AD-A258 887

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IS A LIQUID PROPELLANT GUN A VIABLE OPTION FOR THE FUTURE MAIN BATTLE TANK IN THE UNITED STATES ARMY?

A thesis presented to the Faculty of the U.S. Army Command and General Staff College in partial fulfillment of the requirements for the degree

MASTER OF MILITARY ART AND SCIENCE

by

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B.S., United States Military Academy, 1978
M.B.A., Florida Institute of Technology, 1987

Fort Leavenworth, Kansas
1992

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
5 June 1992

3. REPORT TYPE AND DATES COVERED
Master's Thesis, 1 Aug 91 - 5 June 92

4. TITLE AND SUBTITLE
Is a Liquid Propellant Gun a Viable Option for the Future Main Battle Tank in the United States Army?

5. FUNDING NUMBERS

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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Ft. Leavenworth, KS 66027-6900

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This study is an examination of three areas: historical U.S. liquid propellant development, liquid propellant logistical considerations and the technical considerations in the application of a liquid propellant gun in a combat vehicle. The study examines the potential and demonstrated benefits of liquid propellants for the military. The study uses the solid propellant guns technology as the baseline to conduct a comparison of liquid propellant guns in the same operational requirements. The analysis by the author on the logistical impacts focuses on the industrial base conversion, production costs of propellants, ammunition transportation requirements, and liquid propellant demilitarization. The analysis continues with a discussion on combat vehicle survivability, firepower, and mobility. This study concludes that a liquid propellant gun is a viable option for the Army to pursue. The primary logistical advantage with liquid propellant is volume efficiency which impacts storage, transportation, and ammunition processing. A tank equipped with a liquid propellant gun has advantages over a solid propellant gun in rates of fire, basic ammunition load capability, survivability of the system, and vehicle weight reductions.

14. SUBJECT TERMS
Liquid Propellants, Solid Propellants, Bulk Loaded Liquid Propellant Gun, Regenerative Liquid Propellant Gun, Main Battle Tank, Weapon System Study, Firepower

15. NUMBER OF PAGES
112

16. PRICE CODE

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

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THESIS APPROVAL PAGE

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The opinions and conclusions expressed herein are those of the student author and do not necessarily represent the views of the U.S. Army Command and General Staff College or any other governmental agency. (References to this study should include the foregoing statement.)

ABSTRACT

IS A LIQUID PROPELLANT GUN A VIABLE OPTION FOR THE FUTURE MAIN BATTLE TANK IN THE UNITED STATES ARMY by MAJ Curtis L. McCoy, USA, 112 pages.

This study is an examination of three areas: historical U.S. liquid propellant development, liquid propellant logistical considerations and the technical considerations in the application of a liquid propellant gun in a combat vehicle. The study examines the potential and demonstrated benefits of liquid propellants for the military. The study uses the solid propellant guns technology as the baseline to conduct a comparison of liquid propellant guns in the same operational requirements.

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This study concludes that a liquid propellant gun is a viable option for the Army to pursue. The primary logistical advantage with liquid propellant is volume efficiency which impacts storage, transportation, and ammunition processing. A tank equipped with a liquid propellant gun has advantages over a solid propellant gun in rates of fire, basic ammunition load capability, survivability of the system, and vehicle weight reductions.

ACKNOWLEDGEMENTS

I would like to recognize several people whose help and support have made this study possible. First, I want to thank my wife, Eleane and my children, Sarah, Jason and Andrew. This thesis would not have been completed without their total love, prayers, spiritual support, understanding and hours of long editing and typing support.

Second, I would like to extend my appreciation to the members of my research committee, Mr. James F. Fox, Mr. Dwain H. Skelton, and COL Wilfred Dellva. Their patience and objective insights were instrumental in my completion of this thesis.

Third, I would like to thank the members of my A221, Research Methodology II, seminar group. The group, led by COL Robert A. Gimbert, provided the logistical insights that were critical to effective analytical review of the project. The group provided the needed encouragement during the winter months of Term II which assisted me in staying on course.

Finally, I would like to thank the staff in the Combined Arms Research Library. Especially Craig McLean and John Rogers for their insight on how to find research materials, professional encouragement and assistance which formed a foundation for the completion of my thesis.

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CHAPTER 1

DEFINING THE PROBLEM

Introduction

The primary purpose of this thesis is to examine whether the Army should continue development and adopt the liquid propellant gun (LPG), or remain solely with the current projected improvements of the solid propellant gun (SPG) for the future main battle tank. The focus of this discussion will be on the several key elements of the life cycle process of both technologies with respect to the future main battle tank. A baseline combat vehicle, the M1A1 Abrams Main Battle Tank, will be used to compare SPG and LPG technologies.

Today's Army's arsenal of weapon systems relies heavily on one type of propulsion delivery system. Solid Propellants (SP) have been the principal means of delivery for conventional munitions. SP charges have met the need for the military for decades. Even with the currently available and emerging technologies, the advances in SPs have been relatively minor. These small advances in SPs have been achieved at great expense. Advances have been limited at best!

Background

Slow technology advances in SPs, primarily related to increased muzzle velocities in tank cannons, have forced a constant review of the state-of-the-art propulsion technologies and possible future technologies. Slow progress towards increased muzzle velocity coupled with the desire to reduce costs, and increase efficiency while meeting current mission requirements have brought about a new school of thought. In searching for new, more efficient systems in the field of propulsion, the application of Liquid Propellants (LPs) to gun systems is one possible promising option. The desired characteristic of any future gun requirement is to have lethality on the modern battlefield preferably at extended ranges greater than the effective range of the enemy's armament. For the purposes of this paper, it will be considered that ranges from 0 - 2000 m will be defined as a close range and 2000 - 3000 m will be the extended range. To achieve that end, accuracy and mass firepower are considered to be very important elements. LPs could possibly offer these advantages over SPs.

Assumptions

(1) A regenerative LPG for the M1A1 tank could be demonstrated during FY94.

(2) Reliability and maintainability characteristics are solvable on the LPG.

(3) Two basic 120mm rounds M829A1, Armor Piercing Fin Stabilized Discarding Sabot (APFSDS-T) and the M830, High Explosive Anti-tank Multipurpose with Tracer (HEAT-MP-T) will be used for all technologies.

(4) A baseline vehicle, the M1A1 Abrams Main Battle Tank, will be used to compare the different technologies.

(5) Information about the Army's current gun propulsion technologies is available for review.

(6) The LPG will have an autoloader system on the M1A1 tank or a future main battle tank.

Definitions

(1) Solid Propellant Gun (SPG), conventional propuision technology on the current Army tank fleet, is the basic chemical energy propulsion used to propel the family of cannon fired projectiles down range. The current solid propellant round consists of a projectile partially enclosed by a combustible case of granular type propellant.

(2) Liquid Propellant Gun (LPG) is a concept based on mechanical control of the amount of propellant in the compustion chamber. There are three general types of LPGs:

a. Bulk Loaded LPG: It is essentially a solid propellant gun with the necessary changes to accommodate the new propellant in the breech. The propellant initially fills the combustion chamber behind the projectile before ignition. All the propellant is ignited at one time

b. Regenerative LPG: The gas pressure in the combustion chamber pumps additional propellant into the combustion chamber during the ballistic cycle.

c. Externally - pumped LPG: An externally powered pump forces the additional propellant into the combustion chamber during the ballistic cycle.

(3) Liquid Propellant Traveling Charge Gun (LPTCG) is the concept of loading liquid propellant into a dispenser attached to the projectile. Initial acceleration is provided by burning a propellant charge in the chamber between the traveling-charge dispenser and the barrel face. The driving charge may be a solid or liquid propellant.

(4) Vulnerability - The characteristics of a system that cause it to suffer a loss of combat utility or reduction of capability to perform the designated mission(s) as a result of having been subjected to a hostile environment on the battlefield.

(5) Lethality - The ability of a system to cause the loss of, or a degradation in, the ability of a target system to complete its designated mission(s).

(6) Survivability - The capability of a system (resulting from the synergism between personnel, materiel design, tactics, techniques, procedures and doctrine) to avoid, withstand or recover in hostile (man-made and natural) environments without suffering an impairment of its ability to accomplish its designated mission.

(7) Armor Piercing Fin Stablized Discarding Sabot - This a round which is a one piece depleted uranium kinetic energy (KE) penetrator with a combustible case. It is found in the 120mm class of ammunition as a M829, a M829A1 and a M829E2 and in the 105mm class of ammunition as a M774, a M833 and a M900.

(8) High Explosive Anti-tank with Tracer - This a shaped charged warhead round which has a combustible case with a multiaction fuse. It is found in the 120mm class of ammunition as a M830 and in the 105mm class of ammunition as M456.

(9) SMART Ammunition - These are high explosive target activated "fire and forget" cannon launched munitions such as the XM943 smart target activated, fire and forget (STAFF) 120mm tank round and the armor piercing enhanced kinetic energy weapon (X-rod) round coupled with a terminal guidance.

(10) Enhanced Kinetic Energy Weapon (X-rod) - It is an advanced tank fired, guided kinetic energy projectile system capable of defeating targets at extended ranges. A superior hit probability is expected by using competing concepts, command guided or "fire and forget' guidance.

Limitations

This document will be written at the unclassified level to enable the widest dissemination of the document to the Department of Defense community. Most of the advanced technologies are classified and though not addressed in any depth here, the level of unclassified treatment will give the reader a basic knowledge of the concept.

Delimitations

The objective of this study is to concentrate on the liquid propellant gun concept. Although there is work ongoing in traveling charge propulsion and electromagnetic propulsion, the study will focus on the liquid propellant gun with primary application to the M1A1, Abrams tank.

Significance of the Study

The United States has spent and is still spending large amounts of money to develop an improved main gun platform for the tank. The tank is generally considered one of the dominant ground weapon systems on the battlefield, as was shown in the Southwest Asia (SWA) campaign during Operation Desert Storm. The tank contributes to the major success or failure in land mounted warfare. It is one of the key elements in the combined arms team for the Army ground maneuver forces in AirLand Doctrine. The need for increased lethality on the modern battlefield has always driven the requirements for a better tank cannon. The intent of this study is to show through historical, logistical and technical factors the significantly enhanced capability the liquid propellant gun might offer as a combat multiplier when it is mounted on a tank in a combined arms team.

Methodology

The primary research methodologies used in this thesis are a descriptive archival and a comparative analytical evaluation. The descriptive archival methodology is designed to concentrate in liquid gun propulsion with subheaders in combat vehicle firepower, combat vehicle survivability and combat vehicle sustainment on the future battlefield.

Past studies are an excellent source to establish a common foundation from which to start the thesis. During the review of past technology developments in LP, criteria can be determined to evaluate the potential for the system in the future. These sources are critical to providing an analytical base from which to project conclusions for the future of LPGs in tanks.

The review of past studies includes sources related to the technical design characteristics of LPG. There is a large body of information in technical reports which describes the experiments which range from bulk loading to a regenerative gun in actual hardware mounts. Due to the rapidly changing technology there appears to be questions whether a LPG is now plausible on a combat vehicle on the battlefield.

To arrive at an end state in this thesis which addresses whether LPG is an option for the future main battle tank, critical performance elements have developed from the above research materials. These elements are used as the criteria to compare the two technologies against the baseline M1A1 tank.

Chapter 1 - Defining the Problem

The primary objective in Chapter 1 is the introduction of LP as an alternate gun propulsion when compared against the current SP conventional technology which is being used on the M1A1 tank today. The introduction provides the foundation for the thesis and describes the game rules for the study by enumerating the assumptions, definitions and limitations. The chapter concludes with the study's significance and the research methodology to be used.

Chapter 2 - Survey of Literature

Chapter 2 focuses on the variety and quality of relevant research sources used by the author in the preparation if this study. The chapter is subdivided into three useful parts: historical LPG development, technical considerations and logistical considerations.

Chapter 3 - History of Liquid Propellant Development

Chapter 3 reviews the historical development of the Department of Defense (DOD) Liquid Propellant (LP) Program from the end of World War II to the present. The chapter is divided into four defined periods in which there were focused LP programs. These periods are Post World War II (1947-1950), (1950-1957), (1968-1977) and (1977 to the present). Engineering achievements and concept developments are addressed from each period.

Chapter 4 - Conventional Gun Propulsion Review

Chapter 4 summarizes the primary conventional gun propulsion concepts currently being studied in the research and development community. A brief definition of each concept is discussed followed by its advantages and disadvantages. The objective of this portion of the thesis is to develop an elementary understanding of the DOD research and development community's efforts to gain marked improvement in the solid propellant guns. This should be the foundation from which to assess the LPG.

Chapter 5 - Logistical Analysis

Chapter 5 provides the reader an analysis of the logistical impact of the LPG on the sustainment system. A direct comparison of the SPG and LPG is directed at the industrial base conversion, cost saving factors, commercial production of LP, transportation issues, manpower resupply, and demilitarization and disposal of propellants. Hopefully, the chapter will give the reader a basic appreciation of the logistical ramifications of LP.

Chapter 6 - Combat Vehicle Impact Analysis

Chapter 6 provides the reader an analysis of the LPG from the three functional tank requirements: survivability, firepower and mobility. The author conducts a subjective evaluation of the functional requirements in a direct comparison between the SPG and LPG.

Chapter 7 - Conclusions and Recommendations

The answer to the thesis is determined based on the analysis conducted in Chapters 5 and 6. It draws a conclusion of the meaning of the study. It also relates the study to other works and make recommendations for future studies.

Summary

The purpose of Chapter 1 was to explain the importance of the study and the three areas being investigated. The introduction and background outlined the need for a new gun propulsion technology, identified a possible candidate for review, drew the framework of the study, stated the described research methodology to be used throughout the effort, and the mechanical structure of the thesis by chapter. The need for a new gun propulsion system for the Army's main battle tank could not be greater than at this time. The future does not promise any near-term breakthroughs in the solid propellant arena. Concepts such as electrothermal technology are not a near-term options in solving the gun propulsion requirements of today but liquid propellant could be!

CHAPTER 2

SURVEY OF LITERATURE

Introduction

This survey of literature performs a two-fold mission. It first demonstrates to the reader the technical sources and variety of research materials used in this study. Secondly, the survey provides a basis from which further research can be conducted by any reader in the three principal study areas. The three study areas are: historical Army liquid propellant gun development, emerging gun propulsion technologies and the criteria to evaluate both them and the logistical impact of sustaining new weapon systems.

The primary source of research material was the Combined Arms Research Library (CARL) at Fort Leavenworth, Kansas. Also, the study incorporated supplemental publications and notes which were provided to or developed by the writer during a previous assignment at the U.S. Army Ballistic Research Laboratory. Additionally, the Combined Arms Command, Combat Developments activity provided information pertaining to current or ongoing development in the liquid propellant gun program.

A majority of the research material used can be divided into three categories; books, government documents and periodicals. Books provided an excellent review of trends and the development of tank cannons in combat vehicles. They also assisted in establishing the criteria to evaluate a new emerging technology against the currently employed technology. U.S. Government documents were a primary source of collecting data, from actual test firing and modeling, to evaluate the liquid propellant guns against conventional solid propellant guns. Periodicals also established additional criteria for evaluations and outside viewpoints on trends in armored vehicle developments.

This chapter is divided into three parts: historical, emerging gun propulsion technology and logistical considerations. Each section identifies the essential research material used to explore that area of interest.

Part I

Historical

There is a significant amount of research material available on the development of tanks from World War I to the present. The materials provide a very good worldwide view of current technology development but lack greatly in discussing, in any depth, emerging advanced technologies. The only clear source documents that discuss the historical development of liquid propellant propulsion are in government documents. The following is a concise summary of those critical source documents which trace the origin of the liquid propellant program in the United States with a desired cannon application in a weapon system.

Books

In Antitank, Richard E. Simpkin provides a very wide look "at what kind of doctrine, major equipment and force structure the mechanized battle as a whole, on the ground and in the air space just above it, may call for in the closing decade of this century of technological revolutions."[1] Simpkin attempts "to lead with technical arguments and the state of the art, and to look at the principles and trends of weapon systems rather than their historical origins."[2] He concludes with the impact of new weapon systems factors on training, logistics and manning.

In Technology in War: Impact of Science and Weapon Development on the Modern Battlefield, Kenneth Macksey explores the impact of technology on current and emerging weapon systems. He spans his discussion from 1915-2000. He is able to identify specific key developments on main battle tanks and trace their projected technological advancements to the year 2000.

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[1]Richard E. Simpkin, Antitank: An Air mechanized Response to Armored Threats in the 90s (Elmsford, NY: Pergamon Press, Inc., 1982), 8.

[2]Ibid.

R.P. Hunnicutt has written a series of books which provide a summarized, in depth review of the U.S. Army tank program from 1914 to the present. Firepower: A History of the American Heavy Tank, Sherman: A History of the American Medium Tank, Patton: A History of the American Main Battle Tank, and Abrams: A History of the American Main Battle Tank provide a well versed look at trends in the evolution of the armored tank force especially in types of fire control systems, gun mounting, tank guns, and automatic loading equipment.

U.S. Government Documents

"Liquid Propellant Guns," by Walter F. Morrison, John D. Knapton, and Melvin J. Bulman provides an excellent review which summarizes liquid propellant gun research in the United States. Liquid propellants have been the focus of periodic research efforts from just after the Second World War to the present.[3] This paper discusses, in depth, the historical development of bulk loaded liquid propellant guns and regenerative liquid propellant guns. The bulk of the technological summary data generated in the report is focused on the historical progression of the interior ballistics of bulk loaded liquid propellant guns and regenerative liquid propellant guns.

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[3] Walter F. Morrison, John D. Knapton and Melvin J. Bulman, "Liquid Propellant Guns," ADA188575 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, October 1987), 1.

"Liquid Propellants for Gun Applications," by Walter F. Morrison, John D. Knapton, and Guenter Klingenberg is a survey of some of the recent and ongoing liquid propellant research in both the United States and Germany. It provides a brief summary of past investigations and the limiting technology factors to liquid propellant development. The survey includes Germany's progress and major obstacles to overcome in successfully demonstrating a liquid propellant in a 105mm or greater test fixture. It concludes that liquid propellant propulsion has evolved over the past forty years into a goal to develop improved liquid propellant regenerative designs and component mechanisms and to further improve existing propellant candidates.[4]

"The Interior Ballistics of Regenerative Liquid Propellant Guns," by Walter F. Morrison, Paul G. Baer, Melvin J. Bulman, and John Mandzy is a paper which summarizes the current development of large caliber regenerative liquid monopropellant guns. Also it reviews the experimental test firing results of regenerative liquid propellant guns ranging from 0.35 inch to 105mm. The paper traces liquid propellant developed from the 1940s to the present, to include the major engineering test failures during the 1970s. It concludes that

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[4] Walter F. Morrison, John D. Knapton and Guenter Klingenberg, "Liquid Propellants for Gun Applications," ADB090195 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, January 1985), 36.

the focus of the U.S. Army liquid propellant efforts is the development and testing of a 155mm, technology demonstration fixture.[5]

"Tri-Service Plan for Liquid Propellant Technology for Gun Applications," by Richard H. Comer and Walter F. Morrison is a plan prepared by the Task Force Group for Liquid Propellant Guns and approved by the Joint Directors of Laboratories. It was not implemented. An updated version of this program was presented to the Director of Defense Research and Engineering for discussion with the House Armed Services Committee staff in August 1979, but no program was initiated. A synopsis of events since then leading to the August 1979 version of the Tri-Service Plan for Liquid Propellant Technology for Gun Applications is contained within the documentation.

"Liquid Propellant Technology Program," by Walter F. Morrison was prepared at the request of Lieutenant General D. Keith, Deputy Chief of Staff, Research, Development and Acquisition, in 1981 to develop a program which would "provide the liquid propellant technology base required to decide the advisability of developing liquid propellant guns for the

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[5]Walter F. Morrison, Paul G. Baer, Melvin J. Bulman and John Mandzy, "The Interior Ballistics of Regenerative Liquid Propellant Guns," ADA190020 (Aberdeen Proving Ground, MD: October 1987), 32.

1990s."[6] This document tied the Department of Defense services together into a Tri-Service program focused on liquid propellants.

Part II

Emerging Gun Propulsion Technologies

Books do not address in any specific detail the subject of advanced gun propulsion programs which currently revolutionize the armored combat vehicle. Most documents of that nature are classified and will not be part of this study. The largest source of unclassified materials which discusses liquid propellant guns is government technical reports. Periodicals assist in the evaluation of new technologies by identifying additional areas of consideration Periodicals contain additional thoughts on the subject which are worth review.

Books

Human Factors in Mechanized Warfare, by Richard E. Simpkin attempts "to explore in depth the basic facts of a tanker's life and their influences on how he is trained and led and how his machine is designed."[7] The book focuses on

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[6] Walter F. Morrison, "Liquid Propellant Technology Program," ADB056054 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, January 1981), 1.

[7] Richard Simpkin, Human Factors in Mechanized Warfare, (Elmsford, New York: Pergamon Press Inc., 1983): 4.

the key elements the analysts and subsystem designers must address in developing a modern combat vehicle. Simpkin is able to further address key differences between East and West in design technology philosophies.

The Dangers of New Weapon Systems, edited by William Gutleridge and Trevor Taylor is a series of inter-related papers, methods and criteria to assess current and new weapons technologies. The subjects range from criteria for evaluating the dangers and characteristics of new weapon systems, to the process of weapons development and mechanism to manage and control it.

Tank Warfare, by Richard E. Simpkin begins with a broad look at the development of tank warfare and attempts to identify trends to the present. Simpkin takes an in-depth look at the tank design factors of firepower, mobility, survivability, fightability, and design constraints. The book includes lessons learned by NATO and the Soviet Union in tank design.

U.S. Government Documents

"Liquid Propellant Traveling Charge Gun Concept", by Eugene Ashley is a report which "explores the feasibility of a liquid propellant traveling charge gun concept, which has been proposed as a means for improving the performance of high velocity guns."[8] The growth potential for a liquid propellant gun system with a traveling charge is discussed in depth with muzzle velocity measurements taken from actual firings.

"A Propulsion System Comparison Study For the 120mm Anti-Armor Cannon," by Paul G. Baer, Catherine F. Banz, Ingo W. May, and Walter F. Morrison is a study which explores the different types of near term advanced technologies impact on the performance of a 120mm high performance cannon. The investigation includes an examination of the limits to performance potential of conventional gun propulsion and compares them to the potential performance of a regenerative liquid propellant gun. The study was focused on key interior ballistic parameters which were used throughout the parametric study. The clear determining factor was the potential for increased muzzle velocity which could result in significant improvements in overall gun system effectiveness. The study used a criteria of five to ten percent increases in striking velocity as important enough to justify substantial developmental effort on such technology.[9]

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[8]Eugene Ashley, "Liquid Propellant Traveling Charge Gun Concept," ADA033971 (Burlington, VT: General Electric Company, November 1976), 1.

[9]Paul G. Baer, Catherine F. Banz, Ingo W. May and Walter F. Morrison, "A Propulsion System Comparison Study for the 120mm Anti-Armor Cannon," ADA187175 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, August 1987), 1.

"Comparison of Predicted Muzzle Flash For Solid and Regenerative Liquid Propellant Guns," by Paul G. Baer, Ingo W. May, and Walter F. Morrison is a paper which addresses muzzle flash and the associated blast issues for the charge designer and the soldier on the battlefield. The paper uses a 155mm self-propelled Howitzer as the baseline combat vehicle. The paper has an excellent discussion on the predicted potential for muzzle flash between a regenerative liquid propellant gun and a conventional solid propellant gun. The muzzle flash calculations used M30A1 propellant gun and hydroxyl ammonium nitrate (HAN) based liquid propellant, LPG 1845, for the 155mm liquid propellant gun. The reduced vehicle signature with the use of liquid propellants emphasized an implied reduction in crew and vehicle vulnerability on the modern battlefield.

"Reclassification and Grease Compatibility Studies for Liquid propellants," by William J. Cruice is a study to determine the outcome of various greases coming in contact with liquid propellants in gun fixtures. The results address the possible crew and vehicle vulnerabilities if ignition should cccur from the decomposition of the liquid propellant by this contact.

"Tech Base Propulsion Technologies Effects on Weapon System Reliability," by Faust Denicola, Walter Arnold, Gayle Beavers, Paul Crise, and Jane Krolewski is a study using U.S. Army Materiel Systems Analysis Activity (AMSAA) methodology for estimating the reliability of weapons systems early in development even prior to any system testing. The study addresses four types of advanced gun propulsion: advanced solids propellant (SP), liquid propellant (LP), electromagnetic (EM), and electrothermal (ET) for three different weapon system types: artillery, armor and air defense. The study identifies the high risk subsystems on the above listed advanced weapon systems technologies.

"The Effect of Propellant Composition on Secondary Muzzle Blast Overpressure," by George E. Keller studies the secondary muzzle flash from the reignition of a mixture of fuel-rich exhaust gases and the entrained air in cannon systems. The study examines three factors which affect secondary muzzle flash: chemical factors, physical factors and mechanical factors.

"Sensitivity Characterization of Low Vulnerability (LOVA) Propellants," by M.S. Kirshenbaum, L. Avrami and B. Strauss is a technical report that describes the results of an investigation that was conducted to determine the sensitivity properties of a number of candidate LOVA propellants. The report includes thermochemical properties in the comparison between the LOVA candidates and the current conventional propellants.[10]

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[10] M.S. Kirshenbaum, L. Avrami and B. Strauss, "Sensitivity Characterization of Low Vulnerability (LOVA) Propellants," ADA126130 (Dover, NJ: U.S. Army Armament Research and Development Command, Large Caliber Weapon Systems Laboratory, March 1983), 1.

"Low Temperature Properties of HAN-Based Liquid Propellants," by John D. Knapton and Walter F. Morrison is a study to examine the dynamic viscosity of potential liquid propellants from room temperature to about -65 degrees Celsius.

"Combustion Processes in Consolidated Propellants," by Ingo W. May and Arpad A. Juhasz is a memorandum report which exams the research efforts for higher muzzle velocities in gun propulsion through consolidated propellants as a means of increasing the charge-to projectile mass ratio for a given chamber volume.[11]

"Liquid Propellants For Gun Applications," by Walter F. Morrison, John D Knapton, and Guenter Klingenberg is a technical report of the state-of-the-art liquid propellant technology, its potential and limitations, as well as a prognosis for its development and application. The potential benefits of the liquid propellant portion of the survey addresses advantages in the areas of technical, system performance, operational potential, logistical, and financial. In particular the report addresses the operational potential in design criteria, such as Nuclear Biological and Chemical

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[11] Ingo W. May and Arpad A. Juhasz, "Combustion Processes in Consolidated Propellants," ADA101163 (Aberdeen Proving Ground, MD: U.S. Army Armament Research and Development Command, Ballistic Research Laboratory, May 1981), 1.

protection, vulnerability reduction, mobility issues, transportability and resupply related to a liquid propellant gun system.[12]

"Liquid Propellant Guns," by Walter F. Morrison, John D. Knapton and Melvin J. Bulman is a study which includes a comparison of the performance of monopropellants, bulk loaded propellant guns, and conventional solid propellant guns.

"The Accuracy of Tank Main Armament", by Joseph M. Olah and Fred L. Bunn is a report which discusses the accuracy of main armaments on armored systems; with a focus on tank cannons. It presents an indepth discussion into the classes and sources of gun error. Also, it describes required data to calculate hit probabilities of tank fired munitions. The paper identifies possible criteria which should be addressed in any new weapon system.

"Detailed Characterization of the Interior Ballistics of Slotted Stick Propellant," by Frederick W. Robbins and Albert W. Horat is a technical report which investigates slotted stick propellant development. The study attempts to identify those mechanisms which increase the thermodynamic

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[12]Morrison, "Liquid Propellants for Gun Applications," 31-32.

efficiency of stick propellants over granular propellants for a given charge weight.[13]

"Test Results From a Two-Stage Traveling Charge Liquid Propellant Gun," by Irvin C. Stobie, John D. Knapton, Bruce D. Bensinger, and Robert A. Pate is a test report for a 40mm fractional traveling charge (FTC) gun system. The test demonstrated the ability to apply a liquid traveling charge to a projectile with a conventional solid propellant charge.

"High Performance Regenerative Liquid Propellant Gun Study," by J. Michael VanDerwerken is a study which examines the advantages of a high performance regenerative liquid propellant gun in a future main battle tank. "The key issues evaluated were liquid propellant (LP) gun configurations, gun performance characteristics, LP weapon system integration feasibility, vulnerability and logistics."[14]

"Ballistic Investigations of a High-Performance, Regenerative, Liquid Propellant Gun," by Cris Watson, John D. Knapton, Walter F. Morrison, and D. Maher is an investigation in the application of liquid propellants for gun propulsion systems". This study demonstrates that a 30mm, liquid

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[13]Frederick W. Robbins and Albert W. Horat, "Detailed Characterization of the Interior Ballistics of Slotted Stick Propellant," ADA147499 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, September 1984), 9.

[14]Michael J. VanDerwerken, "High Performance Regenerative Liquid Propellant Gun Study," ADB099639 (Pittsfield, MA: General Electric Company, Ordnance Systems, February 1986), 1.

propellant regenerative gun can operate in the high-performance, tank-cannon regime."[15]

Periodicals

"The Two-Man Tank: An Idea Whose Time Has Come," by Linwood E. Blackburn compares the current main battle tank designs with future designs. It is a good discussion of the advantages which technology has enabled the tank designers to go from a four man crew to a two man crew. He summarizes the advantages of tank design with crews that have less than four personnel, in the areas of reduced vehicle size, reduced vulnerability, reduced procurement and operating costs, and improved strategic transportability.

"Human Factors Challenges in Armored Vehicle Design," by R. Mark Brown discusses three human factors which he felt challenges the design evolution of armored vehicles. They are weight versus survivability, worldwide adaptability of combat vehicles, and crewmen information overload. He presents a discussion on the size and weight trade off within any new weapon system that effects human factors.

"The Heavily-Armored Gun-Armed Main Battle Tank is not Optimized for Mechanized Warfare," by Craig Koerner and

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[15]Cris Watson, John D. Knapton, Walter F. Morrison and D. Maher, "Ballistic Investigating of a High-Performance Regenerative Liquid Propellant Gun," ADA224593 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, February 1990), 1.

Michael O'Connor is an interesting article on design philosophy driven by the modern tactical battlefield requirements. They developed a discussion on the impact of increased vehicle weight in relationship to vision, concealment, mobility, and dependence on a vulnerable logistical tail which might raise some questions on the impact of liquid propellants.

"Future Tank Guns, Part I: Solid and Liquid Propellant Guns," by R. M. Ogorkiewicz discusses the future prospects and alternatives for increasing projectile penetrating through an increased muzzle energy. The article addresses one method to improve the effectiveness of a projectile is by increasing the energy per unit of cross-sectional area.[16] To achieve that end state, the author discusses the options of increasing the calibre of the tank gun or increasing muzzle velocity of the projectile. A parametric comparison between solid propellant and liquid propellant is conducted in the 120mm calibre. The study indicates an enhancement of vehicle survivability as a result of reduced propellant vulnerability. The article concludes that the growth potential of liquid propellant is in a two stage liquid propellant gun with a traveling charge.

[16]R. M. Ogorkiewicz, "Future Tank Guns, Part I: Solid and Liquid Propellant Guns," International Defense Review, Vol. 23, No. 12/1990: 1377.

"Liquid Propellant Artillery Proving Begins in the U.S.," by Rupert Pengelley, discusses the liquid propellant (LP) research and development efforts being conducted by General Electric in the 155mm howitzer class weapons system. The article compares test firing results in muzzle velocity and chamber pressure reproducibility on the test bed 155mm system. The article concludes with the potential positive benefits of LP in reduced vulnerability to counter-battery fire and the chances of detection by artillery locating radar diminished by resorting to multi-round TOT engagements at low elevation angles.[17]

"Extended Range for 155mm Artillery," by Terrence Ringwood takes a look at the major components that comprise an artillery system and their contributions to range performance. He explores the advantages and disadvantages in the current developmental efforts to improve range performance through solid and liquid propellants .

"The Return of the Gunned Tank Destroyer," by Steven R. Witkowski is an analysis of the Soviet Armored threat, current antitank technology, and doctrine. The article addresses the growth potential of technologies such as electromagnetic rail guns, liquid propellant guns and hyper-velocity missiles which he believes are not mature enough for

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[17]Rupert Pengelley, "Liquid Propellant Artillery Proving Begins in the U.S.," International Defense Review, Vol. 23, No. 12/1990: 1379-1380.

battlefield application. Conventional cannons are his only solution for meeting any problem in the future.

"Liquid Propellant Charges for Gun and Mortar Ammunition," by Wolfram Witt and Karlheinz Reinelt explores the potential advantages of liquid propellant charges for gun ammunition. The employment of liquid propellants in gun ammunition could lead to benefits which reduce the vulnerability of propellant detonation when hit by enemy fire, employs combustible case ammunition which has a lower weight than the current generation of solid propellant ammunition and smaller dimensions, permit incremental charge loading for the gun system depending on firing range requirements, and which could create financial savings in the ammunition-manufacturing process.[18]

"Developing a Tank Autoloader," by John C. Woznick addresses some essential criteria in the areas of vehicle integration, lethality, survivability, and sustainability if an autoloader is to be applied to a future combat vehicle.

Part III

Logistical Considerations

The sustainment of the combat maneuver elements plays as major an impact on the battlefield as the combat weapon

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[18]Wolfram Witt and Karlheinz Reinelt, "Liquid Propellant Charges for Gun and Mortar Ammunition," International Defense Review, Vol. 14, No. 1/1981, 64.

systems. To develop a new weapon system is only one part of the equation. The sustainment aspects of the equipment require major consideration prior to fielding. The primary sources of the logistical analysis of liquid propellant are in government documents.

U.S. Government Documents

"Classification of Liquid Gun Propellants and Raw Materials for Transportation and Storage", by William J. Cruice is the result of a study "to evaluate the hazardous properties of constituents and formulations of candidate liquid gun propellants for the purpose of classification in transportation."[19] The study has very interesting test results with several of the possible liquid propellant candidates having to be classified as Military CLASS 2 Explosives.

"Liquid Propellants for Gun Applications," by Walter Morrison, John D. Knapton and Guenter Klingenberg is a technical report which discusses the potential benefits of liquid propellant guns. The report concludes that the primary system advantage is "design flexibility which results from reduced volume requirements for ammunition stowage,

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[19]William J. Cruice. "Classification of Liquid Gun Propellants and Raw Materials for Transportation and Storage," ADA100729 (Rockaway, NY: Hazards Research Corporation, May 1981), 1.

automation, and propellant stowage remote from the fighting compartment."[20] The design flexibility of liquid propellants leads to logistical benefits in the storage, transport and ammunition processing.[21]

"Logistics Analysis of the Impacts of Liquid Propellant on the Ammunition Resupply System," by Maureen M. Stark is a study of the comparative cost and performance analysis of a liquid propellant gun system. The study specifically addresses the impact of liquid propellant on the supply and transportation systems. The baseline vehicle studied was a 155mm self-propelled howitzer. A comparison was made not only with solid propellant technology of today as exemplified by the bag charges used in modern artillery, but also with possible emerging solid propellant technologies projected for use in the field by the year 2000 against the liquid propellant concept. Especially interesting was the discussion on the significant savings in manpower and equipment usage when considering the effects of liquid propellant on the ammunition resupply system. The study concludes that liquid propellants show a potential for reducing the requirement for personnel and equipment within

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[20]Morrison, 32.

[21]Ibid.

the ammunition resupply system, as compared to bag charge solid propellants.[22]

"An Analysis of the Impacts of Transitioning a Liquid Propellant (LP) and an LP Gun System into the Army's Inventory," by Maureen M. Stark is a study which investigates the potential problems associated with introducing a liquid propellant weapon system into the inventory. The key areas identified in the study are: pre-production planning for LP facilities, production of LP during transition, stockpile conversion, weapon system transition, developmental testing (DT)/operational testing (OT), and Rationalization, Standardization, and Interoperability (RSI) considerations.[23] The baseline vehicle studied was a 155mm self-propelled howitzer.

"High Performance Regenerative Liquid Propellant Gun Study," by J. Michael VanDerwerken is a study which examines the advantages of a high performance regenerative liquid propellant gun in a future main battle tank. Logistical issues such as manpower requirements and time lines for ammunition resupply were examined for both solid and liquid propellants.

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[22]Maureen M. Stark, "Logistics Analysis of the Impacts of Liquid Propellant on the Ammunition Resupply System," ADB087488 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, October 1984), 37.

[23]Maureen M. Stark, "An Analysis of the Impacts of Transitioning of Liquid Propellant (LP) and a LP Gun System in the Army's Inventory," ADB100559 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, March 1986), 2.

Summary

The primary research sources used in this study were discussed and briefly related to the research topic. The bibliography provides the complete listing of all sources consulted. The parts addressed in this section of the thesis reflect the four areas of investigation: U.S. Army liquid propellant gun development program history, the emerging gun propulsion technologies and the criteria to evaluate them and the logistical impact of sustaining a liquid propellant program in the field. Each part attempted to identify the author's key source material used to develop this thesis.

The most helpful sources for the author were Government Technical Reports conducted at the Ballistic Research Laboratory (BRL). The BRL appears to be the lead Department of Defense Laboratory working the issues and attempting to develop a liquid propellant 120mm. anti-armor cannon for the main battle tank. This thesis attempts from a user point of view to support why that effort should be completed.

CHAPTER 3

HISTORY OF LIQUID PROPELLANT DEVELOPMENT

Introduction

To understand the current level of technology of a liquid propellant gun (LPG), a historical review of the Department of Defense (DOD) LPG research and development efforts beginning in 1947 and continuing to the present will be discussed. The types of LPG concepts and historical development associated with each will be briefly explored. The goal of this portion of the study is to gain an elementary understanding of the LPG and the different methods to achieve gun propulsion.

Chapter 3 will not attempt to provide an in-depth analysis of every liquid propellant (LP) effort past and present in the DOD. Such an effort would be monumental and beyond the limits of this thesis. The objective will be to provide a trend of the major efforts directly after World War II and focus the reader on the current concepts which promise application in the near future.

LP development in the DOD can be subdivided into four defined periods. The first, Post World War II (1947-1950), explored the initial propulsion concepts in externally powered regenerative guns, direct injection regenerative guns and bulk loaded propellant guns. The powered pump had to be externally mounted and was very large. The research quickly dropped the externally powered regenerative gun for military application and continued on the other two.

The second period, (1950-1957), was focused on the bulk loaded propellant gun (BLPG) and the regenerative liquid propellant gun (RLPG). Problems related to stability during the interior ballistic phases and the shift from cannons to rockets at the end of the Korean Conflict all but ended DOD efforts in the LP program. The period from 1957-1968 saw very little if any research in LP.

The third period, (1968-1977), saw a relook into the possible potential of LP in the military. The major research was directed toward the bulk loading concept. The major impetus in reviving the LP program in this period was the Army's involvement in the Vietnam War and the need to improve the current gun propulsion technology. The Navy was the lead agency and believed LP would provide an answer to improving the current gun propulsion used on ship weapon systems.

The final period, 1977 to the present, began an investigation in LP which focused the research efforts predominantly on regenerative injection. Again the Navy initially led the way until a Tri-Service Plan for Liquid

Propellant Technology for Gun Application was revived in March 1980[1] and turned into the DOD Liquid Propellant Technology Program.[2]

The Army has reached a point where the current gun propulsion technology shows small growth potential in the near future. The efforts to make combat vehicles more survivable by reducing propellant vulnerability and increasing the lethality of cannons is an on-going mission of the DOD research and development community. One current attempt to meet this requirement is through advanced gun propulsion concepts on the drawing board. To better understand these concepts, LP will be analyzed from its conception to the current efforts through a historical discussion. In order, to understand the LP program, designers must first review the two competing concepts: bulk loaded liquid propellant guns (BLLPGs) and regenerative liquid propellant guns (RLPG).

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[1]Richard H. Comer and Walter F. Morrison, "Tri-Service Plan for Liquid Propellant Technology for Gun Applications," ADB055274L (Aberdeen Proving, MD: U.S. Army Ballistic Research Laboratory, September 1980), 9.

[2]Walter F. Morrison, "Liquid Propellant Technology Program," ADB056054L (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, January 1981), 5.

Part I

Bulk Loaded Propellant Guns

"The bulk-loaded liquid propellant gun (BLLPG) is mechanically the simplest implementation of the liquid propellant concept."[3] The BLLPG currently has two types of loading methods: monopropellants, Figure 1. Schematic Diagram on a Monopropellant Bulk Loaded Propellant Gun, or bipropellants, Figure 2. Schematic Diagram of a Biopropellant Bulk Loaded Propellant Gun. In both methods, the projectile is placed in the bore end of the chamber to form a seal. The breech is closed and the air is removed by either a venting or preferably by vacuum line to prevent bubbles in the liquid propellant which can lead to a catastrophic effect during the subsequent combustion process.[4] The entire volume of propellant required to fire the projectile is pumped into the combustion chamber at one time. In the monopropellant loading method, the propellant is pumped directly from the storage tank to the chamber as shown in Figure 1. Schematic Diagram of a Monpropellant Bulk Loaded Propellant Gun). In the bipropellant loading method, a pump and valve system on each

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[3]Walter F. Morrison, John D. Knapton and Guenter Klingenberg, "Liquid Propellants for Gun Applications," ADB090195 (Aberdeen Proving Ground, MD: Ballistic Research Laboratory, January 1985), 9.

[4]T.W Terry, S.R. Jackson, C.E.S. Ryley, B.E. Jones and P.J.H. Wormell, Fighting Vehicles, (London, Great Britain: BPCC Wheatons Ltd., Exeter, 1991), 42.

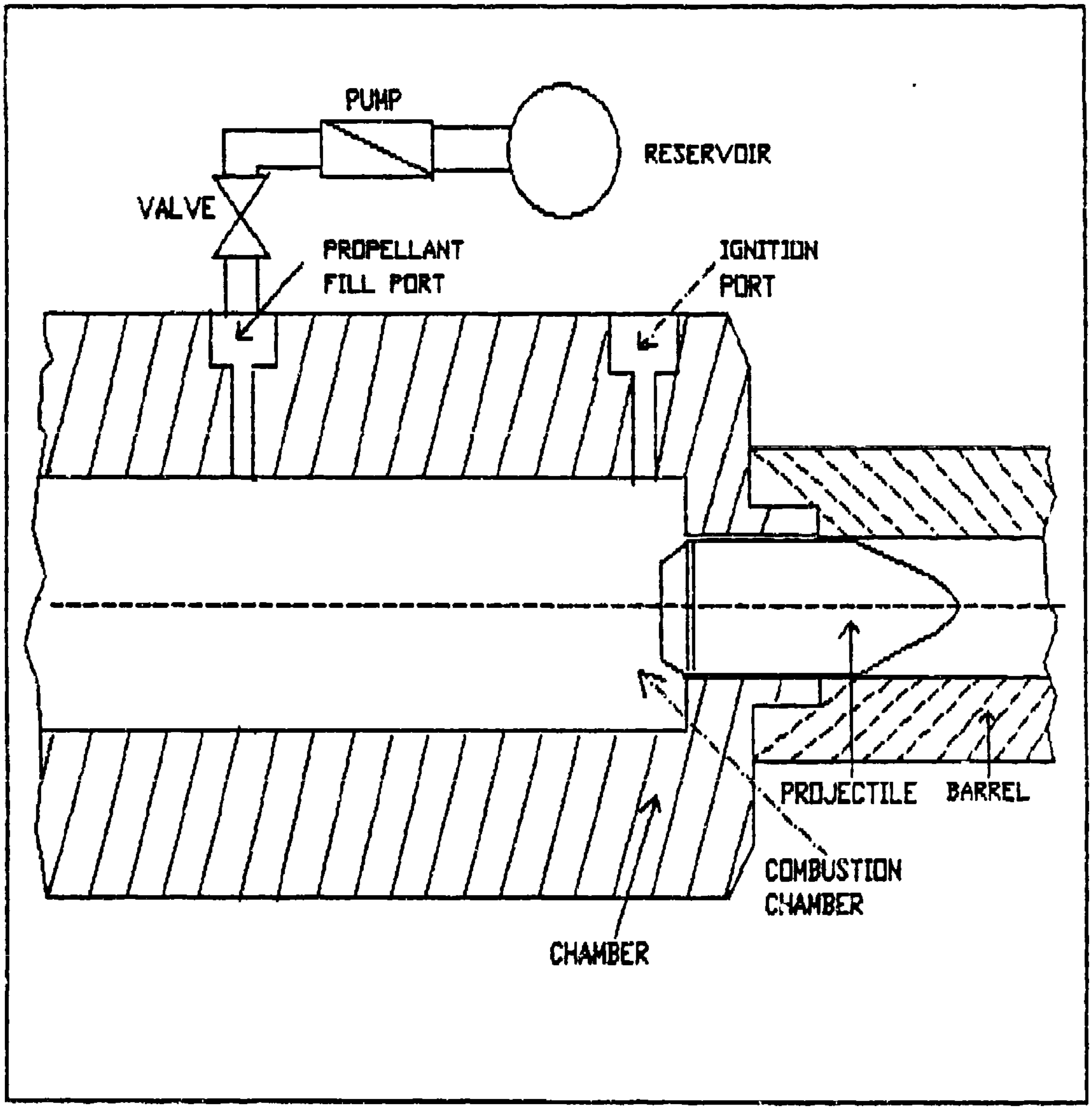

FIGURE 1. SCHEMATIC DIAGRAM OF A MONOPROPELLANT BULK LOADED PROPELLANT GUN

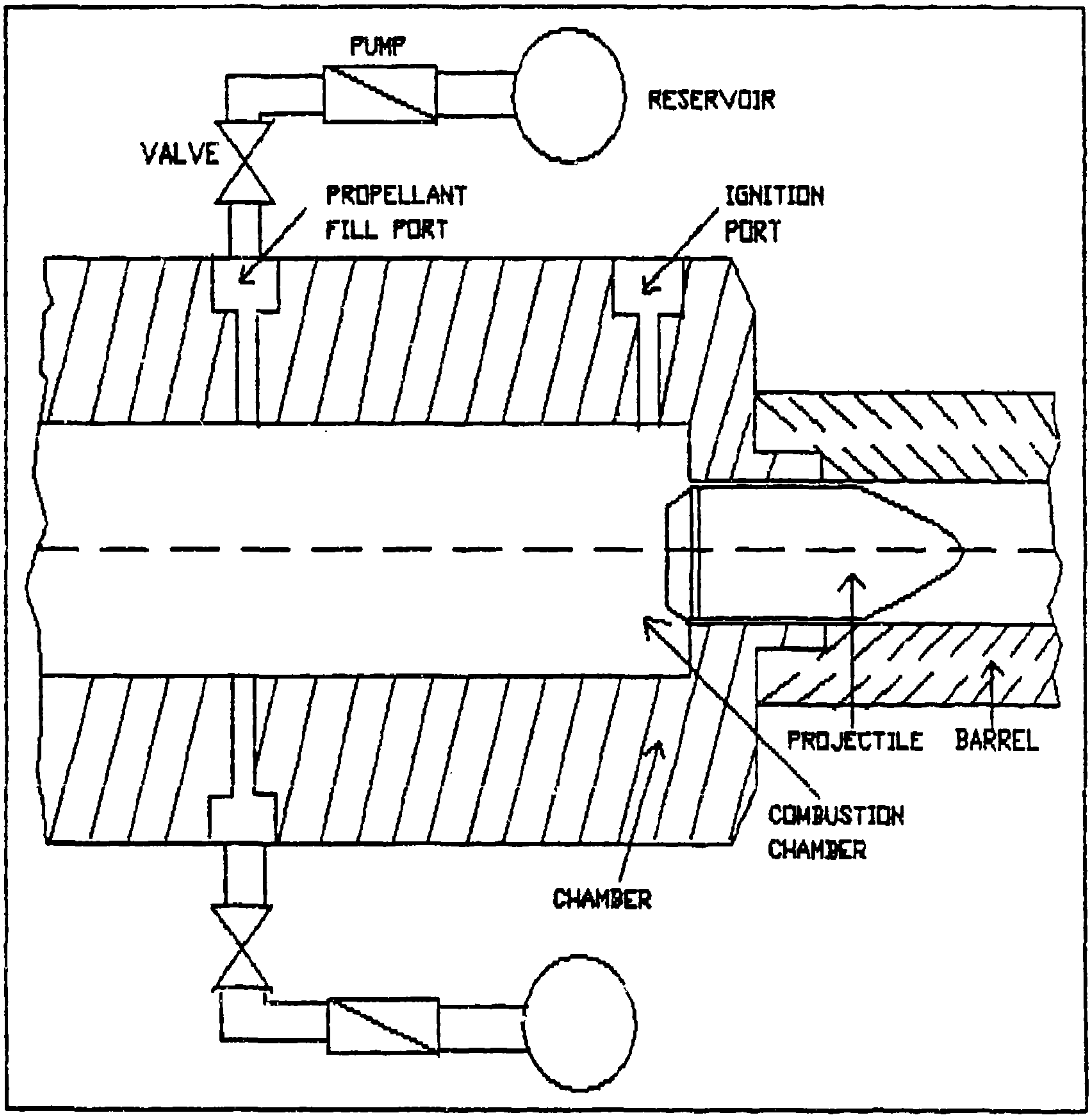

FIGURE 2. SCHEMATIC DIAGRAM OF A BIOPROPELLANT BULK LOADED PROPELLANT GUN

storage tank controls the rate of fill into the chamber to ensure both components are well mixed prior to combustion[5] as shown in Figure 2. Schematic Diagram of a Monopropellant Bulk Loaded Propellant Gun.

The next step is the combustion process as illustrated in Figure 3. Interior Ballistic Cycle of a Bulk Loaded Propellant Gun. The liquid can be ignited from one of three locations: in the wall of the chamber, at the base of the projectile, or in the breech. The breech ignition can be a variety of methods ranging from electric spark to a hot wire.

Once the combustion process is initiated, pressurization is achieved and the projectile is placed in motion. "As the projectile and liquid column are accelerated down the tube, the gas cavity will penetrate the liquid column, creating what is known as the Rayleigh-Taylor instability."[6] When this occurs, a ring of liquid remains on the chamber walls. "Hot gases flow at high velocity through this ring, which results in turbulent gas-liquid mixing at the inner surface of the ring which is called the Kelvin-Helmholtz

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[5]Wolfram Witt and Karlheinz Reinelt, "Liquid Propellant Charges for Gun and Mortar Ammunition," International Defense Review, Vol. 14, No. 1.1981: 65.

[6]Morrison, 10.

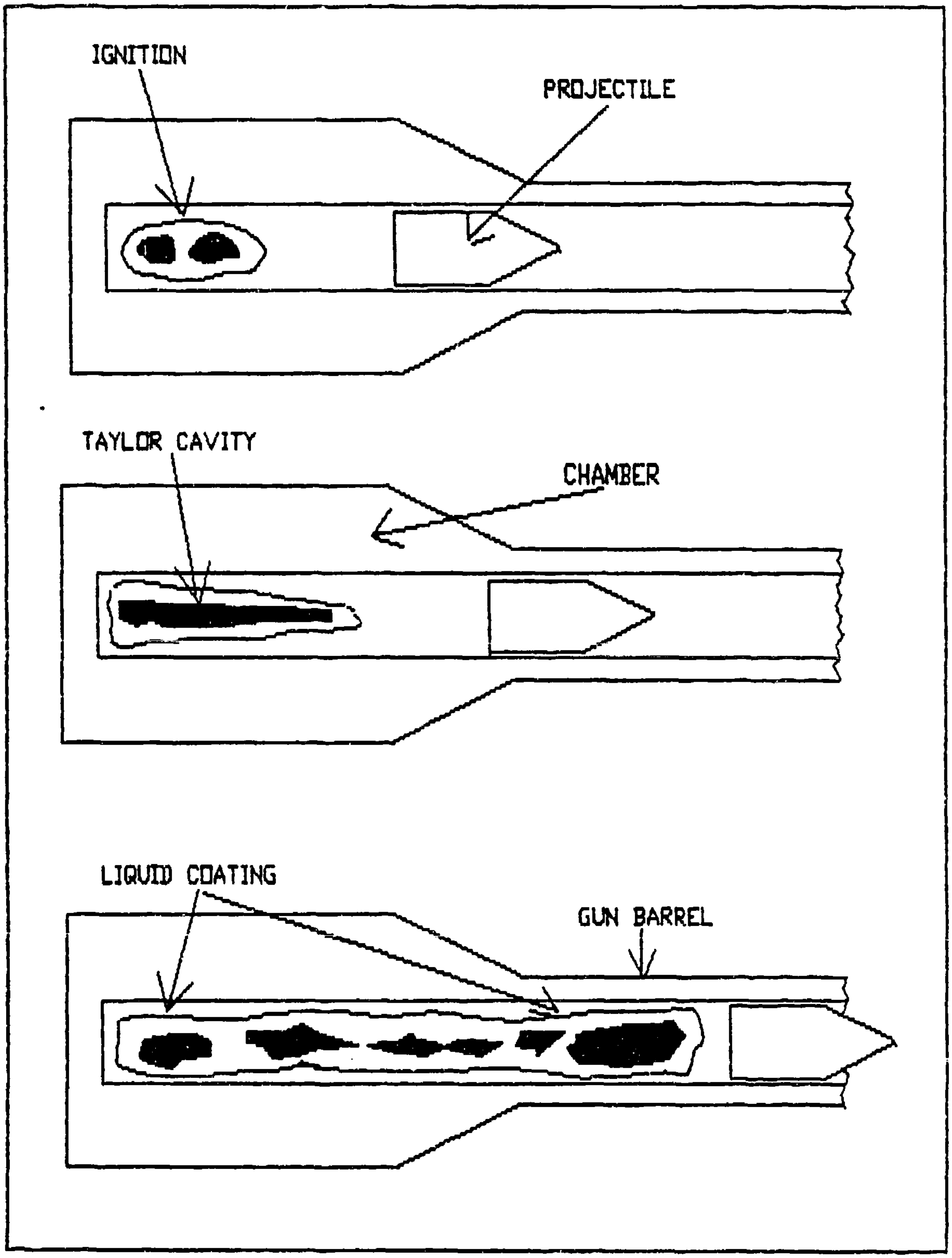

FIGURE 3. INTERIOR BALLISTIC CYCLE OF A BULK LOADED PROPELLANT GUN

instability."[7] "The Kelvin-Helmholtz instability can produce the large surface area needed for consumption of the propellant in the gun and would also lead to very rapid combustion after mixing in the area of the burning surface."[8] This mechanism produces a rapid increase in the area of the burning surface.

The major difficulty with BLLPG "has been variability in ballistics and occasional catastrophic failures of test hardware."[9] Most BLLPG which have overpressured and led to a failure have been blamed on errors in ignition. The irregular high pressures associated with bulk loading have not been fully controlled or understood as of yet. The critical element in a BLLPG appears to be the ignition system. "The coupling in space and time of the igniter's energy to the liquid propellant (LP), controls the evolution of the ballistic process."[10] As a result, the development work has been done on a trial and error basis, which is not very efficient. The studies and assessments thus far indicate

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[7]Walter F. Morrison, "Liquid Propellants," Ballistic Science and Technology Tutorial Interior Ballistics, (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, May 1991), 104.

[8]Morrison, "Liquid Propellants for Gun Applications," 11.

[9]Ibid.

[10]Morrison, Ballistic Science and Technology Tutorial Interior Ballistics, 106.

BLLPG would not be a good candidate for a possible LPG system in a future combat vehicle.

Part II

Regenerative Liquid Propellant Gun

"The regenerative liquid propellant gun (RLPG) is mechanically more complex than the BLLPG, but has been demonstrated to be capable of more precise ballistic control."[11] The RLPG currently has two loading methods: monopropellants, Figure 4. Schematic Diagram of a Monopropellant Regenerative Injection Liquid Propellant Gun and bipropellants, Figure 5. Schematic Diagram of a Bipropellant Regenerative Injection Liquid Propellant Gun. In the RLPG, the propellant initially fills a reservoir which is separated from the combustion chamber by a piston, and is pumped into the combustion chamber during the ballistic process through injectors in the piston as shown in Figure 4 and Figure 5. The piston is the critical element which divides the chamber into a combustion chamber and a propellant reservoir. The injector orifices in the piston head are shown schematically in Figure 4 and Figure 5. "An ignition train,

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[11]Morrison, "Liquid Propellants for Gun Applications," 11.

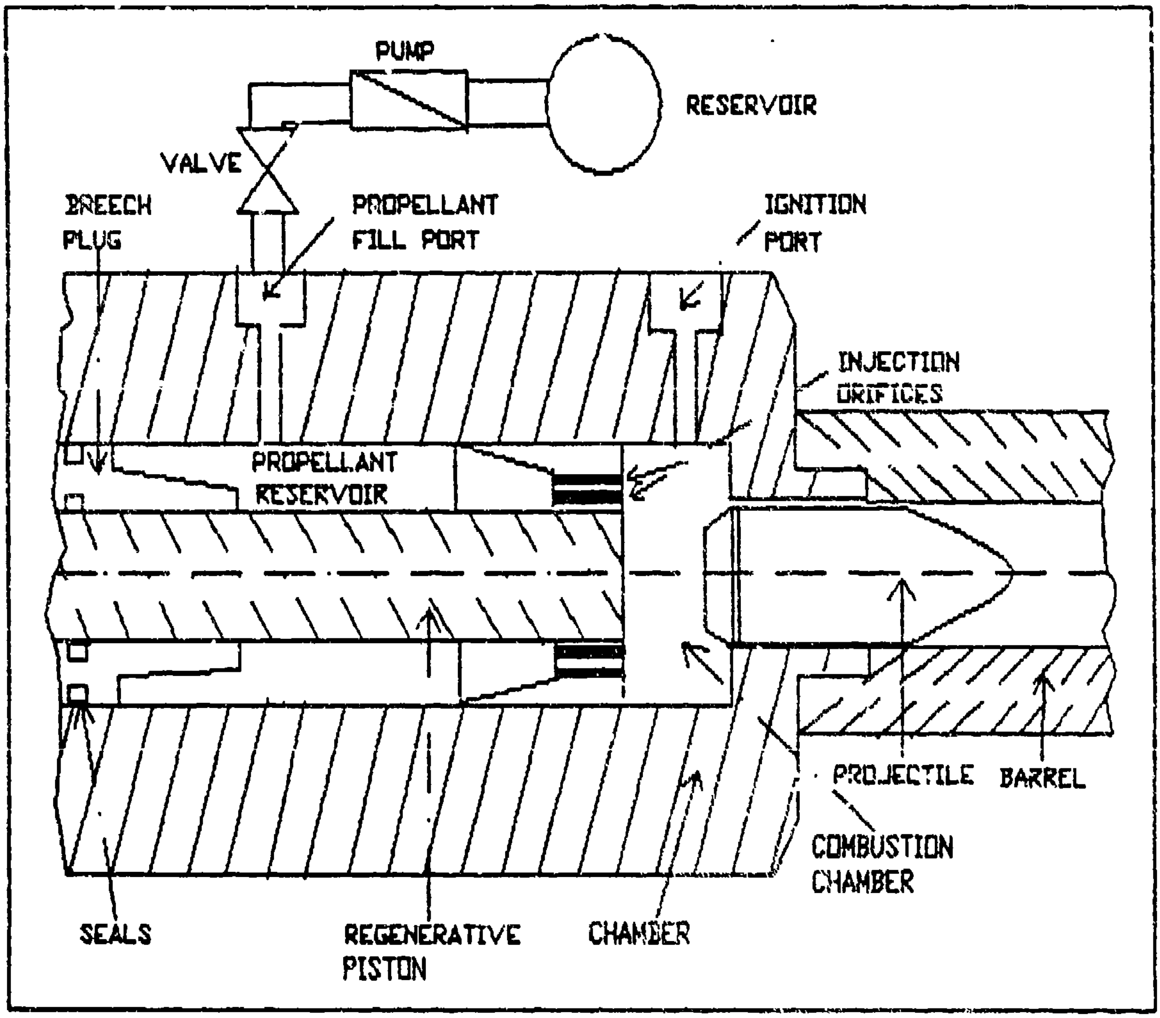

FIGURE 4. SCHEMATIC DIAGRAM OF A MONOPROPELLANT REGENERATIVE INJECTION LIQUID PROPELLANT GUN

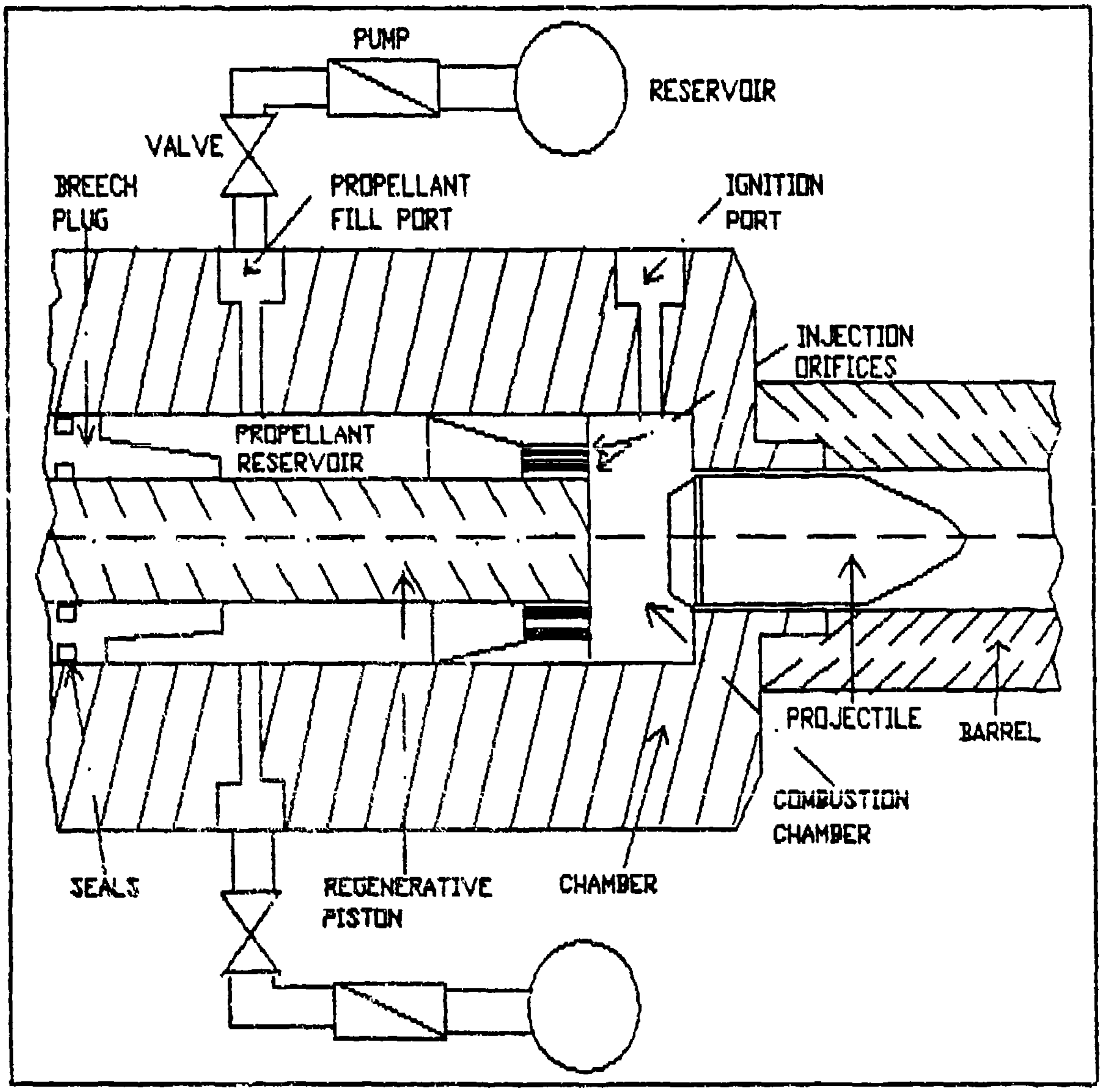

FIGURE 5. SCHEMATIC DIAGRAM OF A BIPROPELLANT REGENERATIVE INJECTION LIQUID PROPELLANT GUN

consisting of a primer, an ignition charge and in some cases a booster charge complete the system."[12]

Two primary functions must be performed to make the RLPG process successful. The first function is the controlled rate propellant is injected into the combustion chamber during ignition (Figure 6). As a result of this metered propellant flow, the combustion cycle is very stable and controlled since there is never more than a small quantity of unburned propellant in the combustion chamber at any time. The ability to meter the amount of propellant into the combustion chamber permits "tailoring the chamber pressure for a desired effect."[13] "The metering pressure process is termed 'regenerative' because the propellant pumping pressure is obtained by hydraulic multiplication of the combustion chamber."[14] The hydraulic action supplies the energy required to pump the liquid through the injectors.

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[12]Morrison, Ballistic Science and Technology Tutorial Interior Ballistics, 108.

[13]Morrison, "Liquid Propellants for Gun Applications," 11.

[14]R.D.M. Furlong, "Liquid Propellant for Future SP Howitzers?" International Defense Review Vol 16 (December 1983), 1765.

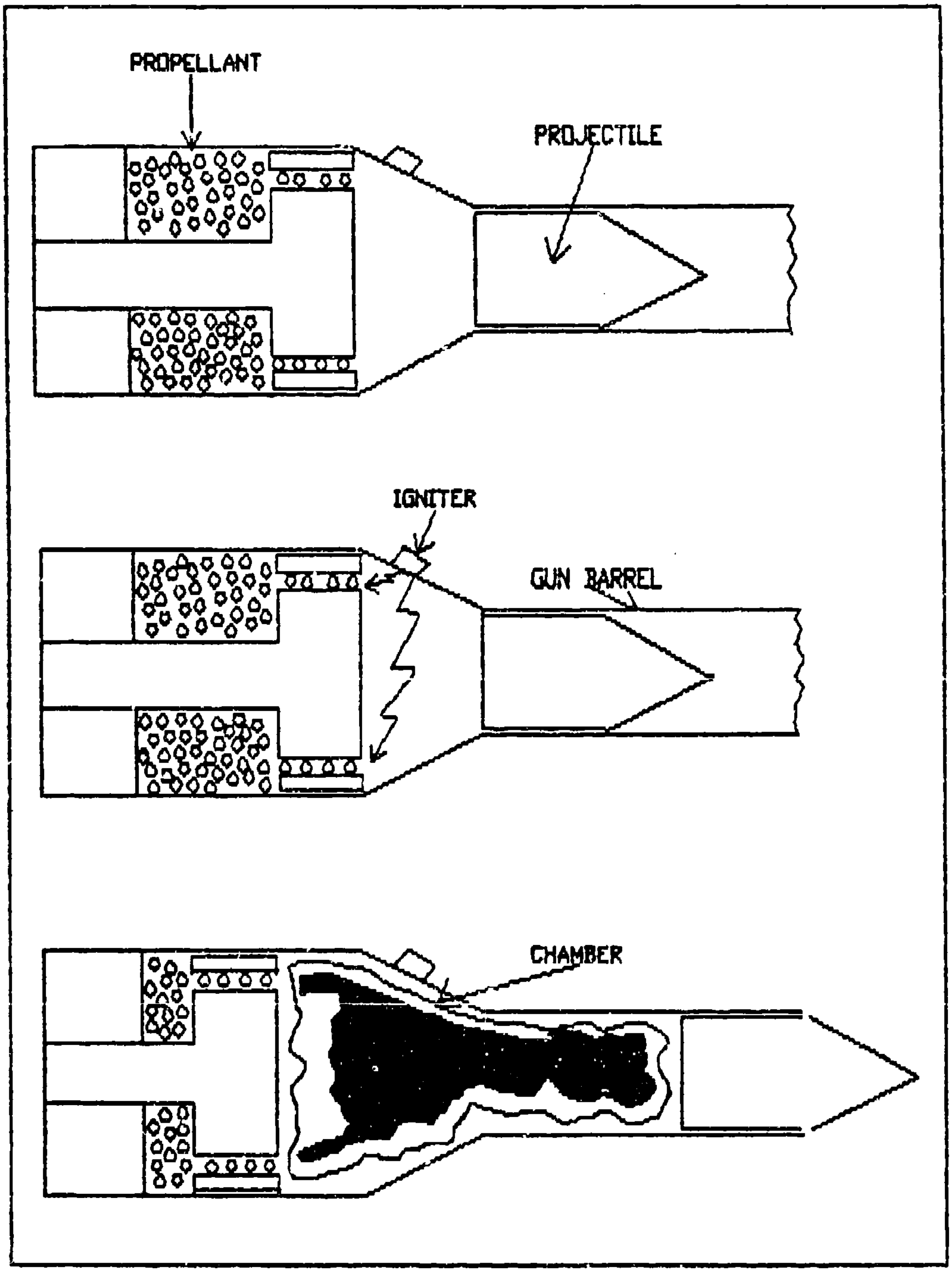

FIGURE 6. INTERIOR BALLISTIC CYCLE OF A REGENERATIVE LIQUID PROPELLANT GUN

The second function is the requirement for the propellant to be atomized as it enters the combustion chamber as shown in Figure 6. Interior Ballistic Cycle of a Regenerative Liquid Propellant Gun. "This is accomplished by using a set of injector orifices at the same location in the combustion chamber."[15] Both functions are performed by the differential area piston, with propellant injection taking place through orifices drilled through the face of the piston as shown in Figure 5. The key is the amount of propellant available for combustion at any time is controlled by the injection process. In general the process of a RLPG can be modeled when the two functions are combined for the hydraulic response of the regenerative piston and the LP reservoir. This action is based on the smaller area on the unburned propellant side of the piston head than on the larger area on the combustion side of the piston. This differential is the corner stone to the injection and atomization of the LP in the combustion process.

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[15] J. Mandzy, P.G. Cushman and T. Magoon, "Liquid Propellant Technology Final Report," ADB097031 (Pittsfield, MA: General Electric Ordnance Systems Division, October 1985), 6.

Part III

A Review of Past Liquid Propellant Developments

Liquid propellant research in the United States began shortly after World War II ended. Between 1946-1950, three basic types of LPG propulsion concepts were being investigated: direct injection, both externally powered and regenerative, and bulk loaded.[16] The first was an externally powered injection device which achieved velocities up to 7000 ft/s.[17] Military application was considered but was determined not to be feasible due to the need for an external power source. The second approach being researched was experiments in bulk loaded LPG with encapsulated propellants. Velocities in the range of 11,300 ft/s were reported.[18] Last, a regenerative injector study was completed and an effort to develop a 37mm RLPG was initiated.

From 1950 to 1957, work was conducted on both the BLLPG and RLPG concepts. Several 90mm tank guns were eventually tested in two separate programs with hydrazide monopropellants.[19] Problems developed with variability in the

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[16] Walter F. Morrison, Paul G. Baer, Melvin J. Bulman and John Mandzy, "The Interior Ballistics of Regenerative Liquid Propellant Guns," ADA190020 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, October 1987), 1.

[17] Walter F. Morrison, John D, Knapton and Melvin J. Bulman "Liquid Propellant Guns," ADA188575 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, October 1987), 3.

[18] Ibid.

[19] Ibid.

bulk loaded firings which exceeded that of conventional guns. "Following the end of the Korean Conflict, interest in LPG research began to diminish, and by 1957, with the increasing emphasis on rockets and missiles, both tactical and strategic, nearly all LPG research had stopped."[20]

"The rising interest in rockets in the late 1950s and the general decline of gun propulsion research in the Army nearly ended all support of the LP program into the early 1960s."[21] "By the late 1960s, the Vietnam War experience had demonstrated the continued need for gun systems in all applications: air to air, air defense, fire support, etc."[22] The Navy took the lead during this period and began the first major research and development efforts in LP since 1957. The Naval Weapons Center, China Lake, began studies on a LP cannon for air defense. At the same time, the Naval Ordnance Station, Indian Head, began development of a new class of liquid monopropellants based on hydroxyl ammonium nitrate (HAN).[23] These Navy programs were the foundation which caused

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[20]Ibid.

[21]Morrison, "Liquid Propellants for Gun Applications," 14.

[22]Morrison, "Liquid Propellant Guns," 4.

[23]Ibid.

a renewed interest throughout the Department of Defense research community in the potential of LP.

LPG research and development in the 1970s can be broken down into two categories: bulk loading and regenerative injection. "Prior to 1976, bulk loading was the primary focus of the development effort, and from 1978 to the present, the focus has shifted almost exclusively to regenerative injection."[24] Again the Navy lead the Department of Defense research community in LP development during the period. The Navy's BLLPG program was focused toward a large caliber shipboard gun and a small caliber air defense gun system.[25] The Navy successfully demonstrated a small caliber 37mm air defense gun but the " ballistic control required for safety at high rates of fire demonstrated ballistic variability which was still large compared to conventional guns of the same caliber."[26] There were never any "large caliber firings conducted in conjunction with this program, due to problems in controlling high chamber variability in the 37mm test fixture."[27]

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[24] Ibid.

[25] Morrison, "Liquid Propellants for Gun Applications," 14.

[26] Morrison, "Liquid Propellant Guns," 4.

[27] Ibid.

The Defense Advanced Research Projects Agency (DARPA) initiated concurrent research to "develop a high velocity 75mm LPG cannon for application in light armored vehicles."[28] In order to meet program milestones, testing in the program was accelerated despite marginal smaller caliber performance evaluations. These development efforts concentrated solely on the bulk loaded concept due to its mechanical simplicity. "In 1976, two successive firings in the DARPA 75mm program resulted in catastrophic failure."[29] As a result of these major failures, all major Department of Defense LPG programs in the United States were terminated.[30]

Research for candidates in liquid propellants and a 30mm cannon development effort still continued on a smaller scale in the U.S. Army Ballistic Research Laboratory and General Electric Company.[31] In 1978 a new family of HAN-based LPs was developed and a rapid fire 30mm RLPG cannon was demonstrated.[32] This caused renewed interest in LP by the Army in the early 1980s and a 105mm regenerative test fixture

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[28]Ibid.

[29]Ibid., 9.

[30]Walter F. Morrison, Paul G, Baer, Melvin J. Bulman and John Mandzy, "Interior Ballistics of Regenerative Liquid Propellant Guns," ADA190020 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, October 1987), 1.

[31]Morrison, "Liquid Propellants For Gun Applications," 15.

[32]Ibid.

was designed, fabricated and tested. "The significant accomplishments in these efforts have been the high degree of ballistic control and excellent reproducability in pressure and muzzle velocity."[33] This has resulted in the Army developing and testing a 155mm RLPG system for a self propelled howitzer.

Summary

The objective of this section was to review the major historical developments within the United States in the LP program from its beginning following World War II to the present. This review identified four distinct periods in which LP was a possible concept as a gun propulsion system on combat vehicles.

Initially there was a period of technology development, a feasibility demonstration conducted, and efforts toward the development of prototype hardware. Numerous gun fixtures were developed and fired but none were fielded.

The second period, 1950 to 1957, saw support for the program fade by the mid-1950s and all work had been abandoned by 1960. Three factors contributed to that: slow technical progress due to the complexities of the interior ballistics of the systems, reduced interest in new gun systems after the Korean conflict and the shift from guns to rockets.

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[33]Morrison, "Liquid Propellant Guns," 5.

In the third period, LP efforts were revived but focused solely on the bulk loaded concept because of its mechanical simplicity. The greatest test fixture failures in the program occurred in 1976 which resulted in a shift to RLPGs.

The fourth period has taken the DOD from the late 1970s to the present which has demonstrated several 105mm test fixtures which show great promise. The desire for growth potential and increased lethality on the battlefield in a RLPG has been shown in historical trends and is worthy of future investigations in the Army.

CHAPTER 4

CONVENTIONAL GUN PROPULSION REVIEW

Introduction

To establish a baseline for the major conventional gun propulsion technologies, they be briefly analyzed for their advantages and disadvantages. The review includes current and advanced technologies under development within the Department of Defense (DOD) research and development community. The goal is to identify those concepts which show growth potential in the near-term future as a possible improvement to the Solid Propellant Gun (SPG). "SPGs have successfully armed tanks mainly because progressive improvements made them capable of defeating the increasingly heavy armor of the opposing tanks, which represent their most demanding targets."[1] One of the methods of increasing the penetration capability of any tank cannon without increasing the size of the gun or introducing a new technology is through increasing the energy output of the propellant. An objective of this improved propellant is an increased muzzle velocity which means increased weapon

[1]R. M. Ogorkiewicz, "Future Tank Guns, Part I: Solid and Liquid Propellant Guns," International Defense Review, Vol.24, No. 9/1991: 1377.

system lethality and increased crew survivability on the modern battlefield. The maximum velocity that can be achieved is determined by the type of propellant and the mass of the projectile used in a gun system. Therefore, the limiting factors become the amount of propellant that can be loaded in the gun and the maximum pressure the gun can withstand. The weight of propellant depends on the maximum loading density. The chapter addresses several propellant concepts which attempt to increase the loading density. The chapter will be broken down into conventional propulsion and advanced conventional propulsion.

Part I

Conventional Propulsion

I. Conventional Propulsion - chemical energy propulsion technology:

- o Multiperforation Granular Propellants
- o Slotted Stick Propellants
- o Low Vulnerability Ammunition (LOVA) Propellants
- o Deterred Propellants
- o Modular Charges
- o Multiplex Charges

A. Multiperforation Granular Propellants:

Increasing the perforations from 1 or 7 to 19 or 37 perforation grains creates a relatively larger burning surface.[2] Since the propellant gas generation rate is proportional to the burning area, it may be possible to get higher relative pressures late in the interior ballistic cycle.

1. Advantage:

Higher relative pressures may result in higher muzzle velocities. (It gets more usable propellant in the breech.)

2. Disadvantages:

a. Propellant grains are physically larger than those in a standard charge, therefore, it may be difficult to achieve required loading density.

b. There is a possible increase in muzzle blast which is a survivability issue related to the combat system.

c. The higher projectile velocities could result in increased gun tube wear reducing the expected life of the cannon.

B. Slotted Stick Propellants:

The propellant is in bundle packs which are more dense than randomly loaded granular propellant, resulting in a larger mass being loaded into the chamber. The natural channels presented by bundled stick propellant allow the

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[2]Paul G. Baer, Catherine F. Banz, Ingo W. May and Walter F. Morrison, "A Propulsion System Comparison Study For the 120mm Anti-Armor Cannon," ADA187175 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, August 1987), 13-14.

length of the chamber to be almost immediately bathed in igniter and early combustion gases, promoting rapid flame spread because of the good pressure equilibration.[3]

1. Advantages:

a. The diminished resistance to gas flow reduces the propensity for pressure waves and renders the potential for simplified and less expensive charge designs.

b. The increased loading density permits the use of the larger charge weight needed with cooler, less energetic, propellants. These propellants result in decreased gun tube wear, muzzle flash and blast.

2. Disadvantage:

Since the sticks tend to remain in the chamber during the ballistic cycle, the propellant gases are forced to flow over the origin of rifling and erosion could possibly occur.

C. LOVA Propellants:

The general characteristics of LOVA propellants consist of nitramine dispersed in an inert binder matrix. These low vulnerability properties are a result of a higher threshold for thermal ignition, lower burning rate at lower

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[3]Frederick W. Robbins and Albert W. Horat, "Detailed Characterization of the Interior Ballistics of Slotted Stick Propellant," ADA147499 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, September 1984), 9-11.

pressures, and improved mechanical properties compared to conventional nitrocellulose based propellants.[4]

1. Advantage:

There is a reduction of vulnerability of a fire or explosion with on-board propellant as a result of the higher flame temperature of ignition.

2. Disadvantage:

There are flash and erosion problems with gun tubes that use these propellants.

D. Deterred Propellants:

Standard propellants are treated to infuse a slow burn rate. This results in a slower burn rate in the early portion of the interior ballistic cycle until the deterred layer is depleted. Then there is a more rapid burn in the later portion of the cycle to approach a more constant pressure operation.[5]

1. Advantage:

With a constant pressure operation during the interior ballistics cycle, higher muzzle velocities may be achievable. The loading density is not impacted though a larger charge

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[4]M.S. Kirshenbaum, L. Avrami and B. Strauss, "Sensitivity Characterization of Low Vulnerability (LOVA) Propellants," ADA126130 (Dover, NJ: U.S. Army Armament Research and Development Command, Large Caliber Weapons Systems Laboratory, March 1983), 1.

[5]Baer, 3.

weight which is required due to the lower energy of the deterred layer.

2. Disadvantage:

The production process has not demonstrated the capability of uniform consistent coating of a multi-perforated propellant grain with a deterrent.

E. Multiple Charges:

This concept is applicable to those situations that require a variety of velocities from the same cannon and projectile combination.[6]

1. Advantage:

Only the required amount of propellant is used.

2. Disadvantage:

There is a potential for case residue when firing at low pressures and cold temperatures. Also there is a possible non-uniform flame spread and pressure waves associated with multiple charges.

F. Multiplex Charges:

The aim is to obtain a super progressivity. Progressivity is a change in a grain's mass burning rate

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[6]L. E. Harris, A. Grabowsky, J. Shib-Thornton, P. Hui and A. J. Beardell, "Unicharge for Extended Range Ordnance," 25th JANNAF Combustion Meeting, CPIA PUB 498, Vol. IV, ADB133554 (Huntsville, AL: NASA-Marshall Space Flight Center, October 1988), 455-456.

brought about by the change in the grain's surface as burning proceeds. Progressivity is desired to obtain the maximum chamber pressure very quickly and maintain it until propellant burnout.

1. Advantage:

It offers the highest performance attainable with conventional propulsion methods.

2. Disadvantage:

The concept depends on the development of grain geometries (such as rosette) that have not been manufactured.

Part II

Advanced Conventional Propulsion

II. Advanced Conventional Propulsion - developmental enhanced chemical energy propulsion technology:

- o Consolidated charge
- o Enhanced Local Combustion Concepts
- o Programmed Fracture Propellant Grain
- o Soft-Launch Concepts
- o Solid Propellant Traveling Charge

A. Consolidated Charge:

A consolidated charge is a charge fabricated essentially from standard gun propellant in a way to produce a monolithic structure which retains many of the characteristics of the initial propellant. To accomplish this process, the propellant is first softened with a solvent, then pressed into the desired bulk densities.[7] There is an increase in density mass by grain coating and binding. The concept permits compacted propellant to be place into the gun chamber which increases the charge-to-projectile mass ratio for a given chamber volume. It attempts to maintain higher reactive pressures late in ballistic cycle.

1. Advantage:

Larger charge weights can be packed into a fixed chamber volume, thus higher muzzle velocities may be achieved.

2. Disadvantage:

The production and manufacturing technology is currently a problem. Consolidated charges may be inherently more subject to round-to-round irreproducibility than are the loose granular charges.

B. Enhanced Local Combustion Concepts:

The accumulation of gases within the perforation leads to locally high pressures and faster burning rates on internal surfaces. If understood and controlled, it can be exploited as a means to achieve major increases in effective progressivity.

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[7]Leon R. Scott, "Consolidated Propellant Charge Investigation, Volume I: Preparation of Consolidated Charge Increments," ADB0433967 (Magna, Utah: Hercules Inc. Aerospace Division, November 1979), 1.

1. Advantages:

a. Larger charge weights can be employed without increasing maximum chamber pressures, allowing higher performance with the same propellant composition.

b. Increases in basic ammunition stowed load on combat vehicle may be possible, if coupled with the high loading density of stick propellant.

2. Disadvantage:

There are problems associated with individual propellant grains withstanding the higher internal pressures. The problem is exacerbated by temperature extremes. High temperatures enhance the local burning rate effect. A low temperature deteriorates propellant mechanical and burn rate properties.

C. Programmed Fracture Propellant Grain:

This is a technique to increase progressivity. A given propellant geometry that may already be progressive is manufactured such that it burns on the grain exterior a distance, at which time, the grain will fracture, yielding a programmed increase in the available surface area. This leads again to increased pressures in the later portion of the cycle until a specified (programmed) burn of the interior ballistic cycle is completed.[8]

1. Advantages:

a. A larger charge weight can be employed without increasing the maximum chamber pressure, allowing greater velocities of projectiles at the same pressure or the same velocity at lower pressures.

b. Temperature dependence may be exploited, to reduce sensitivity to conditioning temperatures.

2. Disadvantages:

It requires an average reproducible fracture event which is not possible if the elimination of lot-to-lot differences in propellant is not achieved.

D. Soft-Launch Concepts:

This concept employs propelling charge materials and configurations which either significantly reduce the undesirable nature of gas and solid phase inputs to the shell or substantially interferes with or mitigates them before reaching any sensitive portion of the projectile. This concept exploits recent advances in high-permeability charge and tailored-ignition methods.

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[8]G. E. Keller and A. W. Horst, "The Effects of Propellant Grain Fracture on the Interior Ballistics of Guns," 25th JANNAF Combustion Meeting, CPIA PUB 498, Vol. IV, ADB133554 (Huntsville, AL: NASA-Marshall Space Flight Center, October 1988), 479-480.

1. Advantage:

This type of charge is attempting to permit firing which ensures reliable operations of sophisticated projectiles through controlled interior ballistics.

2. Disadvantage:

A harsher launch environment resulting from the interior ballistic cycle might result in a decreased probability of hit of a munition against a specific target.

E. Solid Propellant Traveling Charge:

It entails affixing part the charge to the projectile itself. Gases are generated at the base of the projectile and pressure losses from the gun breech to the end of the gun tube are not as great.[9]

1. Advantage:

Higher muzzle velocities may be achieved with the current generation of munitions which couple a traveling charge with them.

2. Disadvantages:

a. The mass of the traveling charge must be accelerated along with the projectile down the gun tube.

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[9]Faust Denicola, Walter Arnold, Gayle Beavers, Paul Crise and Jane Krolewski, "Tech Base Propulsion Technologies Effects on Weapon Systems Reliability," ADB145132 (Aberdeen Proving Ground, MD: U.S. Army Materiel Systems Analysis Activity, February 1990), 3.

b. There are severe mechanical, as well as combustion requirements which must be overcome to make a traveling charge concept successful.

c. Traveling charges tend to amplify round to round dispersion.

Summary

The primary conventional gun propulsion technologies being investigated by the Army were reviewed in relationship to conventional propulsion and advanced conventional propulsion. It gave a brief overview of each concept and the advantages and disadvantages as currently known by the author. Higher muzzle velocities might be achievable over time with certain concepts. The time to develop these concepts to maturity, coupled with the associated costs, causes the researcher and developer to explore new technologies which do look promising in the near future over solid propellant (SP) concepts. Energetic materials, such as liquid propellants, which could possibly lead to better gun propellants for improved performance, less erosion and enhanced survivability characteristics are critical to the growth of future tank cannons. The next chapter will begin a discuss on one such technology, liquid propellants, which increase the energy of propellants. The chapter will focus its discussion on the logistical impact of liquid propellants as a new propulsion for tank cannons.

CHAPTER 5

LOGISTICAL CONSIDERATIONS

Introduction

There are major issues in logistics which must be discussed if a new technology possibly to be to be fielded. One method is to draw a comparison between the base-line vehicle, a M1A1 Abrams tank with a Solid Propellant Gun (SPG), and a M1A1 Abrams tank with a Liquid Propellant Gun (LPG) continues. The chapter drawing a direct comparison between the tow technologies by analyzing the issues in industrial base conversion, production cost savings factors between SPG and LPG, commercial production of liquid propellants (LP), transportation factors, manpower resupply requirements and demilitarization and disposal of propellants.

Part I

Industrial Base Conversion

One of the key issues of many logisticians about the use of LPG for selected weapons is the conversion of the industrial base to produce two types of ammunition, one for the LPG program and one for the SPG program. Therefore, the primary goal is to use the existing family of projectiles in their current configurations for LPG by reducing the number of design modifications. Minimizing the number of projectile modifications for a new weapon system results in lower costs and reduced testing for type classification for use in the field.

The LPG program already has two advantages in the type of projectiles required for a LPG. First, a LPG uses caseless ammunition which only requires the projectile. Secondly, the current LP designs will permit the use of M830, High Explosive Anti-tank, Multipurpose with Tracer (HEAT-MP-T) and M829A1, Armor Piercing Fin Stabilized Discarding Sabot with Tracer (APFSDS-T) rounds used in SPGs with minimal modification to the current generation of projectiles.

The M829A1, APFSDS-T kinetic energy (KE) ammunition uses a subcaliber long rod penetrator stabilized in flight by fins. The design objective of a KE penetrator "consists of applying sufficient energy at the point of attack to overmatch the capability and strength of the target material to resist penetration."[1] Today's generation of long rod penetrators achieves that design objective by traveling at supersonic speeds and massing high concentrations of kinetic energy in a relatively small surface target area. The desired end state is a perforation resulting in the defeat of the target.

[1]T.W. Terry, S.R. Jackson, C.E.S. Ryley, B.E. Jones and P.J.H. Wormell, Fighting Vehicles (London, Great Britain: BPCC Wheatons Ltd., Exeter, 1991), 28.

Another secondary method of achieving a perforation of the target is through the use of chemical energy ammunition.

The M830, HEAT-MP-T chemical energy ammunition employs a high-explosive (HE) warhead to produce lethal effects on targets. When the HEAT-MP-T round impacts a target, the fuze detonates the HE which, in turn, fragments the casing, as well as producing a highly penetrating jet of metal in the forward direction from the conical, copper liner at the front end of the casing.[2] Again the desired end state is the perforation of the target. "It is the residual penetrator and the debris fragments that are the major contributors to lethal effects inside the target once it has been perforated."[3] The characteristics of each of the rounds listed above are summarized in Table 1. Ammunition Data[4].

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[2]Andrew M. Dietrich, "Warhead Mechanics," Ballistic Science and Technology Tutorial Terminal Ballistics Division, (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, April 1991), 30.

[3]Ibid., 58.

[4]U.S. Army, TM 9-2350-264-10-3, Operators Manual, Tank, Combat, Full-Tracked: 120-mm Gun, M1A1, (2350-01-087-1092), General Abrams (Washington D.C.: Department of the Army, 1991), 5-7.

TABLE 1. AMMUNITION DATA		
COMPLETE ROUND	M829A1 APFSDS-T	M830 HEAT-MP-T
WEIGHT	46.2 lb	53.4 lb
LENGTH	38.7 in	38.6 in
PROPELLANT TYPE	JA-2	Stick DIGL-RP
PROJECTILE		
TYPE	APFSDS-T	Multiple Purpose
LENGTH	Classified	33.1 in
WEIGHT	Classified	29.8 lb
RANGE	3000 meters	2500 meters

Just a slight modification to the M830, HEAT-MP-T and the M829A1 in the form of a handling plug to the rear of the projectile would make the current generation of tank fired munitions interchangeable with the LPG system. The industrial base could continue to provide M830 HEAT-T and M829A1 APFSDS-T to both types of gun systems until the transition was complete. The manufacturer would only produce projectiles for the LP systems and complete projectiles with case for the solid propellant (SP) systems. The normal expense associated with a major ammunition redesign effort would not be experienced, resulting in a much lower industrial base conversion cost. The other critical factor which must be addressed is propellant production by both in the SPG and the LPG.

Part II

Propellant Production Cost Savings Factors

One of the advantages to the caseless rounds in the LPG system is that manufacturing only the projectile for a weapon system would greatly reduce cost. In comparison, the current process of producing a SP round is very expensive and hazardous. It requires detailed and precise coating and weight specifications for each grain of propellant. The propellant grains must be a certain size and mass in order to meet firing and performance table standards which predict the flight of a projectile. This process of coating, weighing, propellant charge packing, and assembly of propellants is very time-consuming. The process is also hazardous, and the materials are extremely flammable, requiring strict safety standards. The end result is a solid one piece SP round which requires precision assembly and high costs.

The opposite is required for the LPG system which consists of two major munition components. These two components, propellant and projectile, are not merged with each other until they are placed together in the breech for combustion process. The LP process eliminates the requirement to assembly a projectile and propellant at the production plant. The projectile is manufactured separate from the propellant. Since there are no requirements for assembly of propellant and projectile prior to combat operations, the production requirements are less for LP rounds as compared to SP rounds, thus cost is reduced.

Part III

Commercial Production of Liquid Propellants

The current LP chosen to be used is called hydroxyl ammonium nitrate (HAN). The "commercial proprietary process for the production of HAN involves the electrolysis of nitric acid."[5] The availability of natural resources at a low cost made HAN LP even more promising. With the same relatively small existing commercial production base, "the propellant cost would be equivalent to solids, about $4.00 per pound."[6] "If the process is scaled to provide to the military the HAN required to produce 100 million pounds of LP yearly, the estimated cost of the HAN drops 75% of the current commercial price."[7] Several Ballistic Research Laboratory (BRL) studies assume that during a period of mobilization production output might well excess 20 million pounds a month, which the

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[5]Walter F. Morrison, "The Application of Liquid Propellant Gun Technology to Field Artillery," (Proceedings of 20th JANNAF Propulsion Meeting, CPIA PUB 370, Vol. II, February 1983), 133.

[6]Ibid., 131.

[7]Ibid.

potential cost savings could quickly surpass the required investment to implement liquid propellants.[8] A comparison of LP with the current propellant production costs associated with SP is summarized in Table 2. Estimated Costs of Propellants[9]. This would indicate a definite potential reduction in LP production costs from the current SP production program.

TABLE 2. ESTIMATED COSTS OF PROPELLANTS	
CHARGE	PACKAGED PROPELLANT COST/LB
M3A1	$11.40
M4A2	$7.53
M119A2	$6.04
M203	$10.01
M30A1	$13.02
JA-2	$16.24
LP-1845	$.71

Part IV

Transportation Issues

Another aspect of cost reduction is transportation. The safety requirements associated with transporting SPs require special packing materials and handling standards. The key comparison in LP verses SP is the attempt to pack

[8] Walter F. Morrison, John D. Knapton and Guenter Klingenberg, "Liquid Propellants for Gun Applications," ADB090195 (Aberdeen Proving Ground, MD, January 1985), 34.

[9] Morrison: 35.

equivalent weights of projectiles and propellants per load. SP ammunition cannot compete with LP because of packing requirements. Ammunition packaging requirements have gone unchecked to a point that SP ammunition "packaging represents 50% of the total weight."[10] This impacts on the entire logistical system by increasing shipping costs, packaging costs, and transportation requirements. One alternative which can reduce these packaging requirements is the LP program.

The current logistical burden associated with SPs is significantly reduced by design with the LP program. In a LP propellant base logistical system, the ammunition transportation requirements can be reduced by more than 30% at the user level, and the ability to sustain operations can be increased by more than 40%.[11] These reductions in transportation and resupply requirements are a result of the LPs high packing density.[12] Figure 7. Logistical Advantages of Liquid Propellants demonstrates the projected logistical advantages of liquid propellants on the tactical battlefield

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[10]Maureen M. Stark, "Logistics Analysis of the Impacts of Liquid Propellants on the Ammunition Resupply System," ADB087488L (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, October 1984), 11.

[11]John D. Knapton, Irvin C. Stobie, Richard H. Comer and William F. Stansbury, "Survey of Ballistic Data from High Velocity Liquid Propellant Gun Firings," BRL-R-2005 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, August 1977), 26.

[12]Stark, 11.

from the Corps ammunition storage point (ASP), to the Division ammunition transfer point (ATP), to the Brigade ATP and finally to the user which needs the Class V for the combat vehicles. Figure 7. Logistical Advantages of Liquid Propellants shows the results of a comparison between the LP propellant system to the established solid propellant Class V resupply system. When recent logistical studies were evaluated with LP as the primary propellant on the battlefield, all levels of logistical support, from Corps to the user, experienced reductions in the transportation requirements and increases in total Class V inventory on hand.

These reductions in transportation were the largest gains which were due in part to the ability to transport LPs in bulk. The procedures used in bulk petroleum movements can be applied to LPs. The key limiting factor in transporting SPs is volume. The inverse is true of LPs. LP packaging densities reach weight limits (gross out) before reaching volume limits (cube out) Table 3. Cube Verses Weight Comparisons[13]. Table 4. ATP Trailer Comparisons[14] is a comparison between SPs and LPs with a base requirement for a fixed number of charges. The results support a conclusion that a reduction in transportation requirements would be achieved if LP is hauled in bulk. The density per unit volume

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[13] Ibid., 17.

[14] Ibid., 23.

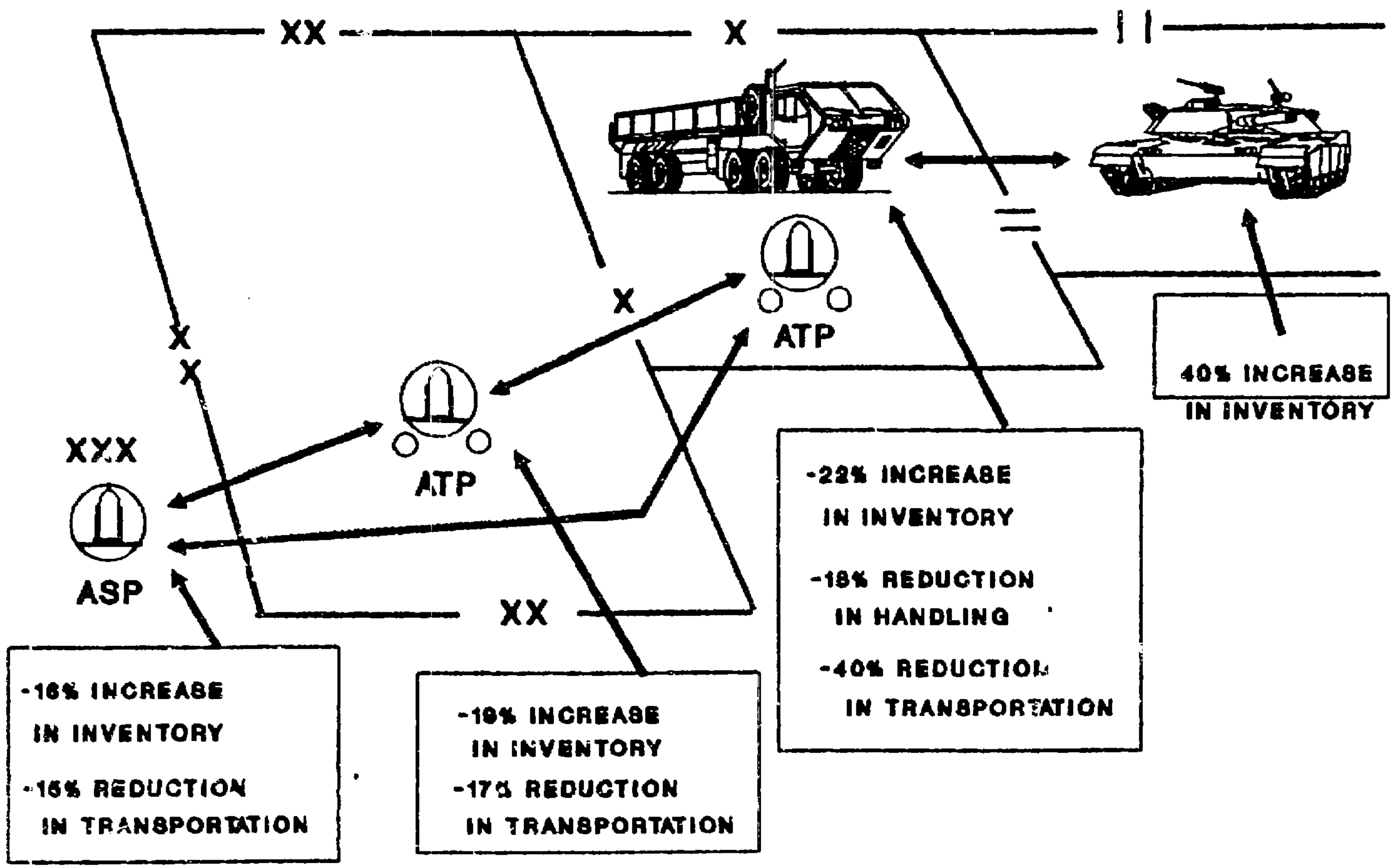

FIGURE 7. LOGISTICAL ADVANTAGES OF LIQUID PROPELLANTS

TABLE 3. CUBE VERSES WEIGHT COMPARISONS			
PROPELLANT	NO. OF CHARGES	WEIGHT (LB)	CUBE (CU FT)
Solid-bag SP	40	1757	55
15-gal Drum LP	139	2680	44
55-gal Drum LP	169	2990	47
500-gal Bldr LP	384	6361	104

TABLE 4. ATP TRAILER COMPARISONS						
Propel Qty Type	NO. of Pallets Req'd	Base Area Req'd (sq ft)	Base Area per S&P (sq ft)	No. of S&P Trl	Weight S&P (STONS)	Total Weight (STONS)
Solid-bag SP	61.27	873	218	4	13.5	53.8
15-gal Drum LP	17.55	234	117	2	11.8	23.5
55-gal Drum LP	14.36	171	171	1	21.5	21.5
500-gal Bldr LP	.33	149	149	1	20.1	20.1

of LP is more efficient which would maximize the load hauling transportation assets and increase the available inventory at each ATP or ASP. The end result would be a reduction in the logistical burdens by using LPs.

To further enhance the efficiency of LP from the ATP to the user, the medium and quantity by which LPs are moved determines the total efficiency of the logistical system. If LP resupply is modeled after a gas station type of operation, in the same manner as petroleum products, then the advantage of LPs is realized and maximized. This means moving LPs in large bulk until the last possible point in the logistical chain.

The current projectile resupply system has proved to be efficient, and can move ammunition with relative ease until actual loading occurs from supply vehicle to tank. The current SP rounds are packaged in fiber tubes, which are in wooden boxes packed on pallets and banded. Transportation of these boxes of ammunition to the M1A1 tank from the supply vehicle is currently done by ***human chain***. This whole process of unpacking and loading a tank may take more than an hour, which is an unreasonable amount of time for troops and combat vehicles to spend away from the battlefield. The exposure of crews, combat vehicles, and resupply vehicles must be reduced.

The new depot pack system which is being used on the new generation of supply vehicles permits 49 rounds to be easily accessible in one wooden box. This has reduced resupply time with SP ammunition to about 30 minutes per vehicle. If a resupply is occurring on a LP system, the primary advantages are the movement of propellant by pumps from storage tanks on the resupply vehicle to storage tanks on the combat vehicle, and the transfer of only projectiles. These projectiles do not have the case or propellant associated with SP ammunition, thus they are approximately 45% of the normal weight of a SP round. This means less weight being loaded in a combat vehicle by hand. The "total projectile/propellant rearm time of 30 minutes for SPs could be reduced to eight minutes for LPs"[15] on a M1A1 tank under ideal conditions.

One drawback needs to be noted concerning HAN LPs. HAN LPs are very susceptible to contamination. "Since this propellant is a water-based solution, some foreign matter found in the field will readily dissolve in it."[16] The most critical point for LPs is the transfer operation. Contamination can occur when the LP is transferred from one supply vehicle to another, or in transition to a combat vehicle. The movement of LPs through pumps, lines, hoses, and

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[15]J. M. VanDerwerken, "High Performance Regenerative Liquid Propellant Gun Study," ADB099639L (Pittsfield, PA: General Electric Company, Ordnance Systems, February 1986), 61.

[16]Ibid., 58.

connections is when LPs are the most susceptible to contamination. The system must be examined and designed to reduce the contamination problem.

Part V

Demilitarization Issues

The demilitarization and disposal of propellants is a major issue, especially in today's society. The SPs disposal is normally accomplished by a burning process which can be extremely hazardous. The HAN LPs are just the opposite since they are biodegradable. The "conclusions are that HAN-based LPs can potentially be released directly into the soil, without adverse environmental effects. This greatly reduces problems in disposal."[17] Systems which have water based properties are ideal for disposal and are not hazardous.

Summary

The objective of this logistical assessment was to discuss some key areas which effect costs savings that the decision maker must address early in the development of a possible new technology for application on a combat vehicle. The LPG factors for sustainment which address the industrial base conversion for production, unit production costs, commercial production, transportation comparison, rearm

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[17]Morrison, "The Application of Liquid Propellant Gun Technology to Field Artillery," 133.

requirements and demilitarization and disposal of pr ‹ ˋ ˜ ˋt›
have shown major cost reductions associated with each of them
when compared to the SPG program. These factors are critical
elements in Operations and Sustainment funding which must be
addressed over the life cycle of the LPG, especially with a
Department of Defense (DOD) trend which projects a reduction
in funding in the near future. The next chapter will assess
the tactical impact of LPs on the modern combat vehicle.

CHAPTER 6

COMBAT VEHICLE ANALYSIS

Introduction

The objective of Chapter 6 is to address those aspects of the Liquid Propellant Gun (LPG) technical design that impact on it acceptance. There are technical advancements within the LPG program which must be analyzed to ensure a leap ahead over the current technology being used by the soldier on the battlefield. The M1A1 Abrams tank will still be the baseline vehicle used in this discussion since it is the current technology being used by the Army.

A tank has three major requirements which it must meet in order to achieve mission success against today's THREAT. They are mobility, firepower and survivability. These requirements can be traced from the first tank development during World War I to the present M1A1 Abrams main battle tank.

Part I

Survivability

The current M1A1 tank's interior can be reconfigured to accommodate a liquid propellant (LP) system. There are many advantages associated with the redesign and placement of the projectiles and the propellant in the vehicle. The small projectiles in a LPG system will permit storage of 56 rounds on-board verses 40 rounds on a solid propellant (SP) system[1] (Table 5. Comparison of M1A1 Solid Propellant Verses Liquid Propellant Vehicle Systems[2]).

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[1] J. M. VanDerwerken, "High Performance Regenerative Liquid Propellant Gun Study," ADB099639 (Pittsfield, PA: General Electric Company, Ordnance Systems, February 1986), 78.

[2] John Mandzy, "High Performance Regenerative LP Tank Gun," Contract Number DAAA 15-87-C-0097 (Pittsfield, MA: General Electric Company, Defense Systems Division, June 1988), 3-23.

TABLE 5. COMPARISON OF M1A1 SOLID PROPELLANT VERSES LIQUID PROPELLANT VEHICLE SYSTEMS		
	M1A1	M1A1-LP
Gun Performance Muzzle Velocity	1676 M/Sec	1877 M/sec
Stowed Rounds	40	56
Ready Rounds (Automated)	17 (Hand Loaded)	48
Rate of Fire		
KE	8 Rds/Min	15 Rds/Min
CE (HEAT)	8 Rds/Min	13 Rds/Min
Vehicle Weight Stowed Load	62.2 Metric Tons (68.9 Tons)	58.2 Metric Tons (64.5 Tons)

The LPG system will permit the crew to be reduced to three men, and will introduce an autoloader which has access to 48 rounds as shown in Table 5. Comparison of M1A1 Solid Propellant Verses Liquid Propellant Vehicle Systems. The SP system requires a loader who has access to only 17 rounds before he must transfer from the hull storage rack and the tank commander's semi-ready rack. The availability of rounds and time to reload are key factors in both systems which were examined in Chapter 5. The LPG system showed a saving in rearm/refit time from 30 minutes in a SPG system verses 8 minutes with a LPG system. The goal to further reduce the crew's vulnerability to the THREAT is achieve in a LPG.

There are drawbacks with the LPG, with the autoloader, over a manual SPG system for loading and firing projectiles. The autoloader must be proven reliable and if failure occurs, a system has to be available to load rounds manually. This manual mode on the LP system must be as efficient as the manual mode on the M1A1-SP system. The other aspect of an autoloader is the safety of the crew around "fast-moving machinery within a manned compartment"[3] A proven degree of safety must be established prior to the use of the autoloader.

The other major advantage in a LPG is the handling and storage requirements of the propellant. The propellant offers unique abilities since it is a fluid and can assume any shape for storage on the vehicle. "As a result, monopropellants require only about 75% of the volume of solid propellants containing the same amount of energy."[4] This permits all space behind the ammunition bustle rack in the hull to be

[3]VanDerwerken, 44.

[4]R.M. Ogorkiewiez, "Future Tank Guns, Part 1: Solid and Liquid Propellant Guns, " International Defense Review, Vol. 23, No. 12/1990: 1379.

utilized. The M1A1-LP by design can store "850 liters"[5] of LP which is designed with a 30% excess above its basic load of projectiles. Design of these LP tanks if damaged must prevent any LP from spilling directly into the crew compartment. If heat is associated with the spillage, a possibility exists that noxious fumes could develop with HAN LPs. The HAN LP's exhibit relatively "low shock sensitivity and low flammability and are very difficult to ignite at atmospheric pressure."[6] HAN LP will not release the majority of its stored energy unless it is placed under high pressure in a chamber.[7] This type of LP greatly enhances crew survivability and reduces vehicle vulnerability.

Also associated with reduced vulnerability are the limits placed on muzzle flash and blast found with gun systems. Muzzle flash gives a direct signature to the enemy, and increases a vehicle's vulnerability. "Secondary muzzle flash and blast result from the ignition of combustible gases that are products of propellant combustion, a situation not

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[5]VanDerwerken, 45.

[6]Maureen M. Stark, "Logistics Analysis of the Impacts of Liquid Propellants on the Ammunition Resupply System," ADB087488L (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, October 1984), 126.

[7]N. Klein, "Liquid Propellants for Use in Guns - A Review," BRL-TR-2641 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, February 1985), 28.

present in LPs."[8] HAN LPs are stoichiometric, oxygen balanced, muzzle exhaust would not be fuel rich (the equilibrium products of solid propellants are 40% combustibles by weight whereas the analogous figure for HAN-based LPs is less than 1%).[9] The reduction in flame temperature and combustible products, again reduces vulnerability and increases the survivability of the vehicle.

The explosion of on-board stowed ammunition is the single major cause which destroys combat vehicles and kills crews. The "use of SPs has always resulted in reduced safety and increased system vulnerability, primarily due to high propellant flammability."[10] The HAN LP offers a new type of propellant which has unique characteristics reducing vulnerability and also reduces vulnerability by enabling storage from the crew component. These factors increase combat staying power of military vehicles.

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[8]Ibid., 29.

[9]Walter F. Morrison, John D. Knapton and Guenter Klingenberg, "Liquid Propellants for Gun Applications," ADB090195 (Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratory, January 1985), 33.

[10]Walter F. Morrison, "The Application of Liquid Propellant Gun Technology to Field Artillery," (Proceedings of 20th JANNAF Propulsion Meeting, CPIA, PUB 370, Vol. II, February 1983), 125.

Part II

Firepower

The addition of an autoloader on M1A1-LP will affect the burst rate or rate of fire of the vehicle. The LP system will be able to fire at 15 rounds per minute with kinetic energy (KE) penetrator and 13 rounds per minute with chemical energy (CE) round.[11] The M1A1-SP system has a rate of fire of 8 rounds per minute with KE or CE as shown in Table 5. Comparison of M1A1 Solid Propellant Verses Liquid Propellant Vehicle Systems. The manual system is more reliable, but the trade-off with the autoloader offers a higher rate of fire and more rounds to fire, prior to reloading. This increased rate of fire gives the tactical commander a marked advantage compared to previous weapon systems firing rates because he can sustain a fight longer and engage multiple targets quicker on the battlefield.

If the LP autoloader system should malfunction or a misfire should occur, the rate of fire and downloading procedures have not been studied in an operational environment. These are key issues which must be addressed and engineered properly in a LPG system to ensure the survivability of the crew and vehicle in a hostile environment. Under these types of degraded conditions, manual rates of fire must be addressed early in the development process.

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[11]VanDerwerken, 80.

Although the current LPG prototype system does not offer an increase in muzzle velocity over the previous SP system at 1676 m/sec, if the current progress and developments on the LPG system are continued, a 10-14% increase in muzzle velocity can be obtained compared to only a 2-4% increase in SPs.[12] The growth potential in a two stage LPG is currently being explored. The traveling charge concept affords higher muzzle velocities over the current growth development of SPGs.

Part III

Mobility

Another concern is vehicle weight. The M1A1 has a vehicle weight of 62.2 metric tons. The M1A1-LP with the increased stowed load and automated feed system will decrease the vehicle weight to 58.2 metric tons as shown in Table 5. Comparison of M1A1 Solid Propellant Verses Liquid Propellant Vehicle Systems. This is a result of a crew reduction from four to a three men on the M1A1-LP. A reduced crew gives the armor community the option of armoring less volume. Therefore, it would assist in the weight reduction in a M1A1-LP.

Another crucial factor in weight constraints is the air transportability of a vehicle. The M1A1-LP can still be transported on the C5A or C5B Galaxy air transport aircraft.

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[12] Ogorkiewiez, 1379-1380.

The other factors such as rail movement, heavy equipment transporter or cross country mobility are not degraded in any form with the LPG.

Summary

Chapter 6 has identified the three characteristics associated with a tank: survivability, firepower and mobility. The LPG system impact in each of those areas was evaluated for their affect on the M1A1 tank. The outcome of the evaluation showed the tank should perform as well or better with the LP than it does with the SP technology.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Introduction

The purpose of this final portion of the thesis is to answer the research question whether the Army should continue development and adopt the Liquid Propellant Gun (LPG), or remain solely with the current projected improvements of the Solid Propellant Gun (SPG) for the future main battle tank. The objective of Chapters 2-6 was to answer that question in a systematic matter which addressed both sides of the issue. This section of the study summarizes the conclusions drawn from each aspect of the liquid propellant gun discussed in this thesis.

Part I

Conclusions

The objective of this thesis was to answer the research question: Is a liquid propellant gun a viable option for the future main battle tank in the United States Army? To investigate the question, the liquid propellant gun (LPG) was examined in three areas: the historical development of liquid propellants (LP), the logistical impact of LPs and the impact of LP on a combat vehicle. Several major conclusions can be drawn from this effort which give LPG advantages over the solid propellant gun (SPG).

The LPG clearly shows great potential over the SPG. A LP system could be integrated into today's combat vehicles and yield positive comparative results. Rates of fire for combat vehicles can be increased without taxing the logistical system. More of LPs potential could be exploited if the vehicles were designed to exploit the LPG system.

The primary logistical advantage of LPs is volume efficiency which leads to benefits with regard to storage, transport, and ammunition processing. Studies indicate a reduction in man-hours and equipment in the resuppiy of LPs over SPs. This reduction in man-hours is a function of the resupply rate. If LPs are moved in bulk, the large savings will be realized. This bulk movement, coupled with the increased on-board stowage capacity of propellant and projectiles in combat vehicles, will reduce the dependence on frequent resupply.

LPs add extreme flexibility to vehicle design criterion which results in reduced propellant volume requirements and permits remote stowage within the vehicle. The propellant can, by design, be stowed in remote places away from the fighting compartment of the vehicle, greatly enhancing survivability of the vehicle and crew. The other characteristics which add to increased survivability are the low flammability, low shock sensitivity, and requirements to ignite the propellant. These factors put HAN LPs ahead of any of the current SPs in reducing the vulnerability of equipment and men.

The current production base and availability of raw materials for LPs is already established. The cost reduction over SPs would be the result of a simpler operation which does not require a high degree of precision and safety levels. Projected production costs could easily be half or less of SPs. A possible increase in cost would be handling and shipping procedures to prevent contamination of the LP.

The demilitarization and disposal technique of burning SPs is becoming less desirable and is not a safe process. Since HAN LPs are nontoxic and biodegradable, society may be more willing to accept the disposal methods of non-burning. HAN LPs will present no future hazards when it is no longer required.

The advantages of LPs for today's and future combat vehicles give the tactical commander an edge needed to meet the THREAT nations. The rising cost of new technology and new weapons has forced the military community to be better stewards of the tax payer's money, and get the most *bang for the buck*. If the Army is searching for a new and better cost effective new and better system in the field of propulsion, the liquid propellant gun system is a possible solution.

Part II

Recommendation

Work on HAN LPs and LPG should not be discontinued at this point. Current research must continue to ensure safety, handling, storage, transportation, and vulnerability are addressed in the LP program over the full range of environmental conditions encountered in military use.

The design of the regenerative mechanism for a LPG must meet the reliability, maintainability, and availability requirements of today's military equipment. The high pressure seals, mechanical parts, igniter issue, and projectile loading must all be addressed to reduce failure at any critical point on the battlefield.

Future combat vehicles need to be designed around the LPG to maximize the benefits of LPs. LP will make combat vehicles more survivable and lethal on the modern battlefield.

Summary

The projected increase in vehicle lethality and crew survivability enhancements afforded in a liquid propellant gun can not be overlooked. The Army has reached a point in technology development where the old solid propellant gun has reached limits in which the growth potential is very small at great costs to the Department of Defense. The need for a new gun propulsion technology which can meet the needs of the

Armor force in the year 2000 is at a critical decision point. A liquid propellant gun is a viable option for the future of the Army's main battle tank.

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