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Cost-Benefit Analysis of Surface-to-Air-Missiles for Guided Missile Destroyer Loadout

June 2025

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ABSTRACT

This thesis explores the tradeoffs in risk and costs for missile loadouts on Arleigh Burke–class destroyers with an eye towards firing doctrines. With China being the main threat in the Indo-Pacific, it is important to have a balanced approach to missile defense that is cost-beneficial and capable of protecting the ship and its crew from inbound Chinese missile threats.

We focus on two missile doctrines and the estimated costs for an Arleigh Burke–class destroyer, crew, and the missiles shot. The two main missile-firing doctrines used for naval air missile defense are shoot-look-shoot and shoot-shoot-look-shoot.

Our work demonstrates that a 60% SM-2 and 40% SM-6 ratio is the best loadout for a 96-cell VLS onboard a Flight I DDG with 50% capacity allocated for self-defense missiles. The SM-2 shoot-shoot-look-shoot firing doctrine has a lower net present value than the shoot-look-shoot SM-6 firing doctrine. This shows that the SM-2 missile doctrine increases the probability of survival, which lowers the risk to the ship and should be the preferred method between the two doctrines.

This research recommends a 60% SM-2 and 40% SM-6 loadout plan. It also prioritizes SM-6 missiles with a shoot-shoot-look-shoot missile-firing doctrine for hypersonic missile threats. For a supersonic missile threat, an SM-2 with a shoot-shoot-look-shoot missile-firing doctrine should be used, and for subsonic missile threats, an SM-2 with a shoot-look-shoot missile-firing doctrine should be used.

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To my amazing wife and daughter, thank you both for all your love and support during this entire process. Sydney, I can’t thank you enough for the sacrifices you’ve made for our family and for helping me accomplish this amazing goal. You have been my rock and sounding board through the late nights and early mornings, and I could not have done this without you.

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LIST OF ACRONYMS AND ABBREVIATIONS

ASCM	Anti-Ship Cruise Missile
ASM	Anti-Ship Missile
CIWS	Close-In Weapons System
DDG	Guided Missile Destroyer
DEW	Directed Energy Weapon
DoD	Department of Defense
DON	Department of the Navy
ESSM	Evolved Sea Sparrow Missile
F2T2EA	Find, Fix, Track, Target, Engage, and Assess
GAO	Government Accountability Office
HGV	Hypersonic Glide Vehicle
IAMD	Integrated Air and Missile Defense
MOD	Modifier
NATO	North Atlantic Treaty Organization
NPV	Net Present Value
OMB	Office of Management and Budget
P_d	Probability of Detection
P_e	Probability of Execution
P_k	Probability of Kill
PLAN	People's Liberation Army Navy
PRC	People's Republic of China
P_s	Probability of Survival
SAM	Surface-to-Air Missile
SM	Standard Missile
SS-L-S	Shoot-Shoot-Look-Shoot
S-L-S	Shoot-Look-Shoot
TLAM	Tomahawk Land Attack Missile
VLS	Vertical Launch System

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I. INTRODUCTION

The United States is facing a growing issue in the Indo-Pacific region—the increasing number of missiles and ships of China's People's Liberation Army Navy (PLAN). The PLAN is currently the world's largest naval fleet (U.S. Department of Defense, 2024), and it continues to expand robustly. By the end of 2023, according to the Department of Defense Military and Security Developments involving the People's Republic of China Report, the PLAN had commissioned twenty-five new Luyang III destroyers, all with 64-cell multipurpose vertical launch systems (VLS) that can launch anti-ship cruise missiles (ASCM), surface-to-air missiles (SAMs), and anti-submarine missiles (U.S. Department of Defense, 2024). In 2024, the PLAN added eight new Renhai class cruisers, each with a missile capacity of 112, new destroyers, and two different classes of frigates (U.S. Department of Defense, 2024). In 2025, the PLAN is expected to maintain or increase its current shipbuilding pace (U.S. Department of Defense, 2024). The increased missile threat and surface force of the PLAN is an issue for the United States because it threatens the self-defense of American naval ships (U.S. Department of Defense, 2024).

The Standard Missile (SM)-6 and SM-2 are the United States Navy's leading SAMs currently used by surface combatants in the fleet. Both missiles protect ships against the PLAN's growing missile threats. The SM-6 is the most technologically advanced SAM because of its increased range and active seeker capability. However, the SM-6 costs approximately $3.9 million (Missile Defense Advocacy Alliance, 2024), a more expensive price tag than the SM-2. The SM-2 is cheaper at $2.1 million (Missile Defense Advocacy Alliance, 2024) but does not have as much capability as the SM-6. In missile defense, the missiles used should be effective against threats and fiscally sustainable. Understanding the tradeoff between cost and capability is a constant factor in developing a strategic plan.

The primary question of the thesis is: What constitutes the most cost-effective self-defense missile loadout for an Arleigh Burke-class guided missile destroyer (DDG) based on the probability of survival against PLAN anti-ship cruise missiles? The secondary question is: How do missile-firing doctrines and missile capabilities combine to impact a ship's survivability against PLAN ASCMs in the Indo-Pacific region?

The research presented in this thesis explores the cost-benefit analysis of the SM-6 and SM-2 missiles. This analysis aims to provide a method for maintaining a high probability of ship survival while being selective with the missiles used from a cost perspective. A cost-beneficial combination of missiles and missile-firing policy enables naval leaders to allocate resources based on cost-benefit and the best probability of survival.

The most capable SAM that the U.S. Navy has is the SM-6, which should be reserved for only high-end threats such as hypersonic missiles and utilized with a shoot-shoot-look-shoot firing doctrine to have a 91% probability of survival (see Chapter IV, Section C: Ship Survivability Results). The SM-2 is the most cost-beneficial missile and should make up the majority of a ship's self-defense missile inventory. For medium and lower-level threats such as supersonic and subsonic missiles, the SM-2 is the best weapon to employ (see Chapter IV, Section B: Net Present Value Results). The SM-2 should utilize a shoot-shoot-look-shoot firing doctrine for medium threats and a shoot-look-shoot firing doctrine for lower-level threats due to the higher probability of survival and lower risk and capability of the missile. The probability of survival for each missile threat when using the prescribed missile and firing doctrine averages 96% for supersonic missiles and 95% for subsonic missiles.

The missile loadout benefits change based on the flight or version of the DDG and mission objectives. For research purposes, a balanced approach was based on a 96-cell vertical launching system onboard a Flight I DDG. 50% of missile capacity was used for offensive-based missiles such as Tomahawk land attack missiles, Anti-Submarine Rockets, and SM-3s. The remaining 50% was used for SM-6 and SM-2. The most beneficial self-defense loadout would be 40% SM-6 and 60% SM-2, with an estimated total loadout cost of $135 million.

The research presented contributes to the literature by providing a data-driven framework for the cost-benefit analysis of missile loadouts and firing doctrine. Previous research has been conducted on calculating the probabilities, theorizing strategies, and firing doctrines related to integrated missile defense (IAMD). This research incorporates the current cost and capabilities based on recent budget and missile technology. Combining the cost-benefits in this research with the firing doctrines currently used in the fleet equips naval leadership with the tools to make informed decisions on resource allocation and missile defense strategies. This research helps to ensure the security and sustainability of American interests.

The Navy benefits from this research by understanding how to better allocate missile resources based on a balanced approach to cost and survivability. By becoming more balanced in its allocation, the Navy can be more strategic and economical. Based on the possible conflict between the U.S. and China, it is important to have a cost-beneficial missile loadout strategy. This can be achieved through sustainable firing doctrines that achieve optimal missile conservation and defense. Practicing sustainable missile defense allows naval surface combatants to maintain a long-term operational presence in the Indo-Pacific region and increases a ship's operational readiness without quickly exhausting missile inventory.

The thesis is divided into five chapters. Chapter I introduces the problem of the PLAN's increased number of missiles and ships while focusing on the primary and secondary thesis questions. Chapter II covers the background, providing an overview of the history of integrated missile defense, major adversaries, important geographical areas of the Indo-Pacific, and a literature review. The literature review identifies research gaps and findings concerning the Chinese threat and the cost-benefit analysis of different authors who are experts in this field. Chapter III provides the data and methodology used to conduct this research. It focuses on current missile technology, large surface platforms, assumptions, and equations used to support the findings of this research. Chapter IV highlights the key findings and discusses recommendations for how naval leaders can implement them in the fleet and alternatives based on future technology. Finally, Chapter V summarizes and concludes the research with its implications for the fleet.

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II. BACKGROUND

The background of this research provides pertinent information that aids the reader in understanding the history of ship missile defense and geopolitical relationships between the U.S., Soviet Union, and China. As the world evolves, so has missile technology and geopolitical relationships. Understanding the history of geopolitical relationships between all three countries gives an understanding of how each country has contributed to missile defense technology. This thesis examines the strategic implications of those relationships and how they have transformed into current geopolitical situations. A literature review is included to express current research conducted by subject matter experts. The literature that has been written further explains the current threat of Chinese missiles and its Navy.

A. HISTORY OF INTEGRATED MISSILE DEFENSE

Naval missile defense began with the development of integrated air missile defense (IAMD), a concept introduced by the North Atlantic Treaty Organization (NATO) in 1961 (NATO, 2025). IAMD was designed to protect NATO allies from the threat of nuclear ballistic missiles by incorporating a layered defense structure (NATO, 2025). This system combines multiple missile defense platforms, utilizing active Ballistic Missile Defense systems to intercept and neutralize incoming threats before they reach their targets (NATO, 2025). As IAMD technology advanced, the Department of the Navy (DON) sought to integrate these capabilities into naval vessels. This was accomplished by the invention of the Aegis Combat System, a revolutionary command-and-control platform designed to unify all defensive components on a ship. First deployed in 1983 aboard the USS Ticonderoga, Aegis has since become the foundation of the Navy's missile defense strategy (DefenceLab, 2024).

According to the U.S. Navy's Aegis Weapon System fact files, the main component of the Aegis Combat System is the AN/SPY-1 phased array radar (U.S. Navy, 2021). This radar enables the ship to detect, track, and engage multiple targets at the same time (U.S. Navy, 2021). Once a threat has been identified, the Aegis Combat System can automatically coordinate an interception, utilizing surface-to-air missiles (SAMs) to neutralize incoming hostile missiles (U.S. Navy, 2021). The U.S. Navy primarily relies on the Standard Missile (SM) series, including the SM-2 and SM-6, which are deployed fleet-wide to defend against anti-ship cruise missiles (ASCMs) and ballistic missile threats (U.S. Navy, 2021).

A key advantage of IAMD is having the capability to connect land and sea-based elements together and share the same operational picture. This allows multiple platforms to work collectively to defend any area against missile threats. By working jointly with other platforms, Aegis can extend a ship's ability to find, fix, track, target, engage, and assess (F2T2EA) threats, significantly strengthening a naval ship's defense. Aegis is essentially the eyes, ears, and brain of the ship that allows it to inform the crew of inbound missile threats. This is why the Arleigh Burke-class destroyer plays such a crucial role in the U.S. Navy's missile defense strategy (U.S. Navy, 2025).

The first Arleigh Burke-class destroyer (DDG) was commissioned on July 4, 1991, and has been the backbone of the Navy ever since (U.S. Navy, 2025). As the Navy's primary surface vessel equipped with the Aegis Combat System, DDGs can operate as both independent units and integrated components of a broader fleet defense network. To date, seventy-four Arleigh Burke-class destroyers have been delivered, with an additional twenty-five currently under contract (U.S. Navy, 2025). With the combination of the Aegis Combat System and the deployment of SM-2 and SM-6 missiles, the Arleigh Burke-class destroyers are at the tip of the spear and provide a strategic advantage against evolving missile threats, ensuring the Navy's ability to maintain superiority in an increasingly complex threat environment.

B. THE COLD WAR

During the Cold War, the U.S. and Soviet Union had differing ideologies and governments, which created political and military tension between the two countries. The world entered the space age, and neither country wanted to be left behind. Both countries spent heavily on Inter Continental Ballistic Missile (ICBM) technology, leading to the first arms race between them. The arms race was centered on developing intercontinental nuclear missile capabilities. In 1957, the Soviet Union successfully launched the R-7

Semyorka, which was the first ICBM to be successfully launched (Britannica, n.d.). The following year, the U.S. created the National Aeronautics and Space Administration (NASA) (NASA, 2023).

The Cold War accelerated both countries' missile programs and led to a massive technological boost for intercontinental nuclear missile development. The tension between the two countries continued to grow, and each country created stockpiles of nuclear missiles to compete against each other. In 1962, the United States deployed nuclear missiles to Turkey, putting the Soviet Union under direct threat of a nuclear attack. In retaliation, the Soviet Union deployed nuclear missiles to Cuba (Air Force Historical Support Division, n.d.). This culminated in the Cuban Missile Crisis of 1962, which ended with both countries understanding that diplomacy was the best way forward (Britannica, 2025).

In 1991, the Soviet Union dissolved into multiple republics and ceased to exist, effectively ending the Cold War. In its place, a new Russian government came into power and needed regional partners to help strengthen its military. In 1992, Russia signed the Military-Technical Agreement with China to achieve this goal (Blivas, 2020). Through this agreement, China purchased many weapons and missiles.

C. CHINA

China became the focus of U.S. foreign and defense policy in 2011(Blackwill & Fontaine, 2024). This policy change emphasized a pivot to Asia by improving military alliances with countries in the Indo-Pacific region (Blackwill & Fontaine, 2024), such as Japan, Taiwan, and the Philippines. The U.S. also invested in regional military facilities, increased military deployments, and negotiated access to regional defense sites to protect against China's growing naval fleet and missile arsenal (Nicastro, 2023). The U.S. Ballistic Missile Defense (BMD) system expanded in the Pacific, with deployments in Japan, South Korea, Guam, and others, all aimed at countering Chinese missile threats (Arms Control Association, 2019).

During this time, in response, China adopted an anti-access and anti-denial (A2/ AD) strategy. This strategy is a militaristic approach to prevent adversaries, particularly the United States, from operating in key regions, such as the Western Pacific and the South China Sea (Joshi, 2019). Figure 1 shows how China's A2/AD strategy aims to deter U.S. naval vessels from the region. The goal is to deter or delay U.S. forces from intervening in regional conflicts, especially concerning Taiwan. Even today, China continues to cause conflicts and raise tensions with other countries in the region.

Figure 1 shows a visual depiction of how China's A2/AD strategy utilizes missile technology to deny naval access to surface combatants in the East and South China Sea.

Figure 1. China A2/AD Strategy. Source: Joshi (2019).

Most countries in the first island chain are directly affected by China's A2/AD strategy. This geographical chain of islands includes Japan, Taiwan, the Philippines, and the surrounding waters. These islands create a natural containment barrier between China and the open Pacific Ocean. Because of this natural barrier, China aims to keep U.S. naval forces from entering this area by using its navy and its long-range missiles to achieve that goal.

D. LITERATURE REVIEW

The literature review focuses on the current research on missile defense and China's threat to U.S. interests in the Indo-Pacific region. It aims to provide knowledge that has been found and explain how this thesis increases knowledge on missile defense.

E. ESCALATING CHALLENGE FOR THE NAVY

In a recent thesis, "An Escalating Challenge for the Navy: How to Defeat the Growing Missile Threat in the Indo-Pacific," Hannah Andera (2024) discusses two key challenges faced by the United States Navy in the Indo-Pacific region. First, she states that budgetary and cost-benefit analysis "highlighted issues with ship and missile production capacity, high costs of interceptors, and budgetary constraints that limit the Navy's ability to outfit ships with adequate missile defense for a potential conflict" (2024, p. 62) Ship self-defense is a growing problem because increasing costs of missile production could outpace budget resources. The United States' main missile interceptors are the SM-6 and SM-2 missiles. Both missiles are used to combat the missile threat in the Pacific, but both are very costly. Based on the current production cycle, the United States may not have enough missiles to combat the threat. According to the Department of Defense, "Numerically, the PRC has the largest navy in the world, with a battle force of over 370 ships and submarines, including more than 140 major surface combatants" (U.S. Department of Defense, 2024, p. 7). China's naval fleet and missile arsenal, both land and sea-based, remain significant threats to U.S. warships, which should be capable of defending themselves.

Second, according to Andera (2024), over-reliance on high-cost systems increases vulnerability to adversaries' cost-effective missile swarms. The thesis references how recent conflicts in the Red Sea demonstrate why it is essential to devise an affordable missile defense strategy. According to Andera, this strategy should address the challenges that ships will face against more cost-efficient drones and missile threats. She concluded that collaborating with regional allies and integrating air missile defense was essential to enhancing deterrence and missile defense.

The research agrees with Andera that the missile threat in the Indo-Pacific region is a very real and significant problem. Based on the current defense posture and the United States' missile resources, naval platforms will be inadequate for a possible large-scale conflict. However, Andera's research falls short of developing a cost-effective method to allocate the resources the U.S. currently has. This thesis addresses this shortcoming by utilizing survival probability based on the current missile threat in the Indo-Pacific, the capabilities of the United States' missiles, and current missile-firing policies being utilized in the fleet.

F. COST-EFFECTIVENESS OF HARD-KILL VS. SOFT-KILL THESIS

Other literature has also been written about ship self-defense. In 2022, a thesis titled "Naval Surface Warfare: A Cost-Effectiveness Analysis of Hard-Kill Versus Soft-Kill for Ship Self-Defense" by Galen T. Mander, Zachary P. Enix, and Antoine E. Deraoui addressed which method for ship self-defense is more cost-effective. They explain in their research the difference between a hard-kill and a soft-kill regarding a ship's self-defense capabilities: "Hard-kill employments from a surface unit can involve standard missiles. These are the missiles onboard U.S. Navy ships that are used for self-defense and can be used for offensive actions as well. Soft-kills involve using the electronic warfare suite on surface ships" (Mander et al., 2022, p. 5).

Using Mander et al.'s terminology for soft and hard-kills, the difference between the two types of mission success is based on how the inbound missile threats are deterred from harming the ship. When using hard-kill methods, the ship employs either SM-2, SM-6, or Evolved Sea Sparrow Missiles (ESSM). The number of missiles fired is based on the policies of shoot-look-shoot or shoot-shoot-look-shoot. This means that if a shoot-look-shoot policy is in place, then when the ship detects an inbound missile threat, it will shoot one missile and then look to verify that the inbound threat was destroyed. If not, then the ship would fire one more missile. If the policy is shoot-shoot-look-shoot, then the ship will shoot two missiles, then look to verify that the inbound missile threat is destroyed, and then shoot one more missile if not destroyed. Each missile's type, amount expended, and probability of kill determine a ship's survival probability.

Soft-kill methods involve using the electronic spectrum to detect the signals emitted from inbound missile threats (Mander et al., 2022). The ship can use other diversion tactics that can divert the missile away from the ship. These threats can be deterred from hitting the ship and causing damage, mainly through electronic countermeasures such as decoys or jamming. When using decoys, ships can manipulate the missile's guidance system and cause it to track a false target (Mander et al., 2022). The threat can also be diverted by using jamming techniques. These techniques effectively reduce the range of the missile seeker and allow the ship to get out of range (Filipoff, 2024). Once the ship is out of range of the missile seeker, the threat will lose its target and is effectively diverted from the ship.

There are distinct differences between a hard and soft-kill, but both are types of mission success for a ship's self-defense. Both mission kills are significant points that Mander et al. discuss. If a ship can divert a missile through soft-kill methods, it can use its missile capacity for more offensive-oriented missiles. While this is the case, the pros and cons of soft and hard-kill methods for ship defense lie predominantly in their mission effectiveness and cost-effectiveness. Hard-kill missile defense tactics are more mission-effective but less cost-effective. In contrast, soft-kill electronic attack methods are more cost-effective but not as mission-effective.

While this may be true, there is an issue with how Mander et al. calculates their effectiveness results for future missile engagements. Mander et al. use a "single missile vs. single missile" context to frame their results, which may not completely encompass the complete picture of a potential Chinese engagement. Chinese missile attacks will usually contain a combination of subsonic and supersonic missiles and active and semi-active missiles to have the highest probability of mission success. The Chinese will not usually use only one missile when attacking a ship, but instead, they will use a salvo of missiles to attack a ship.

G. RED STAR OVER THE PACIFIC

An influential book, *Red Star Over the Pacific*, by James R. Holmes and Toshi Yoshihara, discusses three key findings that the United States needs to address to stop the rise of Chinese influence in the region. First, Alfred Thayer Mahan's theories of sea power and maritime dominance are evident in China's strategy to increase its regional influence, and China's maritime strategy is based on Mahanian principles (Holmes & Yoshihara, 2019). According to Holmes and Yoshihara, China is focused on an anti-access and anti-denial strategy that aims to keep the United States out of the first island chain. The authors describe this Chinese ideology as "China's Dream." Holmes and Yoshihara believe that this dream is President Xi Jinping's bold proclamation to return the Chinese nation back to what he believes is its rightful place as the major power in the Asian Pacific (Holmes & Yoshihara, 2019).

The second key finding of Holmes and Yoshihara is the economic and political implications of China's activities. China's strategy includes initiatives like the Belt and Road Initiative and the construction of overseas naval bases in African countries such as Djibouti (Holmes & Yoshihara, 2019). China's main goal is to project power as far as it possibly can and push back American influence as far as possible from its shores (Holmes & Yoshihara, 2019). Based on Holmes and Yoshihara's writings and conclusions, President Jinping and the Chinese nation plan to accomplish this dream by building and investing in the country's military capabilities (Holmes & Yoshihara, 2019). This dream also incorporates President Xi's ambition to increase the Chinese economy and economic partnerships worldwide. It aims to increase its diplomatic influence with surrounding nations. Overall, the Chinese dream is to make China the leading power in the world and to remedy the humiliation that the Chinese people feel they have suffered for decades (Holmes & Yoshihara, 2019).

The third key finding is China's modernization of the navy and how its growth directly threatens U.S. maritime dominance (Holmes & Yoshihara, 2019). As China's Navy becomes more capable and its technology continues to advance, its ability to deny United States Naval surface combatants access to the first island chain becomes an increasing obstacle for naval strategies to overcome. The authors discuss China's ability to launch long-range over-the-horizon missiles from mainland China and various naval platforms.

When examining the text, it is easy to agree with the Holmes and Yoshihara's (2019) findings that China is the rising power in the Indo-Pacific region. China's ability to conduct over-horizon missile strikes on U.S. Naval vessels from the mainland poses a significant threat to the United States' interests as well as allied partners in the region. The authors provide ample references that verify the key points of their argument. First, missiles are the primary weapon threat to any surface combatant in the Indo-Pacific region. Second, China bases its ability to win at sea solely on its ability to destroy American naval vessels, specifically the Arleigh Burke-class destroyer and the American Aircraft Carrier. Third, these battles at sea will likely be quick, decisive, and lethal. Based on the number of ships that will be needed and the number of missiles expended, China is preparing for future battles in the Pacific. (Holmes & Yoshihara, 2019)

H. LITERATURE REVIEW SUMMARY

The problem that the United States is facing is a growing naval and economic power in the Indo-Pacific region. In her CNO Navigation Plan for America's Warfighting Navy, Admiral Lisa Franchetti stated, "The Chairman of the People's Republic of China has told his forces to be ready for war by 2027" (U.S. Navy, 2024, p. 6). China's dream of becoming the leading power in the area is a genuine threat that should be taken seriously. The United States should have a strategically sound and cost-effective plan that adequately meets the needs of the Navy. This thesis calculates the probability of survival for an Arleigh Burke-class destroyer based on missile expenditure, missile type, probability of kill, and missile policy. This thesis further researches the problem presented in the literature. By understanding the Chinese capabilities and limitations, the United States can better allocate resources and assets that will effectively win in the Pacific and produce the highest probability of survival and success. By analyzing how to be cost-effective with limited resources, naval commanders can be better prepared to stop the rising maritime power of the Chinese if a conflict were to happen in the Pacific.

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III. DATA AND METHODOLOGY

The data and methodology for this thesis are a combination of quantitative results and theoretical probabilities. All data used in this research was gathered from unclassified resources. The data introduces missiles and platforms used in American and Chinese navies. To evaluate the cost-benefits of missile loadouts, this thesis utilizes performance metrics, cost estimates, and engagement probabilities to calculate the most cost-beneficial loadout. The methodology of this thesis begins with the main assumptions made to provide the scope and parameters used to calculate the results. Followed by the equations used to simulate and model engagement probabilities and, finally, missile-firing doctrines that U.S. destroyers will use.

A. ARLEIGH BURKE-CLASS DESTROYERS

The Arleigh Burke-class destroyers are the most versatile warships in the U.S. Navy, known for their speed, advanced combat systems, and robust design. These vessels measure 505 feet long, with a beam of 66 feet, a draft of 36 feet, and a height of 153 feet (Naval Technology, 2024). They have a displacement of 8,558 tons and can achieve speeds exceeding 31 knots (Naval Technology, 2024). These ships are designed for survivability and constructed primarily from steel, with aluminum funnels and vital areas fortified by dual steel layers and 70 tons of Kevlar armor (Naval Technology, 2024). There are three versions, also known as flights of the Arleigh Burke-class destroyer, and each version is equipped with the Aegis Combat System. This system integrates sensors and weapon systems on the ship to counter anti-ship missile threats effectively (Naval Technology, 2024).

B. OVERVIEW OF PRIMARY U.S. NAVY SURFACE-TO-AIR MISSILES

1. Standard Missile 2

The SM-2, as seen in Figure 2, is a major component of the Aegis Weapon System used to combat missile threats. The SM-2 has a range of 185–370 km and can consummate engagements at altitudes of 1000–33000 m (Missile Defense Project, 2016a). The SM-2 interceptor is designed to launch from a Mk 41 Vertical Launching System (VLS), which can be found on U.S. guided missile destroyers and cruisers. The purpose and mission of this missile is to engage anti-ship cruise missiles (ASCM) at high speeds and altitudes. SM-2 is equipped with a midcourse guidance system and uses radar support from the ship to help illuminate inbound missiles during the terminal intercept phase (Missile Defense Project, 2016a).

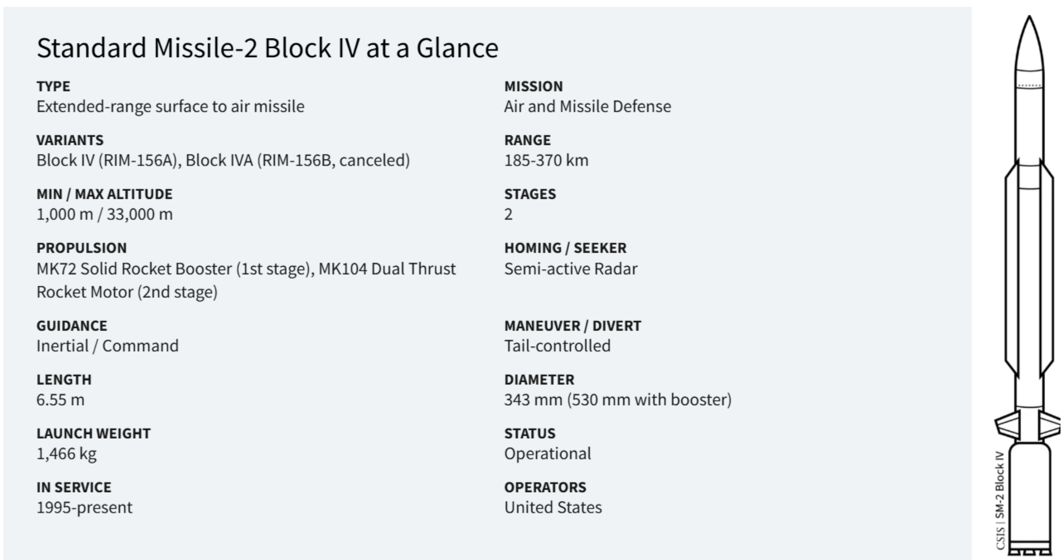


Figure 2. SM-2 Block IV Capabilities and Limitations. Source: Missile Defense Project (2016a).

2. Standard Missile 6

The SM-6 missile, as seen in Figure 3, is one of the Navy's most capable missiles in its arsenal. It is a multi-mission missile that can conduct anti-air warfare and terminal ballistic defense and has anti-ship strike capabilities (Missile Defense Project, 2016b). The SM-6 is a ship-launched surface-to-air missile with a range of 370 km, a speed of 1.03 km/s, and a warhead weight of 64 kg. The Navy has manufactured the SM-6 to perform strike missions as an alternative to the Tomahawk strike missile (Missile Defense Project, 2016b). The SM-6 combines the airframe of the SM-2 with the propulsion system of the SM-3 while also adding an active seeker (Missile Defense Project, 2016b). The active seeker increases the SM-6 capabilities by increasing its range to engage targets further than shipboard radars. The combination of the seeker, airframe, and propulsion system makes the SM-6 one of the most technologically advanced missiles in the fleet.

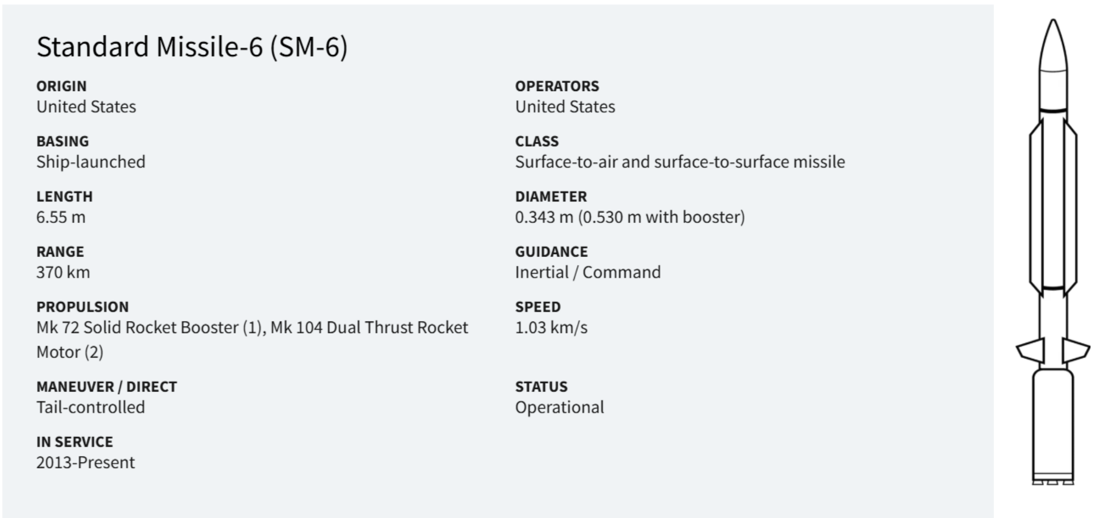


Figure 3. SM-6 Capabilities and Limitations. Source: Missile Defense Project (2016b).

C. OVERVIEW OF PLAN ANTI-SHIP CRUISE MISSILES

1. YJ-83

The YJ-83 can be used on most PLAN platforms, making it one of the easiest and most effective anti-ship missiles (ASM) to deploy on surface vessels. The missile has a range of 180 km, a speed of Mach 0.9, and flies at an altitude of 20 m above sea level. (Janes, 2024). There is also an air variant of this missile, the YJ-83K. It can be fired from the JH-7A and H-6G, with an increased range of 250 km, and the YJ-82 is the submarine-launched variant with an estimated range of 30 km (Janes, 2024).

2. YJ-62

The YJ-62 ASM is similar to the YJ-83, the primary difference being its launch platforms and increased range. While the YJ-62's speed and altitude are the same as the YJ-83, it has an increased range of 280 km (Janes, 2024). This missile can only be deployed on Type 052C Luyang II-class destroyers for a sea-based launch platform or a land-based launch platform from coastal defense batteries. The coastal defense batteries can be equipped with three YJ-62 missiles on a road-mobile transporter (Janes, 2024).

3. YJ-18

The YJ-18 is a modified version of the Russian SS-N-27B "sizzler" with a range of 530km, a cruise speed of Mach 0.8, and a supersonic terminal speed of Mach 3 (Janes, 2024). Its launch platforms include the Luyang III and Renhai destroyers. A submarine-launched variant may be carried on the nuclear submarine Shang, and the SongYuan submarines (Janes, 2024).

4. YJ-12

The YJ-12 is an air-launched supersonic long-range ASM, which has a solid rocket booster and liquid-fueled ramjet, similar to the Russian Kh-31 that China first acquired from Russia in the late 90s, propelling the missile at a speed between Mach 2 and 4 (Janes, 2024). The range is about 500 km, and the missile has a 250 kg warhead (Janes, 2024). The H-6J aircraft has underwing pylons that can carry six of these missiles (Janes, 2024).

5. YJ-21

The YJ-21 is a surface-launched anti-ship hypersonic missile with a range of 1000+ km and a speed of Mach 9 (Ozberk, 2022). It is deployed from the Type 055 Renhai destroyer, utilizing its vertical launch system (Ozberk, 2022). Table 1 briefly references PLAN's missile capabilities, platform, and key features.

Table 1. PLAN Missile Capabilities and Limitations. Adapted from Janes (2024).

Missile	Platforms	Range	Speed	Key Features
YJ-83	Type 022, Type 056, Type 054A, Type 051C; JH-7A, H-6G (air-launched); Submarines (YJ-82 variant)	180 km (sea-launched), 250 km (air-launched), 30 km (submarine-launched)	Mach 0.9 (subsonic)	Widely used ASM with variants for air, sea, and submarine launches
YJ-62	Type 052C destroyers, Coastal defense batteries (land-based)	280 km	Subsonic	Deployed on destroyers and road-mobile coastal defense systems
YJ-18	Type 052D, Type 055 destroyers; Type 093, Type 039/ 039A submarines	530 km	Mach 0.8 (cruise), Mach 3 (terminal)	Advanced ASM supersonic terminal phase for effectiveness
YJ-12	H-6J aircraft	500 km	Mach 2–4 (supersonic)	Air-launched supersonic ASM
YJ-21	Type 055 destroyers	1000+ km	Mach 9 (hypersonic)	Hypersonic missile launched from the Type 055 destroyer

D. ASSUMPTIONS

The following assumptions were made when comparing United States missiles to the PLAN missiles and are centered on a baseline scale. The SM-6 and SM-2 each have their baseline of capabilities, a combination of their range, speed, and explosive payload. It can also be assumed that all United States surface ships utilize the Aegis Weapon System to find, fix, track, target, engage, and assess all inbound missile targets (F2T2EA). The Aegis Weapon System is the ship's primary approach to neutralize missile threats in self-defense. Based on this assumption, it can also be assumed for this research that the Aegis Weapons system detection system has a probability of detecting an inbound missile threat at a minimum of 90% (Mander et al., 2022). This can be expressed as a constant of $P_d = .9$ and found in Tables 2 and 3.

For this research, the focus is on the missile intercept aspect of an engagement, which can be assumed to be the missile's hard-kill lethality. The assumption is that missile interception means that the ship survives a missile engagement, and if the missile is not intercepted, the ship will be destroyed. This does not account for soft-kill tactics, close-in weapon systems (CIWS), or other tactics that can be used to defend against inbound missiles.

E. EQUATIONS

The probability of kill equation is the probability that a missile intercepts and destroys an inbound missile in a single shot. This probability can be expressed as the variable P_k. The P_k equation has three variables. The first variable is the probability of execution Pe, the statistical baseline for each missile based on previous successful missile engagements. The second variable is the inbound missile's designated modifier (MOD), which highlights the capabilities of each inbound missile threat. The third is the probability of detection P_d, which is the assumed capability of the Aegis Weapon System of 90%. Values for each variable have been placed in Tables 2 and 3, with the results in Figure 4.

$$P_k = P_d(P_e MOD)$$ (Dutta, 2014, p.124).

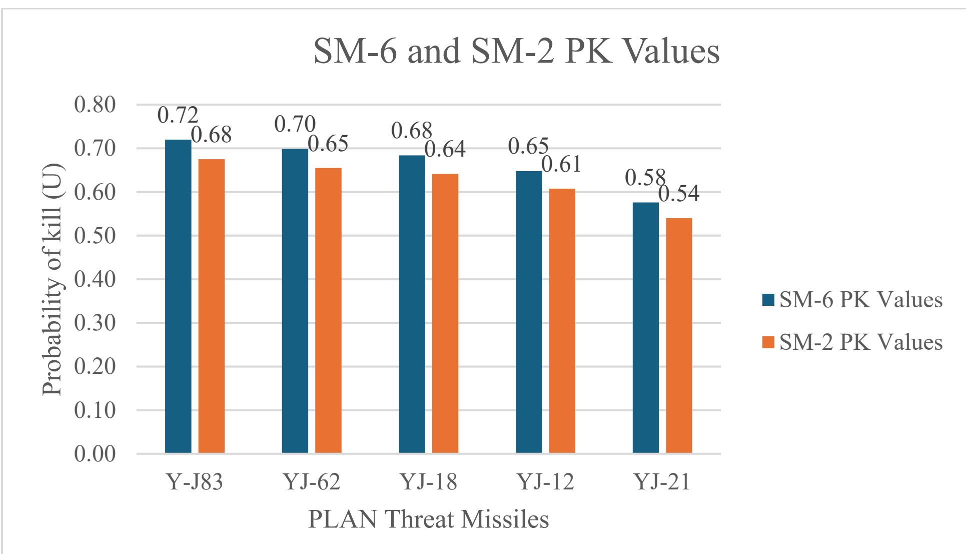
Table 2. SM-6 Variable Inputs

Missile	Y-J83	YJ-62	YJ-18	YJ-12	YJ-21
P_e	0.8	0.8	0.8	0.8	0.8
P_d	0.9	0.9	0.9	0.9	0.9
Mod	1	0.97	0.95	0.9	0.8

Table 3. SM-2 Variable Inputs

Missile	Y-J83	YJ-62	YJ-18	YJ-12	YJ-21
P_e	0.75	0.75	0.75	0.75	0.75
P_d	0.9	0.9	0.9	0.9	0.9
Mod	1	0.97	0.95	0.9	0.8

All variable numbers for SM-2 and SM-6 missiles were estimated based on Mander et al.'s (2022) thesis figures. All Pk values are notional and unclassified.



These values represent the probability of the ship's defensive systems successfully defeating the inbound missile in a single engagement.

Figure 4. SM-6 and SM-2 P_K Values.

F. SURVIVABILITY

The ship survivability equation provides a mathematical framework for evaluating a missile's effectiveness against inbound enemy threats. Using the calculated P_k from the prior equation, the survivability equation equates to the probability of missile intercept. The higher the probability of missile interception, the more likely the ship will survive a missile threat from an enemy surface combatant. The variable n equals the number of missiles shot at a single inbound missile threat. The variable used for the probability of survival is Ps (Dutta, 2014, p.124):

$$Ps = Pd\,(1 - (1 - Pk)^n$$

This research focuses on the missile intercept aspect of an engagement, which can be assumed to be the hard-kill lethality of a missile. The assumption is that missile interception means that the ship survives a missile engagement, and if the missile is not intercepted, the ship will be destroyed. This research does not account for soft-kill tactics, close-in weapon systems (CIWS), or other tactics that can be used to defend against inbound missiles.

Table 4. Probability of Survival against Inbound Missiles Using an SM-6

# of missiles	YJ-83	YJ-62	YJ-18	YJ-12	YJ-21
2	83%	82%	81%	79%	74%
3	88%	88%	87%	86%	83%
4	89%	89%	89%	89%	87%
5	90%	90%	90%	90%	89%
6	90%	90%	90%	90%	89%

The probability that a missile will successfully intercept an inbound missile threat is explained in a two-step process. Each expresses different aspects of a missile engagement between the United States Navy and the People's Liberation Army Navy. These equations aim to give quantitative results for each element of an engagement that culminate into the overall survivability equation of a ship and its crew. The survivability of the SM-6 and SM-2 based on the number of missiles fired can be found in Tables 4 and 5.

Table 5. Probability of Survival against Inbound Missiles Using an SM-2

# of missiles	YJ-83	YJ-62	YJ-18	YJ-12	YJ-21
2	80%	79%	78%	76%	71%
3	87%	86%	86%	85%	81%
4	89%	89%	89%	88%	86%
5	90%	90%	89%	89%	88%
6	90%	90%	90%	90%	89%

G. MISSILE-FIRING DOCTRINE

Two commonly used missile-firing doctrines used for naval air missile defense are shoot-look-shoot and shoot-shoot-look-shoot. The term shoot refers to the specific action of launching a missile from a platform to intercept an inbound missile threat. The term look refers to confirming that the inbound missile has been destroyed and assessing whether to shoot another missile. The missile-firing doctrine is implemented to mitigate reaction time and conserve ammo so that a DDG can operate effectively. The destroyer's commanding officer decides which doctrine and ordinance should be implemented for missile defense.

The advantage of a shoot-look-shoot doctrine is that a ship can conserve missiles by only firing one missile at an inbound threat and then looking to assess if the threat was destroyed. If the inbound threat was not destroyed, the ship would need to shoot another missile to destroy that threat. By only firing one missile and then assessing whether to fire another, the ship can better maintain a one-to-one ratio for inbound threats. The con to this doctrine is the time it takes to look and assess the kill of the inbound threat. If the inbound threat moves too fast, the ship may not have enough time to assess and shoot another missile before impact.

The benefit of a shoot-shoot-look-shoot doctrine is that the second missile is automatically shot before assessing if the inbound threat was destroyed. By firing a second shot, the ship increases the probability of survival. The con for this doctrine is that the ship uses two missiles for every inbound threat, which quickly depletes a ship's missile inventory.

H. NAVY BUDGET AND DIRECT COSTS FOR ANALYSIS

The money that funds the Department of Defense (DoD) is allocated between all four military branches and agencies under its authority. The DoD requested 849.8 billion for the 2025 fiscal year (FY) budget (U.S. Department of Defense, 2024). In 2024, the DON stated in a press release that it requested $257.6 billion for the 2025 FY Budget (U.S. Department of the Navy, 2024). Based on this press release, there were five primary areas for which the Navy allocated funds: military construction, research and development, procurement, military personnel, and operations and maintenance. The geopolitical environment at the time of the request and in the predicted future greatly influences how the Navy allocates its budget. When procuring ships and missiles, the Navy needs to know the cost of each item and how each platform and weapon helps to advance its priorities and goals.

1. Procurement Cost for an Arleigh Burke-class Destroyer

The Navy's shipbuilding plan sets the goals for the Navy's procurement of ships and assets that the Navy will add to the fleet. The interests of the Navy's shipbuilding plan are centered on the current objectives and targets of the Navy. In FY 2025, the procurement cost for a Flight III Arleigh Burke-class destroyer is $2.5 billion (Congressional Research Service, 2024, p. 2). The Navy will continue to buy more ships to meet the 2025 shipbuilding plan goal of increasing the fleet to at least 381 ships (Congressional Budget Office, 2025). The procurement cost is important to understand how the higher cost of shipbuilding affects the lethality of the fleet and how it compares to the shipbuilding of the PRC.

2. Procurement Cost for SM-6 and SM-2

As of February 2024, the procurement cost for an SM-6 and SM-2 are $3.9 and $2.1 million, respectively (Missile Defense Advocacy Alliance, 2024).

3. Cost of the Crew

The best estimate for the average cost of military personnel is about $11.8 million (Kniesner et al., 2015; Kniesner et al., 2024). When adjusted for inflation, for 2024, the average cost is approximately $14.1 million. Multiply this average cost by 305 for the personnel on a fully crewed Arleigh Burke-class destroyer. Provides a total crew cost of approximately $4.3 billion. The data and methods used to conduct this analysis were gathered from unclassified sources and are purely theoretically based.

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IV. COST-BENEFIT ANALYSIS AND RESULTS

A. COST-BENEFIT RESULTS

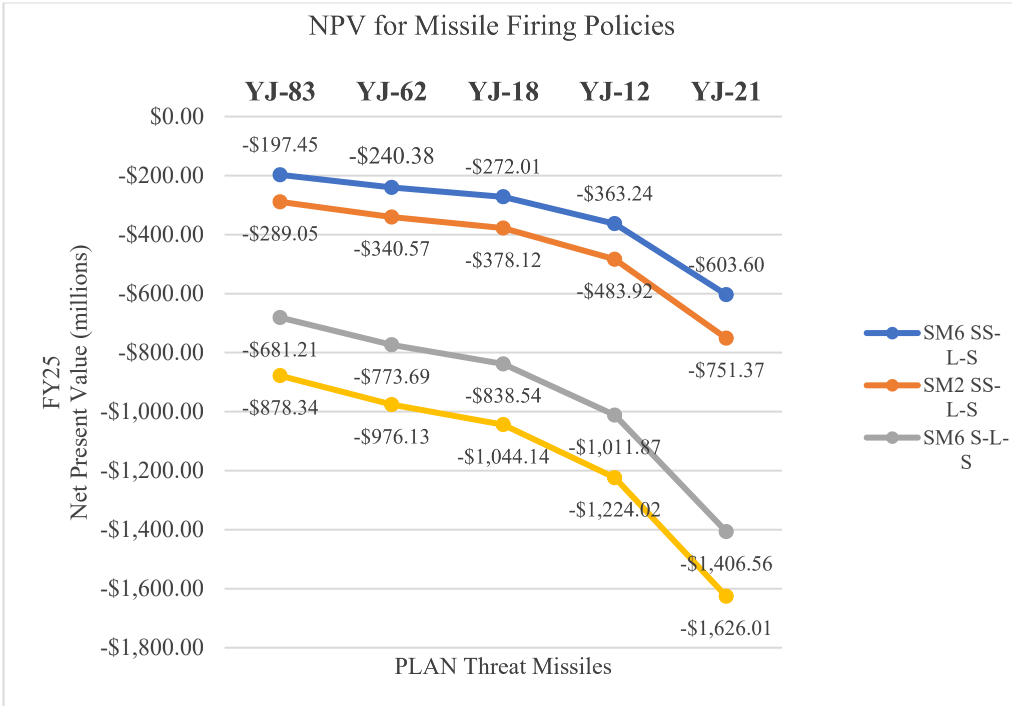
The cost-benefit analysis shows that a 60% SM-2 and 40% SM-6 ratio is the most cost-beneficial missile loadout for a 96-cell VLS onboard a Flight I DDG with 50% capacity allocated for self-defense missiles. Employing a 60% to 40% ratio is the best because it allows DDGs to defend against the largest array of missile threats. This missile loadout provides a balanced solution against coverage, inventory, and cost constraints. When a DDG allocates all SM-6 missiles to only high-end threats, such as the hypersonic YJ-21 missile, with the SM-6 missiles and commits the remaining SM-2 missiles to the medium and low-end threats, such as the YJ-12 or YJ-63, then there is a potential of over sixteen above 90% survivability engagements with enemy inbound missiles. This assumes that each engagement is statistically independent and that the crew is well-trained while performing in the ship's best interest. Missile loadout ratios, individual missile costs, and total missile costs can be seen in Table 6. The chart shows the cost differences between different ratios that could be used for a missile loadout. A 31% SM-6 and 69% SM-2 missile loadout would be cheaper by $7.2 million ; however, it cuts a DDG's ability to defend against hypersonic threats with a full salvo by 37%. A 50% SM-2 and 50% SM-6 missile loadout would be more expensive by $9.01 million and decrease the ability to defend against supersonic and subsonic missile threats due to a decrease in SM-2 missiles.

Table 6. Missile Ratios and Costs. Adapted from Missile Defense Advocacy Alliance (2024).

% SM-6	% SM-2	# of SM-6	# of SM-2	SM-6 Cost (million)	SM-2 Cost (million)	Total Cost (million)
31%	69%	15	33	$58.52	$69.30	$127.83
40%	60%	19	29	$74.13	$60.90	$135.03
50%	50%	24	24	$93.64	$50.40	$144.04

B. NET PRESENT VALUE RESULTS

Net present value (NPV) is defined as the accumulated cost of the missiles used in an engagement, a DDG, and the crew. Estimated crew costs are calculated by multiplying 305 sailors, the typical number of sailors on a DDG, and $14.1 million, the estimated cost of a single service member (Kniesner et al., 2015; Kniesner et al., 2024). The number of missiles expended is based on the inbound threat and the missile-firing doctrine in place. Based on the graph in Figure 7, the NPV for both missile-firing doctrines against each threat can be seen. Based on this figure, the shoot-shoot-look-shoot firing doctrine with SM-6 missiles gives the lowest net present value for all five threats. This is due to a higher probability of survival when using the most capable missile against all five threats. The lower net present value shows the lower risk of damage to ships and crew based on a higher probability of survival. A shoot-shoot-look-shoot with SM-2 missiles also shows a similar net present value, but slightly more due to its lower capabilities. In comparison, the SM-2 shoot-shoot-look-shoot firing doctrine has a lower net present value than the shoot-look-shoot SM-6 firing doctrine across all threats. This shows that the SM-2 doctrine increases the probability of survival and lowers risk with a lower-cost missile. This is why this doctrine and missile combination should be the preferred method between the two doctrines. Based on this finding, a shoot-shoot-look-shoot with SM-2 missile salvo should be employed over a shoot-look-shoot with SM-6, making it the preferred policy for medium threats. For the lower-end threats, the shoot-look-shoot firing doctrine with SM-2 is the most cost-beneficial engagement combination due to its low expenditure and cost.

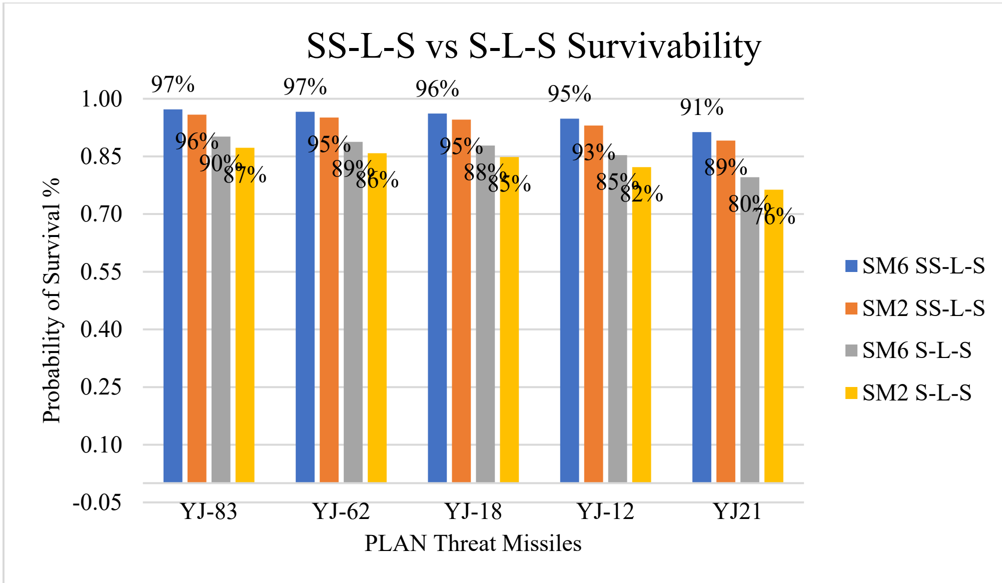


This chart highlights the tradeoff between firing doctrine and threat as measured by net present value. All costs are measured in FY25 dollars.

Figure 5. Net Present Value of DDG and Crew

C. SHIP SURVIVABILITY RESULTS

Ship survivability increases or decreases based on the missile doctrine put in place. Results for firing doctrine and missile combination can be seen in Figure 7. The doctrine and missile combination with the highest probability of ship survival is an all SM-6 shoot-shoot-look-shoot, regardless of the threat. By shooting an extra missile with a shoot-shoot-look-shoot doctrine, a ship's survivability increases by about 7%.



This chart highlights that a SS-L-S SM-6 missile-firing doctrine is the best for survivability.

Figure 6. SS-L-S vs. S-L-S Survivability

D. DISCUSSION

1. The Most Cost-Beneficial Loadout Based on the Ship's Probability of Survival Is a Split between 60% SM-2 And 40% SM-6

A 60/40 ratio missile loadout gives the ship the most balanced approach based on research on current Chinese missile threats. The total cost for this loadout is $135 million, with the potential to intercept 16–18 missiles with an above 90% probability of ship survival. The benefit of this loadout is that it supports a firing doctrine that allocates SM-6 missiles to hypersonic threats and SM-2 missiles to super and subsonic missile threats, and it keeps a DDG's probability of survival above 90%. This loadout is based on theoretical analysis, and the threats could be distributed differently than described in this thesis. However, based on the methodology of this thesis, this method can grow and learn based on new threats and probabilities put in place.

2. A Shoot-Shoot-Look-Shoot Policy Compensates for the SM-2's Lower Capabilities, Making It Nearly Equal to the Shoot-Shoot-Look-Shoot Capability of the SM-6

While less capable than the SM-6, a shoot-shoot-look-shoot firing doctrine combined with SM-2 missiles is better than a shoot-look-shoot policy with SM-6 missiles. From a cost perspective, a shoot-look-shoot policy is better to save on missile consumption. When applying the NPV analysis, the risk of losing the ship and crew heavily outweighs the benefits of missile conservation, this is true for all five Chinese missile threats. A DDG can mitigate risks and protect the ship by shooting more missiles. Therefore, a shoot-shoot-look-shoot with SM-2 missiles should be the preferred firing doctrine when compared to a shoot-look-shoot firing doctrine with SM-6 missiles.

E. RECOMMENDATIONS

Recommendations include incorporating a 60% SM-2 and 40% SM-6 missile loadout, having a missile defense strategy based on soft and hard-kill weapons, increasing production on the SM-6 due to new and evolving threats in the future, and allocating more money towards research and development.

1. 60% SM-2 and 40% SM-6 Missile Loadout Plan

Based on the findings, this research recommends a 60% SM-2 and 40% loadout plan. While also allocating SM-6s to hypersonic missiles and SM-2s to supersonic and subsonic missile threats. This provides the highest survivability while also prioritizing missile conservation.

2. For Future Missile Defense Engagements, Integrate Hard-Kill and Soft-Kill Missile Tactics

The United States should not depend solely on hard-kill methods to defeat the PLAN threat in the Indo-Pacific region. Hard and soft-kill tactics should be used to defend against all inbound missile threats. Utilizing soft-kill tactics increases the cost-benefits of the loadout through missile conservation.

3. Increase Production and Lower the Cost Of SM-6 Missiles

The current cost of the SM-6 is $3.9 million, and it is one of the most capable SAMs that the United States has in its arsenal. Combined with the missile-firing doctrine of shoot-shoot-look-shoot, the probability of a ship surviving the engagement is approximately 95% based on the threat. Based on this result, it is imperative to maintain SM-6 missile inventories by lowering costs and increasing production.

4. Allocate Money to Research New Technology

The U.S. can stay at the forefront of technology by allocating more money to research and development. Research and development help to discover new technology and weapons. One of the latest weapons that the Navy is developing and testing is the Directed Energy Weapon (DEW). The Office of Naval Research states, "Directed energy weapons are defined as electromagnetic systems capable of converting chemical or electrical energy to radiated energy and focusing it on a target, resulting in physical damage that degrades, neutralizes, defeats, or destroys an adversarial capability" (Office of Naval Research, 2024). Directed energy weapons could be the future of combatting ASCMs and cheap drone swarms. The benefit of this type of weapon is that it has almost limitless ammunition at an extremely low cost. The disadvantage of the weapon system is the amount of energy required to fire.

According to the GAO report, "Directed Energy Weapons, DoD should focus on Transition Planning," the "DoD spends about $1 billion annually on directed energy—concentrated electromagnetic energy—weapons, including high-energy lasers and high-power microwaves" (U.S. Government Accountability Office, 2023). While there has been a push for these weapons, there is an issue with moving them from the prototype phase to the acquisition phase. By continuing to invest in the research and development of the Directed Energy Weapon, the Navy emphasizes innovation and being on the cutting edge of technology.

V. CONCLUSION

In conclusion, the key facts are that the People's Republic of China is the United States' greatest threat in the Indo-Pacific region. The United States Navy should have a strategically sound plan to compete and win against China. The DoD and the DON budget allocation should reflect the goals and objectives that allow a sustainable cost-beneficial plan to compete against Chinese platforms and missiles.

The findings and recommendations of this research are that SM-6 missiles should be used with a shoot-shoot-look-shoot against hypersonic threats. SM-2 missiles should be used with a shoot-shoot-look-shoot firing policy against medium threats and a shoot-look-shoot firing policy against subsonic threats. When prioritizing these threats with the specified firing doctrine, the most cost-beneficial missile loadout for a 96-cell VLS onboard a flight I DDG with 50% capacity allocated for self-defense missiles would be 60% allocation for SM-2 missiles and 40% allocation for SM-6 missiles. This missile loadout allows for the most well-balanced variety of missile threats while maintaining a probability of survival of at least 87% for each salvo. Using the recommended missile loadout and firing doctrine, a DDG can intercept six hypersonic missiles and a maximum of nine supersonic or 14 subsonic missiles.

Overall, China aims to increase its power and influence in the Indo-Pacific region and will use its large naval fleet and advanced missile technology to achieve that goal. This thesis provides a theoretical loadout allocation strategy that balances cost and survivability based on current Chinese missile threats. By balancing cost and missile defense, the U.S. Navy can compete against China's naval strategy and maintain naval dominance.

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