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Dissertation

Improving Standoff Bombing Capacity in the Face of Anti-Access Area Denial Threats

Jordan Rozsa

RAND CORPORATION

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This document was submitted as a dissertation in September 2015 in partial fulfillment of the requirements of the doctoral degree in public policy analysis at the Pardee RAND Graduate School. The faculty committee that supervised and approved the dissertation consisted of James S. Chow (Chair), Fred Timson, and Christopher A. Mouton.

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Preface

The current United States Air Force (USAF) bomber force is comprised of aging, non-stealthy B-1 and B-52 aircraft along with a small fleet of stealthy B-2s. In an advanced anti-access/area denial (A2/AD) environment, these aircraft may be forced to operate at a standoff range with long-range cruise missiles due to enemy air defenses. In some cases the demand for cruise missiles may exceed the rate at which the bomber fleet can supply them. It may be necessary to procure new aircraft and develop and produce more cruise missiles.

For his Ph.D. dissertation at the Pardee RAND Graduate School, the author addressed the issue of standoff capacity in A2/AD environments using a cost-effectiveness methodology. He compared the effectiveness of standoff aircraft alternatives using demand-based and capabilities-based analyses. He determined costs for alternatives using statistical analysis, and made recommendations based on cost-effectiveness. The results of his efforts are reported in this document.

The research reported here began within the Force Modernization and Employment Program of RAND Project AIR FORCE as part of a fiscal year 2014 project, "Long-Range Strike Optimization to Counter Anti-Access and Area Denial." After this project ended, additional funding from RAND Project Air Force and the RAND National Security Research Division was provided. The target audience for this dissertation is Air Force leadership and policy makers, and particularly leaders of Pacific Air Forces (PACAF) and United States Pacific Command (USPACOM).

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Abstract

The threat environment of the 21st century consists of increasing numbers of advanced anti-access/area denial (A2/AD) defense systems which place significant pressure on the current United States Air Force (USAF) bomber fleet. In a scenario with A2/AD systems, conventional USAF bombers will likely be relegated to a standoff role. The ability of the current bomber inventory to handle the challenges of stressing combat scenarios remains in question. This research seeks to address the issue of whether or not there is a capability gap given certain threat scenarios and how the Air Force could allocate resources to alleviate this potential capability gap. The primary aircraft alternatives considered are commercial-derivative and military cargo-derivative arsenal aircraft. Demand for and effectiveness of arsenal aircraft alternatives are assessed through parametric and exploratory analysis. Costs are analyzed using multivariate regression analysis and cost analogies. These methods provide cost-effectiveness comparisons among a variety of USAF policy options. Meeting warfighting demands highlighted in this report would be well served by developing new types of cruise missiles and procuring them in sufficient quantities. Improving weapon effectiveness will significantly decrease target demand by a factor of up to 5.6, varying by target set. If arsenal aircraft are procured to deliver these standoff weapons, the C-17 is the most cost-effective option due to avoidance of development costs, although there would be penalties incurred for reopening the production line. The B-1 and B-52 aircraft should be replaced early to eliminate high operating costs associated with the aging fleet. Using existing cargo aircraft (C-130, C-17, and C-5) for these missions as dual role aircraft yields minimal costs compared to procuring new aircraft.

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Context and Background

United States Air Force (USAF) bombers have operated in generally uncontested airspace in the vast majority of conflicts over the last 20 years. However, the increasing prevalence of ballistic missiles and surface-to-air missiles (SAMs) throughout the world imposes greater threats to the bomber fleet.[1] Ballistic missiles threaten theater airbases and discourage close-in basing for aircraft. SAMs limit U.S. access to enemy airspace directly overhead and therefore restrict access to traditional overflight bombing. In a scenario where the airspace is highly contested, bombers will likely need sufficient air support, such as large numbers of escorting fighters and support aircraft equipped with radar-jamming equipment, to perform missions and may still be operating at high risk.

Many potential U.S. adversaries possess or are in the process of acquiring these so-called advanced anti-access/area denial (A2/AD) defense systems, defined in the U.S. Department of Defense (DoD) 2010 Quadrennial Defense Review as weapon systems that "seek to deny outside countries the ability to project power into a region, thereby allowing aggression or other destabilizing actions to be conducted by the anti-access power."[2]

As ballistic missiles and long-range SAMs are proliferated, the bomber force will need to adapt to continue to operate in an A2/AD environment. There are at least three primary strategies to mitigate the A2/AD threats to U.S. bombers:[3]

1. Locate U.S. aircraft at bases outside of ballistic missile range to thwart enemy offensive counter-air capabilities. Other basing options could also be employed such as hardened parking structures, better air defense of bases, decoys and deception, etc.
2. Employ stealthy penetrating bombers to enable operations against advanced enemy air defenses. There currently is a small force of 16 combat-coded stealthy B-2 bombers.[4] The

[1] Ballistic missiles are weapons that follow a ballistic trajectory to deliver an explosive payload to a fixed land target from relatively far ranges. These missiles are generally launched from land-based launching sites or from ships and submarines. Ranges for these kinds of missiles can vary, but in this analysis we are less concerned with intercontinental ballistic missiles (ICBMs) and more concerned with ballistic missiles that can threaten theater basing. SAMs can be launched from land or sea. The primary targets for SAM systems are any incoming enemy air asset, whether it is an aircraft, ballistic missile, or other long-range weapons.

[2] *Quadrennial Defense Review*, P.L. 11-383, 2010.

[3] In principle, ballistic missiles could also be used to strike targets and mitigate A2/AD threats. However, this topic was outside of the scope of the study.

[4] Only a proportion of combat-coded aircraft would be available in a conflict due to some aircraft being not mission capable due to scheduled and unscheduled maintenance.

Air Force is in the process of developing a new penetrating bomber, but it will not be operational until around 2030.

3. Employ standoff bombers with long-range cruise missiles to defeat advanced enemy air defenses. The U.S. Air Force currently has 96 combat-coded bombers capable of carrying long-range cruise missiles. Additional standoff capacity could be provided by acquiring aircraft that can launch large amounts of cruise missiles, referred to in this report as "arsenal aircraft." [5]

While it would be interesting to compare the relative utility of each of these strategies in mitigating threats to the bomber fleet, the scope of this study was to address the third strategy. In particular, this study focused on the policy option of acquiring arsenal aircraft to provide sufficient standoff capacity in high target demand A2/AD scenarios.

Policy Issue and Purpose of Research

Policy makers face near-term and far-term challenges regarding the bomber fleet. The consideration of these challenges is critical to determining what action should be taken and when. In the near term, a potential capacity gap exists. As non-stealthy platforms, both the B-1 and B-52 will have limited ability to penetrate into contested airspace with advanced air defense threats.[6] The B-2 has stealth capability, but if the enemy has advanced air defenses, the B-2s may not be able to penetrate enemy airspace. The Air Force is investing in a new stealth bomber, the long-range strike bomber (LRS-B), which is projected to have initial operational capability (IOC) in the 2030 timeframe. If the LRS-B is assumed to fill the capability gaps present with regard to AD threats (an assumption which may not be valid depending on how advanced enemy air defenses evolve by the time LRS-B is operational), then there exists a potential shortfall in the U.S. bomber fleet until the LRS-B reaches IOC. Increasing standoff bombing capacity is a viable option for policy makers to mitigate risk in A2/AD scenarios. There may be a need to acquire additional standoff bombers to supplement the current bomber fleet during times when the demand for cruise missile strikes exceeds the near-term supply of firepower, or the rate at which cruise missiles can be launched.

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[5] The term "arsenal aircraft" describes a dedicated aircraft that can carry large amounts of cruise missiles. The most commonly theorized versions of these arsenal aircraft are derived from commercial or military cargo aircraft that are converted to carry and launch cruise missiles. Their primary employment would be to use these weapons from standoff distances and hence can be considered to be a subset of the more general phrase, standoff bombers.

[6] We consider advanced air defense threats to include long-range systems like the SA-20 with a range of 200 kilometers which was first introduced in 1992 but, to date, has yet to be encountered in any U.S.US air operations. The B-1 and B-52 have continued to demonstrate their utility in providing long-range and persistent strike capabilities in scenarios with permissive or less advanced air defense threats, such as in the recent operations in Iraq and Afghanistan.

The far-term challenge for policy makers involves the age of the bomber fleet. The current portfolio of U.S. bombers includes the B-2, B-1, and B-52 which are about 21, 27, and 53 years old respectively. The Air Force has decided to extend the life of the B-1 and B-52 to 2040. At that point, Air Force leaders have planned to use the LRS-B as the sole long-range strike aircraft.[7] However, like many military acquisition programs, the LRS-B faces potential risk. The number of LRS-B aircraft to be produced may not reach the number we expect this early in the development stage. In addition, necking down to the LRS-B as the only bomber type in the fleet faces risk if advances in enemy air defenses negate its postulated penetration capabilities. The stealth technology on the LRS-B is likely to be more advanced than that of any other aircraft. However, if threat air defense technology evolves to being able to defeat stealth, feasibly striking targets with the LRS-B might require the use of long-range standoff missiles. In that case, the LRS-B would end up being an extremely expensive standoff bomber. The far-term bomber force structure should be shaped by these kinds of considerations.[8]

This dissertation provides insight into how to mitigate the increased threat risk to U.S. bombers with a specific focus on the strategy of employing standoff bombers with long-range cruise missiles to defeat advanced enemy air defenses. Understanding the relative tradeoffs among standoff bombing alternatives will be important for policy makers considering the age and potential capacity gaps of the current bombers. Especially in an increasingly constrained budget environment, there would be major implications if standoff bombing alternatives are found to be a more cost-effective way of spending limited defense funds. The following research questions were addressed in this study:

1. What is the potential demand for standoff bombing capability in the new A2/AD threat environment?
2. How effective are standoff alternatives in terms of launching cruise missiles?
3. What will it cost to acquire and maintain standoff alternatives?
4. Of the bomber alternatives considered in this study, which are the most cost effective?

This research was a quantitative analysis that compared 10 different bomber alternatives in terms of their ability to function in a standoff role by launching cruise missiles in the required numbers and required distances in the A2/AD threat environment. The alternatives were analyzed in terms of their costs and their ability to meet the demand for bomber capacity in four potential wartime situations: halting an army, halting an amphibious invasion, preventing enemy air operations by attacking runways, and attacking time-critical fixed targets.

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[7] John A. Tirpak, "Bomber Futures," *Air Force Magazine Daily Report*, June 26, 2015.

[8] It is likely that the LRS-B will be equipped with the capacity to fire long-range cruise missiles due to the uncertainty that LRS-B stealth capability will remain relevant during the entirety of its lifetime. However, the details of the LRS-B program are not publicly available. For this reason, specific analysis of the LRS-B with regard to standoff capacity is outside the scope of this dissertation.

The study answers the proposed research questions using quantitative data from a variety of sources. Cost and effectiveness of standoff alternatives were compared using demand-based and capabilities-based analyses. The first stage of this effort addressed the first research question; it determined whether or not this added capability is necessary and sufficient in a variety of potential A2/AD threat scenarios that are particularly stressing for the current fleet. A suite of models were used to conduct exploratory analyses to determine the demand for standoff capability. The second stage addressed the second research question; it measured the effectiveness of the alternatives to deliver long-range standoff weapons (i.e., to launch cruise missiles). Engineering analysis and a sortie rate model were used to determine effectiveness. The third stage captured the acquisition and sustainment costs for the aircraft systems being considered, and did so using cost analogies and multivariate regression analysis. Lastly, the cost-effectiveness of each alternative was analyzed over a variety of policy options with a fixed-effectiveness approach.

Key Messages

Several alternatives for arsenal aircraft were considered, including commercial derivative procurement (A380F, A330F, 777F, 747-8F, 767-300F), military cargo derivative procurement (C-17), and military cargo derivative dual role (C-17, C-5, C-130). These options could be employed to either replace the existing capacity of the aging B-52 and B-1 fleets, or to supplement these fleets in times of high demand for standoff bombing capability.

In addition to today's fixed-target strike cruise missiles, demand for new standoff weapon capabilities could help address a wide variety of important targets. This analysis identifies anti-ship and counter-runway cruise missiles as two important capabilities that could contribute to bomber effectiveness in A2/AD conflicts. Cruise missiles would also need to be acquired in large quantities to handle the potentially large time-critical target demand found in this study.

If new standoff weapons are developed, there is still a potential shortfall of standoff firing capacity available for A2/AD scenarios Policy makers have two classes of options when confronting the problem of standoff capacity shortfalls. The first is to reduce the demand for cruise missiles in stressing scenarios. The adversary is, of course, responsible in large part for the target demand. However, there are many alternative solutions that can increase the effectiveness of the attack and thereby reduce the number of missiles needed to strike the given set of targets. The second is to increase the supply of cruise missile firepower. This is accomplished simply by increasing capacity in the form of procuring more aircraft.

The following are the findings and implications regarding the reduction of cruise missile demand:

- **Improving intelligence, surveillance, and reconnaissance (ISR) capabilities is an effective way of reducing enemy halt distance in the case of a land invasion.** If target locations are accurate, or in other words if cruise missiles are capable of receiving

updates on target location throughout the flight path, the halt distance of a land invasion can be reduced by a factor of up to 5.6. This would imply that for a fixed halt distance, the number of missiles required would be reduced by a significant amount. Mobile targets generally are not an ideal target for cruise missiles. However, if standoff bombing were required in such a scenario the investment in better ISR would be recommended for decision makers.

- **Anti-ship cruise missiles (ASCM) sensor ability can reduce cruise missile demand significantly in the case of an amphibious invasion.** If an enemy employs a strategy using ship decoys during the amphibious invasion, the number of cruise missiles required to destroy 50 percent of the invading fleet can be reduced by a factor of up to 4.2 if ASCMs can discriminate between ship targets.
- **Larger salvo sizes and longer firing intervals can increase survivability and overcome weaknesses in battle damage assessment ability during an amphibious invasion.** Against any defended target, the more missiles that arrive simultaneously, the more overwhelmed the enemy air defenses will be. This will lead to larger numbers of leakers that get past the defenses and can attack the target. In the case of moving targets such as ships in an amphibious invasion, battle damage assessment prevents cruise missiles from striking targets that are already defeated. With longer intervals between salvos, the destroyed, non-moving targets will be left behind the formation and there will be fewer redundant target strikes.
- **Accurate intelligence on airbases that have high priority aircraft can reduce the number of runways required for attack.** While circular error probable (CEP) is a major factor in how effective cruise missiles are in destroying fixed targets, another avenue to reducing cruise missile requirements is to know which targets to strike. In the case of runways, intelligence that distinguishes runways that are operating combat aircraft from general military runways can reduce the total number of targets by a factor of up to 2.4. This reduction would increase substantially if, for instance, fighter aircraft were the primary aircraft of interest.

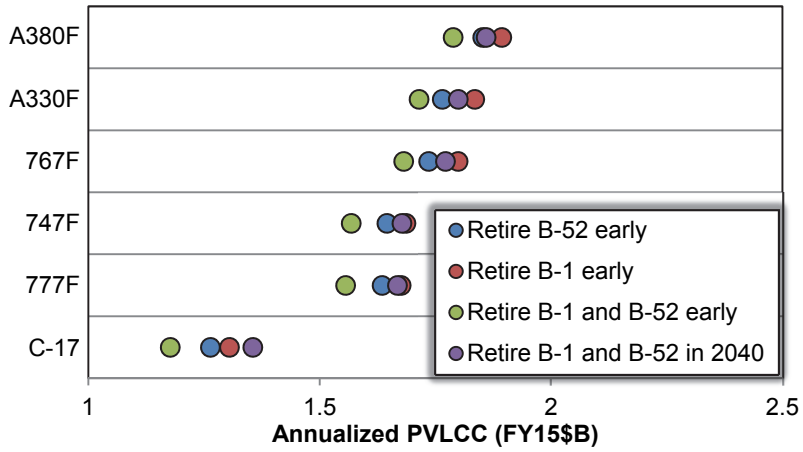
The other class of findings in this report relate to increasing the cruise missile firing capacity of the bomber fleet. The following are the findings and implications of options for increasing standoff bombing capacity:

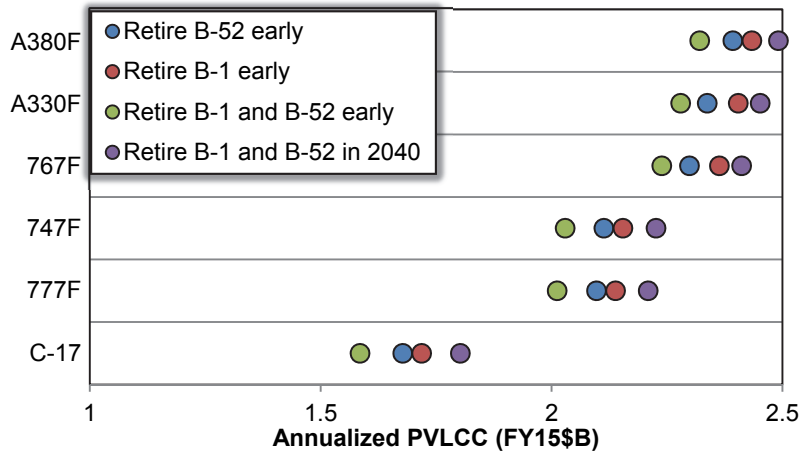
- **Target demand across target types under best-case assumptions yields a demand less than the current bomber capability. Worst-case assumptions yield a demand much more than current bomber capability.** Realistically, the current bombers can handle any number of targets if they are spread out over a long-enough time period. Where the current fleet runs into problems is when the rate at which targets need to be attacked exceeds the rate at which the current bombers can fire cruise missiles. The rate analyzed in this report was cruise missiles fired per day given an operating radius of 1000 nautical miles. With full loadout configurations, the current bombers can handle a rate of

roughly 960 cruise missiles per day. The demand analysis in this report yielded a range of cruise missiles required in the theater of 510-2500 depending on the analysis assumptions, which is accordingly 53-266 percent of the current bomber capability.

- **Of the procurement options, the C-17 was found to be the most cost-effective.** Several procurement strategies were tested among the arsenal alternatives. These strategies were categorized into two classes: replacing the current bomber capacity, and replacing/supplementing the current bombers to meet a high-demand capacity. Within these classes, each strategy contained a timeline of retirement for the B-1 and B-52 aircraft. After retirement, the aircraft would be replaced by arsenal aircraft procurement. The first two strategies were to retire either the B-1 or the B-52 early, and retire the remaining bomber at the scheduled retirement year 2040. The third option was to retire both the B-1 and B-52 early, and the fourth option was to keep both aircraft until the retirement year and replace them with arsenal aircraft starting in 2040. There was not a huge amount of variation among these strategies as shown in Figure S.1, although the option to retire both the B-1 and B-52 early was consistently the lowest cost option. The C-17 was also consistent in being the lowest cost arsenal alternative, in part due to the avoidance of large engineering and manufacturing development (EMD) costs.

Figure S.1. Annualized Present Value Life-cycle Cost (PVLCC) for Different Procurement Strategies for Replacing the Current Capacity (Top) and Supplementing the Fleet for a Higher Capacity (Bottom)





- **Using existing cargo aircraft as dual role aircraft could be highly cost effective but somewhat stressing to the cargo fleet.** The option to use existing military cargo aircraft as needed to fill the capacity gap would yield the least cost by far. There would be no aircraft acquisition program since these aircraft are already operational. The only costs would be a relatively small amount of development and procurement cost for a launching system, and operating and support (O&S) costs would be minimal as the aircraft would be mostly operating in their primary cargo mission. However, this option presents challenges in the form of opportunity cost to the cargo fleet. If demand for cruise missiles does not interfere with the cargo mission, this dual role option would incur negligible cost. In scenarios where military cargo aircraft are in high demand, borrowing a handful of aircraft for cruise missile employment may prevent theater cargo requirements from being satisfied. However, perhaps this shortfall is not as extreme as one would expect. If the C-17, C-5, or C-130 were to be used to supplement the current bomber shortfall, the required aircraft would be only five percent, 11 percent and 13 percent of their respective fleet size. It may be the case that even these small percentages exceed the available aircraft during a conflict of significant proportions. However, it is interesting to note that with such a small number of required aircraft, there may be some room for these missions if theater cargo demand isn't excessively high.

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I am very grateful to the members of my dissertation committee, namely Jim Chow, Fred Timson, and Christopher Mouton. They were invaluable to me and provided me with incredible support throughout the entire research process. Jim was an exceptional chair and a mentor to me on this dissertation effort and on the many projects that I was privileged to work on with him. Fred has a wealth of knowledge regarding costs analysis and very graciously guided me through my analysis. Chris consistently encouraged me to push the envelope on my analysis and to take analytic risks. I am very grateful for my outside reviewer, David Sacko, and for the excellent feedback he gave me in discussing the strategic context of my research questions.

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Abbreviations

A2/AD	Anti-Access/Area Denial
AFI	Air Force Instruction
AFPAM	Air Force Pamphlet
AFTOC	Air Force Total Ownership Cost
AFV	Armored Fighting Vehicles
ALCM	Air-Launched Cruise Missile
APACHE	Arme Propulsee A Charges Ejectables
APUC	Average Procurement Unit Cost
ASCM	Anti-Ship Cruise Missile
ATACMS	Army Tactical Missile System
BAT	Brilliant Anti-Tank (submunition)
BDA	Battle Damage Assessment
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CEP	Circular Error Probable
CAIG	Cost Analysis Improvement Group
CER	Cost Estimating Relationship
CIWS	Close-in Weapon System
CLS	Contractor Logistic Support
CMCA	Cruise Missile Carrier Aircraft
CSRL	Common Strategic Rotary Launcher
DOD	Department of Defense
EMD	Engineering and Manufacturing Development
GPS	Global Positioning System
ICBM	Intercontinental Ballistic Missile
IIR	Imaging Infrared
INS	Inertial Navigation System
IOC	Initial Operational Capability

IRTGSM	Infrared Terminally Guided Submunitions
ISR	Intelligence, Surveillance and Reconnaissance
JASSM	Joint Air-to-Surface Standoff Missile
JPADS	Joint Precision Airdrop System
JSOW	Joint Standoff Weapon
LRS-B	Long Range Strike Bomber
MALD	Miniature Air-Launched Decoy
MCALS	MALD Cargo Aircraft Launch System
MD	Mission Design
MDS	Mission Design Series
MOS	Minimum Operating Surface
NM	Nautical Miles
O&S	Operating and Support
OOA	Out of Action
OSA/VIPSAM	Operational Support Airlift/Very Important Person Special Air Mission
PAI	Primary Aircraft Inventory
PGM	Precision Guided Munitions
PLAN	People's Liberation Army Navy
PMAI	Primary Mission Aircraft Inventory
POL	Petroleum, Oil and Lubricants
PVLCC	Present Value Life-Cycle Cost
RDT&E	Research, Development, Test and Evaluation
SAM	Surface-to-Air Missile
SEAD	Suppression of Enemy Air Defenses
SFW	Sensor-Fused Weapon
TAAM	Tactical Anti-Airfield Missile
TAI	Total Aircraft Inventory
USAF	United States Air Force
USN	United States Navy

UXO	Unexploded Ordnance

1. Introduction

U.S. Bombers Face New Challenges from Ballistic and Surface-to-Air Missiles

U.S. Air Force bombers have operated in generally uncontested airspace in the vast majority of conflicts over the last 20 years. However, the increasing prevalence of ballistic missiles and surface-to-air missiles (SAMs) throughout the world imposes greater threats to the bomber fleet. Ballistic missiles threaten theater airbases and discourage close-in basing for aircraft. SAMs limit U.S. access to enemy airspace directly overhead and therefore restrict access to traditional overflight bombing. In a scenario where the airspace is highly contested, bombers will likely need sufficient air support, such as large numbers of escorting fighters and support aircraft equipped with radar-jamming equipment, to perform missions and may still be operating at high risk.

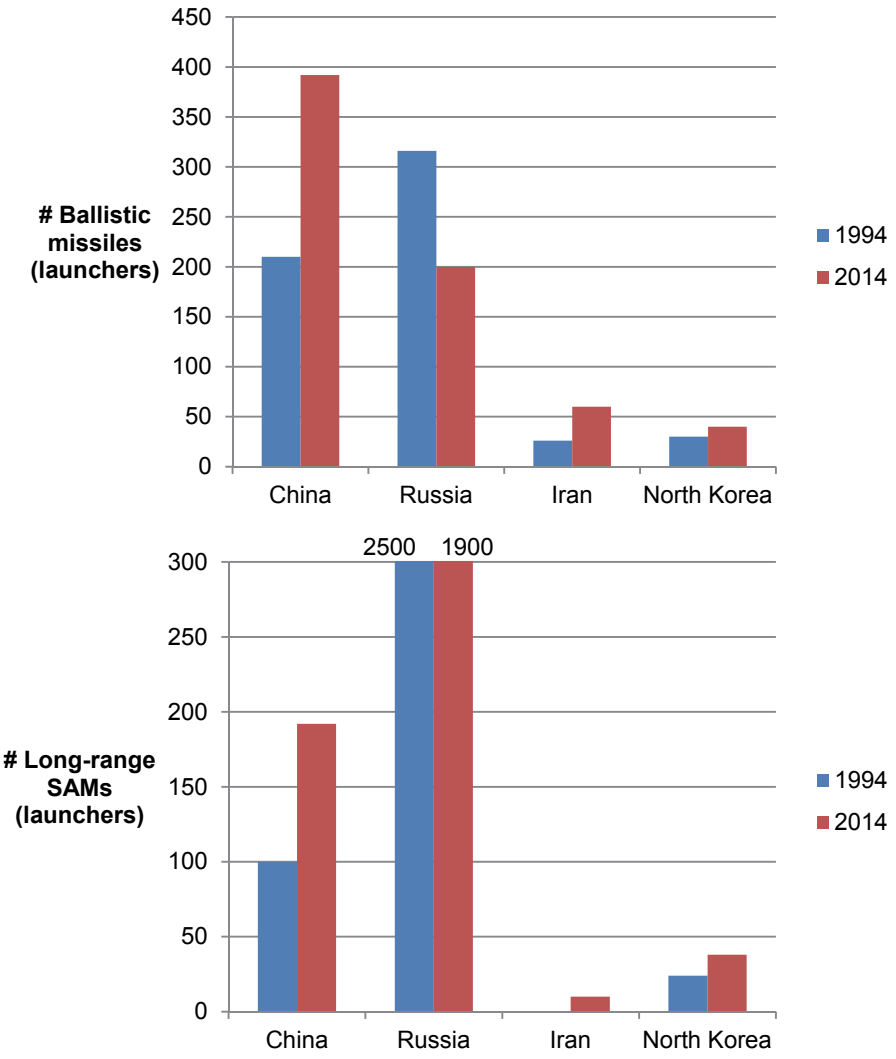
Many potential U.S. adversaries possess or are in the process of acquiring these so-called advanced anti-access/area denial (A2/AD) defense systems, defined in the U.S. Department of Defense (DoD) 2010 Quadrennial Defense Review as weapon systems that "seek to deny outside countries the ability to project power into a region, thereby allowing aggression or other destabilizing actions to be conducted by the anti-access power."[9]

The number of ballistic missiles in certain threat countries has increased over the last 20 years as shown in the top plot of Figure 1.1. Increasing numbers of SAMs are shown on the bottom plot over the same time period. [10] The increased amounts of these systems indicate an increased level of A2/AD threat capability. Ballistic missiles are a means for an enemy to threaten close-in U.S. airbases, which contributes to A2 capability. SAMs are a tool that can be used by an adversary to threaten non-stealthy platforms and thereby prevent normal air operations in a region, which contributes to AD capability.

[9] Krepinevich further explains the A2/AD concept, "If anti-access (A2) strategies aim to prevent US forces entry into a theater of operations, then area-denial (AD) operations aim to prevent their freedom of action in the more narrow confines of the area under an enemy's direct control. AD operations thus include actions by an adversary in the air, on land, and on and under the sea to contest and prevent US joint operations within their defended battlespace." Andrew F. Krepinevich, Barry D. Watts, and Robert O. Work, *Meeting the Anti-Access and Area Denial Challenge,* ed., Center for Strategic and Budgetary Assessments, 2003.

[10] Not included in these plots are inventories for long-range cruise missiles. Cruise missiles are self-propelled, guided bombs that fly at a level trajectory to a target. These weapons also pose a threat to U.S. bases due to their long range.

Figure 1.1. Increasing Numbers of SAMs and Ballistic Missiles from 1999-2013 in Potential Threat Countries[11]



China, North Korea, Russia, and Iran Pose Threats to the United States

Four nations are identified in Figure 1.1 as having A2/AD capabilities, namely China, North Korea, Russia, and Iran. However, the increase or sustainment of capability alone is not enough to justify a U.S. change in force structure. Capability is only half of the equation. As it stands, there are many more nations than these selected four that possess capability that would make

[11] Long-range SAMs are defined here as air defense systems with a maximum range greater than 50 km. Ballistic missile number excludes ICBMs and FROGs (Free Rocket Over Ground). Large decreases in Russian inventories for ballistic missiles and SAMs are caused by the retirement of Scud missiles and the SA-5. Data was gathered from: "The Military Balance," no. 113:1, 2013.

conventional bombing difficult in a conflict. The likelihood of a nation to become an adversary is another important aspect of threat considerations. Some commentary must be made here on the strategic intent of these four nations. In describing the global strategic environment, the National Military Strategy of the United States of America published by the Joint Chiefs of Staff explicitly mentions these four nations as critical actors that are threatening U.S. national security interests.[12] It is important to consider each nation's strategic interests to determine what might motivate them to use military force and prompt a U.S. response.

China is perhaps the most economically able to exercise hegemonic influence and contend militarily with the United States. As prominently as China is portrayed in the Pacific theater, Chinese strategic goals are somewhat unclear. In fact, the government has yet to officially release a document that expounds their strategic goals and the means to reach them.[13] There have been recent actions taken by the Chinese government that have put increasing pressure in the Asia-Pacific region. Land reclamation efforts and involvement in the South China Sea have been somewhat aggressive and indicate that China is seeking to advance regional interests. The wave of nationalism that has influenced leaders motivates the idea of resolving these territorial disputes by force if necessary. In the long term, the aspiration would be to render regional powers submissive and dependent on China. Although the possibility of pursuing this strategy is unclear, Chinese actions as of late have been somewhat alarming, including disputes at the Sino-Indian border, Spratly and Paracel islands, and confrontations with U.S. ships in China's exclusive economic zone.[14] Opposition from the international community has increased tensions and Chinese aggression. In terms of opposing Western influence, there is not a large likelihood of direct confrontation seeing that the U.S. is China's leading trade partner and a disturbance of that balance could hurt the Chinese economy more than help it. There is far more likelihood of proxy conflicts that could lead to escalated conflict with the U.S. and China.

The geopolitical environment poses several potential venues where a conflict may arise between the United States and China. Some of these potential conflicts include: conflict between China and South Korea following a collapse of the North Korean regime, an escalation of the tensions between China and Taiwan, a dispute between China and Vietnam over natural resources in the South China Sea, and a border dispute between China and India.[15] Of these postulated conflicts, a scenario in the Taiwan Strait where China forces reunification of Taiwan continues to be the primary driver of Chinese military investment.[16]

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[12] *National Military Strategy of the United States of America*: Joint Chiefs of Staff, 2015.

[13] Wang Jisi, "China's search for a grand strategy," *Foreign Affairs,* Vol. 90, no. 2, 2011.

[14] Jeff M. Smith, "Beware China's Grand Strategy," *Foreign Affairs,* Vol. 94, no. 3, 2015.

[15] James Dobbins et al., *Conflict with China: Prospects, Consequences, and Strategies for Deterrence*, Santa Monica, CA: RAND Corporation, 2011.

[16] *Annual Report to Congress: Military and Security Developments Involving the People's Republic of China 2014*: Office of the Secretary of Defense, 2015.

North Korea poses considerable challenges to U.S. national security. There are three primary reasons for the criticality of the North Korea regime to the United States.[17] First, one of its core national objectives is to reunify the Korean peninsula under control of the North. Although this may be infeasible in the near future, it is a primary motivator for North Korea force development. This is a key point of contention due to the U.S. involvement in South Korean national security. Second, North Korea has been actively pursuing both nuclear weapon and intercontinental ballistic missile (ICBM) capability. Aside from pure military advantage, these capabilities would offer North Korea a bargaining chip with the United States, a deterrent, and a tool for domestic propaganda.[18] Third, the proliferation of nuclear weapons is a grave concern. North Korea proved to be willing to proliferate its nuclear technology when it provided Libya with uranium.[19] Plagued by a crippled quality of life for the general populace, the need for money may be a contributor as to why North Korea would seek proliferation.

Russia is focused on three primary goals in terms of its foreign policy and strategic interests: increasing prestige, supporting economic growth, and demonstrating power to pursue policy.[20] History seems to be a primary motivator for these priorities among Russian leaders. The collapse of the Soviet Union in 1991 not only weakened the economy, but caused Russia to be portrayed as dependent on the West after an era of being in fierce economic, military, and political competition with the West. Fueled by economic growth since the collapse, Russia has again sought to oppose pro-Western governments. One particular avenue to greater prestige lies in Russia's post-soviet neighbors. Russia has proven that it is committed to retaining influence over neighboring countries that were formerly a part of the Soviet Union, for if these countries drift from Russian influence, they will be perceived as doing so at Russia's expense.[21] One particular case of this is Ukraine, which is becoming increasingly disposed to the West. Russia has used direct and proxy force to seize Crimea and intervene in Ukraine, indicating that Russia is willing to violate a number of agreements it has signed[22] in order to achieve its strategic interests.[23] While these developments are of great concern to U.S. decision makers, it would likely take a larger event for the United States to consider deploying forces or performing airstrikes in a conflict with Russia. Perhaps there is a more relative concern in Russian arms deals as it relates

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[17] *Annual Report to Congress: Military and Security Developments Involving the Democratic People's Republic of Korea*: Office of the Secretary of Defense, 2015.

[18] Jung-Chul Lee and Inwook Kim, "Making Sense of North Korea," *Foreign Affairs*, 2015.

[19] Annual Report to Congress: Military and Security Developments Involving the Democratic People's Republic of Korea.

[20] *Russian foreign policy: sources and implications,* ed., Santa Monica, CA, RAND Corporation, 2009.

[21] ed.

[22] These include the U.N. Charter, Helsinki Accords, Russia-NATO Founding Act, Budapest Memorandum, and the Intermediate-Range Nuclear Forces Treaty.

[23] National Military Strategy of the United States of America.

to A2/AD. Russia has been at the forefront of developing and selling highly advanced air defense systems. This is particularly disconcerting since Iran, China, and North Korea have each been beneficiaries of Russia's air defense systems exports.

The strategic environment in Iran has recently evolved quite rapidly. Iran's geopolitical power comes as a result of its large population and territory, along with abundant wealth in oil and natural gas. Considering itself the hegemonic power in the Gulf, Iran seeks to use its power to enhance not only regional but global stature.[24] However, much of Iran's economic and military efforts are spent on national security efforts with highly unstable neighbors.[25] Amidst the regional turmoil, Iran has been pursuing nuclear and missile delivery technologies contrary to U.N resolutions which has been met by strict sanctions.[26] In an effort to remove these sanctions in return for a reduced nuclear program, Iran made a deal with the P5+1[27] on July 15, 2015. This deal involves reduced uranium stockpiles, reduced numbers of centrifuges, reduced capability for plutonium, and increased inspection activities from the International Atomic Energy Agency (IAEA). Once the required drawdowns are completed, the time it would take Iran to create nuclear weapons will increase from two or three months to one year.[28] And if Iran failed to comply with the terms of the deal or misled IAEA inspectors, the breakout time for achieving nuclear weapons would be reduced. If Iran did decide to breakout, Israel will likely push for airstrikes against nuclear facilities. With Russia's pending delivery of S-300 air defense systems to Iran in 2016, U.S. air strikes would be very difficult and may need to use standoff capability.[29]

If the United States is to be involved in a conflict with any of the nations aforementioned, it would need to rely on capabilities that have long range and are survivable in an A2/AD environment. The United States could maintain technological and geographic advantage through more survivable platforms or platforms that can attack from outside air defense threat ranges. Forward basing will need some operational resilience to deny or degrade enemy ballistic missiles; otherwise the aircraft would need to be based farther away to avoid this risk.

In a major conflict with these threats, there will be a high premium on destroying certain targets early in the conflict. The ability of bombers to operate in A2/AD is a significant consideration with respect to the joint operations that would make the destruction of those targets

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[24] Thomas Juneau, "Iran under Rouhani: Still Alone in the World," *Middle East Policy,* Vol. 21, no. 4, , 2014. Mohammad Javad Zarif, "What Iran Really Wants," *Foreign Affairs,* Vol. 93, no. 3, 2014.

[25] Kayhan Barzegar, "Iran's Foreign Policy Strategy after Saddam," *Washington Quarterly,* Vol. 33, no. 1, , 2009/2010.

[26] National Military Strategy of the United States of America.

[27] The P5+1 is a group of six world powers and includes the United States, China, France, Russia, the United Kingdom, and Germany. In addition to the P5+1, the European Union also participated in the diplomatic efforts of the Iran nuclear deal.

[28] "The Historic Deal that Will Prevent Iran from Acquiring a Nuclear Weapon," (The White House).

[29] Ilya Arkhipov, "Russia Plans to Send S-300 Missile Systems for Iran by 2016," in *Bloomberg*.

possible. A U.S. first strike using cruise missiles to "knock down the door" of enemy A2/AD capabilities could be beneficial for the operations of the other U.S. military assets.[30] The U.S. Army's ability to use airlift in theater would be greatly hindered if sufficient enemy air defense assets are not suppressed or destroyed. U.S. attacks on Chinese ports may also provide sufficient freedom of navigation to the U.S. Navy in such an environment. Although it is true that these services have certain capabilities that would allow them to attack these assets themselves, the strategic import of Air Force bombers offers high flexibility and responsiveness as a critical instrument to degrade adversarial A2/AD capabilities.

Shifts in U.S. strategy have prioritized China and North Korea in national security discussions. At the end of 2011, the Obama Administration announced a rebalancing of U.S. priorities toward the Asia-Pacific region. This rebalancing has placed a higher emphasis on the region in regard to military planning.[31] Not least in this planning is the need to mitigate the increased risk to U.S. bombers. The research described in this dissertation explores options for doing so.

Mitigating the Threat to U.S. Bombers

As ballistic missiles and long-range SAMs are proliferated, the bomber force will need to adapt to continue to operate in an A2/AD environment. There are at least three primary strategies to mitigate the A2/AD threats to U.S. bombers:

1. Locate U.S. aircraft at bases outside of ballistic missile range to thwart enemy air defenses. Other basing options could also be employed such as hardened parking structures, better air defense of bases, decoys and deception, etc.
2. Employ stealthy penetrating bombers to enable operations against advanced enemy air defenses. There currently is a small force of 16 combat-coded stealthy B-2 bombers. The Air Force is in the process of developing a new penetrating bomber, but it will not be operational until around 2030.
3. Employ standoff bombers with long-range cruise missiles to defeat advanced enemy air defenses. The U.S. Air Force currently has 96 combat-coded bombers capable of carrying long-range cruise missiles. Additional standoff capacity could be provided by acquiring arsenal aircraft.

While it would be interesting to compare the utility of each of these strategies in mitigating threats to the bomber fleet, this study addresses the third strategy. In particular, this study focuses on the policy option of acquiring arsenal aircraft to provide sufficient standoff capacity in high demand scenarios.

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[30] Krepinevich, Watts, and Work, ed.

[31] Michael A. Miller, *U.S. Air Force Bomber Sustainment and Modernization: Background and Issues for Congress*: Congressional Research Service, April 23, 2013.

Studies have shown that there are significant increases in bomber survivability either by making them stealthier or having longer standoff ranges;[32] i.e., increasing the distance from which they can strike. However, with increasing air defense capabilities, current stealthy platforms may be forced to operate in a standoff role. In a recent report to the U.S. Congress, USAF Colonel Michael Miller assessed each of the existing bombers and found that the mission effectiveness of each bomber is eroded in the face of AD threats. In particular, the report stated, "For the first time since the B-2 aircraft became fully operational capable, the weapon system's survivability is in question in the face of advancing twenty-first century A2/AD threats."[33] Even the effectiveness of bombers with modernization upgrades is uncertain in AD environments, which may lead to the necessity of intermediate technology and strategy for structuring the bomber fleet. The report also suggests that the actual procurement of long-range strike bombers may not reach the planned procurement of 80-100 aircraft, and the anticipated initial operating capability date around 2030 may be delayed. Historical trends indicate that this may be the case, and if so, the projected bomber fleet may suffer further risk in AD scenarios. It is therefore questionable as to whether or not the aging fleet can operate effectively in this threat environment until the LRS-B becomes operational and even then, whether or not stealth in the future will effectively penetrate enemy territory. Upgrades to the bomber fleet will be necessary in the interim to maintain their suitability in potential AD conflicts. Even with upgrades, the current bombers may be required to operate in a standoff role.

There are obvious shortfalls when investing primarily in standoff capability. A preferred approach would be to ensure a balance between penetrating and standoff assets. A study conducted by the Congressional Budget Office in 2006 compared a variety of alternatives to long-range strike. These alternatives included multiple stealthy bomber variants, unmanned aerial vehicles, and an arsenal aircraft such as a C-17 with long-range cruise missiles.[34] One particular stealthy bomber alternative was subsonic and similar in concept to the LRS-B planned to enter the bomber fleet in the 2030 timeframe. Comparisons between the arsenal concept and the long-range subsonic bomber concept in that study are relevant to comparisons between the broader set of standoff bomber concepts to be analyzed in this dissertation and the LRS-B. The alternatives in that study were compared using several metrics which were: reach, responsiveness, firepower, payload flexibility, and survivability. Of particular interest is the degree to which the arsenal plane can attack targets in enemy territory. As a standoff bomber, the arsenal aircraft would not be able to reach deep into larger countries, whereas the longer range stealth bombers could strike anywhere in the territory provided that the enemy does not possess

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[32] Glenn Buchan and David R. Frelinger, "Providing an Effective Bomber Force for the Future," 1994.

[33] Miller.

[34] Robie Samanta Roy and David Arthur, *Alternatives for Long-Range Ground Attack Systems*: U.S. Congressional Budget Office, March 2006.

air defenses advanced enough to engage stealthy aircraft. Assuming the standoff bomber would use a cruise missile with a range of 500 nautical miles, a bomber would be able to threaten any point within 75 percent of the world's countries.[35] This analysis did not distinguish countries who may be potential adversaries, but the geography and air defenses of Iran and China would prevent total coverage and are of particular interest as potential adversaries.

It is important to consider not only the risk to the bomber, but also the operational risk to all air assets involved. In particular, the targeting information required for a large salvo of cruise missiles could be quite a burden on support aircraft. Using standoff bombers to launch a first strike may be limited by targeting assets, either in the number of cruise missiles that can be fired or the distance that the cruise missiles can penetrate. Campaign analyses conducted in the 1990s confirmed the idea that the driving factor of efficiency in different campaign scenarios was not the size and composition of the bomber fleet, but rather the availability, timeliness, and accuracy of information required by the bombers munitions.[36] The information needed for this type of attack will likely impose a cost on information assets in the campaign.

Policy makers face near-term and far-term challenges regarding the bomber fleet. The consideration of these challenges is critical to determining what action should be taken and when. In the near term, a potential capacity gap exists before the LRS-B becomes operational. As non-stealthy platforms, both the B-1 and B-52 will have limited ability to penetrate into contested airspace with advanced air defense threats. The B-2 has stealth capability, but if the enemy has advanced air defenses the B-2s may not be able to penetrate enemy airspace. The Air Force is investing in a new stealth bomber, the LRS-B, which is projected to have initial operational capability (IOC) in the 2030 timeframe. If the LRS-B is assumed to fill the capability gaps present with regard to AD threats (an assumption which may not be valid depending on how advanced enemy air defenses evolve by the time LRS-B is operational), then there exists a potential shortfall in the U.S. bomber fleet until the LRS-B reaches IOC. Increasing standoff bombing capacity is a viable option for policy makers to mitigate risk in A2/AD scenarios. There may be a need to acquire additional standoff bombers to supplement the current bomber fleet during times when the demand for cruise missile strikes exceeds the supply of firepower available in the near term.[37]

The far-term challenge for policy makers involves the age of the bomber fleet. The current portfolio of U.S. bombers includes the B-2, B-1, and B-52 which are about 21, 27, and 53 years old respectively. The Air Force has decided to extend the life of the B-1 and B-52 to 2040. At that point, Air Force leaders have planned to use the LRS-B as the sole long-range strike aircraft.

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[35] _____.

[36] Barry D. Watts, *Long-Range Strike: Imperatives, Urgency and Options,* ed., Center for Strategic and Budgetary Assessments, 2005.

[37] The term "firepower" is used in this dissertation to describe the rate at which weapons can be fired.

However, like many military acquisition programs, the LRS-B faces potential risk. The number of LRS-B aircraft to be produced may not reach the number we expect this early in the development stage. In addition, necking down to the LRS-B as the only bomber type in the fleet faces risk if advances in enemy air defenses negate its postulated penetration capabilities. The stealth technology on the LRS-B is likely to be more advanced than that of any other aircraft. However, if threat air defense technology evolves to being able to defeat stealth, feasibly striking targets with the LRS-B might require the use of long-range standoff missiles. In that case, the LRS-B would end up being an extremely expensive standoff bomber. The far-term bomber force structure should be shaped by these kinds of considerations.

Research Questions and Scope

This dissertation provides insight into how to mitigate the increased risks to U.S. bombers with a specific focus on the strategy of employing standoff bombers with long-range cruise missiles to defeat advanced enemy air defenses. Understanding the relative tradeoffs among standoff bombing alternatives will be important for policy makers considering the age and potential capacity gaps of the current bombers. Especially in an increasingly constrained budget environment, there would be major implications if standoff bombing alternatives are found to be a more cost-effective way of spending limited defense funds. The following research questions were addressed in this study:

1. What is the potential demand for standoff bombing capability in the new A2/AD threat environment?
2. How effective are standoff alternatives in terms of launching cruise missiles?
3. What will it cost to acquire and maintain standoff alternatives?
4. Of the bomber alternatives considered in this study, which are the most cost effective?

This research was a quantitative analysis that compared 10 different bomber alternatives in terms of their ability to function in a standoff role by launching cruise missiles in the required numbers and required distances in the A2/AD threat environment. The alternatives were analyzed in terms of their costs and their ability to meet the demand for bomber capacity in four potential wartime situations: halting an army, halting an amphibious invasion, preventing enemy air operations by attacking runways, and attacking time-critical fixed targets.

The study answers the proposed research questions using quantitative data from a variety of sources. Cost and effectiveness of standoff alternatives were compared using demand-based and capabilities-based analyses. The first stage of this effort addressed the first research question; it determined whether or not this added capability is necessary and sufficient in a variety of potential A2/AD threat scenarios that are particularly stressing for the current fleet. A suite of models were used to conduct exploratory analyses to determine the demand for standoff capability. The second stage addressed the second research question; it measured the effectiveness of the alternatives to deliver long-range standoff weapons (i.e., to launch cruise

missiles). Engineering analysis and a sortie rate model were used to determine effectiveness. The third stage captured the acquisition and sustainment costs for the aircraft systems being considered, and did so using cost analogies and multivariate regression analysis. Lastly, the cost-effectiveness of each alternative was analyzed over a variety of policy options with a fixed-effectiveness approach.

Overall Methodology of this Report Accounts for Uncertainty in Defense Planning

Military conflicts are comprised of complex interactions. Human beings and organizations involved in military conflict think and act differently at the strategic, operational, and tactical level. Through a scientific lens, these conflicts have been termed "complex adaptive systems."[38] As a result, the uncertainty associated with addressing the spectrum of potential military conflict is both large and persistent. This dissertation performs policy analysis to address these high level uncertainties

Historically, many approaches to dealing with uncertainty in policy analysis have been to simply ignore it. In some cases, ignoring uncertainty may be a viable approach to a policy problem. However, there a few guiding principles that suggest when uncertainty needs to be considered in an analysis. The first is that uncertainty should be considered when the target audience displays some propensity toward accepting or averting risk. The second guideline is that if an analysis requires the combination of uncertain information from a variety of sources, uncertainty should be address. The last is that we need to worry about uncertainty when a policy maker must decide whether or not to invest resources to acquire new things.[39]

If uncertainty needs to be addressed, how do we deal with it? One common idea used in describing an approach to dealing with uncertainty is to develop solutions that are **f**lexible for taking on different scenarios, **a**daptive to unanticipated circumstances, and **r**obust to shocks and surprises (FAR).[40] To reach solutions that are flexible, adaptive, and robust, we must broaden the analytic lens and account for a variety of different contingencies while addressing variation in the assumptions used in the analysis. This high level of breadth needed for an analysis using a large number of exogenous and endogenous parameters requires a methodology that can examine the uncertainty in a scenario. The "exploratory analysis" concept lends itself to such an examination.

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[38] Paul K. Davis, "Uncertainty-Sensitive Planning," in *New challenges, new tools for defense decisionmaking*, ed. Stuart E. Johnson, et al. (Santa Monica, CA: RAND Corporation, 2003).

[39] M. Granger Morgan, Max Henrion, and Mitchell Small, *Uncertainty: a guide to dealing with uncertainty in quantitative risk and policy analysis,* ed., Cambridge, New York, Cambridge University Press, 1990.

[40] Paul K. Davis, *Lessons from RAND's work on planning under uncertainty for national security,* ed., Santa Monica, CA, RAND Corporation, 2012.

Exploratory analysis is defined as the study of how a modeled outcome changes as all of the input variables are allowed to change simultaneously. Using this kind of analysis allows a high-level view of the outcomes for the entire space of possible inputs.[41] The concept of exploratory analysis expands upon sensitivity analysis. Sensitivity analysis generally alters one variable at a time and measures how the output changes on the margin. There are several benefits to using an exploratory analysis approach. First, there is greater flexibility of decision-making. With a large amount of trade space, decision makers are left with more options. Second, the robustness of the solution is increased. Third, there is less inherent risk due to the large amount of potential outcomes analyzed. And fourth, the model becomes more transparent and the user is able to understand the relationships between variables at a higher level.[42]

The purpose of this demand and effectiveness analysis was twofold: to understand high level tradeoffs in A2/AD scenarios and to determine an appropriate force structure of arsenal aircraft. Through exploratory analysis, the target sets can be seen at a higher level and led to insights regarding the interaction of variables. Through cost-effectiveness analysis, options for a robust force structure can be identified. Doing so would inform the discussion of whether or not arsenal aircraft are necessary and how many might be needed to supplement the current force.

The methods used in this dissertation are largely exploratory in the case of demand analysis. A diversity of models and tools were used, which allow for an appropriate breadth of results. At the end of the exploratory demand analysis, a theater level demand is constructed which allows for a cost-effectiveness approach to determine the least costing option at the given performance level. Ideally, several demand scenarios would be constructed to allow for flexibility of the proposed solution. However, detailed scenario construction was outside of the scope of this study. The methodology that was used to address each question is described briefly below and in detail within each chapter.

Organization of the Report

This report is organized to address the research questions in order, as follows. Each chapter restates the question at hand, provides additional context and background material about the question, and describes the methodology used to address the questions, findings of the analyses, and policy implications based on findings.

Chapter 2 - *What is the potential demand for standoff bombing capability in the new A2/AD threat environment?*

A literature review was conducted to identify technical characteristics for a variety of campaign scenarios. Since China is currently poised to be the most threatening potential U.S. adversary

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[41] ———, *Analysis to inform defense planning despite austerity,* ed., Santa Monica, CA, RAND Corporation, 2014.

[42] Arthur C. Brooks, Steven C. Bankes, and Bart Bennett, *Weapon mix and exploratory analysis: a case study,* ed., Santa Monica, CA, RAND Corporation, 1997.

with AD capabilities, several of the scenarios were drawn from potential conflicts with China. Previous RAND efforts have attempted to characterize scenario force requirements in A2 environments.[43] This dissertation builds on previous research by using a suite of exploratory models that analyze AD construct parametrically.

Chapter 3 *- How effective are standoff alternatives in terms of launching cruise missiles?*
To determine effectiveness, quantitative modeling was applied to each of the aircraft that offer a standoff alternative. Specifically, a sortie rate model was developed in concert with a constraint analysis to find the capacity of each alternative to carry long-range weapons and the rate at which they can fire them over the duration of a campaign. Once these metrics were calculated, they were compared to the previously determined scenario demands.

Chapter 4 *- What will it cost to acquire and maintain standoff alternatives?*
Multivariate regression analysis was used to estimate operating and support costs, and log-log linear regression and case study techniques were used to estimate the cost of acquisition. Together, these analyses yielded a cost model that predicts the average present value life cycle cost of each aircraft alternative.

Chapter 5 *- Of the bomber alternatives considered in this study, which are the most cost effective?*
Using the developed cost model, quantitative analysis identified tradeoffs as well as sensitivities to certain assumptions. Qualitative tradeoffs, such as risk and feasibility of the alternatives, are discussed.

Chapter 6 *– Conclusions* -- Provides a discussion of the findings and of the policy implications for DOD and the Air Force.

[43] Paul K. Davis, Jimmie McEver, and Barry Wilson, *Measuring Interdiction Capabilities in the Presence of Anti-Access Strategies: Exploratory Analysis to Inform Adaptive Strategy for the Persian Gulf*, Santa Monica, CA: RAND Corporation, 2002.

2. What is the Potential Demand for Standoff Bombing Capability in the New A2/AD Threat Environment?

Overview

The fact that many more countries are acquiring ballistic missiles and SAMs suggests that the demand for U.S. standoff aircraft will grow. But nobody can accurately predict the nature of future conflicts, and it is difficult to predict exactly what the demand for standoff aircraft will be. There are endless factors that cause a high amount of uncertainty in such predictions. It is not just a matter of where or when a conflict will arise. Other important variables include what other nations will be involved, what geopolitical factors will be at play, and what known and unknown advances the enemy will make. This high level of uncertainty motivates defense planning to strive for robustness. Robust plans require a minimal amount of adjustment no matter what happens in actual conflict; they have the best worst-case value over all scenarios. Planners must allow for a wide variety of conflict scenarios and ensure that the United States is able to respond effectively no matter what is required. Standoff aircraft with the ability to fire cruise missiles play a role in this type of planning.

This chapter addresses the issue of how much standoff bombing capacity is needed in a variety of target scenarios for an A2/AD conflict. Along with analyzing target demands, this chapter identified the standoff bombing gap between what the current bomber fleet can provide and what potential future conflicts will demand. The chapter is divided into the following sections; included here are the top-level research findings for each target set.

- **Halting an army:** The utility of using air assets against a large land invasion comes from the slowing capability of air to ground strikes used in support of friendly ground forces and other assets. Together, the combination of air and ground combat forces can more easily halt an army. Significant advances need to be made in cruise missile ability to find targets and in intelligence, surveillance, and reconnaissance (ISR) ability to communicate with the cruise missile to provide updates on target location. Without these advances, procuring arsenal aircraft will not provide much utility in this target scenario.
- **Halting an amphibious invasion:** An amphibious halt is a stressing scenario because of the short window of opportunity to strike amphibious ships, particularly in the Taiwan Strait. If the adversary employs confusion tactics such as interspersing decoys in each assault formation, the number of cruise missiles required increases significantly if the cruise missile cannot distinguish decoys from critical targets.
- **Striking time-critical fixed targets:** Fixed-target demand, along with all other target set demands in this chapter, is largely affected by U.S. cruise missile survivability. An adversary's advanced air defenses would cause a decrease in survivability, but U.S.

actions could counteract this negative effect. Missile swarming, terrain masking, stealth, and offensive electronic countermeasures could all contribute to making the missile attack more survivable.

- **Striking runways to prevent enemy air operations:** Attacking runways from which critical enemy aircraft operate would degrade the enemy's sortie rates. Degraded sortie rates would mean a slower pace of the adversary's air campaign, and would translate to more protection and air superiority for U.S. aircraft. The cruise missile demand is not terribly high, but runway repair capability makes this target set a recurring demand through the scenario. The demand could be reduced by having greater intelligence of the locations of critical enemy aircraft.
- **Theater-level demand:** War-time theater-level demands are the driving factor for determining force structure. A daily demand is constructed, combining all target sets except halting an army. Under best case assumptions, the current bomber standoff capacity is capable of handling the demand for cruise missiles. Worst case assumptions cause the demand to exceed bomber capacity, and under these assumptions it would be a viable option to acquire arsenal aircraft to fill the shortfall.

Conditions that Necessitate the Acquisition of Arsenal Aircraft

Arsenal aircraft may be a desired solution for a potential standoff bombing capability shortfall if three conditions are met: (1) the targets are compatible with long-range missile attacks; (2) the threat environment is such that bombers will need to operate from standoff positions; and (3) the time criticality and number of targets are both high.

(1) Targets are Compatible with Long-Range Missile Attacks

The first condition that would call for standoff bombers is that targets are compatible with long-range missile attacks. There are several types of targets that may limit the effectiveness of cruise missiles, such as mobile targets, hardened or deeply buried targets, or targets that are geographically dispersed.[44] Long-range cruise missiles typically strike targets using Global Positioning System/Inertial Navigation System (GPS/INS) guidance. In order to strike a mobile target, the cruise missile would need to receive data link updates from C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance) assets regarding the target position or have sufficient capability to autonomously track the target. In a scenario with sufficient AD, airborne C4ISR assets may not be able to get within range to track the target and provide the necessary updates, which limits a cruise missile's ability to strike mobile targets such as enemy ground forces or mobile SAMs. Space-based ISR could potentially make mobile targets more feasible. Hardened or deeply buried targets such as bunkers or shelters

[44] Buchan and Frelinger.

would require a penetrating unitary warhead. Currently, all cruise missiles are equipped with unitary munitions. The magnitude of the blast may not be sufficient for certain target types. Targets like armored vehicles or trucks are generally geographically dispersed and therefore reduce cruise missile efficiency if unitary munitions are used. If standoff capability is highly desired, it may be necessary to fit cruise missile payloads with submunitions to expand the realm of cruise missile targets sets (i.e., to use "area weapons").[45]

(2) Bombers Need to Operate from Standoff Positions

If the United States achieves air supremacy at the outset of a campaign, the sheer number of U.S. aircraft that have overflight will likely be able to satisfy any air-to-surface mission demand. However, if an adversary's AD capability is able to push U.S. aircraft back to operate at a standoff distance, the firepower from air assets is reduced considerably. Standoff effectiveness is degraded by the limited number of aircraft that can carry long-range munitions, the payload differences between carrying bombs versus carrying cruise missiles, and the weapon effectiveness of overflight bombs versus cruise missiles. These factors each contribute to the difficulty of long-range munitions fulfilling large numbers of air-to-surface strike requirements.

(3) Time Criticality and Number of Targets are High

The third condition to justify the procurement of additional standoff bombing firepower relies on variables that are dictated by the threat characteristics. If an adversary is a small country and does not have many targets, there should be no reason that the current U.S. force structure couldn't handle the target demand. If a larger country becomes adversarial, the high amount of targets could be offset by low time criticality. The United States could handle the demand up to a certain number of strikes per day and in this case would be limited only by weapon supply, not by the rate of weapon launches. If the scenario becomes time critical, though, and a high number of targets needs to be prosecuted in a short amount of time, the rate of strikes required could exceed the maximum rate available provided by existing U.S. forces. In a case like this, arsenal aircraft could have a niche role for providing additional firepower.

Potential Missions for Arsenal Aircraft

Bombers operating from a standoff position may not be effective performing all air-to-surface missions necessary for a successful campaign given the current cruise missile capabilities. Missions such as suppression of enemy air defenses (SEAD) and attacking hard or deeply buried targets would present challenges if long-range standoff weapons were used exclusively. However, there are target sets where standoff attacks would be effective and perhaps even preferred over using stealthy penetrating platforms.

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[45] Submunitions are smaller weapons that are carried as a warhead on a larger weapon. When the larger weapon approaches an aim point, the submunitions are released to attack multiple targets.

Table 2.1 displays typical target types for long-range missile attacks. Fixed targets are ideal for a long-range missile. These kinds of targets are generally preplanned well in advance, and the missile can autonomously fly and attack the programmed target. Cruise missile penetration capability may be limited by enemy air defenses. If 5th generation fighters are being used for SEAD, the air defenses may be more reluctant to expose themselves while firing at the cruise missiles. U.S. cruise missiles could also be programmed to seek air defense radars should they decide to defend against a U.S. cruise missile attack. Regardless of the penetration capability, today's cruise missiles have sufficient endgame accuracy to arrive within close proximity of fixed targets. Mobile targets are much more complicated. Current Air Force cruise missiles fly autonomously using GPS or INS guidance, giving mobile targets an opportunity to escape the targeted location. It is therefore questionable as to whether current cruise missiles could provide enough utility to a mission such as halting an invading army. Long-range attacks against amphibious targets would be much more feasible. For instance, an infrared seeker on an anti-ship cruise missile allows endgame target tracking and greatly enhances the missile effectiveness. In all cases other than generic fixed targets, new cruise missile capabilities would need to be developed in order to make the mission more feasible for standoff attacks.

The nature of the target set with regard to scenario timing is also important to consider. During a war, targets with more immediate utility are generally attacked first. Attacking fixed targets such as infrastructure or leadership compounds may not be time critical to decision makers since the effects are not as immediate or apparent. It could be argued that these targets should be of less priority than targets that directly affect an enemy's combat capability. However, there would likely be a proportion of fixed targets that are time critical and would need to be attacked immediately. These types of time critical fixed targets are included in this analysis. Attacking runways may or may not be vulnerable to such arguments, as there may be a possibility for short-term military utility in destroying these targets. For example, attacking an airfield to either destroy planes or close runways would have a direct effect on an enemy's sortie rates, which could benefit U.S. forces. Mobile targets seem to be the most time critical in nature. An invasion, either on land or on sea, is an immediate threat. With U.S. troops in contact with enemy units, it would be critical to halt the enemy's advance as soon as possible.

Table 2.1. Examples of Target Sets for Air-to-Ground Missions

Target type	Example	Feasible for existing cruise missiles?	Time critical?	Objective
Mobile targets	Halting an army	Needs anti-armor sub-munitions	Yes	Halt invading army in X km
	Halting an amphibious invasion	Needs anti-ship seeker and warhead	Yes	Destroy 50% of invasion fleet
Runways	Attacking runways daily	Needs counter-runway submunitions	?	Keep runways closed

Other time-critical fixed targets	Oil refineries, power plants, command posts, bunkers, bridges, soft targets	Yes	Yes	Destroy with 80% probability

The following discussion is focused on target sets. Although there is a connection in some cases to real world threats, these target sets can be viewed generically and can apply to a number of potential threats. Parameters like number of targets, air defense capability, and timing of enemy advances are all dependent upon the type of threat that arises. This analysis used parameters pertaining to both the target and threat characteristics to explore the potential demand for long-range cruise missiles.

Demand for Standoff Bombers to Halt an Army

The first and perhaps most difficult of the target sets to be analyzed is an invading army. Air strikes from long-range munitions will serve as a means to slow the advance of the invading army and support friendly ground forces. For purposes of this analysis, the primary outcome was the distance that the invading army is able to travel before they are halted by the supporting air strikes. The invading army consists of a certain number of armored fighting vehicles (AFVs), which seems to be an acceptable metric of enemy force capability.[46] The invading army halts when a certain proportion of their AFVs are destroyed. The measure of halt distance in this analysis should be seen as more of a measure of capability rather than a measure of what actually will happen. Many factors such as concealment and irregular warfare could complicate the scenario and would be likely actions in a real world case. Although attrition is an important metric in defense planning, it should be viewed here as more descriptive than doctrinal.

To evaluate this target set, a family of three models was used to provide appropriate levels of detail. Each of the following models was integrated into a single working model using a visual software package called Analytica. Excel was used as a primary interface between Analytica models.

Multi-model Structure and Assumptions used to Analyze a Halt Scenario

Previous RAND analysis investigated the effects that anti-access strategies had on interdiction capabilities of U.S. forces. The specific interdiction case that was analyzed was a halt scenario viewed parametrically and analyzed using exploratory techniques. A complex closed-form model was previously developed at RAND using Analytica, which was called EXHALT-CF ("**ex**ploring the **halt** problem - **c**losed **f**orm"). The model calculates the distance and time it takes to halt an invading army as a function of several parameters, such as the number of blue aircraft, blue aircraft weapon effectiveness, the time it takes to accomplish SEAD missions, red and blue ground force sizes, and red maneuvering parameters like AFV spacing

[46] Davis, McEver, and Wilson.

and velocity.[47] In this report, the words "blue" and "red" are used in reference to friendly or enemy forces. We follow the general convention that blue refers to friendly forces and red refers to enemy forces.

Two primary halt strategies were modeled in the original EXHALT model. The first was a simple brute force method where AFVs are attacked by air-delivered munitions until the number of AFVs killed exceeded the break point for the invading army. This can be referred to as in-depth attrition, where there is no particular concern given as to where in the formation AFVs are targeted. The second strategy involves attacking the leading edge of the formation to achieve a slowing effect (an approach suggested by the late General Glenn Kent, USAF, retired, as part of a RAND project for the Air Force). Vehicles destroyed at the front of the formation effectively slow the enemy advance. If halt distance is the optimization variable, the leading edge strategy wins every time due to the benefit of slowing effects. This analysis altered the original model to add a variable that accounted for additional arsenal aircraft in the scenario. This required changing the underlying closed-form mathematical equations and by so doing eliminated the leading edge strategy from the model. The results shown in this analysis are for in-depth attrition only. It should be noted that although the absolute values of halt distance would change with respect to the strategy used, the relative effectiveness and the tradeoffs between different variables are likely to remain intact.

The original model did not satisfy the objectives of this analysis, so several adjustments were made. The original model adjusted weapon effectiveness purely parametrically, which provides interesting insight but may not be enough resolution to accurately depict the effects of arsenal aircraft in a scenario. In order to capture the effects of factors like submunitions, missile updates, and sortie rate degrades, a weapon model and sortie rate model were used to complement EXHALT-CF.

A stochastic weapon effectiveness model called PEM ("**P**GM **E**ffectiveness **M**odifier") was developed during previous RAND analysis.[48] The model was conveniently written in Analytica, making the integration of PEM and EXHALT-CF quite simple. PEM calculates the number of AFV kills per missile salvo and is a function of weapon characteristics (submunition footprint, descent time, time of last update, etc.), red maneuver pattern, terrain features and employment tactics. This model is largely parametric, and has been calibrated to higher resolution models. Specific data on weapon effectiveness has been gathered from a combination of high resolution models and Air Force field tests. PEM is a stochastic model, using probability distributions for variables such as time of arrival error.

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[47] A description of the model can be found in: Davis, McEver, and Wilson (2002).

[48] Paul K. Davis, James H. Bigelow, and Jimmie McEver, *Effects of Terrain, Maneuver Tactics, and C4ISR on the Effectiveness of Long-Range Precision Fires,* ed., RAND Corporation, 2000a.

Some changes were made to PEM to account for varying focuses of this analysis. The primary change to PEM was the expansion of the variable for time of last update. If, for instance, the munitions have a time of last update of zero, the cruise missile gets updates on the target location until it reaches the target. When dealing with A2/AD capabilities, the time of last update could be substantial. A launch platform operating at a standoff range will be limited in how close it can fly to the target due to threats from air defenses and enemy aircraft. The highly advanced SA-21 missile has a range of 216 nautical miles. Flying at high subsonic speeds, a cruise missile launched at that distance from a target may take roughly half an hour. Enemy aircraft would likely push the launch platform beyond the SA-21 range, and targets may be further inland. For this reason, the time of last update which previously ranged from zero to 20 minutes was expanded to range from zero to 60 minutes.

A sortie rate model was created to add resolution to the number, effectiveness, and type of aircraft involved in the scenario. This model is a function of flight time, turnaround time, weapon characteristics, and range/payload. The previously calculated range-payload and sortie rate plots were used as an input to this model. The model varies two key parameters: distance to theater and large aircraft turnaround time, as these are the primary variables of uncertainty. Aircraft speed and flight time may vary depending on atmospheric conditions, but will remain relatively constant. The distance to the theater was varied to account for a variety of enemy capabilities to threaten U.S. basing. Ballistic and cruise missiles are the primary instruments of A2, and depending on an adversary's possession of these systems bombers may have to be based further away from the target location. It is assumed that fighters would be based at half the distance to the fight due to their shorter ranges. This assumption may not hold in some cases. However, for the purposes of evaluating A2/AD threats this seems to be reasonable. Large aircraft turnaround time was also varied to account for limitations of capabilities at certain bases that affect reloading and refueling times.

A prescribed force structure was used in the analysis as a baseline. For this interdiction mission the following aircraft were utilized: B-1, B-52, F-15E, and an arsenal aircraft. The arsenal aircraft was arbitrarily assumed to be a Boeing 777F. Although the arsenal aircraft varied in how many were used in the scenario, the other three aircraft types used a fixed number of aircraft. Two-thirds of the primary mission aircraft inventory (PMAI) was used for this baseline number of aircraft, which can be seen in Table 2.2. This selected baseline force structure is speculative, supposing that in a large land invasion there would be numerous aircraft deployed for support. Adjusting the baseline number of aircraft is not likely to have a huge effect on the results of the exploratory analysis, especially if the relationship between halt distance and number of aircraft is linear. The absolute number of arsenal aircraft would vary as the baseline force structure changed. However, the analysis of this target set is more focused on the relative effect of arsenal aircraft rather than the specific number required. The weapons capacity for each aircraft varied depending on the range to the target. A generic cruise missile was used for the long-range attacks, and a CBU-105 was used in short-range attacks.

Table 2.2. Aircraft Used in Halt Analysis

Aircraft type	Number in scenario	Long-range weapon loadout[a]	Short-range weapon loadout[b]
B-1	24	24	30
B-52	30	12	16
F-15E	88	4	12
Arsenal Aircraft	Varies	67	0

[a] The JASSM loadout was used here for each aircraft. The B-52 will be able to carry 20 JASSMs following the 1760 Internal Weapons Bay Upgrade, which is currently scheduled to be complete in October 2017.[49]
[b] These short-range weapon loadouts are based on possible loadouts of CBU-105. However, the bombers can carry much more unguided munitions such as the unguided version of the sensor-fused weapon (SFW), the CBU-97. This analysis assumes guided munitions are used in attacking AFVs.

This analysis assumed that all aircraft to be used are already in theater. It is assumed that interdiction missions are conducted within a larger air campaign that includes an initial period of time where SEAD is performed. Before successful SEAD is accomplished, the interdiction aircraft are relegated to perform attacks from a standoff position. This models two important characteristics of long-range versus short-range attacks: differences in weapon carriage and differences in weapon effectiveness. Fewer long-range munitions can be carried per sortie, and long-range weapons have less effectiveness against mobile targets, both of which degrade the effectiveness of each aircraft per sortie. After SEAD is accomplished, the aircraft are able to perform missions using overflight bombing. One distinction to note is that arsenal aircraft are not used in the post-SEAD phase. It is important to consider that it could be feasible to configure the arsenal aircraft to carry types of short-range munitions. This decision hinges on the policy problem at hand. That is, whether we are trying to solve a short-term capability gap in the interim of LRS-B development, or a long-term replacement of the aging bomber fleet. The latter issue would be the catalyst for designing the arsenal aircraft to have payload flexibility.

Table 2.3 shows parameters of interest that were varied in this analysis. The spacing between AFVs is consistent with previous work that used 50 m and 100 m spacing between vehicles.[50] That study also used similar parameter values for the number of AFVs. The variation in spacing up to 400 m was used in the study that developed EXHALT-CF.[51]

[49] Gareth Jennings, "USAF begins testing of B-52 weapons upgrade," *IHS Jane's International Defence Review*, January 18, 2015.

[50] David A. Ochmanek et al., *To Find, and Not to Yield. How Advances in Information and Firepower can Transform Theater Warfare*, Santa Monica, CA: RAND Corporation, 1998.

[51] Davis, McEver, and Wilson.

Table 2.3. Model Parameters and Values Used[52]

Model parameter	Parametric variation
Number of arsenal aircraft	0 – 50, increments of 5
Number of AFVs to kill	1000 – 9000, increments of 2000
SEAD time (days)	1 – 9, increments of 2
AFV spacing (km)	0.05, 0.1, 0.2, 0.4
Time of last target update to missile (min)	0 – 60, increments of 10
Submunition type	ATACMS/BAT, SFW
Fraction of AFVs in formation packet	0.5 – 1, increments of 0.1
Enemy A2 capability	Permissive, contested, highly contested [a]

NOTE: By merging the three Analytica models, the number of parameters available to vary becomes quite extensive. Although many other parameters were investigated during the course of this analysis, these parameters are considered to be the most relevant.
[a] These indices essentially designate what the U.S. base posture would look like under three different levels of A2. The principle variable altered by these designations is the distance to target, which affects the sortie rates of the aircraft flying to and from the launch point. Specifically, "Permissive" = 1000 nautical miles, "Contested" = 2000 nautical miles, and "Highly contested" = 3000 nautical miles. The F-15E is assumed to be able to operate closer at half the bomber range.
ATACMS/BAT = Army Tactical Missile System/ Brilliant Antitank submunitions

Results

This analysis is purely exploratory and is meant to gather insights into the halt problem. Halting a land invasion may prove to be a difficult task depending on the assumptions of cruise missile capabilities. The utility of using air assets against a large land invasion comes from the slowing capability of air to ground strikes used in support of friendly ground forces and other assets. Together, the combination of air and ground combat forces can more easily halt an army. Previous RAND analysis asserts that long-range systems can rapidly attrit mechanized forces so long as these systems are equipped with appropriate munitions and supported by intelligence and battle management capabilities.[53] Recommendations in the analysis of this target set are made for

[52] This is an incomplete list of factors that could cause variation in the outcome of a halt scenario. For example, one omitted factor that is important and uncertain is the rate of enemy troop advancement. Although all sources of uncertainty could not be accounted for, this analysis does provide an exploratory view of the different measures of U.S. capability.

[53] Ochmanek et al.

improvements that would be required for long-range strikes of land forces to have more legitimate effectiveness in slowing enemy advances.

It is fitting here to discuss the options for submunitions to be used on cruise missiles. RAND analysis has addressed the effectiveness of submunitions over unitary warheads. The study stated, for example, that when attacking aircraft in the open, a missile with a 75 pound payload is about three times more effective using submunitions than using a unitary warhead.[54] This difference is caused by the benefit of the dispersal of submunitions versus the unitary blast. In this example, aircraft are much more vulnerable to second order effects such as blast or fragmentation if the munition is not a direct hit. Armored vehicles would require more penetrating munitions. It has been shown that submunitions like Skeet (hockey-puck shaped submunition used on BLU-108 system), infrared terminally guided submunitions (IRTGSM), and brilliant antitank (BAT) submunitions can be effective against armored vehicles.[55] Skeet submunitions remain an active member of Air Force munitions, being the primary component of the CBU-97/CBU-105 sensor-fused weapon (SFW). The more advanced BAT was chosen over the IRTGSM, but the integration of BAT into the Army Tactical Missile System (ATACMS) was eventually cancelled. Each of these submunitions could be a potential candidate for enhancing current cruise missiles.

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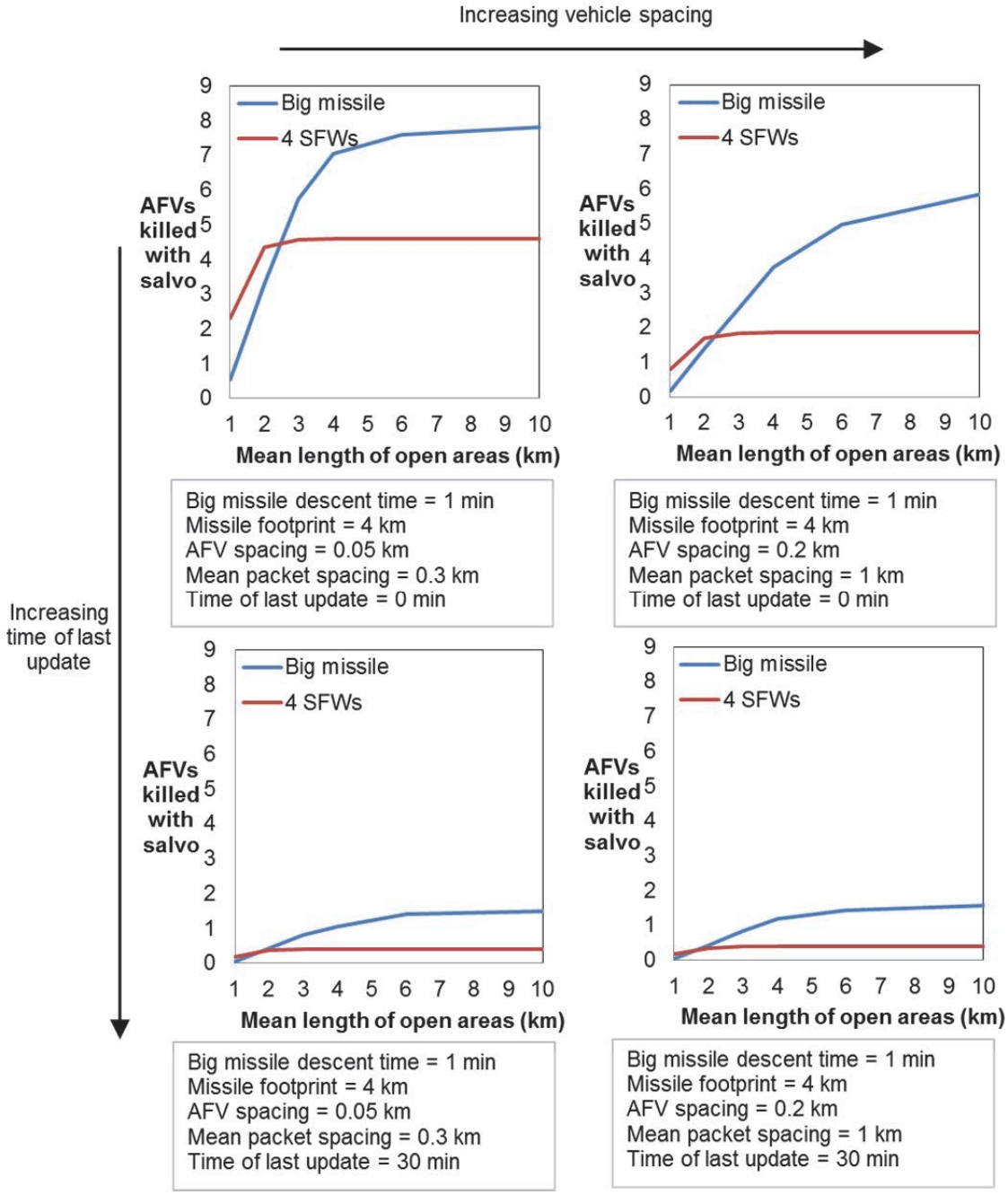
[54] John Stillion and David T. Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks,* ed., Santa Monica, CA, RAND Corporation, 1999.

[55] Glenn Buchan, Dave Frelinger, and Tom Herbert, "Use of Long-Range Bombers to Counter Armored Invasions," (Santa Monica, CA: RAND Corporation, 1992).; Davis, Bigelow, and McEver, ed.

Figure 2.1. Comparison of BAT and Skeet Effectiveness Varying Openness of Terrain, Vehicle Spacing, and Time of Last Update



NOTE: The labels for the weapon type use the term "Big Missile," which in PEM is synonymous to a missile like ATACMS using BAT. The label for "4 SFWs" is a weapon type used in PEM essentially synonymous to an F-16 with four SFWs.

Previous analysis has shown that IRTGSM outperforms Skeet when varying assumptions like flight time and vehicle formation. IRTGSM was responsible for more kills in the scenario and was less likely to attack the same vehicle multiple times.[56] BAT submunitions were also analyzed versus Skeet. Due to the smaller submunition footprint of Skeet, Skeet was more sensitive to changes in flight time and timing error.[57] Using the PEM model, another interesting result was found comparing Skeet to BAT. Figure 2.1 displays a comparison of Skeet and BAT over the independent variable of mean length of open areas. As the mean length decreases, indicating a more dense and mixed terrain, the SFW becomes relatively more effective. The break-even point in the comparison seems to be somewhere between two and three km length of open areas. This point holds even with changes to time of last update or vehicle spacing. If future conflicts are expected to be fought exclusively in dense, mixed terrain, it might be more beneficial to invest in integrating Skeet submunitions onto cruise missiles. However, due to the higher average effectiveness of BAT and large uncertainty of terrain in future conflicts, it may be more advisable to invest in a submunition similar to BAT.

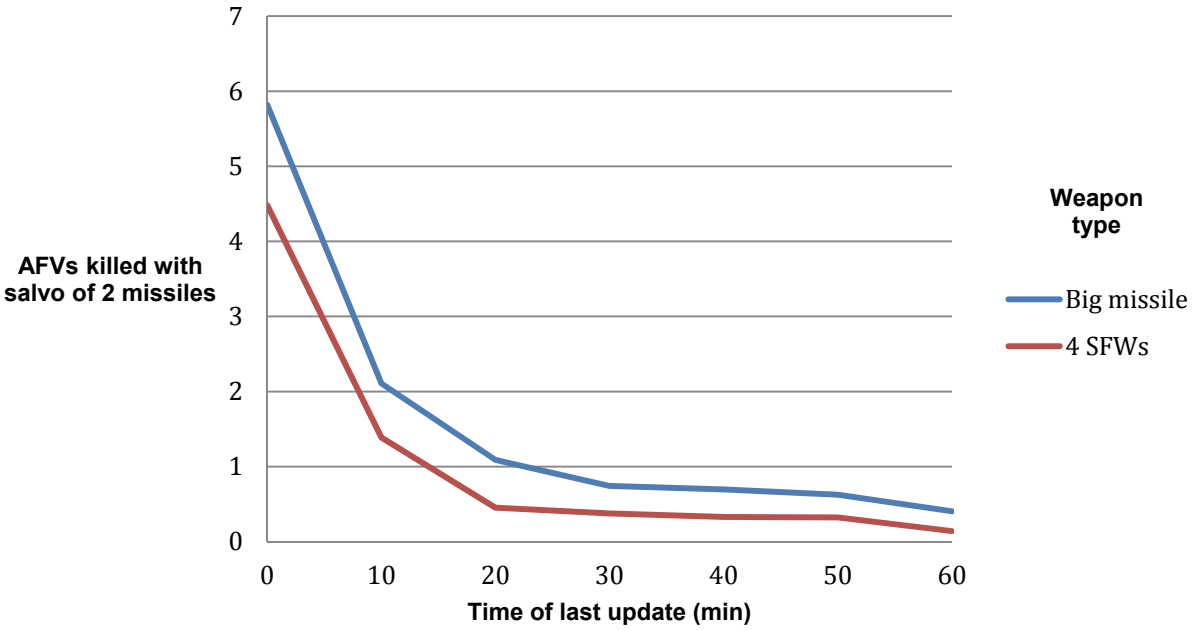
Effectiveness in the PEM is measured by the number of AFV kills resulting from a salvo of two missiles. Figure 2.2 shows results directly from the PEM model, comparing the BAT and SFW weapon types over the independent variable, time of last update. As observed in this result, the time of last update has a nonlinear relationship with weapon effectiveness. The largest losses in effectiveness come in the zero to 20 minute range for time of last update. These results emphasize the importance of having some provision for target location updates when attacking mobile targets with long-range munitions. The PEM model stochastically calculates the expected kills which can be affected by any number of things. Factors like radar limitations, observation angles, hills, alternative routes, and non-constant speeds of troop advancement can inhibit an accurate estimate of where the formation will be at the time of the missile arrival.[58] Increased time of last update propagates these errors as indicated in Figure 2.2.

[56] Buchan, Frelinger, and Herbert.

[57] Davis, Bigelow, and McEver, ed.

[58] _____, ed.

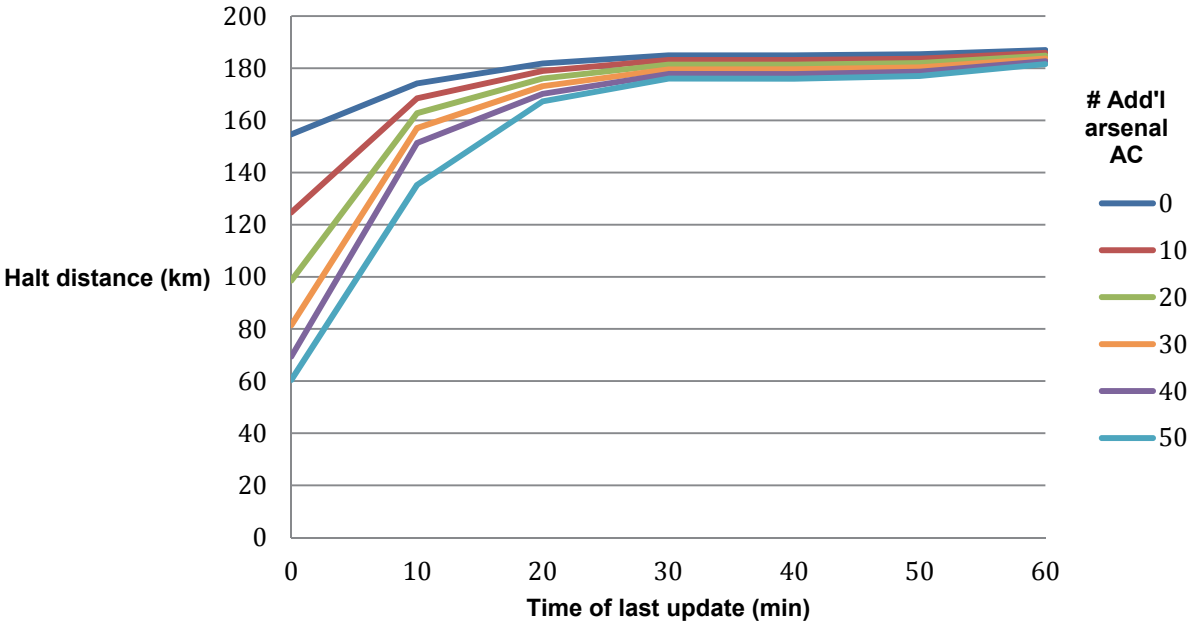
Figure 2.2. Effect of Time of Last Update on Weapon Effectiveness



The results presented in Figure 2.2 are an input to the EXHALT model used in this analysis. Analytica software has the unique feature of array abstraction, which allows for the dimensionality of certain variables to be preserved during array operations.[59] Thus, the critical variables contained in PEM output are transferred seamlessly to EXHALT. Results from EXHALT are shown in Figure 2.3, where the halt distance is displayed as the dependent variable, compared over time of last update and number of additional arsenal aircraft. As expected, the reduced weapon effectiveness that occurs when time of last update increases is apparent in the larger halt distance. Adding arsenal aircraft to the scenario lowers the halt distance. However, there seems to be differential effectiveness in the addition of arsenal aircraft depending on the time of last update. As the time of last update decreases, the effectiveness of adding arsenal aircraft increases.

[59] Lumina Decision Systems, "Analytica User Guide," (2011).

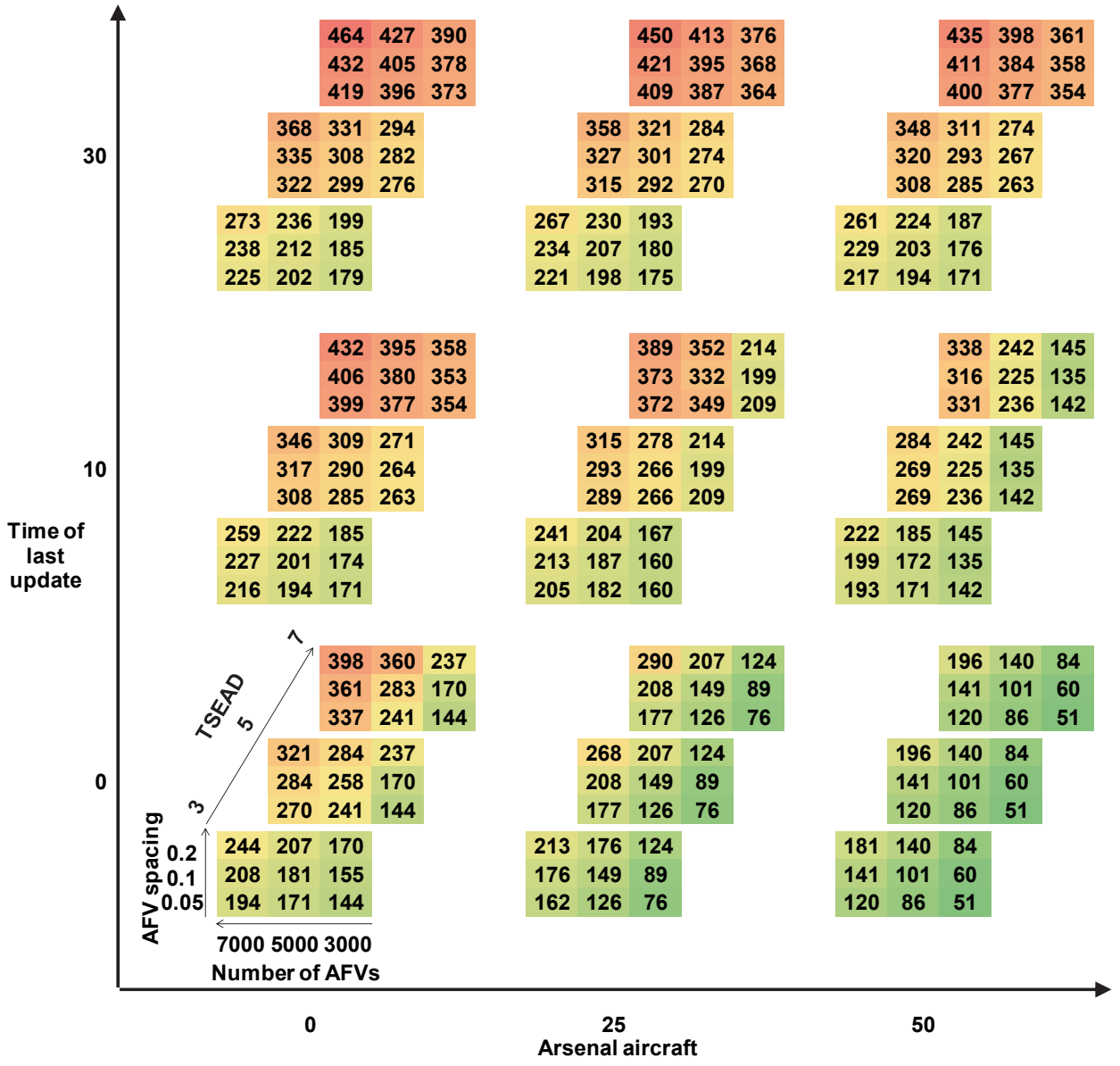
Figure 2.3. Effect of Time of Last Update and Number of Arsenal Aircraft on Halt Distance



Exploratory analysis shows the effects of changing several variables simultaneously. The graphic depicted in Figure 2.4 allows for comparison of the dependent variable with five critical variables in the scenario: SEAD time (units of days), AFV spacing (units of kilometers), number of AFVs to kill, time of last update, and number of additional arsenal aircraft. The dependent variable is halt distance which is shown within the cells in Figure 2.4 (with units of kilometers). These parameters are arranged so that halt distance decreases going down and to the right on Figure 2.4.

SEAD time: The effects of SEAD time on halt distance are fairly intuitive. Before SEAD is accomplished, the aircraft performing interdiction against the invading army are doing so with long-range munitions. These long-range munitions allow the aircraft to operate beyond the range of menacing air defenses. However, there are two factors that cause overflight bombing to be more effective than standoff bombing in this case. First, the bombers have less payload capacity to carry cruise missiles and are therefore firing fewer munitions per sortie in a standoff case. Second, the effectiveness of long-range munitions is degraded by long flight times. Once SEAD is finished, these aircraft can embark on overflight missions which increase the number of munitions dropped per day in the scenario. The longer it takes to suppress and destroy enemy air defenses, the longer blue will be operating with less effective sorties. The SEAD times displayed in Figure 2.4 are arbitrary. The time it takes for SEAD to be accomplished is designated in the figure by the variable T_{SEAD}.

Figure 2.4. Results of Exploratory Analysis of Halt Problem using BAT[60]



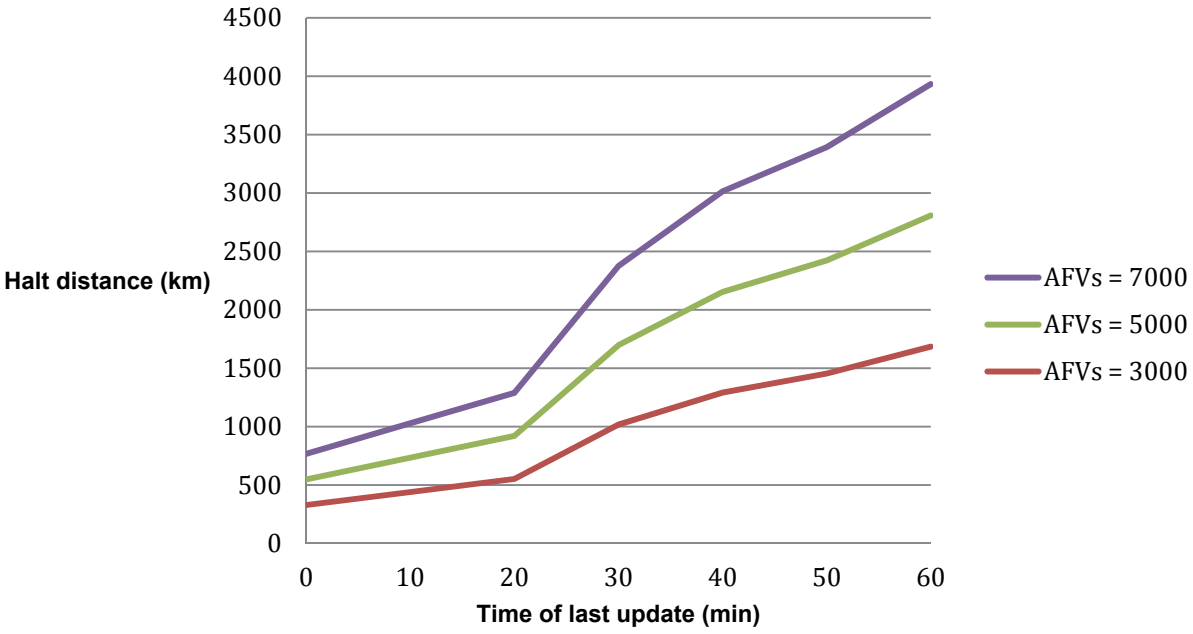
NOTE: Halt distance is shown within each cell, with conditional formatting correlating with the cell values. Both the BAT and SFW cases are standardized to the same range of formatting, 0-500 km.

One can imagine a scenario where bombers are never permitted overflight due to SEAD not being completed. In such cases there no doubt would be plenty of interdiction missions flown by stealthy or high performance aircraft that are more capable of operating in the face of SAM

[60] This idea for this unique exploratory display is credited to the following report: Paul K. Davis and Angela O'Mahony, *A computational model of public support for insurgency and terrorism: a prototype for more-general social-science modeling,* ed., Santa Monica, CA, RAND Corporation, 2013.

threats. For comparison, Figure 2.5 shows the performance of blue air assets in halting the invading force when SEAD is not accomplished. The results indicate astoundingly high halt distances when missiles do not get timely updates to target location.[61] The cruise missile demand would be excessively high in such a case. The analysis performed did not include stealthy penetrators, so these results represent cases where either stealthy bombers are not able to penetrate a highly stressing air defense environment or that they are not being tasked to the mission (e.g. insufficient numbers of stealthy bombers are procured, or stealthy bombers are busy being tasked to other missions). This result emphasizes the importance of SEAD capability. It should be stated, though, that if long-range munitions receive sufficient updates or are "smart" enough to perform their own target tracking, halting the invading force could be feasible even without SEAD being completed.

Figure 2.5. Halt Distances in the Event That SEAD is Not Accomplished



AFV spacing: The effects of AFV spacing are somewhat beneficial to both red and blue forces. On one hand, red may choose to "dilute" its formation, leading to fewer vehicles within the submunition footprint of blue missiles. With fewer targets to attack, weapon effectiveness could decrease considerably. However, there are many other factors that may lead to red choosing to "condense" its formation and thereby decrease AFV spacing, even at the cost of higher

[61] Again, it is important here to recognize that the halt distance is considered in this analysis to be a measure of capability rather than what would actually happen. Modern warfare would not involve an army marching 4000 km into enemy territory as depicted in Figure 2.5.

effectiveness of blue missiles. If AFVs are too distributed, there could be a higher risk of loss when coming into contact with opposing ground forces. The invasion forces would also move slower as a result of lower density of AFV movement, which would lead to a longer road march and therefore more time being vulnerable to blue missile attacks. Commanders may feel as though they have less control over troops if the formation is too widely spaced.[62] Red commanders will likely factor these scenario dependent parameters into the decision of how to space vehicles during an invasion. Figure 2.4 shows a positive correlation between AFV spacing and halt distance, but this is caused solely by changes in weapon effectiveness in the PEM model. If a leading edge strategy were adopted, the correlation of these variables would likely change to account for effects like slower invasion movement with more widely spaced vehicles. This model is purely in-depth interdiction without accounting for any slowing effects.

Number of AFVs to be killed: The number of AFVs to be killed is a direct input to determining the halt distance. In a leading edge strategy, other factors would play a role in halting the army such as the local break point of a segment of an invading column. Destroying or halting part of the leading edge of a column causes the troops movement that follows in that column to be slowed down. Also, if enough attrition occurs in one part of a column, the remaining forces may be considered "out of action" if they are stuck or if there isn't sufficient command and control to unite them with the rest of the formation. This model does not account for leading edge effects which is why the direct input for AFVs to be killed is used. In a real world context, the countries listed in Table 2.4 may be seen as potential threats the United States could encounter. If, for instance, China were to conduct a land invasion of a neighboring country, Chinese military commanders might use something like 50 percent of the total AFV inventory in the invasion. Perhaps an invading force of that size would halt if 50 percent of it were destroyed, in which case the input to the model would be around 5000 AFVs to kill. The range of AFVs to kill used in Figure 2.4 may be too high or too small depending on assumptions of overall force size and break point of the invading force.

Table 2.4. Number of Operating AFVs by Country[63]

Country	Total number of AFVs
China	19558
Russia	14306
North Korea	11660
Iran	4796

[62] PGM Effectiveness Multiplier - Model Comments, RAND Corporation, Santa Monica, CA.

[63] The Military Balance.

Time of last update: On its own, the parameter for time of last update has a significant effect on halt distance. Previous simulations conducted by the Defense Science Board in 1998 provided insight to the process of selecting targets and updating missile aim points. Using a man-in-the-loop process, the simulations identified that the delay from gathering intelligence data from RSTA, allowing time for decision making and the time to implement the decision, ranged from 10 to 20 minutes.[64] This indicates that an important factor in cruise missile employment is the necessary planning and decision making. An alternative to this would be to provide the missile with more autonomous guidance and targeting systems. If the missile can track the target and update its own aim point, the weapon effectiveness would increase. Also, if better ISR assets were in place and if the turnaround time for man-in-the-loop updates to the missile were shorter, the missile would have a smaller time-on-arrival error and therefore be much more effective.
Number of arsenal aircraft: The results for arsenal aircraft are shown in Figure 2.3 and Figure 2.4. In every case, additional arsenal aircraft provide some benefit, offering increased firepower before SEAD is accomplished. This is especially important when SEAD takes longer to be completed. This is shown in Figure 2.4 as the reduction in halt distance is a bit more pronounced in most cases when T_{SEAD} is seven days. If SEAD is never fully accomplished, the addition of arsenal aircraft could prove to be extremely beneficial to the outcome of the scenario (see Figure 2.5). Arsenal aircraft and enhanced cruise missile capability are highly dependent on each other. In Figure 2.4, the halt distance decreases much more dramatically as arsenal aircraft are added for an update time of zero minutes versus an update time of 30 minutes. If arsenal aircraft are purchased, investments should also be made in cruise missile capability to garner the greatest benefit in the halt scenario.

Figure 2.6 provides the same results of exploratory analysis as the earlier figure (Figure 2.4), this time for SFW as the weapon of choice. There is slightly poorer performance for the SFW when compared to BAT in every combination of variables listed. These results were conducted using a mean length of open areas of 3 km, which puts the BAT at a slight advantage. If the open areas parameter was changed to 1 or 2, the SFW would slightly outperform BAT. In general, the same trends are observed with both the BAT and SFW munitions.

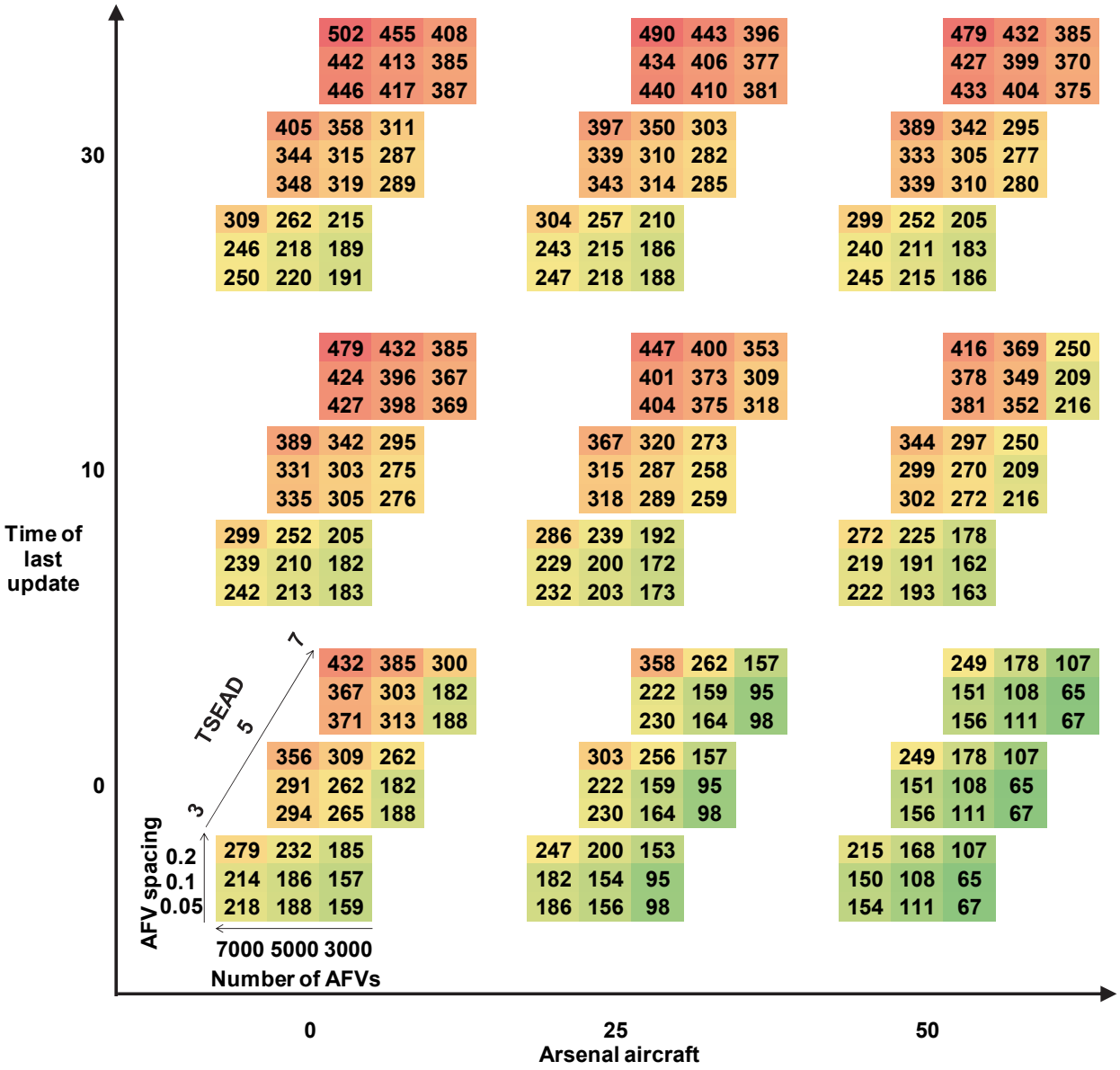
The halt problem is a stressing scenario for many players. ISR assets, whether airborne or on the ground, must be able to get close enough to identify and select hostile targets. With a large-scale invasion, there may be less of a need to determine where targets are, but rather when to attack the targets. This is especially important in varying terrain. In a desert, the tracking of targets may be a much simpler task. Command and control units must be able to quickly assess, analyze, and approve the proposed targets and relay that information to the operators in the launch platform. Aircraft must have adequate protection from enemy threats, whether through standoff range or air escorts. The missiles themselves will need to penetrate air defenses and if

[64] Davis, Bigelow, and McEver, ed.

possible, track targets when the missile gets closer. Although this analysis did not explicitly model factors such as operational planning and employment of cruise missiles, there are valuable insights to be gained. The key takeaway from this exploratory analysis of the halt problem is the same conclusion drawn by previous RAND studies: inefficiencies from standoff munitions must be compensated for with more firepower or with smarter munitions, or a combination of the two.[65]

[65] Buchan, Frelinger, and Herbert.

Figure 2.6. Results of Exploratory Analysis of Halt Problem using SFW



Demand for Standoff Bombers to Halt an Amphibious Invasion

Large scale amphibious operations are extremely complex and require significant coordination and planning. One particular context where it seems possible that an amphibious invasion might occur is in the conflict between China and Taiwan. The Department of Defense (DOD) has stated that there is a possibility of a Chinese amphibious invasion of Taiwan, citing

Chinese writings on strategy and operational concepts.[66] At the present time, there may not be sufficient capacity in the People's Liberation Army Navy (PLAN) amphibious fleet to support such an operation, but future developments could overcome the capacity gap.

There are many reasons why China would refrain from conducting a large scale military operation against Taiwan. Human and economic costs are likely a major deterrent. The economic shock would be felt not only by the countries involved, but worldwide. The United States involvement in Taiwan would inevitably bring the two superpowers into direct military contact, which would temporarily break a major trade link. And lastly, the probability of success may not be sufficiently high in the near term given China's underdeveloped Navy.

There are a number of reasons for using this scenario as a case for demand analysis.[67] Although it may be more likely for China to conduct smaller scale operations and missile attacks, the large scale invasion provides a useful exercise for defense planners. It is also an interesting scenario to look at in the context of standoff bombing. The air involvement in such an operation would be significant, with anti-ship cruise missiles (ASCM) being responsible for a proportion of ship strikes. Small scale enemy amphibious operations would probably not require a large number of ASCMs. However, in a "worst case" scenario, the demand for cruise missiles may exceed the supply of U.S. firepower.

The adversary's strategy for the amphibious transportation of troops is also an important consideration. This strategy is largely dependent on the transport capacity of the amphibious fleet. If there is sufficient capacity, the enemy could decide to attempt a mass transport of as many troops as possible on the first wave of the assault. If the transport capacity is insufficient for this kind of an operation, the invasion could be spread over several days. The former case would be a more challenging scenario for the U.S. especially if the adversary could gain a strategic advantage by transporting enough troops on the first day. This case is used in the analysis to follow.

Amphibious Invasion Model

An event-stepped Monte Carlo simulation was used to model the effectiveness of ASCMs attacking an amphibious formation.[68] Figure 2.7 displays a notional diagram of the basic model setup. In this model, the invasion is modeled at the formation level with the adversary's formation consisting of troop transport ships, escort ships with air defenses, and decoy ships. A

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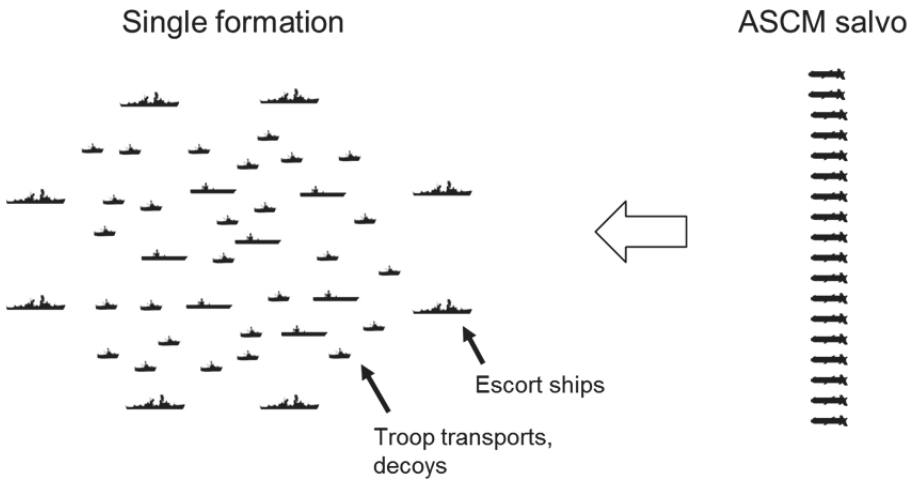
[66] U.S. Department of Defense, *Annual Report to Congress: Military and Security Developments Involving the People's Republic of China*, Washington, D.C.: Office of the Secretary of Defense, 2014, http://purl.fdlp.gov/GPO/gpo12242.

[67] The arguments for using a large scale operation in the Taiwan strait as a military planning scenario are more explicitly outlined in the following reference: David A. Shlapak, David T. Orletsky, and Barry Wilson, *Dire strait?: Military aspects of the China-Taiwan confrontation and options for U.S. policy,* ed., Santa Monica, CA, RAND Corporation, 2000.

[68] The model used for this analysis was developed by Paul Dreyer, a mathematician at the RAND Corporation.

specified number of cruise missiles are fired at the amphibious fleet and damage to the fleet is assessed after each cruise missile salvo. Model inputs include characteristics of ships (i.e., quantity, ground force capacity, missile defense systems) and characteristics of cruise missiles (i.e., CEP, scan range, probability of kill). Once the inputs are specified, the model cycles through each cruise missile in the salvo to determine which air defenses it will be exposed to and which ship it will attack.

Figure 2.7. Diagram of Amphibious Invasion Model Setup



The validation of input data was a critical step in ensuring the results would be accurate and appropriate. Cruise missile parameters were derived from multiple sources. It was assumed that the cruise missiles would approach the enemy formation at low altitude, on the order of 100 feet above sea level. This would greatly reduce the radar horizon of the air defenses, thereby providing more survivability through less shot opportunities by the escort ships. Flying at that altitude yields a radar horizon, and alternatively a cruise missile seeker range, of 30 km. Using parameters for a Joint Standoff Weapon (JSOW) field of view,[69] the seeker angle was calculated to be approximately seven degrees.

The effectiveness of the cruise missile to destroy a ship upon a direct strike is also a significant metric to validate. Due to the active radar terminal guidance employed on the U.S. AGM-84 Harpoon missile, the CEP is assumed to be zero.[70] Previous analysis of historical ASCM effectiveness has shown a high rate of ships that are not sunk even when hit by a missile. Table 2.5 presents data on the ASCM attacks spanning from 1967-1992. This analysis assumes

[69] Kyle Travis Turco, "Development of the Joint Stand Off Weapon (JSOW) Moving Target Capability: AGM-154 Block Three program" (University of Tennessee - Knoxville, 2006).

[70] There is likely some error even with the endgame seeker. However, for the purposes of this model it is assumed that every cruise missile that attacks a ship is going to hit that ship.

that a ship that is placed out of action (OOA) by a missile attack is considered "killed." In the context of a large scale invasion, the time delay caused by putting a ship out of action is critical to preventing the forces from arriving at the beachhead. To find an estimate for P(Kill|Hit), the number of ships OOA is divided by the number of hits. The ship categories that seem most applicable to a military context are ships that are defended or defendable, so a P(Kill|Hit) value of 0.5 is used in the analysis and is varied to account for uncertainty.

Table 2.5. ASCM Effectiveness[71]

Ship category	# Hits	# Ships OOA	# Ships sunk	Total missiles	P(Kill|Hit)
Defenseless	57.5	42	12	63	0.73
Defendable	26	13	6	38	0.5
Defended	32	16	13	121	0.5
Sum	115.5	71	31	222	0.62

The quantity and capacity of ships in the PLAN fleet is presented in Table 2.6. The ship types are categorical and encompass a wide variety of ships in the PLAN fleet. The numbers presented here are the weighted average of all ships in the fleet with similar troop transport capacities. In order to normalize the comparison, the transport capacity is calculated in terms of the "tank equivalents," or the amount of weight in tanks a ship can carry. The escort ships are classified into medium and large based on the missile defense capabilities of each ship. A weighted average was used to calculate the missile defense capability of each escort ship type.

Table 2.6. PLAN Order of Battle[72]

Ship type	Average tank equivalents	Number
LPD/LSM	5.8	62
LST	10.6	26
Landing craft	0.9	175
Medium escort	0	22
Large escort	0	25

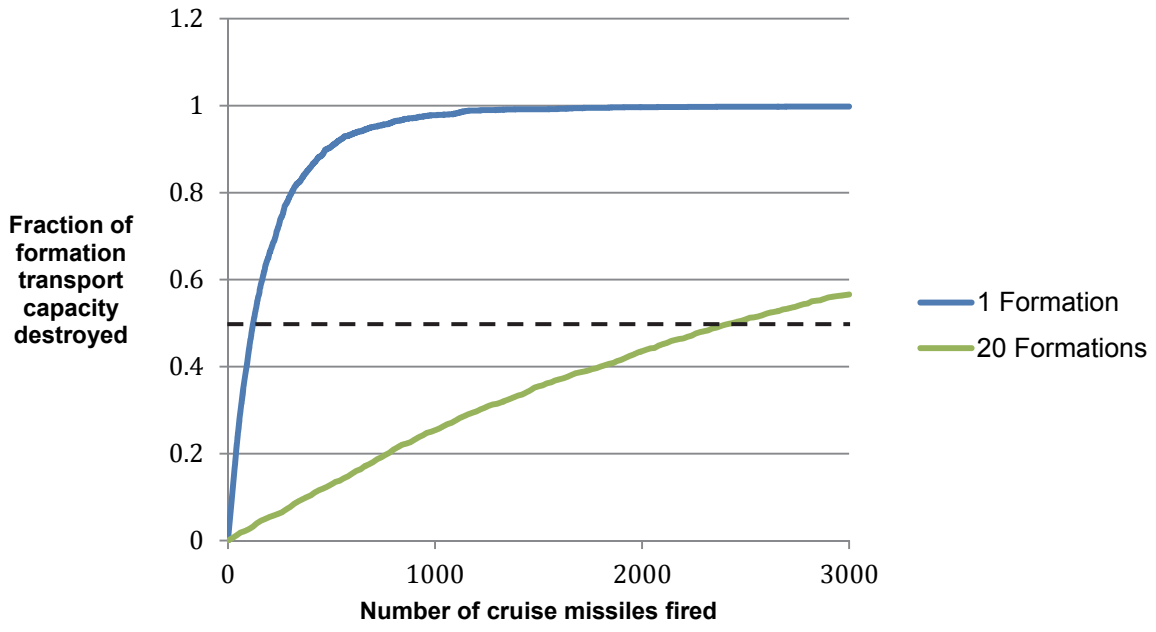
[71] The data in this table is gathered from the following report: John C. Schulte, *An analysis of the historical effectiveness of anti-ship cruise missiles in littoral warfare*, Monterey, CA: Naval Postgraduate School, 1994.

[72] Ship inventory and troop capacity were gathered from the following sources: The Military Balance. and "Chinese Navy Sea Lift," *Jane's Amphibious and Special Forces*, July 2, 2012.

The amphibious invasion model analyzes missile survivability against a layered missile defense. Previous kill chain analysis presented Monte Carlo results for survivability of 18 types of operational ASCMs against a generic ship comparable to an Arleigh Burke class destroyer.[73] The report from that kill chain analysis presented survival probabilities for each missile at each shot from the missile defense system. In order to gather generic missile defense effectiveness as an input to the amphibious invasion model, an average of survival probabilities was calculated for both Close-in Weapon System (CIWS) and SAM. As a result, the single shot probability of kill for both the short-range SAM and CIWS was approximately 0.9. This is parameterized in the model to account for uncertainty. Other missile defense specifications such as range were assumed to be similar to U.S. systems.

The model output consisted of a cumulative damage function as shown in Figure 2.8. The amount of damage done by each cruise missile is incrementally added to the overall damage. This kind of output allows a damage threshold to be applied. For instance, in Figure 2.8 the damage threshold is set to 50 percent which means that 122 ASCMs will need to be fired at one formation to reach that damage threshold. If there are 20 formations, the number of ASCMs required increases to 2435.

Figure 2.8. (Notional) Cumulative ASCM Damage to Amphibious Fleet



[73] Roy M. Smith, "Using kill-chain analysis to develop surface ship CONOPS to defend against anti-ship cruise missiles" (Monterey, California. Naval Postgraduate School, 2010).

The number of iterations for this model was selected based on estimates of model precision. The model has inherent variation that cannot be controlled without changing the model structure itself. The sample size can be increased to obtain a smaller confidence interval, which allows this analysis to confidently distinguish results that vary sufficiently. Based on a 90 percent confidence interval and using a Student's t-distribution, a sample size of 1,000 iterations was chosen, which yields an absolute error of 2.63 missiles required.

Results

For this analysis, a damage criterion is assumed. The USAF will attempt to achieve this damage criterion on the first wave of the assault. There may be significant support from ground and naval assets, which may lessen the number of targets required for USAF attack. If there was little warning before the invasion commenced, USAF forces may be the primary allied forces in the region during the first wave of the assault. This analysis focuses solely on USAF capability with the caveat that the damage criterion is subject to change depending on the level of involvement from other services.

The enemy's ability to use decoys within the formation could significantly increase the demand for cruise missiles depending on the cruise missile sensor capability. Commercial transport or fishing ships could be employed to distract incoming cruise missiles, making it less likely that the larger ships carrying significant numbers of troops would be destroyed. Radar reflectors could potentially be deployed to further confuse the cruise missile sensor, as is already operated in the existing FDS3 Naval Decoy System.[74] The number of decoys deployed by red amphibious forces and the cruise missile sensor capability are treated parametrically to account for various combinations of competing capabilities. Figure 2.9 displays four cases, combining red's tactics of using zero or 100 decoys and blue's cruise missile sensor capability of no target discrimination versus perfect target discrimination. The first result to note is that when the cruise missile can perfectly discriminate between ships, there is no difference in the cumulative damage curves. The number of additional cruise missiles required is higher when there is no discrimination capability between targets. This is especially true for the case with 100 decoys, which is shown to have a much slower growth rate for destroying red transport capacity. For the cases with zero decoys there is some difference in the cumulative damage curves between discrimination capabilities. This is a result of the fact that there is greater utility in destroying a large transport ship over a small transport ship, and in the perfect discrimination case the larger ships are prioritized.

[74] "FDS3 Naval Decoy System: Ship Deployed Floating Countermeasure," ed. Airborne Systems (2014).

Figure 2.9. Cumulative Damage to One Formation

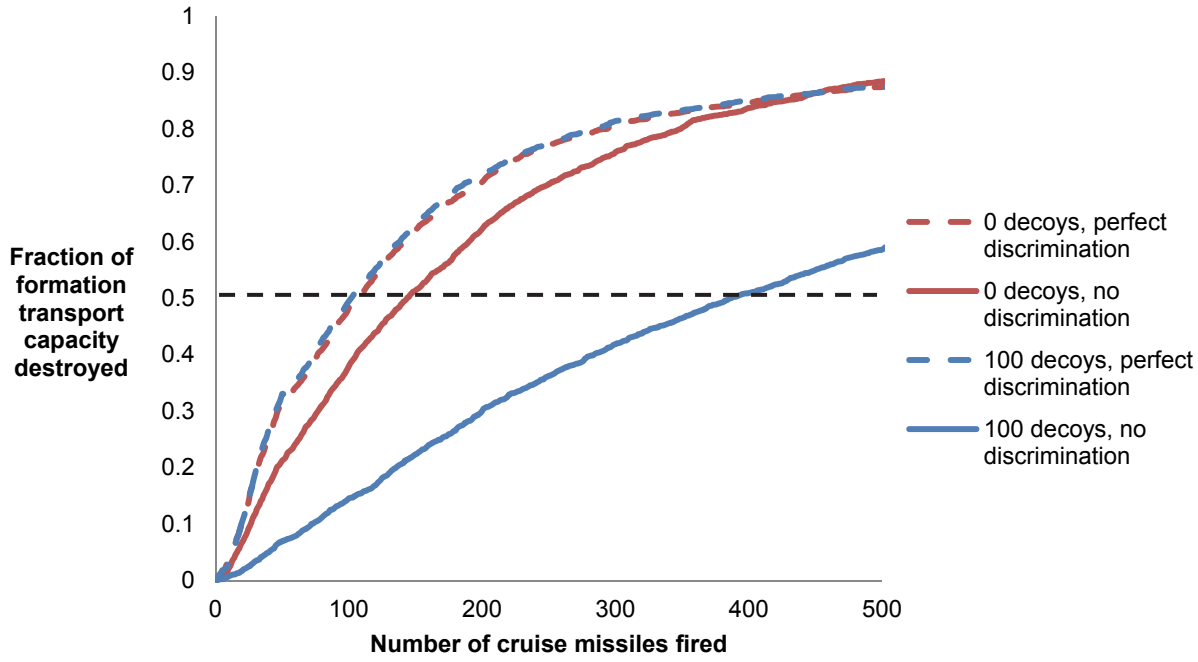


Figure 2.10 and Figure 2.11 show the results of the exploratory analysis of the amphibious invasion scenario. These figures allow the comparison of six scenario variables with regard to the outcome metric, which is the number of ASCMs required to destroy 50 percent transport capacity of a single formation. These variables are: ASCM sensor capability, number of decoys, ASCM salvo size, ASCM P(Kill|Hit), ship air defense P_K, and ASCM battle damage assessment ability (compared between the two figures). The parameters in each figure have been arranged so that the number of cruise missiles required decreases going down and to the right on the figure. *ASCM Sensor Capability*: The number of cruise missiles required is highly sensitive to sensor capability. The existing Harpoon missile uses a radar seeker for terminal guidance. If a capability were added to allow the missile to distinguish between radar signatures, the benefit would be significant. Radar reflectors would make this more difficult and the seeker would have to then distinguish based on not only the size of the signature but on the signature itself. Investments in this kind of technology may prove to be more cost effective than simply buying more launch capacity.

Figure 2.10. Results of Exploratory Analysis of Amphibious Halt without Battle Damage Assessment

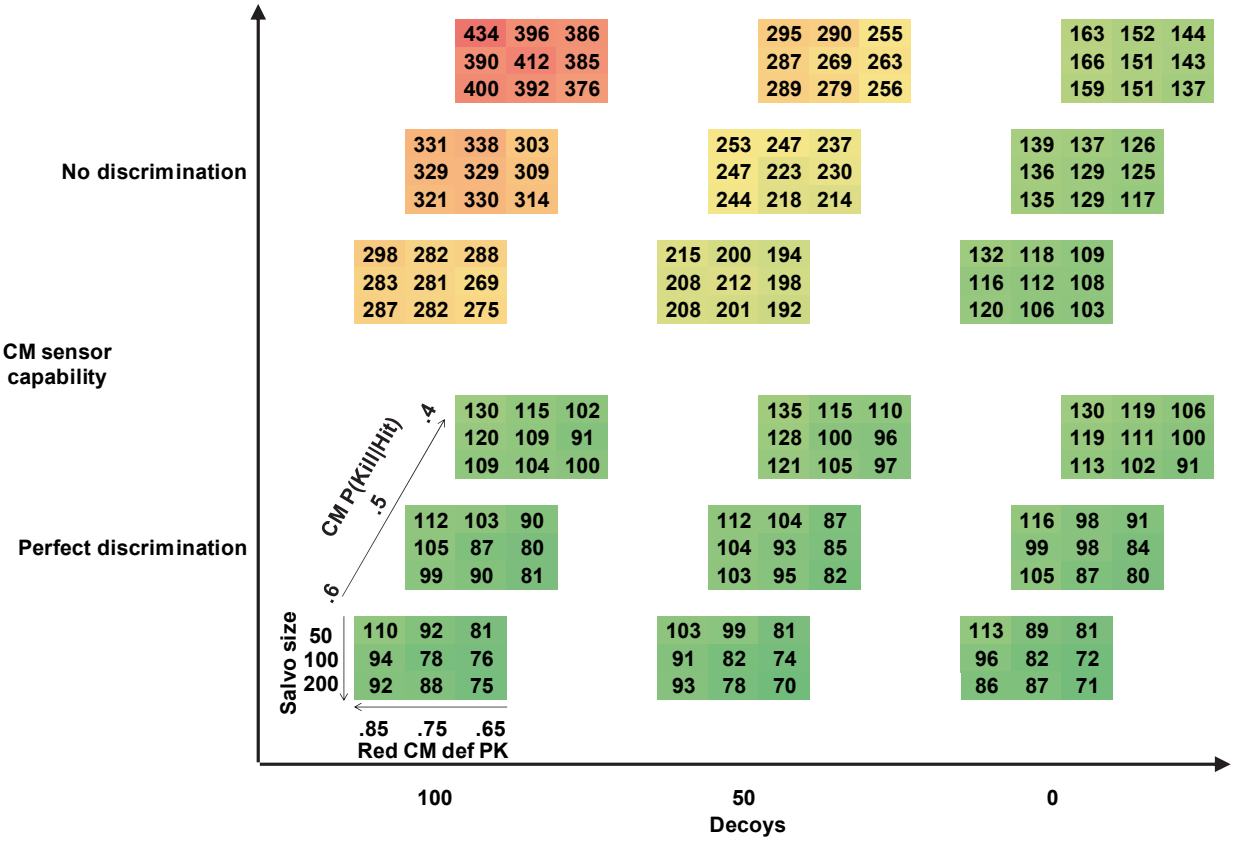
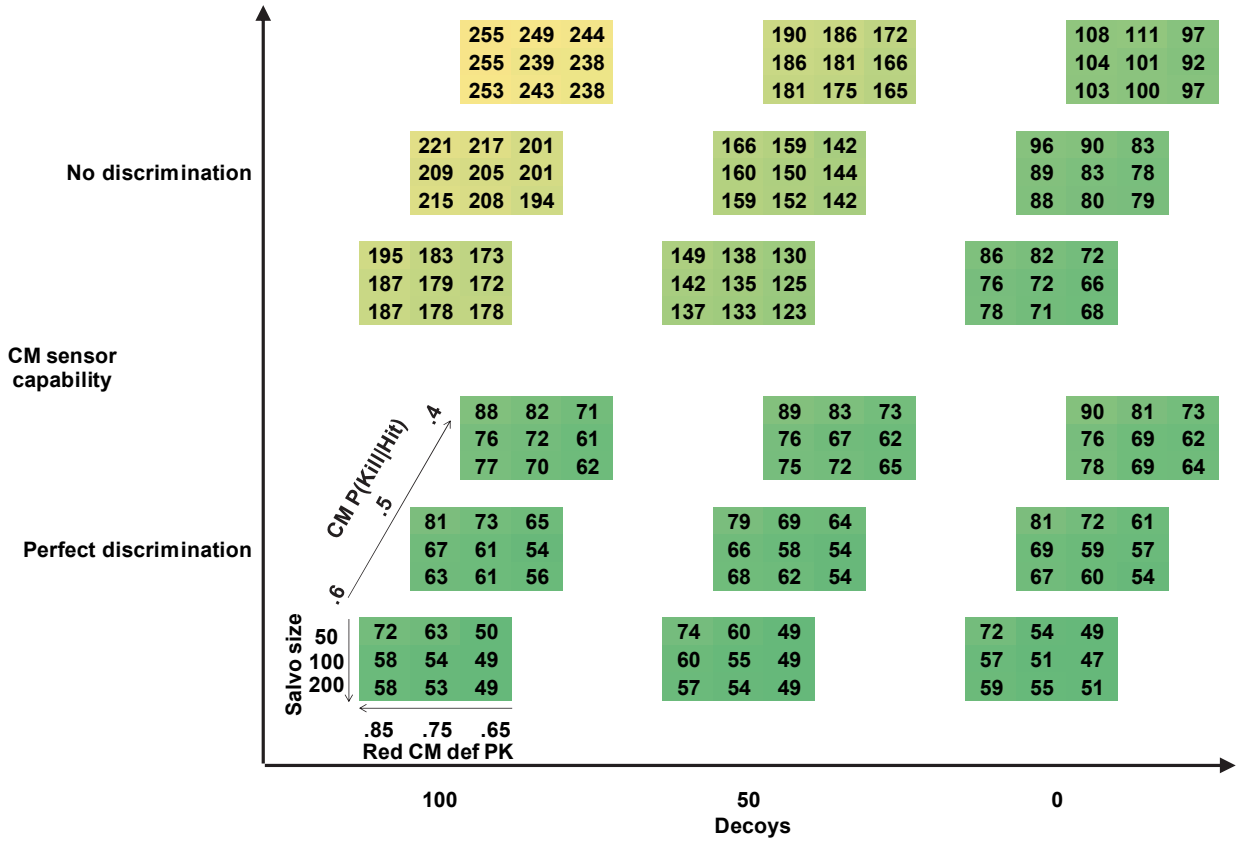


Figure 2.11. Results of Exploratory Analysis of Amphibious Halt with Battle Damage Assessment



NOTE: The number displayed within each box is the number of ASCMs required to achieve 50 percent destruction of the formation's transport capacity. The color scheme is a color gradient based on the highest, middle, and lowest values contained in the data.

Number of Decoys: Adding decoys to the formation adds a significant amount of complexity to the scenario for blue attacks. This analysis modeled the number of decoys with values of zero, 50 and 100. Investing in more decoys could be highly beneficial to red, but it would be a risky investment if blue has sufficient sensor capabilities. This is seen in both figures in the perfect discrimination row. For all variations in scenario variables in this row, there is very little change in the number of missiles required. In other words, red's two policy levers of increasing decoys or increasing air defense capabilities don't have a very significant effect if blue can discriminate. Due to large salvo sizes, the missile defenses are overwhelmed in every case and blue is able to target high-value ships. Perhaps if the salvo size was smaller there would be a greater distinction and red could do better if investments were made in air defenses. Another potential confusion tactic would be to employ obscurant smoke. Ships could release radar-absorbing, carbon-fiber clouds that could prevent the incoming ASCM from detecting the ship as shown in recent tests

by the U.S. Navy.[75] This feature is not included in the analysis but is noted as an additional confusion tactic.

Ship Air Defense P_K: An increase in a ship's air defense probability of kill will cause an increased missile requirement, which is intuitive. There are a number of ways red can make things more difficult for the ASCMs. More accurate missiles would obviously have a direct impact on the number of missiles required. However, there are other factors such as the range of the SAMs and the magazine contained on each escort ship. Over-the-horizon capability will improve the number of kills by providing more shot opportunities for the red defense system. This analysis assumed a limit on the number of simultaneous engagements possible by the air defense system. With a synchronized missile salvo, the air defenses will get only a limited number of shots off while a large portion of the missiles will penetrate. If there was additional capability to target more missiles, air defenses would not be as overwhelmed. Electronic countermeasures such as jamming could also be employed by red to degrade ASCM effectiveness.

ASCM Salvo Size: Much more complicated tactics such as swarming or offensive countermeasures are not modeled here. These tactics could have an effect on cruise missile demand. However, this model does not have the fidelity to simulate such tactics and is limited to using the size of the salvo as the primary instrument for blue tactics. By increasing the salvo size, blue has a greater overwhelming effect on red air defenses. This would require much more coordination among launching platforms to synchronize launches. Although the results aren't highly sensitive to salvo size, if blue can manage larger salvos, more cruise missiles could be saved for later attacks. This of course depends on the total inventory of cruise missiles to begin with.

ASCM P(Kill|Hit): There is a reasonable amount of variation with regard to the cruise missile kill effectiveness given a hit. This seems to be more apparent when there is a combination of decoys and non-discriminating cruise missiles. When there is a shallower rate of growth for cumulative damage (see Figure 2.9), small perturbations in the growth lead to large variation in missile requirement. This parameter would probably be seen as more of a way to capture uncertainty rather than a policy option. Perhaps this parameter could be improved by investing in larger explosives on cruise missiles, but it may not be the most cost effective investment depending on the missile's ability to discriminate.

ASCM Battle Damage Assessment (BDA): The increase in the number of missiles required when there is no battle damage assessment is considerable, and it may be worth improving BDA capability. However, in a scenario with a dense target environment it would be very difficult to assess whether or not a target is destroyed and to communicate that to other incoming ASCMs. Perhaps it would be easier to merely time the cruise missile salvos at long enough intervals so

[75] "7th Fleet Tests Innovative Missile Defense System," *U.S. 7th Fleet Public Affairs*, 2014.

the ships that are out of action would be stagnant in the wake of the formation and would not be mistakenly targeted. If there was some need for the salvos to be temporally closer together, investments could be made for ASCM data link and communication of battle damage to the salvos that follow the first ones.

An amphibious halt is a stressing scenario as a result of the short window of opportunity to strike amphibious ships, particularly in a Taiwan Strait scenario. There are a number of policy options for the United States for reducing the strain on the bomber force in terms of ASCM demand. Perhaps an effective option would be to invest in sufficient sensor capability to handle the potential confusion tactics red could employ. It is recommended that ASCM salvos be large and given adequate time intervals to reduce the cruise missile demand. Additionally, ISR assets could provide much needed information on the level of success of the ASCM attacks. This would allow the United States to conserve missiles in the event that the damage threshold is reached. Accurate locations of each formation would also be critical to ensuring that the cruise missiles arrive at the correct location for the formation attack.

Demand for Standoff Bombers with Fixed-Point Targets

Fixed-point targets are the most well-suited target class for current cruise missiles. Table 2.7 presents a list of potential targets.

Table 2.7. Types of Fixed Targets with Size and Hardness of Target[76]

Targets	Target size (meters x meters)[a]	Target hardness
Bridges	30 x 4	Hard
Command posts/bunkers	13 x 13	Hard
Power plants (four turbines)	15 x 15	Medium
Oil refineries		
10 process towers	15 x 15	Medium
Three control rooms	20 x 20	Medium
Buildings	20 x 20	Medium/soft

[a] The target size presented here accounts for the target's vulnerable area in relation to a cruise missile with a 1000 lb. HE payload.

[76] The table presented here is derived from Edward R. Harshberger, *Long-range conventional missiles: issues for near-term development,* ed., Santa Monica, CA, RAND Corporation, 1991.

Fixed-Target Model

The fixed-target model created in this analysis is based on equations for single-shot probability of kill for a rectangular target.[77] Assuming a 60 degree ingress angle, the cruise missile's CEP is separated into x and y components, specifically the range error probable (REP) and cross-range error probable (CREP). For both the x and y dimension, a normal distribution is constructed using the REP and CREP values, and the target dimensions are then used to determine the probability that the missile will fall within the bounds of the target dimensions. Multiplying the x and y probabilities yields the overall probability of a hit for the rectangular target.

This analysis assumes that if the target is hit by the cruise missile, the target is destroyed. More complex models could provide greater resolution for partial or incomplete damage to a target. However, this level of analysis is sufficient for a general look at demand for cruise missiles. The model also does not explicitly model air defenses, so the survivability and reliability of the missile is represented by a parameter that multiplies the single shot probability of hit.

Results

The number of missiles relates to the overall probability of hit through the following equation:

$$P_n(H \geq 1) = 1 - (1 - P_{SSH})^n \quad (1)$$

The variable $P_n(H \geq 1)$ is the probability that at least one missile will hit the target out of n shots and P_{SSH} is the single shot probability of hit. Figure 2.12 shows the results of this equation where differences in target dimensions affect the overall probability of hit through varying P_{SSH}.

[77] This approach is described in more detail in the following reference: J. S. Przemieniecki, *Mathematical methods in defense analyses*. Third edition ed., Reston, VA, American Institute of Aeronautics and Astronautics, 2000.

Figure 2.12. Variation in Probability of Hit versus Number of Missiles for Different Target Types (CEP Fixed at 10 meters)

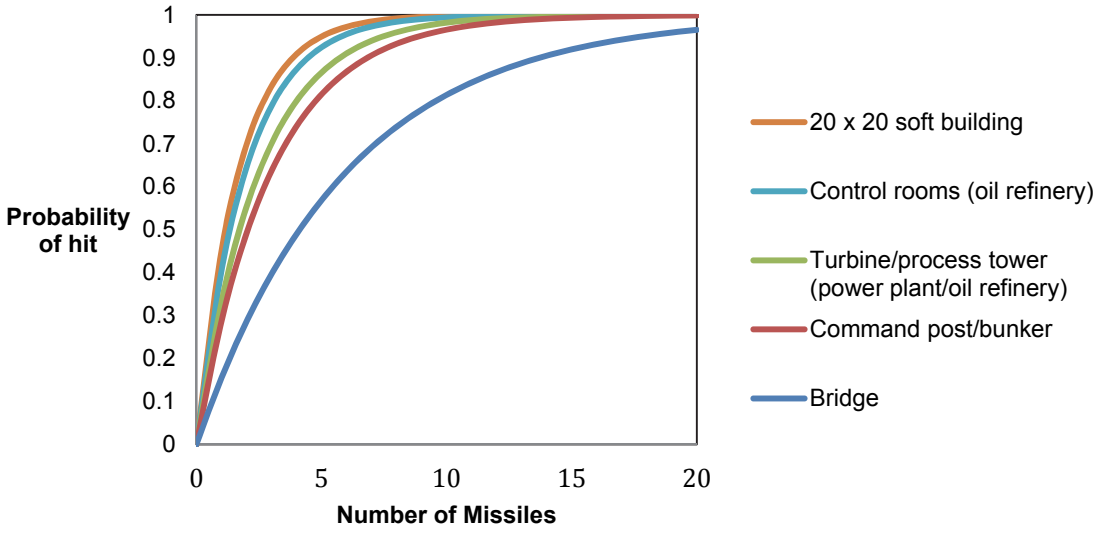


Figure 2.13 presents similar results, this time holding the number of missiles fixed at one while varying CEP. As CEP decreases, the greater accuracy of the missile leads to a higher probability of hit for a given target.

Figure 2.13. Variation in Probability of Hit versus CEP for Different Target Types (For 1 Missile)

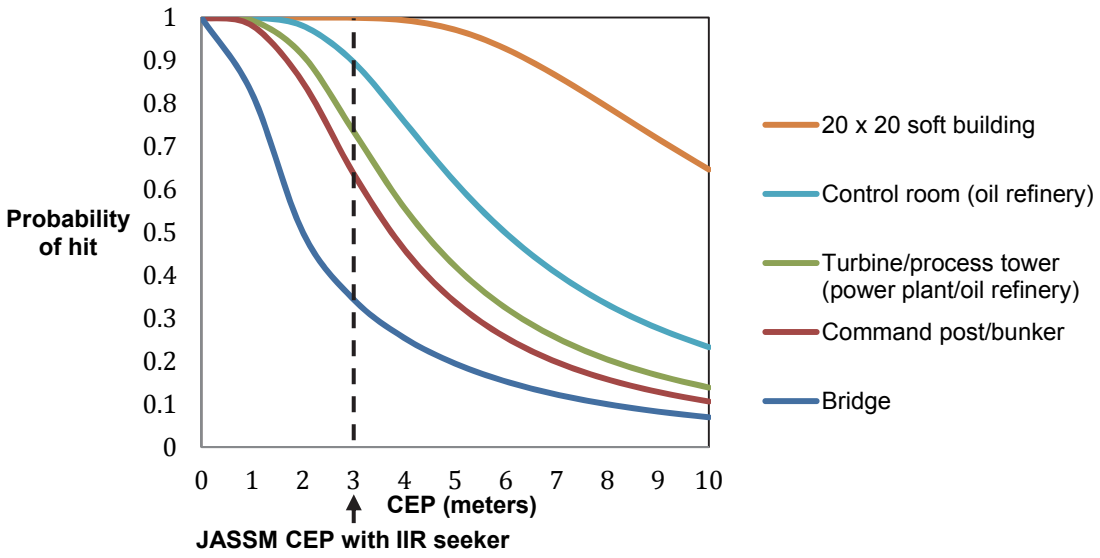


Figure 2.14 and Figure 2.15 display the three dimensional space for CEP, number of missiles, and probability of destruction. The probability of destruction referenced in these figures is defined similar to Equation 1. Equation 2 shows that the parameters $P_{Reliability}$ and $P_{Survivability}$ are

multiplied by the P_{SSH} term to account for the probability that each missile will fail to make it to the target area.

$$P_n(H \geq 1) = 1 - (1 - P_{Reliability} \cdot P_{Survivability} \cdot P_{SSH})^n \quad (2)$$

The first case presented in Figure 2.14 is highly favorable, where there is a 90 percent chance the missile will be reliable and a 90 percent chance the missile will survive the flight to the target. Ranges for the probabilities of destruction are presented in the legend of Figure 2.14 to facilitate the use of thresholds. For instance, if an attack was being planned against a bridge target using missiles with a CEP of 3m and the desired probability of destruction was 0.8, the attack would require the use of five missiles. As targets become larger and softer, the threshold regions become increasingly advantageous.

In a contested environment against a threat with area denial capability, there would be little hope of achieving a $P_{Survivability}$ of 0.9. Figure 2.15 presents results using a $P_{Survivability}$ of 0.5 which may be a little more realistic against advanced threats. When compared side by side, the conditions are much less favorable for the less survivable case. For several target types shown in Figure 2.15, a CEP of more than 10 will require a substantial number of missiles to meet a damage criterion of 0.8. Presence of advanced air defenses would cause a drop in the survivability variable, but blue tactics could counteract this negative effect. Missile swarming, terrain masking, stealth, and offensive electronic countermeasures could all contribute to making the missile attack more survivable.

Figure 2.14. Probability of Destruction for Various Target Types, $P_{Reliability}$ = 0.9, $P_{Survivability}$ = 0.9

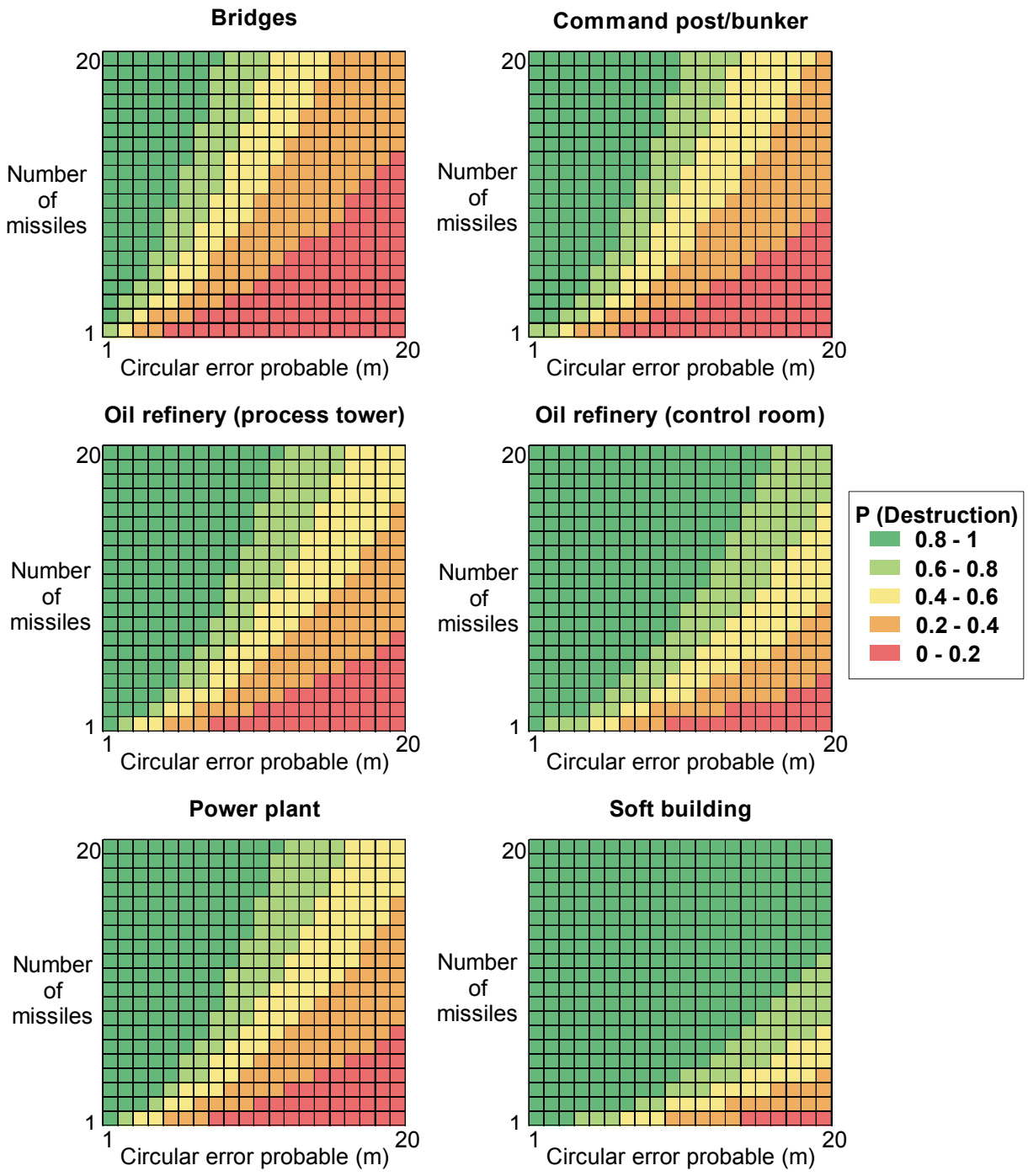
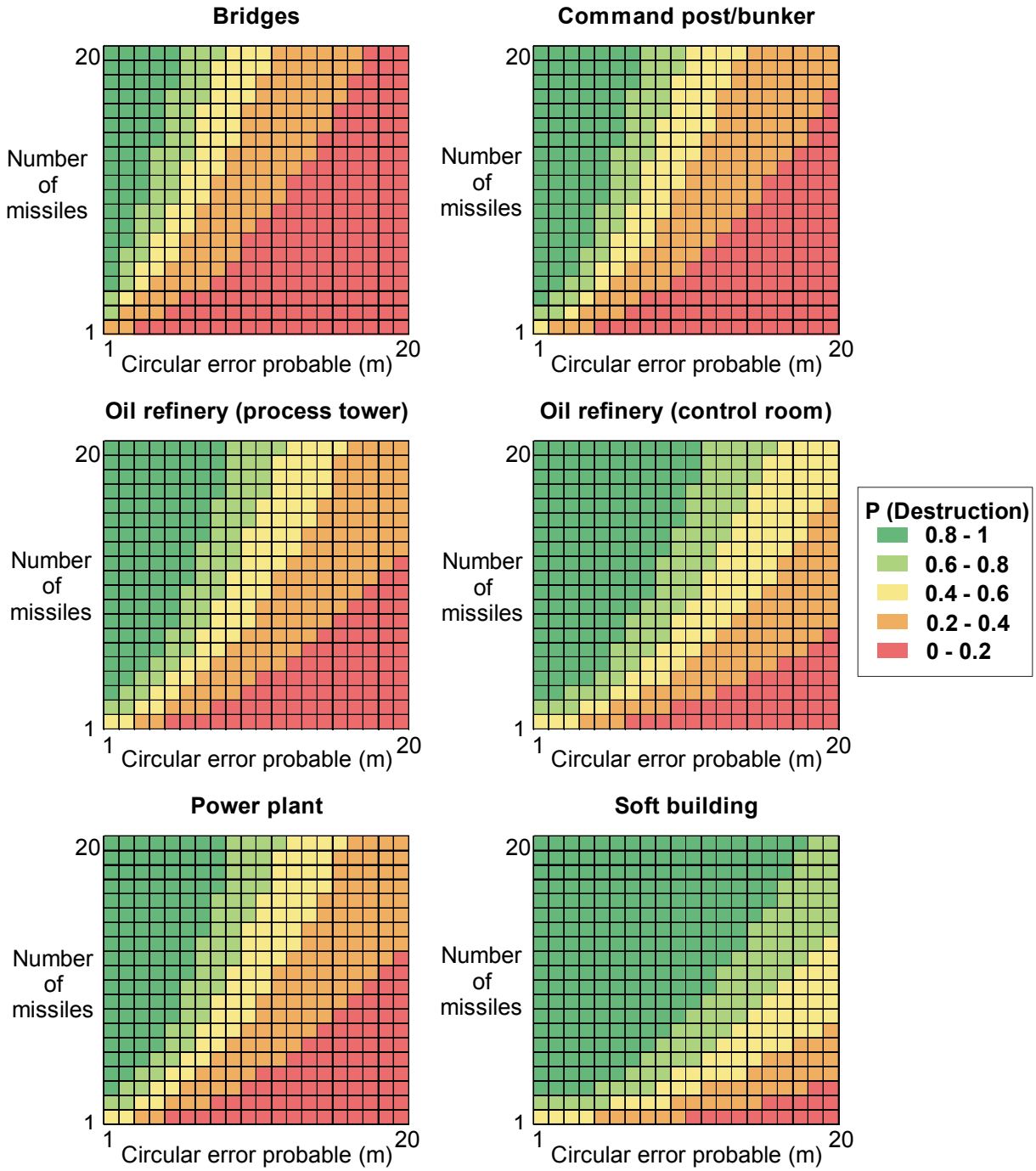


Figure 2.15. Probability of Destruction for Various Target Types, $P_{Reliability} = 0.9$, $P_{Survivability} = 0.5$



Demand for Standoff Bombers in a Runway Closure

Achieving air superiority in a war against an adversary that has significant A2/AD capability will be of extremely high importance. An adversary's anti-access strategies could require U.S. aircraft to operate out of more distant bases to ensure aircraft preservation, which would degrade sortie rates. During air operations, U.S. aircraft would have limited reach into enemy territory because of an enemy's AD capabilities to threaten critical airspace.

A critical component of air superiority is to gain advantage over enemy aircraft. Advantage can be attained in a variety of ways. The most apparent is to destroy enemy aircraft while they are either in the air or on the ground. Another approach is to degrade the enemy's sortie rates. Previous RAND analysis has identified several ways of doing this, including attacking personnel, equipment, aircraft spare parts, munitions, logistics materials, building materials, and petroleum, oil, and lubricants (POL).[78] All of these strategies accomplish the same purpose, which is to limit enemy aircraft participation in the air battle. Each of these strategies may have differing degrees of effectiveness.

One U.S. strategy that could potentially mitigate the risks is to attempt to degrade enemy aircraft sortie rates through runway attacks. Degraded sortie rates would mean a slower pace of the adversary's air campaign, and would translate to more protection and air superiority for U.S. aircraft. Because runways can be repaired, attacking runways would be a recurring target set, whereas attacking aircraft would only be a single attack as long as the aircraft are successfully destroyed. The missile requirement may then be considerably higher for runway attacks due to the recurring nature of the target demand. This analysis does not explicitly model all types of airbase attacks to determine an optimal strategy. Rather, a runway attack is assumed while other potential strategies are qualitatively considered.

A runway closure would be achieved by expending runway penetrating munitions at critical aim points along the runway to deny a minimum operating surface (MOS) for the aircraft at the base. If enough craters are made on the runway, the aircraft on the ground will not have enough length and width on the runway to takeoff or land. This would delay air operations until runway repair personnel were able to adequately repair enough craters to allow a MOS to be available. In an A2/AD environment, cruise missiles could be an ideal candidate for this kind of mission. However, due to the combination of the hardened surface of the runway and the amount of aim points that would need to be targeted, unitary blasts from cruise missiles are not a desirable means to close runways.[79] Cruise missiles would be more effective if equipped with runway penetrating submunitions.

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[78] Donald E. Emerson, *TSARINA: user's guide to a computer model for damage assessment of complex airbase targets,* ed., Santa Monica, CA, RAND Corporation, 1980.

[79] Harshberger, ed.

Table 2.8. List of Previously Developed Anti-Runway Submunitions[80]

Bomblet	Number of bomblets carried in weapon	Carrier	Carriage type	Country
KRISS	10	APACHE	Cruise missile	France
STABO	224	MW-q/DWS-24/39	Dispenser	Germany
BetAB	12	RBK-500	Dispenser	Russia
SAP	8	BME 330 AR	Bomb	Spain
SG-357	30	JP-233	Dispenser	UK
BLU-106/B	24	AGM-109H	Cruise missile	USA

Table 2.8 displays a list of previously developed anti-runway bomblets. Several of the options use a dispenser or bomb carriage type, which in an A2/AD scenario would put a high amount of risk on the aircraft tasked to deliver the submunitions directly over the target. A more feasible option would be to load runway penetrating submunitions onto cruise missiles that would then act as a delivery platform. The AGM-109H Tactical Anti-Airfield Missile (TAAM) was a candidate for this kind of mission, but was never produced by the United States. A viable alternative that could be used as an analogous submunition is the French KRISS submunition which was produced as a payload for the APACHE cruise missile. Table 2.9 shows a comparison between the French cruise missile and the probable U.S. cruise missile of choice, the JASSM. For the purposes of this analysis, the two cruise missiles seem to be similar enough in both weight and spatial dimensions to be able to assume equal submunition carriage for the U.S. JASSM. There is the possibility of lesser submunition carriage due to the slightly smaller JASSM size. However, new advances in weapon development could mean smaller submunitions which would increase JASSM capacity.

[80] Ove Dullum, "Cluster weapons–military utility and alternatives," *Norwegian Defence Research Establishment (FFI),* Vol. 1, 2008.

Table 2.9. Comparison of JASSM and Apache Capacity Characteristics[81,82]

		
Name	Joint air-to-surface standoff missile (JASSM)	Arme propulsée a charges ejectables (APACHE)
Country	United States	France
Length (meters)	4.3	5.1
Width (meters)	0.55	0.63
Height (meters)	0.45	0.48
Weight (lbs.)	2250	2711

Potential Challenges for a Runway Attack Strategy

One argument against attacking parked aircraft in an A2/AD environment is the lengthy flight times of the cruise missiles. With flight times of up to one hour, enemy radar will likely acquire the cruise missile which would give the airbase some warning before the missile strike. Enemy aircraft could potentially be scrambled to take off quickly and wait in the airspace until the missile attack is complete. This would render the attack on parked aircraft ineffective. The same could be said about runway attacks, and aircraft that are scrambled could divert to another airbase and continue their operations uninterrupted. To overcome this, a potential strategy would be to launch a large attack on all airbases at once to prevent diverted aircraft from being able to land at an undamaged airfield.

Runway repair is a key component of a runway attack strategy. To be successful, a runway attack needs to be conducted in the same intervals of time that are required for rapid runway repair teams to repair craters. The faster the adversary can repair runways, the more frequent U.S. aircraft will need to launch attacks against that airbase. As a point of comparison, the USAF deploys a standardized set of civil engineer teams with equipment and vehicles to rapidly repair runway damage. The basic set of equipment, vehicles, and materials deployed provides crews with the capability of repairing one crater in four hours. A second and third level of supplies can

[81] "AGM-158 JASSM," *Jane's Strategic Weapon Systems: Offensive Weapons*, .

[82] "Apache AP," *Jane's Strategic Weapon Systems: Offensive Weapons*.

be used to repair more craters. The second level of runway repair capabilities allows six craters to be repaired in four hours, and the third level allows 12 craters to be repaired in four hours.[83] Additional research on the topic of rapid runway repair suggests that the four hour metric is quite optimistic. Just clearing unexploded ordnance (UXO) and bomblets and repainting the runway centerline required up to seven hours.[84] The same study conducted a mathematical simulation that showed large variation in the overall repair times based on climate changes, which affect human, equipment, and epoxy efficiency. The study concluded with a range of minimum times to repair a 7000-foot long runway with extensive damage, minimum repair times ranging from nine to 28 hours depending on weather. For rainy weather, the repair times were infinitely large due to the epoxy not being able to cure, indicating that repair would have to wait for the rainy weather to end. The scenarios that the study used to evaluate were actual scenarios used to train repair teams. The scenarios used many different kinds of damage including spalls, bomblets, and UXO, which may not all be as applicable or in the quantities presented in that study as when runway penetrating submunitions are used.

The ISR capabilities used by the United States would be critical in reducing the number of missiles required. For instance, the number of airbases to be attacked could be reduced greatly if decision makers know at which bases critical enemy aircraft are operating. Additionally, BDA provided by ISR assets would be critical in determining how fast the enemy can repair the damage and produce sorties. Without the intelligence, the United States will be relegated to attack all applicable bases at a certain rate of assumed enemy runway repair capability, which may be vastly different among bases.

A Model of a Runway Attack

To determine the number of missiles required to close a runway of a particular size, a Monte Carlo simulation was created. This simulation relied upon several key variables. The runway width and length were varied parametrically to account for a wide range of runway sizes. In order to provide a conservative assumption, a MOS of 750 meters length and 20 meters width was used on the basis of denying fighter operations.[85] An alternative strategy would be only to attempt to deny large aircraft such as bombers, but denying fighter operations seems to be particularly relevant in an A2/AD scenario where control of the airspace is critical. The number of submunitions carried on the cruise missile was assumed to be 10, comparable to the KRISS submunition payload on the Apache cruise missile (see Table 2.8 and Table 2.9).

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[83] *Air Force Pamphlet (AFPAM) 10-219, Airfield Damage Repair Operations*, Washington, D.C.: Department of the Air Force, May 27, 2011.

[84] David Duncan, *Rapid Runway Repair (RRR): An Optimization for Minimum Operating Strip (MOS) Selection*, Wright-Patterson Air Force Base, OH: Department of the Air Force Air University, 2007.

[85] Harshberger, ed.

Aim point errors are propagated through both cruise missile and submunition CEP. JASSM CEP ranges from three meters with imaging infrared (IIR) targeting to 13 meters with a GPS/INS system.[86] The bias in the cruise missile aim point will then be inherited by the deploying submunition, which will have its own CEP. The submunition CEP was varied from five to 10 meters. The actual CEP may be more or less than this range depending on factors such as the precision of the submunition release from the cruise missile or the altitude of the submunition release point.

The number of missiles used to close the runway was varied incrementally. The number of aim points depends upon the size of the runway and the size of the MOS. If the U.S. goal was to limit the runway operating surfaces to less than or equal to the MOS, the total number of aim points would be described by the following equation:

$$Aimpoints = \left\lfloor \frac{Runway\ Width}{MOS\ Width} \right\rfloor \cdot \left\lfloor \frac{Runway\ Length}{MOS\ Length} \right\rfloor \quad (3)$$

The simulation models each individual submunition and recalculates the actual aim point based on random draws from a normal distribution based on the CEP of the missile and submunition. The model then determines if there is still an available MOS width in between craters in the event that a width-wise cut fails. A total of 1000 iterations of the model were run with the number of successes recorded. If a 75 percent confidence is desired for the probability of a successful runway closure, the threshold for the number of missiles can be calculated based on the simulation runs.

Results

Figure 2.16 and Figure 2.17 display the results for the number of cruise missiles required to achieve a desired confidence. The numbers do not seem particularly large due to the use of runway penetrating submunitions. Were it not for the use of these submunitions the demand would be excessively large, requiring at least one cruise missile for each aim point. As a reference, the number of aim points calculated in the model for a runway with the dimensions 3500 meters x 70 meters is 12. For the high CEP case, five total missiles are required which results in 50 total submunitions, with an average number of submunitions allocated per aim point of 4.17. A unitary warhead attack may result in larger craters and longer repair times, but would need an extremely large salvo of missiles to obtain a similar number of craters.

It is apparent that Figure 2.16 has slightly higher missile requirements than Figure 2.17, indicating that fewer missiles would be needed with a lower CEP. The distinction is not very large, perhaps because of the previous point that there are several submunitions released per aim point. There are several other factors that are not modeled but could play an important role. The technical characteristics of the launching mechanism are not modeled in this analysis. A single

[86] U.S. Department of Defense, "Selected Acquisition Report: Joint Air-to-Surface Standoff Missile (JASSM)," (Washington, D.C.).

cruise missile could fly multiple passes over a runway and release submunitions over different aim points on each pass. If the cruise missile could rapidly release several submunitions at a particular aim point, and if the submunitions themselves had some sort of guidance system, multiple passes may not be necessary which would in turn decrease the risk to the cruise missile of being shot by air defenses.

Some non-monotonicity occurs in the model, as can be seen in Figure 2.16 and Figure 2.17 for the runway size of 3250 meters x 50 meters. This is not an error in the programming, but rather it an artifact of the imposed threshold of a minimum operating surface. The equation used for the number of aim points produces discontinuities in the input data. For example, when the runway length reaches 1500 meters, one aim point lengthwise will not suffice in denying the MOS. The number of aim points actually doubles, which can be further magnified if the width is large enough to require multiple aim points.

Figure 2.16. Missiles Required to have a 75 Percent Probability of a Successful Runway Closure, High CEP Case (JASSM CEP = 13 meters, Submunition CEP = 10 meters)

Runway width (meters) \ Runway length (meters)	750	1000	1250	1500	1750	2000	2250	2500	2750	3000	3250	3500
20	1	1	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	2	2	2
30	1	1	1	1	1	1	1	1	1	2	2	2
35	1	1	1	1	1	1	2	2	2	2	2	2
40	1	1	1	1	1	1	2	2	2	3	3	3
45	1	1	1	2	2	2	2	2	2	3	3	3
50	1	1	1	2	2	2	3	3	3	4	3	4
55	1	1	1	2	2	2	3	3	3	4	4	4
60	1	1	1	2	2	2	3	3	3	4	4	4
65	1	1	1	2	2	2	4	4	4	5	5	5
70	1	1	1	3	3	3	4	4	4	5	5	5

Figure 2.17. Missiles Required to Have a 75 Percent Probability of a Successful Runway Closure, Low CEP Case (JASSM CEP = 5 meters, Submunition CEP = 5 meters)

Runway width (meters) \ Runway length (meters)	750	1000	1250	1500	1750	2000	2250	2500	2750	3000	3250	3500
20	1	1	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1	1
35	1	1	1	1	1	1	1	1	1	2	2	2
40	1	1	1	1	1	1	1	1	1	2	2	2
45	1	1	1	1	1	1	2	2	2	2	2	2
50	1	1	1	1	1	1	2	2	2	3	2	3
55	1	1	1	2	2	2	2	2	2	3	3	3
60	1	1	1	2	2	2	2	2	2	3	3	3
65	1	1	1	2	2	2	3	3	3	4	4	4
70	1	1	1	2	2	2	3	3	3	4	4	4

Demand for Standoff Bombers and Cruise Missiles at the Theater Level

Findings to this point have been presented at the engagement level. However, war-time theater-level demands are the driving factor for determining force structure. As the demand is characterized in this section, it is important to consider both (1) the supply, or inventory, of current and planned cruise missiles and (2) the rate at which the cruise missiles can be launched, which is a factor of the current bomber fleet capacity. As this study is focused on supplementing the bomber force, the primary focus here is whether or not it is possible for the rate of demand to exceed the current bomber firepower. Theater level demands for the four target sets are included in the discussion to follow, along with a notional scenario involving a combination of target demands.

1. The strategic goal of halting an army was investigated in this chapter through exploratory analysis. Force structure analysis dealing with this target set may be infeasible as it would be quite burdensome to the cruise missile inventory. Shown in Table 2.10 is the daily cruise missile use for the halt scenario. For stressing scenarios involving longer SEAD times, the daily use of cruise missiles at this rate would quickly deplete the supply. The shortest SEAD time investigated was three days, but in reality an A2/AD scenario may require much more time before the region is deemed safe enough for bomber operation. It would likely be a better investment to upgrade the missile seeker and ISR target update capabilities rather than simply purchasing more cruise missiles and more aircraft.

Table 2.10. Daily Cruise Missiles Used for Halting an Army

	Permissive	Contested	Highly contested
0 Arsenal AC	1750	1337	1083
25 Arsenal AC	3334	2580	2105
50 Arsenal AC	6502	5065	4150

NOTE: The terms permissive, contested, and highly contested are used to indicate a mission radius of 500, 1000, and 2000 nautical miles to the target from the base at which the bomber sorties are originating.

2. Results from the amphibious invasion discussed earlier in this chapter are simply multiplied by 10 to account for a full scale invasion using ten identical formations.[87] This assumes that formations are spaced enough apart so that cruise missiles do not attack multiple formations. Table 2.11 shows the number of required missiles to destroy 50% of this invading fleet.

[87] The number of formations used was arbitrary. The PLAN order of battle was arranged into ten formations. More or less formations could be specified, but the size of the formation would need to be altered to account for a fixed PLAN ship inventory.

Table 2.11. Number of Missiles Required to Destroy 50% of 10 Invading Amphibious Formations

	Perfect target discrimination	No target discrimination
0 Decoys	900	1080
50 Decoys	890	1900
100 Decoys	880	2550

NOTE: The perfect discrimination case seems to have counter-intuitive results. These small variations are within the standard error of the amphibious simulation.

3. The numbers of fixed targets for each target type are shown in Table 2.12. Also shown in this table are the demands for the single target case, which come directly from the fixed target analysis results discussed earlier. We assume that each target type has an equal proportion of the overall number of fixed targets in the scenario. We then assume that there is a certain fraction of the targets that are time critical and need to be attacked on the first day of the conflict. The number of strikes required on the days following the first day of the conflict is reduced. The results for both the single target requirement in Table 2.12 and the overall target requirements in Table 2.13 vary significantly with respect to changes in the assumptions for cruise missile CEP and survival probability. The more staggering variation is the extreme change from three meters to 13 meters CEP. The JASSM is capable of both accuracies depending on the guidance system used.

Table 2.12. Fixed-Target Theater Demand[88]

	Number of targets	Time critical targets (Day 1 strikes)	Daily strikes (after Day 1)	Single target requirement			
				CEP = 13 meters		CEP = 3 meters	
				Ps = 0.9	Ps = 0.5	Ps = 0.9	Ps = 0.5
Bridges	50	5	2	45	81	5	10
Command posts	50	5	2	30	54	3	5
Bunkers	50	5	2	30	54	3	5
Power plant	50	5	2	23	41	2	5
Oil refineries	50	5	2				
Towers				23	41	2	5
Control rooms				13	24	2	4
Political target	50	5	2	4	7	1	3
Total	300	30	12	145	261	16	32

[88] This analysis assumes a total of 300 fixed targets with 10 percent of them being time critical. A similar approach was used in the following study: Buchan and Frelinger. For simplicity, the proportion of each target types is assumed to be the same. More detailed analysis could investigate actual numbers of potential targets.

NOTE: The total here is a sum of all the target demands except for oil refinery towers. Since the refinery targets are comprised of the two target sets, it is up to the decision maker which kind of refinery attack to use. Here it is chosen because it requires fewer missiles, but there may be other tradeoffs such as accuracy of intelligence or length of effect of the attack.

Table 2.13 shows the missile demand for the total number of fixed targets in the theater. This is derived from Table 2.12, where the total number of time-critical and non-time-critical targets is multiplied by the single target case for missile demand. These results vary significantly with respect to changes in the assumptions for cruise missile CEP and survival probability, with the more abrupt variation being the change from 3 meters to 13 meters CEP. The JASSM is capable of either accuracy depending on the guidance system used. Although 3-meter accuracy would be ideal, there would be significantly more work involved in target planning to ensure the missiles have imaging for each target.[89] Investing in improvements for target and route planning could improve the feasibility of using the JASSM IIR against every target.

Table 2.13. Fixed-Target Requirements for the First and Following Days of Conflict

	First day requirement				Following daily requirement			
	CEP = 13 meters		CEP = 3 meters		CEP = 13 meters		CEP = 3 meters	
	Ps = 0.9	Ps = 0.5	Ps = 0.9	Ps = 0.5	Ps = 0.9	Ps = 0.5	Ps = 0.9	Ps = 0.5
Bridges	225	405	25	50	90	162	10	20
Command posts	150	270	15	25	60	108	6	10
Bunkers	150	270	15	25	60	108	6	10
Power plant	460	820	40	100	184	328	16	40
Oil refineries								
Towers	1150	2050	100	250	460	820	40	100
Control rooms	195	360	30	60	78	144	12	24
Political target	20	35	5	15	8	14	2	6
Total	1200	2160	130	275	480	864	52	110

4. Table 2.14 shows the number of runways for several countries. If these runway dimensions are known, the number of missiles required for successful runway closures of all airfields can be calculated. The countries shown in the table were selected because of their current and potential A2/AD capabilities as well as their possession of large quantities of aircraft. Iran and North Korea do not have aircraft as advanced as the aircraft possessed by China and Russia, but they do have aircraft in significant numbers. Iran and North Korea also have less advanced air defense systems, which would lead to either faster SEAD times or more permissive bomber operations.

[89] The amount of planning it would take coordinate this amount of cruise missile strikes would be incredibly burdensome. If these amounts of cruise missiles are expected to be fired and if an arsenal aircraft is going to be procured to handle this level of cruise missile demand, there would have to be significant investments made to ensure that planning capabilities are adequate.

Perhaps shorter-range weapons could be used in these scenarios to attack a portion of the runways. China and Russia, on the other hand, have highly advanced air defenses and a much larger geographical dispersion of bases to attack. Bombers could not target all desired airfields in these cases, but could attack relevant bases close to the conflict zone.

The key takeaway from this aggregated runway analysis is that intelligence regarding enemy aircraft locations is critical for reducing missile demand. It would not be politically feasible or cost effective to attack all runways including civilian operated airfields. A potential strategy would be to attack all military operated airfields. An even more improved strategy would be to attack all military airfields that have combat aircraft assigned. Perhaps the strategic goal would be to deny advanced fighters, in which case intelligence regarding specific locations of these fighters would prove to be highly valuable, further reducing the target set.

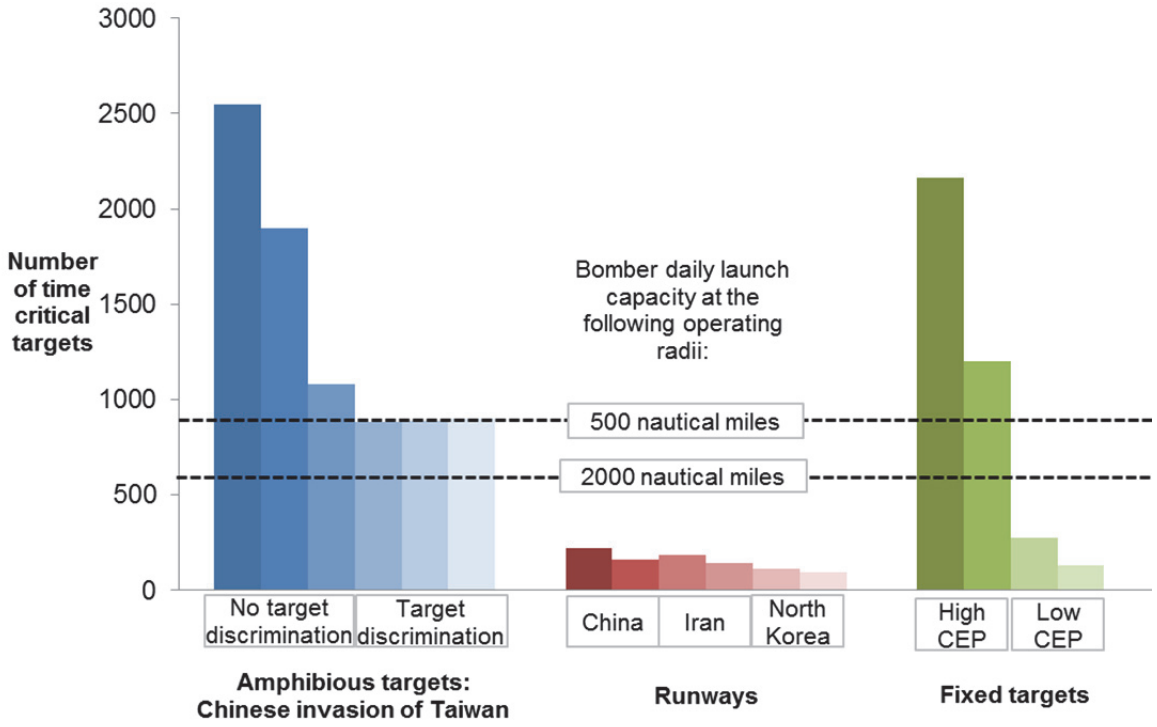
Table 2.14. Number of Airfields and Runways for Potential Adversaries[90]

	All airfields	All runways	Military airfields	Military runways	Combat airfields	Combat runways
China	534	582	128	141	75	75
Russia	695	851	79	86	33	34
Iran	307	336	14	28	11	23
North Korea	74	77	35	36	16	16

Results for the fixed target, runway, and amphibious attack are presented in Figure 2.18. The individual bars on the chart represent results using unique assumptions for that target set. One important thing to consider with regard to the potential need for arsenal aircraft capability is whether or not the demand exceeds the current bomber capacity. The current bomber firepower capacity is shown on the figure as two dotted lines representing different operating ranges. Surge sortie rates were used in conjunction with two thirds of the combat coded bomber force deployed to the theater. For A2/AD scenarios, it is unlikely that bombers will be based 500 nautical miles from the target due to ballistic missile threats to those bases. A 2000 nautical mile radius (distance from base to weapon launch point) would be the most likely operational radius in a Pacific scenario. There is a large variation of potential demand, so the daily demand for cruise missiles is calculated using the best case and worst case assumptions as shown in Figure 2.19 and Figure 2.20. Several of the cases come close to or exceed these thresholds, indicating that there may be a need for additional firepower in these scenarios.

[90] These numbers come from: "Russian Federation," *Jane's World Air Forces*, March 11, 2015, "Iran," *Jane's World Air Forces*, February 25, 2015, "North Korea," *Jane's World Air Forces*, January 6, 2015, "China," *Jane's World Air Forces*, February 24, 2015.

Figure 2.18. Varying Target Demand with Changing Assumptions[91]



NOTE: Amphibious targets are presented here as averages derived from Figure 2.11, multiplied by 10 to account for an invasion involving 10 formations. Runway targets vary for each country by high and low CEP assumptions. Russian runway analysis was not conducted, but would likely be less than China due to Russia having fewer military runways. The fixed targets vary by $P_{survivability}$ of 0.9 to 0.5.

In Figure 2.19 and Figure 2.20, the dotted lines indicating bomber firepower capacity are replicated. The demand for cruise missiles on Day 1 of the conflict is spread over the first two days in these figures for two reasons, the first being that the presence of an extremely time critical threat such as an amphibious invasion would probably lead decision makers to forego the fixed targets until the amphibious invasion fleet is attacked. The second reason for presenting it in this manner is that the amphibious scenario is more relevant to a China-Taiwan scenario. If another scenario is postulated, the first column can be ignored and the second column can be assumed as the day one target demand.

Figure 2.19 indicates that the worst case assumptions increase the demand significantly, not just on Day 1 but throughout the scenario. The requirement to re-attack runways is driven by the

[91] The bomber daily launch capacity reported in this chart is comprised of the cruise missile launch capacity of the B-1 and B-52. These daily launch capacities are described in greater detail in the following chapter. Although the B-2 can also fire cruise missiles, it is excluded from this daily launch capacity calculation. There will be a demand for other targets sets during the first day of a conflict that can only be attacked by penetrating assets, and we assume that the B-2 will be used in this critical role at the start of the conflict.

enemy's ability to repair runways, which is assumed to be possible within 24 hours. The fixed-target demand can be reduced by decision makers if the war is expected to last a long time. The targets could be spread over a longer period of time if there is not as much time criticality involved. On the other hand, if the war is likely to be short, decision makers may ignore certain fixed targets if the enemy will not immediately feel the strategic impact of the fixed-target strikes.

Figure 2.19. Daily Target Demand for Worst Case Assumptions

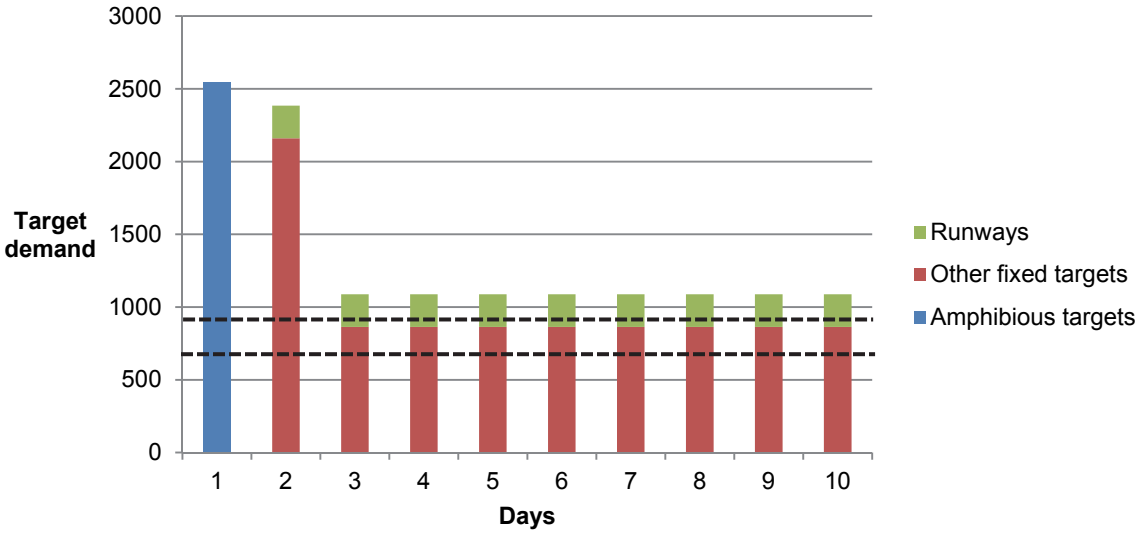
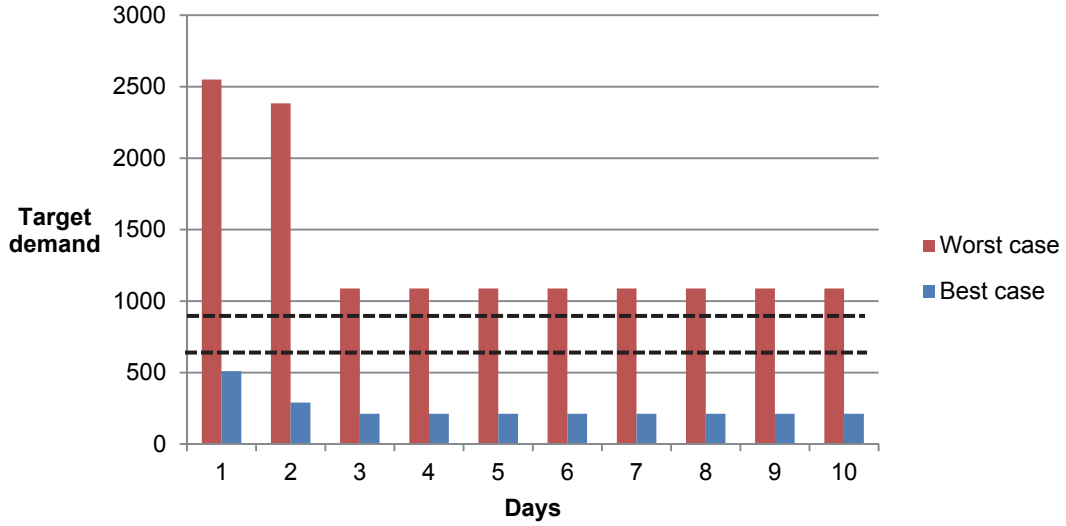


Figure 2.20. Daily Target Demand with Best and Worst Case Assumptions



One notable result from Figure 2.20 is that the best case demand for Day 1 comes close to reaching the lower dotted line, which represents the current bomber firepower capacity at an operating radius of 2000 nautical miles. The Day 1 demand represents the amount required to destroy 50 percent of the carrying capacity of an amphibious invasion. If there will be joint support in this kind of conflict, it would reduce the actual number of targets for the Air Force to strike. Regardless of the joint support, the key takeaway here is that even under favorable assumptions in an amphibious invasion the results for cruise missile demand almost reach the current bomber capacity. If force structure decisions are made conservatively, a spike in demand in the early days in a scenario may justify the acquisition of additional firepower capacity.

Summary of Findings

This chapter has addressed the question of how much standoff bombing capacity would be needed in an A2/AD conflict. Through exploratory modeling and simulation, a level of cruise missile demand has been identified for four primary target sets: halting an army, halting an amphibious invasion, striking time-critical fixed targets, and striking runways to degrade enemy air operations. The halt scenarios and time critical fixed targets proved to be the most arduous when using standoff assets. Runway targets were less burdensome, although runway repair capabilities would cause this target set to be recurring throughout the conflict. Fixed targets are the only target set that is fully compatible with current cruise missiles. The other three target sets would require development of more advanced cruise missiles that could carry anti-armor submunitions, ant-ship seekers, and runway penetrating submunitions. Cruise missile inventories would also need to be increased substantially to sustain the high levels of target demand identified in this analysis.

The core of the research question considered in this chapter is whether or not there is a shortfall in capacity for standoff operations. By combining target sets, we can construct a theater target demand. Under best case assumptions, the demand comes close to but does not exceed the current bomber fleet standoff capacity. Under worst case assumptions, this target demand largely exceeds the current bomber standoff capacity. It would be a viable option to acquire arsenal aircraft to fill this shortfall.

Aside from providing a measure of capacity gap in standoff bombing, this analysis also provided insight for indirect methods of reducing cruise missile demand. Improving ISR capabilities is an effective way of reducing enemy halt distance in the case of a land invasion. ASCM sensor ability can reduce cruise missile demand significantly in the case of an amphibious invasion. Larger salvo sizes and longer firing intervals can increase survivability and overcome weaknesses in battle damage assessment ability during an amphibious invasion. Accurate intelligence on airbases that have high priority aircraft can reduce the number of runways required for attack.

3. How Effective are Standoff Alternatives in Terms of Launching Cruise Missiles?

Overview

This chapter addresses the second of the research questions. It provides background information on the arsenal concept as well as capacity and performance comparisons for standoff alternatives. Arsenal aircraft are systems where long-range cruise missiles are launched in large quantities from large military cargo derivative or commercial derivative aircraft. They may be the best alternative for launching missiles into enemy territory while maintaining a safe distance from enemy air defenses. Arsenal aircraft's primary employment would be from standoff distances and hence can be considered to be a subset of the more general standoff bombers.

A total of 10 aircraft are analyzed in terms of their ability to carry and launch cruise missiles. These include current bombers, commercial derivative arsenal aircraft, and military cargo arsenal aircraft. In almost every case, the capacity of the aircraft to carry cruise missiles is limited by how much weight they can carry. Commercial derivatives are assumed to have a higher weight penalty for the installation of their launching system, whereas military cargo derivatives are assumed to have a smaller weight penalty because of their ability to deliver cargo through the rear opening. This assumption differentially affects the available payload for these alternatives, which is confirmed in the range-payload analysis. Commercial derivatives seem to have an advantage in terms of the unrefueled distance they can travel, i.e. the aircraft range. However, tanker orbits could of course extend aircraft ranges albeit at a cost.

The Arsenal Concept and Alternatives to Conventional Bombers

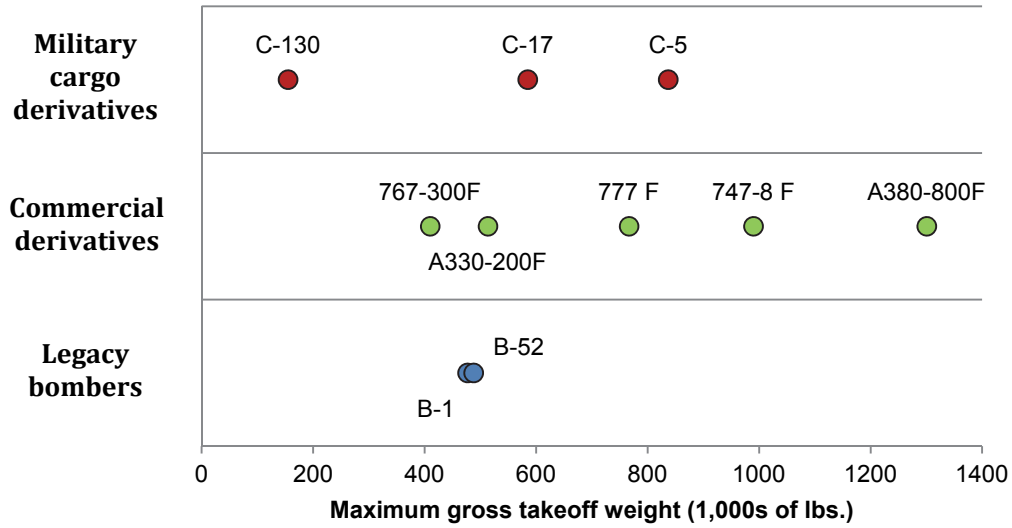
The arsenal concept was born in the 1970s. The air-launched cruise missile (ALCM) program was in its early stages, which made striking targets from long distance a reality. When the B-1 bomber program was cancelled by the Carter administration in 1977, the Cruise Missile Carrier Aircraft (CMCA) was explored by USAF as an alternate means of employing the cruise missiles under development.[92] Douglas Graves, Boeing Aerospace vice president at the time, made the following statement, which expressed the overall interest in the CMCA. "The large aircraft provides a maximum operational flexibility in terms of the number of missiles desired, the

[92] Wayne Biddle, "U.S. Faces Bomber Choice," (The New York Times).

operational radius and the number of tankers necessary to support the missions."[93] The idea of operational flexibility remains relevant in today's threat environment. The flexibility to launch a large salvo of cruise missiles all at once is appealing considering the potential for high intensity conflict with limited launch capacity from current legacy bombers.[94] Eventually the B-1 program was restarted in 1982, and the arsenal concept was abandoned. Since that time, the concept has occasionally arisen during discussion of future USAF aircraft procurement programs but ultimately was not pursued further.

Today, however, arsenal aircraft may be well suited for combat given new threats from enemy ballistic missiles, cruise missiles and SAMs. A total of 10 arsenal alternatives are considered in this analysis. A broad range of aircraft sizes were used in an attempt to determine the most cost effective platform. Figure 3.1 shows a comparison of the sizes of each alternative. These aircraft alternatives can be characterized by three aircraft classes: aircraft derived from military cargo aircraft; aircraft derived from commercial aircraft; and legacy bombers. These classes are discussed further below.

Figure 3.1. Size Comparison of Aircraft Alternatives



[93] Richard G. O'Lone, "Boeing Proposes 747 as Missile Launcher," *Aviation Week & Space Technology*, September 5, 1977.

[94] When the term "legacy bomber" is used in this report, it is referring to the B-1 and B-52 aircraft. The B-2 in most contexts is also referred to as a legacy bomber and, as stated earlier, can carry cruise missiles. However, due to its stealth capabilities, it is assumed that the B-2 will be involved in other missions that will exclude it from contributing to cruise missile capacity. We therefore omit the B-2 from the "legacy bomber" term in this report.

Military Cargo Derivative Aircraft

One possibility is to launch cruise missiles from a cargo aircraft. The three premier military inter-theater and intra-theater airlift platforms are considered in this analysis: C-130, C-17, and C-5. Each of these aircraft is characterized by low continuous cargo floors. The cruise missile launching mechanism could be used as a "roll-on/roll-off" system that could be utilized in a conflict.[95] With each aircraft currently being used in an airlift role, the roll-on/roll-off could allow these aircraft to continue operating in an airlift role and to have a dual role for arsenal missiles during times of high target demand.

Another option would be to procure new military cargo aircraft and create a dedicated fleet of arsenal aircraft.[96] This could be accomplished by reopening the closed C-17 production line.[97] With a dedicated fleet, this capability could be used as a replacement for the aging legacy bombers.

Commercial Derivative Aircraft

Another class of arsenal aircraft alternatives is based on a modified commercial airliner as a standoff bomber. The idea of modifying a commercial aircraft to carry and launch large numbers of cruise missiles is not new. When the B-1 program was cancelled in the 1970s, other methods of employing bombs (particularly cruise missiles) were explored. One of the options of that time was an idea by Boeing to convert a 747 airliner into a cruise missile launcher. By Boeing's projections, the arsenal aircraft would be capable of holding up to 90 cruise missiles.

The Boeing schematics for a 747 CMCA provide some insight into the kind of launching mechanism that would be required for such a concept. This schematic is shown in Figure 3.2, which illustrates a series of rail-type shifting rotary launchers that sequentially launch cruise missiles from an opening in the side of the aircraft fuselage.

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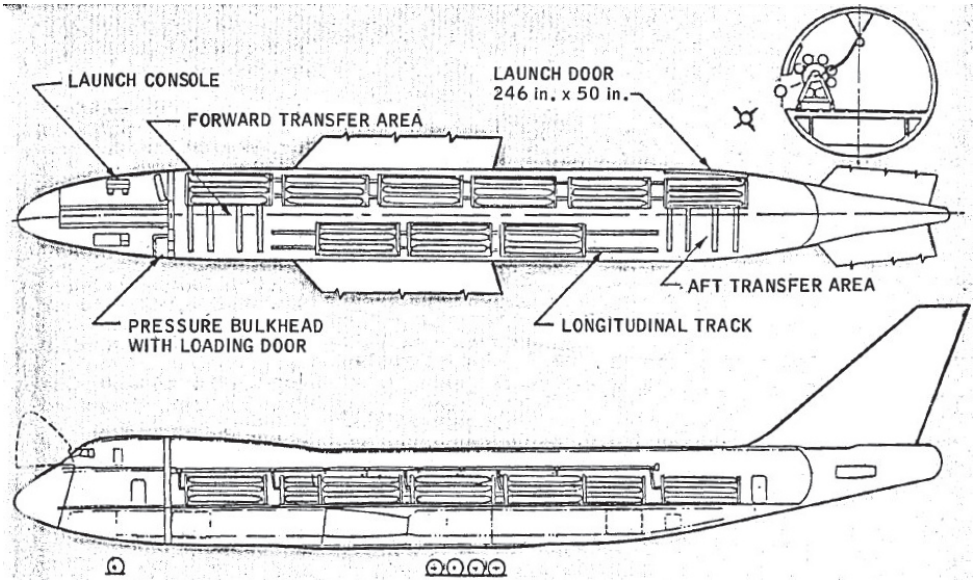
[95] Gurler Ari, *Cargo Aircraft Bombing System (CABS)*, Wright-Patterson AFB, OH: Air Force Institute of Technology School of Engineering and Management, 2003.

Bryan J. Benson, *Transport-Bombers: A Conceptual Shift in Precision Guided Munitions Delivery*, Maxwell AFB, AL: Air University School of Advanced Airpower Studies, 1996.

[96] The C-130J aircraft are actually still in production. Acquiring a fleet of these aircraft to use as dedicated arsenal aircraft would avoid the production line restart penalty associated with C-17 procurement. However, the C-130 (as shown later in this chapter) does not have an optimal range for operating in the Pacific, which is a primary theater of interest with regard to A2/AD. The limited range and slow airspeed provide some operational constraints that inhibit this aircraft. For this reason, this aircraft is not considered as a procurement option that would be designed to replace the bomber fleet.

[97] Reopening a closed production capability is not something new. In fact, there have been several historical examples of production lines being reopened. See John Birkler et al., *Reconstituting a production capability: an analysis of candidates for production re-start,* ed., Santa Monica, CA, RAND Corporation, 1992.

Figure 3.2. Boeing Schematic of CMCA Concept[98]



Several commercial freighters currently available were chosen for the analysis. This includes Boeing 737-300F, 777 F and 747-8F, as well as Airbus A330-200F and A380-800F. These aircraft are characterized by large payload capacity and a high continuous cargo floor. Commercial freighters indicated here will not continue production indefinitely. If the decision to pursue an arsenal aircraft is made 10 or 20 years from now, these exact planes may not be available for purchase off the production line and analysis will have to take into account the newer aircraft in production.

Legacy Bombers

The existing bombers, namely the B-52, and B-1, offer one method of delivering quantities of cruise missiles to a target location. However, these legacy bombers are characterized by internal bomb bays of limited volume. The maximum cruise missile loadout for these aircraft would require large numbers of aircraft delivering cruise missiles during times of high demand for long-range strikes. The B-2 is also capable of firing cruise. As previously mentioned in this report, in an A2/AD scenario there would be a demand for other targets sets during the first day of a conflict that can only be attacked by penetrating assets, and we assume that the B-2 will be used in this critical role at the start of the conflict.

[98] O'Lone.

Missile Launching System is an Important Consideration in Arsenal Development

The launching system to be used in an arsenal aircraft is an important consideration with regard to cost and effectiveness. Alternative launching systems can be categorized into the following classes.[99]

- **Fixed-position carriage launchers:** This type of launcher could be used on either commercially-derived or military cargo-derived aircraft. Missiles would be ejected horizontally from the aircraft through aft doors or through aircraft launching tubes. Cargo aircraft are already demonstrating this kind of launching mechanism in the miniature air-launched decoy (MALD) Cargo Aircraft Launch System (MCALS) that are discussed later in this report. An application of tube-launched cruise missiles is yet to be developed. The 737-derived P-8 maritime patrol aircraft has launching tubes used for sonobuoy deployment, but these are ejected out the bottom of the aircraft.
- **Fixed-position linear launchers**: Missiles launched using this system would be ejected through the bottom of the aircraft. These systems are commonly employed in bomb bays as free fall bomb racks. This kind of launching system would be limited by the number of missiles that can be stored above the bomb bay and may not be an optimal use of payload and space on a large arsenal aircraft.
- **Rotary launchers**: This class of launching mechanism was developed in the 1970s. The launchers can be either fixed or moveable, rotating to eject missiles through the bottom or side of the aircraft. Current bombers use rotary launchers that are fixed above the bomb bay door. This system would be an inefficient use of storage space on a larger aircraft, so a moveable system of rotary launchers would likely be the ideal candidate for this class of launcher.

An important feature of the launching system is the rate at which the cruise missiles can be fired. A moveable rotary system might have a considerable delay between launching the missiles from one rotary to the next. If this were true, launching a big volley of missiles using multiple rotaries would take a significant amount of time. This could be an issue for target demand scenarios where a large salvo of missiles is needed quickly, such as the amphibious invasion scenario discussed in the previous chapter. The cruise missile firing rate of each launching system is not analyzed quantitatively in this dissertation, but is noted here as an important consideration that might be a limiting factor if commercial derivative aircraft use rotary launchers.

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[99] Harold W. Bartel and James M. McAvoy, *Cavity oscillation in cruise missile carrier aircraft*: Lockheed-Georgia Co Marietta Structures Technology Division, 1981.

Metrics for Comparing Standoff Alternatives

The metrics used in this research for comparing the standoff alternatives are aircraft performance, including range-payload capabilities and sortie rates, and cruise missile carriage capacity.

Aircraft Capacity for Carrying Cruise Missiles

One of the primary metrics that was used to compare alternatives is the capacity of each alternative to carry cruise missiles. For the sake of comparison, a few assumptions were made with regard to the different launching mechanisms potentially available for each aircraft type. Military cargo derivatives are assumed to use fixed-position carriage launchers such as racks or pallets. Commercial derivatives are assumed to use rotary launchers, as depicted previously in Figure 3.2. Legacy bombers already have a maximum loadout configuration, which was used in the analysis.[100]

There are two competing constraints in terms of carrying capacity: weight and volume. Both constraints were determined for each aircraft and the most limiting constraint was chosen. For the commercial derivatives, volume considerations were addressed by obtaining the geometry of the fuselage from manufacturer data. The number of rotary launchers that can fit on the cargo floor was calculated. For weight considerations, commercial derivatives will incur the additional weight of the rotary launchers and other structural modifications for the launcher. The original Boeing design for a 747 CMCA had 90,000 pounds reserved for handling and launch equipment of the 290,000 pounds total payload.[101] This is roughly one third of the payload, which is the assumption used in the weight constraint analysis for commercial derivatives. The number of cruise missiles that can fit on the aircraft using the rotary launchers was compared to the weight limit of total available payload divided by the weight of the cruise missile. For this dissertation we used the Joint Air-to-Surface Standoff Missile (JASSM). For military cargo derivatives, the volume constraint was found by essentially stacking JASSMs on top of each other in a rack configuration, using height and width constraints on 463L pallets.[102] For weight constraints, the fixed-position carriage launchers were assumed to have minimal weight, so 95 percent of the payload on the military cargo derivatives was assumed to be available for cruise missile

[100] The B-52 1760 Internal Weapons Bay Upgrade is assumed in the analysis, which increases the B-52's maximum cruise missile loadout from 12 to 20.

[101] O'Lone.

[102] Missiles are stored in sealed containers. Containers must be opened inside the aircraft and missiles moved to the launching mechanism. This requires crew and space. Opened containers must be restacked or tossed. Otherwise some rack system would be required. Operating and support costs would increase for munitions ground crew.

carriage.[103] The weight constraint was found by dividing available payload by cruise missile weight. A summary of aircraft parameters used in this constraint analysis is shown in Table 3.1.

Table 3.1. Summary of Aircraft Parameters used in Effectiveness Calculations

	Operating empty weight	MGTOW	Max fuel weight	Max payload	Cruise speed (Mach)
A380-800F	552975	1300725	572025	333275	0.82
777 F	318300	766800	320863	228700	0.84
767-300 F	188100	410000	161740	120900	0.80
747-8 F	434600	990000	400218	292400	0.85
A330-200F	249923	513677	240754	143300	0.82
C-17	276500	585000	244854	164900	0.74
C-5	374000	837000	332500	261000	0.78
C-130	76469	155000	62530	42000	0.52
B-1	192800	477000	180000	133800	0.90
B-52	190000	488000	298000	97000	0.77

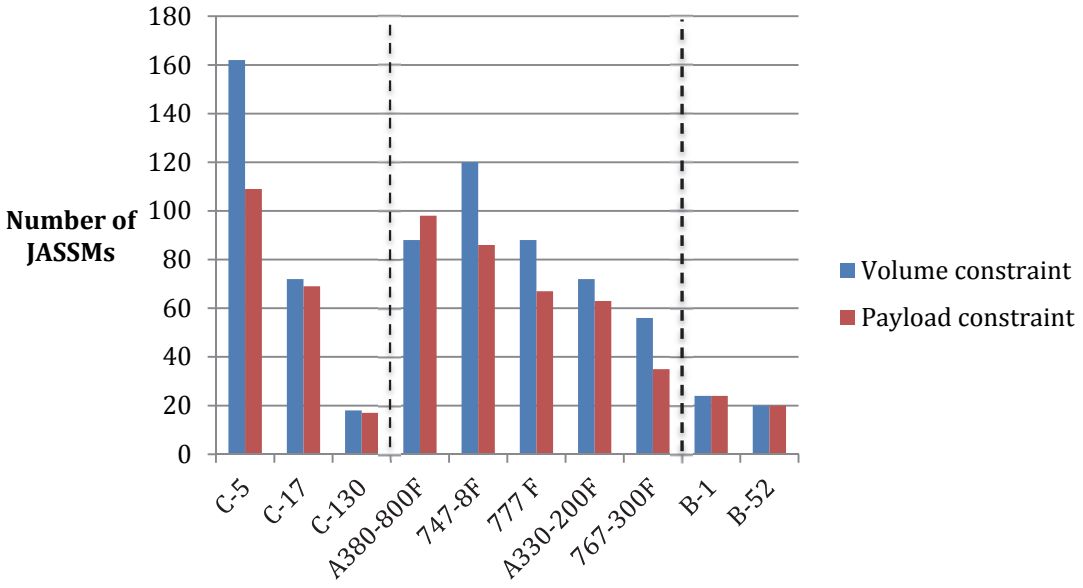
Figure 3.3 presents a comparison of volume and payload constraints for each aircraft. In this figure, legacy bombers assume a fixed carriage capacity and therefore have equal volume and weight constraints. For the most part, the payload constraint is the limiting factor. However, in the case of the A380-800F, the volume constraint is less than the weight constraint. It is interesting to note that the payload of the A380-800F is much higher than the rest of the commercial derivative alternatives. However, the 747-8F has the higher capacity in terms of volume. The reason for this is that the shifting rotary launcher system is assumed to operate one level of launchers on the cargo floor. The A380-800F can in fact fit a second level of rotary launchers above the first, which would greatly increase the capacity and cause the weight

[103] This assumption was derived from a rough estimate of 463L pallet weight. For instance, a C-130 can carry six 463L pallets (see the following reference: "Defense Transportation Regulation Part III, Appendix V - Aircraft Load Planning and Documentation," (U.S. Transportation Command).). These pallets weight roughly 300 lbs. each, so the total weight of the pallets would be 1,800 lbs. or 4% of the C-130 available payload.

This may sounds like an optimistic assumption. The truth is that the uncertainty about the launching system used in commercial derivatives and military cargo derivatives is highly uncertain and could vary significantly. As a general observation, though, the military cargo derivatives will probably have a launching system that weighs less than the commercial transport derivatives.

constraint to be limiting. However, the feasibility of rotating these rotary launchers within the fuselage may be questionable. For this reason, the assumption for a single level of rotary launchers was used. Another observation from Figure 3.3 is that the aircraft with the biggest difference between the volume and weight constraint may have an inefficient use of volume within the aircraft. For instance, the 747-8F can carry much more volume than payload in terms of JASSMs, so the cost of paying for a bigger aircraft may be offset by the lack of utilization of the entire cargo volume.

Figure 3.3. Volume versus Weight Constraints for JASSM Carriage in Aircraft Alternatives



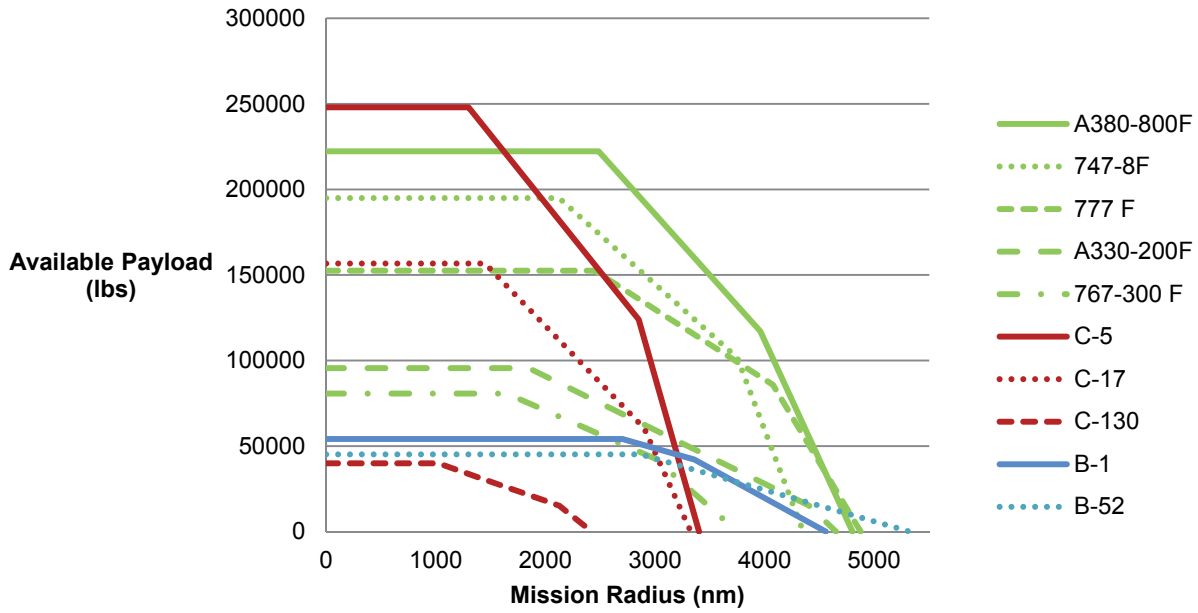
Performance of the Aircraft

In an attempt to determine the relative advantages of each arsenal alternative, an effectiveness analysis was conducted that compared radius-payload capabilities and sortie rates. Range-payload charts were gathered from manufacturer data for the commercial aircraft and flight manuals were used to determine the range-payload charts for military aircraft.[104] The highest points on the curve in Figure 3.4 represent the maximum structural payload. This

[104] Although the range-payload frontier is not linear, this analysis assumes linearity between points on the range-payload charts for simplicity. Data were extracted from Boeing and Airbus technical documents; see *Aircraft Characteristics - Airport and Maintenance Planning*: Airbus. and *Airplane Characteristics for Airport Planning*: Boeing. Data on military cargo derivatives were gathered from: "C-5M Super Galaxy: Unmatched Capability in Strategic Airlift," (Lockheed Martin). and "C-17 Globemaster III: Pocket Guide, Block 19 Edition," (Boeing, 2010).. General aircraft characteristics for legacy bombers were extracted from flight manuals; see "Air Force Tactics, Techniques and Procedures (AFTTP) 3-1.B-1," (Department of the Air Force). and "Air Force Tactics, Techniques and Procedures (AFTTP) 3-1.B-52," (Department of the Air Force).

maximum payload assumes that the launching system in the commercial aircraft would use one third of the available payload weight. Military cargo aircraft are assumed to use a palletized launching system, which will likely have a minimal effect on available payload. From left to right, the range-payload relationship trades payload and fuel for range until available payload becomes zero, indicating the aircraft's ferry range. Tanker support would provide unconstrained operation at maximum payload. However, for this analysis we do not consider tanker support and instead decrement payload as illustrated in Figure 3.4.

Figure 3.4. Radius-payload Comparison[105]



NOTE: The available payloads presented in this figure have been reduced to account for the weight of the launching system (33 percent of payload for commercial derivatives, 5 percent of payload for military cargo derivatives)

Several assumptions were made to calculate sortie rates at different ranges. Previous RAND analysis estimated sortie rates using the following equation[106], where *FT* is the flight time, *TAT* is the turnaround time, and *MT* is the maintenance time:

[105] The range payload chart is calculated for the bombers assuming that the payload is not dropped during the sortie but is returned to the base. This was done in order to keep the range payload charts comparable with the commercial and military cargo charts that are assuming a constant payload throughout the mission. Each chart would have some improvement in range if the payload was assumed to be dropped halfway through the sortie. Without the payload on the return flight, the total weight of the aircraft would be less and would lead to more efficient fuel use, which would extend the range of the aircraft.

[106] See Stillion and Orletsky, ed.

$$SR = \frac{24\ hours}{FT + TAT + MT}$$

That analysis used F-15 and F-16 data to determine the following relationship between maintenance time and flight time:

$$MT = 0.68FT + 3.4$$

There are two important caveats to this relationship. The first is that this relationship assumes average maintenance time. There are cases where no scheduled or unscheduled maintenance is required on the aircraft which would temporarily increase the sortie rate. The second caveat is that applying the fighter maintenance relationship to bombers may yield overly-optimistic sortie rates. With these caveats noted, these equations were used in this arsenal aircraft analysis to generate sortie rates.

Considerations of flight time assumed that the times to climb and descend were comparable to times for cruising flight. All aircraft were assumed to have the same turn time of 12 hours. Ideally, to increase the fidelity of this assumption the turn time would be dependent on refueling times, maintenance times, and weapons loading times. However, due to the uncertainty of these times (and in particular, maintenance times) for commercially derived aircraft, the turn time was applied equally to all alternatives.

Crew ratio, crew rest, and duty day limitations were also considered in this sortie rate analysis. Authorized bomber crew ratios were averaged and applied to all arsenal alternatives.[107] Guidance from Air Force Instruction (AFI) 11-202 provides limitations on crew rest and duty day for aircrews.[108] Minimum crew rest for all aircrews is 12 hours. Since we assume a 12 hour turn time for bomber aircraft, the "turn time" for aircrews will always be less than the time the bomber aircraft is on the ground for maintenance and turnaround operations. Regardless of the turn time differential, a sufficiently low crew ratio can degrade the sortie rate. To determine the smallest crew ratio allowable before sortie rates are affected, "cycle times" of the aircraft and aircrew must be compared. Cycle time here is defined as the time from the beginning of a sortie to the time the aircraft or aircrew becomes available to perform another subsequent sortie. For example, if a sortie lasts such that the duty day for an aircrew is 12 hours, the aircrew would receive 12 hours of crew rest following that sortie and the associated cycle time would be 24 hours from the start of the first sortie to the time that the aircrew is available to fly again. If the aircraft takes 18 hours to turn, the cycle time for the aircraft is 30 hours. The ratio of aircrew cycle time to aircraft cycle time becomes 0.8, which is the minimum crew ratio allowable before sortie rates begin to degrade based on aircrew limitations. For this analysis, authorized crew

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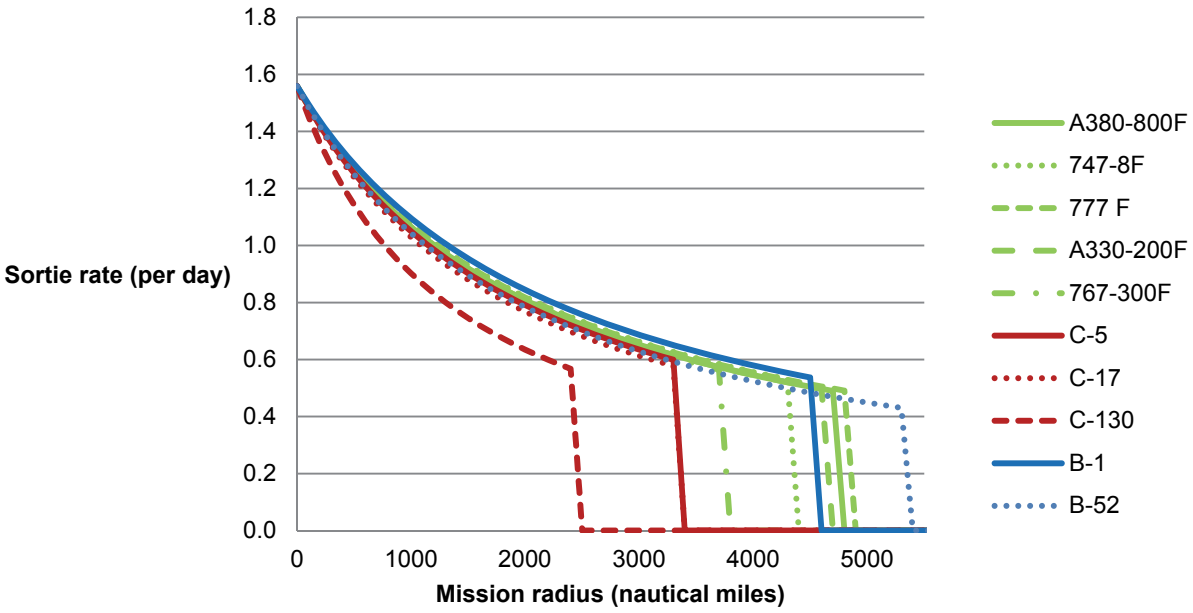
[107] *Air Force Pamphlet (AFPAM) 10-1403, Air Mobility Planning Factors*, Washington, D.C.: Department of the Air Force, December 12, 2011.

[108] *Air Force Instruction 11-202, Volume 3: Flying Operations, General Flight Rules*, Washington. D.C.: Department of the Air Force, April 5, 2006.

ratios specified by AFI 65-503 were not low enough to cause degraded sortie rates based on the assumption that aircrews "turn" faster than bomber aircraft.[109]

Being dual control aircraft, basic bomber crews can operate at a maximum duty day of 16 hours. Augmented crews provide additional crew members to allow rest periods where duty days are expected to be greater than 16 hours but less than 24 hours.[110] For this analysis, it was assumed that an augmented aircrew was 1.5 times a basic aircrew (i.e., a third pilot will be added to the aircrew). Since crew augmentation alters the effective crew ratio, the possibility of sortie rate degradation from low crew ratios becomes more apparent. However, the turn times for bomber aircraft are sufficiently greater than the crew rest period that sortie rates are not decreased. This analysis assumes surge sortie rates and doesn't take into consideration the 30-day and 90-day flying hour limitations on aircrews. Figure 3.5 illustrates the variation in sortie rates. Each curve comes to a halt as the range approaches the maximum range of the aircraft. All of the curves converge on the same point on the y axis. This is caused by the uniformity of the assumption for aircraft turn time of 12 hours.

Figure 3.5. Sortie Rate Comparison

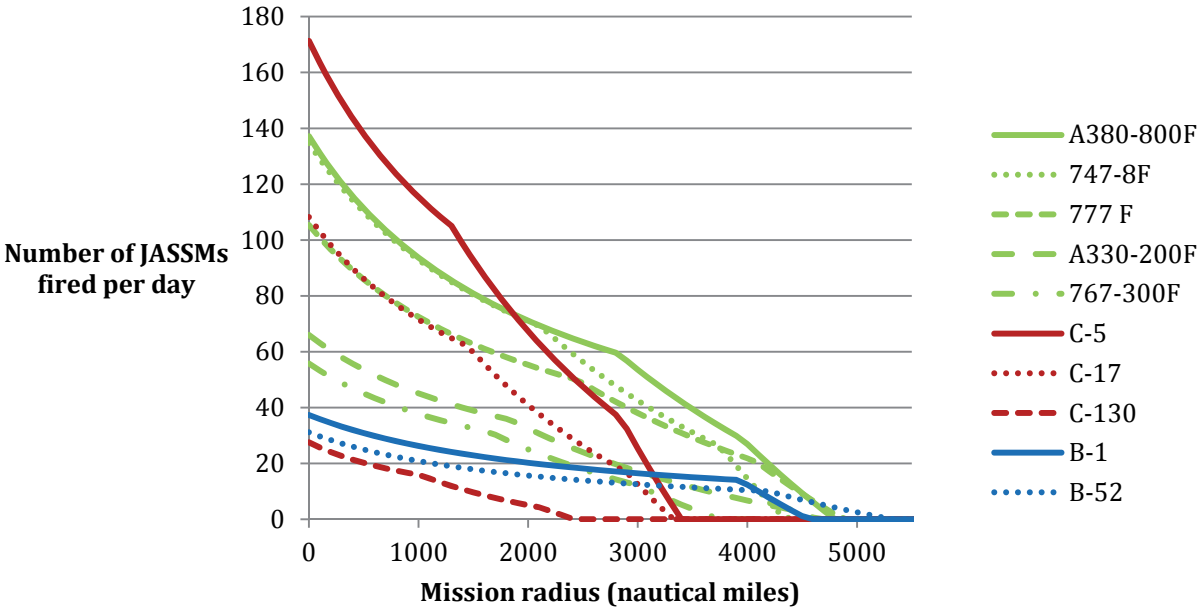


[109] *Authorized Aircrew Composition - Active Forces (Table A36-1)*, Washington, D.C.: Department of the Air Force, June 1, 2013.

[110] Air Force Instruction 11-202, Volume 3: Flying Operations, General Flight Rules.

The product of the ranges and payloads in Figure 3.4 and the sortie rates in Figure 3.5 yields maximum firepower that can be delivered per day at a specified range (Figure 3.6). We use the number of JASSMs as our measure of firepower.

Figure 3.6. Firepower per Day



To interpret Figure 3.6, one must take a specific range and compare the fire rate of cruise missiles, which in this case is Joint Air-to-Surface Standoff Missiles (JASSM). For example, at a 1000 nautical mile mission radius, the C-5 could launch the most missiles in a day at 115 missiles. This range-specific comparison is input to the scenario demand analysis presented in the following chapter.

Summary of Findings

From this analysis it is quite clear that the current bombers have a significant disadvantage when it comes to carrying cruise missiles. Their low storage capacity contributes to the overall issue that the current bombers may not have enough standoff firepower to handle certain stressing scenarios. Commercial derivative and military cargo arsenal aircraft have significantly higher cruise missile launch capacity and could provide supplemental standoff bombing capacity. Commercial derivative aircraft have longer ranges, which would reduce the tanker demand especially in the Pacific where longer ranges of operation are necessary. On the other hand, commercial derivatives have a larger weight penalty relative to military cargo derivatives due to the weight of the launching system. Military cargo derivatives might then have a more efficient use of payload due to this differential weight penalty.

4. What Will it Cost to Acquire and Maintain Standoff Alternatives?

Overview

The costs of the alternatives are analyzed in this section. Costs are divided into two stages. The first stage includes costs that are incurred when the aircraft is developed and procured. The second stage consists of the remaining lifetime of the aircraft where money is spent to operate and sustain the aircraft. The following approaches were used to calculate costs in this analysis:

- **First stage--acquisition costs (development and procurement):** Commercial derivative arsenal costs are analyzed through regression of data from selected acquisition reports. Costs for a total of 13 new-build aircraft and two commercial derivative aircraft are used as data points in the regression. The two commercial derivative aircraft included in the data are the P-8 and KC-46. These aircraft provide some insight to cost by being somewhat analogous to arsenal aircraft acquisition. However, the P-8 and KC-46 may not be the best at representing the modifications to the aircraft that would be required. The C-17 is another procurement option, in which case a cost penalty would be assessed for having to restart the production line. Already existing military cargo derivatives would be a low-cost option. Development and procurement of the launching system would be the only acquisition costs required by existing military cargo aircraft, which are assessed through cost analogies.
- **Second stage—keeping the aircraft operational:** Dedicated arsenal aircraft will need to be sustained throughout their lifetimes. Sustainment costs are assessed through multivariate regression of historical cost data. The statistical model created from this regression is demonstrated to have predictive accuracy during the procurement phase and steady state of aircraft operation. Crew and fuel costs are calculated separately using alternate methods.

In general, this cost analysis indicates that results scale roughly with weight of the aircraft for a fixed buy size. The C-17 acquisition incurs a penalty for restarting the production line but avoids the high development costs associated with building a new airplane. Using existing cargo aircraft would yield minimal cost since there would be minimal acquisition and sustainment costs.

General Approach for Cost Analysis of Arsenal Options

At this time, design of an arsenal aircraft including the weapon launching system is not defined in any detail. Because of this, cost estimations are expected to be somewhat imprecise.

The cost estimating approach must respect this lack of definition, yet provide sufficient detail to demonstrate the methodology and to arrive at consistent estimates among arsenal aircraft alternatives. Several cost estimating approaches can be used to predict the costs of a conceptual aircraft. They include: (1) A bottom-up approach based on detailed engineering/manufacturing design analysis, (2) Parametric/analogous methods, with input based on preliminary design analysis, and (3) A conceptual estimation based on a few general characteristics common in any preliminary design. Detailed and preliminary design analyses are outside of the scope of this dissertation. Although these methods provide more accuracy, they are highly intensive. We must use a combination of top-level, statistical estimating methods using acquisition data for past USAF and USN programs and operating cost data for current USAF aircraft. Analogies of similar aircraft programs are also used to provide some cost inferences. The methods and data are described in more detail throughout this chapter, which is organized around the three primary components of the lifecycle cost of an aircraft: (1) research, development, test, and evaluation (RDT&E); (2) procurement; and (3) operating and support (O&S). According to recent selected acquisition reports, O&S costs account for the majority of lifecycle costs at an average of 63 percent. Procurement costs account for 30 percent of the program lifecycle costs, and RDT&E accounts for seven percent.[111] This analysis assumes that military construction and aircraft disposal costs are negligible.

Cost data used to determine estimated costs for arsenal aircraft were obtained from several sources including selected acquisition reports and the president's budget documents. All costs shown in this dissertation have been adjusted to constant FY2015 values using appropriate USAF and USN indices.

Acquisition Cost Estimating Techniques are Informed by Analogies of Existing Systems

Acquisition costs can be defined as the sum of three primary categories of costs: RDT&E, MILCON, and procurement. Some systems require construction of facilities, which is identified as MILCON, or military construction. This analysis ignores MILCON costs due to the small magnitude of these costs compared to the other costs and focuses primarily on RDT&E and procurement. Converting a commercial or military cargo aircraft into a bomber has not been attempted in the history of USAF acquisition efforts.[112] If a conversion had been made, estimating acquisition costs could include parametric techniques, engineering estimates, or cost

[111] "Operating and Support Cost-Estimating Guide," (Office of the Secretary of Defense, 2014).

[112] The AC-130 is an example of converting a military transport into a gunship. However, gunship aircraft have several significant design differences from bombers.

proportions. However, without the relevant data, this analysis is left to use cost analogies based on existing systems and data.

Due to the major differences in the procurement strategy between commercial derivatives and military cargo derivatives, the acquisition cost analogies were conducted separately for each aircraft type. Costs for commercial derivatives were estimated using aircraft acquisition programs, whereas costs for military cargo derivatives were estimated using acquisition programs for launching systems. Although there may not be data for aircraft that are representative of this kind of procurement and modification, there are aircraft that have undergone similar modifications. Specifically, the USN P-8A, which is a commercially derived maritime patrol aircraft, and the USAF KC-46A, which is a commercially derived tanker, provide some insight as to how much an arsenal aircraft might cost. Although the modifications will not be exactly the same, the cost may be comparable due to similar military grade systems that are added to the aircraft. The other kind of acquisition effort to be investigated here is the conversion of a military cargo aircraft into an arsenal aircraft. There is one recent analogy which may be similar to the kind of launching system required on a military cargo aircraft. Raytheon's MALD Cargo Aircraft Launch System (MCALS) seems to be a potential candidate for launching cruise missiles. These three analogies were used in an attempt to capture an estimate of acquisition costs for the various arsenal aircraft alternatives.

Analogy 1: P-8A

The P-8A Poseidon is a multi-mission maritime aircraft based on the Boeing 737-800. Its predecessor, the P-3C Orion, was also a commercial-derivative aircraft based on the Lockheed L118 Electra. The P-8A contract was awarded to Boeing in 2009 to replace the aging P-3C fleet. With a primary mission of anti-surface and anti-submarine warfare, the aircraft employs a full range of maritime patrol equipment and weapons. It is seemingly a prime example of the cost of militarizing a commercial aircraft for a combat role. Features of the P-8 program could serve as an estimation baseline for the arsenal aircraft.

Figure 4.1. Photo of P-8A Aircraft[113]

The amount of mission equipment that was added and the level of structural modifications that were made to the baseline Boeing 737-800 were significant. Table 4.1 summarizes the changes that were made. The equipment required for the aircraft to perform maritime surveillance would be overkill for an arsenal aircraft. It could even be argued that countermeasures are not necessary if the arsenal aircraft is going to operate exclusively at standoff distances, far away from any air-to-air or surface-to-air threats. The P-8A itself was designed to operate in permissive environments, yet countermeasures were included as a measure of security. Standard military avionics and weapon control systems would be necessary for a standoff bomber, but other systems on the P-8A may be not quite analogous to the arsenal concept.

On the other hand, P-8A structural modifications may be similar to the modifications that would be made to a commercially derived aircraft to convert it to an arsenal aircraft. Both the P-8A and the arsenal aircraft would require the creation of an internal weapons bay, although the arsenal aircraft's weapons bay would be much larger. Cutting a weapons bay out of a commercial fuselage would require a considerable amount of structural reinforcements. In addition, the arsenal aircraft would need a complex launching system to carry and release cruise missiles in very large quantities. The P-8A has a free fall bomb rack, but the arsenal aircraft would need some sort of rotary launching system.

The operating empty weight of the Boeing 737-800 aircraft is 91,300 pounds. After modifications, the operating empty weight of the P-8A is 133,500 pounds. The total difference in operating empty weight is 42,200 pounds, or in other words, the weight of the baseline commercial aircraft was increased by 46 percent through modifications. This represents the net

[113] From www.navair.navy.mil

difference in weight, but there may have been material removed from the 737-800 which implies a "new weight" greater than the 42,000 change in OEW.

Table 4.1. Modifications to Boeing's Baseline Commercial Aircraft during P-8A Development[114]

Equipment
Standard military avionics
Inmarsat antennae
Link 11, Link 16
Advanced airborne sensor (AAS)
Active multi-static and passive acoustic sensor system
Digital EO/IR sensor system
Electronic support measures (ESM) system
Directional infrared countermeasures (DIRCM)
Electronic warfare management system (EWMS)
Flight management and digital stores management system
Up to 7 operators consoles
Structural modifications
In-flight reloadable sonobuoy launchers
Additional fuel in aft baggage hold
Internal weapons bay
Wing-mounted and centerline pylons for weapon carriage

The planned procurement of the P-8A for use as a multi-mission maritime aircraft would result in 109 aircraft and span 10 years of aircraft production. The cost metric used in this analysis was average procurement unit cost (APUC), which is the total procurement cost divided by the number of units produced. This APUC value changes with respect to the number of aircraft produced. This is caused by the fact that aircraft procurement programs generally experience some learning or improvement as more aircraft are produced. According to projected cost estimates, the expected APUC would be approximately $216 million.[115] The learning curve for this buy was roughly 90 percent.[116] These cost estimates may not be exactly applicable to arsenal aircraft for a few reasons. The first is that the buy size of the P-8A fleet could be much higher than the buy size of arsenal aircraft. A smaller buy size may correlate with a different learning curve assumption. The length of aircraft production may also differ depending on the complexity of the aircraft modifications.

Analogy 2: KC-46A

The KC-46 aircraft is currently being developed as a replacement for the aging USAF tanker fleet. This aircraft is another example of a militarized commercial aircraft, derived from a Boeing

[114] Data found in the following sources: "Boeing P-8A Poseidon," *Jane's All the World's Aircraft*, 31 Dec 2014.; "P-8A Multi-Mission Maritime Aircraft (MMA)," in *U.S. Navy Fact File* (U.S. Navy, 2009).

[115] Adjusted cost, FY15 dollars

[116] Data retrieved from U.S. Department of Defense, *Selected Acquisition Report, P-8A Poseidon Multi-Mission Maritime Aircraft*, December 2014. Learning curve calculated using end item recurring flyaway costs, aligned with quantity. Learning curve theory will be discussed in the procurement section of this chapter.

767-2C to perform a specific mission. Part of the modifications to the aircraft will include additional fuel capacity and an aerial refueling boom system. These systems are much different than those that would be required by an arsenal aircraft, and the KC-46A will not be a weaponized aircraft. However, it still provides some utility in being analogous to a commercial derivative aircraft.

Figure 4.2. Depiction of KC-46A Aircraft[117]

As shown in Table 4.2, the KC-46A requires fewer equipment and structure modifications to make it an appropriate replacement for the USAF tanker fleet than the P-8A required to turn it into a multi-mission maritime aircraft. The KC-46A will be operating primarily in permissive environments; the assumption is that arsenal aircraft also will operate in permissive environments. Perhaps warning radar and countermeasures would be added to the arsenal aircraft as appropriate insurance especially considering the large amounts of expensive cruise missiles carried on one aircraft.[118]

The operating empty weight target for the KC-46A program is 204,000 pounds Boeing currently projects that the aircraft will meet that target. Assuming the operating empty weight for the baseline 767-2C aircraft is approximately 172,000 pounds, the weight will increase by 32,000 pounds or 18.5 percent of the original weight during modifications.[119] In terms of percent

[117] From AF Factsheet

[118] Adding some defensive capability to the arsenal aircraft may reduce the need to provide escorts for the high value asset. Aside from the standard SAM and fighter threats, there also exist threats from enemy special forces that could operate near U.S. airbases. A special forces team operating man-portable air-defense systems (MANPADS) could destroy a large amount of U.S. firepower if the arsenal aircraft did not have defensive capabilities.

[119] The numbers presented here are rough estimates. If a design for an arsenal aircraft existed, there could be more precision as to the exact weight of modifications, in which case an analysis of cost per pound of modifications might have been sufficient for estimating costs.

increase, the P-8A program is more than double the percentage weight increase of the KC-46. In reference to the estimated change in weight of the arsenal aircraft options, the assumption is that one third of the maximum payload will be used to make the necessary modifications. Under that assumption, all commercial arsenal options range from 19-24 percent increase in weight from the baseline commercial aircraft. However, there would be a large amount of additional modifications besides the launching system itself, so the percent increase in weight metric may not be the best representation of cost.

Table 4.2. Modifications to Baseline Commercial Aircraft during KC-46A Development[120]

Equipment
Standard military avionics
SATCOM terminal
Link 16
Mission control system
Digital radar warning receiver, anti-jam GPS receiver
Tactical situational awareness system (TSAS)
Large aircraft infrared countermeasures (LAIRCM)
Air refueling operator's station with panoramic three-dimensional displays
Structural modifications
Multipoint refueling system
Additional fuel tanks

Like P-8A production, KC-46A production is expected to reach a large number of total aircraft inventory—175 aircraft by 2027. The projected APUC is estimated to be $191 million.

Analogy 3: MCALS

The previous analogies are an attempt to describe a commercial derivative arsenal aircraft. The P-8A and KC-46A are not perfect analogies, but rather offer a potential upper and lower bound. Similarly, there are no perfect analogies for a launching system to be used with a cargo aircraft. However, there are some examples of systems that were acquired that are somewhat analogous and can provide insight into the costs associated with a military cargo derivative arsenal aircraft.

Raytheon has developed a system for launching miniature air-launched decoys (MALD) from the back of a C-130. This concept was demonstrated in 2011 using the MALD Cargo Air Launched System (MCALS). The demonstration launch of a MALD decoy is illustrated in Figure 4.3. MCALS consists of a steel frame that can hold up to eight MALDs. It is loaded onto cargo aircraft using a standard cargo pallet. Each MALD is ejected from MCALS and initiates an ignition sequence.[121] This type of system may be desirable for an arsenal aircraft application,

[120] Data from the following sources: "Boeing 767 Military Versions," *Jane's All the World's Aircraft*, Feb 6, 2015.; Michael Sullivan et al., *KC-46 Tanker Aircraft: Program Generally on Track, but Upcoming Schedule Remains Challenging*: Government Accountability Office, 2014.

[121] "Raytheon Deploys Miniature Air Launched Decoys From C-130 Cargo Aircraft," (Raytheon).

especially if it were designed to be a roll-on/roll-off system. For the MCALS, there would have to be only minimal structural modifications made to the aircraft. With bigger aircraft and much higher load capacity, the launching structure would have to be much larger. With multiple launching structures loaded in sequence, there may be an argument to develop a new launching system that simultaneously releases an entire pallet of cruise missiles out the back of the aircraft.

Figure 4.3. Photo of a MALD Decoy being Launched from a C-130 Using MCALS[122]

The MCALS system is currently a Raytheon funded program, and no public cost data are available. For this reason, it is necessary to use other analogies to provide upper and lower bounds for the cost of this type of launching system. It should be noted that the analogies used to estimate the launching system are far from perfect. In addition, the costs of launching systems estimated through these analogies are orders of magnitude smaller than the costs of an aircraft, so the weight of importance is not exactly critical in attaining exact estimates for this kind of a system.

The two analogies selected for this analysis are joint precision airdrop system (JPADS) and the common strategic rotary launcher (CSRL). The purpose of JPADS is to provide sustainment to combat troops using high altitude precision airdrop as a means to deliver supplies directly in a theater. JPADS consists of several types of off-the-shelf government cargo pallets used on several aircraft including the C-130 and C-17, in which case they are released out of the back of the aircraft using a parachute system.[123] The JPADS acquisition could be seen as potentially a comparable acquisition project to an arsenal-type launcher in terms of cost. Dealing with live weapons would likely increase the RDT&E and procurement bill, so JPADS may serve as a

[122] Photo retrieved from Jane's Defense Weekly

[123] Richard Benney et al., "DOD JPADS programs overview and NATO activities" (paper presented at the AIAA Aerodynamic Decelerators Conference, 2007).

lower bound estimate as to what might actually occur in military cargo derivative arsenal aircraft.

As an upper bound for costs, one particular launching system that was integrated into combat aircraft was the CSRL. The CSRL was designed to reduce acquisition costs for a weapons launcher for the B-1 and B-52 programs by acquiring a common launcher that could be used for each of them as well as future strategic bombers. What makes the CSRL somewhat comparable to the military cargo arsenal aircraft is that the CSRL is a removable launcher that can be preloaded, just as a pallet launcher could be preloaded before it is placed on the aircraft. The fact that the CSRL needed provisions for launching nuclear weapons makes the CSRL an upper bound due to the high costs associated with nuclear capable systems. Table 4.3 shows a comparison of the costs for these two programs. The RDT&E costs are comparable, whereas the procurement costs are orders of magnitude different.

Table 4.3. Comparison of JPADS and CSRL Costs (FY15 $ Millions)

	JPADS[124]	CSRL[125]
RDT&E	$78.9	$528
APUC	$0.007	$6.11

Development Cost

RDT&E costs, referred to more generally as "development" costs in this report, are the recurring and nonrecurring costs associated with efforts to research and develop new systems. Development costs were estimated using multivariate regression analysis for commercial derivative acquisition programs. Development costs for military cargo derivatives were estimated using cost analogies and other cost data.

Commercial Derivatives

Previous RAND analysis developed a relationship between acquisition costs and aircraft empty weight using data from selected acquisition reports. The result of the analysis was a univariate regression model with the natural log of the cost as the outcome variable and the natural log of the aircraft weight as the predictor variable. The aircraft included in that univariate regression were the following: AV-8B, B-1, B-2, C-17, C-5, F-14, F-15, F-16, F/A-18A/B, F/A-18E/F, F-22, F-35, and V-22.

[124] These estimates were found using FY11-FY14 President's Budgets.

[125] U.S. Department of Defense, *Selected Acquisition Report: Common Strategic Rotary Launcher (CSRL)*, Washington, D.C., December, 1988.

Multiple studies have shown weight to have a positive correlation with aircraft costs.[126] In fact, of previous empirical investigations, it was found that only three variables provide the most utility in cost estimating relationships for aircraft. These variables include aircraft quantity, speed, and weight. Quantity produced has little bearing on the RDT&E cost, and for this analysis was accounted for in procurement costs. The underlying logic behind the relationship between cost and weight seems intuitive—the more material and equipment an aircraft has, the more it will cost to build and maintain. For this analysis of acquisition costs, empty weight was used as the primary weight metric. Weights such as combat weight or maximum gross takeoff weight account for the weight of fuel, weapons, and crew. In acquisition dollars, the cost of the fuel, weapons, and crew weight is irrelevant and not exactly representative.

This RAND-developed model would be a candidate for predicting the costs associated with a commercial derivative arsenal aircraft. However, there are a few caveats to consider. The first is that the aircraft in the regression are all new design, new-build aircraft. As such, the costs for the aircraft are likely much higher than the costs of commercial derivative acquisitions. KC-46 and P-8 costs are included in the data set to account for this distinction. Another caveat in using this kind of approach is that the small number of data points restricts the number of predictor variables that can be used. A general rule of thumb suggests that the ratio of predictor variables to data points be no more than 1:10. This regression slightly exceeds that rule with a ratio of 1:5 using three variables: empty weight, commercial derivative (dummy variable), and stealth (dummy variable).[127] The resulting regression model yields statistical results shown in Table 4.4. Rather than using RDT&E cost, this relationship instead regresses engineering and manufacturing development (EMD) costs on aircraft empty weight. EMD costs are incurred after an EMD contract is awarded. RDT&E costs include the EMD funds as well as funds spent before the EMD contract, and in some instances, costs for modifications following original EMD completion. Due to these inconsistencies, EMD costs are used in the RAND developed model.

Table 4.4. EMD Regression Results

	ln(EMD cost)
ln (Empty weight)	0.293*
	(0.11)

[126] See Ronald Wayne Hess and H. P. Romanoff, *Aircraft airframe cost estimating relationships: study approach and conclusions,* ed., Santa Monica, CA, RAND Corporation, 1987.; G. S. Levenson et al., *Cost-estimating relationships for aircraft airframes,* ed., Santa Monica, CA, RAND Corporation, 1972.

[127] Other variables may have some influence in the model but had to be excluded due to the small number of data points. These include the combat capabilities of the aircraft, material composition of the aircraft, and aerodynamic properties like maximum speed.

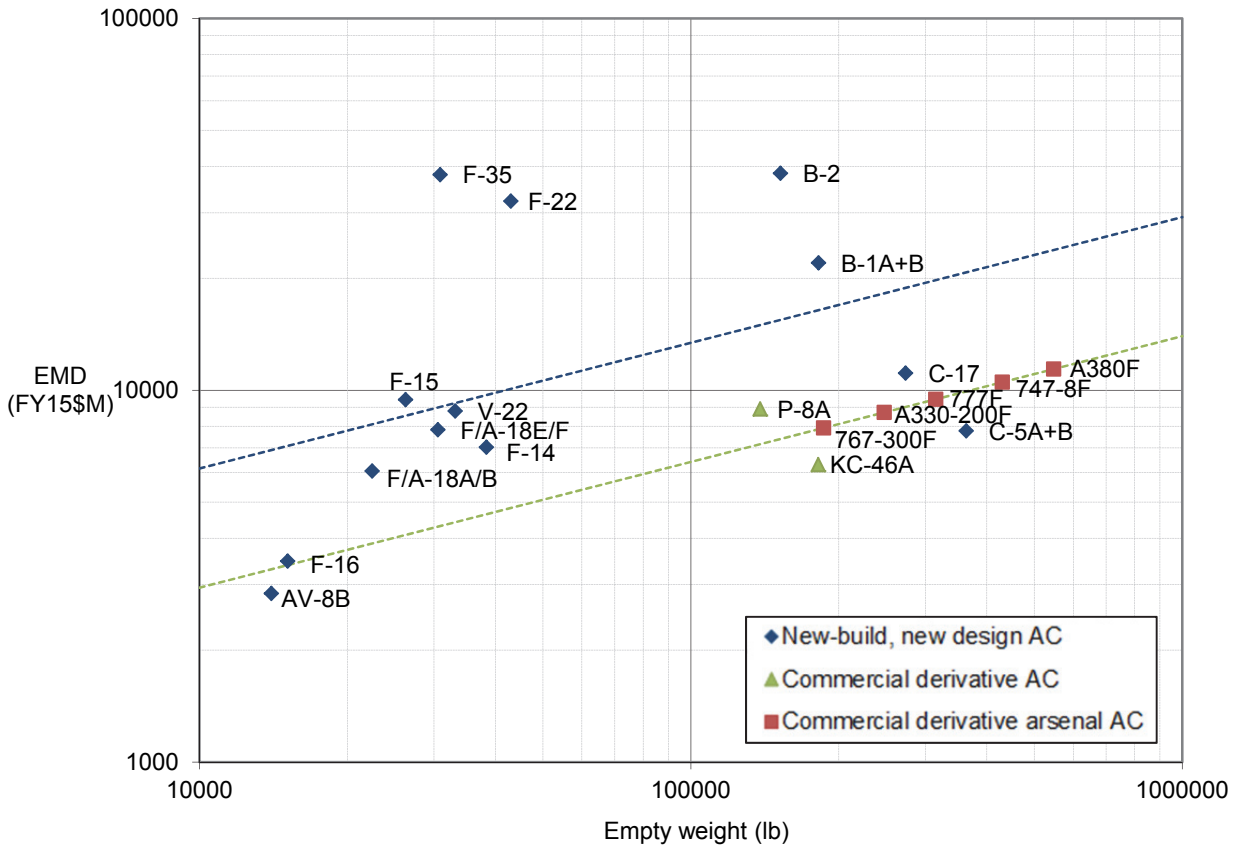
$\delta_{\text{Commercial derivative}}$	-0.334
	(0.34)
δ_{Stealth}	1.529***
	(0.27)
Constant	5.751***
	(1.16)
R^2_{adjusted}	0.745
Root MSE	0.406
N	15

This table presents the results of OLS regression with EMD (FY15$M) as the outcome variable. Standard errors are shown in parentheses.
* p<0.05, ** p<0.01, *** p<0.001

Figure 4.4 shows the data points used to determine the regression results. The blue diamonds on the plot represent the aircraft used to determine the relationship between EMD cost and empty weight. The blue line in the center of the plot represents the estimated log-log relationship between empty and EMD cost for new build aircraft. The P-8 and KC-46 acquisition programs are plotted on the chart as green diamonds. They both fall near the lower end of the estimates which happens to be at the edge of the standard error of the regression. In fact, the KC-46 falls outside the standard error range of the estimate.[128] If these cases are representative of commercial derivative acquisitions, they would indicate that the central regression line for new build aircraft overestimates commercial derivative costs. Because of this, we account for the fact that these data points are commercial derivative aircraft using a dummy variable in the regression. The red squares on the plot indicate estimates of EMD cost for the five commercial derivative alternatives. The relationship between EMD cost and empty weight for commercial derivatives falls exactly between the P-8 and KC-46. It may be the case that the complexity of modifying a commercial aircraft to carry a large amount of weapons will result in higher costs. However, there is little else that can be inferred on a major defense acquisition program on something like an arsenal aircraft that has never been accomplished before.

[128] Boeing is currently overrunning the fixed development contract significantly. It is important to note that adjustments have been made to the costs of other programs among the 13 in the sample set to account for contractor losses, since SARs report only the costs to the government. In general, the KC-46 is in much earlier stages than the P-8 which should indicate that the KC-46 costs are probably more variable. With the adjustment, the point indicating KC-46 development cost would increase to account for this recent development. However, KC-46 and P-8 cost data were obtained from 2014 SARs so we leave the point as is.

Figure 4.4. Relationship between EMD Cost and Aircraft Empty Weight



NOTE: Empty weights for arsenal alternatives are for baseline commercial aircraft. The blue line indicates the relationship between EMD and empty weight for new build AC. The green line represents the same relationship, controlling for commercial derivatives. The commercial derivative arsenal aircraft fall along the green line since that is the primary relationship used to predict EMD costs for the alternatives.

Military Derivatives

Estimates for the military cargo version of arsenal aircraft were determined in this analysis using a different method entirely. The estimates for military derivative aircraft are obtained by taking the average of the upper and lower bound estimates of the JPADS and CSRL EMD costs. It is important to note that this method is much simpler than the method used for the commercial derivatives. The development costs are expected to be much less than that of the commercially derived aircraft. Newly built aircraft have to undergo intensive flight test and evaluation of all the various subsystems on the aircraft. Mission specific testing is also conducted to measure effectiveness parameters. Military cargo derivatives will for the most part avoid the development effort associated with aircraft acquisition programs. Rather, the development effort will be dedicated to testing the launching system and ensuring that the weapons are ejected successfully under a variety of conditions. The analogies of JPADS and CSRL will be used to inform the estimate. These programs required the testing of these systems and are segregated from RDT&E costs associated with aircraft acquisition. This analysis assumes that the cost of research and

development for the launching system of a military cargo arsenal aircraft is the average of JPADS and CSRL cost. Using costs from Table 4.3, the estimated cost of a notional cargo derivative launcher is $304 million.

Procurement Cost

Procurement costs are estimated in a similar manner as EMD costs. The procurement cost of an acquisition program is comprised of recurring and nonrecurring costs associated with the production of the aircraft, plus the costs of initial spares, data, training, support equipment and other activities and equipment to establish an operational unit. The cost metric used in this analysis was APUC. For the regression analysis of APUC versus empty weight, the cost of the first 100 aircraft is used. This quantity generally is sufficient for the production program to stabilize but is early enough to avoid the cost change associated with model changes.

The cost-effectiveness analysis described in the next chapter did not result in arsenal aircraft with production quantities of exactly 100. Hence, we need to adjust the APUC obtained using the regression analysis described here to other quantities. The basic learning-curve theory is that as the total quantity of units doubles, the cost per unit is reduced by a percentage of the former cost.[129] The cumulative average cost can be represented by the following power function:

$$C_{Avg} = C_0 x^{\log(S)/\log(2)}$$

In this equation, C_{Avg} is the cumulative average cost of all units, C_0 is the cost of the first unit produced, x is the number of units produced, and S is learning rate or the rate at which cumulative average cost decreases as quantity doubles.[130] This equation is presented here for demonstration, and was used in Chapter 5 of this report when different buy sizes are analyzed.

Commercial Derivatives

APUC values for the first 100 production aircraft are analyzed using the same set of predictor variables as the EMD analysis. The same caveats from that analysis are also observed here. Table 4.5 shows the statistical results from the APUC regression. The standard error of the outcome variable is comparable to the EMD model.

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[129] The learning curves for commercial derivatives and C-17 production are slightly different. Commercial derivative aircraft will experience a significant amount of learning improvement because the modification processes will undergo improvements in efficiency, coordination, etc. The C-17 has already been in production for quite some time and will not experience as much learning improvement due to the number of units already produced. There will, however, be a learning curve penalty assessed due to the time lapse from closing and reopening the production line.

[130] H. E. Boren and Hugh G. Campbell, *Learning Curve Tables: Vol. 1, 55-69 Percent Slopes,* ed., Santa Monica, CA, RAND Corporation, 1970.

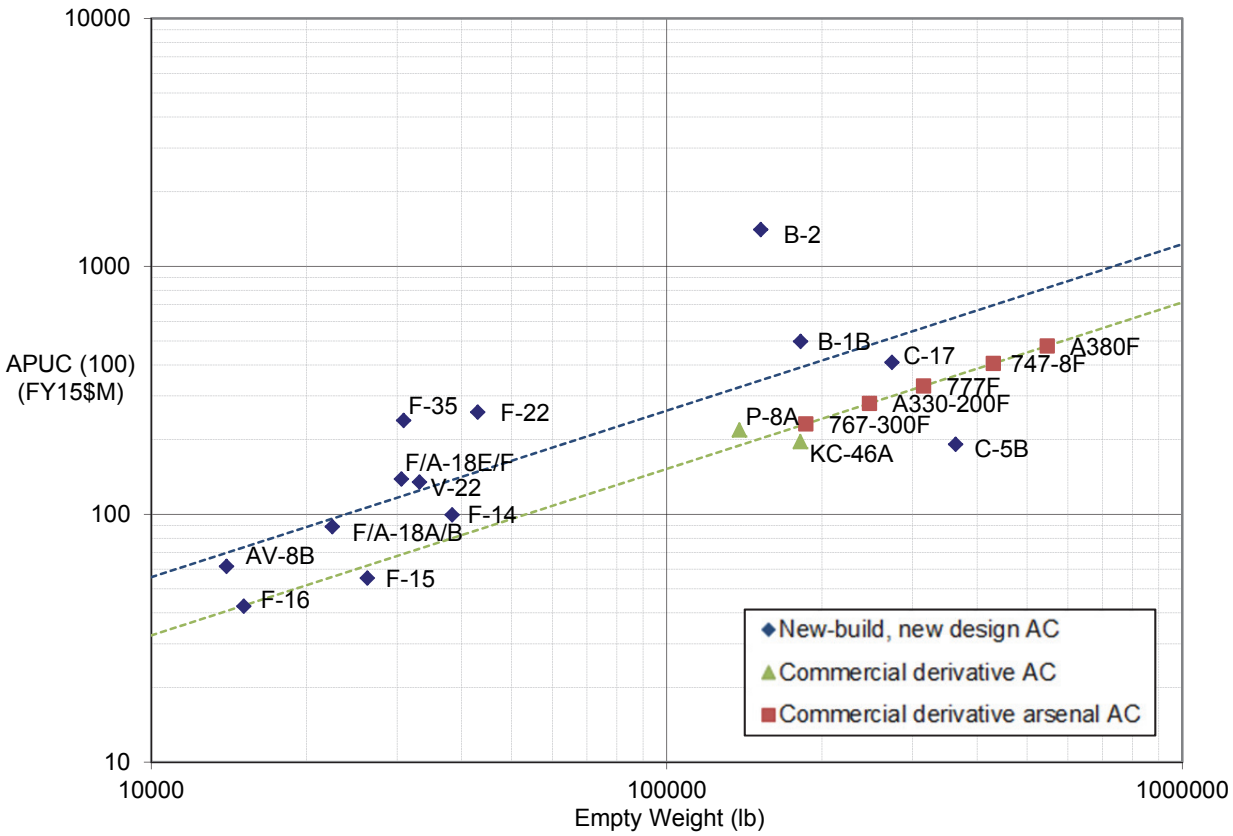
Table 4.5. APUC Regression Results

	ln(APUC)
ln (Empty weight)	0.638***
	(0.12)
$\delta_{\text{Commercial derivative}}$	-0.237
	(0.37)
δ_{Stealth}	1.155**
	(0.29)
Constant	-2.064
	(1.25)
R^2_{adjusted}	0.771
Root MSE	0.439
N	15

This table presents the results of OLS regression with APUC (FY15$M) as the outcome variable. Standard errors are shown in parentheses.
* p<0.05, ** p<0.01, *** p<0.001

APUC values are plotted versus empty weight in Figure 4.5. In general, the same trends are observed here as the EMD plot. Commercial derivative aircraft are overlaid on the plot for comparison and are below the center line for their empty weights. Procurement costs are determined for commercial derivative options by regressing over all the data points and including a dummy variable for commercial derivative aircraft. The resulting estimations are included on the plot for all five commercial derivative alternatives.

Figure 4.5. Procurement Cost versus Aircraft Weight for New-Build Military Aircraft



NOTE: The procurement cost displayed in this chart is the APUC for a buy size of 100 aircraft. The blue line indicates the relationship between APUC and empty weight for new build AC. The green line represents the same relationship, controlling for commercial derivatives. The commercial derivative arsenal aircraft fall along the green line since that is the primary relationship used to predict APUC costs for the alternatives.

Military Derivatives

The military could procure more C-17s, but that is the only feasible procurement option among military cargo derivatives for procuring new aircraft. The C-17 production line closed in 2015 and would have to be restarted. If the production line were reopened, the program would incur the costs of tooling, possible new production facilities, and airframe engineering labor. A previous study provided insight into the cost increase during a C-17 production restart. The program acquisition cost would be $392 million for a purchase of 25 aircraft which includes a restart penalty and learning curve penalty.[131] In addition, the launching mechanism will also have a procurement cost. To capture an average of the extreme difference in APUC reported in Table 4.3, a logarithm was taken of each cost and averaged, yielding an APUC of the proposed

[131] John C. Graser et al., *Options for and costs of retaining C-17 aircraft production-only tooling,* ed., Santa Monica, CA, RAND Corporation, 2012.

launching system to be $0.207 million.[132] This purchased launching system is assumed to account for all cruise missiles carried on a C-17. So, for a buy size of 25 C-17 aircraft, the total procurement cost of the launching system is $5.17 million.

The C-130J is still in production and would not incur a penalty to restart the line. However, in this context we are addressing a potential replacement for the legacy bombers. The C-130 might not be an optimal case for replacement due to its limited range and speed. For this reason the C-130 is only considered as dual role option along with the C-17 and C-5. These three fleets would require a different strategy of "borrowing" aircraft during a time of conflict to use them as arsenal aircraft. Since there would be no aircraft procurement costs associated with this strategy, the C-130, C-5 and C-17 dual role aircraft would only incur development and procurement costs of launching systems if these airframes were selected.

Operating and Support Costs are Analyzed with Regression of Historical Data

It is a difficult task to estimate how much a system will cost to operate when it has not yet been developed. Conveniently, each aircraft system being considered in this analysis already exists in either the military or commercial world. Adequate cost data from commercial airlines is understandably unavailable to the general public, which prevents a detailed analysis. However, even if this data were available, the operations of commercial and military aircraft are so different that the analysis of commercial cost data would not provide an accurate comparison. However, the aim of this analysis is not to provide the exact future costs. Rather, it is designed to make relative comparisons among the arsenal aircraft alternatives. This section presents an approach to estimating O&S costs that is reasonable and consistent among all aircraft alternatives so that such comparisons can be made.

O&S costs consist of "sustainment costs incurred from the initial system development through the end of system operations."[133] O&S costs occur over a much longer time horizon than other aircraft costs such as RDT&E or acquisition costs. As noted earlier the majority of the life-cycle costs of an aircraft is attributed to O&S.[134] It is therefore important to consider O&S costs early in program development because decisions made during the early stages of the program have a significant effect on O&S costs down the line.

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[132] There is some uncertainty here about the cost and design of such a system. This APUC is for a launching system that stays on the C-17 as cruise missiles are released versus an expendable launching system where cruise missiles are launched in pallets. This makes the calculations simpler since only one launcher is needed per aircraft.

[133] Operating and Support Cost-Estimating Guide.

[134] Operating and Support Cost-Estimating Guide.

Data Description

The Air Force Total Ownership Cost (AFTOC) database was used to obtain historical O&S costs for each aircraft in the inventory. The data spans from fiscal years 1996 to 2014 and is reported annually. Multiple aggregation levels of data are reported in the database, including mission design (MD), mission design series (MDS), aircraft mission and major command. The reporting structure for O&S costs follows a categorization developed by OSD's Cost Analysis Improvement Group. The top two levels of categorization are shown in Table 4.6. Only the first level sub-categories (and in a few cases the second-level) are modeled in this analysis. The Logistics, Installations, and Mission Support-Enterprise View (LIMS-EV) was also used to obtain data for various predictors. This data provides metrics for the availability, status, maintenance, and utilization of military aircraft. The data can be disaggregated into the theater, command, base, wing, group, and squadron level.

Table 4.6 presents the spending proportion of overall O&S, divided into AFTOC reporting categories. The aircraft of interest reported here are the B-1, B-2, and B-52, as well as a column representing all aircraft in active duty, National Guard, and reserve inventory. For each column, the first-level cost categories of unit personnel, unit operations, maintenance, and continuing system improvements account for over 90 percent of the total O&S cost.

Table 4.6. O&S Spending Proportions

	B-1B	B-2A	B-52H	All AC
1.0 Unit personnel	**0.21**	**0.22**	**0.31**	**0.28**
1.1 Operations personnel	0.04	0.04	0.07	0.07
1.2 Maintenance personnel	0.15	0.13	0.17	0.16
1.3 Other direct support personnel	0.02	0.05	0.07	0.06
2.0 Unit operations	**0.21**	**0.12**	**0.23**	**0.26**
2.1 Operating material (i.e. aviation fuel)	0.20	0.07	0.21	0.22
2.2 Support services	0.01	0.05	0.01	0.03
2.3 Temporary Duty	0.00	0.00	0.00	0.01
3.0 Maintenance	**0.39**	**0.35**	**0.35**	**0.32**
3.1 Organizational maintenance & support (consumables and DLRs)	0.31	0.19	0.16	0.25
3.2 Intermediate Maintenance	0.00	0.00	0.00	0.00
3.3 Depot maintenance - overhaul/rework	0.08	0.16	0.18	0.07
4.0 Sustaining support	**0.03**	**0.06**	**0.03**	**0.01**
4.1 System specific training	0.00	0.00	0.00	0.00
4.2 Support equipment replacement	0.00	0.00	0.00	0.00
4.3 Operating equipment replacement	0.00	0.00	0.00	0.00
4.4 Sustaining engineering & program management	0.03	0.05	0.02	0.01
4.5 Other sustaining support (e.g. testing)	0.00	0.01	0.00	0.00
5.0 Continuing system improvements	**0.14**	**0.23**	**0.07**	**0.08**

5.1 Hardware modifications/modernization	0.06	0.12	0.04	0.07
5.2 Software maintenance & modifications	0.07	0.12	0.03	0.01
6.0 Indirect support	**0.01**	**0.02**	**0.02**	**0.05**
6.1 Installation support	0.01	0.02	0.02	0.03
6.2 Personnel support	0.00	0.00	0.00	0.00
6.3 General training & education	0.00	0.00	0.00	0.02

NOTE: These proportions are calculated using the average spending over the period FY96-FY14. All active duty, National Guard, and reserve aircraft are included in the estimates. DLR = Depot Level Repairable.

The cost data reported in AFTOC accounts for 186 different MDS. For purposes of predicting costs for a very specific type of aircraft, it was necessary to include only certain aircraft in the regression. The decision of which aircraft to include was based on logic rather than metrics. This analysis is attempting to predict the O&S costs for a group of aircraft, each well over 100,000 pounds maximum takeoff weight and varying from current cargo aircraft to potential commercial derivatives. The current legacy bombers (B-1, B-52) seem to be ideal candidates to include in the regression data since the arsenal aircraft will ultimately act as bombers. The B-2 is included in the discussion in this section, but is excluded from the regression data on account of stealth costs which would bias the predictions. It is also important to include current military cargo aircraft that may be considered for this mission, such as the C-17, C-5, and C-130. These military cargo aircraft are more representative of the airframe being looked at for this mission. All aircraft with a mission designation other than cargo and bomber are excluded from the analysis due to their dissimilarity to the predicted aircraft. Additionally, aircraft that have a maximum takeoff weight under 100,000 pounds are excluded from the regression for the same reason, which leaves the C-135, C-137, C-141, C-32, C-40, and C-9 aircraft in the data set. The AC-130 is also included in the data as an example of a military cargo aircraft modified to operate in a combat role. Ultimately, these aircraft were chosen because they were determined to be more representative of the predicted arsenal aircraft.

One particular difficulty in analyzing AFTOC data for these particular aircraft is the amount of contractor logistic support (CLS) used by certain aircraft. As shown in Figure 4.6, the aircraft on the left use a significantly high proportion of CLS, whereas the aircraft on the right have more organic support. If CLS reporting followed the same cost element structure and definitions as the Cost Analysis Improvement Group (CAIG) structures used by AFTOC, there would be no need to change the O&S cost regression. However, previous analysis shows that there is significant dissimilarity in the data structures of CLS costs and AFTOC categories.[135] Because of this, CLS costs are not recorded in the appropriate AFTOC category.

[135] Michael Boito, Cynthia R. Cook, and John C. Graser, *Contractor logistics support in the U.S. Air Force,* ed., Santa Monica, CA, RAND Corporation, 2009.

Figure 4.6. CLS Proportions and Costs for Each Aircraft in Regression Data[136]

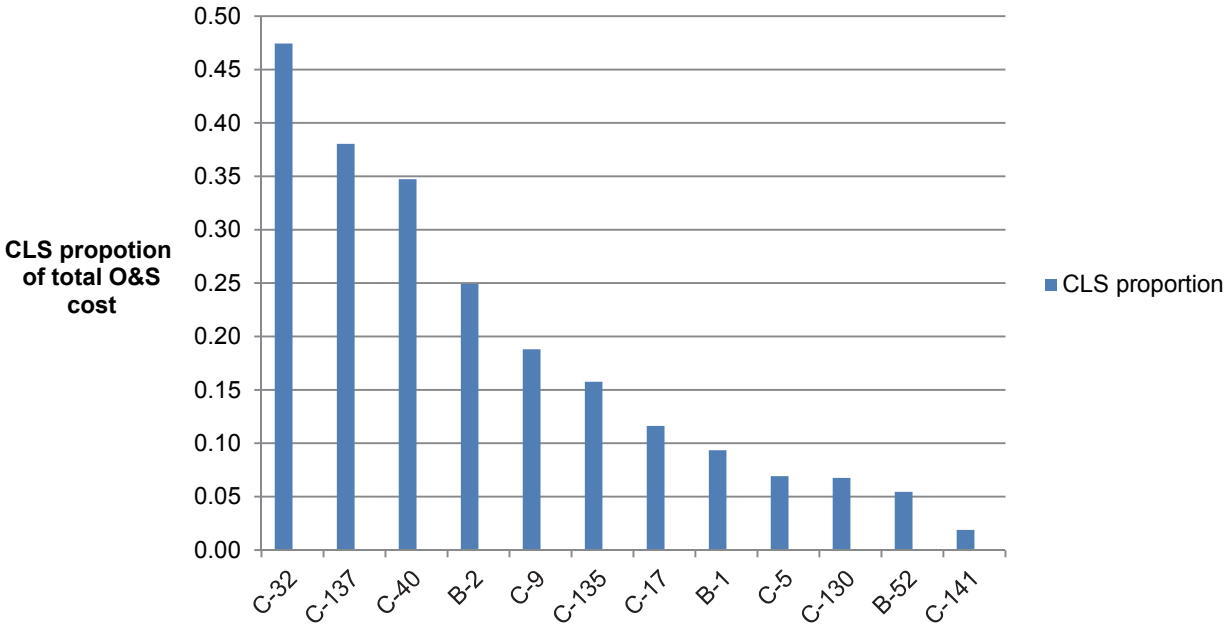

Table 4.7 presents a comparison of CLS and non-CLS aircraft cost proportions for aircraft in the dataset. It is apparent that the money spent in CLS efforts is rolled into a single reporting category, which makes a comparison across cost categories impossible without significant bias. To account for this reporting inconsistency, it is necessary to merge AFTOC categories. The allocation for CLS is mostly contained in AFTOC category 3.0 Maintenance. However, as noted in Table 4.7, there is a large inconsistency in maintenance personnel reporting which is contained in CAIG 1.2. For this analysis, categories 1.2 and 3.0 are combined to reduce the bias.

Table 4.7. Cost Proportion Comparison of CLS to non-CLS Aircraft

CAIG category	CLS (%)	Non-CLS (%)
Maintenance personnel total (1.2)	8.51	20.08
DLRs (3.1.3)	0.18	12.80
Depot maintenance (3.3)	0.08	14.74
CLS (3.1.4)	35.73	4.49

NOTE: Aircraft with CLS cost proportions of over 20 percent are assigned to be CLS aircraft. These include C-32, C-137, C-40, and B-2. Aircraft with less than this percentage are non-CLS, and include C-9, C-135, C-17, B-1, C-5, C-130, B-52, and C-141.

Data from AFTOC can be accessed at the MD level or at the MDS level. The MD is a more aggregated designator as it includes several MDS. An aircraft off the production line receives a

[136] Averages of cost data from FY96-FY14

new MDS whenever there is a major modification that makes the newly produced aircraft different than previous versions. A regression using data at the MD level will suffer from inconsistencies in the fleet age parameter. For example, if two versions of an aircraft were produced 20 years apart, the average age of the fleet when the new version is produced could be 10 years. In reality, of course, there are two fleets, one in its first year of service and one in its twenty-first. This measure would be inaccurate if age is a significant predictor of cost, which it is in this analysis. Because of that inconsistency with some of the aircraft in the data set, the MDS level is used in the regression model. The standard errors greatly improved in the model when MDS level data were used instead of MD level data.

Estimation Approach and Model Specification

This analysis estimated O&S costs using several different techniques. Each AFTOC category was analyzed separately due to the differing variability in each category with respect to aircraft and fleet characteristics. Since the arsenal aircraft that are the target of this analysis have not entered the acquisition phase, it was most appropriate to use cost-estimating relationships (CERs) for most cost categories. The exceptions to this approach are shown in Table 4.8. The operations personnel category represents the cost of the aircrews that operate the aircraft. The crew ratio and crew composition is not likely to change with the parameters used in the CERs. For this reason, the crew costs were calculated separately. Fuel costs also must be determined using something other than regression. Although fuel efficiency depends upon weight among other considerations, the use of CERs seems to be less transparent and open to more criticism when estimating an aircraft's fuel use. For this reason, an analysis of aircraft fuel burn rates was used in this analysis.

Table 4.8. O&S Estimating Approach

Category	AFTOC categories	Cost estimation method
Operations personnel	1.1	Crew ratio/composition
Other direct support personnel	1.3	CER
Avionics fuel	2.1.1.1	Range-payload analysis
Other unit operations	Other 2.0	CER
Maintenance	1.2 + 3.0	CER
Modifications and support	4.0 + 5.0 + 6.0	CER
Total O&S	All except crew and fuel	CER

For the rest of the cost categories, CERs was used in this theoretical analysis. Other techniques such as engineering analysis, cost extrapolation, or cost factors would be useful in more mature programs. Cost proportions are a simplified way to account for cost categories that

would be very difficult to predict otherwise. For instance, the category of "continuing system improvement" includes modifications made to the aircraft hardware or software most likely driven by changing operational requirements. These modifications in general rely on technological advances in the aerospace and defense industries, which are very difficult to quantify in the form of an independent variable. A past study of O&S costs used proportion techniques to estimate costs of CAIG categories that are difficult to model with CERs.[137] This same use of cost proportions was considered for this analysis. The cost proportion is essentially a univariate regression model, with the slope of the line being the cost proportion as indicated by the data. For the data set being used, the cost proportion method yielded higher standard errors than simple regressions with one or two predictor variables. This analysis used CERs exclusively rather than proportions to predict the specified AFTOC cost categories.

With aircraft costs being observed over time, the costs are arranged conveniently into panel data. This implies that there are two primary regression procedures that may be used. One is to perform a panel regression using generalized least squares (GLS) procedures. A random-effects model would be required in this case since there are variables that don't change over time such as aircraft weight. A downside to this approach is that predicting aircraft costs with increased age would not be the most transparent approach in determining how to account for fixed effects that uniquely occur in a given fiscal year. Another regression approach would be to use ordinary least squares (OLS) procedures using aircraft age as the parameter to determine how costs change over time. Both of these regression approaches were examined in this analysis and the estimation accuracies were compared between the two models. The OLS method proved to have a slightly smaller standard error. Because of lower standard errors and higher model transparency, the OLS approach was selected to be used for this analysis.

Including command variables in the model was considered as a way to improve its statistical accuracy. Various USAF commands operate and maintain their aircraft differently, and including these commands as dummy variables could account for more unobserved variation in the data. This approach was tested, but it did not lead to greater statistical accuracy and the data was therefore aggregated across commands for analysis.

In cost analysis, log-linear form has been frequently used in regression. Several advantages come with the use of this functional form, including ease of coefficient interpretation, control over heteroscedasticity (non-uniform error variance), and capturing interaction effects among covariates.[138] The underlying question to be addressed when considering the natural log transformation of the outcome variable is whether the error term should be additive or multiplicative. This error specification can be analyzed using residual plots with the outcome

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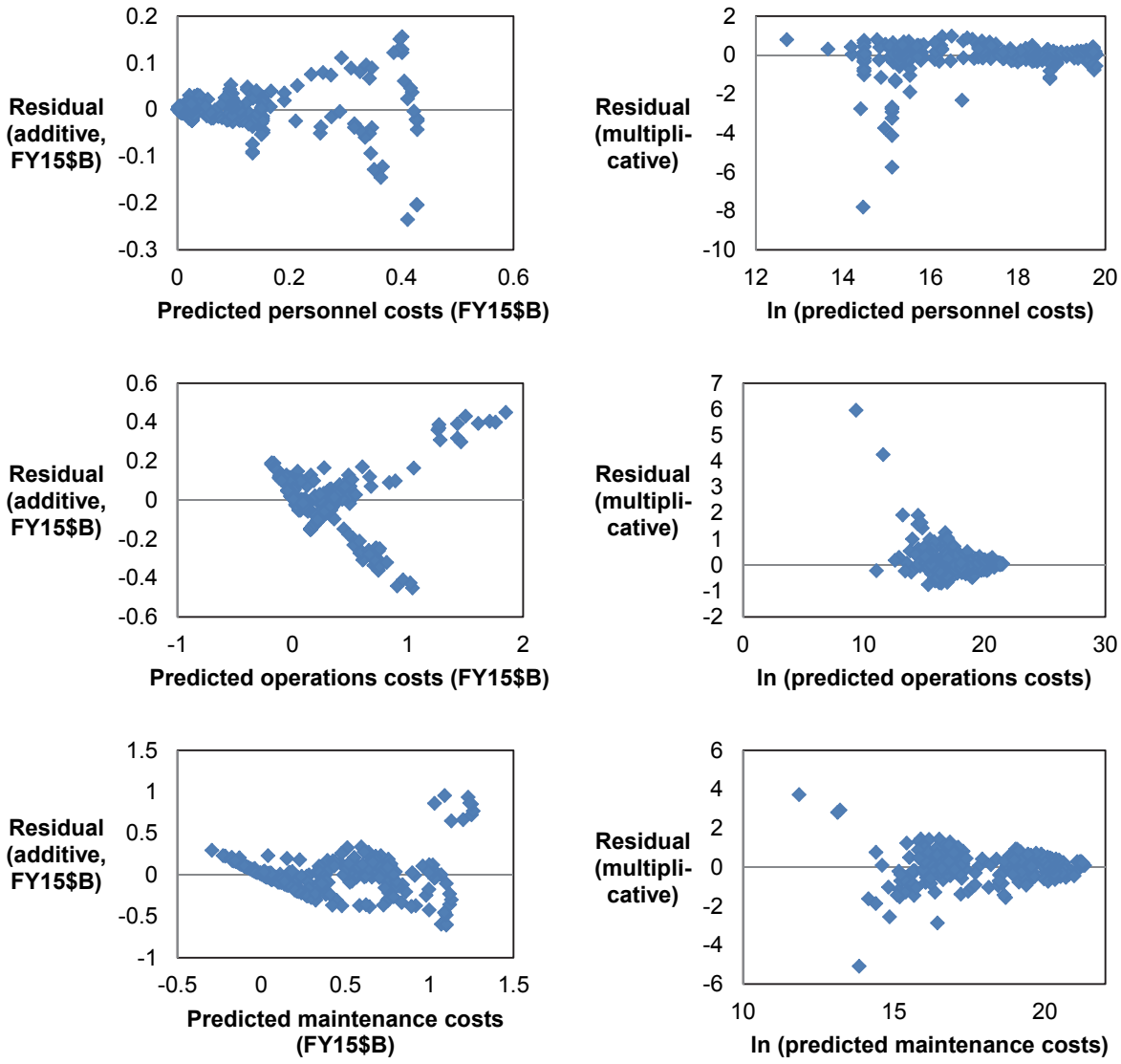
[137] Michael Kennedy et al., *UH-1N business case analysis,* ed., Santa Monica, CA, RAND Corporation, 2014.

[138] Gregory G. Hildebrandt and Man-Bing Sze, *An estimation of USAF aircraft operating and support cost relations,* ed., Santa Monica, CA, RAND Corporation, 1990.

variable as shown in Figure 4.7. The left column of plots shows the residuals plotted against the predicted cost values for unit personnel, unit operations, and maintenance. These three cost categories are shown because they have the largest error variance. In each case, the variance of the residuals increases as the predicted cost increases, indicating heteroscedasticity. In other words, the error term seems to have a multiplicative effect as cost increases, so a natural log transformation is appropriate. Another aspect of a natural log transformation that would be helpful for this model has to do with the predictions that are less than zero. There should not be any negative costs associated with the arsenal aircraft being predicted. A log-linear model prevents this, since the natural log transformation of the outcome variable produces only positive numbers. This is illustrated in the right column of plots in Figure 4.7. The log transformation still produces some heteroscedasticity. Ultimately, the decision is an analytic judgement call, and since the predictions are all positive values the natural log transformation was chosen for this analysis.

Figure 4.7. Residual Plot for Outcome Variables With (Left Column) and Without (Right Column) Natural Log Transformation



Two levels of regression approaches were used to develop O&S CERs. The highest level involves a single equation with the total cost as the outcome variable. This total cost metric is somewhat opaque in terms of knowing what kinds of covariate dependencies there are in the model. Although this approach comes with the penalty of a more limited look at the effects of different variables, it is preferred in this analysis because it aggregates and therefore reduces the unobserved biases in each cost category. The second level of regression was to disaggregate the costs into subcategories and regress with each category as the outcome variable. The exception in this estimation approach was categories 4.0 – 6.0, consisting of sustaining support, continuing system improvements (or modifications), and indirect support. Modifications costs carry most of

the weight of this combined category and are highly variable. By combining these categories, the variability is curbed and the estimates become more accurate. Table 4.9 presents the cost categories used in the analysis by column. The first three rows indicate whether these costs are fixed, vary by flying hours, and/or vary with inventory. Personnel costs, for instance, will still be incurred even if the aircraft have zero flying hours, since the essential personnel will still need to receive pay as long as the aircraft are still in the inventory. On the other hand, operations costs would be greatly affected if flying hours were zero. The operations costs are composed almost entirely of fuel costs and are directly linked to flying hours. Maintenance costs are slightly more complicated because the aircraft receives some maintenance when certain milestones in flight hours are reached. If the fleet size decreases, the cost for these scheduled maintenance procedures will also decrease. Lastly, modifications and support costs are generally seen as fixed costs for the fleet.

Table 4.9. Regression Variables Used with O&S Cost Categories

		Total O&S	Personnel	Operations	Maintenance	Modifications and support
Cost element variation	Fixed costs	X				X
	Varies by flying hour	X		X	X	
	Varies by total aircraft inventory (TAI)	X	X		X	
Covariates used	Max takeoff weight	X	X	X	X	X
	Flying hours per aircraft	X			X	
	Total aircraft inventory	X	X		X	
	Combat aircraft (dummy)	X		X	X	X
	OSA/VIPSAM aircraft (dummy)	X		X	X	X
	Average fleet age	X			X	
	Percent mission capable	X			X	X
	Average sortie duration	X			X	X
	Contractor logistic support (dummy)	X		X	X	X
	Total flying hours			X		X

NOTE: OSA/VIPSAM = Operational support airlift/very important person special air mission

The covariates shown in Table 4.9 were chosen in part because of the different dependencies on flying hours and inventory.[139] Cases where the cost varied with both flying hours and

[139] Max gross takeoff weight is used for the O&S analysis, as empty weights were not available for all arsenal aircraft alternatives.

inventory presented a challenge for model multicollinearity, or near-linear dependence among covariates. When this happens in a regression model, the variance of each coefficient is inflated, making it difficult to estimate each parameter with precision. For the total O&S and maintenance case, this problem was fixed by using flying hours per aircraft as a variable instead of fleet-wide flying hours. This metric still captures the workload for the aircraft while avoiding multicollinearity.

Statistical and practical significance were both considered when covariates were chosen for each model. Statistical significance addresses the issue of whether or not there is a relationship between predictor variables and the outcome variable. The t statistic for the coefficient for each variable is considered in determining which variables to retain in the equation for regression. Several other metrics are available for making decisions based on statistical significance. In this analysis, a brute force method was used to compare model statistics like $R^2_{adjusted}$, mean squared error (MSE), Akaike information criterion (AIC), and Bayesian information criterion (BIC) in all combinations of the potential covariates.[140] However, the top ranked models included combinations of covariates that did not have much practical significance. Practical significance addresses the issue of whether or not the size and sign of the coefficients on the regression variables make practical sense. For example, it is not readily apparent that if an aircraft has longer missions, there should be a change in the number of personnel in the unit. Ultimately it was determined that increasing the practical significance of the model justified the slight loss in the standard error of the model.

Residual diagnostics were examined to determine unusual and influential data, as well as assumptions of normality and linearity. Several data points had high residuals and high leverage, meaning the addition of the irregular data point caused a significant shift in the regression. These data points had in common that they were for aircraft that had zero inventory that year or for aircraft that had zero or negative cost.[141] These observations were dropped from the data since this analysis aims at predicting costs for a fleet with non-zero inventory and positive costs.

The data appeared to be roughly normally distributed. However, with a natural log transformation of the outcome variable it was necessary also to transform several covariates that had a nonlinear relationship with cost. The variables for weight, flight hours, and inventory were

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[140] $R^2_{adjusted}$, MSE, AIC, and BIC are statistical measures of the regression model's accuracy and precision. $R^2_{adjusted}$ is the proportion of variation in the outcome variable that can be explained by the predictor variables. MSE is the mean of the squared error terms in the model, which indicates how well the regression fits the data points. AIC and BIC are both measures of the overall quality of potential models. AIC addresses the expected predictive performance of a model. BIC measures the Bayesian predictive likelihood that the model under consideration is the true model. Sources: Douglas C. Montgomery, Elizabeth A. Peck, and G. Geoffrey Vining, *Introduction to linear regression analysis*. 5th ed., Vol. , John Wiley & Sons, 2012.; Jouni Kuha, "AIC and BIC comparisons of assumptions and performance," *Sociological Methods & Research,* Vol. 33, no. 2, 2004.

[141] Negative costs occur when accounting adjustments are made

all transformed using natural logs, which created linear relationships in the model between all covariates and the outcome variable. The regression was weighted by total aircraft inventory.[142]

Regression of Total O&S Cost Indicates Predictive Accuracy

The regression output is compared between the aggregated cost model for total O&S costs and the disaggregated cost models for each cost category. The aggregated cost model is chosen as the primary model for making predictions of arsenal aircraft O&S costs. The disaggregated models are included to show cost dependencies and relationships. Regression outputs are displayed in Table 4.10. Parameter input values for the alternatives are shown in Table 4.11.

Table 4.10. O&S Regression Results

	Total O&S cost	Personnel cost	Operations cost	Maintenance cost	Modifications and support cost
Weight	0.703***	-0.015	-0.046	0.879***	0.431***
	(0.07)	(0.04)	(0.04)	(0.07)	(0.08)
Flying hours per AC	0.518***			0.653***	
	(0.08)			(0.10)	
TAI	0.902***	1.006***		0.959***	
	(0.02)	(0.02)		(0.03)	
δ_{Combat}	0.825***		0.269***	1.041***	1.252***
	(0.10)		(0.08)	(0.11)	(0.16)
$\delta_{OSA/VIPSAM}$	0.563***		-0.431	0.493*	-0.064
	(0.14)		(0.25)	(0.21)	(0.26)
Percent mission capable	-0.561			-0.426	-2.719***
	(0.31)			(0.33)	(0.35)
Age	0.004			0.007**	
	(0.00)			(0.00)	
Average sortie duration	-0.176***			-0.212***	-0.210***
	(0.03)			(0.04)	(0.05)
$\delta_{Contractor\ logistic\ support}$	-0.202		-0.151*	-0.246	0.061
	(0.11)		(0.06)	(0.13)	(0.09)
Total flying hours			0.784***		0.736***

[142] The term "weighted" used here represents a technique used in statistical analysis. Essentially, for each data point the entire regression equation is multiplied by the weight being used, which in this case is total aircraft inventory. Although the argument for using weighted regression often is not clear cut, the general rule of thumb is to use weighting if it causes the regression to be closer to the target values you are trying to estimate. The dataset being used in this analysis has several data points with very small aircraft inventories. The arsenal aircraft alternatives, however, are procured in large amounts, so weighting was determined to be necessary to make the regression equation more relevant for estimating arsenal aircraft costs. Source: Joshua D. Angrist and Jörn-Steffen Pischke, *Mostly harmless econometrics: An empiricist's companion,* ed., Princeton University Press, 2008.

			(0.03)		(0.05)
Constant	5.121***	13.587***	9.954***	1.278	7.908***
	(1.14)	(0.54)	(0.78)	(1.30)	(1.07)
$R^2_{adjusted}$	0.876	0.833	0.799	0.871	0.630
Root MSE	0.287	0.429	0.417	0.319	0.515
N	339	349	349	338	316

NOTE: Each column represents a separate regression equation, with the dependent variable in each case being the natural log of the cost categories presented in the first row. The following predictor variables are also represented by a natural log transformation: weight, flying hours per aircraft, TAI, and total flying hours. Robust standard errors are used. Standard errors are shown in parentheses. OLS regression was used with analytic weighting of the data by average inventory. The cost is in 2015 dollars.
* p<0.05, ** p<0.01, *** p<0.001

The variation in coefficient values across these models should not worry us because the models represent different cost categories which are fundamentally different from each other. The contribution of each variable to the cost models is quite informative. The variable for aircraft maximum takeoff weight is highly significant among all equations. The coefficient for weight is statistically significant with the exception of personnel and operations costs. Within this dataset, larger aircraft may not necessarily have larger crews or larger amounts of support personnel. All other equations yield a high size effect which makes intuitive sense. Larger aircraft have more parts that need to be maintained and larger engines that are generally more expensive to maintain.[143] The effect of aircraft weight in this study is comparable to recent efforts that have modeled O&S in a similar manner.[144]

Results for the age variable are consistent with prior literature. The total O&S equation indicates that as the age of the fleet increases by one year, the total O&S cost increases by 0.4 percent. It is expected that over time, the costs associated with maintaining an aircraft will increase. This result was found in several prior studies; perhaps the most applicable to this effort is the work by Pyles in 2003. That study analyzed the lifecycle patterns of aircraft maintenance and modification workloads and material consumption. Age was reported as not having a direct correlation with increased workload. Rather, age is an indicator of material-deterioration and maintenance-response processes that change over time. Technology gaps were also reported as a significant factor of cost growth, and over time the advancement of technology will drive higher O&S costs especially for combat aircraft.[145]

Categories that are variable with TAI yield a high coefficient value for aircraft inventory. For all equations that contain the variable for TAI, the relationship is nearly linear in log form. Doubling the size of the fleet should nearly double the costs according to the model. This result

[143] Raymond A. Pyles, *Aging Aircraft,* ed., Santa Monica, CA, RAND Corporation, 2003.

[144] Christopher A. Mouton et al., *Reducing long-term costs while preserving a robust strategic airlift fleet: options for the current fleet and next-generation aircraft,* ed., Santa Monica, CA, RAND Corporation, 2012.

[145] Pyles, ed.

may be slightly biased due to the aircraft inventories contained in the data set. A few aircraft have high inventories such as the bombers and primary cargo aircraft. However, there are several aircraft that have a TAI of less than 10. It may be the case that as the fleet gets sufficiently large, the effect of TAI lessens since there is more infrastructure in place.

Combat aircraft are significantly more expensive in every cost category. The additional systems used by combat aircraft such as weapon delivery systems and defensive countermeasures may be responsible for this increase in cost. Because fighter aircraft are excluded from this analysis, the only aircraft in the dataset that could have confounding characteristics is the B-1 due to its afterburning engines. Afterburning engines not only account for higher fuel costs, but there are probably also differences in the maintenance costs. The B-2 was removed from the dataset due to the high cost of stealth that would have been included in the combat dummy variable. Since this analysis is trying only to capture the effects of turning military cargo aircraft or commercial freighters into combat aircraft, we are trying to account for the cost effect of maintaining and operating all the subsystems that would need to be added to the aircraft.

The dummy variable included in the model for operational support airlift/very important person special air mission (OSA/VIPSAM) aircraft is exactly correlated with aircraft that are commercially derived. Although it may make sense that commercially derived aircraft would have lower costs, it is impossible to distinguish the effects of derivative aircraft from OSA/VIPSAM in this data set due to the perfect correlation between the two variables. OSA/VIPSAM aircraft are more expensive to operate, which could be why the coefficient is positive, indicating that the increased costs from this mission outweigh the potential cost reduction of using a commercial derivative. Regardless, we cannot distinguish these effects from each other due to correlation in the data.

Contractor logistic support (CLS) produces an interesting result. The coefficient is insignificant for all equations except for the total O&S and maintenance equation, which makes sense since the bulk of CLS is used for aircraft maintenance. The results indicate that aircraft that spend on average at least 20 percent of total O&S costs on CLS will have maintenance costs that are about 25 percent lower than non-CLS aircraft. CLS is generally seen as being positively correlated with cost, so there may be some collinearity issues. The size of this effect is slightly lessened when the cost categories are summed into the total O&S equation.

Table 4.11. Parameters Used for Arsenal Aircraft Alternatives in O&S Regression

	MGTOW (lbs.)	Flying hours per aircraft[a]	δ_{combat}	$\delta_{OSA/VIPSAM}$	Mission capable (%)[b]	Average sortie duration (hrs)[c]	δ_{CLS}
A380F	1300725	245	1	0	0.875	5.63	1
777F	766800	245	1	0	0.875	5.63	1

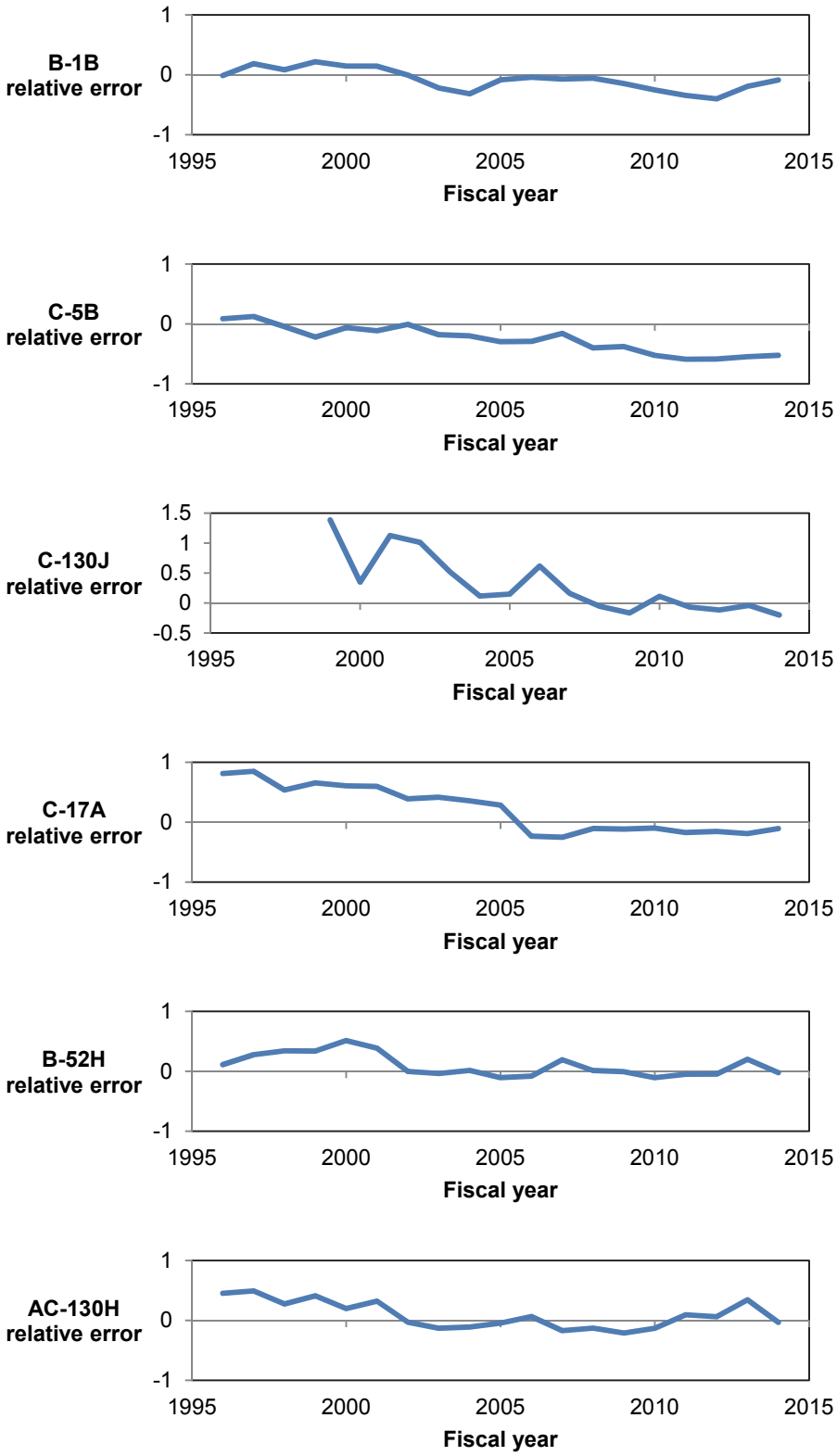
767F	408000	245	1	0	0.875	5.63	1
747F	975000	245	1	0	0.875	5.63	1
A330F	513677	245	1	0	0.875	5.63	1
B-1	477000	245	1	0	0.68	5.63	0
B-52	488000	245	1	0	0.74	5.63	0
C-17	585000	245	1	0	0.875	5.63	1

[a] The estimate for flying hours per aircraft is the average bomber flying hours from FY97-FY01 (AFTOC). This was an attempt at obtaining the peacetime aircraft flying hours prior to Operation Enduring Freedom/Operation Iraqi Freedom
[b] For each arsenal aircraft alternative, the mission capable rate standard for the C-17 was used. The B-1 and B-52 mission capable rates are a five-year average of actual rates (LIMS-EV).
[c] Sortie duration shown here is the five-year average of bomber aircraft sorties (LIMS-EV).
NOTE: Estimation parameters not depicted in this table are TAI, age, and total flying hours. These parameters are omitted in this table because they change over time.

Figure 4.8 depicts the predictive accuracy of the model for some of the aircraft included in the model. The model seems to accurately predict the data with a few exceptions. Unusual spikes in the data causes inaccuracy. This can be seen in particular in the B-1B data. The increase in actual costs from FY10-FY12 is caused by an increase in modifications cost. The model does not account for these irregular, sporadic jumps in modifications cost but rather predicts the long-term averaged modifications costs. Another exception occurs in FY03 for the B-1B and FY05 for the C-5B, when aircraft were cut from the fleet. In the early 2000s, 26 B-1B aircraft were retired. The relative error takes a few years to level off, which may be a factor of retirement costs included in the reporting or engine overhaul work that was being done during those years to the B-1B. In the C-5B case, the fleet began losing aircraft to retirement in FY05. The predicted values significantly under-predict the retirement phase due to the additional costs associated with retiring aircraft. We are not attempting to model retirement costs and therefore this exception to the predictive accuracy of the model can be disregarded.

The model has more predictive accuracy during the procurement phase and steady state of aircraft operation. This is beneficial to the analysis because these are the primary phases that are used in the lifecycle cost estimations for the aircraft alternatives. The C-17A and C-130J each provide an example of a fleet in the procurement phase. The model predicts these costs with a decent amount of accuracy in terms of absolute error even though the relative errors seem high in the figure. The B-52H and AC-130H provide examples of aircraft fleets that are for the most part constant in TAI. For the purposes of this analysis, the aircraft alternatives will be procured over a span of several years and then maintained at the same number of total aircraft through the lifetime of the platform. The accuracy of the model in predicting costs of aircraft in steady state inventory plays a major role in the present value life-cycle cost (PVLCC) calculations since the majority of the aircraft's life cycle will be spent in this steady state phase.

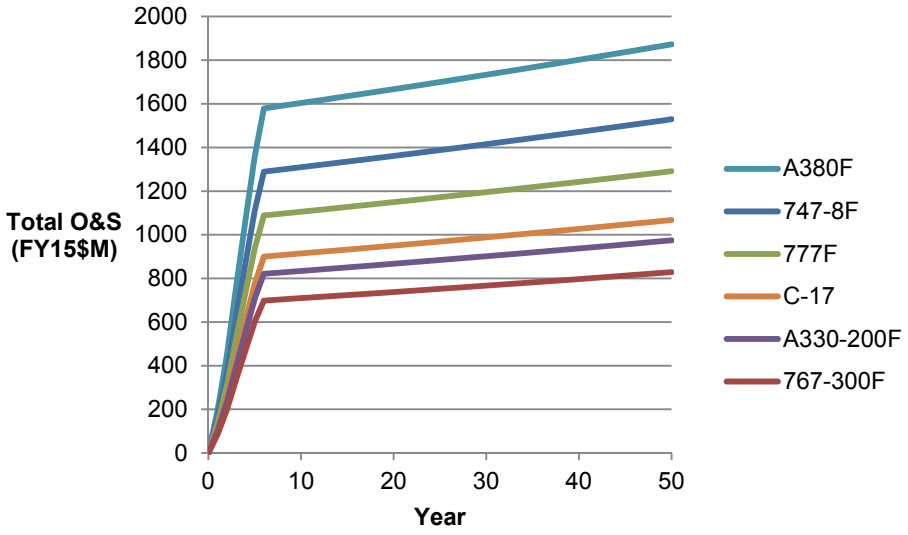
Figure 4.8. Relative Error of Model Cost Predictions Compared to Actual O&S Costs



Cost predictions over time for the various aircraft alternatives are shown in Figure 4.9. Several assumptions were made on the model input values for these aircraft. The peacetime training requirement for flight hours was calculated using an average of B-1 and B-52 flying hours per aircraft from FY97-FY01, since these were the only years of peacetime operations. It is assumed that 245 flying hours per aircraft is roughly the amount of peacetime flying hours per year for each of the considered arsenal aircraft.

The mission capable rates for these arsenal aircraft may be more comparable to newly built military aircraft rather than the whole set of aircraft in the dataset. The C-17A is a prime candidate for using an analogous mission capable rate because it is the newest heavy aircraft in the Air Force. The standard for the C-17A mission capable rate is 87.5 percent, which is used for the input variable for all arsenal aircraft alternatives. Commercial aircraft operate at mission capable rates higher than 90 percent. However, this is caused by different maintenance procedures in the civilian world which focuses on preventative repair and field maintenance in order to reduce depot maintenance.[146] A shift of these aircraft to military operations would cause a decrease in the mission capable rate experienced in civilian operation.

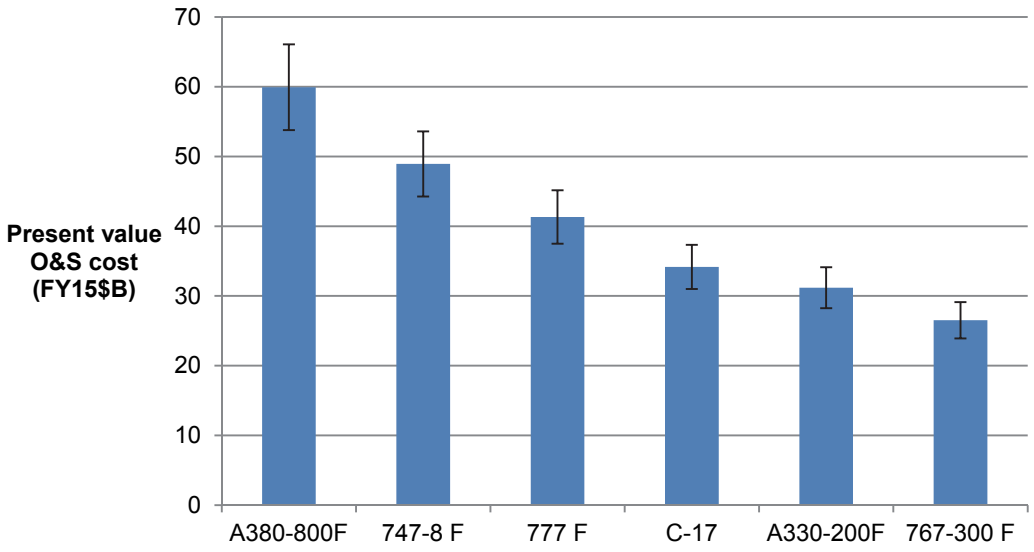
Figure 4.9. Cost Predictions for Arsenal Aircraft Alternatives



[146] Alan Eckbreth et al., *Sustaining Air Force Aging Aircraft into the 21st Century*, Washington, D.C.: U.S. Air Force Scientific Advisory Board, 2011.

The fleet inventory is calculated using a typical production schedule. The cost comparison in this section is for a fixed buy size. Fixed-effectiveness is explored in the following chapter.[147] For the analysis presented here, each alternative undergoes a procurement of 100 aircraft in six years. The age of the fleet is calculated based on a weighted average of the aircraft organized into cohorts by procurement year. With non-varying values for flying hours/TAI, mission capable rate, and TAI, the only varying parameter for each alternative is the maximum takeoff weight.

Figure 4.10. Present Value O&S Cost of Arsenal Aircraft Alternatives Excluding Fuel and Crew Costs



NOTE: These calculations are for a fleet size of 100 aircraft. Costs are discounted at a real discount rate of 1.4 percent per guidance from the Office of Management and Budget, Circular A-94 Appendix C.

Figure 4.10 depicts the comparison of present value O&S less fuel and crew costs for each of the aircraft alternatives. Without consideration of effectiveness in this chapter, the comparison is only relevant for comparing costs of the platforms. The A380F is the most expensive platform, because it is the largest platform and can carry the largest payload. Error bars have been overlaid on the plot, which range from about 9-10 percent of the overall cost.

Other aircraft that are not included in this analysis may be considered qualitatively. One option may be to use existing military cargo aircraft for this kind of a mission, in which case the O&S costs would be minimal since the aircraft would be operating mostly in a mobility role. The

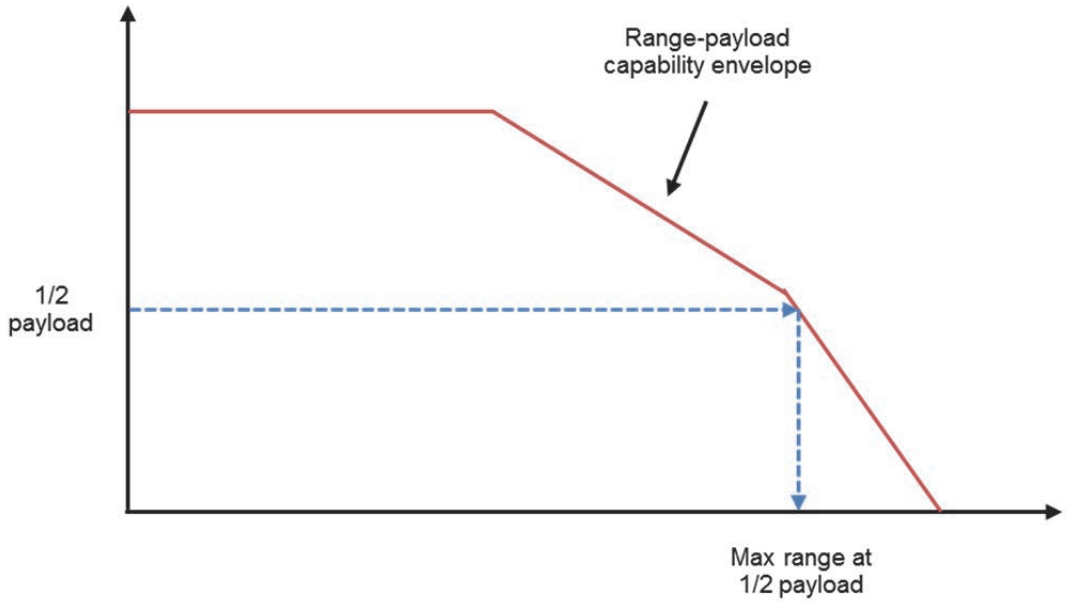
[147] The aircraft procurement is fixed at 100 for this O&S analysis. The actual number does not have much bearing, so long as it is held constant to compare relative costs among alternatives. The cost-effectiveness section varies the buy size.

C-17 is included in the analysis, although it can only be procured if the production line is restarted. The kind of scenario where this capability would be needed is one that is also very stressing to mobility aircraft. Although it would be nice to merely borrow a mobility aircraft and use some roll-on/roll-off system for a short amount of time, the likelihood of there being available aircraft in that scenario is slim. If it were possible to do this, the only new O&S support costs incurred would be the incremental increase in costs for training aircrews for the mission and for using the aircraft in time of need. Otherwise, the fleet costs would probably not change significantly.

Crew and Fuel Costs were Calculated Separately from Total O&S

Crew and fuel costs are calculated separately from the CER analysis. Crew costs were calculated using the B-1 as an analogous platform for crew ratios and compositions. The B-1 is reported to have a crew ratio of 1.31 per TAI. The crew for the B-1 consists of two pilots and two combat systems officers.[148] The average officer's annual composite rate is $154,544 which includes officer pay (basic, housing, subsistence), health care accrual, retired pay accrual, and other miscellaneous costs.[149] Aircraft inventory is multiplied by the crew ratio and crew size to obtain the total number of personnel, which is then multiplied by the average pay.

Figure 4.11. Range-Payload Illustration



[148] "Air Force Instruction 65-503 Attachment 36-1, Authorized Aircrew Composition," (Department of the Air Force).

[149] "Air Force Instruction 65-503 Attachment 19-2, Active AF Standard Composite Rate and Grade," ed. Air Force.

Range-payload data was used in calculating fuel costs. Without information on the aircraft's specific fuel burn rates, an approximate value for fuel burn was determined. On the range-payload charts presented earlier in this report, the values at the edge of the envelope for these charts have a known amount of total fuel burned during the particular flight. A diagram illustrating this envelope is shown in Figure 4.11. Assuming each aircraft will carry half of the maximum payload on average, the maximum range at that particular aircraft weight can then be determined. Fuel reserves were assumed to be 10 percent. The total onboard fuel excluding the reserves was divided by the amount of time to fly a mission at the half payload range at an average cruise speed, which yielded an estimate for fuel burn rate. The rates calculated in this manner were comparable to those reported in Air Force Pamphlet (AFPAM) 10-1403. Since there were aircraft analyzed in this study that were not included in AFPAM 10-1403, it was necessary to adopt this methodology. The results from this fuel analysis are shown in Table 4.12.

Table 4.12. Fuel Burn Rate for Alternatives

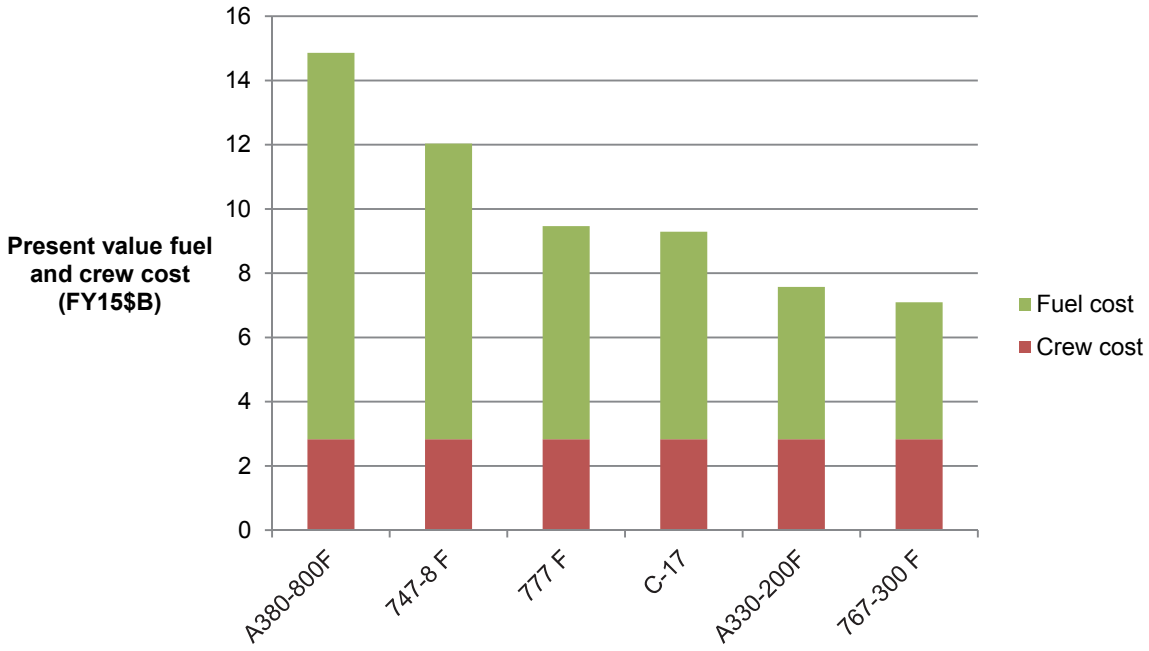
	Fuel flow (lbs./hr)
A380-800F	31558
777 F	17400
767-300 F	11193
747-8 F	24144
A330-200F	12438
C-17	16953
C-5	25081
C-130	4220
B-1	12831
B-52	12577

It is important to note that these fuel burn rates vary with mission profile, aircraft configuration, speed, altitude, and atmospheric conditions. However, it is anticipated that the relative fuel burn rates among the alternative aircraft would not change if the mentioned parameters are changed uniformly and proportionately. Figure 4.12 presents the results from the crew and fuel analysis. Crew costs are the same among the alternatives as a result of assuming equal crew ratios and crew composition for every alternative. The price per gallon of fuel was assumed to be constant at $2.98/gallon.[150] With the exception of the C-17, fuel costs increase as

[150] *FAA Aerospace Forecast Fiscal Years 2015-2035*: Federal Aviation Administration, 2014.

the aircraft weight increases. Part of the reason the C-17 has a higher fuel burn rate than the heavier 777 may be that the commercial airline aircraft are optimally designed for fuel efficient flight, whereas the C-17 was built with military utility in mind. The wide-body fuselage of the C-17 is highly effective for military cargo missions, but it comes with increased drag and less efficient fuel use. The crew and fuel costs shown in Figure 4.12 account for roughly 20-25 percent of the overall costs, which is in agreement with the cost proportions presented earlier in Table 4.6.

Figure 4.12. Fuel Cost and Crew Cost Results



Summary of Findings

The results of this cost analysis indicate that costs scale with weight of the aircraft for a fixed buy size. The A380F, the largest alternative considered in the analysis, is the costliest alternative according to the estimation methodologies used in this analysis. The C-17 acquisition option incurs a penalty of restarting the production line, but avoids the high development costs associated with building a new airplane.

Procuring a new aircraft would incur costs that are orders of magnitude larger than the costs associated with using existing cargo aircraft for the mission. Existing cargo aircraft would need to be equipped with some kind of launching system, perhaps comparable to the Raytheon-developed MCALS. An analogy was used to estimate the development and procurement costs for this kind of launching system. The option to use existing military aircraft is not included in the comparison of procurement programs because the cost is so minimal.

These results show the cost for a fixed buy size of 100 aircraft. The cost-effectiveness analysis, which follows, determined the fleet sizes for each alternative based on the quantity of aircraft required to meet the target demand.

5. Of the Bomber Alternatives Considered in this Study, Which are the Most Cost-Effective?

Overview

This section compares the costs of arsenal aircraft alternatives for varying policy options to either supplement or replace the current legacy bomber fleet in meeting high demand scenarios. Assessments of cost effectiveness include how and when to procure the aircraft in order to incur minimal cost. There are unrealized benefits intentionally left out of this analysis due to limits in the scope of this dissertation. Namely, considerations for payload flexibility and nuclear capability are considered here only qualitatively.

A fixed-effectiveness methodology was used to determine the number and cost of each alternative needed to provide sufficient standoff capacity in stressing scenarios. Each alternative was analyzed over a set of policy options. Two overarching policy options are to either replace the bomber fleet while maintaining the current level of bomber standoff capacity or to supplement the bomber fleet to handle higher demand. Within these two overarching policy options, the B-1 and B-52 can be retired as soon as possible, or retired at their projected retirement date of 2040, either at the same time or spaced apart. For purposes of comparison, it is assumed that all B-1 and B-52 aircraft will be replaced by arsenal aircraft. The result of this analysis is a recommendation of the alternative and policy option that provide the least cost.

Arsenal Development Options

Strategies for developing arsenal aircraft hinge upon the size of the demand for cruise missiles. If the cruise missile demand is high enough, the firepower required in a scenario will exceed that which is available from the current legacy bombers. If the expected demand for cruise missiles is not expected to exceed the legacy bomber capacity, then perhaps the best option would be to procure enough arsenal aircraft to maintain the same capability as the retiring legacy bombers. The first decision point, then, can be stated as whether it is more desirable to maintain current cruise missile launch capacity or to supplement the bombers to meet a higher potential future demand. B-1 and B-52 aircraft may be retired if an arsenal aircraft is capable of replacing the current bomber capability over a variety of missions. In this analysis, the bombers were assumed to be retired and replaced by arsenal aircraft. The Air Force has extended the lifetime of the B-1 and B-52 to 2040, but there may be some cost savings if these aging fleets are retired earlier. If one fleet is retired early while the other is retired as planned in 2040, it would make sense to maintain the production line for the arsenal aircraft and divide the procurement into two stages spaced far enough apart to allow the replacement of two fleets with one aircraft. This option would avoid incurring additional development costs of purchasing two different aircraft replacements, one for each legacy bomber.

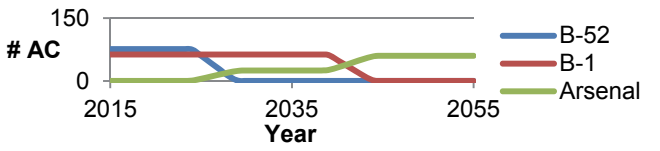
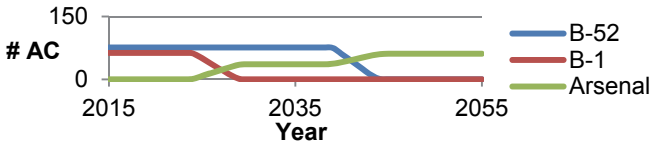
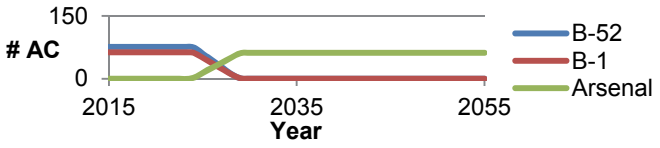
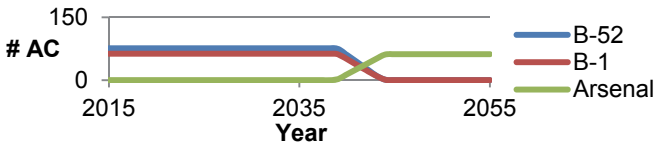
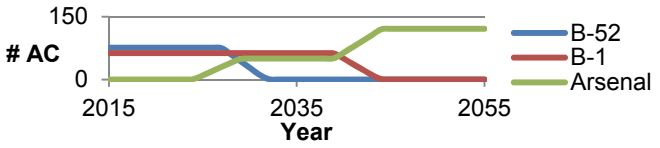
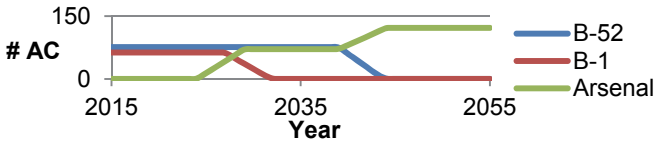
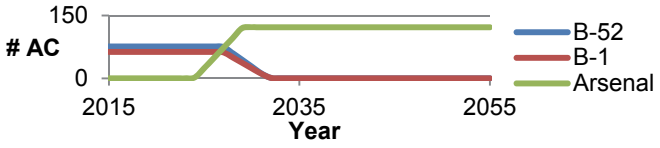
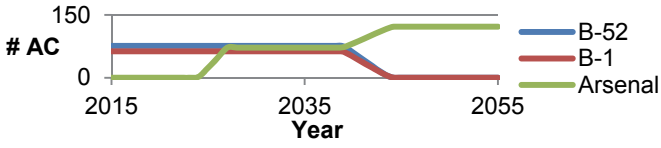
Table 5.1 presents a summary of potential policy options that could be pursued if an arsenal aircraft were acquired.[151] Notional timeline representations of each procurement option are also included in the table. In every case, procurement begins in the tenth year to allow time for development.

The consideration of these policy options may lead to some skepticism in regard to two particular capabilities of the current fleet. The first is the capability for stand-in conventional bombing. The B-52 and B-1 are used for a range of missions much more diverse than just attacking with cruise missiles. As of late, the B-1 even has been used in a close air support role. If future conflicts look anything like the recent conflicts that have relied on long-range strike, there will be a large need for stand-in conventional bombing. The LRS-B will be able to handle a significant amount of stand-in bombing if the planned buy quantity is reached. Nevertheless, the arsenal plane may need some payload flexibility if it is to replace some or all of the B-1 and B-52 fleet, even if it may lead to higher costs in the launching system development. Another potential concern is the nuclear role of the B-52. The LRS-B is expected to be nuclear capable and will eventually replace the B-52 nuclear role. Retiring the B-52 early and replacing it with arsenal aircraft would leave a shortfall in nuclear capable aircraft until the LRS-B is produced in sufficient numbers.[152] This may cause policy makers to favor options where the B-52 is kept in the fleet until after the LRS-B is produced.

[151] As indicated in Chapter 2, significant improvements need to be made to long-range cruise missile capabilities for standoff bombing to be relevant in high demand target sets. Also indicated in that chapter is the high amount of cruise missile demand on the first day of the conflict. For the necessary numbers of cruise missiles to be launched, there will need to be increased production of cruise missiles to support the target demand. If arsenal aircraft are supposed to enter operation by 2025 as depicted in these figures, a necessary condition will be to have cruise missiles in sufficient quantities with sufficient capabilities. This would be ambitious but executable within the given timeframes.

[152] The issues of capacity shortfalls in conventional bombing and nuclear capability are mentioned here as an observation, but are not considered in the analysis as this is beyond the scope of the dissertation research.

Table 5.1. Summary of Arsenal Aircraft Policy Options

Desired cruise missile capacity	Procurement strategy		Timeline
Current capacity	Replace current capacity as soon as possible	Retire B-52 as soon as possible	
		Retire B-1 as soon as possible	
		Retire B-1 & B-52 as soon as possible	
	Maintain current fleet	Retire B-1 & B-52 in 2040	
Future demand	Replace current fleet as soon as possible, supplement for higher capacity	Retire B-52 as soon as possible	
		Retire B-1 as soon as possible	
		Retire B-1 & B-52 as soon as possible	
	Maintain/ supplement current fleet	Retire B-1 & B-52 in 2040	

Methodology

There are two approaches to analyze alternative aircraft and the set of policy options for integrating these alternative aircraft into the bomber fleet. The first is to use a fixed-horizon approach, where a timeframe is selected and the costs are represented as net present values. Assets that remain at the end of the time period are assigned some salvage value using a straight-line depreciation of the asset. The other potential approach is to use an infinite-horizon. Under this approach, when the fleet of arsenal aircraft used to replace the legacy bombers reaches its prescribed lifetime, another identical fleet is acquired to replace the aged arsenal fleet. Replacement fleets are purchased at the beginning of every lifecycle in perpetuity. Using a discount rate, a finite cost can be derived from the infinite sum of the geometric series of discounted annual costs.[153] This approach more accurately captures the costs and benefits associated with each of the policy options. One of the driving costs of these policy options is the O&S cost associated with the aged legacy bomber fleet. The longer the acquisition of a replacement is delayed, the higher the net present value cost will be to sustain the aging fleet. The economic benefits of delaying the acquisition of a replacement arsenal fleet are realized not only in the delay of the program costs of the first replacement fleet, but also all following replacement fleets. If each policy option started on the same day and lasted the same amount of time, these two approaches would be identical. However, since the decisions are offset as shown in Table 5.1, the infinite horizon approach more accurately represents the full economic costs and benefits.[154] Although the outcome of each of these two approaches may not be largely different, the infinite horizon approach is preferred in this analysis due to its greater anticipated fidelity.

Figure 5.1 depicts a notional example of an infinite horizon analysis as it pertains to arsenal aircraft policy options. This figure represents a case where the bomber retirement occurs in two stages with the B-52 retiring first. As each fleet is retired, a certain number of arsenal aircraft are produced. Each delivery of arsenal aircraft retires at a different point, causing the buildup and retirement phases to look somewhat scattered. As the first cohort of arsenal aircraft is retired, a new arsenal program commences and aircraft are produced to replace the retiring aircraft. This cycle continues indefinitely.

The cost analysis of this report used a fixed buy size for all alternatives. This section maps the cruise missile demand and arsenal aircraft effectiveness to the program costs. By using a fixed-effectiveness approach, the primary goal is to minimize the monetary costs. Results are

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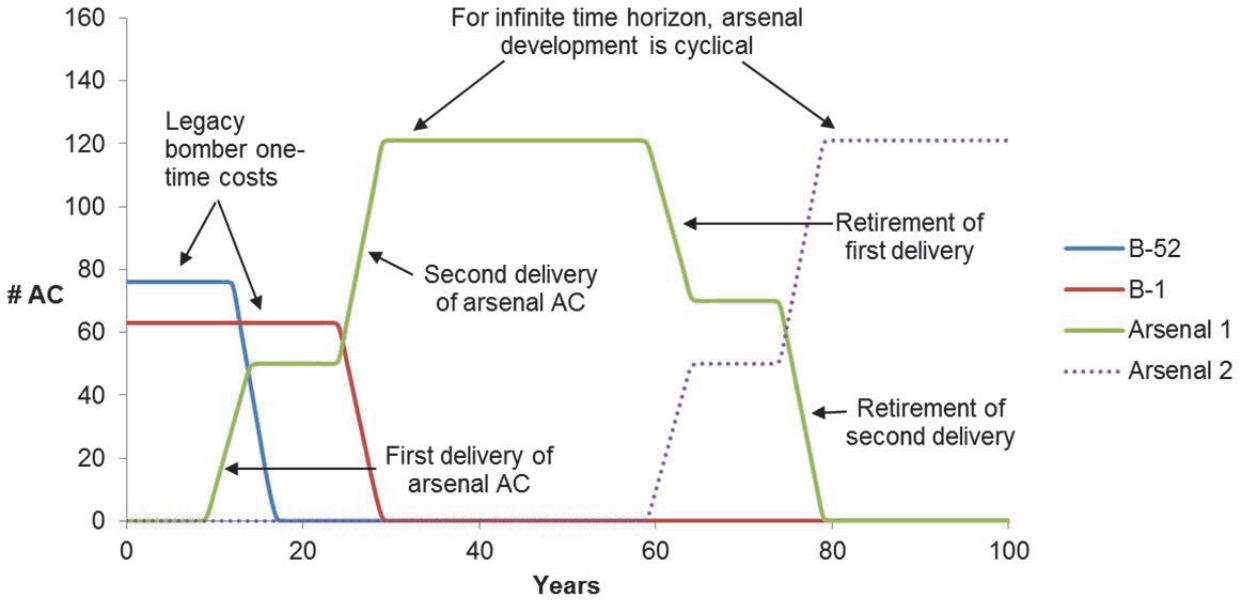
[153] For a detailed derivation of the infinite horizon calculations, see Appendix A.

[154] This is based on a discussion with Michael Kennedy with reference to the methodology used in the following report: Michael Kennedy et al., *Analysis of alternatives (AoA) for KC-135 recapitalization: executive summary,* ed., Santa Monica, CA, RAND Corporation, 2006.

presented in the form of net present value (NPV) using a real discount rate of 1.4 percent.[155] The lifetime for the arsenal aircraft is assumed to be 50 years. This assumption is consistent with previous RAND analysis that investigated the optimal time to replace military aircraft, varying assumptions of O&S cost growth. With zero cost growth and infrequent fluctuations in O&S cost, the optimal cost-minimizing replacement interval is 51 years.[156]

Figure 5.1. Notional Example of Infinite Time Horizon for Aircraft Development



Results

Current Capacity

The PVLCC of the current legacy bombers was calculated for a remaining lifespan of up to 25 years depending on the policy option. These costs are comprised of the O&S costs for the bombers, which cost increases in log linear form with age. The arsenal aircraft alternatives all consist of development, procurement, and O&S costs. In cases where one or both of the legacy bombers is retired early, there will be an early spike in costs that exceeds the steady state legacy bomber O&S costs. However, the O&S costs in all cases will be much smaller than legacy bomber costs due to the smaller fleet of arsenal aircraft. The savings in high O&S costs of an aging fleet are what make it more cost effective to retire legacy bombers early.

[155] Real discount rate for a 30-year maturity as provided by the Office of Management and Budget.

[156] Victoria A. Greenfield and David Persselin, *An economic framework for evaluating military aircraft replacement,* ed., Santa Monica, CA, RAND Corporation, 2002.

The required number of aircraft to replace the legacy bomber cruise missile capacity is shown in Table 5.2. Of these options, the A380-800F and 747-8F have the largest capacity for cruise missiles and therefore require the smallest number of aircraft to replace the existing capacity. Interestingly enough, the numbers of aircraft required to replace either the B-1 fleet or B-52 fleet are almost identical. The cruise missile firepower provided by these two fleets is essentially equal. Although the B-52 has slightly more aircraft, the B-1 has slightly more capacity, which accounts for this result.

The LRS-B was not explicitly analyzed in this dissertation. However, it is interesting to note that if the LRS-B were to replace all legacy bombers with a buy of 100 aircraft, each LRS-B would need to carry about 30 cruise missiles to maintain the same standoff capacity.[157] The details of the new aircraft's dimensions are currently unavailable to the general public, so there may be a shortfall in standoff capacity if the buy size or the weapons loadout are not as big as we anticipate.

Table 5.2. Number of Arsenal Aircraft Required to Replace Legacy Bomber Fleet Capacity[158]

	Number of arsenal aircraft required		
	Replace B-52	**Replace B-1**	**Replace B-1 and B-52**
A380F	18	18	36
A330-200F	37	36	73
767-300F	44	43	87
777F	23	23	46
747-8F	18	18	36
C-17	23	23	46

NOTE: The "capacity" used in this comparison is the daily firepower capacity from an operating range of 1000 nautical miles. The numbers of required aircraft are in terms of TAI and include effects from mission capable rates.

These numbers are then combined with cost, resulting in the costs indicated by the bars in Figure 5.2. Legacy bomber costs are only incurred once and not repeated along the infinite time horizon. The policy option for retiring both the B-52 and the B-1 early has the smallest cost,

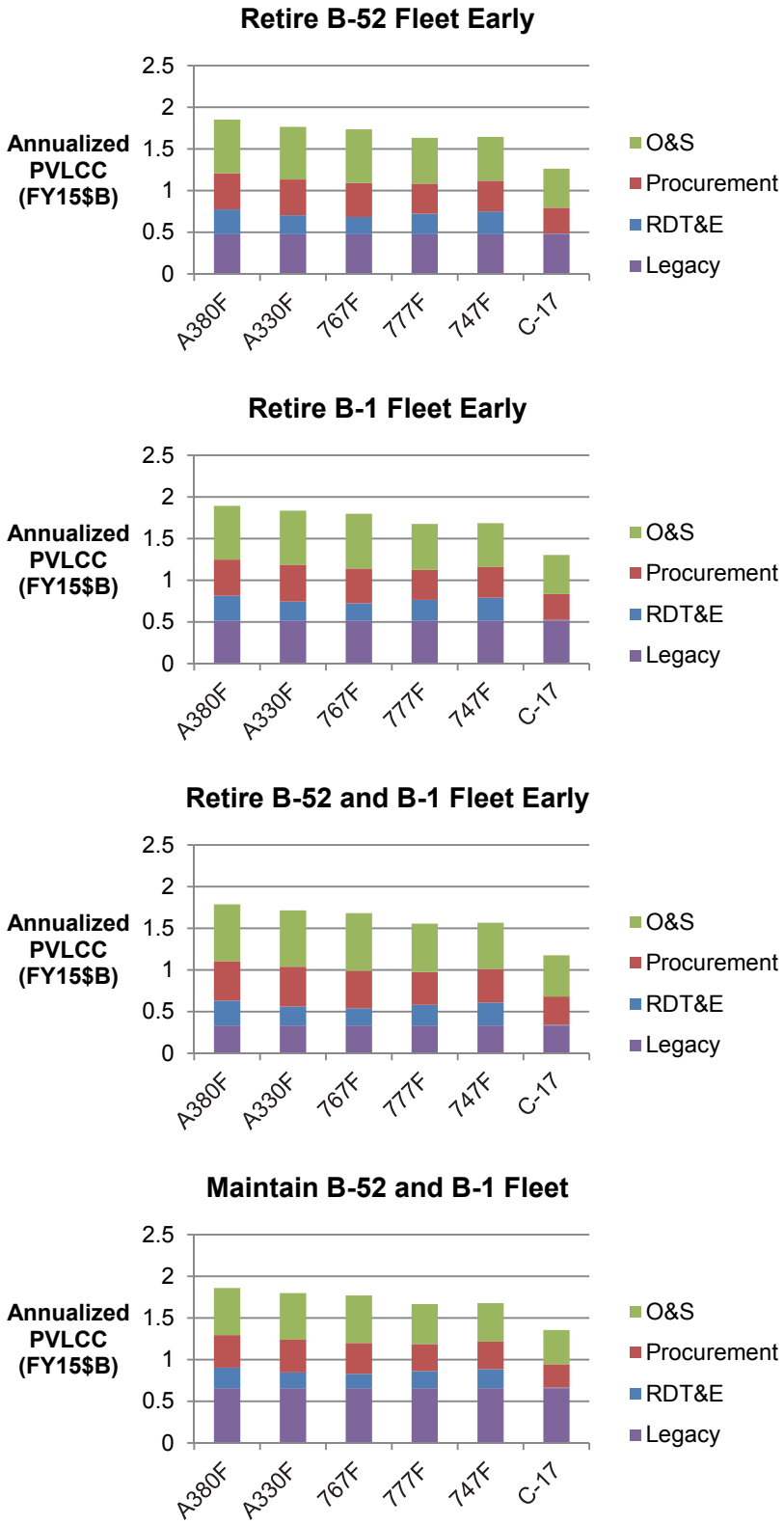
[157] This assumes that the mission capable rate would be comparable to the current legacy bombers.

[158] The TAI discussed here is based on a comparison of the effectiveness of the fleet's PMAI. To get from PMAI to TAI, two ratios were used. The first, as discussed in the demand section of this report, is that two thirds of the PAI (primary aircraft inventory) is PMAI. The second is that the ratio of PAI to TAI will be equivalent to the current legacy bomber ratio. This ratio accounts for aircraft that will be used as trainer aircraft, spares, etc. According to current legacy bomber numbers, this ratio is 0.57.

while keeping both aircraft yields the highest cost. For every arsenal alternative, the percent difference from the lowest costing policy option to the highest costing policy option ranges from six percent (A380F) to 15 percent (C-17). Within each policy option, the C-17 tends to be the lowest-cost alternative and the A380F is the highest-cost alternative. There is not a huge amount of variation among the commercial derivative aircraft, as they are all within 15 percent of the lowest commercial derivative alternative. The C-17 is somewhat promising due in part to low EMD costs. Costs for the average commercial derivative range from 30 percent to 41 percent more expensive than the C-17 costs.

Aircraft modifications may be needed to expand the payload flexibility of arsenal aircraft to accommodate the conventional bombing mission demand if all bombers were retired early. Perhaps a more desirable strategy for those concerned about this would be to replace only a part of the legacy fleet. For instance, if the B-52s were retired early and replaced by arsenal aircraft, the conventional bombing mission could still be served by the B-1s and incoming LRS-Bs while the arsenal aircraft could serve as a primarily supplemental force to handle higher than normal cruise missile demands. The results in Figure 5.2 indicate that policy makers should be indifferent in terms of realized costs between retiring the B-52 early and retiring the B-1 early. As discussed earlier, there are reasons why the Air Force may want to preserve the B-52 to maintain a nuclear capable fleet at least until the LRS-B can replace its nuclear capability, but without considering that mission the two options result in near identical costs. As with any analysis involving comparisons of investment options, there is a certain level of uncertainty resulting from assumptions, data, and methodology. Appendix B of this report contains an analysis of the statistical uncertainty of these estimates.

Figure 5.2. Present Value Life Cycle Cost (Infinite Horizon) of Options for Replacing Current Legacy Bomber Cruise Missile Capacity



NOTE: PVLCCs are calculated for a 50-year lifecycle from the start of aircraft procurement. Development is assumed to last 10 years, and procurement is assumed to last for six years in every case. Legacy retirement costs are O&S only and do not include disposal costs. Costs are discounted at 1.4 percent as suggested by OMB. An 85 percent learning rate is assumed for all commercial aircraft. C-17s are assumed to have a 95 percent learning rate.[159]

Future Demand

The same assumptions used in the current capacity case are also used here. The demand section of this report informed the number of aircraft needed to be acquired in this analysis, which is shown in Table 5.3. While there were several target sets analyzed and a variety of assumptions, it was deemed most appropriate to use an average of the best and worst case assumptions for the theater level demand. Under worst case assumptions, the highest daily cruise missile demand turned out to be 2550, and under best case assumptions the demand was 510, which yields an average demand of 1530 for this analysis. These numbers are driven by the Day 1 demand which consists solely of the amphibious invasion. The next highest demand consists of runways and fixed targets and is not much lower than the Day 1 demand. This analysis uses the amphibious invasion peak demand, but fluctuations in the daily demand are considered later in this section.

Table 5.3. Number of Arsenal Aircraft Required to Supplement Legacy Bomber Fleet Capacity

	Number of arsenal aircraft required [a]			
	Replace B-52	**Replace B-1**	**Replace B-1 & B-52**	**Maintain B-1 & B-52 [b]**
A380F	39	38	56	21
A330-200F	80	79	116	43
767-300F	95	94	138	51
777F	50	49	72	27
747-8F	39	39	57	21
C-17	50	50	73	27

NOTE: The "capacity" used in this comparison is the daily firepower capacity from an operating range of 1000 nautical miles. The numbers of required aircraft are in terms of TAI and include effects from mission capable rates.

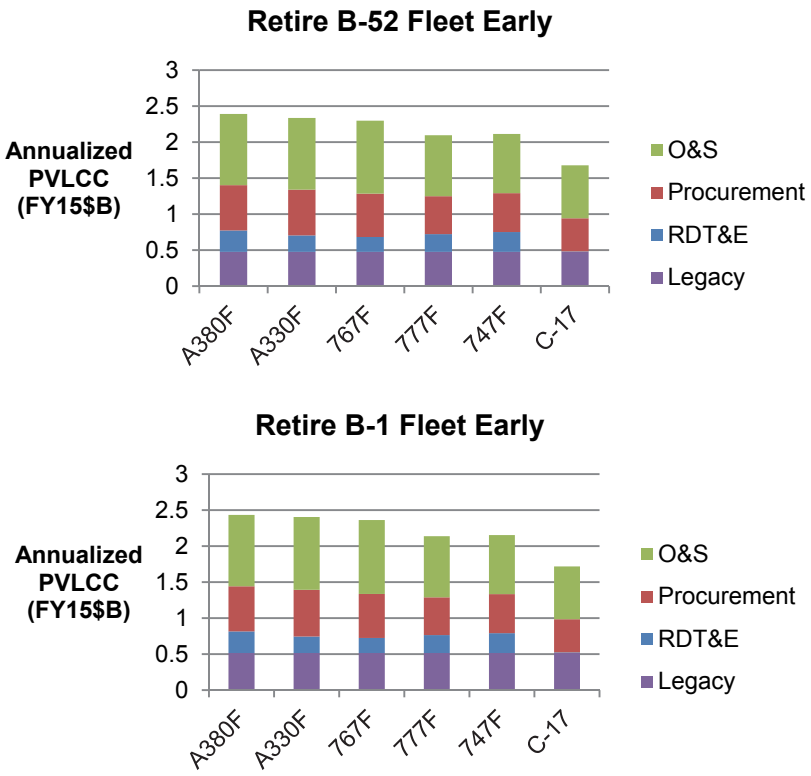
[a] The theater demand from Figure 2.20 was used to determine the number of arsenal aircraft needed. An average of the best and worst case assumptions was taken and represented here as a potential cruise missile demand.

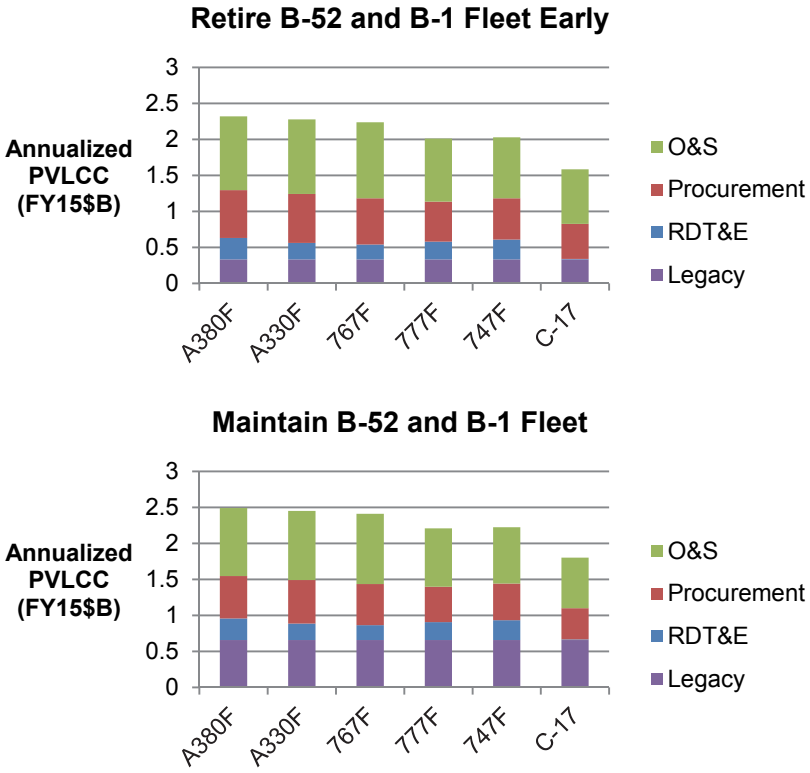
[b] This represents the number of arsenal aircraft that must be procured in the near term to supplement the current bombers. When the bombers are retired, another aircraft will be acquired in the numbers shown in Table 5.2.

[159] Derived from assumptions and results in the following report: Graser et al., ed.

The results of this future demand analysis are similar to those of the current capacity analysis. The lowest-cost option would be to retire both the B-1 and B-52 early. The highest-cost option is to maintain the legacy fleet and retire it at the planned year of 2040. Due to the age of the legacy fleet, high O&S costs make this option somewhat less desirable. The highest-cost option ranges from 7 percent to 14 percent higher than the lowest-cost option, depending on the arsenal alternative. The C-17 ends up again as the cheapest arsenal alternative, with the average commercial derivative being 31 percent to 37 percent higher depending on the policy option.

Figure 5.3. Present Value Life Cycle Cost (Infinite Horizon) of Options for Supplementing Current Legacy Bomber Cruise Missile Capacity





Other Military Cargo Derivatives

The policy option of using existing military cargo aircraft to serve in an arsenal role was not explicitly modeled in the cost section due to the minimal amount of funding it would take to use these aircraft. There would obviously be some development costs, and some crew and training costs. But these aircraft are already procured and if they were used only as needed, there would be minimal O&S involved. The major setback in this policy option is that the use of these aircraft in a scenario where the cargo mission would be extremely demanding would be overstressing to the fleet. It would be hard to imagine how the existing cargo fleet could ever replace the bombers. Under this option, cargo aircraft would have to be removed permanently from the cargo mission in order to fulfill the bomber role. The more realistic scenario is where the cargo aircraft are used as a niche capability only in times of excess demand. The demand required in this kind of scenario is portrayed in Table 5.4.

Table 5.4. Number of Existing Cargo Aircraft Required to Supplement Legacy Bombers in Arsenal Role[160]

	Policy option: Keep B-1 and B-52		
	TAI	Number of AC for arsenal mission	Percent of TAI
C-17	222	11	0.05
C-5	64	7	0.11
C-130	358	45	0.13

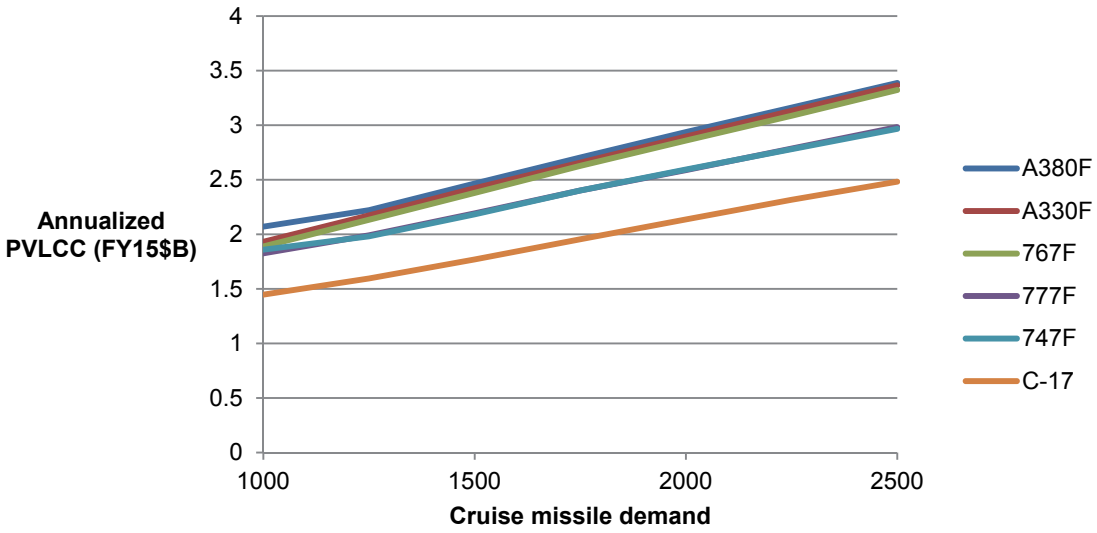
The number of aircraft is a surprisingly small proportion of the total fleet. In the case of the C-17, only five percent of the TAI is required to fulfill the excess demand that the legacy bombers cannot attain with their given capacity. It may be the case that even the 11 C-17s needed would still exceed the available aircraft during a conflict of significant proportions. However, it is interesting to note that with such a small number of required aircraft, there may be some room for these missions if theater cargo demand isn't exceedingly high.

Cost-Effectiveness Findings are Influenced by Certain Analysis Drivers

The theater cruise missile demand varies significantly depending on the assumptions used in the demand analysis. Demand can range anywhere from 510 to 2550 cruise missiles required per day. The current bomber fleet can handle up to 960 cruise missiles per day at an operating range of 1000 nautical miles, which leaves a large spectrum of the cruise missiles demand unattainable without some supplemental capacity. Due to the uncertainty of the exact amount of required demand, a sensitivity exercise was conducted to determine how cost changed with missile demand. This is illustrated in Figure 5.4. At the far left side of the graph, as the demand approaches the amount attainable by the current bombers, there are some nonlinear trends, although they do not greatly affect the ordering of the aircraft in terms of minimal cost. The proportional decrease in cost between commercial derivatives and the C-17 remains relatively constant as the demand increases.

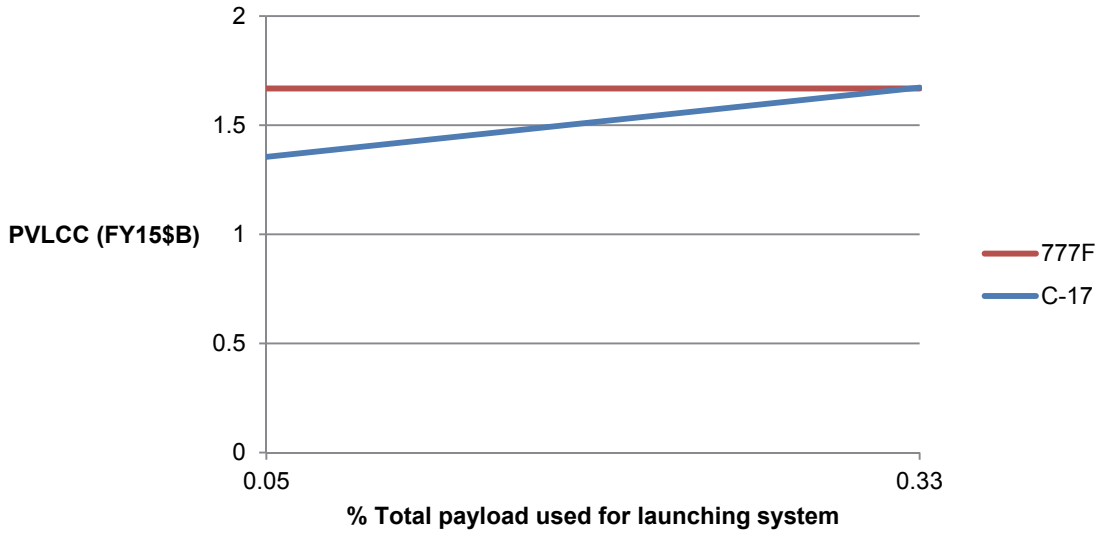
[160] It is important to note that the number of required aircraft calculated here is not the same as the TAI calculated for the acquisition of arsenal aircraft. The number of existing military cargo aircraft required is the pure number of aircraft needed to fulfill the mission, since the larger fleet already has spares and training planes. If the launching system was truly a roll-on/roll-off system, there may not be any need to have dedicated training aircraft for this mission.

Figure 5.4. Cost Sensitivity to Cruise Missile Demand



A large area of uncertainty in this analysis is the launching systems used by aircraft alternatives. Rather than performing an engineering level design of an internal launching system, this analysis relied on cost analogies, regression of cost data, and assumptions regarding the weight of the launching system. The assumption used in this analysis for the weight of the launching system is subject to change if an arsenal aircraft is pursued. To capture the uncertainty regarding the weight of the launching system, this analysis performed cost-effectiveness analysis on the high and low end assumptions of launching system weight for military cargo derivatives. The launching system weight for a commercial derivative was derived from the Boeing concept of a CMCA, which was assumed to be 33 percent of the total available payload. This assumption for military cargo derivatives was only five percent of the total payload. In reality, these proportions may vary although it can be expected that the weight of a rack system would be less than the weight of a rotary launcher system. Figure 5.5 shows the results of the PVLCC for the two least-costing options, the C-17 and 777F. If the proportion of launching system weight is equal among these alternatives, coincidentally there is no difference in the cost. However, as the proportion of the launching system weight for the C-17 is decreased, the cost for the C-17 becomes significantly less than the 777F cost.

Figure 5.5. Cost Sensitivity to Assumption of Total Payload Used for Launching System



One consistent result of this analysis is that the least costing option is to retire both the B-1 and B-52 early and replace them with an arsenal aircraft. This analysis did not take into account the option of extending the service life of the B-1 and B-52 well past their retirement age. These bombers will need to be replaced at some point, so the arsenal aircraft is assumed to be that replacement. If the assumption is to replace the aging fleet, there is a tradeoff between the high acquisition cost associated with purchasing a new aircraft and the high O&S cost associated with keeping the legacy bombers in the fleet. According to this analysis, it turns out that the O&S cost of the aging fleet outweighs the near-term acquisition costs of a new aircraft program. Part of the reason for this is the comparison of O&S cost to cruise missile carriage, which is shown in Figure 5.6. The B-1 and B-52 have high O&S cost compared to the small amount of cruise missiles they can carry, relative to the other arsenal options. Figure 5.7 illustrates the same result but as a ratio, which helps explain why the C-17 is the least costing alternative. Aside from having a much smaller development cost than the commercial derivative acquisition programs, the C-17 also has the highest ratio of firepower to O&S cost.

Figure 5.6. Comparison of O&S Cost and Cruise Missile Carriage Capacity for Aircraft Alternatives

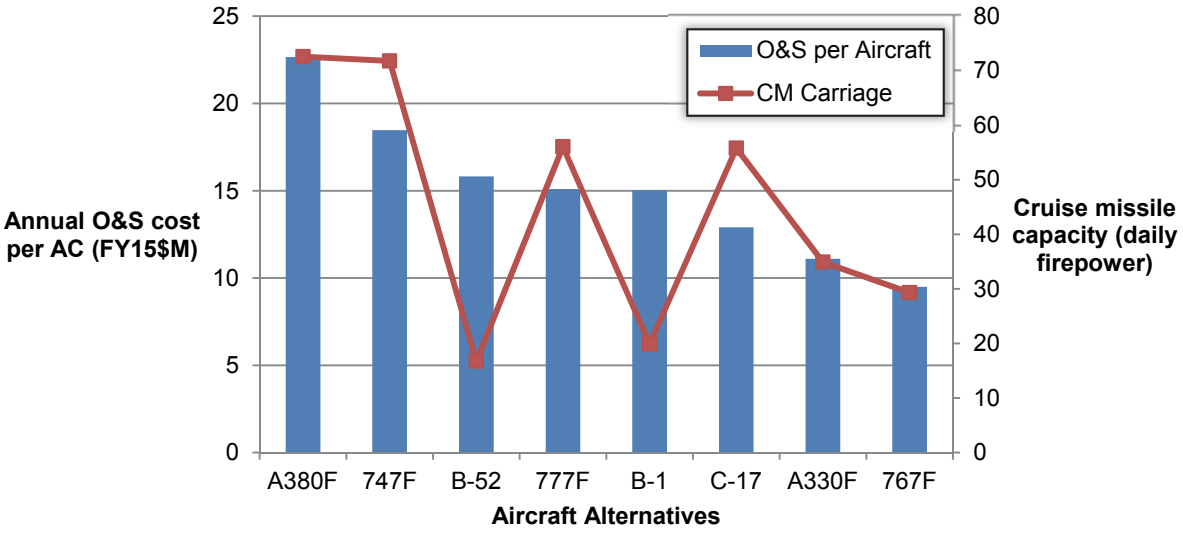
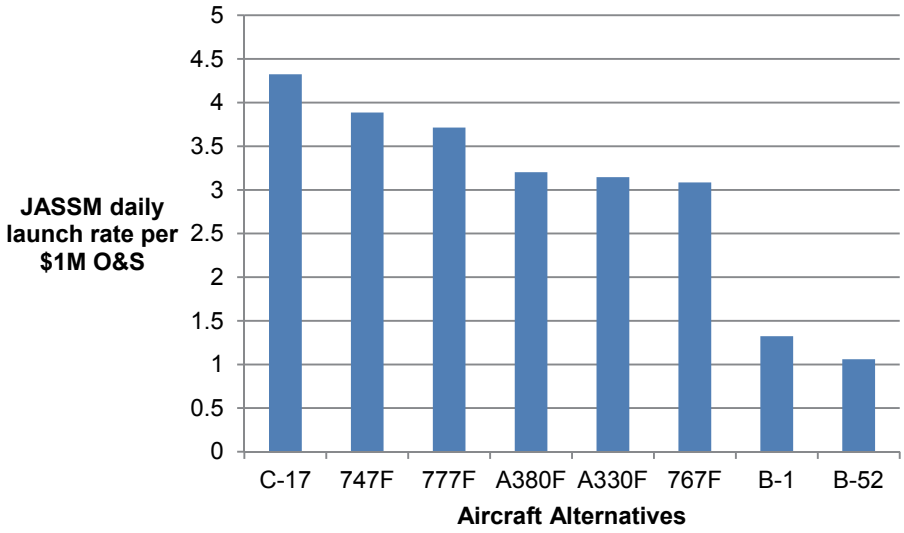


Figure 5.7. JASSM Daily Launch Rate per $1 Million O&S

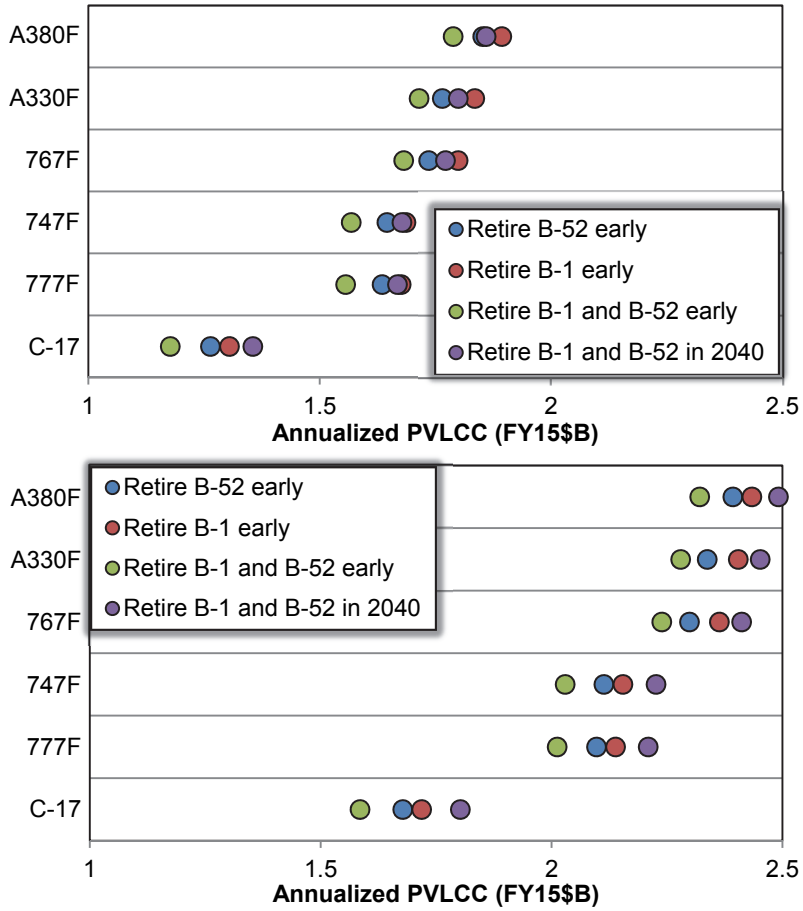


Summary of Findings

The C-17 is the most cost effective of the procurement options even with the incurred penalty of reopening the production line. Several procurement strategies were tested among the arsenal alternatives. These strategies were categorized into two classes: replacing the current bomber capacity, and replacing/supplementing the current bombers to meet a high-demand capacity. Within these classes, there were differing strategies as to when each bomber fleet would be retired. There was not a huge amount of variation among these strategies, although the option to

retire both the B-1 and B-52 early was consistently the lowest cost option. The C-17 was also consistent in being the lowest-cost arsenal alternative as a result of low development costs. These results are shown in Figure 5.8.

Figure 5.8. Annualized PVLCC for Different Procurement Strategies for Replacing the Current Capacity (Top) and Supplementing the Fleet for a Higher Capacity (Bottom)[161]



Using existing aircraft would be highly cost effective, but would be somewhat stressing to the cargo fleet. The option to use existing military cargo aircraft and use them only when there is an excessive demand for standoff bombing is the most cost-effective solution. This is a result of minimal EMD and procurement costs. These aircraft are already operating in the fleet, and O&S

[161] It is interesting to note that the ordering of policy options for commercial derivatives is not the same for both figures. This is caused by the difference in the number of aircraft procured in each option. The development cost remains constant with respect to the buy size. When the buy size decreases, the proportion of development cost to overall PVLCC increases. In other words, the development cost becomes a bigger driver of the results for smaller buy sizes. This also explains why the ordering of policy options for the C-17 is the same in both figures, as the C-17 incurs minimal development cost and is not subject to this effect.

costs would be minimal as the aircraft would be mostly operating in their primary cargo mission. The only acquisition cost would be that of a launching system. However, this option presents challenges in the form of opportunity cost to the cargo fleet. In an already stressed cargo mission, borrowing a handful of aircraft may prevent the cargo fleet from meeting their demands. However, perhaps this shortfall is not as extreme as one would expect. The required aircraft would be only five percent, 11 percent and 13 percent of the fleet size for the C-17, C-5, and C-130 respectively.

6. Conclusions

This dissertation has addressed several research questions in an effort to provide more insight on the issue of improving standoff bombing capacity in A2/AD environments. This issue is particularly relevant for Air Force policy makers who need to ensure the bomber fleet is survivable and potent. The LRS-B would certainly provide that to the fleet. However, there remains a potential near-term capacity gap in terms of the standoff capacity of the current bomber fleet before the LRS-B is operational. There also remains the far-term issue of the need to retire the aging bomber fleet. Acquiring new standoff capacity is a potential solution to these policy problems. This report analyzed several alternatives that could be viable options for increasing standoff capacity.

To that end, this chapter presents the overall findings and implications of this research. Several alternatives for arsenal aircraft were considered, including commercial derivative procurement (A380F, A330F, 777F, 747-8F, 767-300F), military cargo derivative procurement (C-17), and military cargo derivative dual role (C-17, C-5, C-130). These options could be employed to either replace the existing capacity of the aging B-52 and B-1 fleets, or to supplement these fleets in times of high demand for standoff bombing capability.

In addition to today's fixed-target strike cruise missiles, demand for new standoff weapon capabilities could help address a wide variety of important targets. This analysis identifies anti-ship and counter-runway cruise missiles as two important capabilities that could contribute to bomber effectiveness in A2/AD conflicts. Cruise missiles would also need to be acquired in large quantities to handle the potentially large time-critical target demand found in this study.

If new standoff weapons are developed, there is still a potential shortfall of standoff firing capacity available for A2/AD scenarios. Policy makers have two classes of options when confronting the problem of standoff capacity shortfalls. The first is to reduce the demand for cruise missiles in stressing scenarios. The adversary is, of course, responsible in large part for the target demand. However, there are many alternative solutions that can increase the effectiveness of the attack and thereby reduce the number of missiles needed to strike the given set of targets. The second is to increase the supply of cruise missile firepower. This is accomplished simply by increasing capacity in the form of procuring more aircraft.

The following are the findings and implications regarding reduction of cruise missile demand:

- **Improving ISR capabilities is an effective way of reducing enemy halt distance in the case of a land invasion.** If target locations are accurate, or in other words if cruise missiles are capable of receiving updates on target location throughout the flight path, the halt distance of a land invasion can be reduced by a factor of up to 5.6 (see Figure 2.6 of this report). This would imply that for a fixed halt distance, the number of missiles

required would be reduced by a significant amount. Mobile targets generally are not an ideal target for cruise missiles. However, if standoff bombing were required in such a scenario the investment in better ISR would be recommended for decision makers.

- **ASCM sensor ability can reduce cruise missile demand significantly in the case of an amphibious invasion.** If the enemy employs a strategy using ship decoys during the amphibious invasion, the number of cruise missiles required to destroy 50 percent of the invading fleet can be reduced by a factor of up to 4.2 if ASCMs can discriminate between ship targets.
- **Larger salvo sizes and longer firing intervals can increase survivability and overcome weaknesses in battle damage assessment ability during an amphibious invasion.** Against any defended target, the more missiles that arrive simultaneously, the more overwhelmed the enemy air defenses will be. This will lead to larger numbers of leakers that get past the defenses and attack the targets. In the case of moving targets such as ships in an amphibious invasion, battle damage assessment prevents cruise missiles from striking targets that are already defeated. With longer intervals between salvos, the destroyed, non-moving targets will be left behind the formation and there will be fewer redundant target strikes.
- **Accurate intelligence on airbases that have high priority aircraft can reduce the number of runways required for attack.** While CEP is a major factor in how effective cruise missiles are in destroying fixed targets, another avenue to reducing cruise missile requirements is to know which targets to strike. In the case of runways, intelligence that distinguishes runways that are operating combat aircraft from general military runways can reduce the total number of targets by a factor of up to 2.4 (see Table 2.14). This reduction would increase substantially if, for instance, fighter aircraft were the primary aircraft of interest.

The other class of findings in this report relate to increasing the cruise missile firing capacity of the bomber fleet. The following are the findings and implications of options for increasing standoff bombing capacity:

- **Target demand among target types under best-case assumptions yields a demand less than the current bomber capability. Worst case assumptions yield a demand much more than current bomber capability.** Realistically, the current bombers can handle any number of targets if they are spread out over a long-enough time period. Where the current fleet runs into problems is when the rate at which targets need to be attacked exceeds the rate at which the current bombers can fire cruise missiles. The rate analyzed in this report was cruise missiles fired per day given an operating radius of 1000 nautical miles. With full loadout configurations, the current bombers can handle a rate of roughly 960 cruise missiles per day. The demand analysis in this report yielded a range of cruise missiles required in the theater of 510-2500 depending on the analysis assumptions, which is correspondingly 53-266 percent of the current bomber capability.

- **Of the procurement options, the C-17 was found to be the most cost-effective.** Several procurement strategies were tested among the arsenal alternatives. These strategies were categorized into two classes: replacing the current bomber capacity, and replacing/supplementing the current bombers to meet a high demand capacity. Within these classes, each strategy contained a timeline of retirement for the B-1 and B-52 aircraft. After retirement, the aircraft would be replaced by arsenal aircraft procurement. The first two strategies were to retire either the B-1 or the B-52 early, and retire the remaining bomber at the scheduled retirement year 2040. The third option was to retire both the B-1 and B-52 early, and the fourth option was to keep both aircraft until the retirement year and replace them with arsenal aircraft starting in 2040. There was not a huge amount of variation among these strategies, although the option to retire both the B-1 and B-52 early was consistently the lowest cost option. The C-17 was also consistent in being the lowest cost arsenal alternative, in part due to the avoidance of large EMD costs.
- **Using existing cargo aircraft as dual role aircraft could be highly cost effective but somewhat stressing to the cargo fleet.** The option to use existing military cargo aircraft as needed to fill the capacity gap would yield the least cost by far. There would be no aircraft acquisition program since these aircraft are already operational. The only costs would be a relatively small amount of development and procurement cost for a launching system, and operating and support (O&S) costs would be minimal as the aircraft would be mostly operating in their primary cargo mission. However, this option presents challenges in the form of opportunity cost to the cargo fleet. If demand for cruise missiles does not interfere with the cargo mission, this dual role option would incur negligible cost. In scenarios where military cargo aircraft are in high demand, borrowing a handful of aircraft for cruise missile employment may prevent theater cargo requirements from being satisfied. However, perhaps this shortfall is not as extreme as one would expect. In reference to Table 5.4 presented in the previous section, if the C-17, C-5, or C-130 were to be used to supplement the current bomber shortfall, the required aircraft would be only five percent, 11 percent and 13 percent of their respective fleet size. It may be the case that even these small percentages exceed the available aircraft during a conflict of significant proportions. However, it is interesting to note that with such a small number of required aircraft, there may be some room for these missions if theater cargo demand isn't excessively high.

Recommendations for Future Work

The sortie rate model used in this analysis was based on simplifying assumptions. The mission flight times were the primary distinguishing feature among the alternatives. In reality, there are several other factors that affect sortie rates. Both scheduled and unscheduled maintenance will keep an aircraft on the ground for some period of time between flights. Regular operations between flights include refueling and reloading munitions onto the aircraft. It would

be interesting to collect and analyze data regarding maintenance, refueling, and reloading times to determine relationships and trends for various aircraft. This would provide more fidelity to a general sortie rate model used in this study.

The LRS-B was largely excluded from this analysis due to the costs and characteristics being publicly unavailable. Once these details become available, the standoff bombing field of study would greatly benefit from a cost-effectiveness analysis of the LRS-B in relation to its ability to both standoff and penetrate. It would be a useful exercise to estimate the risk of cost overruns and cuts to procurement quantities. There is also the risk that at some point, the stealth technology of the LRS-B will be obsolete as enemy air defenses are upgraded. Given these risks, an investment in larger or more effective standoff capacity could be a viable hedge.

A major aspect of the case for acquiring more standoff capacity is the capabilities of the cruise missile. Without certain features that would allow cruise missiles to attack ships and runways, standoff assets would be rendered useless in an A2/AD conflict involving these target sets. The feasibility and costs of new cruise missile developments was not investigated in this dissertation. Further research could analyze the expansion of the role of the cruise missile in A2/AD conflicts. Additionally, tradeoffs between the costs of improving cruise missile efficiency and increasing cruise missile firepower could be addressed. The issue to be addressed by these tradeoffs would be whether or not the U.S. should procure more capable cruise missiles in lesser quantities, or procure larger quantities of less-capable cruise missiles.

One of the conclusions made in this dissertation dealt with using existing military cargo aircraft as dual role aircraft, operating as arsenal aircraft only when a conflict arose where there was a need for more standoff firepower. This solution would be very low costing and would potentially have a shorter time frame for implementation. However, the feasibility of dual role aircraft may be called into question by policy makers. Several policies would need to be implemented to allow this to happen, and an exploration of the required policy changes and alternative policy options would provide greater clarity for the dual role option. These aircraft may not necessarily be “free,” especially during times of high demand for the cargo mission. Opportunity costs were not analyzed explicitly in this report, and a deeper look into these opportunity costs would provide more insight to the true cost of these systems. There also may be other political consequences. For instance, if C-17s have the capability of carrying cruise missiles, would there be any political pushback from nations that currently allow C-17s to operate in their airspace? These considerations would help to determine costs and benefits that are not readily apparent in the promising dual role option.

Appendix A. Infinite Horizon Calculations

Infinite horizon calculations are derived from the following process. We start with a geometric series, where ξ represents the present value cost of an aircraft with a lifetime n. The variable α_t represents the annual program cost, whether it be development, procurement, or O&S, and r is the discount rate.

$$\xi = \sum_{t=1}^{n} \frac{\alpha_t}{(1+r)^{(t-1)}}$$

Suppose we take a single α from the previous geometric series and repeat it every n years for a certain amount of time. If this was done for every value of α from 1 to n, it would represent the summation of present value lifecycle costs for identical aircraft programs acquired every n years, N times.

$$S_N = \sum_{i=1}^{N} \frac{\alpha}{(1+r)^{n(i-1)}}$$

Expanding this geometric series, we obtain the following:

$$S_N = \alpha + \frac{\alpha}{(1+r)^n} + \frac{\alpha}{(1+r)^{2n}} + \cdots + \frac{\alpha}{(1+r)^{nN}}$$

Multiplying both sides of the equation by $\frac{1}{(1+r)^n}$, the right hand side becomes offset by one time step.

$$\frac{1}{(1+r)^n} S_N = \frac{\alpha}{(1+r)^n} + \frac{\alpha}{(1+r)^{2n}} + \cdots + \frac{\alpha}{(1+r)^{nN}} + \frac{\alpha}{(1+r)^{n(1+N)}}$$

We then take the difference of the previous two equations and solve for the sum, S_N. This is the sum of the geometric series, representing the cost of a single year in the aircraft lifecycle, α, repeated every n years, N times.

$$S_N - \frac{1}{(1+r)^n} S_N = \alpha - \frac{\alpha}{(1+r)^{n(1+N)}}$$

$$S_N = \frac{\alpha - \frac{\alpha}{(1+r)^{n(1+N)}}}{1 - \frac{1}{(1+r)^n}}$$

In order to obtain the summation for an infinite number of identical follow-on aircraft programs, we take the limit of S_N as N approaches infinite.

$$\lim_{N\to\infty} S_N = \lim_{N\to\infty} \sum_{i=1}^{N} \frac{\alpha}{(1+r)^{n(i-1)}} = \lim_{N\to\infty} \frac{\alpha - \frac{\alpha}{(1+r)^{n(1+N)}}}{1 - \frac{1}{(1+r)^n}} = \frac{\alpha}{1 - \frac{1}{(1+r)^n}}$$

The sum of the infinite geometric series merely becomes α multiplied by a value we will call β.

$$\beta^{-1} = 1 - \frac{1}{(1+r)^n}$$

To find the sum of the aircraft lifecycle repeated every *n* years for infinity, the present value cost is multiplied by this value β.

$$C_{NPV} = \beta\xi = \beta \sum_{t=1}^{n} \frac{\alpha_t}{(1+r)^{(t-1)}}$$

Annualizing the cost is accomplished by multiplying the net present value of the infinite horizon sum by $\frac{r}{1+r}$.

$$\mathrm{C}_{Annualized} = \beta\xi \left(\frac{r}{1+r}\right)$$

Appendix B. Cost Uncertainty

Uncertainty in arsenal aircraft cost estimates is addressed in this appendix, although it is not meant to be a comprehensive analysis on the subject of uncertainty. Uncertainty can manifest itself in any number of ways. In fact, the policy question itself considered in this dissertation is fraught with uncertainty. There is uncertainty surrounding the geopolitical environment in the time frame being addressed. Countries that currently possess A2/AD capabilities may no longer be major threats to national security when it comes time to operate arsenal aircraft. Procurement of the LRS-B may not be as large in quantity as anticipated. To address these levels of uncertainty sufficiently would be far outside the scope of a dissertation. Rather, this section is intended to provide some insight into cost uncertainty and, as is the purpose of this dissertation, to demonstrate an overall approach to analyzing tradeoffs among arsenal aircraft alternatives.

Uncertainty in demand for arsenal aircraft is addressed by presenting a range of potential scenario demands in earlier chapters. It is anticipated that the uncertainties surrounding the state of the world have more weight in many cases than statistical uncertainty.[162] Even if the demand uncertainty was fully characterized, there would still be some statistical uncertainty in the resulting cost analysis. There are three primary sources of uncertainty in cost analysis.[163]

- **Cost estimating relationships** – Each of the major phases of aircraft lifecycle costs were analyzed using CERs. In each CER, the standard error of the estimate accounts for the uncertainty that the predictor variables do not perfectly explain the outcome variable.
- **Data** – The data used in these CERs is also vulnerable to error. These may be caused by errors in observation or accounting. There may also be errors in the data used as inputs to the CERs for the arsenal aircraft, such as anticipated flying hours or weight.
- **Historical trends not the same as future trends** – Lastly, there may be reason to doubt that trends that have occurred in the past will relate to the future. This is an issue with any analysis that seeks to estimate future costs and extrapolates beyond the available data.

The primary source of uncertainty in this analysis is uncertainty from CERs. Other sources of uncertainty in cost analysis are not addressed.

Since this study compares a variety of alternatives, the uncertainty analysis looked at factors that would discriminate between alternatives. From a data uncertainty standpoint, the input variable that causes a non-uniform effect across all alternatives is aircraft weight. The use of weight in the O&S cost equation references the aircraft MGTOW, which is associated with aerodynamic and structural properties and should not change with internal structural

[162] Gene Harvey Fisher, *Cost considerations in systems analysis,* ed., Santa Monica, CA, RAND Corporation, 1970.
[163] _____, ed.

modifications to be made on arsenal aircraft. The development and procurement costs, however, use empty weight as the primary predictor variable. The growth of weight estimates throughout the development process is highly prevalent among acquisition programs. For commercial derivative aircraft, the weight growth would not be a major discriminating factor since the estimates are derived from the same cost equation. However, the C-17 procurement estimates are derived using another method, so the weight growth will differentially affect the commercial derivatives with respect to the military cargo derivatives. Weight uncertainty is not treated in this analysis due to functionality of the cost model. However, these considerations are noted and would be recommended for follow-on analysis.

Each estimate from the cost CERs involves an unknown probability distribution. These distributions are combined to form a PVLCC estimate which has a distribution of its own. To best analyze the effect of the combination of probability distributions, a Monte Carlo analysis was used. This method conducts a random sampling of all probability distributions and then, through repetition, the probability distribution of the PVLCC can be estimated using statistical methods.

This analysis assumes that each CER used to estimate costs is independent. The development and procurement costs were derived from the same set of data, which consisted of a collection of selected acquisition reports. This may be an issue with respect to correlation because the CERs may be correlated due to the use of a common data set. The numbers used from these SARs are categorically different so it is not anticipated that correlation will be majorly present. In general, cost estimations for development, procurement, and sustainment are somewhat correlated, so the assumption that each methodology produced an independent distribution of estimates is not quite accurate. However, this assumption is conservative and was used in this analysis for simplification purposes. With this assumption of independence, the distributions can be tested using Monte Carlo techniques and combined into an overall distribution of total cost.

The Monte Carlo simulation in this analysis involved 10,000 iterations and used the standard errors of the estimated values for development, procurement, and O&S costs as the standard deviation of the probability distribution. This was implemented using the Excel add-in, Crystal Ball.[164] Figure B.1 to Figure B.6 and Table B.1 to Table B.6 illustrate the resulting distribution of PVLCC for each of the arsenal aircraft alternatives considered, excluding the alternative to use existing cargo aircraft. These results are for the policy option to supplement the bomber fleet capacity and retire the B-1 and B-52 early.

[164] The methodology here is similar to the methodology used in the report by Kennedy et al., ed.

Figure B.1. Probability Distribution for 747F PVLCC for Supplementing the Bomber Fleet with Early Retirement of B-1 and B-52

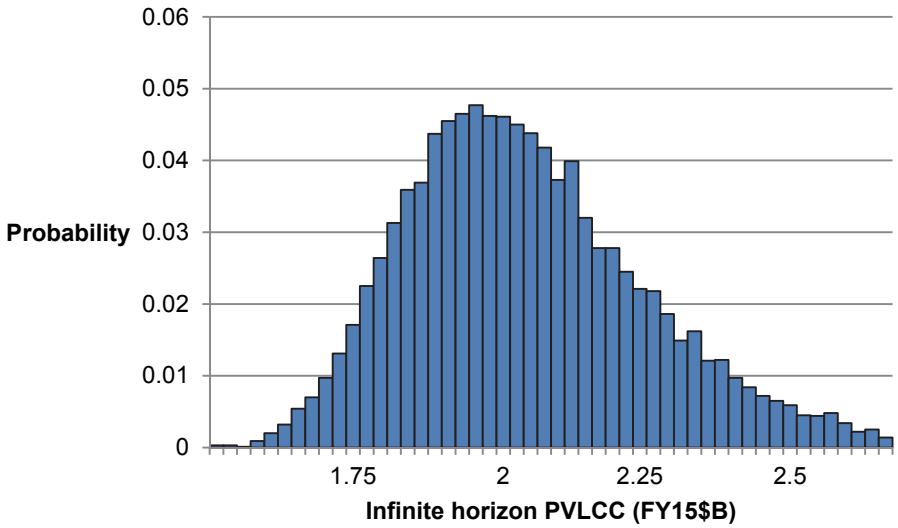


Table B.1. Summary of Monte Carlo Statistics for PVLCC of 747F

PVLCC Forecast Statistics	
Base case	2,007.33
Simulation	
Trials	10,000
Mean	2,053.35
Median	2,023.23
Standard deviation	222.21
Coefficient of variation	0.1082
Best-fit distribution	Lognormal

Figure B.2. Probability Distribution for 767F PVLCC for Supplementing the Bomber Fleet with Early Retirement of B-1 and B-52

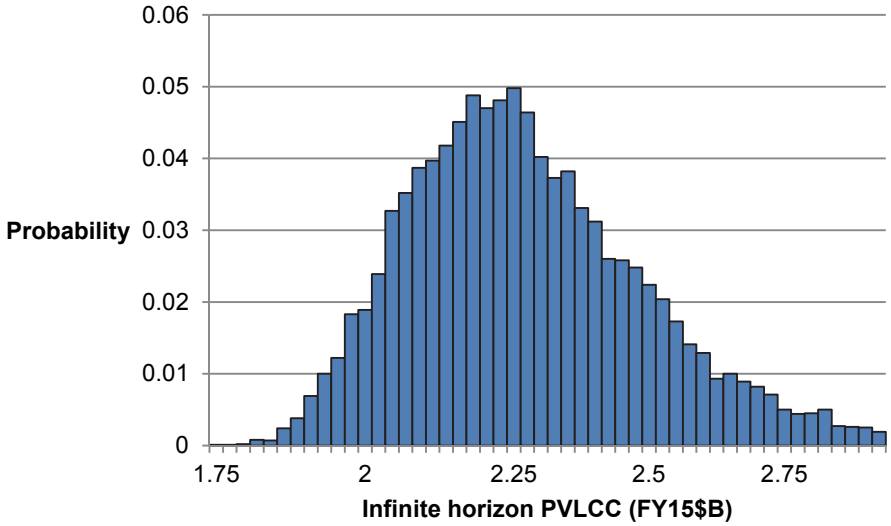


Table B.2. Summary of Monte Carlo Statistics for PVLCC of 767F

PVLCC Forecast Statistics	
Base case	2,247.85
Simulation	
Trials	10,000
Mean	2,288.51
Median	2,259.01
Standard deviation	227.32
Coefficient of variation	0.0993
Best-fit distribution	Lognormal

Figure B.3. Probability Distribution for 777F PVLCC for Supplementing the Bomber Fleet with Early Retirement of B-1 and B-52

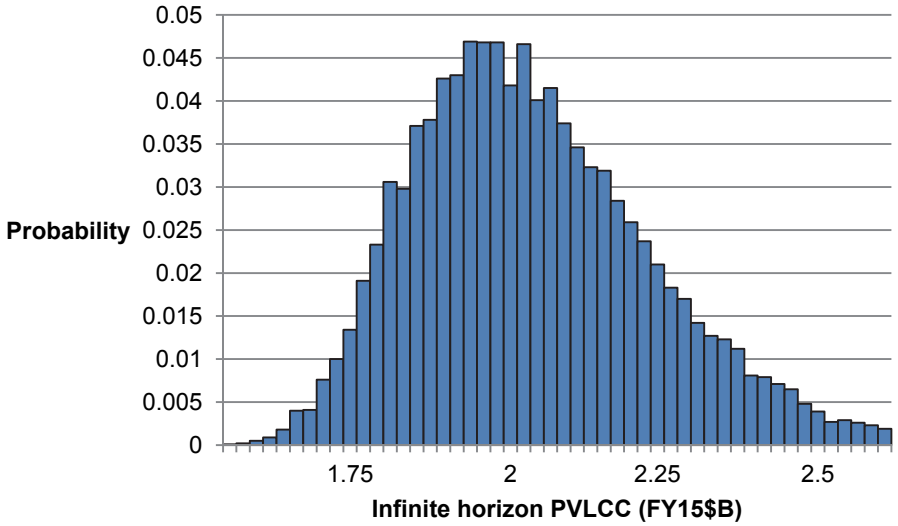


Table B.3. Summary of Monte Carlo Statistics for PVLCC of 777F

PVLCC Forecast Statistics	
Base case	2,001.31
Simulation	
Trials	10,000
Mean	2,044.57
Median	2,018.27
Standard deviation	206.05
Coefficient of variation	0.1008
Best-fit distribution	Lognormal

Figure B.4. Probability Distribution for A330F PVLCC for Supplementing the Bomber Fleet with Early Retirement of B-1 and B-52

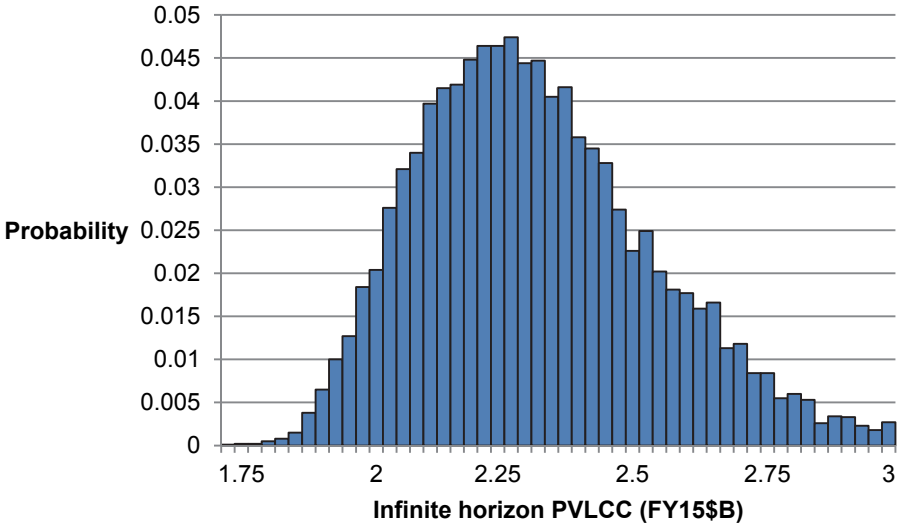


Table B.4. Summary of Monte Carlo Statistics for PVLCC of A330F

PVLCC Forecast Statistics	
Base case	2,279.42
Simulation	
Trials	10,000
Mean	2,321.17
Median	2,289.28
Standard deviation	242.76
Coefficient of variation	0.1046
Best-fit distribution	Lognormal

Figure B.5. Probability Distribution for A380F PVLCC for Supplementing the Bomber Fleet with Early Retirement of B-1 and B-52

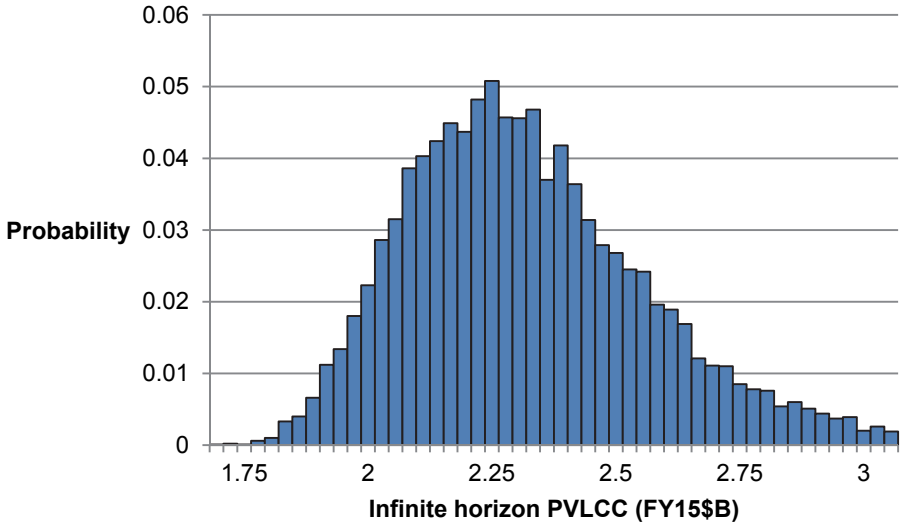


Table B.5. Summary of Monte Carlo Statistics for PVLCC of A380F

PVLCC Forecast Statistics	
Base case	2,288.20
Simulation	
Trials	10,000
Mean	2,341.92
Median	2,305.24
Standard deviation	264.02
Coefficient of variation	0.1127
Best-fit distribution	Lognormal

Figure B.6. Probability Distribution for C-17 PVLCC for Supplementing the Bomber Fleet with Early Retirement of B-1 and B-52

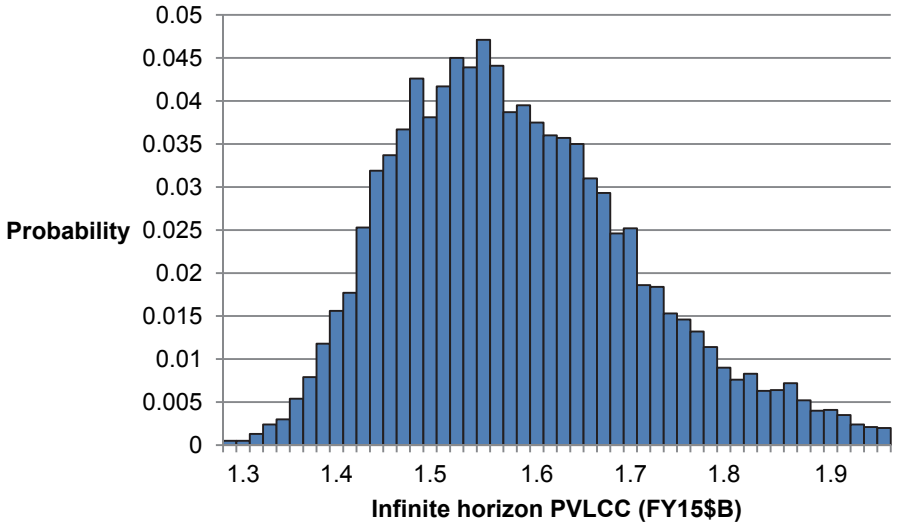


Table B.6. Summary of Monte Carlo Statistics for PVLCC of C-17

PVLCC Forecast Statistics	
Base case	1,564.20
Simulation	
Trials	10,000
Mean	1,590.29
Median	1,570.78
Standard deviation	135.78
Coefficient of variation	0.0854
Best-fit distribution	Lognormal

One of the benefits of uncertainty analysis in cost estimating is that we can obtain a level of confidence for the difference in estimates among policy options. Figure B.7 through Figure B.11 illustrates the percent differences in arsenal aircraft alternatives PVLCCs, ordered from the highest to the least-cost option. In general, statistical significance is determined by a set level of confidence, and in most cases this is 90 percent or 95 percent. The only difference in alternatives that is statistically significant in here is the difference between the C-17 and 777F. So according to this result, we can say with at least 95 percent confidence that the C-17 is the lowest-cost alternative. The other options are not different enough from each other to have this level of confidence in the ordering.

Figure B.7. Probability Distribution for the Percent Difference between A380F and A330F PVLCC (For Policy Option of Supplementing Capacity and Retiring Bombers Early)

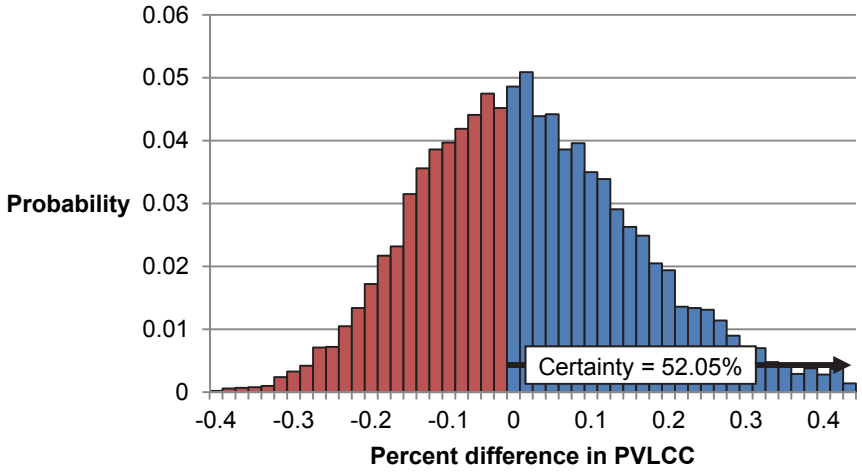


Figure B.8. Probability Distribution for the Percent Difference between A330F and 767F PVLCC (For Policy Option of Supplementing Capacity and Retiring Bombers Early)

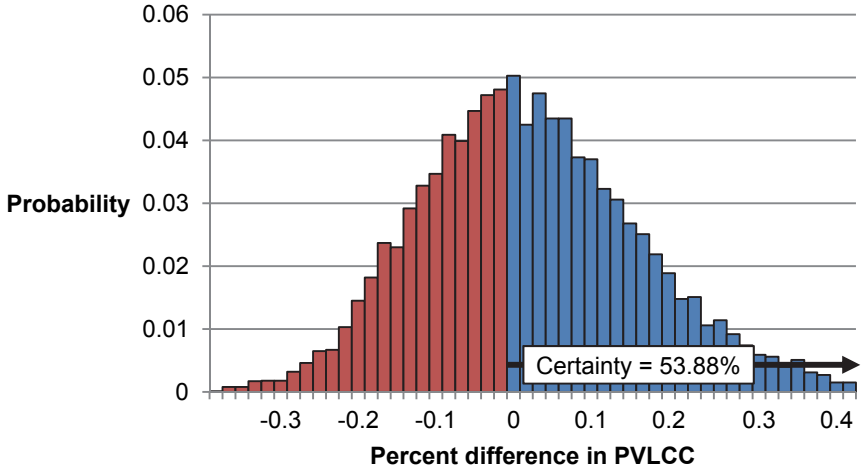


Figure B.9. Probability Distribution for the Percent Difference between 767F and 747F PVLCC (For Policy Option of Supplementing Capacity and Retiring Bombers Early)

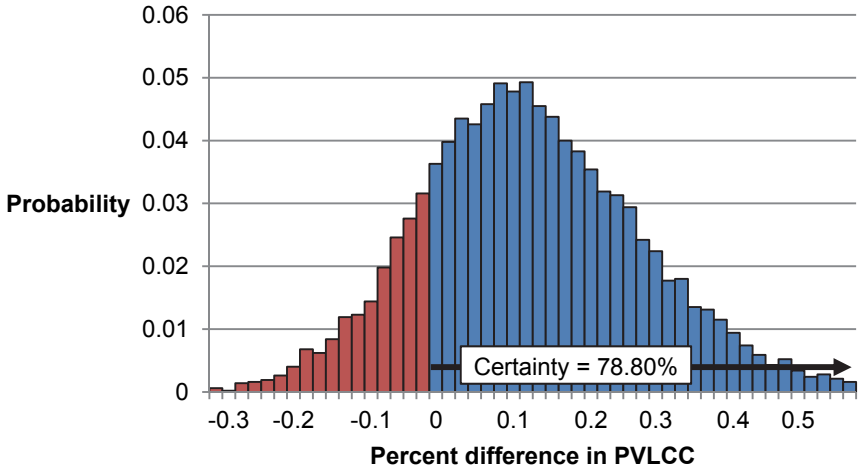


Figure B.10. Probability Distribution for the Percent Difference between 747F and 777F PVLCC (For Policy Option of Supplementing Capacity and Retiring Bombers Early)

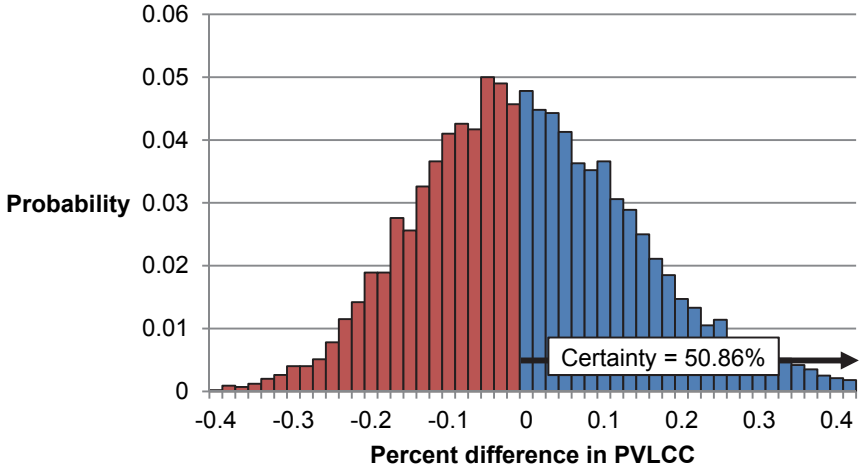
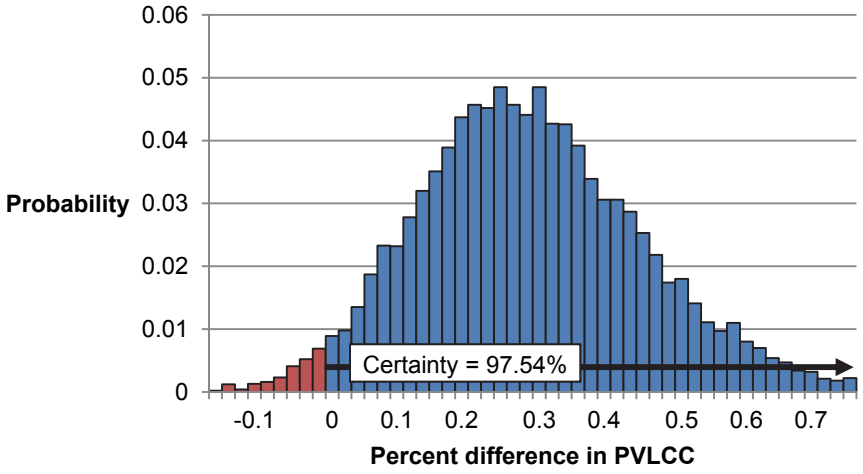


Figure B.11. Probability Distribution for the Percent Difference between 777F and C-17 PVLCC (For Policy Option of Supplementing Capacity and Retiring Bombers Early)



The difference in policy options is also analyzed in terms of uncertainty. Figure B.12 to Figure B.14 display the ordering of policy options from highest to the lowest costing option. The policy options presented here are for replacing the current fleet capacity which is discussed in the arsenal development section in Chapter 5. Supplementing the current capacity yields similar results. In these cases, there are no neighboring policies that are significantly different enough from each other to have any real confidence in the ordering. However, the most and least costing options are significantly different from each other at the 0.1 significance level as indicated in Figure B.15, meaning that we can have confidence that replacing both legacy bombers early is less expensive that replacing both legacy bombers in 2040.

Figure B.12. Probability Distribution for the Percent Difference in PVLCC between Retiring B-1 and B-52 in 2040 and Retiring B-1 Early (Replacing Fleet Capacity, C-17 Case)

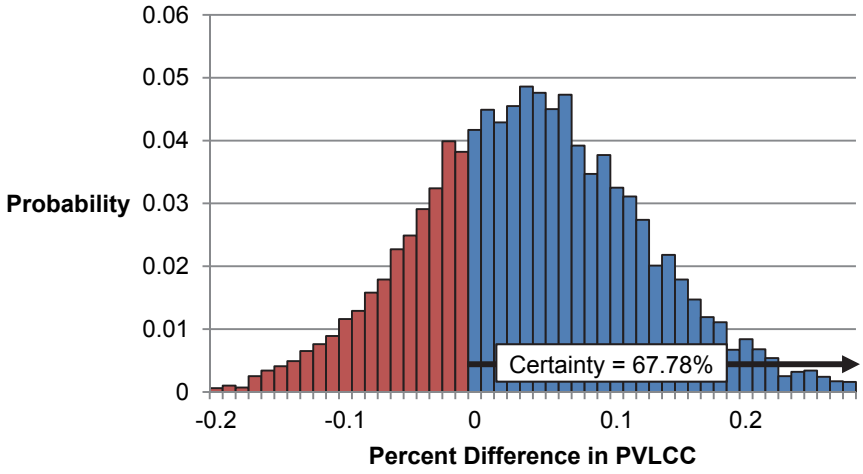


Figure B.13. Probability Distribution for the Percent Difference in PVLCC between Retiring B-1 Early and Retiring B-52 Early (Replacing Fleet Capacity, C-17 Case)

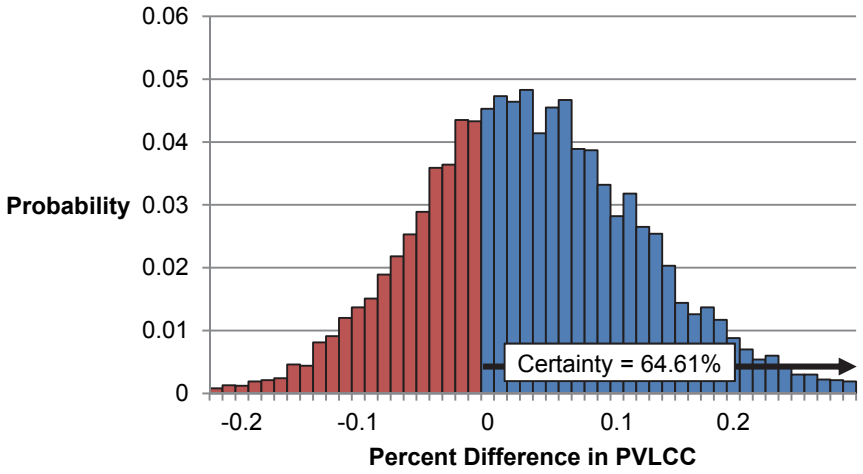


Figure B.14. Probability Distribution for the Percent Difference in PVLCC between Retiring B-52 Early and Retiring B-1 and B-52 Early (Replacing Fleet Capacity, C-17 Case)

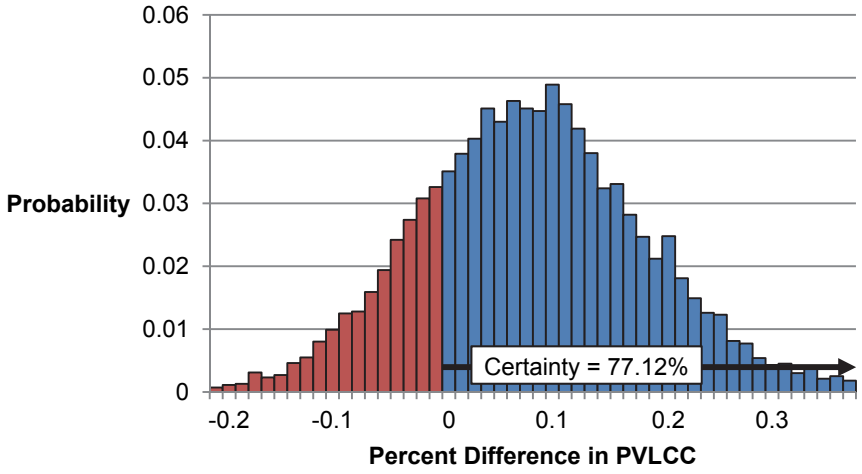
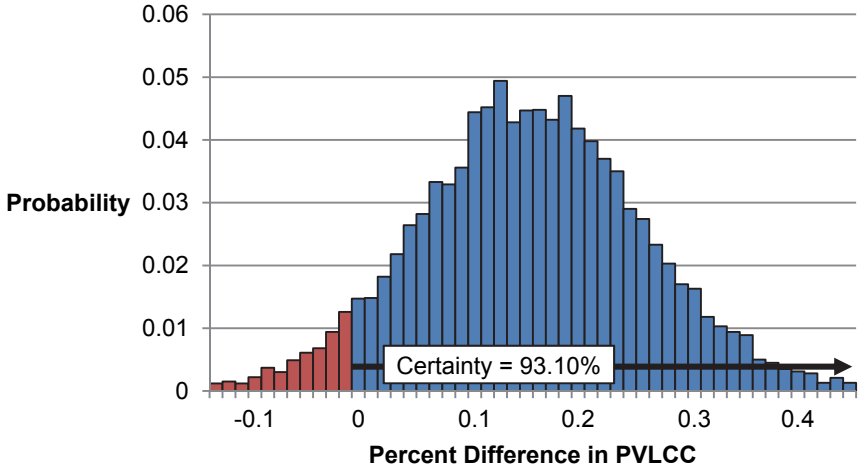


Figure B.15. Probability Distribution for the Percent Difference in PVLCC between Retiring B-1 and B-52 in 2040 and Retiring B-1 and B-52 Early (Replacing Fleet Capacity, C-17 Case)



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