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NAVAL SURFACE WARFARE A COST EFFECTIVENESS ANALYSIS OF HARD-KILL VERSUS SOFT-KILL FOR SHIP SELF DEFENSE

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December 2022

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This project is relevant to military acquisition, U.S. Navy financial management, and Naval Surface Warfare. It examines the cost-effectiveness analysis of potential Navy Surface Ship Electronic Warfare (EW) and vertical launch missile systems (VLS). Our intent is that the research informs the Program Executive Office Information Warfare Systems (PEO/IWS) and OPNAV N96/N2N6 by illustrating the capabilities and costs of EW and missile systems. We examined the effectiveness of Navy systems against a myriad of threat missiles, using estimated percent kill (Pk) calculations that encompassed the underlying sensors consisting of command and control, communications, detection, engagement, and tracking. Our results indicate that the electronic warfare systems, specifically the SLQ-32 (v)7, is the most cost-effective system to deter threat missiles, because of the re-load cost associated with missile systems, specifically the SM-6, SM-2, and ESSM. While the SLQ-32 is the most cost-effective system, we understand the need for redundancy, and we cannot completely disregard defensive missile systems. It is our hope that this research will ultimately aid in strategic decision-making for long-term employment weapons load outs on various ship classes. With more money invested in electronic warfare defense systems, the load out on surface assets can theoretically shift to a more offensive mindset, while still maintaining defensive missiles for the applicable threat environment.

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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

AP	Advanced Procurement
ASCM	Anti-Ship Cruise Missile
CFO	Chief Financial Officer
CG	Guided Missile Cruiser
CIWS	Close In Weapons System
CNO	Chief of Naval Operations
CSG	Carrier Strike Group
DDG	Guided Missile Destroyer
DOD	Department of Defense
EA	Electronic Attack
EMCON	Emission Condition
EO/IR	Electro Optical/Infrared
EP	Electronic Protection
ES	Electronic Support
ESSM	Evolved Sea Sparrow Missile
EW	Electronic Warfare
FLTCOM	Fleet Commander
FYDP	Future Years Defense Program
HGHS	High Gain High Sensitivity
MYP	Multi-Year Procurement
N2	Deputy Chief of Naval Operations for Information Warfare Domain/Director of Naval Intelligence
N8	Deputy Chief of Naval Operations for Integration of Capabilities and Resources
N80	Director, Programming Division
N81	Director, Assessments Division
N96	Director, Surface Warfare Division

NATO	North Atlantic Treaty Organization
OPNAV	Office of the Chief of Naval Operations
OPN	Other Procurement Navy
PEO/IWS	Program Executive Office/Information Warfare Systems
POM	Program Objective Memorandum
PPBE	Planning, Programming, Budgeting, Execution
SAM	Surface to Air Missile
SECNAV	Secretary of the Navy
SEWIP	Surface Electronic Warfare Improvement Program
SM	Standard Missile
TYCOM	Type Commander
USMC	United States Marine Corps
USN	United States Navy
VLS	Vertical Launch System
WPN	Weapons Procurement Navy

I. INTRODUCTION

The United States Navy continually operates in a forward deployed presence around the globe. The Navy's Surface Force resources are being directed towards historic strategic level mission sets and new operational technologies. This shift to new technologies directly impacts each new, and existing ship classes' ability to defend itself against threats while operating over the horizon. These new technologies will enhance the surface force's ability for global power projection and enhance self-defense capabilities. A key component of these new technologies is the future of anti-surface missile self-defense and electronic warfare.

Program Executive Office Information Warfare Systems (PEO/IWS) is the lead acquisition and research component for the surface force's electronic warfare capabilities, and the driving force for defining future capabilities, identifying solutions, and facilitating development and implementations. Their current acquisition of the new Surface Electronic Warfare Improvement Program (SEWIP) and the AN/SLQ-32(V) systems has provided solutions for soft-kill defense. Their research and development on the Vertical Launch System (VLS), Close-in-Weapons System (CIWS), and Standard Missile (SM) systems have provided solutions for hard-kill defense. Each option has a multitude of positive and limiting capability parameters, with varying costs for each system.

Aegis guided missile Arleigh Burke class destroyers and Ticonderoga class cruisers (DDG/CG) are the Navy's most capable air defense units because of their multifunctional phased-array radars and their inventory of numerous anti-air weapons and electronic warfare suites. These ships can defend themselves and other ships in the area from air threats using a combination of SMs and the Evolved Sea Sparrow Missile (ESSM). Electronic warfare capabilities allow DDG/CGs to employ countermeasures that include jamming and decoys in self-defense. These highly technical and advanced combat systems are major investments and evolve over time. The addition of electronic attack capabilities, combined with more capable SMs, is not a low-cost undertaking for the Navy. There is a constant battle inside of the Office of the Chief of Naval Operations (OPNAV) and PEO/

IWS to justify funding requirements, and to prove that money is required for one capability over the other.

While our surface forces are operating globally, they are exposed to a multitude of potential threats from various state and non-state actors. The ability to defend a ship, a Carrier Strike Group (CSG), or another High Value Unit, is crucial to the effective employment of naval assets. If an anti-ship cruise missile (ASCM) is launched at a surface unit, the unit will employ soft-kill or hard-kill tactics to defend themselves and neutralize that threat. Soft-kill tactics include electronic warfare functions, such as electronic attack (EA) or using decoys, and potentially jamming the missile to miss the surface unit. Hard-kill tactics involve using ordinance, including SMs, ESSM or CIWS, from the defending unit to knock the threat missile out of the sky. This paper will focus on examining the costs of both hard-kill and soft-kill tactics and the probabilities of success with each tactic versus various threat missiles. Ultimately, we seek to answer the following question: "With the addition of an electronic attack system capable of neutralizing threats, would surface units be able to onload more offensively capable weapons, thereby expanding their distributed lethality?"

II. BACKGROUND

A. OVERVIEW OF THREATS

A U.S. naval surface ship faces dozens of threats at sea. From enemy submarines, aircraft, mines, torpedoes, electronic and cyber threats, and anti-surface missiles. Anti-surface missiles are traditionally placed into three categories based on speed. From slowest to fastest they are subsonic (speeds less than that of sound), supersonic (speeds typically between Mach-2 and Mach-3, up to 2,300 mph), and hypersonic (Mach-5 to Mach-10) (BrahMos, n.d.). Additionally, a subcategory of hypersonic is the hypersonic-ballistic which carries speeds of Mach-5+ and follows a ballistic trajectory. Missiles will also have a maximum range that is calculated from the weight, size, aerodynamics, and fuel stores, among other key factors. The maximum range of the missile will factor into its overall effectiveness.

In addition to speed and range, missiles utilize a guidance system to hit their target accurately. The most common guidance system is radar homing, with three sub-types: active, semi-active, and passive. Active homing employs an internal radar system on the missile. It stays aimed at the target and the radar system provides continuous guidance signals. Semi-active homing uses a passive receiver while the radar system used to detect the target initially is then used to track it. Passive homing is sometimes also known as "heat seeking" because it uses infrared homing to track its target by the heat the target generates (Palumbo, 2010).

The United States currently has two major actively threatening and two strengthening state adversaries with regards to anti-surface missiles: China and Russia, and Iran and North Korea, respectively. Both China and Russia have developed subsonic missiles that they and other nations use. The Chinese YJ-83 (C-802) is a subsonic missile also used by Iran and North Korea with a top speed of 0.9 Mach with an active radar homing seeker and a max range of 125 miles (Missile Defense Advocacy Alliance, n.d.). The Russian subsonic KH-35 is similar with a top speed of Mach-1, utilizing an active and passive seeker, and a max range of 160 miles, also used by the North Koreans (Missile Defense Advocacy Alliance, n.d.).

Russia's supersonic missiles, the SS-N-22 Sunburn and SS-N-27 Sizzler both have a top speed of Mach-3 with an active and passive seeker, max range of 75 and 185 miles respectively, and are used by other nations (Sunburn used by China and North Korea and Sizzler used by Iran) (Missile Defense Advocacy Alliance, n.d.). The SS-N-27 also has high-speed evasive terminal maneuvers, including a sprint feature to accelerate to its maximum velocity increasing its lethality prior to its target. China's YJ-12 supersonic missile is used only by them and employs a top speed of Mach-4 using active and passive seekers along with terminal sprint capabilities like the SS-N-27 and a max range of 250 miles (Missile Defense Advocacy Alliance, n.d.).

Until now, only China and Russia have developed hypersonic missiles. Russia's SS-N-33 (3M22 Zircon) has a top speed of Mach-9, max range of over 500 miles, and utilizes an active seeker (Missile Defense Advocacy Alliance, n.d.). China has two hypersonic-ballistic anti-ship missiles. Both are considered their "carrier-killer" missiles and have top speed of Mach-10. These are their original DF-21D, and the newly developed YJ-21. The YJ-21 has an unconfirmed top speed of Mach-9 and a range or over 500 miles (Missile Defense Advocacy Alliance, n.d.).

As these nations continue their development of highly sophisticated missiles, the United States must adapt and develop weapons and defense systems to counter these threats. We will consider these threats in comparison to our defensive missiles and electronic warfare systems to understand our capabilities in countering them.

B. DESCRIPTION OF TECHNOLOGIES

To combat the multitude of threats listed above, the U.S. Navy has developed numerous technologies and strategies that have been implemented on today's warships. These technologies can be broken into three basic categories: Detect, Control, and Engage. The various ship classes in the U.S. Navy have vastly different combat systems. For simplicity, we will be focusing on guided missile destroyers and guided missile cruisers. DDGs and CGs are focused on the AEGIS combat system.

The AEGIS combat system is a multifaceted program capable of warfare multiple different ways: strike warfare, anti-submarine, ballistic missile defense, anti-surface, and anti-air (Gregg et al., 2020). "Architecturally, AEGIS is a system of systems comprising elements that include the AEGIS Display System, Command and Decision, SPY Radar, the Standard Missile, Weapon Control System, AEGIS Training, Mission Planner, and Operational Readiness" (Bath, 2020). The above components create the fire control loop that ensures AEGIS mission success (Bath, 2020). This research will focus on air defense, specifically ship self-defense from air to surface or surface to surface missiles.

The SPY radar component of the AEGIS weapons system allows DDGs and CGs to detect incoming threats. Once a threat has been detected, the other components of AEGIS, with input from the human operators, will determine how to engage the threat. There are two options when engaging an incoming missile, a "hard-kill" or a "soft-kill." Hard-kills are when the U.S. Navy vessel uses kinetic action, from a missile or other ordnance, to knock the threat missile out of the sky. Soft kills involve employing a form of electronic warfare to either disable the threat missile, cloak the U.S. Navy vessel so the threat missile cannot see the unit, or jam the sensors on the threat missile to render it ineffective.

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. Our research will focus on two types of Standard Missile, the SM-2 and the SM-6. The SM-2 has been the primary defensive missile on surface units for the past three decades and is employed via the Vertical Launch System component of AEGIS. There are numerous versions of the SM-2, each with varying capabilities and effectiveness against different threat missiles. The SM-6 is the newer version of the SM and is much more capable than the SM-2, with an extended range and more ability to combat different threat missile types. Additionally, the Navy employs the Evolved Sea Sparrow Missile (ESSM) as a shorter range highly maneuverable missile to combat anti-ship threats that have terminal phase maneuvers. The challenge the U.S. Navy faces today is continuing to update the missiles, so they remain effective against the most capable threats, and distributing the new SMs to the surface units, with the current budget they are allocated from Congress.

Soft-kills involve using the electronic warfare suite on surface ships, which is called the SLQ-32. There are three realms of electronic warfare, Electronic Support (ES), Electronic Attack (EA), and Electronic Protection (EP). ES involves collecting signals across the electromagnetic spectrum for data collection and analysis. EA can use jamming, or other techniques to physically disable a threat missile and protect the home unit from attack. EP involves countermeasures and decoys that will either cloak the ship temporarily or create a larger area for the threat missile to lock onto, thereby avoiding the surface asset. The legacy SLQ-32 (v)2, which is installed on most large surface combatants, does not have an electronic attack component. The upgraded SLQ-32 (v)6 is currently being installed on the majority of surface vessels in order to replace the legacy (v)2 and will include an upgraded ES system that is capable of detecting more targets across a wider spectrum. The new SLQ-32 (v)7 includes an EA component and is being installed on one ship, the USS PINCKNEY (DDG 92). The advancement of the EW systems is being funded through the Surface Electronic Warfare Improvement Program. A description of the various versions of SLQ-32 is listed in Table 1.

Table 1. SLQ-32 Versions and Improvements. Source: Hall and Mink (2022).

Block	Incremental Capability Improvement	Installed System Name
N/A	Legacy	AN/SLQ-32
1B1	Specific Emitter Identification (SEI)	
1B2	SEI and Display upgrades	
1B3	High Gain High Sense (HGHS)	
2	Enhanced Electronic Support (ES)	AN/SLQ-32(V)6
2 lite	Enhanced ES for SWaP challenged	AN/SLQ-32C(V)6
3	Enhanced Electronic Attack (EA)	AN/SLQ-32(V)7

The High Gain High Sense (HGHS) components of the upgraded SLQ-32 (v)6 "is a critical improvement for threat correlation, situational awareness, and extending the battle space" (Department of the Navy, 2022, vol. 2, p. 149). The 1B3 and Block 2 units make up the (v)6 system, and the Block 1B3, Block 2, and Block 3 units make up the (v)7 system (Department of the Navy, 2022, vol. 2, p. 149). These added capabilities allow surface units to have a much-needed bolster in the electronic warfare world. The EA component in (v)7 will give drastic improvements to keep pace with threats that are faced when operational on the high seas. It is the hope of PEO/IWS that this improved capability will reduce the requirement for defensive missiles, while allowing units to expand their more offensive capabilities.

The expanded capabilities involved in the SEWIP and the new SLQ-32 (v)7 have the potential to bolster the surface fleets EW capabilities and ship self-defense. Compared with the SMs, the EW suite has the potential to be more cost effective while providing similar protection to surface units. Additionally, if fewer defensive missiles are required onboard surface ships, the Navy could expand their offensive capabilities without sacrificing defense. We will examine the cost per unit of the SMs, ESSMs, the installment costs of the new SLQ-32 system, and compare their effectiveness against various threat missiles.

C. HOW THIS RESEARCH WILL BENEFIT THE NAVY

This research will benefit the United States Navy for several reasons including program effectiveness, ship survival and self-defense, and ship loadout and weapons selection. The Navy must take several factors into consideration when purchasing a new weapon system or missile, writing self-defense doctrine, and selecting weapons for a ship's deployment loadout. This research effectively addresses cost effectiveness of several weapon systems and ship self-defense systems, ship survival while utilizing different systems facing several different enemy threats and helps determine which missiles should be prioritized when arming a ship for deployment.

1. Program Cost Effectiveness and Program Validation

When a significant Navy program goes through development there is significant scrutiny of the budgeting, necessity, benefit, and timeline. With a system like the SLQ-32 (v)7 that costs $60M (Department of the Navy, 2022, vol. 2, p. 178), the Navy is often questioned about its decision-making and program effectiveness. This research will be valuable in determining the value of the SLQ-32 (v)7 and benefit over the (v)6 and other methods of surface ship self-defense. By comparing the SLQ-32(v)7's effectiveness over previous systems as well as "hard kill" defensive missiles and crossing that with the costs, we will be able to show a clear display of the program effectiveness and determine its validity.

2. Likelihood of Survival

This research will give further insight and calculations of the likelihood of survival for U.S. Navy ships employing different hard-kill and soft-kill defenses against several types of enemy anti-surface missiles. As enemy anti-surface technologies and capabilities increase, so does our necessity for comparable defensive systems. The benefit to the U.S. Navy is that this research will provide evidence of the improvement of our surface ship self-defense technology to counter enemy threats and when facing these threats, what the likelihood of survival would be based on the employed self-defense system. Each enemy anti-ship missile has different capabilities and features that give it a higher likelihood of success against out defenses. Additionally, we have different defenses for each type of threat and will examine these against each other, giving the "probability of kill," or likelihood of successful defense for each self-defense strategy versus each anti-ship missile threat.

3. Defensive Weapon Selection

As previously noted, the U.S. Navy employs several types of soft-kill and hard-kill defenses such as standard missiles, electronic attack, decoys, etc. The new SLQ-32 (v)7 gives a more enhanced and well-rounded self-defense capability to the U.S. Navy surface ships which means the operators onboard those ships now have additional choices in their decision-making. By increasing their self-defense capability, operators can now use technologies that are more evenly matched with their threat, meaning an increased likelihood of survival paired with a more cost-effective method.

4. Ship Weapon Loadout Priority

When a U.S. Navy surface ship is deployed or underway on a patrol, they are stocked with a full arsenal of self-defense missiles, torpedoes, anti-ship missiles, land strike missiles, and more, called a "loadout." Depending on the missions that a ship is tasked with, they will have a specific missile and weapons loadout based on what would be needed to accomplish that mission and what threats they may face. With the added defensive capability of the SLQ-32 (v)7, these ships may be fitted with a different loadout to include more offensive and less defensive missiles, increasing their lethality without sacrificing self-defense.

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III. METHODOLOGY

Effectiveness of a ship self-defense system can be defined as the ability of a system to detect, track, engage and destroy an adversary missile threat. Since the potential success of a missile system, or effectiveness, of that system is probabilistic, a simple measure of effectiveness can be used to determine the probability that a missile system would be successful in the defense of the ship. We will express this as:

$$Pk = Pd * (Pe * \text{mod}) . \text{ (Dutta, 2014, p.124).} \quad (1)$$

where Pk is the probability of kill, or the overall probability that the system in question would successfully destroy or incapacitate a certain threat. Pd is the probability of detection of said threat and encompasses the underlying sensors consisting of command and control, communications, detection, engagement, and tracking. Pe is the probability of execution against the same threat. Finally, mod is the value we have assigned to the threat missile for its capabilities above a baseline threat missile (in this case, a subsonic active seeker ASCM). For the purposes of this study, these probabilities are being calculated on a baseline, theoretical basis, to provide background numbers for the financial evaluation in our cost-effectiveness analysis.

All missile engagements will be considered one to one, or the ability of one ship-launched missile to defeat one adversary missile. Each threat missile is evaluated based on type of sensor, effective range, terminal speed and whether it has countermeasures or evasive maneuvers. Ship self-defense missiles will begin with a baseline Pe. The overall Pk will then be modified by the capabilities of the threat missile it is encountering. Because surface ship self-defense missiles all generally use the same AEGIS system for the detection, classification, and engagement of threat missiles, Pd for surface ship missiles will be assumed to be 0.9 without modifiers. This assumes that the SM family of missiles, the Sea Sparrow family, and their associated combat systems, have a 90% chance of detecting and successfully firing a shot against an average capability threat missile.

The overall equation (1) results in a probability unit, measuring the effective probability that one ship self-defense missile or the SLQ-32 (v)7 system, would defeat one threat missile.

A. THREAT MISSILE PE MODIFIERS

(1) YJ-83

The YJ-83 is a subsonic missile with a terminal velocity of 0.9 Mach and an active seeker, some variants of which utilize infrared guidance (Heginbotham et al. 2015, 217). Due to the operational history of U.S. Navy surface ships PONCE and NITZE successfully countering missiles launched by Houthi rebels in 2016 that were likely the YJ-83, no modifiers will be applied to this missile (LaGrone, 2016).

(2) KH-35

The KH-35 is a Russian built subsonic sea-skimming missile with a maximum velocity of 1.0 Mach and an active/passive seeker. Due to its similarities to the YJ-83, as an average capability Russian missile, no modifiers will be applied to this missile (ODIN, 2020).

(3) SS-N-22 "Sunburn"

The SS-N-22 "Sunburn" is a Russian built supersonic sea-skimming missile with a maximum velocity of 3.0 Mach and an active/passive seeker. Due to the speed of supersonic missiles, and the limited amount of time in which ship self-defense systems must react, we have applied a modifier of .05 to this missile (ODIN, 2020).

(4) SS-N-27 "Sizzler"

The SS-N-27 "Sizzler" is a Russian built supersonic sea-skimming missile with a maximum velocity of 3.0 Mach and an active/passive seeker. This missile is capable of high-speed evasive terminal maneuvers, and executes a terminal sprint, where it speeds up to its maximum velocity prior to impact with its target (ODIN, 2020). It is capable of land attack and was used during the 2022 invasion of Ukraine (Newdick, 2022). Due to its advanced capabilities, and current proven operational usage, we have applied a modifier of 1.0 to this missile.

(5) YJ-12

The YJ-12 is a Chinese built supersonic sea-skimming missile with a maximum velocity of 4.0 Mach, an active/passive seeker and terminal sprint capabilities. This missile is capable of being effectively utilized from over 400km, which significantly impacts the ability of the defending ship to anticipate and react to the YJ-12. We have applied a modifier of 1.0 to this missile (Haddick, 2014).

(6) SS-N-33

The SS-N-33 "Zircon" is a Russian built hypersonic maneuvering cruise missile, with a maximum speed of Mach 9.0. It has an operational range of over 1000km and an active seeker. Despite the untested nature of hypersonic missiles in Naval warfare, due to the high speed of hypersonic missiles, the large operational range of this missile, we have applied a modifier of 2.0 to this missile (Staff, 2022).

(7) YJ-21

The YJ-21 is a Chinese built hypersonic cruise missile. Its operational range is over 1000km and has an active seeker. Its maximum speed is likely near Mach 9.0. Due to the large range and high speeds of hypersonic missiles, we have applied a modifier of 2.0 to this missile (Ozberk, 2022).

B. SM-6

1. SM-6 Baseline

The SM-6 is a multi-block missile in the SM family. The most advanced missile in the U.S. arsenal currently deployed for ship self-defense, it has both active and semi active seeking capabilities, with a longer range than the SM-2 and faster flight speeds. The new BLK 1B has capability to counter the hypersonic threat with longer ranges and faster top speeds than the other blocks of SM-6. Because the SM-6 is arguably the most effective ship self-defense missile in our arsenal, we have applied a 0.8 *Pe* baseline to this weapon.

2. SM-6 Against Missile Threats

Figure 1 shows the *Pk* of the SM-6 versus all threat missiles along with Y-axis, and each threat missile from least to most capable along the X axis. With low capability missiles such as the YJ-83, the SM-6 has a 0.72 probability of stopping that threat missile. This probability goes down as the threat missiles become more complex and advanced.

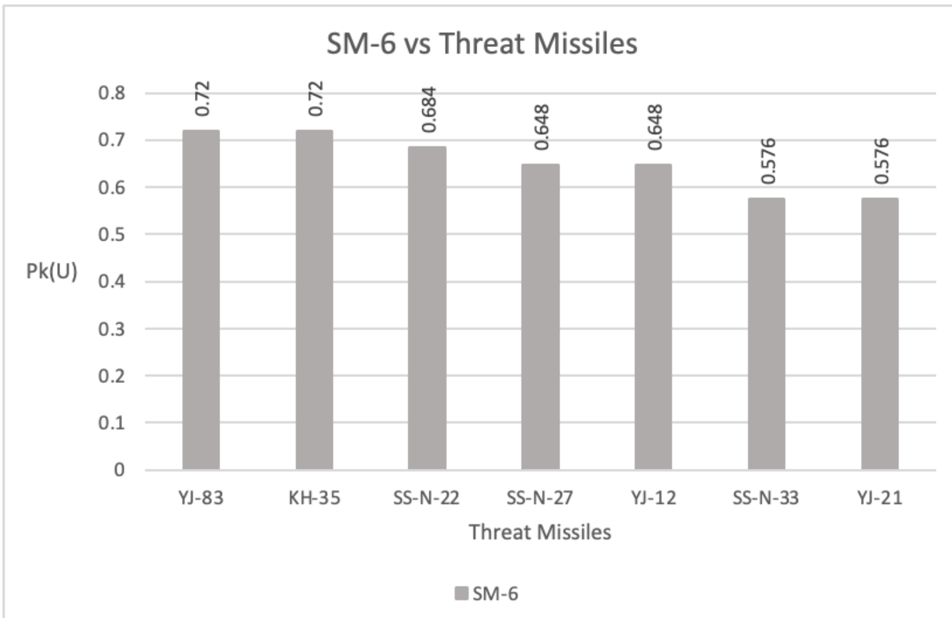

Figure 1. SM-6

C. SM-2

1. SM-2 Baseline

The SM-2 is a multi-block mid-range missile in the SM family. It is the most commonly available and employed ship self-defense missile employed by the U.S. Navy. Different blocks have different capabilities, with block IIIB having a semi active/IR mode, and block IIIC with a terminal active homing mode. The SM-2 is a highly capable missile that can be employed against multiple threats, like the SM-6. The primary difference is that SM-6 is more capable overall, with higher velocities and longer ranges. Due to the multi-threat capability of the SM-2 across its various blocks, we have applied a baseline *Pe* of 0.7 to the SM-2 range of missiles.

2. SM-6 and SM-2 against Missile Threats

Figure 2 shows the SM family of missiles *Pk* versus all threat missiles, with *Pk* on the Y-axis and the threats on the X-axis. The SM-6 is a much more capable missile than the SM-2, so the data reflecting that is not a surprise.

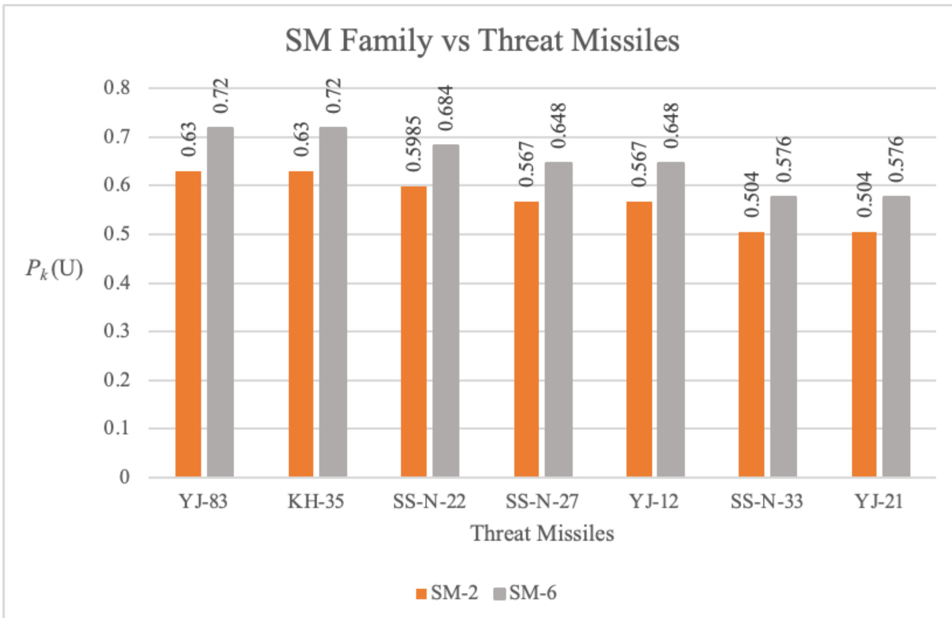

Figure 2. SM Family

D. ESSM

1. ESSM Baseline

The Evolved Sea Sparrow Missile is a point-defense missile system employed by the U.S. Navy. Its specialty is short range engagements and employs a semi-active missile seeker. The ESSM was used by the USS MASON in 2016 when she was engaged by Houthi rebels in the Bab-El Mandeb strait (LaGrone, 2016). The weakness of the ESSM is its limited range and size, in addition to its lack of multi-mission capabilities to counter radar-defeat missiles. Due to its proven capabilities, but also lack of multi-mission capability, we have applied a baseline *Pe* of 0.65 to the ESSM.

E. SHIP SELF-DEFENSE MISSILES AGAINST MISSILE THREAT

Figure 3 shows all the ship self-defense missiles' *Pk* values versus all the threat missiles, with *Pk* on the Y-axis and threats on the X axis. As expected, SM-6 is our most capable missile, followed by SM-2, then ESSM.

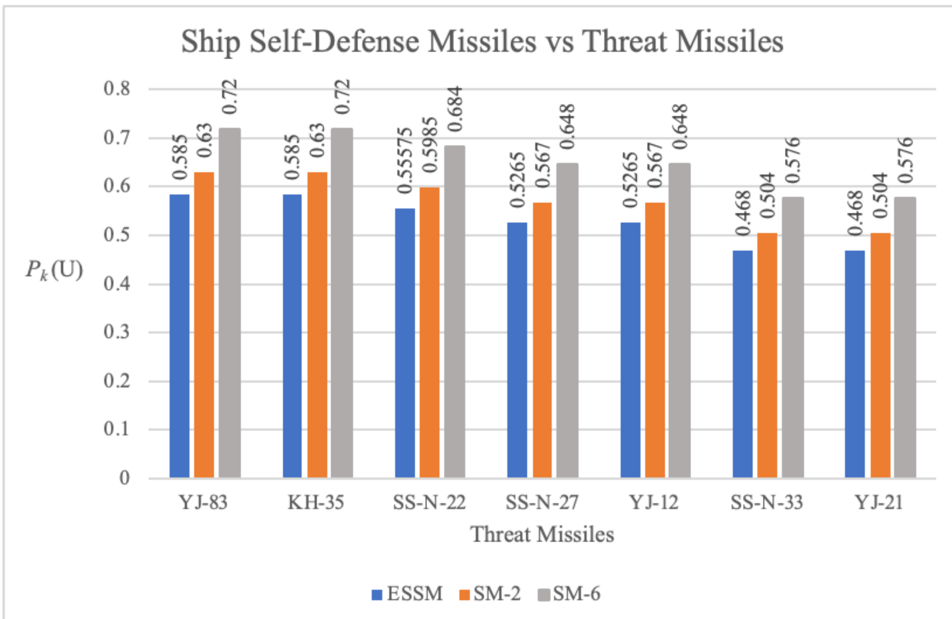

Figure 3. Ship Self-Defense Missiles

F. SLQ-32 (V)7 EFFECTIVENESS

Electronic Warfare systems have some advantages over missile systems in terms of ship self-defense. EW systems can operate covertly, passively detecting inbound missile threats with active seekers, or disrupting the targeting systems of firing platforms. In addition, EW systems with active jamming capabilities are not limited in the number of threat missiles they can defeat, by the number of "rounds" they may have available to them (like with a missile system), but only by their processing power.

The effectiveness of an EW system can be defined in similar terms to the effectiveness of a missile-based ship self-defense system. The underlying probability expression remains the same, but the probability of detection is housed within the same system. In addition, the type of threat missile becomes much more impactful. For example, a passive missile system would hold a distinct advantage over an electronic warfare suite, at times when ships are in an Emissions Control (EMCON) condition. If the underlying sensors utilized for the detection of a threat missile are offline due to an EMCON condition, then the possibility that a passive missile threat could slip through the ship's detection sensors is much higher.

The difference between the SLQ-32 (v)7 and other EW systems is that the robust active jamming capabilities of the SLQ-32 (v)7 allows it to effectively counter enemy missiles. Where previous iterations of the SLQ-32 would only notify the ship of what sort of missile was inbound, the (v)7 can stop those missiles in their tracks (Northrup Grumman, 2022). An additional benefit of the (v)7 system, is that once it is installed, there is no "per-shot" cost, or necessity to reload once out of munitions.

Our assumption with the SLQ-32 (v)7 system is that for a missile with an active seeker, the *Pd* rating will be a 0.9. This assumes that if the threat missile is emitting a signal, then the EW system will detect it at a 90% probability. For missiles with a passive capability, such as the YJ-12 or the Sizzler, the *Pd* rating will be a 0.5. This leaves some possibility that the system will detect the missile if an active component, such as a "pop-up," "last look" or terminal active method of search is used, while still recognizing that until SEWIP blk IV is completed and an EO/IR capability is added to SEWIP, passive seekers pose a challenge to the system (LaGrone, 2021). The *Pe* rating will still be modified, but by 80% of the values listed in A-1 because the factors negatively affecting missile systems such as speed and range do not affect the ability of a computer system to engage and jam a target. Missiles that have passive seekers will be modified by 120%, in order to account for the advantages passive seeker systems have over the SLQ-32 (v)7. Finally, because the block 7 version of the SLQ-32 is the most advanced version of the system in its family (like the SM-6 in its family) the *Pe* baseline for the SLQ-32 (v)7 will be a 0.8.

G. MISSION KILL AND EFFECTIVENESS PROBABILITIES

Figure 4 shows all ship self-defense capacities' *Pk* values versus all threat missiles. *Pk* values are on the Y-axis, and threats are on the X-axis.

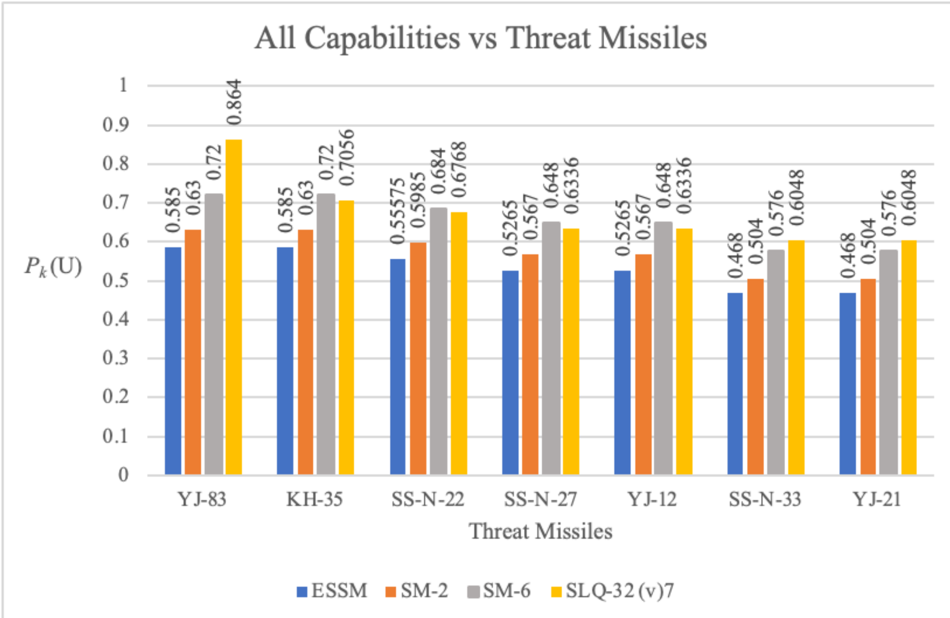

Figure 4. All Capabilities

The results of the effectiveness calculations demonstrate mostly as expected. The SM-6 is the U.S. Navy's most effective surface ship self-defense missile, followed by the SM-2 and ESSM. In a "single missile vs. single missile" context, the SM-6 showed a 0.72 or 72% effectiveness rating against subsonic missiles, an average .648 against supersonic missiles and a .576 against hypersonic missiles. The SLQ-32 (v)7 was marginally more or less efficient than the SM-6 in all aspects other than the categories of active seeker subsonic missiles, and hypersonic missiles, in which the EW system was more efficient. While the SM-6 is extremely efficient against subsonic threats, there stands a small possibility that due to system or missile error, one of these missiles could be missed by an SM-6, and impact with the ship. Because the EW system targets the missiles seeker, it holds a much better chance at stopping the missile. The SM-6 is about 57% effective against hypersonic missiles. The main reason why its rating is lower against this threat is the extreme speeds, lack of available reaction time due to the high speed, and the intangible unknowns surrounding the hypersonic threat. The SLQ-32 (v)7 holds an advantage over the SM-6 (of around 3%) in this regard because if the missiles' seeker cannot find its target due to active jamming, then the speed at which the missile travels is not as much of a concern. However, the intangibles still play a role, and it does not fall outside the realm of possibility that hypersonic missiles could have passive seeker options or jamming defeat countermeasures.

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IV. COST OF U.S. NAVY PROGRAMS AND GOVERNMENT FUNDING

A. FUNDING PRIORITIES

The U.S. Navy is in a constant battle for funding from the government. Not only do they compete against the other branches of the Department of Defense (DOD), but the DOD is competing against the other departments within government. This is critical to understand, and it affects how many SMs the navy can purchase, and how much they can invest in the SLQ-32 program. The U.S. government appropriates funds in two categories, mandatory spending, and discretionary spending. Mandatory spending refers to budget authority that is provided through authorizing legislation rather than one of the 12 annual appropriations acts (Candreva, 2017, p. 48). The largest recipients of mandatory spending are Medicare/Medicaid and Social Security, accounting for approximately 2/3 of the government's budget. Discretionary spending is how most of the government receives its funding. There are 12 annual appropriations that comprise discretionary spending, among them are the annual National Defense Appropriations Act, the Military Construction Act, and the Veterans Affairs Appropriations Act, to name a few (Candreva, 2017, p. 51).

Before the budget is created and submitted to Congress, the Navy participates in the DOD's Planning, Programming, Budgeting, and Execution (PPBE) process. PPBE determines how the Navy allocates their funds once they are appropriated by Congress. For the Navy, the Chief of Naval Operations staff prepares the budget and makes decisions on which programs to fund. "Key stakeholders in the PPBE process include the Chief of Naval Operations, who owns the Navy Program Objective Memorandum (POM); the Deputy Chief of Naval Operations for Integration of Capabilities and Resources (N8); its Programming Division (N80); its Assessment Division (N81); resource sponsors, who define, advocate for, and defend specified subsets of the Navy's capability requirements; and requirements sponsors, who highlight issues of collective importance but do not necessarily have programming authority over the resources involved" (Blickstein et al., 2016, pp. x-xi). The various OPNAV offices will take inputs from the Type Commanders and Fleet Commanders to determine which capabilities are the most crucial for the upcoming budget cycle. "When completed correctly, it ensures that acquisitions and requisite support programs are properly funded, that current priorities are sustained, and that the Navy has made the best—or, increasingly, the least bad—choices given available resources" (Blickstein et al., 2016, p. 8).

The PPBE process is lengthy and plans out on a 5-year basis in accordance with the POM. Because of this, commands constantly look ahead to ensure funding is properly allocated for future needs. The CNO weighs inputs from the TYCOMS and FLTCOMS heavily during this process, to ensure the fleet receives equipment and capabilities that are critical for current and future national security. For funding to be allocated for most major programs, the Program Manager must advocate for the system or equipment. He or she must convince the OPNAV planners that their program is worth investing in and is vital to the everyday operation and security of the fleet. The SLQ-32 system is advocated for by Program Executive Office Information Warfare Systems 2.0 (PEO/IWS 2.0). The Program Managers for the SMs and ESSMs are from PEO/IWS 3.0.

Ultimately, in the OPNAV office, the N8 is responsible for submitting the POM to the CNO for review, and the CNO will submit to the SECNAV. The N8 position is a 3-star Admiral posting and is always filled by someone with a budgeting background, as they will essentially be the CFO for the Navy. The N8 staff receives inputs on the budget from the resource sponsors, in the N9 office inside OPNAV. The chief resource sponsor for the SM/ESSM program is OPNAV N96, the Surface Warfare resource sponsor. The SLQ-32's resource sponsor is in the information warfare domain, or OPNAV N2.

Once the resource sponsors have made their case to the N8 office, N8 will conduct a war game for current and future threats. During this war game, the staff will input all currently funded programs, and programs that will receive allocations in the upcoming fiscal year. The purpose of the war game is to test our programs that the Navy is spending vast sums of money on, against potential advisories to determine if the Navy is spending our money correctly. This is referred to as "requirements assessments." "These assessments include the major studies and analyses that are part of the analytic agenda and major POM deliverables, as well as program reviews and quick-turn evaluations of requirements and performance data" (Blickstein et al., 2016, p. 30). If the results of the war games and fleet exercises indicate everything that has been programmed is sufficient, no changes will be made. However, more likely, the results of the assessments will cause changes in the requirements needed for national security and fleet protection.

Once the requirements and resources have been set, the POM will be developed for the fiscal year and the Future Years Defense Program (FYDP). Balancing the resources and requirements is a difficult task, and often many cuts to programs that would be useful must be made. The Navy POM will then be combined with the USMC POM for the Department of the Navy POM, which will be approved by the SECNAV. After final approval, the POM will be added into the National Defense Authorization Act that will ultimately be passed by Congress and the Senate. Once the act has been passed into Law, the appropriations will become available for use by the Navy. Our main concern will be Weapons Procurement, Navy (WPN) and Other Procurement, Navy (OPN). The missiles from the SM family and the ESSMs are procured using WPN money, and the SLQ-32 system is procured using OPN money. Each of these categories will be explored further in the subsequent sections, as will the specific cost data for each system listed above.

B. MISSILES AND WEAPONS SYSTEMS (WPN MONEY)

The U.S. Navy's missiles and weapons systems are funded via Weapons Procurement, Navy (WPN). This funding includes research and development as well as procurement. WPN is defined in the WPN Justification Book for 2023 as:

> For construction, procurement, production, modification, and modernization of missiles, torpedoes, other weapons, and related support equipment including spare parts, and accessories therefore; expansion of public and private plants, including the land necessary therefore, and such lands and interests therein, may be acquired, and construction prosecuted thereon prior to approval of title; and procurement and installation of equipment, appliances, and machine tools in public and private plants; reserve plant and Government and contractor-owned equipment layaway, $4,738,705,000 to remain available for obligation until September 30, 2025. (Department of the Navy, 2023, vol. 1, p. v)

WPN money is straightforward compared to Other Procurement, Navy (OPN) funding. Weapons are primarily funded based on a procurement basis with unit costs per missile/system. WPN funding does also take into consideration several other factors such as procurement, production, and modernizations/modifications (Department of the Navy, 2023, vol. 1, p. v). The subcategories of WPN budget activity are as follows: Ballistic Missiles, Other Missiles, Torpedoes and Related Equipment, Other Weapons, and Spares and Repair Parts (Department of the Navy, 2023, vol. 1, p. xii). Because we are able to calculate a per unit cost for each of the missiles discussed, it is simpler to understand their cost effectiveness.

The Navy's WPN money breakdown for Standard Missiles and Evolved Sea Sparrow Missiles is in the WPN Justification Book vol. 1 beginning on page 103. We will go through the budgeting information and numbers of the SM-2, SM-6, and ESSM as our primary hard-kill self-defense missiles.

1. Evolved SEASPARROW Missile

The Evolved SEASPARROW Missile is a missile established in a cooperative effort among twelve NATO nations (Department of the Navy, 2023, vol. 1, p. 261). This program was to create an improved version of the RIM-7P SEASPARROW missile that can combat current and future threats with "low altitude, high velocity, and maneuvering characteristics" that the original RIM-7P was unable to engage (Department of the Navy, 2023, vol. 1, p. 261).

The ESSM provides improvements to necessary defensive battlespace against high-speed, highly maneuverable, low-altitude Anti-Ship Cruise Missiles. "The improvements to the guidance system are a dual mode Active/Semi-Active X-Band seeker that is capable of defeating threats such as smaller signatures, increased raid sizes, and adverse environments such as countermeasures" (Department of the Navy, 2023, vol. 1, p. 261). These threats not only include ASCMs, but also Anti-Ship Ballistic Missiles (Department of the Navy, 2023, vol. 1, p. 261).

For fiscal year (FY) 2022, the U.S. Navy procured 108 ESSMs with a total gross weapons cost and obligation authority of $248.619M (Department of the Navy, 2023, vol. 1, p. 262). This cost in inclusive of all hardware, containers, shipping, procurement support, and hardware/maintenance support. The ESSM per unit cost is $2.3M (Department of the Navy, 2023, vol. 1, p. 262). For FY23, the overall projected funding increases to

$282.035M but per unit cost decreases to $2.07M due to increases in Procurement Support ($11.545M), Security and Infrastructure Support ($8.899M), Configuration Management ($570K), and Obsolescence Funding to design out obsolete parts ($10.6M) (Department of the Navy, 2023, vol. 1, p. 262).

2. Standard Missile 2 (SM-2)

The Standard Missile 2 is a medium range Surface-to-Air Missile used for surface ship self-defense and enemy aircraft engagement (Naval Technology, 2022). The newest version is the SM-3 BLK IIIC. "It provides enhanced stream-raid performance against numerous threats via target resolution and missile/target pairing logic, over-the horizon capability for increased depth of fire, enhanced capability against electronic attack and improved firepower due to decreased dependence on illuminators" (Department of the Navy, 2023, vol. 1, p. 287).

Additionally, the plan for the DDG 1000 SM program is to procure SM-2 BLKIII AZ modifications in order to support the deployment of DDG 1000 ships (Department of the Navy, 2023, vol. 1, p. 287). "This line item provides funds to procure SM-2 modification kits to support DDG 1000 Program. Funding includes modification kit installation in SM-2 BLK IIIA rounds as well as hardware and software changes to be compatible with the DDG 1000 radar and combat systems suite" (Department of the Navy, 2023, vol. 1, p. 287).

For FY22, the total gross/weapon system cost is $130.482M with a procured total of 40 SM-2 BLKIIIC, canisters, and BLKIIIAZ modifications. This produces a per unit cost of $3.26M (Department of the Navy, 2023, vol. 1, p. 290).

3. Standard Missile 6 (SM-6)

> The Standard Missile 6 Block I/IA (SM-6 BLK I/IA) is an extended range SAM that provides air superiority and defense from manned-fixed and rotary-winged aircraft, unmanned and arial vehicles, and land attack and anti-ship cruise missiles in flight. (Department of the Navy, 2023, vol. 1, p. 103)

The SM-6 is funded for a five-year Multiyear Procurement (MYP) from FY19-FY23 for 125 missiles per year, a total of up to 625 SM-6s procured over the period (Department of the Navy, 2023, vol. 1, p. 118). By utilizing the MYP, the Navy has realized a five-year savings of $326M versus the single-year procurement for the FY19-23 period (Department of the Navy, 2023, vol. 1, p. 118). The SM-6 Block I/IA All Up Round Missiles provides the blended costs of both Block I and IA missiles.

For FY22 from the MYP the Navy procured 125 SM-6s for a total cost of $598.826M for a gross unit cost of $4.79M per missile (Department of the Navy, 2023, vol. 1, p. 106). This cost includes the hardware of missiles and cannister, engineering support, install and training, and other costs. Additionally, there is Advance Procurement (AP) which provides Economic Order Quantity to reduce costs of contractor effort, material, and components (Department of the Navy, 2023, vol. 1, p. 120). For FY22 the total AP cost is $45.357M, adding another ~$363K per missile for a final unit cost of $5.15M per SM-6 (Department of the Navy, 2023, vol. 1, p. 118).

C. ELECTRONIC WARFARE SYSTEMS (OPN MONEY)

Electronic Warfare systems are funded for procurement and development via Other Procurement, Navy, which is described in the justification workbook by the Department of the Navy as:

> For procurement, production, and modernization of support equipment and materials not otherwise provided for, Navy ordnance (except ordnance for new aircraft, new ships, and ships authorized for conversion); the purchase of passenger motor vehicles for replacement only; expansion of public and private plants, including the land necessary therefore, and such lands and interests therein, may be acquired, and construction prosecuted thereon prior to approval of title; and procurement and installation of equipment, appliances, and machine tools in public and private plants; reserve plant and Government and contractor-owned equipment layaway, $10,746,503,000, to remain available for obligation until September 30, 2025. (Department of the Navy, 2023, vol. 2, p. v)

Because the SLQ-32 systems were installed on surface units when they were initially constructed and commissioned, they could be antiquated and insufficient to combat the modern-day threat. OPN money allows the Navy to re-outfit units with modern, capable systems that can provide added protection to the fast-evolving threats. OPN money is not only for EW systems, as stated in the description from the justification book.

The funding breakdown for the SLQ-32 system is provided in the Department of the Navy's OPN Justification Book vol. 2, beginning on page 145. Because this is OPN money, the per unit cost is not provided, as it is in the case of WPN money. This is because each system is initially expensive up front, then becomes cheaper as the design flaws are worked out and each subsequent system is installed on units. It is also difficult to determine per unit cost because each ship has a different combination of the SLQ-32. Some have v(2), some have (v)6, and one is receiving (v)7. Another reason the per-unit cost is difficult to calculate is, the procurement for the SLQ system can cross over multiple fiscal years. All the money for each version comes from the same allocation, which for FY 2022 was $360.817 million (Department of the Navy, 2022, vol. 2, p. 149). The Navy has already allocated $1,762.176 million towards the SLQ-32 program in previous years and estimates it will cost $8,444.789 million to carry the program to completion (Department of the Navy, 2022, vol. 2, p. 149). These numbers not only include the versions of the SLQ-32 already discussed, but also include the lite versions used by the U.S. Coast Guard.

The majority of the FY22 budget for this line item is going towards the new SLQ-32 (v)7. The total appropriated funds for FY22 were $204.477 million (Department of the Navy, 2022, vol. 2, p. 176). The bulk of the cost is going towards this new unit because of the new EA capabilities it will provide. The hope is that the EA will provide significant protection for the surface unit against most anti-ship cruise missiles. That $204.477 million is the total cost of the SLQ-32 (v)7 system for FY22, which includes procurement costs, support costs, and instillation costs. The procurement allocation was for 3 (v)7 units with a total cost of $178.113 million (Department of the Navy, 2022, vol. 2, p. 178). This would give us a per unit cost of $59.371 million for the three planned procurements. The Navy ultimately plans to procure 58 (v)7 systems at a total cost of $3,504.156 million, for a per unit cost of $60.416 million each (Department of the Navy, 2022, vol. 2, p. 178). This is ultimately an estimation of the costs for future units, but the per unit cost should hover around $60 million before instillation and support costs.

The legacy SLQ-32 (v)6 system is still being procured at a high rate and installed on ships. Some of the older surface units have not yet received the upgrade to the (v)6 system and are scheduled to receive the installment in upcoming maintenance availabilities. Of the total $360 million that was appropriated for FY22 on the SLQ-32 program, a total cost of $84.221 million was appropriated for the (v)6 version of the system, the procurement cost for FY22 totaled $24.013 million for two units (Department of the Navy, 2022, vol. 2, p. 171). This results in a per unit cost of about $12 million for FY22. The estimates to completion for the (v)6 program are 114 units procured at an estimated total procurement cost of $1,122.584 million, giving us a per unit procurement cost of $9.85 million (Department of the Navy, 2022, vol. 2, p. 171). Factoring in future procurements and current procurements, the per unit cost for the (v)6 system averages out to approximately $10.925 million per unit.

There is an extreme difference in price range for the (v)6 and the (v)7 systems. This is because of the added EA capability in the (v)7 system that adds in a much larger layer of protection, which is not included in the legacy (v)6 system, that only includes ES and EP functions. Additionally, the (v)7 system is much larger than the (v)6. When installing the (v)7 system, an additional 5,000 long tons of ballast must be installed in the bilge of the ship. This is because the (v)7 system is so large it will change the righting arm and buoyancy of the ship. How this will affect the draft of a surface unit has not yet been determined.

As we discussed in our *Pk* findings, the SLQ-32 (v)6 is the same detection system as the SLQ-32 (v)7. The (v)7 has the additional capability of EA, which greatly increases the mission kill versus most anti-ship missiles. Because the detection systems in the (v)6 and (v)7 are the same, the probability of detection for both systems is the same. The probability of execution for the (v)7 is much higher than the (v)6, because the (v)6 would have to use an SM or ESSM to neutralize the incoming threat missile. The (v)7 would potentially be able to use EA to disable the missile itself. This ability is the chief reason for the nearly $50 million difference in price per unit between the (v)6 and (v)7. However, the increase in cost should be viewed positively, as this is not a single use system, like the SM's or ESSM's. the SLQ-32 (v)6 and (v)7 can be used indefinitely for the life cycle of the system, which if maintained properly, can be upwards of 20 years. This makes the SLQ-32 systems much more cost effective than the missile systems. However, because the SLQ does not have a 100% probability of kill for all threat missiles, defensive missiles are still needed on surface units.

D. COMPARISON

In comparing the effectiveness of the SM-6, SM-2, ESSM, SLQ-32 (v)6, and SLQ-32 (v)7, we first must compare the *Pk* of each system vs. the cost. For the missile and electronic warfare systems, we will express this as:

$$R = Pk * C \tag{2}$$

where *R* is realized value, or the amount of value we are receiving from the missile when compared to its overall cost, varied based on which missile it is intercepting. *Pk* is the probability of kill vs. a specific threat, and *C* is the cost per unit for the system being evaluated. When evaluating the (v)6 vs. the (v)7, the probability of kill cannot be determined for the (v)6, since it is a detect-only system. For this reason, we will only focus on the realized value of the (v)7 system for the *Pk*, as it is the only one that can render a threat missile ineffective. Below we will discuss our results comparing the SM-6, SM-2, ESSM and the SLQ-32 (v)7 against various threat missiles in terms of cost per engagement. For the U.S. Navy missile systems, we took the per-unit cost of each specific missile, multiplied by the *Pk* for the *R*. This number would be added each time an engagement occurs, for example, if one engagement had a *R* of $2 million, the second engagement would have a *R* of $4 million. This is specific to the SM-6, SM-2, and ESSM systems.

For the SLQ-32 system, because there is no “reload” cost associated with the system, only a one-time installment cost, the *R* from each engagement is subtracted from the total cost of the system. For example, if the *R* of one engagement with SLQ-32 (v)7 is $2 million, and the total cost was $60 million, the left-over cost would be $58 million. However, as the number of engagements with SLQ-32 (v)7 increases, the price per engagement decreases drastically. The cost of the first engagement may be $40,000,000 on average, but after 10 engagements the cost per engagement is below $800,000 and decreases exponentially from there. For comparison, after 10 engagements with a missile with a cost per engagement of $2,000,000 your 11th engagement would make your total cost $22,000,000, assuming that every previous engagement was conducted with the same missile.

For comparison between missiles and the SLQ-32 (v)7 system, we subtracted the realized value of each missile from the unit cost per missile. This leaves us with the effective "cost per shot" per missile use. For the SLQ-32 (v)7 system, we applied the *Pk* value to each engagement utilizing the system. Because the SLQ-32 (v)7 is a single time cost system, the more you use it, the more value you realize. If you pay $60,000,000 for the system, and then only use it once, your cost per use is nearly $41,000,000 (on average), but as you use it more, the cost per use decreases.

(1) YJ-83

When comparing the YJ-83 to ship self-defense systems utilizing the *Pk* modifiers, we can extrapolate the value equivalency of engagements for SLQ-32 (v)7 with the missiles. This equivalency is approximately 10 engagements for ESSM, 11 for SM-2, and 12 for SM-6. In other words, it would take those numbers of engagements with the SLQ-32 (v)7 for the cost per engagement to be cheaper than using a self-defense missile. This is displayed via graphical form in Figure 5, with the cost per engagement (cumulative) on the Y-axis in $USD, and the number of engagements on the X-axis, with the same color legend as the previous figures in this study.

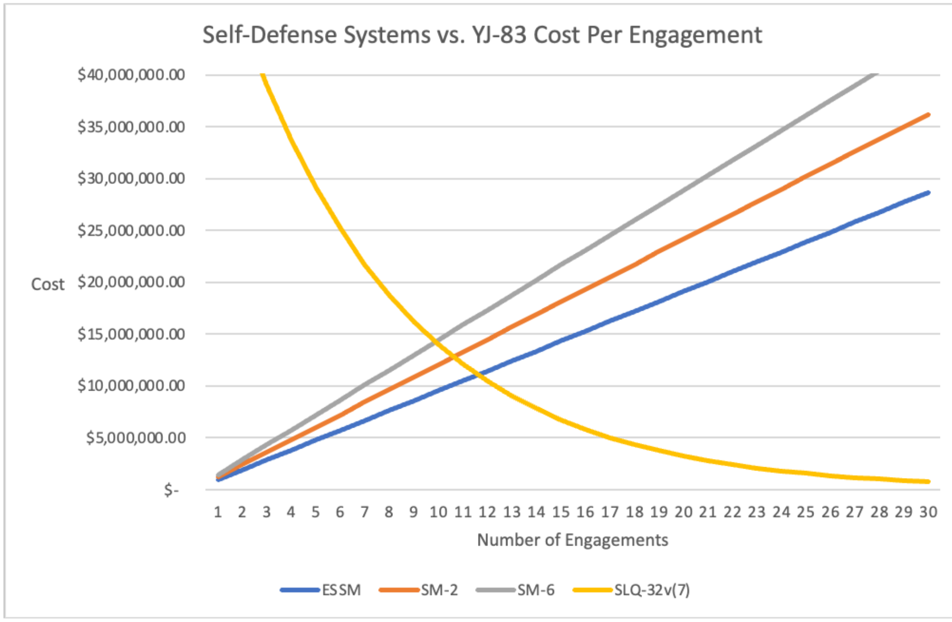

Figure 5. YJ-83 Cost per Engagement.

(2) KH-35

Using the same methods from the graph above, we can extrapolate the following graphs concerning costs per engagement for all threat missiles, as shown in Figure 6. After 5 engagements with the SM-6, or 6 for an SM-2 or ESSM, the SLQ-32 reaches equivalency.

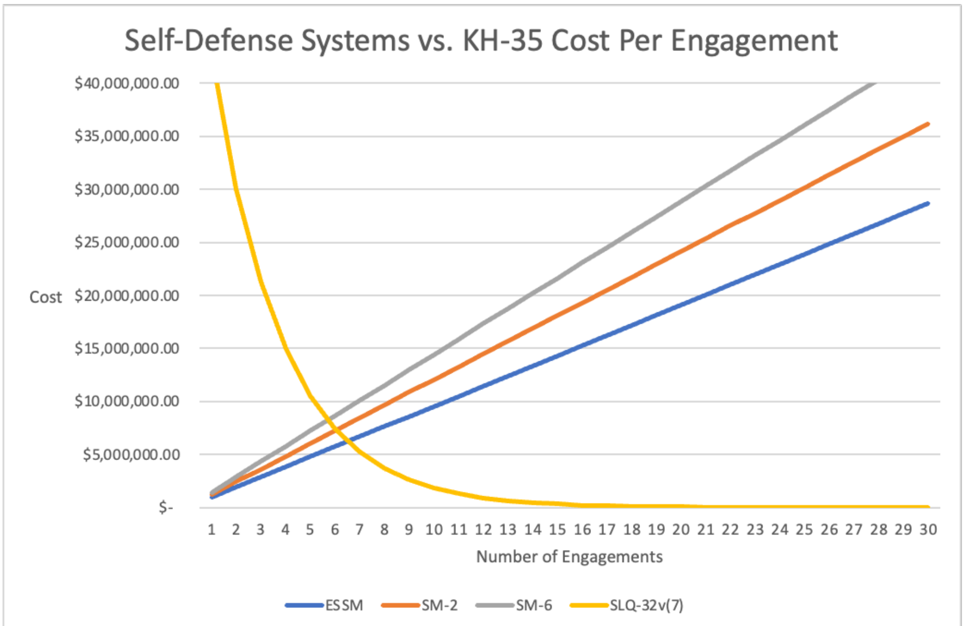

Figure 6. KH-35 Cost per Engagement.

(3) SS-N-22

For the SS-N-22, after 5 engagements with the SM-6, 5 with an SM-2 or 6 with an ESSM, the SLQ-32 reaches equivalency, as shown in Figure 7.

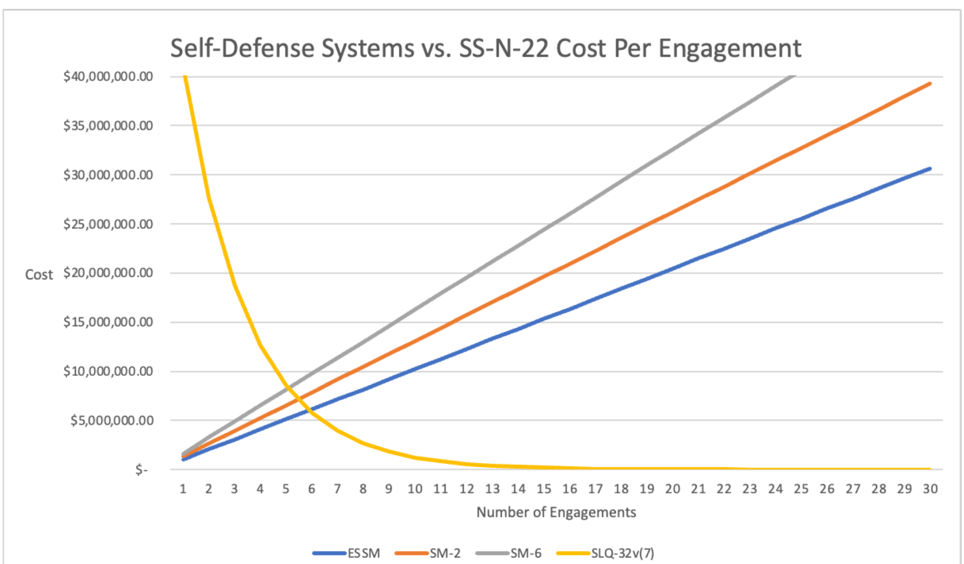

Figure 7. SS-N-22 Cost per Engagement.

(4) SS-N-27

For the SS-N-27, after 4 engagements with the SM-6, 4 with an SM-2 or 5 with an ESSM, the SLQ-32 reaches equivalency, as shown in Figure 8.

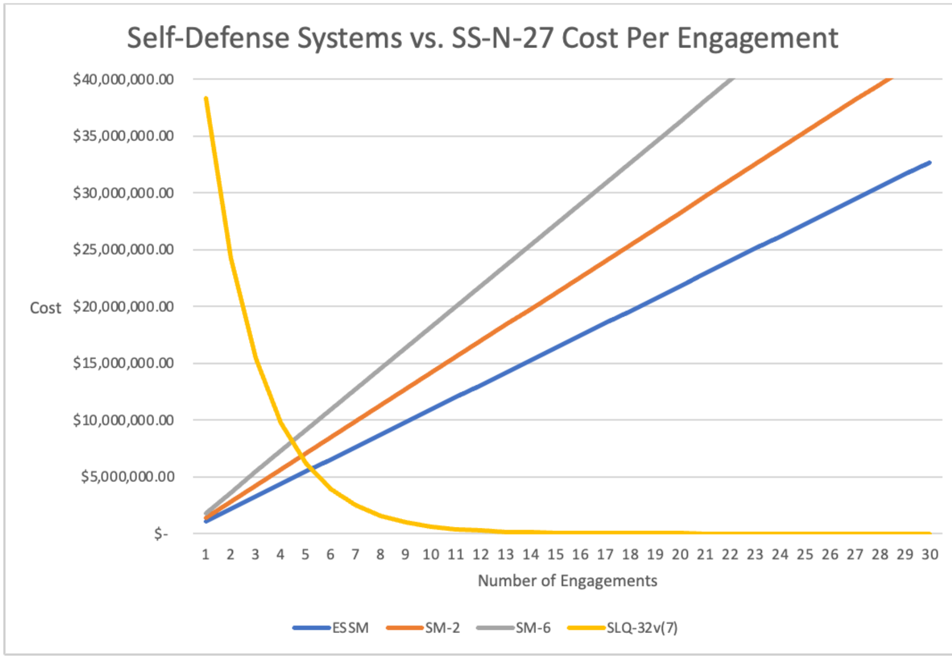

Figure 8. SS-N-27 Cost per Engagement.

(5) YJ-12

For the YJ-12, after 4 engagements with the SM-6, 4 with an SM-2 or 5 with an ESSM, the SLQ-32 reaches equivalency, as shown in Figure 9.

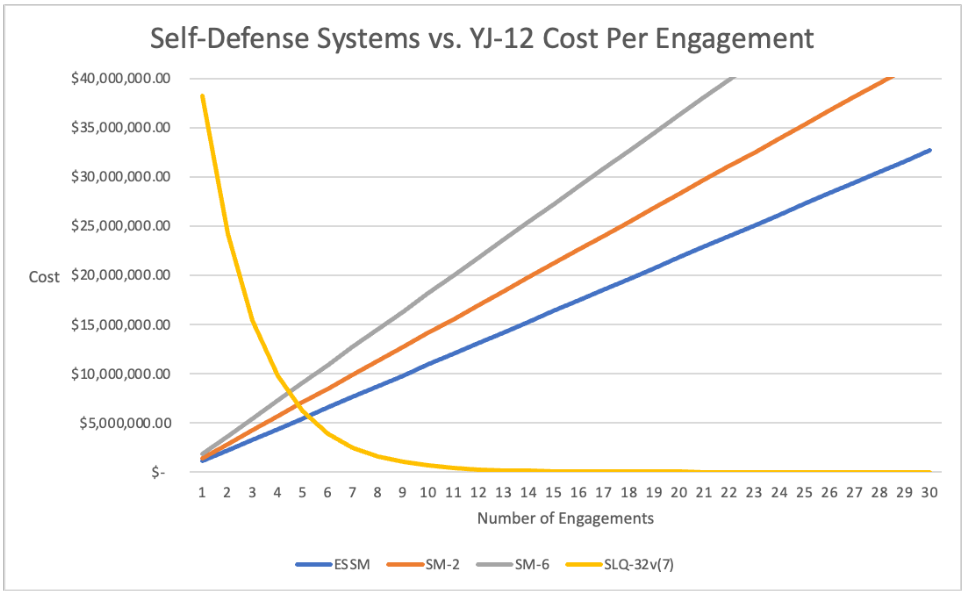

Figure 9. YJ-12 Cost per Engagement.

(6) SS-N-33

For the SS-N-33, after 3 engagements with the SM-6, 4 with an SM-2 or 4 with an ESSM, the SLQ-32 reaches equivalency, as shown in Figure 10.

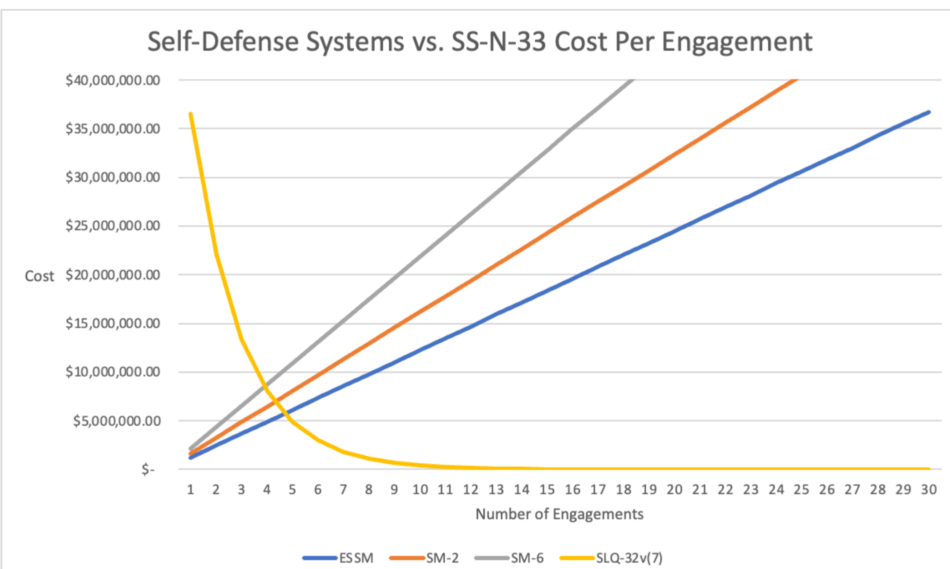

Figure 10. SS-N-33 Cost per Engagement.

(7) YJ-21

For the YJ-21, after 3 engagements with the SM-6, 4 with an SM-2 or 4 with an ESSM, the SLQ-32 reaches equivalency, as shown in Figure 11.

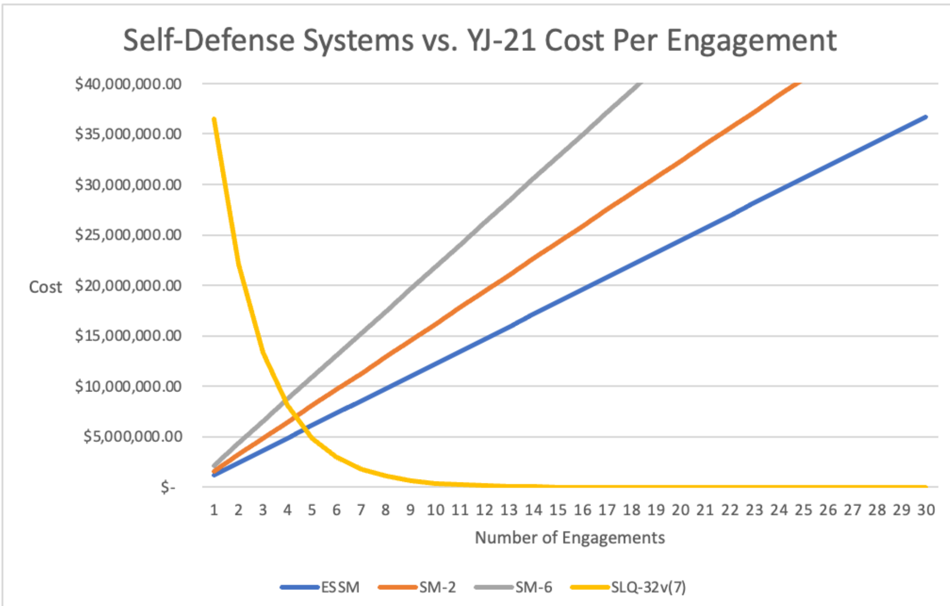

Figure 11. YJ-21 Cost per Engagement.

As outlined in Table 2, the realized value per engagement remains linear for ESSM, SM-2, and SM-6 while increasing exponentially for SLQ-32 (v)7. Since the actual cost per engagement for the missiles is constant, the total cost shows a linear cost growth. Due to the upfront cost of the SLQ-32 (v)7, the realized value is subtracted from the cost, therefore exponentially decreasing the actual cost per engagement.

Table 2. Average Realized Value and Actual Cost per Engagement Comparison.

Value	SM-6	SM-2	ESSM	SLQ-32 (v)7
Unit Cost	$ 5,150,000	$ 3,260,000	$ 2,300,000	$ 60,416,000
Realized Value per Engagement	$ 3,363,671	$ 1,863,090	$ 1,220,380	Varies per Engagement*
Actual Cost per Engagement	$ 1,786,329	$ 1,396,910	$ 1,079,620	Varies per Engagement**

* As the number of engagements increases, the realized value per engagement also increases, asymptoticly approaching the original unit cost as shown in Figure 12.

** As the number of engagements increases, the actual cost per engagement decreases asymptoticly to zero as shown in Figure 13.

As shown in Figure 12, the *R*, or Realized value of SLQ-32 (v)7 starts at zero, when the system has not been used. However, as the system is used to defeat incoming threat missiles, the *R* rapidly approaches the initial cost of installation of the system. Some notable intercept points on this chart are that after two, three, four and six engagements with the system, 60%, 70%, 80% and 90% of the initial unit cost is accounted for in the realized value (respectively).

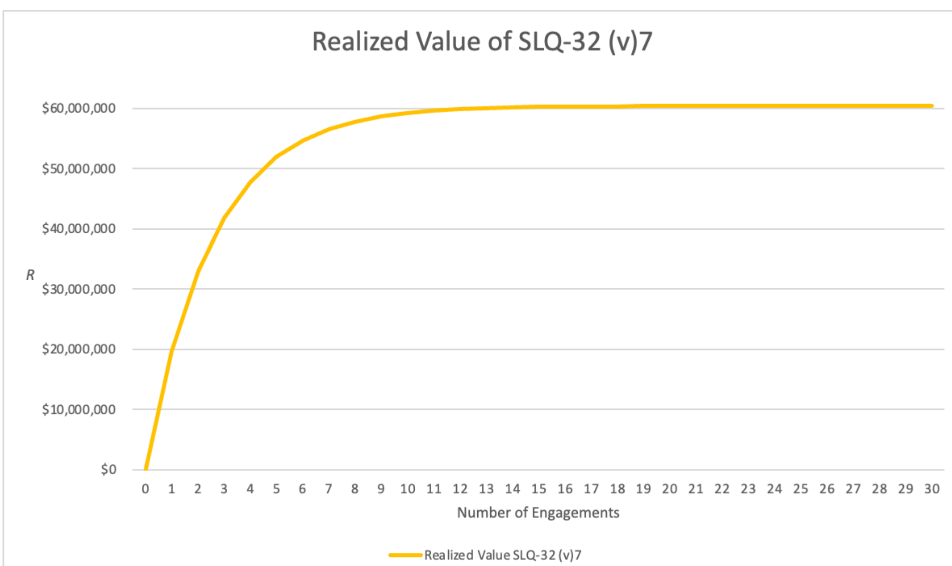

Figure 12. Realized Value.

As shown in Figure 13, when comparing an average *Pk* across all threat missiles per ship self-defense system, after a certain number of engagements, the SLQ-32 (v)7 is the lower cost option compared to all missile options. After 4 engagements with an SM-6, 5 engagements with an SM-2 and 6 engagements with an ESSM, the SLQ-32 is the lower cost option. This means that while the SLQ-32 (v)7 is an extremely effective system, in both weapon system effectiveness, and cost effectiveness, the value of single use missiles should not be overlooked. Its primary benefit is against high-capability supersonic or hypersonic missiles, in which the cumulative cost per engagement can rapidly climb when using self-defense missiles. The more times the SLQ-32 (v)7 is utilized, the more cost effective it becomes.

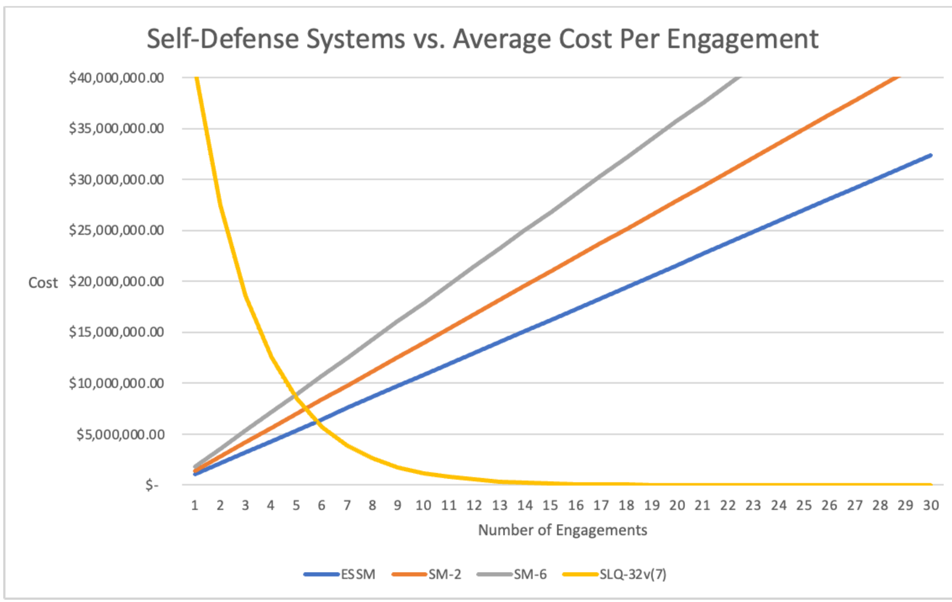

Figure 13. Average Cost per Engagement.

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V. CONCLUSION

With new technologies emerging daily that affect the relative warfighting efficiency of existing ship classes and designs, it is more crucial than ever to develop and employ cost effective systems that will protect our Sailors at sea. With a limited amount of money available, it is necessary for the Navy to prioritize the most cost-effective systems, without losing capabilities for self-defense. This research has been focused on the cost effectiveness of missile self-defense systems and electronic warfare self-defense systems for naval surface units. These hard-kill and soft-kill tactics have been compared against each other and have been correlated into an average cost per engagement as described in the previous chapter. We understand that redundancy with self-defense systems cannot be overlooked. Self-defense missiles cannot and will not become obsolete just because an electronic system is more cost effective. To ensure we protect the Sailors onboard our ships, self-defense missiles will always be utilized.

However, the SLQ-32 (v)7's cost effectiveness cannot be overlooked. While this is an initially cost prohibitive system, the money spent will be realized after a few engagements, with no reload cost associated. We recommend that future research be conducted to determine the optimal weapons loadouts based on the threat area for surface combatants. It is our hope that this research will lead to the possibility of more offensively capable missiles being included in the optimal loadouts, as the need for a larger number of self-defense missiles will be dramatically decreased due to the effectiveness of the SLQ-32 (v)7 electronic attack capability. This technology can protect our fleet and Sailors at a fraction of the cost of traditional hard-kill missile tactics. Even one SLQ-32 (v)7 installed on a surface combatant with a Carrier Strike Group would have the ability to drastically increase the self-defense capabilities of the entire force. With the combination of future research on weapons loadouts and the installation of the (v)7 system onboard new surface units, the surface navy could have better mission specific loadouts, with more distributed lethality, centered around offensive capabilities vice using the limited VLS cells available to them, for defensive purposes.

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