen Proving Ground, MD 21010-5423

Director
U.S. Army Research Laboratory
ATTN: AMSRL-OP-CI-B, Technical Library
Aberdeen Proving Ground, MD 21005-5066

Chief
Benet Weapons Laboratory, CCAC
Armament Research. Development and Engineering Center
U.S. Army Armament, Munitions and Chemical Command
ATTN: SMCAR-CCB-TL
Watervliet, NY 12189-5000

Director
U.S. Army TRADOC Analysis Command-WSMR
ATTN: ATRC-WSS-R
White Sands Missile Range, NM 88002