DETERMINING THE FEASIBILITY OF AN ARMY LASER AIR AND MISSILE DEFENSE SYSTEM

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ABSTRACT

DETERMINING THE FEASIBILITY OF AN ARMY LASER AIR AND MISSILE DEFENSE SYSTEM, by CPT Gabriel Jimenez, 79 pages.

The ability for adversaries to develop air and missile threats continues to improve as technology advances and costs decrease. However, the cost associated with developing and sustaining capabilities to counter these threats increases. The US Army relies primarily on various gun and missile interceptor systems that each defend against a portion of a large spectrum of threats. This thesis questions the sustainability of these systems and seeks to determine the feasibility of developing a single laser-based air and missile defense system.

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There was no feasible way to devote time to this project without the love and support of my wife and children who encourage me and give me strength to persevere.

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ACRONYMS

ABL	Airborne Laser
AMD	Air and Missile Defense
CBO	Congressional Budget Office
CDD	Capabilities Development Document
CFT	Cross-Functional Team
COIL	Chemical Oxygen Iodine Laser
DAS	Defense Acquisition System
FCS	Future Combat Systems
GAO	Government Accountability Office
IAMD	Integrated Air and Missile Defense
ICBM	Intercontinental Ballistic Missile
ICD	Initial Capabilities Document
JCIDS	Joint Capabilities Integration and Development System
JSF	Joint Strike Fighter, also known as the F-35 Lightning
LRIP	Low Rate Initial Production
LSS	Low, Slow, Small
MCS	Mounted Combat System
PAC-2	Patriot Advanced Capability 2
PAC-3	Patriot Advanced Capability 3
PPBE	Planning, Programming, Budget and Execution
SAM-D	Surface to Air Missile Developmental
SDI	Strategic Defense Initiative
STOVL	Short Take-Off and Vertical Landing

TBM	Tactical Ballistic Missile. Also referred to as Theater Ballistic Missile
THEL	Tactical High Energy Laser
TVM	Track-Via-Missile
UAS	Unmanned Aerial Systems

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CHAPTER 1

INTRODUCTION

Purpose

The Army is currently transitioning its focus back to large-scale combat operations against peer adversaries. The National Security Strategy and National Defense Strategy identify Russia and China as the United States' key adversaries that it must be prepared to counter.[1] These nations continue to increase capabilities specifically designed to counter or defeat US systems. Further, they recognize the need to contest the US in the air and space domains in order to shape the land fight and neutralize US dominance.

As technology improves, so do the capability and capacity of air and missile threats that nations employ. The multitude of platforms from ballistic missiles to Unmanned Aerial Systems (UAS) continue to improve. They are more lethal and survivable against Air and Missile Defense (AMD) systems. New technologies, such as hypersonic glide vehicles, are specifically designed to penetrate any AMD envelope.

Historically the Army designed different AMD systems to defeat threats based on type, range, or capability. The current Army inventory is capable of defeating air breathing threats such as helicopters, UAS, and fixed-wing aircraft at various ranges, as well as short and medium range Tactical Ballistic Missiles (TBM). As air and missile threats evolve technologically, AMD systems must modernize to keep pace. Modernization has finite limits requiring the development of new systems to counter

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[1] U.S. President, *National Security Strategy of the United States Of America* (NSS) (Washington, DC: The White House, December 2017), 2, accessed 1 March 2019, https://www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905-2.pdf.

different portions of the threat envelope. This threat envelope spans from small Unmanned Aerial Systems (UAS) and mortars to Intercontinental Ballistic Missiles (ICBM) and high performance fighter jets. It is generally accepted there is no "one size fits all" solution.

Of the current platforms the Army maintains, Patriot was designed to defeat fixed-wing aircraft, but residual capability enabled it to destroy short range ballistic missiles. As such, modernization efforts over the past 30 years primarily focused on increasing its TBM defense capability. The development of THAAD was in response to the need to defeat longer range ballistic missiles at the expense of its inability to counter any other threat type. These two systems are the Army's primary long-range, high altitude defense systems.

For shorter range aerial threats, the Army employs Stinger missiles to defeat UAS and rotary-wing platforms within a limited scope. During OIF and OEF, the threat of rockets, artillery, and mortars necessitated the need to develop a new capability. The Army fielded Counter Rocket, Artillery, Mortar (C-RAM) systems as a base defense system to defeat these smaller threats in Iraq and Afghanistan.

While the current Army inventory of AMD systems is capable, each provides defense against a portion of a spectrum of air and missile threats. The limited range of AMD systems necessitates numerous weapons to defend large areas. The ability to mass threats requires large quantities of interceptors to defeat those threats. The varying types of threats requires different AMD systems to layer their protection in defense of critical assets. The speed in which air and missile attacks can occur requires that AMD coverage be persistent. Even with these challenges, gaps remain across the spectrum that adversaries seek to exploit.

The number of air defense systems currently in the Army's inventory is limited. The Army focused primarily on counter insurgency for the past twenty years. These operations occurred in areas where the US enjoyed complete air dominance. As such, the Army reduced its AMD forces, which has further increased the capacity gap as it refocuses to competition against a peer nation state. In a resource-constrained environment, the Army's air defense assets have primarily focused on protecting critical operational and strategic assets across the world. With the refocusing to large-scale combat operations, the Army is building its maneuver AMD capacity again to support maneuver formations. The Army is also undergoing efforts, primarily through Cross Functional Teams (CFT), to rapidly build systems that close capability gaps and better counter future threats.

These systems are specific to a range of the threats that can affect ground forces. As access to technology improves, it becomes easier for adversaries to acquire inexpensive, yet capable, aerial platforms to employ against friendly forces. Kinetically defeating these threats becomes increasingly expensive. The cost curve associated with building and maintaining defensive systems continues to increase with respect to the cost of developing and fielding threat platforms. Interceptor missiles can cost exponentially more than the threats they are engaging, creating an unsustainable model to counter the spectrum of threats the US faces.

Problem Statement

The US's operation and maintenance of multiple AMD systems to counter a spectrum of inexpensive and increasingly capable threats create an unsustainable cost curve.

Significance of Problem

From 2002 through 2017, the US has spent $123 billion on its Ballistic Missile Defense System comprised of interceptors, radars, and command and control systems.[2] Approximately $1.3 billion is spent on developing new technologies or modernizing existing capabilities annually[3]. Costs will most likely continue to rise for missile defense systems and those high costs will have impacts on the success or failure of these programs.[4] In an effort to maintain pace with emerging threat, the development of new systems creates new challenges. One of the largest challenges the current AMD force faces is the integration of these systems.

New weapon systems are built by different contractors and are not completely interoperable. For example, the Patriot system transmits data within a self-contained network using messaging language specific to and readable only by other Patriot systems. Therefore, in order to exchange critical information with other platforms, Patriot requires

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[2] Government Accountability Office (GAO), *Missile Defense: Some Progress Delivering Capabilities, but Challenges with Testing Transparency and Requirements Development Need to Be Addressed* (Washington, DC: GAO, May 2017), 1, accessed 1 March 2019, https://www.gao.gov/assets/690/684963.pdf.

[3] Ibid., 41.

[4] David Mosher, "Understanding the Extraordinary Cost of Missile Defense," Arms Control Association, December 2000, accessed 4 April 2019, https://www.rand.org/natsec_area/products/missiledefense.html.

an additional system to translate Patriot-specific messages into more universal messages. This problem is ubiquitous to all Air Defense systems. While most Air Defense platforms have the ability to translate their messages to a joint data network through a third-party system, the fidelity of the information is relative to the sender, the data network, and the receiver.

New systems to integrate capabilities like the Integrated Air and Missile Defense Battle Command System (IBCS) have not reached their initial operational capability with significant problems, delaying their fielding after a decade in development. Even with an integrating solution like IBCS, compatibility issues may persist as new systems are incorporated into AMD.

None of the current Army AMD platforms have the capability to defeat hypersonic glide vehicles or provide adequate defense against emerging cruise missile threats. These alone would require the development of new AMD systems which will cost billions of dollars and take years of development before fielding. As mentioned, the addition of new systems would pose similar interoperability challenges associated with the fielding of a new capability. This interoperability is essential to building an Integrated Air and Missile Defense (IAMD) construct to provide a layered defense against threats.

Another challenge AMD missile systems encounter is they are limited by the number of simultaneous engagements they can prosecute. In a complex attack, it is likely that targets can penetrate any air defense "bubble" if they arrive at nearly the same time. An attempt to engage targets using swarm tactics will inevitably saturate a defense system. While interceptors travel at high speeds, an interceptor's fly-out time to its target prohibits subsequent engagements until the target is destroyed.

Developing an AMD system that can rapidly defeat multiple threats would be revolutionary. A laser-based system is able to destroy a target within seconds and rapidly acquire a new target. Furthermore, given lasers travel at the speed of light, its kinetic beam would outpace any threat, to include hypersonic glide vehicles. Pinpoint accuracy of a laser system would enable it defeat small mortar and artillery rounds. Developing such a system would provide flexibility to defeat any air or missile threat, while overall reducing the cost of maintaining and operating multiple systems and their associated ammunition inventories.

The DOD has recognized how critical the challenges are in a rapidly evolving environment where the future battlefield's airspace will be congested with UAS, missiles, and aircraft seeking to penetrate friendly defenses. In 2009, the DOD began the Reliable Electric Laser Initiative (RELI) program. This program spurred numerous prototype laser systems, mentioned later in this thesis, in an effort to address the complexities of the modern and future battlefields. Indeed, while historically laser systems have been large and unpractical, technology is advancing quickly making these systems feasible. Michael Griffin, the Undersecretary of Defense for Research and Engineering said in 2018, "only directed energy could offer the kind of extended magazine, if you will, the extended range, speed of light delivery of the kill."[5] Due to the unwieldiness of past systems, laser-based systems did not have much support from Congress, something Griffin stated, "When I have discussions on the Hill, there is very much -- a lean-forward posture

[5] David Staten, "Senior DOD Official Discusses Future of Directed Energy Weapons," Department of Defense, 21 March 2018, accessed 3 April 2019, https://dod.defense.gov/News/Article/Article/1472095/senior-dod-official-discusses-future-of-directed-energy-weapons/.

now."[6] It is clear that laser technology as a warfighting tool is gaining traction while boasting the promising potential of closing capability gaps at reduced costs.

Research Question

Should the Army focus exclusively on developing a single laser-based Air and Missile Defense weapon system to counter the spectrum of air and missile threats?

Secondary Research Questions

What are the challenges with developing and acquiring multi-role weapon systems?

Is there any precedent or examples of successful laser AMD systems? If so, why were they cancelled?

Can the Army develop a laser-based AMD system without significant cost overruns or schedule delays?

Assumptions

There are several assumptions with respect to researching the feasibility of a laser-based AMD system. First, this thesis explores the merits of a laser-based system for employment by the Army. Chapter 2 provides a synopsis of the acquisitions process which begins as a Department of Defense (DOD) process to identify joint requirements. The applicability of a laser-based AMD system spans the joint force. This thesis will assume a potential laser-based AMD system will be exclusively for the Army. Joint requirements will be addressed by other services. The purpose of this assumption is to limit the scope of this study.

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[6] Staten, "Senior DOD Official Discusses Future of Directed Energy Weapons."

Second, the Army will maintain its current systems and projected/programmed systems of record until they can be phased out. It is obvious that these systems will continue to require maintenance and modernization until they are replaced. However, the purpose of this assumption is to identify the high up-front cost associated with the development of a new capability, while maintaining the current force.

Third, the training, doctrine, and facilities would be developed as needed by the development of a new system. A near-exact cost associated with the fielding of a new system with respect to these other domains is impossible to predict. The requirements for these domains would be identified late in the acquisition process or after as the Army determines where to base these systems. For the purpose of this study, the costs associated with these domains, which are critical in assessing the feasibility of developing a new system, are assumed to be similar to the requirements and costs of current systems.

Fourth, a laser-based system will incorporate current sensors with necessary upgrades to facilitate the new capability. This thesis will not address or argue for the development of new sensors to support a laser-based weapon system. It will assume that a new system can utilize current sensors and would be fielded with an organic targeting radar for which the technology exists. Currently, sensors use various frequency and power levels to provide target fidelity at different ranges for varying threats. There is no one sensor type that can provide the information needed with one frequency. The purpose of this assumption is to focus the study on the merits of a kinetic laser.

Fifth, technical data regarding platforms and their capabilities addressed in this thesis are unclassified and open-source. This lends to the assumption that the capabilities are relatively accurate to their actual performance data.

Scope

This thesis will focus on exploring the need for a materiel solution to address current capability gaps in AMD protection within the US Army. While it will use examples from other services to explore the acquisitions process and issues that arise from developing and procuring new systems, it will focus exclusively on the impact a new laser-based AMD system will have to the US Army. It will aim to identify the key reasons why the development of multi-role platforms or laser-based systems have previously succeeded and analyze the information to draw conclusions regarding the feasibility of an Army laser AMD system. Further, it will seek to determine what are the problems associated with transitioning to exclusively laser-based technology.

The development of a new program will require an adjustment to many or all of the DOTMLPF domains. This thesis does not address the challenges associated with other domains, save potential financial requirements that are needed to holistically assess the feasibility of developing a new capability.

Doctrinally, AMD consists of four elements: active defense, passive defense, attack operations, and mission command.[7] This thesis focuses on the active defense element of physically defeating and air or missile threat in flight. The passive defense and attack operations components are separate, yet complimentary elements to holistic AMD

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[7] Headquarters, Department of the Army (HQDA), Field Manual (FM) 3-01, *US Army Air and Missile Defense Operations* (Washington, DC: Government Priniting Office, November 2015), 1-1.

operations that protect the force and seek to prevent the threat prior to launch, respectively. Mission command is the ability to integrate capabilities into the larger architecture to meet the commander's intent for the particular operation. The purpose of this study is to determine the feasibility of an active defense, laser-based AMD system to replace current legacy systems.

Limitations

All information regarding current and past systems that this thesis compiles is open-source data in the public domain. With the assumption that open-source information of friendly and adversary capabilities is relatively accurate to its classified specifications, this thesis will rely on public information to guide its analysis and conclusions.

The precise costs of the development of a weapon system cannot be calculated exactly due to a multitude of factors and variables throughout the development timeline. For example, should the cost per system be calculated by incorporating all research, testing, procurement, production, etc, the overall cost per system will be significantly higher than actual cost of the production of an individual system. Defense contractors explicitly state they do not entertain inquiries for academic research. As such, facts and figures in this thesis will use program costs available through the governmental budgeting offices and through defense contractors when they do state dollar figures.

Delimitations

This thesis does not thoroughly analyze nor provide commentary for any specific case study regarding whether an acquisition program should have been cancelled or continued to be developed. One key implication for developing and continuing to fund a major defense program regardless of results are the politics of jobs and manufacturing and the congressional support a program receives. These politics can artificially skew the length of time an acquisitions program persists resulting in increased costs and schedule timelines. As such, costs and schedules will be analyzed and evaluated irrespective of these considerations.

This thesis does not address the implications of any case study or a potential laser-based system's effect on other DOTMLPF-P domains other than a material solution. The development of a weapon system will create requirements across DOTMLPF-P that must mature with the system. Specifically, the facilities needed to train, secure, and maintain a large weapon system, most likely in multiple installations across the world, will incur significant costs that cannot be programmed in prior to the acquisition and development of the system and a stationing plan developed by the Army.

Finally, this thesis does not intend to recommend acceptable costs or timetables for the acquisition o a hypothetical laser system. The purpose of this study is rather to identify and analyze comparable systems and to gain insights to the causes that delayed development, increased costs, or demonstrated successful acquisitions programs.

CHAPTER 2

LITERATURE REVIEW

Introduction

This chapter examines several categories of literature to help inform a conclusion as to the feasibility of a laser-based AMD system. It will reference doctrine to determine Army AMD requirements. Secondly this review explores several of the threats AMD must counter. As a major defense acquisition, it is imperative to understand key aspects of the DOD acquisitions process to identify where challenges in development may occur. There have been past attempts to develop prototype or operational laser systems, and this review will highlight several case studies. Finally, this chapter will address the historical precedent of developing multi-role systems to replace legacy platforms.

Army Air and Missile Defense Requirements

The Army's AMD requirements and force structure are capabilities driven and threat driven. The Army will modernize its existing systems or develop new systems to address emerging threats or to incorporate improvements in technology. In general, classifications of air and missile threat types do not change; rather, the capabilities within the classifications vary greatly. FM 3-01 AMD Operations outlines the mission of Army AMD and the threats required to be countered. It defines Air Defense's role as being able, "to provide fires to protect the force and selected geopolitical assets from aerial attack, missile attack, and surveillance."[8] These threats can be classified as missiles (ballistic, cruise, and air-to-surface), air-breathing threats (fixed-wing, rotary-wing, and

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[8] HQDA, FM 3-01, 1-2.

unmanned aerial systems), and artillery (rockets, artillery, and mortar systems). The broad range of capabilities of these categories means their implications traverse all levels of war.

FM 3-0 Operations states that AMD is, "the direct defensive actions taken to protect friendly forces by destroying or reducing the effectiveness of hostile air and ballistic missile threats against friendly forces and assets in support of joint force commander's (JFC) objectives."[9] This includes tactical, operational, and strategic considerations. Further AMD consists of active defense, passive defense, attack operations, and mission command elements. As such, AMD is a holistic effort to protect against attacks, defeat threats affecting critical areas, destroying threats before or after launch, and the systems and leaders to synchronize all the elements.

The challenges associated with active defense quickly escalate due to the rising development and proliferation of air and missile capabilities throughout the world. For example, a ballistic missile is a classification of numerous missiles with ranges from tens to thousands of kilometers. The range of a ballistic missile is proportional to its speed and affects its altitude and trajectory. While a short range ballistic missile travels less than 2 kilometers per second throughout its flightpath, an Intercontinental Ballistic Missile (ICBM) can travel up to seven kilometers a second. Additionally, ICBMs with developed technology such as Russia are capable of mounting multiple warheads per missile. The ability to kinetically defeat the spectrum of these threats requires precision tracking and various types of missiles with different performance capabilities.

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[9] HQDA, FM 3-01, 1-1.

Adversary Capabilities

As technology improves and costs to develop weapons decreases, the United States will continue to face increasing complexities in attempting to defeat air and missile threats. This thesis will focus on several key platforms from adversarial nations outlined in the NDS. The purpose of highlighting these systems is to demonstrate the inherent complexities and ultimately unsustainable nature of attempting to counter the myriad of threats by continuing to developing new weapon systems specific to a limited portion of threats.

The nature of defeating ballistic missile threats with kinetic interceptors is largely a physics problem; the closing velocities associated with two high-speed missiles requires extreme precision, specifically for the AMD interceptor. Currently, the basic method anti-ballistic missile systems use to engage missiles is determining the ballistic flight path in advance of launching an interceptor. The interceptor will then actively or passively locate the target when in close proximity using maneuvering enhancements to precisely defeat the threat. However, all physical interceptors have limitations regarding their ability to maneuver as they approach the target. These limits, as well as the limits of the fire control systems calculating intercept opportunities, result in significantly reduced lethality should a ballistic missile maneuver or contain multiple guided warheads. One example of a maneuvering missile is the SS-26 Iskander developed by Russia. With an operational range of 500km and the ability to deploy decoys, the Iskander is accurate to within 10 meters of its intended target.[10] With the ability to fire two missiles per launcher and

[10] Missile Threat, "SS-26 (Iskander)," Center for Strategic and International Studies, 27 September 2016, accessed 10 March 2019, https://missilethreat.csis.org/missile/ss-26/.

serving in a tactical role, these mobile systems stress the capabilities of anti-ballistic missile systems such as Patriot, which would have difficulty determining the threatened asset while the target is in flight.

The most challenging ballistic missiles to actively defeat are Intercontinental Ballistic Missiles (ICBMs). The Chinese DF-41 has an operational range of 15000km and is able to travel up to Mach 25.[11] While intercepting an ICBM with physical interceptors at these speeds is exceptionally difficult, the fact that each DF-41 is able to carry up to 10 independent nuclear warheads requires, at least, as many interceptors to defeat each warhead. Currently, the US employs Ground Based Interceptors to defend the homeland from ICBMs with a planned total interceptor count of 44.[12] Optimistically, this number of interceptors would enable the defeat of four ICBMs that contain multiple warheads. Should the missile defense systems engage targets with more than one interceptor, this reduces the total number of targets that can be engaged. As of 2014, the ground-based midcourse defense system which employs these interceptors total cost reached $41 billion, further highlighting the unsustainable costs associated with producing a limited ability to defeat one type of threat, namely ICBMs.[13]

Probably the most proliferated and widely available technology to state and non-state actors are UAS drones. Over the past twenty years, UAS have become increasingly inexpensive and sophisticated. Joint doctrine delineates between two categories of UAS:

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[11] Missile Threat, "Dong Feng 41 (DF-41/CSS-X-20)," Center for Strategic and International Studies, 12 August 2016, accessed 10 March 2019, https://missilethreat.csis.org/missile/df-41/.

[12] GAO, *Missile Defense,* 15.

[13] Ibid.

large, high-flying UAS and Low, Small, Slow (LSS) UAS.[14] These LSS are difficult to detect by current AMD sensors due to their small size and low altitudes.[15] Further, their proliferation to partner nations creates difficulty in identifying enemy and friendly systems. LSS are available to front-line troops for surveillance and reconnaissance. Violent extremist organizations such as ISIS employ UAS with improvised explosive devices attached.[16] Russian UAS use in Ukraine demonstrated its employment tactics of target acquisition for artillery, able to conduct fire missions within minutes of locating targets.[17] The flexibility of mission sets for UAS, coupled with the difficulties of detecting, identifying, and defeating large numbers of systems, highlights the complexities UAS bring to the modern AMD force.

Army Acquisition Process

The development of new systems would be subject to the acquisitions process. DA PAM 70-3, The Army Acquisition Procedures outlines the Army's method for research, development and acquisition throughout the entire materiel acquisition

[14] Joint Chiefs of Staff (JCS), Joint Publication (JP) 3-01, *Countering Air and Missile Threats* (Washington, DC: Government Publishing Office, April 2017), accessed 18 November 2018, https://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/jp3_01_pa.pdf?ver=2018-05-16-175020-290, I-2.

[15] Ibid., V-5.

[16] Joby Warrick, "Use of Weaponized Drones by ISIS Spurs Terrorism Fears," *The Washington Post*, 21 February 2017, accessed 14 November 2018, https://www.washingtonpost.com/world/national-security/use-of-weaponized-drones-by-isis-spurs-terrorism-fears/2017/02/21/9d83d51e-f382-11e6-8d72-263470bf0401_story.html?utm_term=.78f3c7698f20.

[17] Kim Hartmann and Keir Giles, "UAV Exploitation: A New Domain for Cyber Power," 2016 International Conference on Cyber Conflict, accessed 15 April 2019, https://mafiadoc.com/uav-exploitation-a-new-domain-for-cyber-power-nato-_599b87c31723dd0c4031cf23.html.

process.[18] This includes procedures and requirements regarding the sustainment of materiel throughout its lifecycle. The acquisition process is divided into three interrelated portions: the Joint Capabilities Integration and Development System (JCIDS), the Defense Acquisition System (DAS), and the Planning, Programming, Budget and Execution (PPBE) process. This section will focus primarily on the JCIDS and DAS as they are the primary processes in which capabilities are matured into systems and fielded to the force which will address the primary and secondary research questions.

The Joint Capabilities Integration and Development System is the DOD method for determining requirements to address capability gaps and the subsequent solutions across the DOTMLPF-P domains. CJCSI 5123.01H, Charter of the Joint Requirements Oversight Council and Implementation of Joint Capabilities Integration and Development System and its accompanying Manual for the Operation of Joint Capabilities Integration and Development System detail the JCIDS process and describe these methods and the JCIDS process.[19] Key to the JCIDS process is the development of an Initial Capabilities

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[18] Headquarters, Department of the Army (HQDA), Department of the Army Pamphlet (DA-PAM) 70-3, *Army Acquisition Procedures* (Washington, DC: Government Publishing Office, September 2018, 1, accessed November 2018, https://armypubs.army.mil/epubs/DR_pubs/DR_a/pdf/web/ARN11426_DAPam70-3_FINAL.pdf.

[19] The Joint Staff, Chairman of the Joint Chiefs of Staff Instruction (CJCSI) 5123.01H, *Charter of the Joint Requirements Oversight Council (JROC) and Implementation of the Joint Capabilities Integration and Development System (JCIDS),* (Washington, DC: Government Publishing Office, 2018), A-11, accessed 25 October 2018, https://www.jcs.mil/Portals/36/Documents/Library/Instructions/CJCSI%205123.01H.pdf?ver=2018-10-26-163922-137.

Document (ICD), which documents the need for a material solution to address a specific capability gap.[20]

The Defense Acquisition System (DAS) is the process to provide capabilities to users.[21] Key to the process is the establishment of the Milestone Decision Authority, which is the overall executive sponsor responsible for any major defense acquisition program.[22] The phases of the DAS are Material Solution Analysis, Technology Maturation and Risk Reduction, Engineering and Manufacturing Development, Production and Deployment, and Operations and Support.[23] Phase I assesses potential solutions to meet the capability gap identified in the ICD.[24] Phase II determines the level of technologies to be integrated into the system, conducts prototyping of system elements, estimate costs, and develop the Capabilities Development Document (CDD).[25] It is the CDD that defines the measurable and testable capabilities of the proposed system

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[20] AcqNotes, "JCIDS Process: Initial Capabilities Document," 13 November 2018, accessed 10 December 2018, http://acqnotes.com/acqnote/acquisitions/initial-capabilities-document-icd.

[21] Department of Defense (DOD), Department of Defense Instruction (DODI) 5000.02, *Operation of the Defense Acquisition System* (Washington, DC: DOD, 10 August 2017), http://acqnotes.com/wp-content/uploads/2014/09/DoD-Instruction-5000.02-The-Defense-Acquisition-System-10-Aug-17-Change-3.pdf.

[22] AcqNotes, "Acquisitions Process: Milestone Decision Authority," 11 July 2017, accessed 10 December 2018, http://acqnotes.com/acqnote/acquisitions/milestone-decision-authority.

[23] DOD, DODI 5000.02, 7.

[24] AcqNotes, "Acquisitions Process: Materiel Solution Analysis (MSA) Phase," 22 May 2018, accessed 10 December 2018, http://acqnotes.com/acqnote/acquisitions/materiel-solutions-analysis-phase.

[25] AcqNotes, "Acquisitions Process: Technology Maturation and Risk Reduction (TMRR) Phase," 22 May 2018, accessed 10 December 2018, http://acqnotes.com/acqnote/acquisitions/technology-development-phase.

as well as its performance attributes.[26] The proposed system is designed and developed during Phase III while ensuring demonstrating its reliability and maintainability as the system transitions to production in Phase IV.[27] During the production of Phase IV, the system is produced in small quantities for testing, named Low-Rate Initial Production (LRIP) before transitioning to full-rate production.[28] It is in Phase V that a capability is used by and supported by users in the field.[29]

High- Energy Laser Research and Development

Over the past fifty years there have been multiple attempts to develop directed energy and laser weapons. While many of these ideas were conceived for a multitude of purposes, both lethal and non-lethal, this thesis will focus on historical examples specific to air and missile defense technologies.

As early as the 1960s, concepts arose to use laser technology to defeat missiles. Known problems at the time were ICBMs were capable of carrying multiple warheads but interceptors tended to destroy the delivery missile instead of the warhead. In order to tackle these challenges, the laser concept centered around a nuclear bomb equipped with

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[26] AcqNotes, "Requirements Development: Capability Development Document (CDD)," 14 August 2018, accessed 10 December 2018, http://acqnotes.com/acqnote/tasks/capability-development-documentrequirements.

[27] AcqNotes, "Acquisition Process: Engineering and Manufacturing Development (EMD) Phase," 22 May 2018, accessed 10 December 2018, http://acqnotes.com/acqnote/acquisitions/emd-phase.

[28] AcqNotes, "Acquisitions Process: Production and Deployment (PD) Phase," 22 May 2018, accessed 10 December 2018, http://acqnotes.com/acqnote/acquisitions/production-and-deployment.

[29] AcqNotes, "Acquisitions Process: Operations and Support (O&S) Phase," 22 May 2018, accessed 10 December 2018, http://acqnotes.com/acqnote/acquisitions/operations-and-support.

X-ray lasers that, when detonated, would focus the laser on incoming missiles. By the 1980s, Project Centaurus and Project Falcon were created as US efforts to develop laser technology against intercontinental ballistic missiles. Centaurus and Falcon were both space-based anti-ballistic missile systems that would provide a first line of defense against any incoming attack.[30] More publicly, they were known under their umbrella term, the Strategic Defense Initiative (SDI), or the "Star Wars" program.

Announced in 1983, President Reagan declared the beginning of SDI to "destroy strategic ballistic missiles before they reached [US] soil" and "rendering nuclear weapons impotent and obsolete."[31] Ultimately, the technology envisioned for SDI had not yet been invented and the leading scientists on these projects grew skeptical wondering if the endeavor was even possible. While testing for SDI-related devices continued throughout the next decade, the collapse of the Soviet Union would result in the cancellation of the program.[32]

By 1995, a joint US and Israeli project started to determine the feasibility of using laser technology to defeat short-range artillery rockets. Named the Nautilus Project, this venture comprised primarily of two experimental laser systems that successfully shot

[30] Claire Zau, "Nuclear Pumped Lasers and the Strategic Defense Initiative," (Stanford University, Stanford, CA, 16 March 2018), accessed 4 March 2019, large.stanford.edu/courses/2017/ph241/zau2/.

[31] Atomic Heritage Foundation, Strategic Defense Initiative (SDI), 18 July 2018, accessed 5 May 2019, https://www.atomicheritage.org/history/strategic-defense-initiative-sdi.

[32] Adam Augustyn, ed., "Strategic Defense Initiative," *Encyclopedia Britannica,* https://www.britannica.com/topic/Strategic-Defense-Initiative.

down a large number of rockets in flight at White Sands Missile Range.[33] Following the success of these demonstrations, the US and Israel agreed to focus on building compact, transportable laser systems. Called the Tactical High Energy Laser (THEL) system, this system was built from multiple trailer-sized structures that, while mobile, were still large. As an experimental system, THEL proved to be effective at downsizing the infrastructure of a capable laser system while still effectively engaging and destroying rockets. However, by 1999, delays and cost overruns cast doubt on the sustainability of the program. Ultimately, THEL was cancelled in 2005 after $300 million was spent over the past decade developing the program.

The most prominent laser-based system to move to the acquisition phase of development is the USAF Airborne Laser (ABL). This was to be a revolutionary laser weapon system that was intended to defeat ballistic missiles in their boost phase while the missiles were ascending. The ABL was a modified Boeing 747 retrofitted with a nose-cone beam control for the laser, fire control systems, and the chemical laser itself.

ABL would serve as a key part of the Ballistic Missile Defense Strategy of 2001. The BMDS called for a layered defense approach to detect and defeat ballistic missiles threating the US and its allies in all three phases of flight: boost, midcourse, and terminal. ABL's laser was designed to heat the frame of a launched missile, stressing the metal until structural failure and the destruction of the missile.

[33] Josef Schwartz, Gerald T. Wilson, and Joel Avidor, "Tactical High Energy Laser," *Proceedings: High Power Lasers and Applications,* no. 4632 (January 2002), accessed 24 November 2018, http://www.northropgrumman.com/Capabilities/ChemicalHighEnergyLaser/TacticalHighEnergyLaser/Documents/pageDocuments/SPIE_Manuscript_Tactical_high-.pdf.

Due to the complexities of developing, manufacturing, and integrating critical technologies, the ABL program cost estimate increased 100% from $1 billion to $2 billion by 2004, along with schedule delays.[34] By 2010, and after spending $5 billion, the ABL program was shelved indefinitely.[35]

Two key issues with ABL were the power of the laser and the operational viability of the system's employment. The laser itself was a megawatt chemical-oxygen iodine laser (COIL). Testing demonstrated this COIL laser was effective up to 600km to destroy liquid fueled ballistic missiles; however, solid fuel missiles or missiles with hardened outer casings required the aircraft to be closer than 300km.[36] Considering the size of the COIL system, effectively requiring the size of the majority of the Boeing 747, increasing the power of the laser would require additional development of a more effective laser system versus additional power components.

The second issue with ABL was the operational employment of such a system. Depending on the adversary nation, the 300km range to reliably destroy a ballistic missile in boost phase may require the aircraft to fly in enemy airspace, at threat by air defense systems. Additional aircraft, such as fighter escorts, fuel tankers, and C2 platforms would also be required to deploy to protect and sustain ABL in flight. Defense Secretary Gates summarized the issues to Congress by stating,

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[34] Government Accountability Office (GAO), *Uncertainties Remain Concerning the Airborne Laser's Cost and Military Utility* (Washington, DC: GAO, 17 May 2004), 2, accessed 1 March 2019, https://www.gao.gov/new.items/d04643r.pdf.

[35] Project Gutenberg Self-Publishing Press, "Boeing YAL-1," accessed 19 Novemeber 2018, http://self.gutenberg.org/articles/Boeing_YAL-1.

[36] Ibid., 1.

> I don't know anybody at the Department of Defense, Mr. Tiahrt, who thinks that this program should, or would, ever be operationally deployed. The reality is that you would need a laser something like 20 to 30 times more powerful than the chemical laser in the plane right now to be able to get any distance from the launch site to fire . . . So, right now the ABL would have to orbit inside the borders of Iran in order to be able to try and use its laser to shoot down that missile in the boost phase...And there's nobody in uniform that I know who believes that this is a workable concept.[37]

Historical Precedent of Multi-Role Systems

The concept of a multi-role system is not new. The US has pursued the enticing idea of consolidating capabilities into one system over the course of the twentieth century in the hopes of creating cost effective platforms as force multipliers. Most notably with aircraft, the F-4 Phantom can be considered the first true multi-role platform. Developed in the 1950s, the F-4 airframe was modified for both air-to-air and air-to-ground roles.

The Joint Strike Fighter

The F-35 Joint Strike Fighter (JSF) is a notable example of the military's attempt to merge capabilities into a single, common airframe. Originally designed to replace the USAF F-16, A-10, USN F/A-18, and USMC F/A-18 and AV-8B, the JSF would meet the requirements of the three services. These include the USN strike fighter capability able to take off and land on carriers, the UMSC short takeoff and landing requirement for their

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[37] Richard D. Burns and Joseph M. Siracusa, *A Global History of the Nuclear Arms Race: Weapons, Strategy, and Politics* (Santa Barbara: Praeger Security International, 2013), 492, accessed 10 November 2018, https://books.google.com/books?id=EX2jAQAAQBAJ&pg=PA492&lpg=PA492&dq=secretary+gates+I+don't+know+anybody+at+the+Department+of+Defense,+Mr.+Tiahrt,+who+thinks+that+this+program+should,+or+would,+ever+be+operationally+deployed&source=bl&ots=JEbQT0H8nx&sig=ACfU3U3PqR2bHK3maih58raaF660F0JI_g&hl=en&sa=X&ved=2ahUKEwiMz7GQudLhAhXGhOAKHak1DgIQ6AEwAXoECAkQAQ#v=onepage&q=secretary%20gates%20I%20don't%20know%20anybody%20at%20the%20Department%20of%20Defense%2C%20Mr.%20Tiahrt%2C%20who%20thinks%20that%20this%20program%20should%2C%20or%20would%2C%20ever%20be%20operationally%20deployed&f=false.

amphibious assault ships, and conventional take off ability for an air-to-ground platform for the USAF.[38] In 1996, Lockheed Martin was awarded the contract to develop the JSF with the concept of keeping procurement costs of the new fighter similar to legacy aircraft.

The key selling point of the JSF was the affordability of the aircraft based on having up to 90 percent common parts on all variants.[39] This next generation fighter would complement the F-22, replace legacy aircraft, and form the basis of America's 5th generation fighter inventory. In 1996, Lockheed Martin was awarded the contract to develop the JSF with the concept of keeping procurement costs of the new fighter similar to legacy aircraft.

One initial problem that plagued the development process was the acquisition approach the DOD used for the JSF. The DOD planned to begin producing F-35 aircraft prior to completion of their testing. In fact, the DOD estimated to have produced 424 aircraft by 2013, the same year which operational testing was expected to be complete.[40] By 2006, the Government Accountability Office outlined in a report to Congress the cost per aircraft increased 32% to $41 million. By 2015, the cost per aircraft increased to an

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[38] Joint Program Office, "The Joint Strike Fighter Program: History," accessed 1 March 2019, http://www.jsf.mil/history/his_f35.htm.

[39] Ibid.

[40] Government Accountability Office (GAO), *Joint Strike Fighter: DOD Plans to Enter Production Before Testing Demonstrates Acceptable Performance* (Washington, DC: GAO, March 2006), 10, accessed 1 March 2019, https://www.gao.gov/new.items/d06356.pdf.

average of $140 million across the variants, or an increase of 360%.[41] By 2019, the estimated cost per platform averaged $104 million across the variants.[42]

The complexity of an F-35 stems from the need to incorporate multiple mission-capable variants within one platform. One example is the nature of landing the aircraft as each service required a different method. The incorporation of short take off and vertical landing (STOVL) at the behest of the USMC proved to be one of the most significant hindrances affecting cost and schedule.[43] In 2011, the Secretary of Defense placed the STOVL variant on probation as to not delay the development and procurement of the USAF and USN variants.[44] In addition to the takeoff and landing challenges, incorporating stealth technology, internal weapons bays, and new radar capabilities, the JSF continues to face cost overruns and delays in scheduling resulting in a Nunn-McCurdy breach requiring the DOD to justify to Congress the reasons for the significant setbacks.

Future Combat Systems

From 2003-2009, the Army sought to modernize itself with the development of the Future Combat Systems (FCS) program. While not a single platform, FCS consisted

[41] Government Accountability Office (GAO), *F-35 Joint Strike Fighter: Development is Nearly Complete, but Deficiencies Found in Testing Need to Be Resolved* (Washington, DC: GAO, June 2018), 4, accessed 1 March 2019, https://www.gao.gov/assets/700/692307.pdf.

[42] F-35 Lightning II, "Producing, Operating, and Supporting a 5th Generation Fighter," Lockheed Martin, accessed 22 February 2019, https://f35.com/about/cost.

[43] Government Accountability Office (GAO), *Joint Strike Fighter: DOD Actions Needed to Further Enhance Restructuring and Address Affordability Risks* (Washington, DC: GAO, June 2012), 15, accessed 2 March 2019, https://www.gao.gov/assets/600/591608.pdf.

[44] Ibid., 45.

of multiple systems that were multipurpose in nature, such as the Manned Ground Vehicle intended to replace the M1 Abrams, M2 Bradley, and M109 Paladin, among others. Cost overruns and delays rapidly beset the FCS program. By 2004, the GAO stated the FCS was, "at significant risk for not delivering required capability within budgeted resources."[45] The GAO summarized the challenges as, "development of a first-of-a-kind network, 18 advanced systems, 53 critical technologies, 157 complementary systems, and 34 million lines of software code… faster than it has taken to develop a single major system."[46] Indeed, the projected costs for developing the FCS was $92 billion in 2004 but increased to $160 billion by 2009 representing a 75% increase in projections.[47] Given a lack of substantial demonstrations of capabilities, the program was cancelled in 2009.

FCS was a system of systems fielded to Army Brigades. As such, the unit of purchase was a complete Brigade's worth of equipment consisting of hundreds of individual components. Cost estimates in available literature are for units of purchase represented as the sum of the Brigade equipment package. This thesis will focus on the Mounted Combat System (MCS) intended to replace the M1 Abrams tank as a representative of FCS to compare its performance with the currently fielded system.

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[45] Government Accountability Office (GAO), *Defense Acquisitions: The Army's Future Combat Systems' Features, Risks, and Alternatives* (Washington, DC: GAO, 1 April 2004), 2, accessed 6 March 2019, https://www.gao.gov/new.items/d04635t.pdf.

[46] Ibid., 2.

[47] Government Accountability Office (GAO), *Defense Acquisitions: 2009 Review of Future Combat System is Critical to Program's Direction* (Washington, DC: GAO, 10 April 2008), 2, accessed 6 March 2019, https://www.gao.gov/new.items/d08638t.pdf.

The concept for the MCS boasted significant improvements over the M1 being more deployable and lethal.[48] It would have a beyond line of sight ability to defeat targets with improved munitions. One significant deviation was the MCS weight of 27 tons[49] versus the 70-ton M1 Abrams. This weight reduction came at cost in reduced armor. According to Army in 2008, the MCS "is being developed to achieve the optimal balance of capabilities to ensure that its lethality, survivability, sustainability and force effectiveness attributes are equal to or better than those of current force vehicles."[50] With a mission of balancing "lighter and faster with improved survivability",[51] the MCS relied less on heavy armor and more on networked capabilities to defeat enemies beyond line of sight,` coupled with an active protection system designed to actively engage incoming projectiles.[52]

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[48] Cliff Calhoun, "Future Combat Systems (FCS) Mounted Combat System (MCS) Provides Unique Capabilities," Future Combat Systems-Cornerstone of Army Modernization, April 2008, accessed 3 March 2019, https://asc.army.mil/docs/pubs/alt/archives/2008/Apr-Jun_2008.pdf.

[49] Christopher G. Pernin, *Lessons from the Army's Future Combat Systems Program* (Santa Monica, CA: RAND Corporation, 2012), 57, accessed 15 May 2019, https://www.rand.org/content/dam/rand/pubs/monographs/2012/RAND_MG1206.pdf.

[50] Army AL&T Magazine Staff, "A Look at the Future Combat Systems (Brigade Combat Team) Program – An Interview with MG Charles A. Cartwright," *Army AL&T: Future Combat Systems: Cornerstone of Army Modernization* (April-June 2008): 6, accessed 3 March 2019, https://asc.army.mil/docs/pubs/alt/archives/2008/Apr-Jun_2008.pdf.

[51] Ibid.

[52] John R. Guardino, "FCS Active Protection System in Top 50 Inventions, U.S. Army*,* 17 November, 2008, accessed 18 March 2019, https://www.army.mil/article/14274/fcs_active_protection_system_in_top_50_inventions.

The Patriot Missile System

The Patriot missile system's roots can be traced back to the 1967 as the US awarded the Raytheon Company the first contract for the development of an air and missile defense system to be named Surface-To-Air Missile-Developmental (SAM-D). The US attempted to develop a weapon system that could counter high-altitude fixed wing aircraft while also defeating helicopters.[53] As SAM-D developed through the 1970s, concerns regarding the survivability of air defense systems against anti-radiation missiles required the incorporation of capabilities to counter these radar-seeking missiles.[54] It would be during the Carter administration that SAM-D was approved for production and renamed Patriot. Due to President Reagan's initiative to a build space and ground missile defense shield, the Patriot system began improving its capabilities to include anti-ballistic missile defense capability and becoming a true multi-role air and missile defense system.[55]

At the time, Patriot incorporated new air defense technologies, some which did not move to production. Two key technologies were the phased array radar and the Track-Via-Missile (TVM) guidance system.[56] The phased array radar was a non-rotating

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[53] Frank N. Schubert and Teresa L. Kraus, eds. "Appendix A: The Patriot Defense System," In *The Whilwind War* (Jacksonville, FL: St. John's Press, 2016), 238, accessed 15 April 2019, https://history.army.mil/books/www/WWWAPENA.HTM.

[54] U.S. Army Comptroller General, "Army Air Defense: SAM-D Program," (Report to Congress, Washington, DC, May 1973), 1, accessed 1 March 2019, https://www.gao.gov/assets/200/194727.pdf.

[55] Schubert and Kraus, "Appendix A," 238.

[56] US Army Comptroller General, "Army Air Defense: SAM-D Program," (Report to Congress, Washington, DC, June 1973), 2, accessed 1 March 2019, https://www.gao.gov/assets/210/200213.pdf.

flat array consisting of antenna elements that electronically formed and steered the radar beam. Whereas previous AMD systems required multiple radars to perform surveillance, tracking, and engagement support, the multi-function Patriot radar was one integrated system that accomplished these tasks.[57] TVM guidance enabled the radar to guide the missile to the target increased accuracy. TVM guidance system was initially a capability with no operational precedent.[58]

Despite a nearly twenty year development timeline, Patriot began its initial fielding to units in 1984.[59] While under the SAM-D program, in 1975 the program experienced an 8% cost increase from $508 million to $548 million.[60] In 1983, the cost of initial production of Patriot systems nearly doubled to $11 billion from expected costs due to hardware issues.[61] However, by 1985, the GAO reported the Patriot production contract on schedule and was identifying potential savings in the program.[62] Patriot

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[57] Christopher Chant, *Raytheon MOM-104A Patriot Surace-To-Air Missile* (London: Brassey's Defence Publishers, 1989), 136.

[58] Ibid., 55.

[59] Ibid., 137.

[60] Government Accountability Office (GAO), *The SAM-D Program* (Washington, DC: GAO, March 1975), 3, accessed 6 March 2019, https://www.gao.gov/assets/80/78755.pdf.

[61] Comptroller General of the United States, "Results of Production Testing Should Be Considered Before Increasing Patriot's Production," (Report to Congress, Washington, DC, January 1983), 1, accessed 1 March 2019, https://www.gao.gov/assets/140/139519.pdf.

[62] Government Accountability Office (GAO), *Defense Budget: Potential Reductions to Army and Marine Corps Missile Budgets* (Washington, DC: GAO, August 1986), 12, accessed 8 March 2019, https://www.gao.gov/assets/80/75746.pdf.

remains the cornerstone of Army AMD capability due to its excellent radar, interceptors, and flexibility to modernize.[63]

[63] Chant, *Raytheon MOM-104A Patriot Surace-To-Air Missile,* 137.

CHAPTER 3

RESEARCH METHODOLOGY

The purpose of this chapter is to describe the methodology this paper will use to research and analyze the feasibility of developing a laser-based air defense system. Using quantitative research, this paper will explore past attempts to develop high energy laser systems for the military, as well as, what the outcomes were of those programs. Further, this thesis will research other examples of the military developing a single system to reduce the costs associated with performing specific missions.

Data Analysis

This section of research methodology describes the method that this thesis will analyze the data to develop conclusions and recommendations. This thesis will use cost, schedule, and performance metrics to determine the feasibility of a laser-based AMD system. This is an effective model because it addresses three key tenants of all acquisitions programs while also being a familiar model to Army organizations seeking to improve AMD with capable yet cost-effective solutions. Additionally, analyzing the historical effectiveness of developing singular platforms to perform multi-role mission sets will provide a secondary metric in determining feasibility.

Measuring Costs

The first step is to analyze the costs associated with developing a new system. This begins with understanding the current technologies available or determining whether new technologies must be researched. Since the requirement to field a new platform is self-evident, the second phase of costs is in regards to the development of prototype systems in the Army's acquisition program. The third phase will be the production of multiple systems based on the needs of the Army to replace current systems. The final costs will be in the expected Operations and Maintenance costs for the lifecycle of the program. Analysis and comparison of a new system as compared to legacy systems will be a key indicator to the feasibility of the endeavor to develop a laser-based AMD system.

With respect to cost, the 1982 Department of Defense Authorization Act established the Nunn-McCurdy amendment. This provision requires the DOD to notify Congress if the total program acquisition unit cost to include expected inflation exceeds 25% of the original estimate.[64] A breach is considered critical once the cost threshold increases at least fifty percent over original estimates.[65] While there have been 74 breaches of this provision between 1997-2011, nearly 40% account for critical breaches, with many of the programs having been terminated due to these cost overruns and corresponding poor performance.

Since the costs of developing a potential system are unknown, this thesis will attempt to quantify the likely cost of such a system by analyzing past attempts at developing either multi-role or laser-based systems as well as using the metrics stipulated in the Nunn-McCurdy amendment as evaluation criteria to determine feasibility. This thesis will focus on the anticipated savings multi-role systems were intended to save over the platforms to be replaced. Since Nunn-McCurdy only requires the Department of

[64] U.S. Congress, Senate, Department of Defense Authorization Act, 1982, S. 815, 97th Congress, 1981, accessed 18 April 2019, https://www.govtrack.us/congress/bills/97/s815.

[65] Government Accountability Office (GAO), *DOD Cost Overruns: Trends in Nunn-McCurdy Breaches and Tools to Manage Weapons Systems Acquisition Costs* (Washington, DC: GAO, 29 March 2011), 1, accessed 1 March 2019, https://www.gao.gov/assets/130/125861.pdf.

Defense to provide an explanation and justification as to why a program breached its appropriated cost estimates, it does not explicitly state a program will be cancelled should costs exceed a specific amount or percentage over its predicted budget. As such, this thesis will use the conjecture that a 100% increase of its expected cost at inception will be unsustainable.

Measuring Performance

This thesis will seek to compare the performance of a laser-based system with legacy kinetic AMD systems. Since no current laser-based AMD system exists in operation, this thesis will infer the likely performance of a laser-based system through analysis of experimental laser programs and the potential capability of a laser-based system in juxtaposition to kinetic missile systems currently fielded. As the Army's predominate AMD weapon system, a comparison to Patriot will aid in establishing a baseline of performance that a future system will need to attain.

Furthermore, the performance of multi-role systems will be evaluated in comparison to the platforms they are meant to replace. Since much of the specific performance data of current systems is classified, this thesis will compare open-source general flight performance data for aircraft while highlighting key technological capabilities of various platforms. Additionally, the MCS will be compared to the M1 Abrams in general capabilities as a metric to represent the performance of FCS.

Measuring Time to Fielding

The third step is to measure the amount of time required to develop and field a potential new laser-based AMD system. The DAS process does not specify a requirement in order to field a new system. Rather, it outlines inputs, aspects, and processes to develop schedules and guides as a method for program managers to control said schedule.

As such, the development of a new platform is based on the complexities of the technologies and systems that must be integrated in support of the requirements and capabilities the platform is designed to achieve. In 2017, the Secretary of the Army, Mark Esper, stated the "process now to acquire something is maybe 10 to 15 years."[66] His testimony to the Senate Armed Services Committee was to describe the current average timeline of acquisitions as unacceptable. However, as the development of CFTs to expedite the development and acquisition of specific systems serves to truncate average timelines, this thesis does not presuppose a laser-based AMD system is an urgent capability requiring an accelerated timeline. As such, the timeline of fifteen years will serve as a benchmark timeframe for an expected delivery date for a new AMD system.

Given the development of a laser-based AMD system is hypothetical in the context of this thesis, the length of time other multi-role systems needed to move through the DAS will serve as an approximate timeline needed to field a complex system. This thesis will use a metric of five years over the initial declared Initial Operational Capability (IOC) schedule as a significant delay, and ten or more years as a critical delay requiring either a restructuring of the program or serving as grounds for cancellation of the program.

Measuring Historical Precedent

The last step will be measuring the feasibility of a laser-based system by looking at historical examples of multi-role platforms. The concept of consolidating capabilities to streamline ease of use or maintenance is not new. However, with complexity comes

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[66] Jen Judson, "US Army Looks to Cuty Typical Acquisition Timeline in Half," *Defense News,* 7 December 2017, accessed 3 April 2019, https://www.defensenews.com/land/2017/12/07/army-looks-to-cut-typical-acquisition-timeline-in-half/.

costs, usually unforeseen, that hamper the original intent of such a system. Cost overruns in other programs will provide a metric to determine expected costs associated with the development of a new system.

This thesis will use the Joint Strike Fighter (JSF), Future Combat System (FCS), and Patriot as historical examples to measure the feasibility of multi-role systems. The JSF is a system currently in development that provides contemporary insight into a multi-role platform plagued by cost overruns and scheduling delays that continues to be developed. The FCS was a cancelled program experiencing delays and soaring costs, illustrating a failed example of a multi-role system and was cancelled as a result. Patriot serves as a fielded multi-role air defense system having been in the Army inventory for nearly 40 years.

CHAPTER 4

ANALYSIS

Introduction

Should the Army transition to a single laser-based AMD system? This chapter intends to explore the question by quantitatively analyzing comparable systems. First, this analysis measured the cost, schedule, and performance of each of these systems based on the expected capabilities and the delivered capabilities. Next, this study used open source data to identify the requirements and acquisitions history of multi-role systems and experimental laser systems. Finally, this study used the metrics outlined to analyze the potential feasibility of a laser-based AMD system.

Multi-Role System Costs

While many major defense acquisitions programs are expensive, this thesis focused primarily on several experimental laser systems and multi-role platforms to identify commonalities across them. With respect to cost, there are several key factors that have forced the cost of programs to inflate well beyond original estimates. Among them are failing to anticipate complexity, modifications of original requirements, and concurrent development.

Complexity of New Capabilities

Complexity is inherent in the development of new systems. However, failing to anticipate the technical challenges of developing a system inevitably lead to cost overruns. One example is the ABL program's failing to fully take into account the optical turbulence its laser would experience onboard an aircraft. In 1997, less than one year after the USAF awarded Boeing the ABL contract, the GAO assessed that Air Force did not have an accurate way to predict the amount of turbulence.[67] As turbulence "causes the laser to wander, spread, and scintillate"[68] reducing effectiveness and constraining its effective range, this was critical requirement to fix. By 2007, this critical technology was still not fully mature.[69]

Each of the aforementioned systems experienced similar issues with failing to deal with complexity. Table 1 outlines the initial expected cost of several overall programs and compares them to the actual cost of the programs as of the listed years.

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[67] Government Accountability Office (GAO), *Theater Missile Defense: Significant Technical Challenges Face the Airborne Laser Program* (Washington, DC: GAO, October 1997), 1, accessed 1 March 2019, https://www.gao.gov/archive/1998/ns98037.pdf.

[68] Frank H. Ruggiero, Joe Werne, Alex Mahalov, Basil Nichols, and Donald E. Wroblewski, "Characterization of High Altitude Turbulence for Air Force Platforms," (Proceedings of the HPCMP Users Group Conference 2007, High Performance Computing Modernization Program: A Bridge to Future Defense, Pittsburgh, PA, 18-21 June 2007), 28, accessed 8 March 2019, https://apps.dtic.mil/dtic/tr/fulltext/u2/p023732.pdf.

[69] Government Accountability Office (GAO), *Defense Acquisitions: Assessments of Selected Weapon Programs* (Washington, DC: GAO, March 2007), 23, accessed 1 May 2019, https://www.gao.gov/new.items/d07406sp.pdf.

Table 1. Costs for Major Acquisition Defense Programs

Program	Expected Cost of Program ($ millions)	Actual Cost of Program ($ millions)	Cost Per System ($ millions)	% cost overrun
ABL	6,1200 (1997)	8,127 (2008)	n/a	33%
FCS	91,000 (2004)	159,000 (2008)	8,000	76%
JSF(A/B/C)	207,178 (2004)	406,000 (2019)	94.3/122.4/121.2	96%

Source: Created by author using data from Christopher Bolkom and Steven A. Hildreth, *Airborne Laser (ABL): Issues for Congress*, Congressional Research Service Report to Congress (Washington, DC: Library of Congress, 18 August 2005), accessed 2 May 2019, https://apps.dtic.mil/dtic/tr/fulltext/u2/a454463.pdf; Government Accountability Office (GAO), *Defense Acquisitions: Assessments of Selected Weapon Programs* (Washington, DC: GAO, March 2008, accessed 2 May 2019, https://www.gao.gov/assets/280/274156.pdf.

Importantly, the JSF and FCS systems were specifically designed to replace legacy systems. With the expected production cost of each unit meant to be similar to those it meant to replace, comparing those costs to the legacy systems demonstrates the new systems affordability. Table 2 illustrates the cost per unit of the JSF and FCS compared to the legacy systems.

Table 2. Multi-Role vs. Legacy System Costs

Platform	Cost Per Unit ($ millions)	% Over Legacy
JSF (F-35A/F-35B/F-35C)	94.3/122.4/121.2	n/a
F-16C	18.8	501%
A-10	18.8	501%
F/A-18E	57	214%
F-15E	31.1	303%
EA-18G	67	182%
FCS (FBCT)	8,000	n/a
ABCT	2,200	365%
IBCT	600	1380%
SBCT	1,800	447%

Source: Created by Author using data from U.S. Air Force, "Air Force Fact Sheets," accessed 4 March 2019, https://www.af.mil/About-Us/Fact-Sheets/; U.S. Navy, "Navy Data: Fact Sheets," accessed 4 March 2019, https://www.navy.mil/navydata/fact.asp; Christopher G. Pernin, *Lessons from the Army's Future Combat Systems Program* (Santa Monica, CA: RAND Corporation, 2012), \accessed 8 May 2019, https://www.rand.org/content/dam/rand/pubs/monographs/2012/RAND_MG1206.pdf.

The Cost of Concurrent Development

Concurrent development in the military is fairly common and has existed throughout our history. The concept of developing a system while overlapping its production has potential advantages of meeting immediate threats and increasing efficiency. Throughout the twentieth century, the US has promoted more or less concurrency in its weapons acquisitions programs as problems or needs arose.[70] The potential negative consequences of concurrent development have been understood that should technical challenges occur in the development process, that process would need to

[70] Congressional Budget Office (CBO), *Concurrent Weapons Development and Production* (Washington, DC: CBO, August 1988), 19, accessed 15 January 2019, http://www.cbo.gov/sites/default/files/cbofiles/ftpdocs/ 55xx/doc5543/doc08b-entire.pdf.

stop while already produced units required modifications. Further, with rapid increases in technology, waiting for technological maturation could render the system obsolete by the time it is scheduled for production.[71] These were issues that plagued the JSF.

The myriad of technologies on the JSF increased the risk of developing and procuring while increasing the costs. From 2007 to 2012, the cost of the JSF program increased $119 billion. A 2012 GAO report directly attributed these cost overruns to "the instability in the program …to be the result of highly concurrent development, testing, and production."[72] Further, an additional $373 million in cost was incurred by the government due to retrofitting produced aircraft to correct deficiencies discovered during flight testing.[73]

Performance of New Systems

This thesis outlined its methodology for measuring performance with a two-fold metric. First, comparing the performance of multi-role systems versus the current platforms provides insight into how a future laser-based AMD system will compare against legacy systems. For this metric, the JSF and MCS will be used. The Patriot system will serve as the second metric to highlight its current capabilities as a standard that a future system must maintain.

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[71] John Venable, "Operational Assessment of the F-35A Argues for Full Program Procurement and Concurrent Development Process," *Backgrounder*, no. 3140 (4 August 2016): 13, accessed 29 February 2019, http://thf-reports.s3.amazonaws.com/2016/BG3140.pdf.

[72] Government Accountability Office (GAO), *Joint Strike Fighter: Restructuring Added Resources and Reduced Risk, but Concurrency is Still a Major Concern* (Washington, DC: GAO, 20 March 2012), 7, accessed 6 March 2019, https://www.gao.gov/assets/590/589454.pdf.

[73] Ibid., 1.

Performance of the JSF

The F-35 JSF was developed with the intention of replacing multiple airframes. In addition to replacing mission sets, the JSF boasted stealth technology, an active electronically scanning radar, and various technological improvements over legacy fighter aircraft. Given the JSF is currently in production, this case study provides the best contemporary example of a new multi-role capability compared to legacy, capable, platforms as an analysis to measure performance improvements.

Comparing open-source information regarding the performance characteristics of the F-35, F/A-18, F-16, and F-15, this thesis analyzed several different variables to assess performance. Table 3 provides a synopsis of general performance characteristics between airframes. This is not an all-inclusive list of differences between these platforms, nor does it describe specific capabilities within avionics or weapons. Rather, it provides a comparison of flight performance.

Table 3. Performance Comparison of US Fighter Aircraft

Category	**F-35**	**F/A-18E**	**F-16**	**F-15E**
Range (miles)	1350	1400	2000	2400
Speed (Mach)	1.6	1.8	2.0	2.5
Ceiling (kft)	>50	>50	>50	>50
Thrust (lbs)	43000	22000/engine	27000	29000/engine

Source: U.S. Air Force, “Air Force Fact Sheets,” accessed 4 march 2019, https://www.af.mil/About-Us/Fact-Sheets/; U.S. Navy, “Navy Data: Fact Sheets,” accessed 4 March 2019, https://www.navy.mil/navydata/fact.asp.

The JSF general performance characteristics are comparable to legacy fighters. With the addition of new technologies and armaments, the F-35 outclasses all older generation fighters in its mission sets. While these technological improvements provide a clear superiority for the JSF, measuring performance without calculating the cost associated with those improvements conflates the system's superiority with a successful acquisitions program. Additionally, with a notion of "quality in quantity" the high cost per airframe will either limit the number of F-35 aircraft that are procured relative to the current number of aircraft among legacy models, or the high cost to field and maintain F-35s will prevent the intended goal of comparable costs to other airframes. Table 4 provides the number of aircraft in the USAF inventory with F-35 projected procurement numbers.

Table 4. Number of Aircraft in USAF Inventory

Program	**F-35**	**A-10**	**F-16**	**F-15**	**F-15E**
Number of Aircraft	1763 (projected)	283	1017	249	219

Source: U.S. Air Force, "Air Force Fact Sheets," accessed 4 march 2019, https://www.af.mil/About-Us/Fact-Sheets/.

Performance of MCS

By 2008, one critical concern with the MCS was its survivability. The MCS has significantly lesser levels of armor than the M1 Abrams in an effort to make a more transportable platform. The requirement for FCS vehicles was to weigh less than 19 tons in order to be C-130 transportable. Moreover, the ability to transport the MCS on a C-130 was identified as the only "non-tradeable requirement".[74] for FCS, which contributed to the lighter weight MCS vehicle. The mitigation for this lack of protection was to come in

[74] Pernin, *Lessons from the Army's Future Combat Systems Program,* 57.

the form of an adaptive protection system and beyond-line-of-sight engagement capability. The MCS would rely on early warning to engage targets prior to threats being able to fire upon it. One of the underlying foundational concepts of FCS was this reliance on a network to provide early warning, but testing demonstrated that this network regularly failed. Should the enemy detect the MCS first, survivability of the platform decreased necessitating heavier armor protection.[75] Adding to these problems, by 2008 the hit avoidance capability in its adaptive protection system still had not demonstrated its ability to compensate for lack of armor protection.[76] Through all these problems, as mentioned in Chapter 2, the experimental MCS weighed 27 tons, well above the specified requirement.

[75] Pernin, *Lessons from the Army's Future Combat Systems Program,* 74.

[76] The Office of the Director, Operational Test and Evaluation, *Future Combat Systems* (Washington, DC: Department of Defense, 2008), 65, accessed 3 March 2019, https://www.dote.osd.mil/pub/reports/FY2008/pdf/army/2008fcs.pdf.

Table 5. Comparison of M1 vs MCS Tank

Program	M1A2 Abrams	Mounted Combat System
Weight (tons)	68.5	27
Range (km)	425	385
Top Speed (km/hr)	68	68
Cross Country Speed (km/hr)	48	37
Armament	120mm/2x7.62mm/.50cal	120mm/MRM
Armor	Depleted Uranium mesh composite	Lightweight composite/ Add-on armor

Source: Created by author using Christopher G. Pernin, *Lessons from the Army's Future Combat Systems Program* (Santa Monica, CA: RAND Corporation, 2012), 57, accessed 15 May 2019, https://www.rand.org/content/dam/rand/pubs/monographs/2012/RAND_MG1206.pdf; Army Recognition, "M1A2 Abrams Main Battle Tank," 19 January 2019, accessed 15 May 2019, https://www.armyrecognition.com/united_states_army_heavy_armoured_vehicles_tank_uk/m1a2_abrams_main_battle_tank_technical_data_sheet_specifications_pictures_video_11610153.html.

Basic general performance characteristics of the two systems indicate relative parity. Indeed, the theoretical capability of the family of MGVs containing a persistent and functional network as well as the adaptive protection system would outclass all the current vehicles they intended to replace. Figure 2 compares the MGV to current vehicles to demonstrate the MGVs capabilities. With respect to the M1, the MCS crew protection rating failed to demonstrate effectiveness of protecting crews from life threatening injuries.[77] The MCS ultimately could not compete against the M1 or adversarial main battle tanks due to its survivability issues and limited performance issues arising from a

[77] Government Accountability Office (GAO), *Defense Acquisitions: Key Decisions to Be Made on Future Combat System* (Washington, DC: GAO, March 2007), 22, accessed 6 March 2019, https://www.gao.gov/assets/260/257754.pdf.

complex FCS program. The immaturity of the networked systems and protection system did not fully develop prior to the cancellation of FCS in 2009.

TPM Topic	Abrams (M1A2)	Bradley (M2A3)	Paladin (M109A6)	Stryker MGS	M113A3 FOV	MRAP
Supply Cross-Leveling Time (minutes) Fuel = ↑ Ammo = ↔	↑	↑	↑	↑	↑	
Maintenance Ratio (MR) (MMW/CH)	↑	↑	↑	↑	↑	
Mean Time Between Sys Abort (MTBSA) (hrs)	↑	↑	↑	↑	↑	
Mean Time to Repair (MTTR) (hrs)	↑	↔	↑	↓	↔	
Platform Availability (Ao)/(OR rates)	↔	↓	↑	↓	↑	↔
Sensor Range Performance	↑	↑	↑	↑	↑	
Crew Protection (Mine)	↔	↑	↑	↑	↑	↓
Crew Protection (RPG, ATGM, HE/HEAT)	↑	↑	↑	↑	↑	↑
Crew Protection (14.5/30 MM 60 Deg Arc.)	↓	↑	↑	↑	↑	↑
Integrated Platform Weight (lbs)	↑	↑	↑	↓	↓	↓
Sustained Speed, Highway (km/h)	↔	↔	↔	↓	↔	↓
Sustained Cross-Country Speed (km/h)	Not available	Not available	Not available	↑	Not available	↑
Dash Speed 0–48 (seconds)	↑	↑	↑	↓	↑	↓
Indirect Fire CEP (%)			↑			
Indirect Fire CEP (meters)			↑			
Primary Armament BLOS Stationary Accuracy (%) (if it meets req it's 100%)	↑					
Primary Armament Accuracy (%) (if it meets req it's 100%)	↔	↔	↑	↔ M	↑ M	↑
Max firing range (kilometers)	↑		↓	↑ M	↑ M	
Max rate if fire (rounds per minute)			↑	↔ M	↑ M	
Emplace response time (seconds)			↑	↑ M	↑ M	

↑ MGV more capable ↓ MGV less capable ↔ Equal capability ☐ Not applicable

Figure 1. Technical Performance Measures of FCS MGV vs. Existing Army Vehicles

Source: Christopher G. Pernin, *Lessons from the Army's Future Combat Systems Program* (Santa Monica, CA: RAND Corporation, 2012), accessed 8 May 2019, https://www.rand.org/content/dam/rand/pubs/monographs/2012/RAND_MG1206.pdf.

Performance of Patriot

As the preeminent AMD weapon system for the US Army, the Patriot system continues to evolve over its lifespan to meet emerging threats. This thesis will use its performance and ability to modernize to indicate baseline capabilities needed from a future laser AMD system. The Patriot system is able to counter the largest threat envelope from UAS to TBMs.[78] Further, it can conduct multiple engagements of various types of targets simultaneously to include in an electromagnetically contested environment. Patriot relies on two varieties of interceptors to engage targets. First is the legacy Patriot Advanced Capability 2 (PAC-2) type interceptor, which itself has been modified and upgraded. The PAC-2 has a proximity detonation warhead that destroys targets with blast fragmentation. The second is the PAC-3 interceptor which is more maneuverable and is a kinetic "hit-to-kill" warhead. US army Patriot units have the ability to use these interceptors to maximize performance against different threats. Limitations of the system include a long reload time requiring units to maintain multiple launchers as well as targets needing to be within specific ranges that allow interceptors to launch and orient to a target. The Patriot system doctrinally requires 45 minutes to emplace the tactical system, and nearly the same in order to move to another location decreasing its survivability. Patriot's radar is a forward facing radar limiting engagements to only within its field of view.

Given these capabilities and limitations, a laser-based AMD system would need the ability to counter this range of threats in an electromagnetically contested environment. Similar or longer emplacement and displacement times decrease the survivability of a system, specifically in operations against a peer adversary that will seek to defeat friendly AMD systems. One key improvement a laser system would have is the negation of reload times, minimizing the number of fielded pieces of equipment needed to be moved or maintained. A laser would also not be constrained to the geometries of

[78] The Office of the Director, Operational Test and Evaluation, *Patriot Advanced Capability-3 (PAC-3)* (Washington, DC: U.S. Department of Defense, 2013), accessed 17 April 2019, https://www.dote.osd.mil/pub/reports/FY2013/pdf/army/2013patriot.pdf.

interceptor flyout restrictions that prevent close engagements with Patriot interceptors. Should a laser system have the ability to engage targets with a 360 degree field of view, this would increase survivability while lowering the number of overall systems required to fully defend critical assets.

Delivering Capabilities on Schedule

Comparing the initial IOC date with when a capability was actually declared IOC serves as a metric in determining whether a program maintained its planned fielding dates. This thesis will use the three variants of the F-35 JSF , ABL, FCS, and Patriot as major acquisitions programs with planned IOC dates and measure their adherence based on the five and ten year schedule delay metrics.

Table 6. Planned and Actual Initial Operational Capability Years

Program	**Initial IOC Date**	**Declared IOC Date**
F-35A (USAF)	2010	2016
F-35B (USN)	2012	2019
F-35C (USMC)	2011	2015
ABL	2006	Cancelled in 2009
Patriot	1980	1984
FCS	2010	Cancelled in 2009

Source: Created by author using Government Accountability Office (GAO), *Defense Acquisitions: Assessments of Major Weapon Programs* (Washington, DC: GAO, May 2003), accessed 5 May 2019, https://www.gao.gov/assets/240/238188.pdf; Jane's 360, "U.S. Navy Declares IOC for F-35C," Jane's, accessed 5 May 2019, https://www.janes.com/article/86951/us-navy-declares-ioc-for-f-35c; Army AL&T Editorial Staff, *Army AL&T: Future Combat Systems* (January-February 2004), accessed 6 May 2019, https://asc.army.mil/docs/pubs/alt/archives/2004/Jan-Feb_2004.pdf; Government Accountability Office (GAO), *Uncertainties Remain Concerning the Airborne Laser's Cost and Military Utility* (Washington, DC: GAO, May 2004), accessed 5 May 2019, https://www.gao.gov/new.items/d04643r.pdf; Comptroller General of the United States, "Results of Production Testing Should Be Considered Before Increasing Patriot's Production" (Report to Congress, Washington, DC, January 1983), accessed 5 May, 2019, https://www.gao.gov/assets/140/139519.pdf.

Comparing these planned and actual dates highlights that each program failed to meet its original IOC date. Patriot and the F-35C for the USMC were declared IOC within a five year window from their original timelines, while the F-35A and F-35B were declared IOC within a ten year window. Consequently, these delays hindered production rates and fielding timelines from original projections. Figure 1 shows the expected delivery of F-35s from 2002 to 2012 and how delays in production affected deliveries.

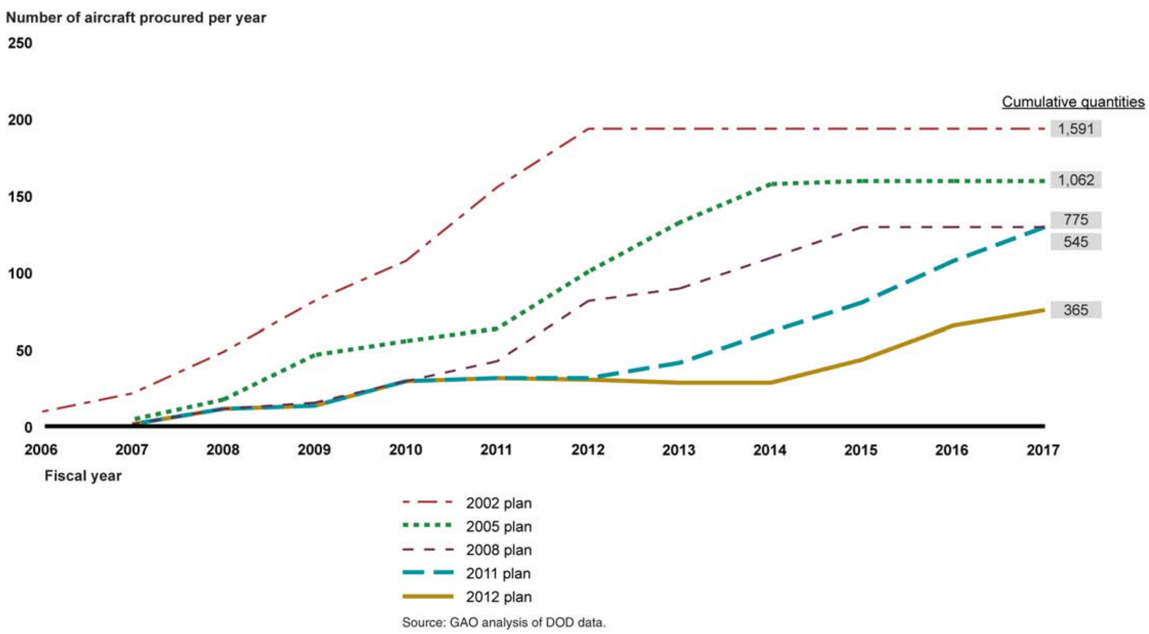

Figure 2. F-35 Planned Procurement from 2002 to 2012

Source: Government Accountability Office (GAO), *Joint Strike Fighter: Restructuring Added Resources and Reduced Risk, but Concurrency is Still a Major Concern* (Washington, DC: GAO, March 2012), accessed 6 March 2019, https://www.gao.gov/assets/590/589454.pdf.

Summary

This thesis used a quantitative approach to analyze the merits of developing a laser-based system. Given no current operational laser system conducting AMD exists in the Army inventory, these analyses extrapolated information regarding the likelihood a hypothetical laser system would stay within its budgeted resources, be developed within its planned timeline, and perform sufficiently to replace current AMD systems.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Thesis Question

The purpose of this thesis was to determine if the Army should transition to a single laser-based AMD system. Analyzing the literature with an attempt to answer three subordinate questions provides a framework for determining a recommendation. By viewing the question through cost, schedule, performance, and precedent, this thesis establishes metrics that inform the recommendation.

Findings

Based on the historical precedent and the issues associated with developing laser or multi-role platforms, the Army should initiate acquisition efforts to begin developing a laser-based AMD system. However, given the spectrum of air and missile threat capabilities and ranges, a single system is most likely untenable. While the ABL utilized a megawatt laser to penetrate a missile in boost-phase, a ground-based laser would most likely not have a clear line-of-sight of an ascending missile, nor would it likely be close enough to the target for a megawatt of power to suffice in the target's destruction. As such, optimal engagements would occur while a ballistic missile is in its midcourse or terminal phase of flight requiring a high-energy laser that would remain relatively large and lack high mobility. This juxtaposes a mobile platform having a smaller power requirement that can maintain tempo with maneuver forces.

Analysis of the costs of the case studies sheds light on two key insights. First, the overall costs of these technologically complex systems exceeded their expected program costs significantly. In the case of the JSF, the program breached the Nunn-McCurdy cost containment law as costs grew to 89% over the original program baseline in 2010.[79] Second, the most dramatic increases in costs were per unit costs over legacy systems. Between FCS and the JSF, the average cost increase was five-fold. Of note, the JSF continues to be produced and the unit cost will likely decrease as production numbers increase.

There are many reasons why major defense acquisitions programs experience cost growth. A general consensus among DOD officials and analysts is the primary cause is unrealistically low cost estimates at the inception of the program.[80] A laser-based AMD system would be comparable to these technologically complex systems. One commonality between these case studies that impacted cost growth was the technological immaturity of the programs through the development. Coupled with concurrent development for the JSF or accelerated timelines for FCS, cost estimates failed to predict actual expenses to procure these systems resulting in Nunn-McCurdy breaches.

When measuring performance, for a single laser-based AMD system to be feasible, it must replicate the capabilities and performance of the legacy systems to be replaced. The F-35 open-source data conclusively demonstrates its ability to out-perform legacy systems albeit at significantly higher costs. The MCS relied on technologies that were immature up until its cancellation to match the survivability of the M1 Abrams.

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[79] Congressional Research Service (CRS), *F-35 Joint Strike Fighter (JSF) Program,* CRS Report for Congress (Washington, DC: Library of Congress, 18 July 2016), accessed 19 March 2019, https://www.everycrsreport.com/files/20160718_RL30563_8bede6a87ca260a4aa65562952c04a3ccc62fd0a.pdf.

[80] Moshe Schwartz and Charles V. O'Connor, *The Nunn-McCurdy Act: Background, Analysis, and Issues for Congress,* Congressional Research Service Report for Congress (Washington, DC: Library of Congress, 12 May 2016), accessed 16 May 2019, https://fas.org/sgp/crs/natsec/R41293.pdf.

Using Patriot as a baseline multi-role AMD system, the laser system would need to be capable of matching Patriot at a minimum in terms of threat envelope and performance. The case for one laser-based AMD system becomes problematic when considering past laser systems high-energy requirement for longer range TBMs versus the mobility needed to maintain pace with maneuver forces and lower power requirements to defeat LSS UAS.

According to DOD leadership, the average timeline for the acquisitions process was 10 to 15 years with each program being unique. This thesis posited that achieving IOC five years over the projected timeline would constitute a significant delay while a 10 year delay would be a threshold warranting cancellation. The JSF and Patriot were the two examined programs that achieved IOC prior to cancellation. Both programs achieved IOC within 10 years of their initial IOC date with the F-35B requiring the longest time of seven years. In examining the case studies, commonalities that led to delayed schedules was the immaturity of the technology at inception and fluid requirements. In the case of the JSF concurrent development also served as a hindrance in achieved targeted dates. The JSF serves as a great analogy to a hypothetical laser-based system given the challenges of complexities of the technology, concurrent development, and evolving requirements, it achieved IOC within the proposed metric of 10 years.

The complexities of the modern battlefield along with the pacing of current and future air and missile threats constitutes a need to revolutionize the US Army's active defense capabilities to counter our adversaries. As these threats continue to evolve the Army would need to develop additional platforms, to include expensive interceptors to close the increasing number of gaps in our AMD coverage. Further, these future systems as well as current systems, lack the ability to counter massed attacks on critical assets. The costs of the current systems will continue to increase while the cost of threats decrease due to technological improvements.

Countering UAS threats poses a significant obstacle to the Army. ATP 3-01.81 states,

> UASs have advanced technologically and proliferated exponentially over the past decade. As technology has progressed, both reconnaissance and attack capabilities have matured to the point where UASs represent a significant threat to Army, joint, and multinational partner operations from both state and non-state actors.[81]

These systems, can be used for surveillance or be weaponized to attack troop formations or critical command and control nodes. A major concern is the ability to mass cheap UAS which can overwhelm maneuver forces to which there would not be enough active air defense capability to defeat them.[82] With the cost of one FIM-92 Stinger missile costing $38,000[83] and one UAS costing $650[84], there is a 58:1 cost ratio in defeating these threats kinetically. In 2017, several engagements with Patriot against drones were

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[81] Headquarters Department of the Army (HQDA), Army Techniques Publication 3-01.81, *Counter-Unmanned Aircraft System* (Washington, DC: Government Printing Office, April 2017), 1-1.

[82] Ibid.

[83] Office of the Under Secretary of Defense (Comptroller), *Procurement Programs (P-1): Department of Defense Budget Fiscal Year 2017* (Washington, DC: Department of Defense, February 2016), 38, accessed 29 March 2019, https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2017/fy2017_p1.pdf.

[84] Mark Pomerlaeau, "How $650 Drones are Creating Problems in Iraq and Syria," *C4ISRNET*, 5 January 2018, accessed 30 March 2019, https://www.c4isrnet.com/unmanned/uas/2018/01/05/how-650-drones-are-creating-problems-in-iraq-and-syria/.

reported.[85] With one Patriot missile costing several million dollars, it is apparent that kinetic engagements against inexpensive UAS is unsustainable.

TBMs pose problems similar to UAS for active defense. Today, the four nations outlined in the NSS as rival actors possess numerous TBMs with varying capabilities.[86] Also less expensive than active defense interceptors, TBMs pose another problem in they are able to target deep behind a forward battle area. This requires anti-ballistic missile defense systems to be postured in likely areas to be targeted, dispersed around an entire operating area. Since the flight time of a short or medium range ballistic missile is less than ten minutes, anti-ballistic missile systems need to be emplaced prior to an expected attack with no opportunity to displace to protect an undefended asset. Specifically Patriot requires the system to be in close proximity to its protected assets in order to defend them.

A transportable laser-based system with sufficient power could theoretically be positioned to defend against multiple threats within its line of sight without having to be constrained by being positioned near its defended assets. For short range UAS threats, a mobile laser that keeps pace with maneuver units can be positioned along avenues of approach or with troop formations to defeat these threats.

The acquisition of a laser-based AMD system would constitute a major defense program which could likely fall victim to the same problems this thesis highlights

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[85] Derek Hawkins, "A US "Ally" Fired a $3 Million Ptriot Missile at a $200 Drone. Spoiler: The Missile Won," *The Washington Post,* 17 March 2017, accessed 27 April 2019, https://www.washingtonpost.com/news/morning-mix/wp/2017/03/17/a-u-s-ally-fired-a-3-million-patriot-missile-at-a-200-drone-spoiler-the-missile-won/?utm_term=.f8d94826f77f.

[86] U.S. President, NSS, 3.

regarding other major defense acquisition programs. Laser-based systems that the DOD has previously attempted to develop were immature in their technology or prototypes that were not feasible for warfighting. However, as of the writing of this thesis, technology has improved to the point where laser systems can be smaller and more effective than their forerunners. Most likely the development of such systems would still face technical challenges similarly experienced by other major acquisition programs. A laser-based system has the potential benefit of time as it is unlikely to become obsolete should it not be produced within a decade. This thesis highlights several recommendations that would aid in the timeline for development.

Promising Solutions

While this thesis highlighted several laser-based AMD systems that were developed, the DOD and defense contractors recognize the promising nature of laser-based AMD systems and are working to develop them. In 2015, Boeing developed Silent Strike, a prototype portable laser system aimed to defeat UAS.[87] This was part of their ongoing efforts to develop a laser capability. Indeed, Boeing has demonstrated over six different porotype laser systems with potential applications for the military.[88] Raytheon currently has a high-energy laser porotype able to be fitted on a vehicle that has proven

[87] Boeing, "Silent Strike: Boeing's Compact Laser Weapons System Tracks and Disables UAVs," 27 August 2017, accessed 12 May 2019, http://www.boeing.com/features/2015/08/bds-compact-laser-08-15.page.

[88] Boeing, "Boeing Laser Systems Destroy Unmanned Aerial Vehicles in Tests," 18 November 2009, accessed 12 May 2019, https://boeing.mediaroom.com/2009-11-18-Boeing-Laser-Systems-Destroy-Unmanned-Aerial-Vehicles-in-Tests.

effective against small UAS.[89] These represent a few of the numerous efforts to move towards this technology.

Recommendations

The complexity associated with the development of a new technology such as a laser-based AMD system to serve as a multi-role platform against the vast array of air and missile threats would most likely cause the acquisition of such a system to be plagued by the delays and costs experienced by other major defense programs. This thesis provides three recommendations key to avoiding the pitfalls seen in comparable development efforts.

The primary recommendation is clearly defining the new system's requirements from the outset.[90] This thesis stated an assumption that evolving requirements, specifically if such a system became a joint platform, would increase the complexity of development and thus this thesis would focus exclusively on an Army platform. However, it is important to underscore that without clear initial requirements for a new capability, the development of a new weapon will inevitably succumb to the same cost overruns and schedule delays that plague other major programs. The JSF and FCS are clear examples of programs hampered by evolving requirements that eventually contributed to the cancellation of one program and the long delay in timelines in another.

[89] Raytheon, "Beam On: A Wide Range of Counter-Drone Technologies Comes of Age," 28 June 2018, accessed 12 May 2019, https://www.raytheon.com/news/feature/beam-on.

[90] AcqNotes, "Requirements Development: Requirement Types," 14 August 2018, accessed 12 May 2019, http://acqnotes.com/acqnote/tasks/requirement-types.

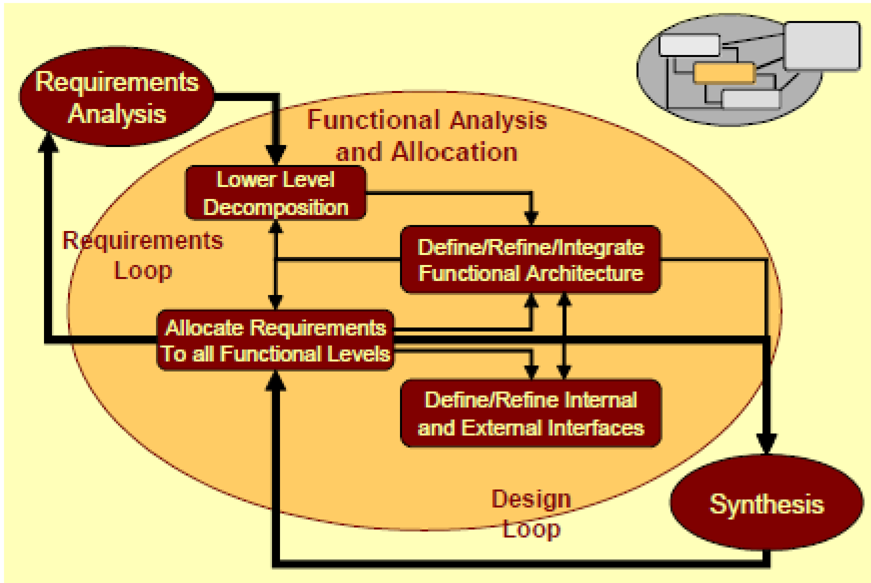

Figure 3. Functional Analysis and Allocation Loop

Source: Acqnotes, "Functional Analysis and Allocation," accessed 1 May 2019, http://acqnotes.com/wp-content/uploads/2014/09/Functional-Analysis-and-Allocation.png.

Laser-based AMD is a significant shift from current AMD methods of primarily missile technology. Unlike FCS, which sought to replace current technology with comparable systems networked together, a high-energy laser as a kinetic defense system will revolutionize AMD by reducing engagement timelines, increasing defense capability against multiple concurrent threats, and expanding our current focus on point defense to a broader area defense. Clearly defining the requirements for this new capability will enable a deliberate acquisitions process that will minimize risks of schedule delays historically associated with spiral development.

A second recommendation is to avoid high concurrent development. As this thesis has explored, the defense industry uses concurrent development in an attempt to reduce costs and to produce new capabilities more rapidly. One concern with the JSF that justified the concurrent development approach was technological obsolescence should the acquisition be successive and lengthy. A laser-based AMD system, being a departure from current AMD methods would unlikely experience this concern. Secondly, current US AMD systems provide adequate defense in limited scope for the preponderance of current threats supporting a longer development timeline for an alternative system. However, the development of new enemy capabilities and the ability to mass air and missile attacks necessitates the need for better AMD systems that can address these threats.

In order to meet the AMD demands of large scale combat operations, a third recommendation is to develop two variants of this capability, a mobile platform and a transportable platform. In order to support the Army maneuver forces, specifically against UAS and rotary-wing threats, an effective system must be mobile and able to maintain pace with frontline maneuver assets. Currently, the Army employs the Avenger system to fulfill this role with the Maneuverable Short Range Air Defense (MSHORAD) Stryker-based platform in development as its replacement.[91] However, both the Avenger and MSHORAD will be limited in number of missiles they can employ to counter enemy swarm tactics or higher altitude threats. For threats affecting operational and strategic assets, a transportable system would be required. This larger platform would replace current mission sets of Patriot, THAAD, and potentially GBI. In a theater setting, it would enable the Joint Force Commander to generate forces while protecting critical command and control nodes and critical infrastructure. Being transportable allows the

[91] Sydney J. Freedberg Jr, "Army Races to Rebuild Short-Range Air Defense: New Lasers, Vehicles, Units," *Breaking Defense,* 21 February 2017, accessed 14 May 2019, https://breakingdefense.com/2017/02/army-races-to-rebuild-short-range-air-defense-new-lasers-vehicles-units/.

system to increase its survivability while being able to displace to protect other assets as priorities change throughout an operation.

Areas for Further Study

This thesis did not examine the effectiveness of various types of lasers. While this study highlighted several past programs that employed lasers, it did not examine the benefits or capabilities of a specific type of laser. The power requirements needed to defeat ICBMs are unknown, but can be assumed to exceed the capabilities of a transportable laser-system. As such, an analysis of laser technology compared to current GMD kinetic interceptors is needed.

As a potential new laser-based system is incorporated into the AMD architecture, as with current systems, command and control in order to prevent fratricide and facilitate effective employment are paramount. Unique to lasers is the linear trajectory of the beam continues indefinitely. It effects diminish over distance, but the range to which the beam can affect an object depends on several factors, including power output, type of laser, and composition of the object. This can affect space-based assets as well as users in the airspace. As such, a robust command and control element able to clear the field of fire will be critical to employing a laser against a target.

Conclusion

Technological advancement creates opportunities for friends and adversaries alike. Our adversaries continue to use affordable technology to exploit capability gaps. This thesis highlighted the significant cost the US spends on missile defense and that gap between missile defense spending and the threats continues to increase. Missile defense requires complex systems to engage air and missile targets, while employing air and missile capabilities becomes easier. This inverse relationship of costs necessitates the need for new solutions. Laser defense systems have been explored since the 1960s but have proved elusive due to their complexity. Each prototype system's successes and failures have brought us closer to making a feasible laser system that removes a reliance on interceptors and negates enemy countermeasures. Should the Army pursue a laser-based AMD system acquisition, with specified requirements and realistic timelines and cost projections, this capability could eventually replace the legacy systems and improve our ability to provide effective AMD for US forces.

GLOSSARY

Air Breathing Threat (ABT). Classification for aerial platforms relying predominately on atmospheric lift. Generally fixed-wing, rotary-wing, unmanned aerial systems, and cruise missiles are considered ABTs.

Air and Missile Defense (AMD). Defensive measures designed to destroy attacking enemy aircraft or missiles in the atmosphere or exo-atmospherically, or to nullify or reduce the effectiveness of such attack.

Area Defense. Using a combination of weapon systems to defend broad areas.

Integration. The ability for multiple systems to transmit, share and interpret information

Point Defense. Protects limited areas, normally a defense of vital elements of forces or installations.

Theater/Tactical Ballistic Missile (TBM). An enemy missile that travels a ballistic trajectory through the majority of its flight path to deliver a payload.

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