Propulsion Technology Effect on Weapon System Reliability

Faust M. Denicola Jr, Army Materiel Systems Analysis Activity; Aberdeen Proving Ground

Key Words: Tech Base Propulsion Technology, Programmed-Splitting Stick Propellant, Solid Propellant Traveling Charge, Regenerative Liquid Propellant Gun, Fractional Traveling Charge, Electromagnetic Propulsion, Railgun, Coilgun, Electrothermal Propulsion.

Abstract

In recent years, the emphasis is to insure quality and reliability as early as possible in the development of the U.S. Army Materiel. AMSAA developed a methodology for estimating the reliability of weapon systems early in development even prior to any system testing. The numerical reliability results of this study are not intended to be used for determining reliability requirements for these weapon systems but instead to give the system designer a better understanding of those subsystems which are expected to be high risk. Because of the complexity of the propulsion technologies/weapon system combinations in the study, only a summary of the total report is given. The tables and results presented are examples of the many which were generated for the study.

Introduction

The Director, U.S. Army Ballistic Research Laboratory (BRL), requested that AMSAA conduct a reliability review of the advanced propellant technologies currently being researched by BRL. Since AMSAA had not previously conducted reliability reviews of systems in such early stages of development, the study had the following objectives:

1. Determine the feasibility of developing a methodology by which the reliability of systems resulting from tech base programs could be estimated.
2. Develop reliability projections of artillery, armor, and air defense weapon systems resulting from the tech base efforts in new propulsion systems.

Scope

This study addresses four types of advanced gun propulsion: advanced solids, liquid propellant, electromagnetic (EM), and electrothermal (ET) for three different weapon systems types: artillery, armor, and air defense. It is not a complete systems study and does not include the overall analysis of system performance, logistics, economics, or production for each of the propulsion system/weapon system combination being studied.

Propulsion Technologies

The propulsion technologies assessed in this study and currently being researched by the BRL are shown in Table 1.

Table 1. Propulsion Technologies

- Advanced Solids
 - Very High Burning Rate (VHBR) Monolithic
 - Programmed - Splitting Stick
 - Traveling Charge (TC)
- Liquid Propellants
 - Regenerative
 - Fractional TC
- Electromagnetic
 - Railgun
 - Coilgun
- Electrothermal
 - ET
 - Combustion Augmented Plasma

Baseline Weapon Systems

A baseline was necessary which defined the most current component design for which data existed for each of the weapon systems used in this study. Reliability estimates for each of these baseline systems with their present performance capabilities were estimated using data from field Sample Data Collection (SDC) reports for artillery and the Initial Production Test (IPT) reports for armor and air defense.

The building block concept was used for defining the new weapon systems with the tech base propulsion technologies. This concept of building the future weapon systems around the baseline provided a basis for comparison of the reliabilities. Each of the baseline subsystem reliabilities were adjusted depending on the estimated effects of the propulsion system components for each of the performance parameters. These projected reliabilities were then compared to the baseline estimates. It is important to remember, when making these comparisons, that the baseline reliabilities are only for the current performance characteristics and the future weapon system reliabilities are for both the current and the increased performance parameters.

Artillery

The 155mm M109A2/A3 self-propelled howitzer was chosen as the artillery baseline weapon system. Since a major objective for applying the new propulsion systems to an artillery howitzer was to increase range, the baseline system should also consider maximum state-of-the-art range capability. As a result, the 155mm Howitzer Improvement Program (HIP) armament subsystem was considered as part of the baseline. This armament subsystem increases the maximum range capability of the M109A2/A3 howitzer to 30 kilometers with a Rocket Assisted Projectile (RAP) which is equal to the range capability presently achieved with the 155mm M198 towed howitzer.

Armor

The M1A1 Abrams tank with the 120mm armament subsystem was used as the armor baseline weapon system. For armor weapon systems, the addition of the new propulsion technologies should provide better performance capability by increasing the muzzle velocity. The muzzle velocity presently achieved by the 120mm armament subsystem on the Abrams tank is 1700 meters per second (mps). The M1A1 IPT reliability data were unique because they were normalized over the miles traveled, i.e., since all testing followed the mission profile, a single estimate based on Mean-Miles-Between-Failures (MMBF) could be given for the total weapon system.

Air Defense

Even though the SGT York air defense gun development program was cancelled, it was chosen as the air defense baseline weapon system because many of its components represent the state-of-the-art designs. The SGT York gun had a 40mm armament subsystem with a muzzle velocity of 1100 mps mounted on an M48A3 tank chassis.

Performance Characteristics

In order to compare the reliability effects of each of the propulsion systems on the baseline weapon systems, it was necessary to define the performance characteristics (both baseline and projected) for each of the three weapon system types. Table 2 lists the performance characteristics chosen for the artillery, armor, and air defense weapon systems.

Table 2. Performance Characteristics Assessed

Artillery

- 30 km range (baseline)
- 50 km

Armor

- 1700 mps muzzle velocity (baseline)
- 2000 mps
- 2500 mps

Air Defense

- 1100 mps muzzle velocity (baseline)
- 2000 mps
- 2500 mps

For artillery, increased range from 30 km (baseline) to 50 km (projected) was the desired performance parameter assumed for the study. To achieve this increased range, it was necessary to propel a RAP or basebleed projectile at a muzzle velocity increased from 800 mps (baseline) to 1050 mps. A 50 km range was chosen because of user interest in this maximum range.

For armor, increased performance could be achieved through greater target penetration by the projectile. To do so, it is necessary to develop new projectiles and to increase muzzle velocity. The three velocities investigated in the study were: 1700 mps, the present velocity; 2000 mps, a velocity considered achievable without major design changes to the weapon system; and 2500 mps, a desired muzzle velocity. This study allowed only those projectile design improvements necessary to adapt the projectile to the new propulsion technologies. It did not consider those projectile design changes necessary to improve target penetration.

For air defense, improved performance could be achieved by reducing the time of flight. This, again, could be accomplished by increasing the muzzle velocity. The reasons for choosing the three velocities given for air defense are the same as those stated previously for armor.

Approach

The introduction of liquid and electromagnetic/electrothermal (EM/ET) propulsion technologies significantly modifies the technique used to calculate weapon system reliability. With conventional advanced solids propulsion systems, the ammunition consists of the propelling charge, projectile, and fuze. The reliability of the propelling charge, along with the projectile and fuze, is binormally distributed; either it works or it doesn't work. Excluding a sticker or an inbore premature, when the propelling charge fails, it does not cause a weapon system mission failure. However,

the addition of liquid propulsion or EM/ET to a weapon system adds components to the armament subsystem that have an inherent reliability which is exponentially distributed, just as the weapon system. Failure of these propulsion components is also a weapon system failure, which degrades the weapon system reliability and availability.

Consultations

Members of the AMSAA team had numerous meetings with the BRL support team to gather information on each of the propulsion technologies. The study objectives were addressed using the combination of BRL's knowledge of these technologies and AMSAA's expertise in the field of weapon system reliability. The following gives examples of the topics discussed during these consultations:

1. How will the propulsion technologies be applied to each of the weapon systems in the study?
2. What are the effects of the application?
3. What weapon design changes are necessary to achieve the performance characteristics of interest?
4. How will these changes affect the baseline reliability?

Ground Rules

In order to make a realistic comparison of each of the weapon/propulsion system combinations, the following ground rules were necessary.

1. Not all propellant technologies were assessed for all weapon system performance levels, as certain combinations were not practical.
2. No consideration was given to excessive weapon system weight which could result with the use of any propulsion technologies. Weight restrictions would have limited the approach for the design of propellant technology application, particularly for EM/ET.
3. Since the Building Block Concept (building the future around the baseline) was used for this study, the only modifications allowed were those necessary to adapt the new propulsion technologies to the baseline system.
4. For this study, the only maintainability effects estimated were on the components for the new propulsion system itself. It is realistic to assume that these additional components will also effect the maintainability on the other subsystems of the baseline weapon system; however, this was not evaluated.

Ratings

The subsystems of the weapon systems were further divided down to the component level for the reliability analysis. The number of subsystem components used to define baseline weapon system reliability depended on the reliability data available for each component. Ratings were then estimated for the components for each propulsion technology assessed. These ratings were determined utilizing BRL's propulsion technology experts and AMSAA's expertise in analyzing weapon system failure modes.

Table 3 is an example of the ratings applied to the components of the air defense weapon system for each of the propulsion technologies assessed. The ratings were applied using a scale from one to ten, with a five meaning that there was no change in baseline reliability. Any number greater than five showed reliability degradation. For example:

4.0	=	-11%	-->	-20%
4.5	=	-01%	-->	-10%
5.0	=	0		
5.5	=	+01%	-->	+10%
6.0	=	+11%	-->	+20%

The first column of Table 3 represents a breakdown of the Air Defense subsystems/components. These components become increasingly more complex for artillery, armor and air defense respectively. An explanation for the Electromagnetic Railgun armament subsystem is shown in Table 4. Estimating the reliability and maintenance of the propulsion subsystems in quantitative terms was not attempted in this study. No satisfactory baseline exists from which numerical reliability and maintainability insight can be derived. Conventional propellants exhibit reliabilities of almost 100 percent and need minimal maintenance. Therefore, all propulsion subsystem estimates are presented in descriptive terms.

Table 3. Air Defense Ratings

												SCALE
												BASELINE
												REDUCED
												IMPROVED
												1-10
												5
												<5
												>5
PROPELLANT TYPE	ADVANCED SOLIDS					LIQUID PROPELLANT					ELECTRO-MAGNETIC	ELECTRO-THERMAL
VELOCITY (MPS)	1100	2000	2500	1100	2000	2500	2500	2500	2500	2500	2500	2500
EFFECTS ON:	MONO/SPLIT	MONO/SPLIT	TC	MONO/SPLIT	TC	RLPG	RLPG:LP-FTC	RLPG:LP-FTC	RLPG:LP-FTC	RAIL	ET/ET-CAP	
AMMO	5	4.5	4	3.5	3.5	5	4.5	4.5	4	4	3.5	3.5
PLATFORM/MOBILITY												
-POWER PACK	5	4.5	4.5	4	4	5	4.5	4.5	4	4	4	3.5
-SUSPENSION	5	4.5	4.5	4	4	5	4.5	4.5	4	4	4	3.5
-TRACK/WHEELS	5	4.5	4.5	4	4	5	4.5	4.5	4	4	4	3.5
FIRE CONTROL												
-RADAR/ACQUISITION	5	5	5	5	5	5	5	5	5	5	4	4.5
TRACK SYSTEM												
-SIGHTS	5	5	5	5	5	5	5	5	5	5	5	5
-COMPUTER	5	5	5	5	5	5	5	5	5	5	3	3.5
POWER & ACTUATION	5	4.5	4.5	4	4	4.5	4	4	3.5	3.5	5	4
ARMAMENT												
-TUBE	6	4	5	3.5	4.5	6	4	5	3.5	4.5	3.5	4
-RECOIL	5	4	4	4	4	5	4	4	4	4	4.5	4
-FEEDER SYSTEM	5	4	4	3	4	7	7	4	6	4	7	2
-BREECH	5	4	4	4	4	3	3	3	3	3	4.5	3
PROPULSION SYSTEM												
-RELIABILITY	N	N	N	N	N	S/M	S/M	S/M	S/M	S/M	H	M/H
-MAINTENANCE	N	N	N	N	N	S/M	S/M	S/M	S/M	S/M	V	V

CODE: N NONE; S SLIGHT; M MODERATE; H HIGH; V VERY HIGH

Table 4. Air Defense Example - RAM Ratings

Propulsion Type	Electro-Magnetic RAIL	
Velocity (MPS)	2500	
Effects On:		
Armament		
- Tube	3.5	a
- Recoil	4.5	b
- Feeder System	7	c
- Breech	4.5	d

- a. Redesign - Heavier, Larger Diameter Tube; More Wear At Higher Velocity.
b. Momentum Higher and Tube Heavier Than Conventional.
c. Simpler Feeder System - No Cartridge Cases.
d. No Breech; Higher Current Power Connectors Must Move With Recoil.

Working Papers

Subsystem reliability estimates were computed for each weapon system/propulsion technology combination at each performance level. The baseline reliabilities of the components were determined from test data for each weapon system. The subsystem reliabilities were then determined by adding the component failure rates together for each subsystem. The reliability of the subsystem is the inverse of the subsystem failure rate. The new reliabilities were determined by adjusting the baseline reliabilities of the components by the percentage corresponding to the ratings given. The new subsystem reliabilities were calculated in the same manner as the baseline systems. The reliabilities of the new systems are shown as bands because they should be used as a guide and not as an absolute.

An example of the air defense working papers, electromagnetic rail at 2500 mps muzzle velocity, is shown in Table 5. The new reliability estimate for the armament subsystem is of particular interest. Although the ratings for the recoil and breech decreased, the armament subsystem reliability improved. This is because the feeder, which was the weakest link, improved.

Table 5. Example of Air Defense Working Papers

EFFECTS ON:	BASELINE SYSTEM *			NEW SYSTEM			OVERALL EFFECTS ON RELIABILITY (%)
	REL	FAILURE RATE	SCORE	REL	FAILURE RATE		
AMMUNITION (M811 & M822)	0.980		3.5	0.974			(-0.6) - (-0.4)
	MMBF			MMBF			
MOBILITY (M1A1)	300	0.0033		250	0.0040		(-17) - (-7)
-POWER PACK	600	0.0017	4	480	0.0021		
-SUSPENSION	3,800	0.0007	4	3,000	0.0003		
-TRACK/WHEELS	780	0.0013	4	620	0.0016		
	MTBF (HR)			MTBF (HR)			
FIRE CONTROL (SGT YORK)	50	0.0196		39	0.0255		(-22) - (-14)
-RADAR/ACQUISITION	70	0.0143	4	56	0.0179		
TRACK SYSTEM							
-SIGHTS	500	0.0020	5	500	0.0020		
-COMPUTER	300	0.0033	3	180	0.0056		
	MTBF (HR)			MTBF (HR)			
POWER & ACTUATION (SGT YORK)	20	0.0500	5	20	0.0500		0
	MRBF			MRBF			
ARMAMENT (SGT YORK)*	2,000	0.0005		2240-2500	0.0004		(+12) - (+25)
-RECOIL	14,200	0.0001	4.5	12,800	0.0001		
-FEEDER	3,400	0.0003	7	4,800	0.0002		
-BREECH	7,600	0.0001	4.5	6,800	0.0001		
	LIFE (RDS)			LIFE (RDS)			
-TUBE	14,200	0.0001	3.5	10,000 -	0.0001		
				11,200			

CODES: N-NONE; S-SLIGHT; M-MODERATE; H-HIGH; V-VERY HIGH

*EXCLUDES TUBE

Overall Effects

The overall reliability effects of the propulsion technologies on the air defense system is given in Table 6. The synergetic effects of the propulsion systems on the weapon system firepower reliabilities are not included in these estimates since the propulsion systems were rated using descriptive terms only. However, these effects along with the propulsion system maintainability effects should be considered when making comparisons.

Conclusions

Because of the complexity of this study, three different weapon systems, nine different propulsion technologies, and eight different performance parameters, there are many conclusions both with regard to: 1) the feasibility of developing a methodology by which the reliability of systems resulting from tech base programs could be estimated, and 2) the reliability effects resulting from the tech base efforts in new propulsion systems.

Methodology

1. Given knowledge of our current weapon systems without significant design changes due to performance parameters and given well defined propulsion technologies, we feel confident that the study results reflect effects which could be expected.

2. As the propulsion technology becomes more complex and as the performance levels increase necessitating more complex weapon system design changes to accommodate these performance levels, our confidence in the estimates on system reliability decreases.

3. Information in the study giving the direction of the rankings of the design effects on system reliability, the failure modes, and the weakest link components are considered accurate and could be used by the weapon system developers to define projected areas of concern.

Table 6. Air Defense - Overall Reliability Effects

MUZZLE VELOCITY (mps)	PROPULSION TECHNOLOGY	AIR DEFENSE OVERALL EFFECTS - RELIABILITY						PROPULSION SYSTEM MAINTAINABILITY
		AMMO (REL)	MOBILITY (MMBF)	FIRE CONTROL (MTBF-HRS)	POWER ACTUATION: (MTBF-HRS)	FIRE POWER		
						ARM*	PROPULSION SYSTEM	
	BASELINE	0.980	300	50	20	1,670		
1100	ADVANCED SOLIDS							
	-MONO/SPLIT	0.980	300	50	20	2,000	N	N
	LIQUID -RLPG	0.980	300	50	18-20	2,000	S/M	S/M
2000	ADVANCED SOLIDS							
	-MONO/SPLIT	0.978-0.980	280-300	50	18-20	1,430-2,000	N	N
	-TC	0.976-0.978	280-300	50	18-20	1,430-2,000	N	N
	LIQUID							
	-RLPG	0.978-0.980	280-300	50	16-18	2,000	S/M	S/M
	-LP-FTC	0.978-0.980	280-300	50	16-18	1,430-1,670	S/M	S/M
2500	ADVANCED SOLIDS							
	-MONO/SPLIT	0.974-0.976	250-280	50	16-18	1,430-2,000	N	N
	-TC	0.974-0.976	250-280	50	16-18	1,430-2,000	N	N
	LIQUID							
	-RLPG	0.976-0.978	250-280	50	14-16	1,670-2,000	S/M	S/M
	-LP-FTC	0.976-0.978	250-280	50	14-16	1,430-1,670	S/M	S/M
	ELECTRO- MAGNETIC							
	-RAIL	0.974-0.976	250-280	39 43	20	2,500	H	V
	ELECTRO- THERMAL							
-ET/ET-CAP	0.974-0.976	220-250	44	16-18	1,430-1,670	M/H	V	

CODE: N NONE; S SLIGHT; M MODERATE; H HIGH; V VERY HIGH

*EXCLUDES TUBE

Reliability Effects and Implications

1. Slight to moderate degradation in reliability can be expected in some cases; but, potential increases in effectiveness and logistics may override reliability effects.

2. Moderate to high degradation effects indicate those areas that reliability needs to be improved. (Red flag)

3. High to very high degradation effects indicate that the weapon system may need to be designed around the technology to assure acceptable reliability.

Limitations

As with many studies, certain limitations existed and should be noted for this study. Although the direction of the rankings of the design effects on system reliability are considered accurate, the degree of the effects is much more difficult to predict and is considered less precise. Also, the ability to see propulsion system future designs, particularly for high performance and complex systems such as EM/ET, is more difficult. Therefore, caution should be

taken when using the projected reliability estimates. These estimates should be used as a guide and not as absolute estimates of reliability. As more data are generated through testing, these estimates should be revised accordingly.

Biography

Mr. Denicola is a supervisory operations research analyst with the U.S. Army Materiel Systems Analysis Activity located at Aberdeen Proving Ground, MD and is currently assigned as Chief, Artillery Systems Section; Artillery Armor, and Air Defense Branch, Reliability, Availability, and Maintainability Division (RAMD). His section's primary responsibilities are to conduct RAM evaluations on developmental weapon systems, ammunition, and associated equipment for the U.S. Army. Also, his section conducts Ammunition Stockpile Reliability Program (ASRP) evaluations on artillery ammunition currently stored throughout the world. He received a B.S. degree in Mathematics from California State College, PA, and has completed many graduate hours in statistics and operations research from the University of Delaware.