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HYPERVELOCITY PROJECTILE: EFFECTS OF A COMMON MUNITION IN MULTI-MISSION OPERATIONS

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SYSTEMS ENGINEERING CAPSTONE REPORT

HYPERVELOCITY PROJECTILE: EFFECTS OF A COMMON MUNITION IN MULTI-MISSION OPERATIONS

by

Salvatore Licci, Daniel S. Millican, Kayla N. Rhynes, and Tamika M. Richardson

June 2021

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This project explored how a common hypervelocity projectile (HVP) munition could support Anti-Air Warfare (AAW), Anti-Surface Warfare (ASUW), and Naval Surface Fire Support (NSFS) missions by comparing the legacy munitions to the HVP fired from U.S. legacy weapon systems. This study examined the effects of HVPs in mission planning, logistics and use in multiple mission areas. The main objective question for the study was, "Will the use of HVP in legacy weapon systems provide equivalent offensive and defensive capability and improve logistic operations in mission planning?" Using model-based systems engineering and architecting, the project formalized the criteria needed to perform a quantitative systems analysis for the operational, or mission, flexibility inherent in the HVP system. An in-depth model was created that analyzes the performance of multiple variables in the scenario for both the inclusion and exclusion of the HVP munition, which provides information of the overall effectiveness. The results provide evidence of the benefit of incorporating the HVPs into the weapon systems load out. There are benefits in cost, resupply, and munitions available, while maintaining performance. Based upon the results of this modeling, the initial hypothesis was confirmed that the effectiveness of HVP munitions improve the overall mission success, as well as deliver a cost effective alternative to using only legacy weapon systems.

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HYPERVELOCITY PROJECTILE: EFFECTS OF A COMMON MUNITION IN MULTI-MISSION OPERATIONS

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Submitted in partial fulfillment of the
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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

AAW	anti-air warfare
ACE	air combat element
AFP	adaptive force package
AGS	advance gun system
AHS	ammunition handling system
ARG	amphibious ready group
ASBM	anti-ship ballistic missile
ASCM	anti-ship cruise missile
ASROC	anti-submarine rocket
ASUW	anti-surface warfare
BMD	ballistic missile defense
CIWS	close-in weapon system
CONOPS	concept of operations
CSBA	Center for Strategic and Budgetary Assessments
CSG	carrier strike group
DOD	Department of Defense
EFFBD	enhanced function flow block diagram
EMRG	electromagnetic railgun
ESG	expeditionary strike group
ESSM	enhanced Sea Sparrow missile
HVP	hypervelocity projectile
ICBM	intercontinental ballistic missile
IRBM	intermediate-range ballistic missile
LACM	land-attack cruise missile
MEU	Marine expeditionary unit
MOE	measure of effectiveness
MOP	measure of performance
NSFS	naval surface fire support

ONR	Office of Naval Research
PGM	precision-guided munition
SAG	surface action group
SAM	surface-to-air missile
SM	standard missile
SME	subject matter expert
SOI	system of interest
TLAM	Tomahawk land-attack missile
UAV	unmanned aerial vehicles
VLS	vertical launching system

EXECUTIVE SUMMARY

This study examines the effects of using Hypervelocity Projectiles (HVPs) as a common munition in the MK 45–5-inch gun onboard the DDG 51 (Arleigh Burke) and CG (Ticonderoga) class naval ships, and the Advanced Gun System (AGS) 155mm guns onboard the DDG 1000 (Zumwalt) class naval ships in mission planning, operations, and logistics. The HVP is a multi-mission munition that can be used in conjunction with legacy weapon systems.

This thesis explored how HVP munition supports Anti-Surface Warfare (ASUW), Anti-Air Warfare (AAW), and Naval Surface Fire Support (NSFS) missions by comparing the legacy munitions to the HVP fired from U.S. legacy weapon systems. The chemically propelled HVP munition provides multi-mission flexibility allowing the warfighter to leave port with a deeper magazine load-out than with just conventional missiles. The HVP munition improves logistics operations of a Naval Expeditionary force composed of DDG and CG ships by alleviating mission-specific weapons configuration for defensive and offensive missions. Deploying HVP munitions to the fleet gives these ships increased capabilities and offers a more practical and cost-efficient alternative to building or refitting ships with electromagnetic railguns and their associated energy support systems.

For this study, the mission scenario focuses on the employment of DDGs and CGs in a Surface Action Group (SAG) conducting AAW, ASUW and NSFS operations. The specific mission scenario focuses on the Pre-Assault Phase of an Operation to Neutralize a Threat to Navigation Posed by Enemy-Held Island. An Adaptive Force Package (AFP) has been formed to seize control and neutralize threatening offensive capabilities and a small contingent of enemy forces located on strategically important Red Island. The AFP consists of an amphibious ready group (ARG) augmented by a SAG consisting of two DDGs and one CG tasked with defending the ARG, gaining sea control of surrounding waters, and neutralizing threatening shore installations prior to an amphibious assault. An operational model was built using ExtendSim to simulate the pre-assault phase of the operation and allow for systems analysis.

Microsoft Excel was used to create a stochastic model which explores the implementation of HVPs in a defensive or offensive engagement against an adversary that might have weapons superiority. The scenario was modeled as a static version through the range target graph and the stochastic model. These tools were used to give an estimation of number of missiles launched, HVP rounds fired, and a statistical outcome of our scenario. The results from analysis using our ExtendSim model, which were analyzed using Minitab, allowed for the ability to validate the data captured by the stochastic model. This enabled the team to analyze the data based on different statistical graphs and charts software to gather the information needed to calculate the measures of effectiveness (MOEs) and measures of performance (MOPs).

The results for the MOEs and MOPs provides evidence of the benefit of incorporating the HVPs into the weapon system load outs. There are benefits in cost, resupply, munitions available while maintaining performance. Each of these confirmed the initial hypothesis that the effectiveness of HVP munitions improve the overall mission success, as well as deliver a cost-effective alternative to using only legacy weapon systems.

The DDG and CG ship's missiles and guns lethality probability data used to model a defensive scenario was unclassified, therefore the results presented in this thesis will need to be run with classified data to achieve realistic results.

I. INTRODUCTION

A. OVERVIEW

The U.S. Navy's mission "is to maintain, train and equip combat-ready Naval forces capable of winning wars, deterring aggression and maintaining freedom of the seas" (U.S. Navy 2017). To achieve this mission, U.S. Navy ships must be able to support several different mission areas and be able to adapt to an ever-changing mission without warning. To do this, naval ships rely on the use of several munition types to support several mission areas. This study examines the effects of using Hypervelocity Projectiles (HVPs) as a common munition in the MK 45–5-inch gun onboard the DDG 51 (Arleigh Burke) and CG (Ticonderoga) class naval ships, and the Advanced Gun System (AGS) 155mm guns onboard the DDG 1000 (Zumwalt) class naval ships in operations, mission planning, and logistics.

B. PROBLEM STATEMENT

Currently, the U.S. Navy relies on several types of munitions to support both the offensive and defensive weapons systems and mission capabilities. Mission needs drive shipboard munitions load-out (i.e., the type and amount of ammunition) taken aboard prior to getting underway. While at sea, if the mission or threat changes significantly, the ships may have a limited ability to adapt and respond based upon their munitions load out and capacity, at least until they can be resupplied at sea or ashore. The need to determine a weapons load-out prior to getting underway, and the variety of mission-specific munitions that must be considered, constrains warfighting flexibility, capability, and capacity. This study examined the effects of HVPs in mission planning, logistics and use, as a common munition for U.S. Navy legacy weapons systems in Anti-Air Warfare (AAW), Anti-Surface Warfare (ASUW), and in Naval Surface Fire Support (NSFS) mission areas.

C. RESEARCH OBJECTIVE

This study explored how a common HVP munition could support ASUW, AAW, and NSFS missions by comparing the legacy munitions to the HVP fired from U.S. legacy weapon systems. The chemically propelled HVP munition provides multi-mission flexibility that allows the warfighter to leave port with a deeper magazine load-out than with just conventional missiles and without having to choose among mission-specific weapons. Using systems engineering and architecting, the project formalized the criteria needed to perform a quantitative systems analysis for the operational, or mission, flexibility inherent in the HVP system.

The main research objective is to address this study question, which states: "Will the use of HVP in legacy weapon systems provide equivalent offensive and defensive capability and improve logistic operations in mission planning?"

D. SYSTEMS ENGINEERING METHOD

The systems engineering method used for this project consists of three phases. It is depicted in Figure 1. Beginning with the initial research phase, the thesis topic was thoroughly researched to gain a better understanding of the system being analyzed. The capability gaps were identified, a stakeholder analysis was conducted, and the operational concept of the current system was analyzed. The different analyses were used to define the scope of the project. Upon completion of that phase, the system architecture phase began. In this phase, an architecture was developed to guide the design and development of the system through requirements allocation, functional analysis, and trade studies. At the completion of phase two, the system analysis phase began. During phase three, the team conducted a comparative discrete events modeling analysis of the legacy munitions versus a common HVP munition fired from legacy weapon systems. Based upon the results of this modeling, recommendations were then provided.

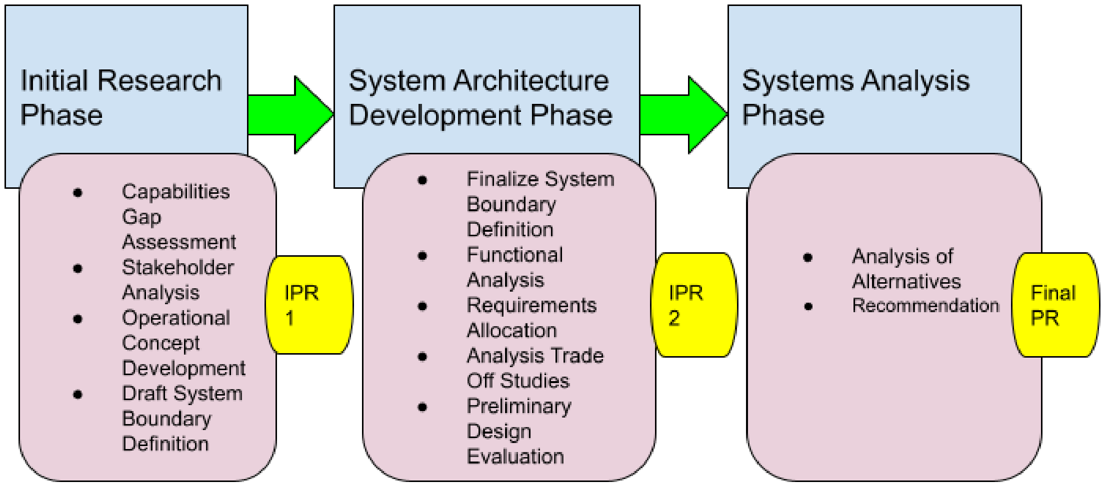

Figure 1. Systems Engineering Method

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II. LITERATURE REVIEW

A. OVERVIEW

Our team compiled a list of research and journal articles that highlight the history and work that has been accomplished on HVPs and the U.S. Navy ships that can employ them. The mission planning and logistics analysis of the potential operational advantages of using an HVP munition load-out aboard U.S. Navy ships required subject matter expert (SME) input and a literary review of unclassified documents. Specifically, this section includes a broad assessment of current capability gaps and an overview of potential ships and weapon systems that could launch the HPVs.

A list of research and journal articles was also compiled on the capabilities of our adversaries. These articles show how the technological advancements, mainly in Russia and China, represent an increased threat from hypersonic weapons.

B. CAPABILITY GAP ANALYSIS

The Center for Strategic and Budgetary Assessments (CSBA) in 2016 conducted a study of the Navy's past and current operational capabilities. The study found today's U.S. naval margin of superiority narrowing in the face of advances being made in weapons technologies by adversaries. As described in greater detail later in this chapter, Russia and China lead in the development and deployment of new weapons, specifically ASCMs and UAVs that "are focused specifically on our vulnerabilities and are increasingly designed from the ground up" (MITRE 2016). These new weapons have greater ranges, are more precise, and are more lethal. Russia is also "modernizing" military assets while China is rapidly expanding its ability to contest U.S. forward naval presence and maritime superiority (Vergun 2020). "As many powers gain the ability to conduct precision strike operations, it will become increasingly difficult and costly for the United States to carry out a forcible entry into a defended region" (Clark and Sloman 2016). According to the CSBA study:

> Amphibious ships and expeditionary troops lack the defensive capacity to protect themselves against the large number of adversary weapons they

> would face given their need to get close to an enemy's shores before offloading Marines. Amphibious forces will have difficulty reducing their vulnerability by conducting landings from farther away, because almost all Marine equipment is too heavy to be lifted by shipboard aircraft, and current surface connectors cannot safely conduct a transit long enough to grant amphibious ships the standoff they need. Although troops could be moved longer distances by air for small raids, the Marine Expeditionary Unit (MEU) Air Combat Element (ACE) is too small to provide enough long-range fires to degrade ground defenses and provide close air support troops conducting the raid. The Navy will have to address these and other challenges to continue exploiting the sea as a maneuver space for offensive operations ashore. (Clark Sloman 2016, iii)

The Navy faces two primary concerns in defending against ASCMs or UAVs: "limited depth of magazine and unfavorable cost exchange ratios" (O'Rourke 2020). The first issue refers to the amount of munitions that a DDG or CG can carry for both defensive and offensive purposes. All three classes of ships (Arleigh Burke DDG, Zumwalt DDG, Ticonderoga CG) rely on surface-to-air missiles (SAMs) and close-in weapon system (CIWS) guns for defense against threats, and either the MK 45 or AGS and tomahawk land attack missiles (TLAMs) for offensive strike. Both the SAMs and TLAMs utilize the MK 41 VLS cells. This degree of commonality allows for limited degree operational flexibility (i.e., a more defensive or offensive posture, or a balance between each posture with the limiting factor being the magazine limit of each ship). Should the mission change while underway and the munition load-out not support the new mission needs, a resupply at sea or in port would be required, delaying a response, or causing a temporary withdrawal from the Area of Operations.

The second issue is the cost of a SAM to shoot down an enemy manned aircraft, ASCM, or UAV. Currently, this can cost the Navy "several hundred thousand dollars per [missile]… to a few million dollars per missile" (O'Rourke 2020). This cost is considered acceptable in situations where only a few SAMs are needed to save the lives of Navy sailors and Naval assets. However, in situations where our adversary can launch swarms of attack aircraft, ASCMs, or UAVs, the cost approaches a prohibitive cost exchange ratio. Both issues will require operational changes as well as new capabilities to maintain the Navy's maritime superiority.

C. HVP WEAPON SYSTEM

1. Background and History of the HVP

In 2005 the Navy started development of a new weapon system that utilized "electricity rather than chemical propellants (i.e., gunpowder charges) to fire projectiles" (O'Rourke 2020). This weapon system was the electromagnetic railgun (EMRG) which can launch a projectile at speeds greater than Mach 5 at sea level. The original intent of the EMRG was to support U.S. Marines with NSFS missions. However, through development it was determined that the EMRG could also be used in defensive capacities against missiles and enemy aircraft. This is due to the HVPs low drag aerodynamic design which enables high velocity, and thus a decreased time-to-target. "The high velocity compact design relieves the need for a rocket motor to extend gun range. Firing smaller, more accurate rounds improve collateral damage requirements and provides potential for deeper magazines and improved shipboard safety" (Defense Systems Information Analysis Center 2015). The HVP can be stored by the hundreds in a Navy surface ship's weapon magazine.

2. Integration into Current Weapon Systems

During the development of the EMRG it was also determined that the projectiles could be physically modified to be fired from the MK 45 – 5-inch (127mm) gun as well as the AGS 155mm gun using traditional chemical charges. When fired from these guns, the projectile is not capable of reaching the speeds and distances the EMRG-fired rounds would achieve, but they are fast and accurate enough to support a "gun-based [anti-ship cruise missile] ASCM defense" as well as anti-air defense system (O'Rourke 2020). This type of defense system would allow for the Vertical Launch System (VLS) missile cells to be configured in a more offensive posture which allows for longer staying time in an Area of Operations. HVPs are also cheaper than the surface to air missiles (SAMs) used in defensive engagements with an estimated cost of $85K per round (O'Rourke 2020).

3. Operational Analysis

In 2018, the Navy conducted a Fleet experiment aboard the guided-missile destroyer USS *Dewey*. The *Dewey* fired 20 HVP projectiles during the 2018 Rim of the

Pacific Exercise, the first known U.S. Navy use of the new HVP projectiles at sea. "The test, conducted by the Navy and the Pentagon's Strategic Capabilities Office as part of the Rim of the Pacific (RIMPAC) 2018 international exercise, was part of a series of studies to prove the Navy could turn the more than 40-year-old deck gun design into an effective and low-cost weapon against cruise missiles and larger unmanned aerial vehicles" (LaGrone 2019). Perhaps the greatest advantage the chemically fired HVP has over the railgun variant is that there are already more than a hundred potential legacy weapon systems in service capable of firing the HVP munition.

> The Navy has approximately 120 Mk. 45 guns in operation, two on each *Ticonderoga*-class guided missile cruiser and one each on the *Arleigh Burke*-class guided missile destroyers. Deploying HVP munitions to the US Navy fleet may give these ships improved abilities and, at least in the near term, offer a more practical and cost-efficient alternative to building or refitting ships with electromagnetic railguns and their associated energy support systems. The technology is also available for larger 155-millimeter projectiles, potentially giving the two Advanced Gun Systems on the *Zumwalt*-class warships ammunition for engaging enemy targets. (Mizokami 2020)

D. NAVAL SHIPS

The U.S. Navy annually presents to Congress a long-range plan for construction of naval vessels, generally referred to as the 30 Year Shipbuilding Plan. Individually, these ships support specific naval mission areas, including military operations, protection of commercial ships, and even humanitarian support. However, it is only with the combined strength of the fleet that the Navy can meet and carry out its mission successfully.

1. Surface Ships

The surface ships described below were identified as being able to employ the HVP munition in their legacy weapon system(s) or as being a part of the Adaptive Force Package (AFP) that the team models for this project.

a. DDG Ships

The Navy began procuring Arleigh Burke class destroyers starting with DDG 51 in FY1985. An example of an Arleigh Burke class destroyer is shown in Figure 2. Since then, a total of 85 ships have been procured through FY2020, including three in FY2020 (Larter 2020). The DDG 51 class cruisers are equipped with the AEGIS combat system, which is an integrated system "that was designed as a total weapon system, from detection to kill" (U.S. Navy 2019). Currently, there are four variants of the DDG 51 class destroyers which are called "Flights" (U.S. Navy 2019). The older Flights of ships are currently being modernized to "ensure the DDG 51 class will remain mission relevance and remain an integral part of the Navy's Sea Power 21 Plan" (U.S. Navy 2019).

Photo credit: Petty Officer 2nd Class Natalie Byers;
https://www.navy.mil/Resources/Photo-Gallery/igphoto/2002516768/

Figure 2. Arleigh Burke Class Destroyer

Since the mid-1990s the Navy has been developing a new class of destroyer, the DDG 1000 (Zumwalt), shown in Figure 3. Due to "cost overruns and the slow maturation of critical technologies" the Navy has since stopped all production efforts for this class of destroyer in support of building new Arleigh Burke class destroyers (Larter 2020). To date there are two Zumwalt class ships in service, neither are forward deployed, and there is one under construction.

Photo credit: U.S. Navy; https://www.public.navy.mil/surfor/ddg1000/Pages/USS-Zumwalt-arrives-in-British-Columbia.aspx.

Figure 3. Zumwalt Class Destroyer

b. CG Ships

The cruisers class of warships, Ticonderoga Class Cruiser shown in Figure 4, are in the process of being modernized in order to work in conjunction with the AEGIS combat system. These updates are happening in order to confirm that the AEGIS Cruisers last through the estimated thirty-five-year service life. These new and improves ships are projected to be more cost effective to operate. The service lives of these ships are extended to operate in the fleet through 2030. "USS *Anzio* (CG-68) and USS *Cape St. George* (CG-71) begins modernization in FY 2017. The CG 47 Class is an important component of the AEGIS Ballistic Missile Defense (BMD) System, where it - together with Arleigh Burke Class Missile Destroyers (DDG 51) - patrols the oceans to detect and track ballistic missiles of all ranges, including Intercontinental Ballistic Missiles" (Forecast International 2021).

Photo credit: MC3 Sawyer Haskins; https://www.navy.mil/Resources/Photo-Gallery/igphoto/2002513367/

Figure 4. Ticonderoga Class Missile Cruiser

c. Amphibious Assault Ship LHD

Amphibious Assault Ships, shown in Figure 5, provide “a means of ship-to-shore movement” and are used to support the Marine Corps in their operations (U.S. Navy 2019). They can launch rotary wing aircraft and aircraft that are capable of Vertical/Short Take-off and Landing, such as the AV-8B and the F-35. They do not have offensive weapon capability but do have defensive weapons that can be used against enemy aircraft and ASCM. For the purposes of this project, those include two rolling airframe missile launchers, two NATO sea sparrow launchers and three Phalanx close-in weapon support guns.

Photo credit: Petty Officer 2nd Class Jacob Bergh; https://www.navy.mil/Resources/Photo-Gallery/igphoto/2002557647/

Figure 5. Amphibious Assault Ship LHD

2. Ship Weapon Systems

a. DDG Weapon Systems

The Arleigh Burke and Zumwalt class destroyers are equipped with several offensive and defensive weapons to support ASUW, AAW and NSFS multi-mission operations, see Table 1.

Table 1. DDG Weapon Systems. Adapted from BAE Systems (2016); U.S. Navy (2017, 2019).

Ship Class	**Weapon**	**Rate of Fire**	**Range**	**Speed**
Arleigh Burke	MK 45 – 5-inch	16-20 rounds/minute	13 NM	UKN
Arleigh Burke	MK 41 Vertical Launch Systems (96 cells)	NA	NA	NA
Both	Close-In Weapon System	3000-4500 rounds/ minute	UKN	UKN
Zumwalt	AGS 155mm	10 rounds/minute	83 NM	UKN
Zumwalt	Vertical Launch Systems (80 cells)	NA	NA	NA
Both	Tomahawk Missile	UKN	700-900 NM	550 MPH
Both	Standard Missile	UKN	90-200 NM	UKN
Both	Evolved Sea Sparrow Missile	UKN	Classified	Classified

b. CG Weapon Systems

The Ticonderoga class destroyers are equipped with several offensive and defensive weapons to support AAW, ASUW, and NSFS multi-mission operations, see Table 2.

Table 2. CG Weapon Systems. Adapted from U.S. Navy (2017; 2019).

Ship Class	**Weapon**	**Rate of Fire**	**Range**	**Speed**
Ticonderoga	(2) MK 45 – 5-inch	16-20 rounds/minute	13 NM	UKN
Ticonderoga	MK 41 VLS (122) cells	N/A	N/A	N/A
Ticonderoga	MK-15 Phalanx 22mm	3000-4500 rounds/minute	UKN	UKN
Ticonderoga	Tomahawk Missile	UKN	700-900 NM	550 MPH
Ticonderoga	Standard Missile	UKN	90-200 NM	UKN
Ticonderoga	Evolved Sea Sparrow Missile	UKN	Classified	Classified

c. MK 45 5-inch Gun

The 5-inch 62-caliber MK45 Mod 4 naval gun, shown in Figure 6, is available in all DDGs and CGs and is employed against surface AAW, ASUW, and NSFS targets. To extend the lethality of the Mk 45 gun, a fully automated Ammunition Handling System (AHS) is paired with the gun. The AHS provide an uninterrupted supply of an entire automated magazine while the gun is firing. "The gun mount includes a 20 round automatic loader drum. The gun's maximum firing rate is 16-20 rounds from the loader drum per minute" (Naval Sea Systems Command 2019). The AHS is also designed to handle HVP extend range ammunition. (BAE Systems 2016).

Photo credit: Petty Officer 3rd Class Maria Llanos, https://www.navy.mil/Resources/Photo-Gallery/igphoto/2002551346/.

Figure 6. MK-45 5-Inch Gun

d. MK 41 VLS

According to Lockheed Martin, the developer of the VLS cells, "the MK 41 ship based VLS is a modular below-the-deck system capable of storing and launching Standard Missiles (SM) which is a key air defense armament of the AEGIS Weapon System" (Fiore 2014). The VLS munition load out is depicted in Figure 7. The MK 41 employed in the CGs are designed with eight forward and aft modules, for a total of 122 cells, and the DDGs in carry 96 cells. The MK 41 system can launch the largest Standard Missiles (SMs). For example, "such as those used to support sea-based, mid-course BMD, and long-range tactical strike missiles, such as the Tomahawk. For air defense, the U.S. fleet is equipped with a Mk 41 VLS designed to support the launch of SMs. This capability continues to be upgraded, including the ability to launch new, improved variants of the SM and the Enhanced Sea Sparrow Missile (ESSM)" (Fiore 2019).

The VLS and the MK 45-gun systems interface with the AEGIS Combat System. "The AEGIS combat system uses powerful computers and radar to track and guide weapons to destroy enemy targets" (Lockheed Martin, 2021). The AEGIS is a U.S. integrated naval weapon system that is compatible with multiple weapon systems. "The VLS was designed as an unmanned missile launcher under the operational control of the missiles it launches as part of either an integrated federated combat system architecture" (Schneider Jr. 1987). To implement a "fast response to multiple diverse threats, the MK 41 VLS can simultaneously prepare one missile in each half of a launcher module and can also fire a four-missile salvo of ESSMs from one canister" (Fiore 2014).

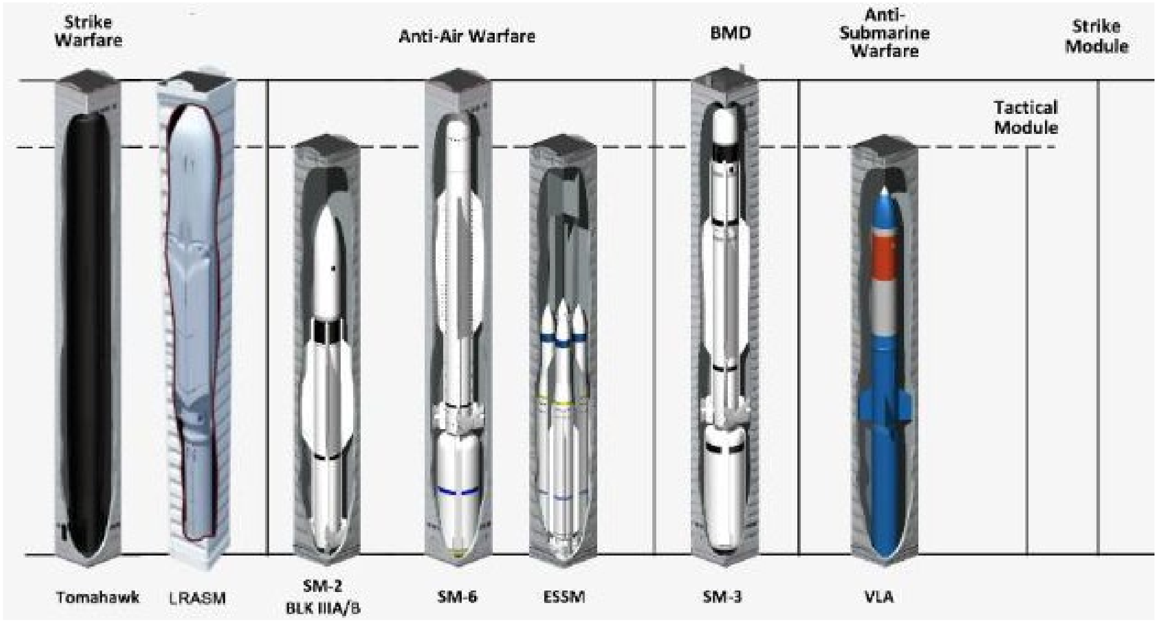

Photo credit: Lockheed Martin; https://www.lockheedmartin.com/content/dam/lockheed-martin/rms/documents/naval-launchers-and-munitions/MK41-VLS-product-card.pdf

Figure 7. VLS Munition Load out Configuration

E. ADVERSARY ANALYSIS

According to the report "Winning the Salvo Competition" that the Center for Strategic and Budgetary Assessments (CSBA) wrote in 2016, the DOD has spent billions of dollars developing and buying a multitude of weapons and systems to counteract guided missile threats. "Missile defense capabilities still lack the capacity to counter large salvos of ballistic missiles, cruise missiles, and other precision-guided munitions (PGMs) that can now be launched by America's enemies" (Liang 2016). Through projects like this one, these scenarios can be modeled for prospective battles against adversaries such as Russia, China and Iran using offensive and defensive salvo equations.

1. Russia

Russian ships are capable of carrying a range of eight to twenty anti-ship missiles. In addition, they typically carry anywhere from fifty to over two hundred surface to air missiles depending on the ship. Russia has made significant advances in their weapons systems, some of them comparable to U.S. capabilities.

2. China

China has increased their capabilities and ramped up their production in recent years. Their capabilities have drastically improved. "China has deployed one of the world's most sophisticated arsenals of ASCMs and land-attack cruise missiles (LACMs) that can be launched from mobile ground launchers, aircraft, ships, and submarines. China's ASCMs and LACMs are complemented by multiple types of ballistic missiles that can reach America's Western Pacific bases and ships at sea" (Clark and Gunzinger 2016). Updated variants of these weaponries include maneuverable reentry vehicles. It is possible that future versions could be equipped with hypersonic glide vehicles

China's navy is equipped with weapons comparable to those employed in the U.S. Navy. Chinese ships typically carry more surface to air missiles than surface to surface missiles. They have the capability of carrying fifty or more surface to air missiles and roughly eight to sixteen anti-ship missiles. After the collapse of the Soviet Union, China was able to procure multiple missile systems and technical assistance to improve their capabilities.

3. Other Adversaries

North Korea and Iran also have weapons capabilities that represent security threats. According to a report prepared for the Center for Strategic and International Studies (Cordesman et al. 2014) Iran has been developing anti-ship missiles that incorporate GPS guidance system making them more precise and can be fired from small ships which are a harder target to hit in retaliation.

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III. SYSTEM ARCHITECTURE DEVELOPMENT

A. STAKEHOLDERS

1. Needs Analysis

There is clearly a need to address the threat of near-peer adversaries using modern, long range weapons systems against friendly maritime targets. The resulting capabilities gap is potentially addressed by HVPs used in multi-mission roles. The HVP capability of being fired from legacy weapon systems may simplify mission planning, improve logistics, increase flexibility for ad hoc mission response, and help mitigate emerging threats.

2. Stakeholder Analysis

The stakeholder analysis table includes four stakeholders that were taken into consideration for this study. The primary stakeholder is the Office of Naval Research (ONR). Additional stakeholders and beneficiaries that were identified are listed in Table 3.

Table 3. Stakeholder Analysis

STAKEHOLDER	TYPE	PRIORITY	NEEDS	GAINS FROM PROJECT
Office of Naval Research (Sponsor)	Primary	1	A Weapon System that: Increases Warfighting Capacity Increases Warfighting Flexibility Increases Warfighting Capability	Answers to the studies objective questions. Will using HVPs: Provide equivalent offensive & defensive capability Improve logistic operations and mission planning
Office of the Chief of Naval Operations	Secondary	1	Same as Primary Stakeholder	Same as Primary Stakeholder
Naval Sea Systems Command (NAVSEA)	Secondary	1	Same as Primary Stakeholder	Same as Primary Stakeholder
BAE Systems	Secondary	2	Not Identified	Potential reason to integrate into other legacy weapons systems

The stakeholder type was based on the level of involvement in the project. The Office of Naval Research is the primary stakeholder because they are funding this project and provided direct input. The other stakeholders are secondary or beneficiaries to this study because they provided no direct input but could benefit from the study.

Using HVPs in legacy weapon systems to provide equivalent offensive and defensive capability and improved logistic operations and mission planning are functions that relate back to the needs of the primary stakeholder. In addition, a model of the HVPs performance will provide the stakeholders with something that can be built upon for further research purposes.

B. OPERATIONAL CONCEPT

The operational concept, shown in Figure 8, includes the operational space and mission scenarios in which the HVP weapons system will operate. The specific mission scenario focuses on the Pre-Assault Phase of an Operation to Neutralize a Threat to Navigation Posed by Enemy-Held Island. An Adaptive Force Package (AFP) has been formed to seize control and neutralize threatening offensive capabilities and a small contingent of enemy forces located on strategically important Red Island. The AFP will consist of an ARG augmented by a Surface Action Group of two DDGs and one CG tasked with defending the ARG, gaining sea control of surrounding waters, and neutralizing threatening shore installations prior to an amphibious assault. Intelligence reports indicate that the island has been fortified with enemy strike aircraft, SAMs, Coastal Defense Missiles, and remotely piloted vehicles (RPVs), and is regularly patrolled by enemy surface ships equipped with ASCMs. Our scenario will focus on a SAG (DDGs and a CG) supporting an ARG in what ADM Swift referred to as an “upgunned ESG” (LaGrone 2016). We use ExtendSim to simulate the pre-assault phase of the operation to include in Preparation of the Battlespace (both defensive and offensive operations by the DDGs and CGs) to gain sea control of the assault lanes and staging areas prior to the landing.

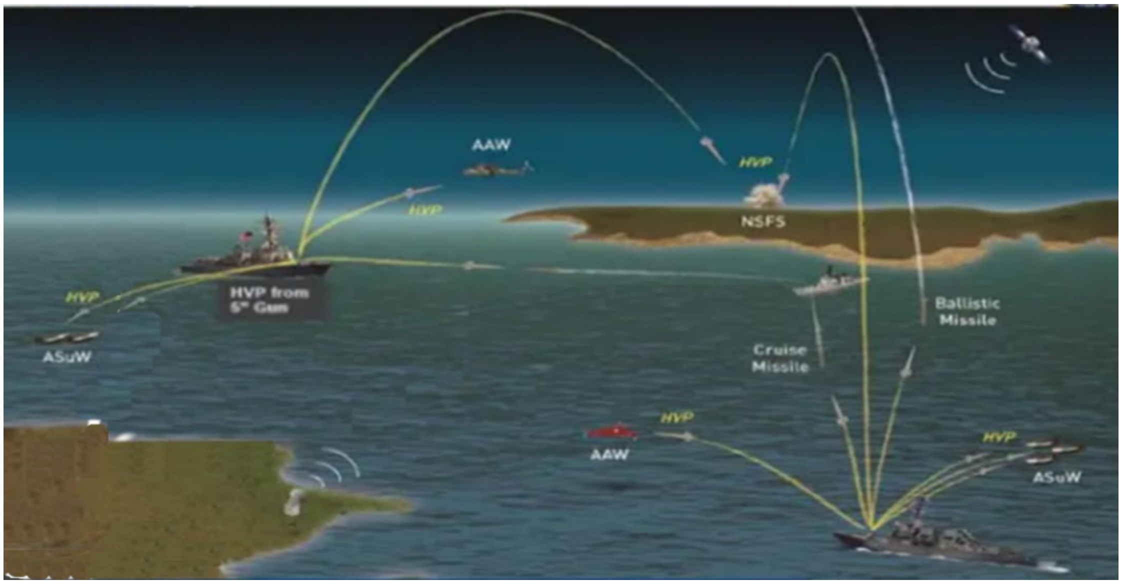

Figure 8. Mission Scenario. Adapted from O'Rourke (2020).

C. FUNCTIONAL DEVELOPMENT

1. Functional Analysis

The functional analysis gives an overview of the system's functions and identifies requirements. A context diagram addresses the relationship between the HVP weapon system and external systems. Beginning with the left-hand side and moving clockwise in Figure 9, it is expected that the increased warfighting capacity and flexibility of the SOS will increase warfighting readiness and enable the Combatant Commander (COCOM) to more readily respond to dynamic mission changes. The HVP weapon system would serve a pivotal role aboard Arleigh Burke, Zumwalt and Ticonderoga class ships by reducing costs associated with legacy weapon systems, simplifying and reducing vulnerabilities associated with resupply and munitions load out, increasing magazine depth, and enhancing multi-mission flexibility.

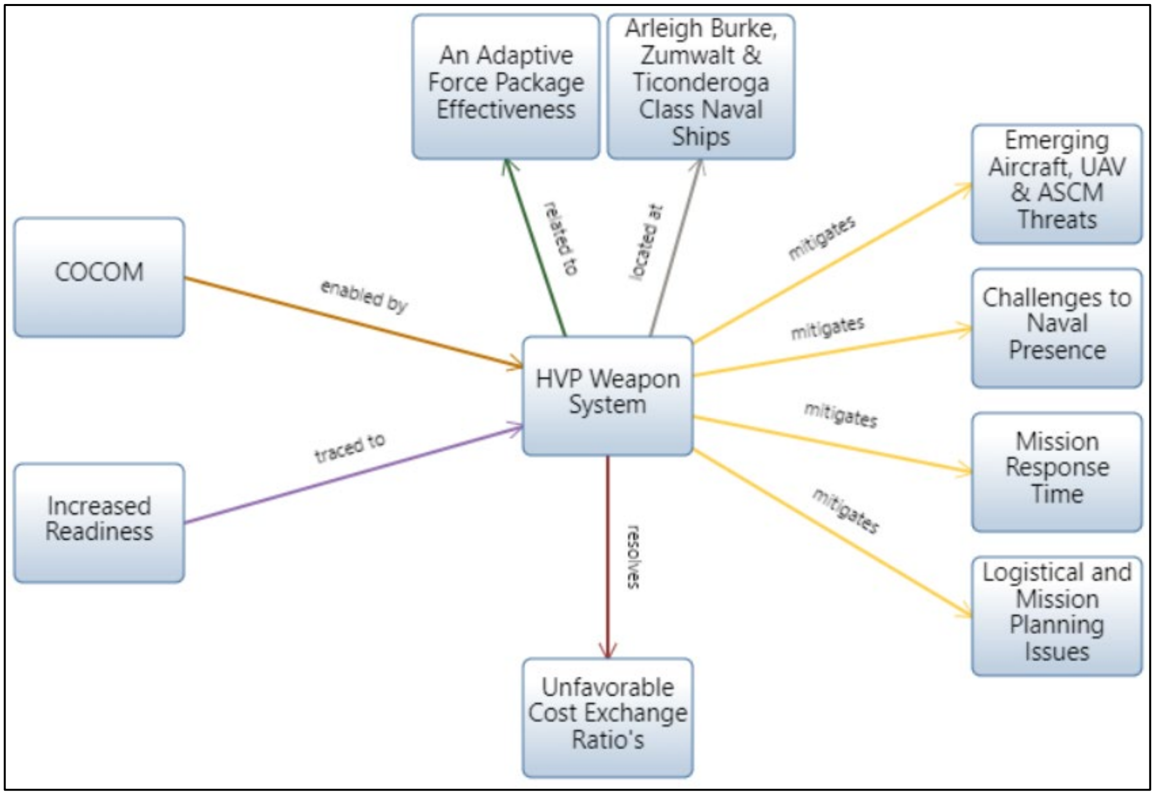

Figure 9. HVP Weapon System Context Diagram

2. Functional Hierarchy

The functional hierarchy, Figure 10, begins with the highest level function that is relative to this project, F.1 Conduct Mission. The Conduct Mission function can be broken down further into the tactical/operational functions of Protect and Escort Asset, AAW, ASUW and NSFS missions.

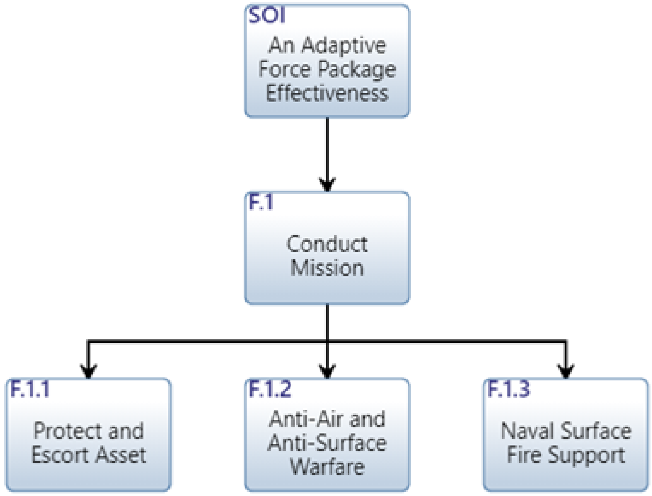

Figure 10. Functional Hierarchy

3. Enhanced Function Flow Block Diagrams (EFFBD)

The EFFBDs are the process and control diagrams derived from the functional hierarchy. These provide a more in depth understanding of how each sub-function operates within the system boundaries and the project model. This begins with Protect and Escort Asset function detecting, tracking, and then intercepting threats, Figure 11. For the purposes of this project, it is assumed to prioritize all threats in the mission scenarios cooperative engagement.

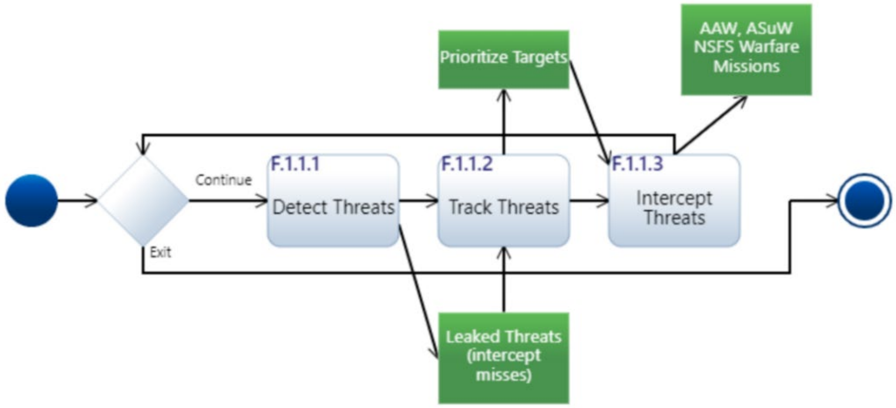

Figure 11. Protect and Escort Asset Function

The Intercept Threats function can be broken out into the different mission types, Figure 12. The function works by first selecting the appropriate weapon for the engagement, then determines whether the munition can be launched or fired based off availability and cycle times of the weapon systems of each ship in the scenario. If both conditions are met, then the missile or HVP round will be launched/shot. If it is not available because of cycle times, the model will launch the first available munition once that criteria have been met. The model will also track and record all munition types spent to determine if a resupply is required at port or at sea.

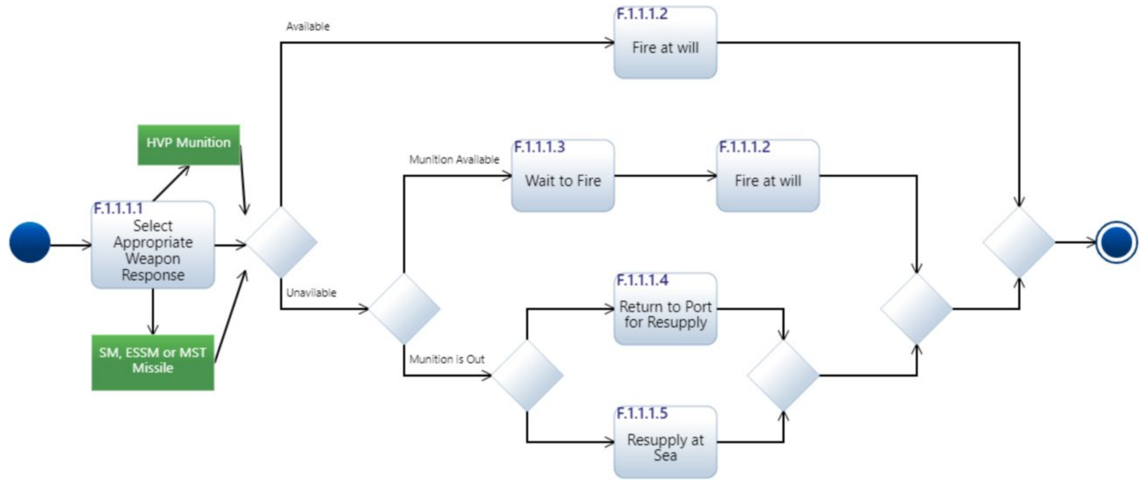

Figure 12. Intercept Threats Function

D. OBJECTIVES HIERARCHY

The objectives hierarchy, in Figure 13, shows three top level objectives which are Increase Warfighting Capacity, Increase Warfighting Flexibility, and Increase Warfighting Capability. Accomplishing these three top level objectives will lead to AFP effectiveness and therefore directly address the primary research question listed in Chapter I. Starting with Warfighting Capacity, the HVP weapon system would enhance logistics and mission planning by using a common munition for ASUW, AAW and NSFS missions that is significantly cheaper than traditional missiles and permits more rounds to be carried onboard. For Warfighting Flexibility, the deeper magazine capacity would provide the Navy the ability to sustain ASUW, AAW and NSFS operations for a longer period than traditional legacy missile systems. Finally, the Warfighting Capability of the HVP weapon system would more effectively mitigate emerging threats while allowing the Navy to better maintain forward presence.

Figure 13 also includes lower level objectives and their associated metrics or system measures. The simulation of the employment of HVP munitions installed on DDGs and CGs is intended to evaluate the potential for improved warfighting capacity, flexibility, and capability of legacy weapons systems. The system measures are directly linked to the objectives. The metrics established below will allow for a quantitative determination of the system's simulated effectiveness and performance.

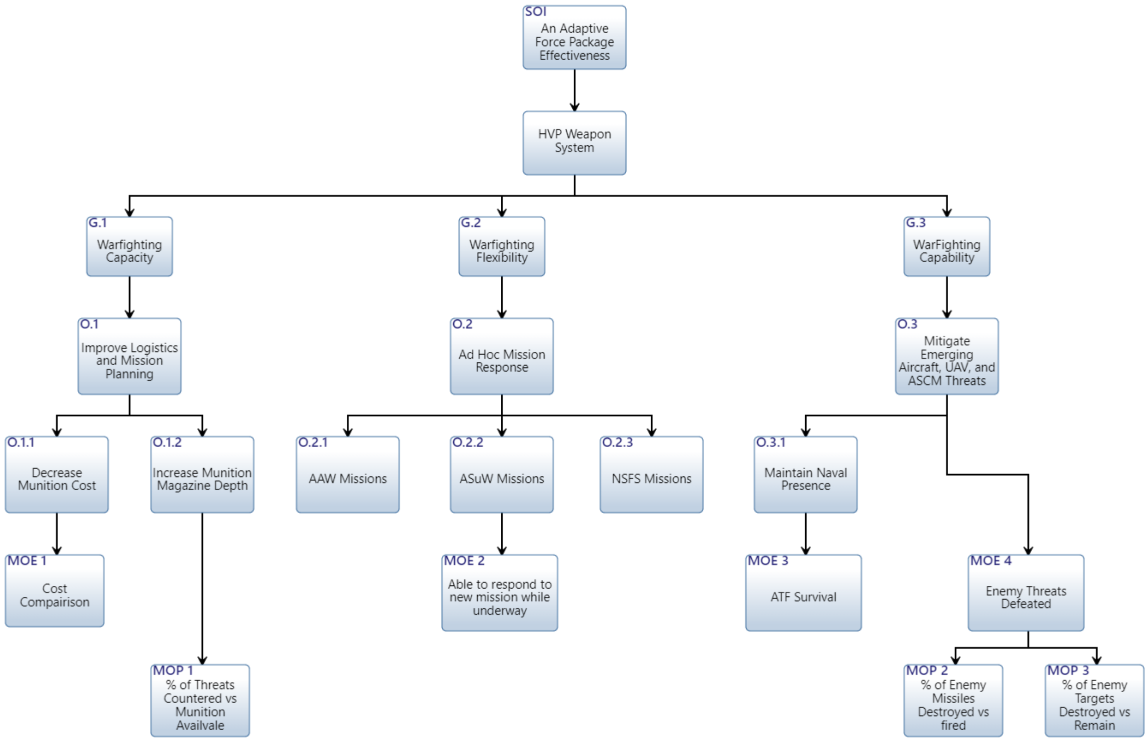

Figure 13. Measures Hierarchy

1. Measures of Effectiveness (MOE)

a. Cost Comparison

This MOE will look at how many missiles are fired in the model scenario with and without the HVP weapon system. The total amount of missiles fired will be multiplied by the estimated average cost of the missile type. Likewise, the number of HVP rounds that were fired are multiplied by their estimated cost. This comparison will look at how much money would be spent in the same model scenario with and without the HVP weapons system.

$$\text{Munition Cost} = \text{Number of rounds fired} \times \text{Munition Cost}$$

b. Respond to new mission while underway

To achieve this, enemy threat types will be staggered throughout the engagement until an end condition is reached. After the engagement, should a win condition be met, an analysis will be done on the remaining munition available. The remaining munition will be compared to the minimum munition needed to support the deployed mission load out as used in the model and described in the 2015 "Vertical Launch System Loadout Planner" Master's thesis by Michael L. Wiederholt, see Chapter IV.

c. AFP Survival

The survival of the AFP is an essential measure of the success of the HVP weapons system when compared to using traditional weapons systems. This measure will look at how many of the AFP forces were not sunk and were still capable of executing missions (not damaged or only have minor damage) to have many forces began the assault. Mathematically this will be calculated using a percent.

$$\text{Percent of Surviving Forces} = \frac{\text{Quantity of Surviving Forces}}{\text{Quantitiy of Initial Forces}} \times 100$$

d. Enemy Threats Defeated

Like the AFP survival, this measure will look at how many red forces are neutralized when using the HVP weapon system compared to traditional weapon systems. Unlike the AFP survival this will look at the threats categorically between aircraft, missiles, surface ships, and NSFS targets. Mathematically this will be calculated using a percent.

$$\text{Percent of Neutralized Threats}_{\text{Missiles, Surface Ships, \& NSFS Targets}} = \frac{\text{Quantity of Neutralized Threats}}{\text{Quantity of Inital Threats}} \times 100$$

2. Measures of Performance (MOP)

a. Percent of Threats Countered Vs Munition Available

This MOP will look to use the percentage of neutralized threats and then compare it to the percent of the remaining munition type for that threat. This measure will show whether the HVP weapon system increases the magazine depth of traditional munition by supplementing its munition in AAW, ASUW, and NSFS missions instead.

$$\text{Percent of Munition}_{\text{Missiles, HVP Rounds}} = \frac{\text{Quantity of Munition After Engagement}}{\text{Quantity of Initial Munition}} \times 100$$

b. Percent of Enemy Missiles Destroyed Vs Fired

This MOP will use the percent of missiles neutralized and compare it to the percent of enemy missiles that hit their target or missed with and without the HVP weapon system.

$$\text{Percent of Enemy Missiles Fired}_{\text{Hit \& Miss}} = \frac{\text{Enemy Missiles Fired}_{\text{Hit \& Miss}}}{\text{Initial Enemy Missiles}}$$

c. Percent of Enemy Targets Destroyed Vs Remain

This MOP will use the percent of enemy targets (aircraft, surface ships, and NSFS targets) neutralized and compare it to the percent of enemy targets that survived with and without the HVP weapon system.

$$\text{Percent of Enemy Remaining Targets}_{\text{Aircraft, Surface Ships, \& NSFS targets}} = \frac{\text{Remaining Enemy Targets}}{\text{Initial Enemy Targets}} \times 100$$

IV. SYSTEM ARCHITECTURE MODEL DESIGN

A. INTRODUCTION AND APPROACH

To determine if HVP munitions will improve or complement the CGs and DDGs weapon load out, we implemented ExtendSim software modeling since it can provide a dynamic model to simulate our scenario that involve multiple ships with a mix of weapon systems. A missile load out for each ship is shown below in section F. The output results of the ExtendSim model were analyzed by the Minitab software to gather the information needed to calculate the MOEs and MOPs. As stated previously in Chapter III, Innoslate EFFBDs were used as the baseline for the flow and structure of the project. The scenario was modeled in Excel as a static version through the range target graph and the stochastic model. These Excel tools were used to give an estimation of number of missiles launched, HVP rounds fired, and a statistical outcome of our scenario. The results of the ExtendSim model were analyzed using Minitab. This tool enabled the team to analyze the data based on different statistical graphs and charts.

B. ASSUMPTIONS AND LIMITATIONS

1. Assumptions

The scenario includes some assumptions for the AFP, the adversaries' weapons, and the HVP weapon system. It can be assumed that the scenario takes place in the daylight hour without any severe weather or rain. It is also assumed that there are no physical obstacles, such as mountains, building, icebergs, etc. This scenario is designed to be in open waters with an adversary island nearby. In addition, it will not consider any civilian air or sea traffic in the vicinity.

It is assumed that the AFP is completely combat capable at the beginning of the mission, even though the AFP is already underway. It is also assumed that the AFP has the capability to detect and track the adversaries prior to entering the engagement range. It is assumed that the variables set for each mission will remain constant and not fluctuate throughout the battle.

It is assumed that the adversaries will have strictly defensive capabilities and are not able to initiate a battle, only respond and engage to incoming missiles and counteract. The adversary missiles are assumed to have the same ranges, velocities, fire rate, probabilities of hit and probabilities of kill. The model is not designed to demonstrate different types of missiles to avoid being classified or implying any one adversary as the enemy of fight.

It is assumed that the HVP has the capability of hitting and killing targets at the same probability throughout the entirety of the mission. It is also assumed that other outside factors have no impact on the overall effectiveness of the HVP. The focus of this project is to isolate what would be directly impacted by the addition or replacement of HVP weapon systems. Therefore, things like chaff, flare and other countermeasures were not considered.

2. Limitations

There are multiple limitations that are identified in this scenario. The elements that have limitations include the AFP, the adversaries and the HVP weapon system. Each of these are limited by the amount of information that can be acquired through open source documentation. It was agreed to keep this project unclassified so no "real" numbers or values were used, just close estimates to get a general idea of the outcome that can be expected.

The AFP is limited in the amount of munitions that can be held throughout the duration of the mission. In addition, the AFP is limited in the amount of planning that can be modeled since the scenario states that the AFP is already underway.

The HVP weapon system is limited on the type of targets it can intercept. O'Rourke (2020) describes using HVPs against ASBM's as "might not [being] able to counter" them. For this reason, the focus of the HVPs in the model will be against ASCM's, leaving defensive missiles to counter ASBM's that are launched against blue surface ships.

C. VARIABLES

Multiple variables were used in the scenario's model such as the following: HVP Modes Status, HVP velocity, MK-45 HVP P(hit), HVP NSFS Max range, Ship hits to disable, and target hits to disable. The HVP mode status is an on/off switch that either includes or excludes HVP rounds in the model. This is the main variable that is analyzed. It will show a direct correlation between the model with legacy missiles only and the model with legacy missiles and HVPs. Table 4 shows which MOE/MOP each variable directly relates to or effects. The HVP mode status is the direct comparison of the legacy weapons with the inclusion and exclusion of the HVP. HVP Status, Velocity, NSFS Max Range, ASCM Max Range, ASCM Min Range and MK-45 P(hit) all directly correlate to each of the MOEs and MOPs because they vary the performance of the HVP munition when it is included. The Ships Hits to Disable correlates to MOEs 3 and 4 and MOPs 1 and 3, but does not directly correlate to the number of munitions fired, the need for resupply or the number of enemy missiles countered. The MOEs and MOPs are listed in Table 5.

Table 4. Variables Mapped to MOEs/MOPs

Variables	**MOE/MOP that it relates to**
MK-45 P(hit)	MOE1, MOE2, MOE3, MOE4, MOP1, MOP2, MOP3
HVP ASCM Min Range (m)	MOE1, MOE2, MOE3, MOE4, MOP1, MOP2, MOP3
HVP ASCM Max Range (m)	MOE1, MOE2, MOE3, MOE4, MOP1, MOP2, MOP3
HVP NSFS Max Range (m)	MOE1, MOE2, MOE3, MOE4, MOP1, MOP2, MOP3
HVP Velocity (m/s)	MOE1, MOE2, MOE3, MOE4, MOP1, MOP2, MOP3
HVP Status	MOE1, MOE2, MOE3, MOE4, MOP1, MOP2, MOP3
Ships Hits to Disable	MOE3, MOE4, MOP1, MOP3
Target Hits to Disable	MOE3, MOE4, MOP1, MOP3

Table 5. MOEs and MOPs

MOEs and MOPs
MOE1: Cost Comparison
MOE2: Respond to New Mission While Underway
MOE3: AFP Survival
MOE4: Enemy ASCM Defeated
MOP1: Percent of Threats Countered Vs Munition Available
MOP2: Percent of Enemy Missiles Destroyed Vs Fired
MOP3: Percent of Enemy Targets Destroyed vs Remaining

D. RANGE TARGET GRAPH

Range-target graph is a modeling technique that determines the engagement windows and intercept times. The graph it produces displays a plot of time versus range to target for the HVP, ESSM, and SM. As seen in Figure 14, the parameters being measured are the initial incoming missile range, incoming missile velocity, AEGIS detection range, SM2 maximum intercept, SM2 minimum intercept, SM2 intercept velocity, time between launches per ship, and process time for the first launch. The range-target graph ultimately defines how many missiles can be fired during an engagement window. The parameters can then be optimized in order to fire the maximum amount of missiles possible within certain intercept ranges to establish limits or bounds within the model. Table 6 displays the information that can be exported from the range-target graph. This quick look of values that change whenever the parameters are changed provide a direct cause and effect relationship between the parameters that are changed and the derived results.

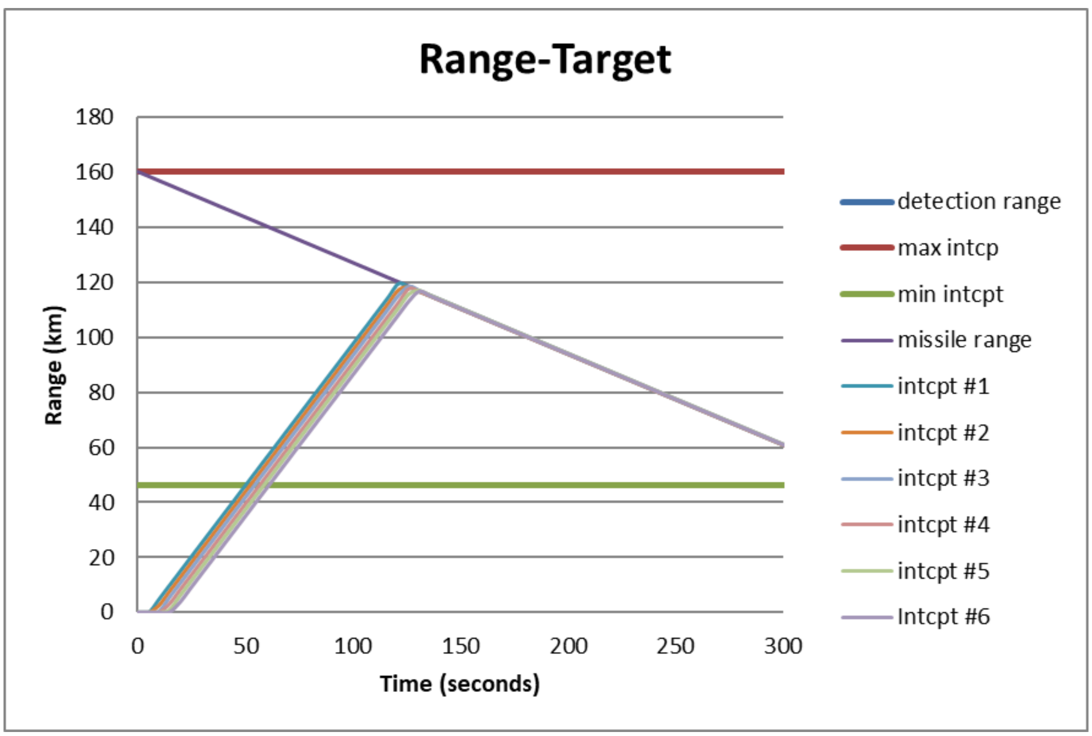

Figure 14. Range Target Graph

A breakdown of the missiles launched and contributing factors are displayed in Table 6.

Table 6. Missiles Launched

Derived quantities	Value
Time step	4.84 s
Time to impact	484.84 s
Time first detect	0 s
Earliest first launch	5 s
Latest last launch	299.59 s
Max number of launches per ship	133
Total number of launches possible	399
Magazine limited number of launches	130
Launches still available	269

E. STOCHASTIC MODEL

Using Excel, a statistical analysis was conducted to give insight of the results from the ExtendSim model. The stochastic calculator emulated the engagement process using a binomial probability distribution. If the same munition is used against two or more different targets, then the amount of munition spent or used against the first engagement is subtracted from the second engagement before the numbers are used in the distribution. For the stochastic calculator several parameters were utilized such as the type of threat, type of platform, and probabilities. The stochastic model allows for different values to be varied in order to simulate an engagement that considers radar cross sections, probabilities of hit, probabilities of kill and etc. as seen in Figure 15. The statistical model determines which one of our 5 ships an ASCM targets based off the radar cross section, which is an arbitrary number for our needs, but it is necessary that the ARG ships be much larger than the CG ships and the CG ships be larger than the DDG ships. This allows for the probability of which ship is chosen to be calculated, and once chosen, the probability of that ship being hit can be calculated. These two probabilities can then be used in conjunction with the

ASCMs that get past the defensive systems to determine if a ship is hit. By assigning a kill probability and using the calculated hits for each ship a calculation for which ship sank can be made. The stochastic model essentially is a mock engagement that provides results of surviving forces on both sides. This can be used to constrain the model to the limitations and capabilities of the systems. It gives an approximate number of what to expect out of the higher fidelity ExtendSim model.

	Land Targets	Enemy Surface Ships	Aircraft Inbound	ASCM Inbound	ARG	CG67	DDG54	DDG62
Number of (n)	10	5	0	134	2	1	1	1
P(hit)				0.9				
Fast % Input for P(hit)				90				
Radar Cross Section (RCS)					10000	3500	3000	3000
P(chosen)					0.339	0.119	0.102	0.102
P(hit|chosen)					0.305	0.107	0.092	0.092
p(kill) if hit					0.125	0.25	0.25	0.25
Spent Munition								
Munition Remaining								

Figure 15. Stochastic Model View

1. Missile Loadout (VLS)

The ExtendSim model has three combatants (one CG, one DDG-54, and one DDG-62), there are six missile types, and one war plan scenario with two missions. Table 7 outlines the ships, the mission, and missile loadout to be distributed across the ships.

Table 7. Missile Loadout

Ship	**War Plan**	**Mission**	**Missile Loadout**				
			ESSM (4/cell)	SM2 MR	SM3	SM6	Maritime Strike Tomahawk
CG67	A	Escort 4	32	71	0	1	42
DDG54	A	SAG1	32	32	0	1	55
DDG62	A	SAG1	36	27	0	13	25

F. DESIGN OF EXPERIMENTS

The design of experiment (DOE) was setup to include different parameters that were varied for the HVP as seen in Table 8. These parameters were used to establish the effects they had on the outcome of the scenario in addition to the interactions that had the most impact. Minitab provided the capability of creating a DOE that was used as a read in database to be varied throughout each of the runs in the model. The HVP mode status was the main variable that was analyzed in this project. Based on the information from the range-target graph and the stochastic model, other variables were identified that could have a potential impact on the outcome. These probabilities of hit percent, ranges and velocities were chosen based on research and documentations describing the HVP munition presently been tested by the U.S. Navy. These parameters serve as important inputs to our Extend sim model which were used to analyze the different MOEs and MOPs. A detailed description of this simulation is available in Appendix A.

Table 8. Design of Experiment

MK-45 HVP P(hit)	HVP ASCM Min range (m)	HVP ASCM Max Range (m)	HVP NSFS Max range (m)	HVP Velocity (m/s)	HVP Status	Ship Hits to Disable	Target Hits to Disable
0.5	8046.72	40233.6	128748	857.5	0	2	1
0.65	16093.4	48280.3	160934	1029	1	4	3
0.75	24140.2	56327	193121	1200.5		6	5
0.85	32186.9	64373.8				8	

G. MODEL VALIDATION

In Table 9, a comparison was conducted of the results from the simulation runs to the stochastic model results. The table depicts the similarities for both results for the legacy systems which contributes to validation of the ExtendSim model.

Table 9. Stochastic Model Validation

6912 Simulation Runs	ExtendSim Model	Excel Stochastic Model
ESSM Intercept	36	43
SM Intercept	100	92

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V. SYSTEM ARCHITECTURE RESULTS AND ANALYSIS

A. EFFECTIVENESS ANALYSIS

1. HVP Mode Status Versus Legacy Weapons

a. MOE 1: Cost Comparison

Using Minitab, an in-depth analysis was conducted on the results from the simulation. The legacy systems were used as a point of comparison for the HVP scenario. The legacy weapons average cost is estimated at $1.7M for the SM, $1.8M for the ESSM, and $2.4M for the MST (Rogoway and Trevithick, 2020). The HVP is averaged to $85,000 per round. As seen in Table 10, it is roughly $89M less to fire the HVP than the legacy systems. The costs are broken out by ship and by missile type and are then compared based on the HVP mode status. The average costs as well as the average number of missiles fired are included. Overall, the average total cost of a mission without the use of HVP rounds is $487M. The average total cost of a mission with HVP rounds included is $398M. The average total savings of using HVP rounds is substantial. This provides clear guidance on the financial benefit of using HVPs in conjunction with the legacy weapon systems.

Table 10. HVP Mode Status vs. Legacy Weapons Costs

Total Sim. Runs	Ship	Munition	Runs with HVP Off Average # of Missiles Fired	Average Cost in Millions ($)	Runs with HVP On Average # of Missile Fired	Average Cost in Millions ($)
6912	DDG 54	MST	22	53	9	22
		SM	32	57	24	43
		ESSM	17	30	15	27
	CG67	MST	18	49	8	19
		SM	71	126	53	93
		ESSM	17	31	15	27
	DDG 62	MST	18	44	6	15
		SM	38	67	28	50
		ESSM	17	31	15	27
Total Cost w/o HVP: $487M Total Cost w/ HVP: $398M Total Savings of $89M						

b. MOE 2: Respond to New Mission While Underway

This MOE was measured by comparing the number of resupplies needed per missile type, per ship based on the HVP mode status. When the HVP mode status was enabled, it decreased the number of resupplies needed for each of the missile types for each ship except for the ESSM on the CG67. When the HVP mode status was enabled, the ESSMs on the CG-67 resupply percentage increased. The MSTs on the DDG 62 required a resupply 100% of the time for both the inclusion and exclusion of the HVP munition, therefore it is listed as null in the resupply analysis table because it did not increase or decrease. Table 11 gives a breakdown of each ship's munition resupply percentage for responding to a new mission while underway when the HVP weapon system is enabled and disabled.

Table 11. Resupply Analysis

Total Runs	Ship	Munition	Runs with HVP Off Resupply Needed	Percent	Runs with HVP On Resupply Needed	Percent
6912	DDG 54	MST	1879	27%	647	9%
		SM	6912	100%	5153	75%
		ESSM	3471	50%	3274	47%
	CG67	MST	6328	92%	1365	20%
		SM	6912	100%	5130	74%
		ESSM	1339	19%	2365	34%
	DDG 62	MST	Null			
		SM	6912	100%	5148	74%
		ESSM	4763	69%	3682	53%

c. MOE 3: AFP Survival

The AFP survival for the HVP weapon system in comparison to the legacy weapons was practically equivalent with a difference of 0.06 percent as seen in Figure 16. Therefore, essentially all the friendly survive the engagements throughout the scenario. Overall, there was a minimal difference in performance based on the survival rate of the friendly forces.

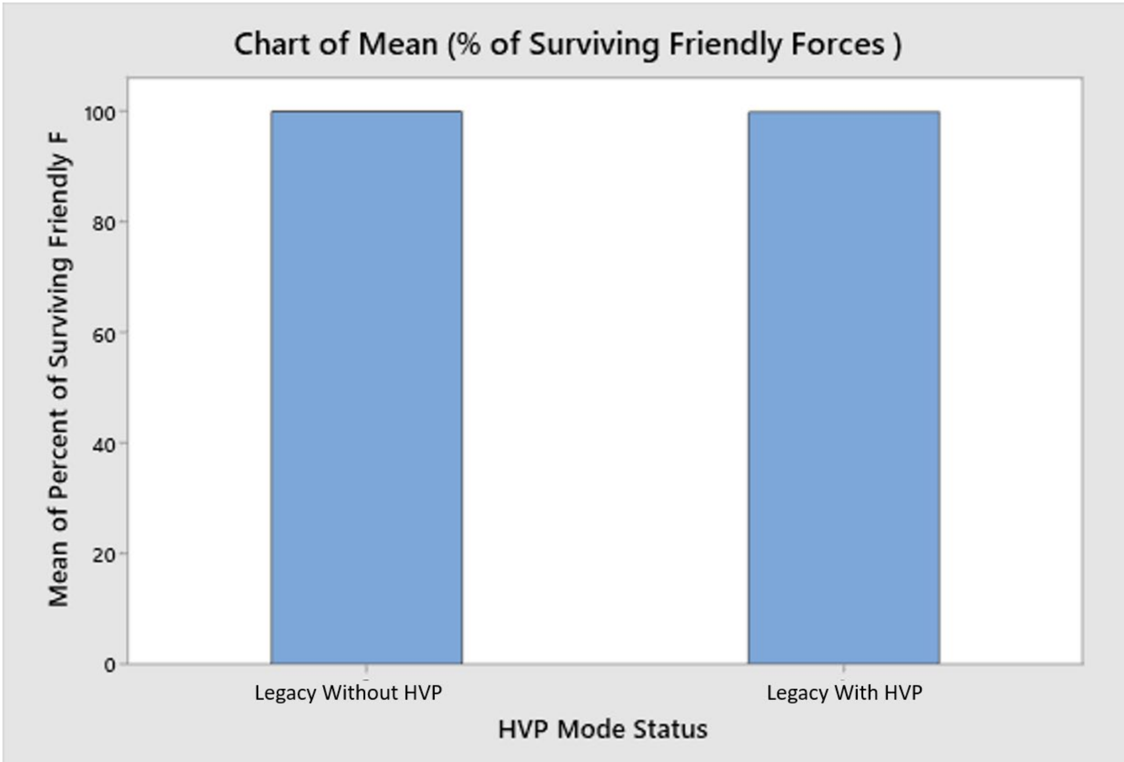

Figure 16. AFP Survival

d. MOE 4: Enemy ASCM Defeated and MOP 2: Percent of Enemy Missiles Destroyed vs. Fired

This MOE examines the percent of enemy anti-ship cruise missiles that are countered or defeated in the model. This is broken out by each individual weapon system. They are compared using the inclusion or exclusion of the HVP mode status. The legacy weapon systems' percent of missiles countered decreases for the inclusion of the HVP. The SMs percentage decreases from 74% to 52%, Figure 17. The ESSMs percentage decreases from 26% to 22%, Figure 18. Lastly, the HVP counter 22%, Figure 19, and the CWIS .03%, Figure 20, when the HVP is enabled. This is due to some of the incoming missiles being countered by the HVP munitions. In addition, a small percentage is being countered by the CWIS. MOP 2 directly relates to this MOE. MOP 2 however, observes the percent of enemy missiles countered instead of by weapon type.

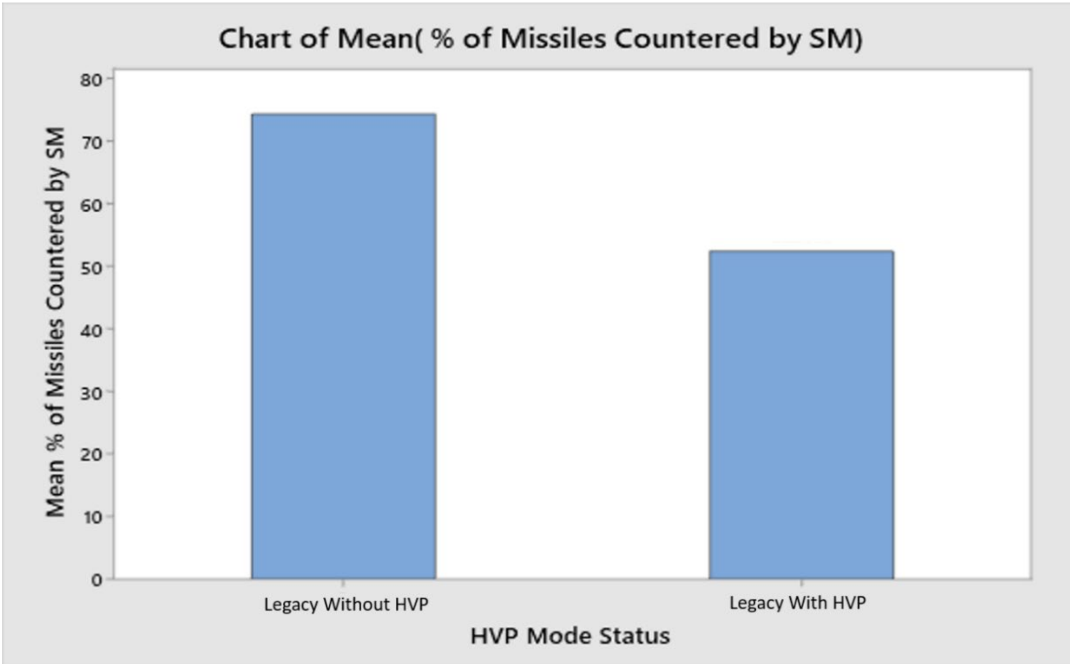

Figure 17. Percent of Missiles Countered by SM

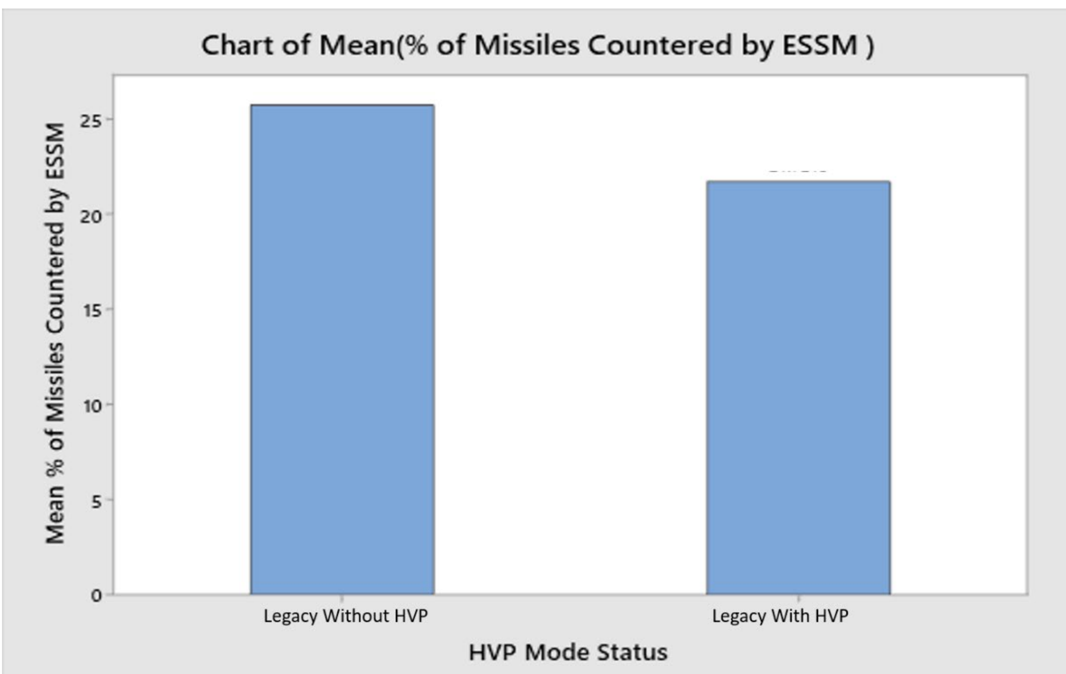

Figure 18. Percent of Missiles Countered by ESSM

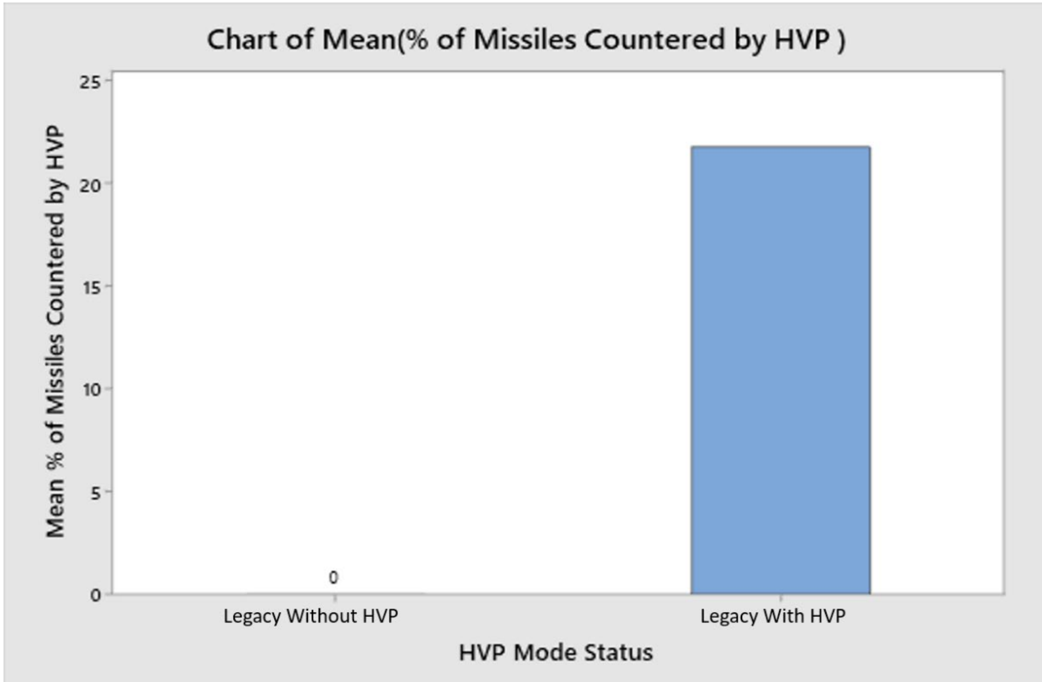

Figure 19. Percent of Missiles Countered by HVP

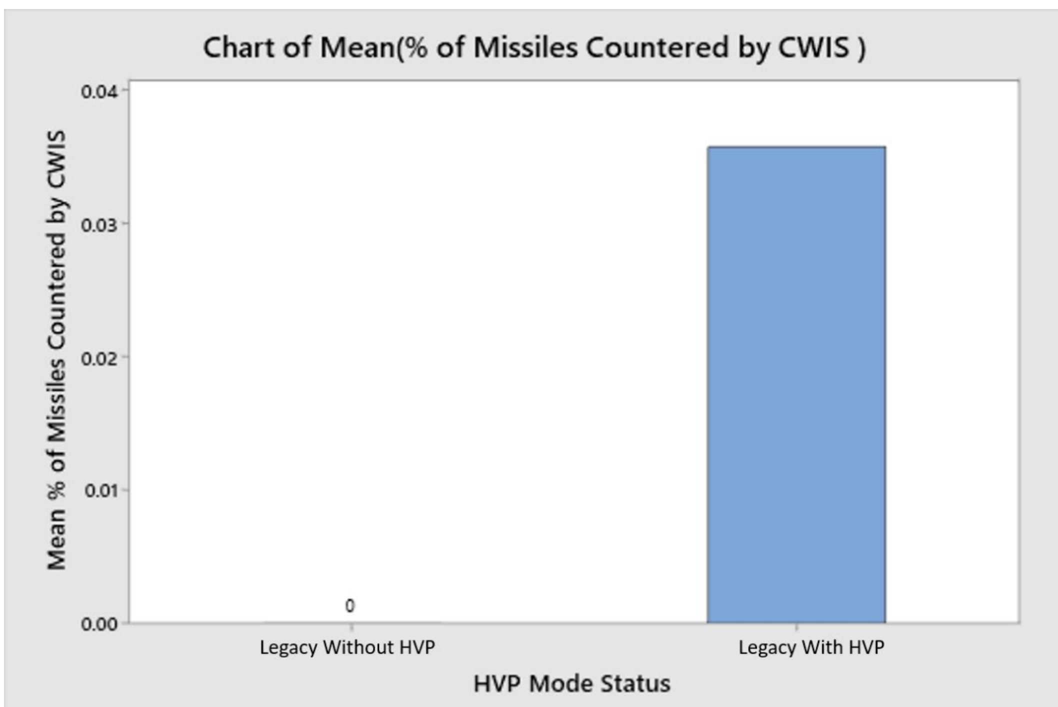

Figure 20. Percent of Missiles Countered by CWIS

MOP 2 displays the total number of enemy missiles fired vs the initial number of enemy missiles. When the HVP Mode Status was disabled, the average percent of enemy missiles fired over the initial enemy missiles is 64.06%. For the enabled HVP Mode Status, percentage is 69.49%. Therefore, slightly more missiles were countered when the HVP was enabled.

e. MOP 1: Percent of Threats Countered vs. Munition Available

When the HVP switch was enabled, the magazine depth for the DDG-54 legacy weapons was increased from 0 percent to 25 percent for the SMs, 60 percent to 84 percent for the MSTs, and 47 percent to 53 percent for the ESSMs. Thus, the inclusion of the HVP weapon system has proven that it will increase the legacy weapon systems magazine depth and the total amount of munitions available. Table 12 breaks down the percent of munitions available by missile type and by ship. They are each compared by the HVP Mode Status.

Table 12. Percent of Munitions Available

Total Sim Runs	Ship	Muni-tion	Initial Munition	Runs with HVP Off			Runs with HVP On		
				Percent of Countered ASCM/ Enemy Targets	Average # of Missiles Fired	Percent of Munition left	Percent of Countered ASCM/ Enemy Targets	Average # of Missiles Fired	Percent of Munition left
6912	DDG 54	SM	32	74.2%	32	0%	52.3%	24	25%
	CG67		71		71	0%		53	25%
	DDG 62		38		38	0%		28	26%
	DDG 54	ESSM	32	25.7	17	47%	21.7	15	53%
	CG67		32		17	47%		15	53%
	DDG 62		28		17	39%		15	46%
	DDG 54	MST	55	99.9%	22	60%	99.1%	9	84%
	CG67		42		18	57%		8	81%
	DDG 62		21		18	14%		6	71%

f. MOP 3: Percent of Enemy Targets Destroyed vs. Remaining

In both figures 21 and 22, it is clear to see that the enemy ships and land targets neutralized by the legacy weapons when the HVP is disabled is practically the same as when the HVP is enabled. The MOP 3 is the percent of enemy targets destroyed vs remaining enemy targets. The graphs show that roughly 99% of the enemy ship and land targets were defeated for both HVP Mode Statuses. So consequentially, there are essentially no remaining enemy targets.

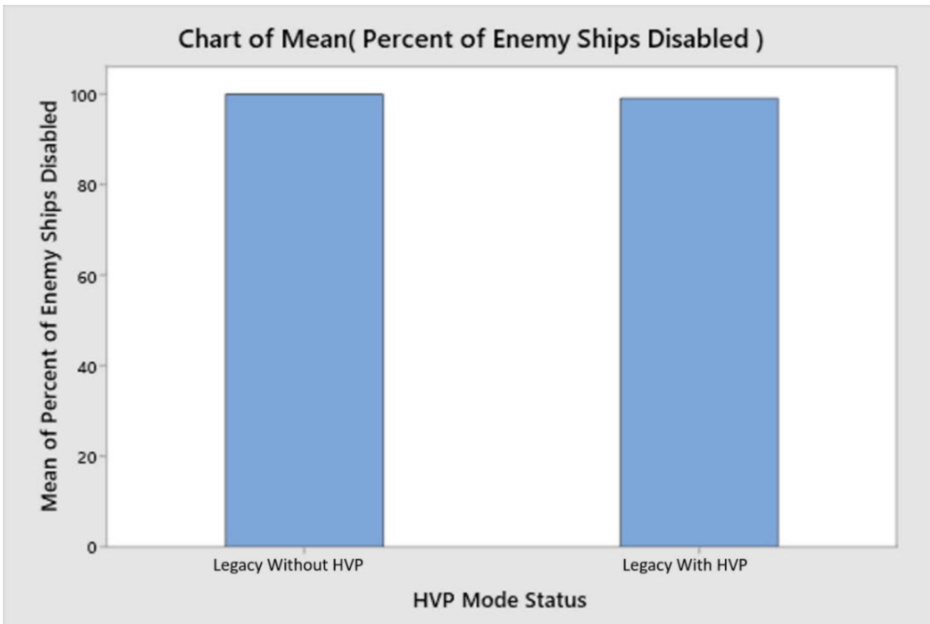

Figure 21. Enemy Ships Disabled

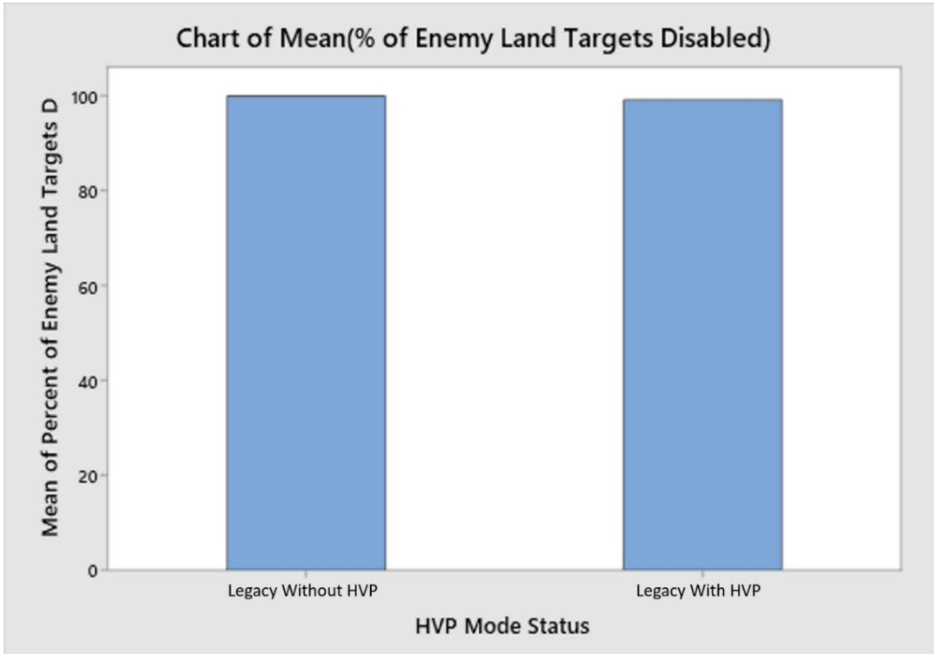

Figure 22. Enemy Land Target Defeated

B. SUMMARY OF RESULTS

The results for the MOEs and MOPs provides evidence of the benefit of incorporating the HVPs into the weapon system load outs. There are benefits in cost, resupply, munitions available while maintaining performance. Each of these confirmed the initial hypothesis that the effectiveness of HVP munitions improve the overall mission success, as well as deliver a cost-effective alternative to using only legacy weapon systems.

The average total cost of a mission in the scenario used for this project without the use of HVP rounds is $487M. The average total cost of a mission with HVP rounds included is $397M. It is roughly $89M less to fire the HVP than the legacy systems alone. This provides clear evidence on the financial benefit of using HVPs in conjunction with the legacy weapon systems.

Furthermore, when the HVP mode status was enabled, it decreased the number of resupplies needed for each of the missile types for each ship except for the ESSM on the CG67. Thus, the inclusion of the HVP weapon system has proven that it will increase the legacy weapon systems magazine depth and the total amount of munitions available.

The HVP munitions also maintained the legacy system performance. The AFP survival for the HVP weapon system in comparison to the legacy weapons was practically equivalent with a difference of 0.06 percent. Overall, there was a minimal difference in performance based on the survival rate of the friendly forces. Additionally, it is clear to see that the enemy ships and land targets neutralized by the legacy weapons when the HVP is disabled is practically the same as when the HVP is enabled. Roughly 99% of the enemy ship and land targets were defeated for both HVP Mode Statuses. So consequentially, there are essentially no remaining enemy targets.

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VI. CONCLUSIONS AND FUTURE RECOMMENDATIONS

A. CONCLUSIONS

Variability in weapon load out is critical to successfully support a wide range of missions in an ad hoc state. The operationally relevant (AAW, ASUW and NSFS) mission scenarios require an asset that can support multi-operational events with little notice or preparation time in planning efforts. HVPs would provide naval operations with improved logistics by minimizing response time and faster execution time. It is a necessary capability improvement in order to meet the evolving challenges to the Navy’s mission.

Decreasing the cost of the battle engagements is ideal and effective that leaves room for money to be spent elsewhere. It provides the possibility to reallocate funds to other munitions or the development of new capabilities. This domino like effect would provide new avenues to be competitive against our adversaries. The HVP munition is significantly cheaper than all the legacy weapons munitions that it would potentially be replacing. This directly increases the quantity of weapon systems that will likely be available for use. An increase in quantity of weapons available will provide the fleet with a better offensive and defensive capability. They can be used for a diverse range of missions.

Overall, the HVP allows the fleet to decrease the total cost of the weapons. In addition, it also increases the number of munitions available for use. There are cost benefits while keeping the same fidelity in performance. By incorporating them into the mission, it will ensure a better cost to benefit and bang for your buck ratio.

B. RECOMMENDATIONS AND FURTHER RESEARCH

The analysis and results of the simulation from this project provide evidence of the benefits of using the HVP munition. It is recommended to create a risk analysis of the incorporation of the HVP munitions. This will enable the DoD to have a certain level of confidence in the HVP munitions after evaluating any potentials risks that the integration would entail. It is also recommended that HVP munitions be incorporated into the current load out within the fleet after conducting a risk analysis. The Navy will also need to continue pursuing new capabilities that can be implemented on existing ships in order to meet new threats from our adversaries.

In the future, it would be valuable to also conduct research into the effectiveness of salvos of HVP and heterogeneous weapon systems. This information will enable a new realm of possibilities of the U.S. military capabilities. In addition, it would be useful to recreate this study on a classified level with more specific parameters and adversary information. Overall, there are many ways the HVP munitions can be utilized to enhance the current capabilities.

APPENDIX

A. EXTENDSIM MODEL

1. Baseline Model

To create the static battlefield scenario that can capture the x and y position of the friendly ships and the enemy ships and enemy land targets that will be used in the ExtendSim model, an Excel chart was implemented. The Excel chart depicts a scaled version of the combat area. The enemy land target consists of ten land targets and the enemy ships consist of five ships with combat capabilities comparable to our friendly ships.

a. Vertical Launch System

The ExtendSim model pictured in Figure 23, represents the MK-41 VLS system employed aboard the DDG and CG ships. The AEGIS system in our model detects the enemy target, then it determines and categorizes the type of target. Once an item has been through the engagement sequence, it will go through the VLS logic. There is an input for the MST, SM, and ESSM per ship. It then enters a queue. From there it enters a disabled switch. If a ship is disabled, the item will go back through the beginning of the sequence. If it isn't disabled, then it will move to the next block and a missile will be launched. The item is assigned a sequence number in the engagement logic that will determine which type of missile is being used to shoot. The coordinates are pulled at any given time in the scenario for the target, ship or missile. This information will provide the current range, which will lead to a calculation of intercept time.

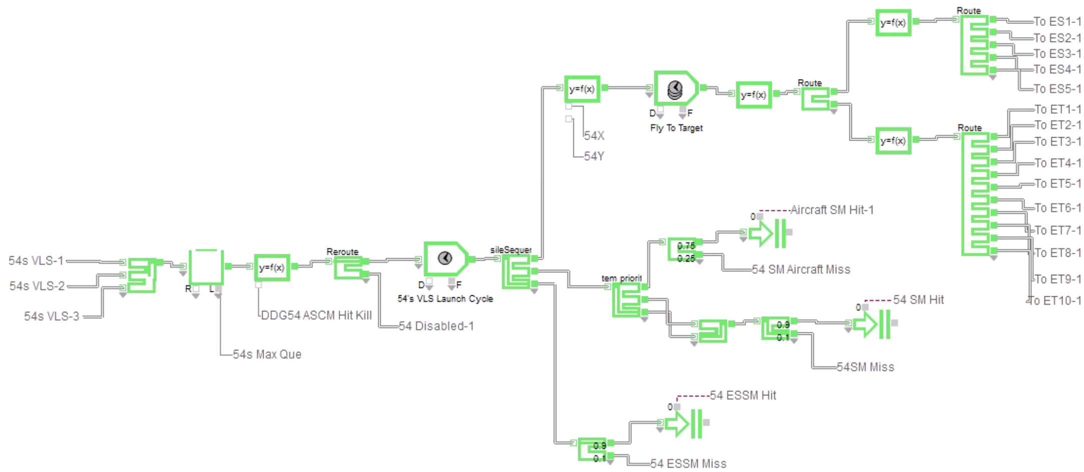

Figure 23. VLS Logic

b. Friendly Ship Creation

The Extendsim model pictured in Figure 24, represents the friendly ships creation. The adaptive force package is composed of two DDG ships one CG ship and two amphibious ships. Each ship is created at time zero with a specified coordinate simultaneously. There is an age and position that changes over time during the model. The unique ship position was assigned by using a conceptual map scenario created in Excel. The ship age is also calculated for intercept times and kept track of so that when a missile or an HVP is shot to counter act an enemy target. The get blocks grab the individual ship position throughout the model whenever it's needed, it can then calculate if the target was hit. The item sits in a queue for the remainder of that run of the model.

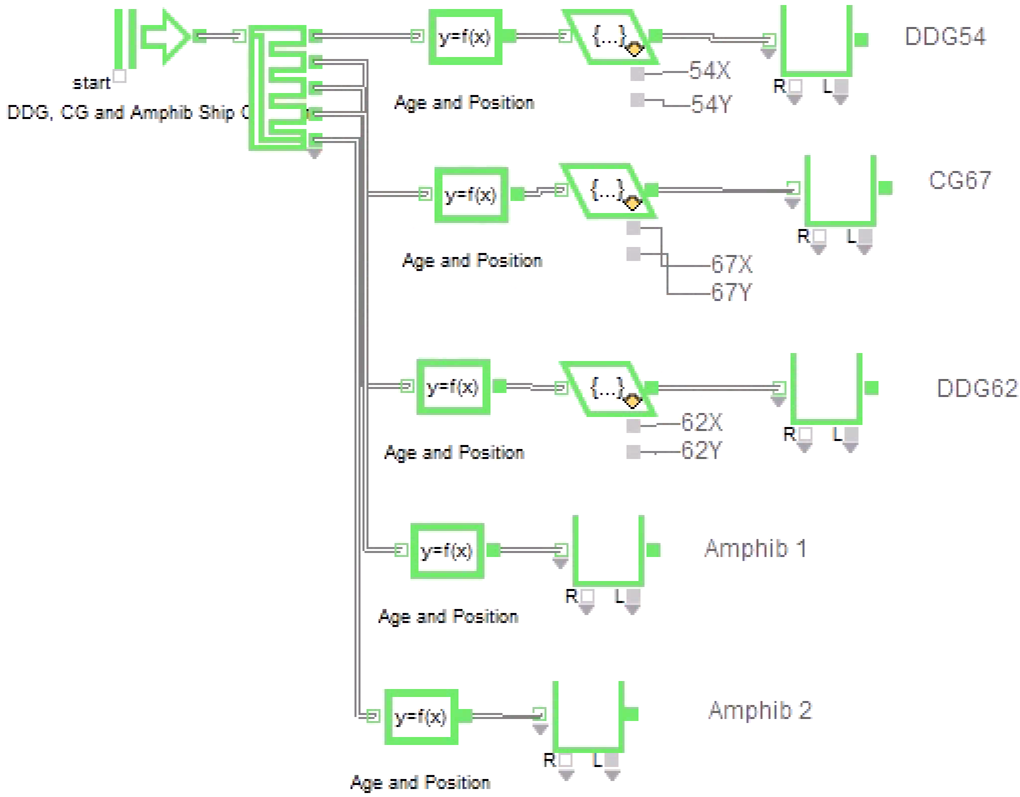

Figure 24. Friendly Ship Creation

c. *Engagement Sequence*

The individual enemy ships, targets, and ASCMs are merged into one engage input each, Figure 25. There is a queue block to hold the items as they come in. The systems will only handle one item at a time in order to efficiently take into consideration the priority of the item. The ships and land targets are given a priority of three and ASCMs are given a priority of two. Priority one is assigned to ASCMs that are going back through the engagement sequence due to being missed in the initial engagement. Only missiles are assigned as priority one and two. If it's priority three it goes down to the MST system. There is an activity block that checks the range and detects the ASCMs. The item then flows into a queue and then the HVP on/off switch. The HVP on/off switch is something that will be discussed later in the next section. It will determine which path the item will take next whether it's the top, middle or bottom path. If there are too many missiles in queue for the HVP they'll be redirected to the VLS/SM system.

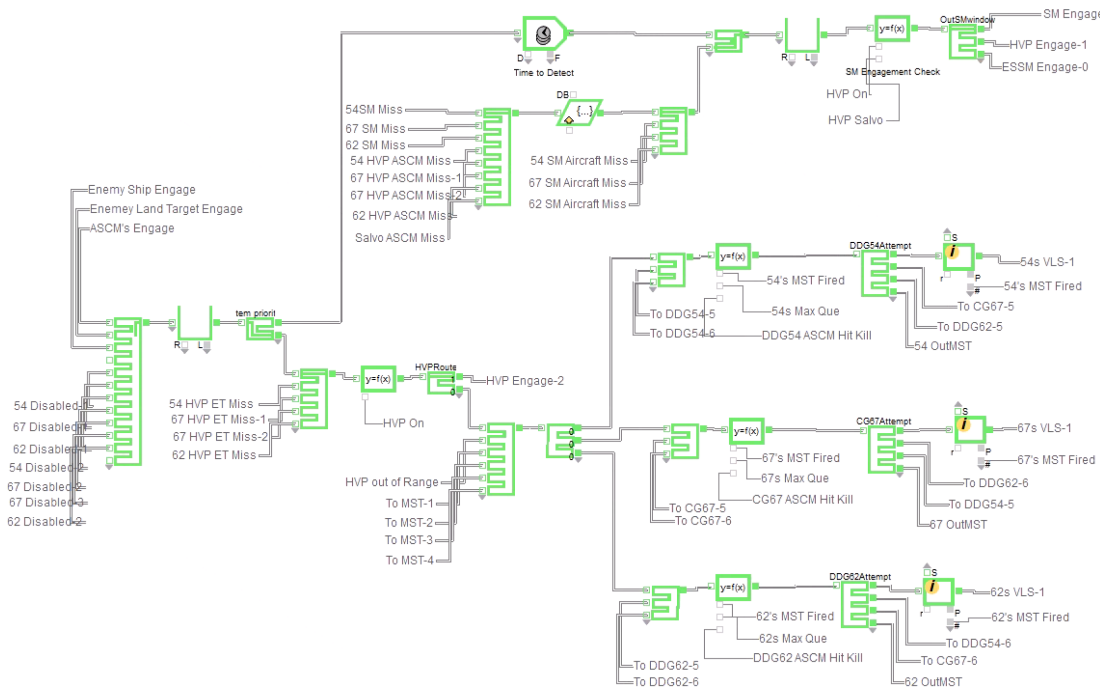

Figure 25. Engagement Logic

d. Standard Missile and Maritime Strike Tomahawk Sequence

The item in the SM engage attribute enters a randomized-out block, Figure 26. This will determine which ship will intercept the missile. It will move into an equation block that determines how many times the missile has been shot at, how many missiles are available to engage it, how many other ships have tried to shoot at it, and it gives it a sequence of one which is important in the VLS logic. If it's been attempted to be shot at three times, then it proceeds to the ESSM logic. This can be from being out of missiles, being overwhelmed and having too many in queue or being disabled. If any of those conditions are met, then it tries to go to the next ship. However, if those conditions aren't met then it will shoot it and a missile will be fired from the VLS.

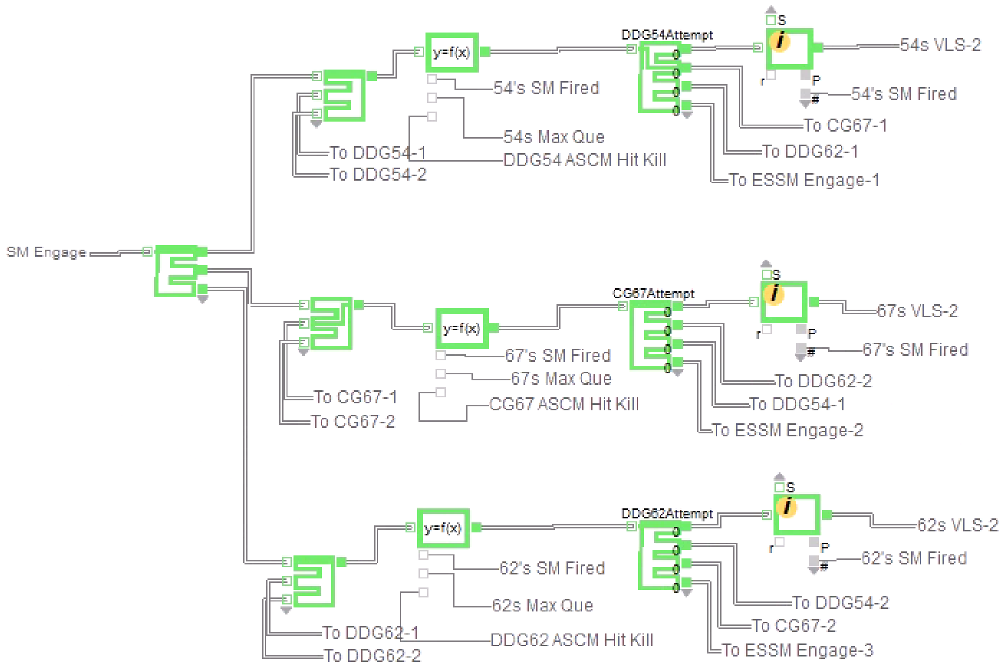

Figure 26. Standard Missile Logic

e. *ESSM Sequence*

For the ESSM logic, figures 27 and 28, the item is input through a common name and the misses are also input. They are assigned a priority. If it is a miss, it will receive a priority one. It will then enter a queue. Following that, the item will be checked to make sure it is in the engagement window. If it's not, then it calculates how long it needs to wait before it becomes in range. The activity block will hold the missile in place for that amount of time. Then it will enter the ESSM engage logic.

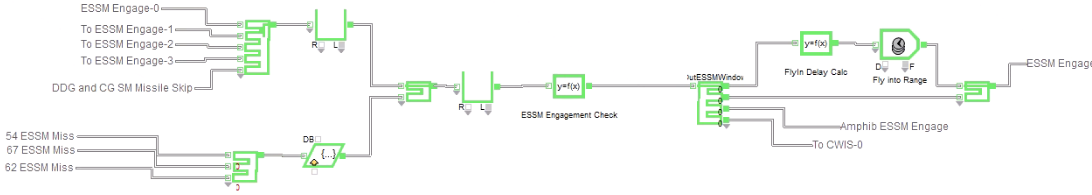

Figure 27. ESSM Engagement Check and Flyin

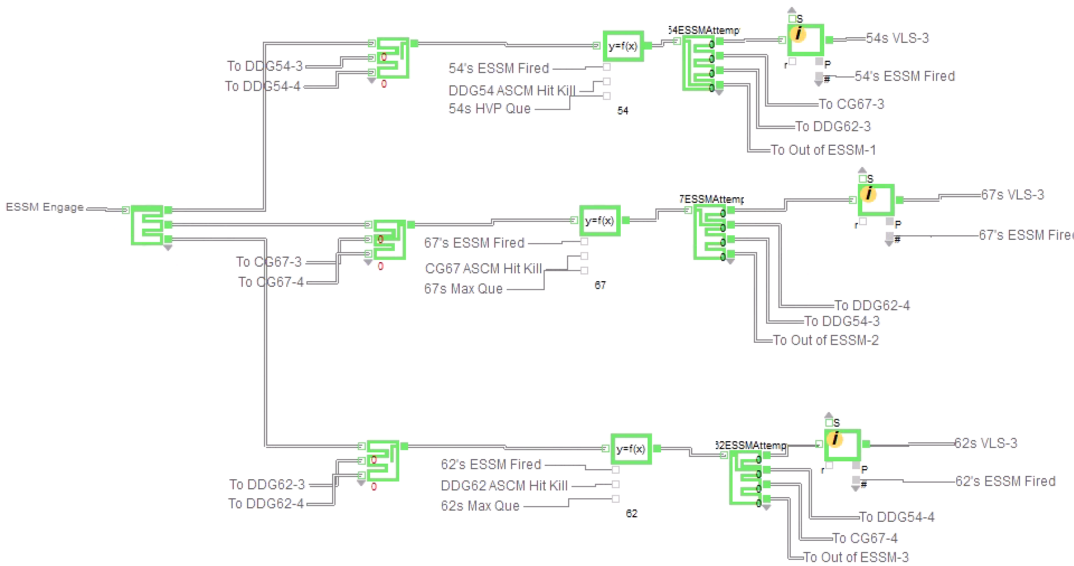

Figure 28. ESSM Fire logic

f. Amphibious Ships

If the CG and the DDGs are out of missiles or disabled, then the amphibious ships will shoot, Figure 29. The incoming missiles will be checked to make sure that they're in range. It is assumed that each of the ships have the same detection range based on the Aegis system. Next, it will check the engagement window. Following that it will be held in a queue before being engaged. Each missile will be shot at and counted and if it's missed it will go back through the cycle. Otherwise, if it's hit, it will exit the model and be counted as a hit. The logic also considers the priority level of the missile.

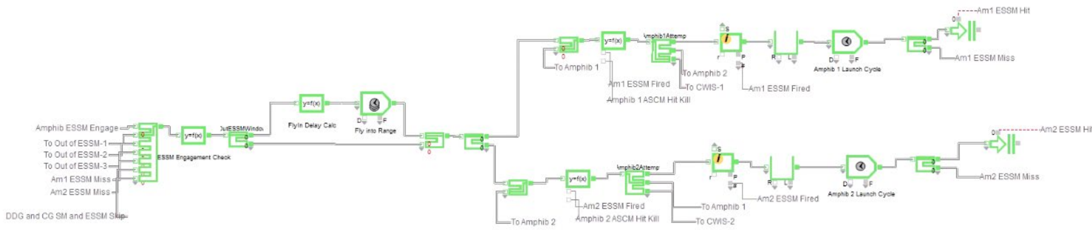

Figure 29. Amphibious Ship Logic

g. CIWS and ASCM

If all the ships are out of missiles, then they will be routed to the CIWS system, Figure 30. It will all enter through the same block. It will check to see if it's in the engagement window. If it is then it proceeds through the engagement. The ASCM is routed based on the ship name associated to it. It will then fly towards that ship and be engaged with that specific ships CIWS system. There is also logic that checks to see if the ship is already disabled. It allows a missile to bypass the CIWS system if the ship is already disabled. Otherwise, it will continue through the engagement. In addition, if it misses the ship then it will exit the simulation as a miss. If it does hit the friendly ships, there is a probability that it will hit us and not disable the ship based on the back of the envelope. Otherwise, it will hit the friendly ship and disable them.

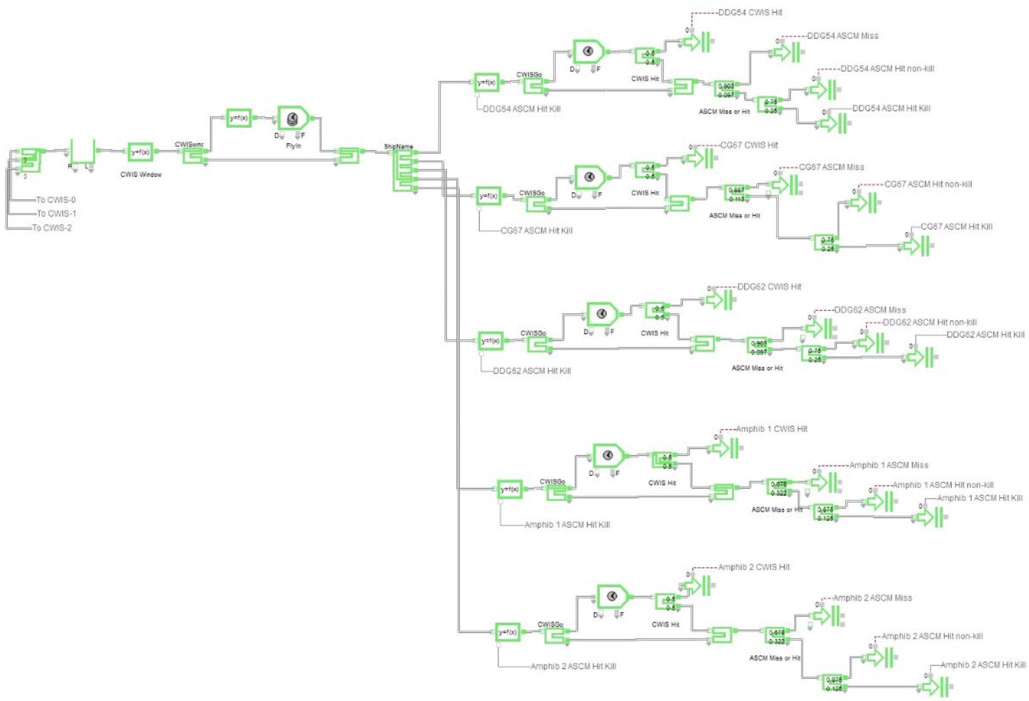

Figure 30. CIWS Engagement and ASCM Missile Resolve Logic

h. Enemy Targets

The enemy ships are created similarly to the friendly ships, Figure 31. They start at time zero. Only one is made per block. However, they are given a priority of one, two or three for sorting purposes in our Aegis system that is being simulated. The ships are each given a name so that they can be tracked through the model. The land targets are also given a name (which range from one through ten) to coincide to the battle scenario constructed in Excel. They are each uniquely identified so that target data collected for each can be saved in a data base for a later analysis. They also have their own unique age and position like the friendly ship creation logic. The get blocks grab the name, age and position as needed throughout the model. The enemy ships and targets then go through a detection sequence. The model simulates a scan of the battle environment. It's given a probability of detection per scan. If it's not located right away, it will scan again. Once it has been found, the friendly ships and missiles move into the engagement sequence of the enemy ships and targets. There are also blocks in place to calculate if the enemy ship has been shot or disabled. Any leftover missiles that would be used to shoot from the disabled ship then exit the scenario. After the enemy missiles have been shot, it passes through an information block so the number of missiles fired can be counted and used in calculations. The following block determines which friendly ship is being targeted. It is based on the back of the envelope which is using the radar cross sections to establish the probability of hit. Therefore, larger ships are targeted more often. There are calculations for intercepts, range, time of first detect, first and last of each of the missiles etc. It is essentially a calculation of distance between two points. After that series of blocks, there is a check to see if all the missiles have been fired. If they have, they are redirected to another ship that has missiles available.

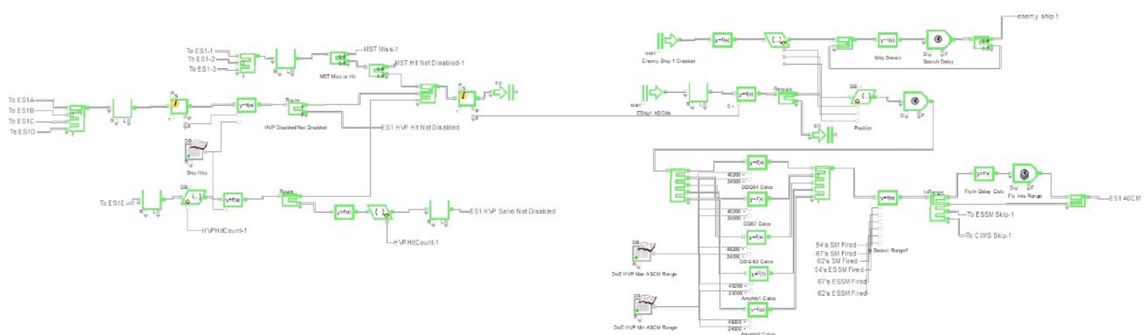

Figure 31. Enemy Ship and Land Targets

2. HVP Model

a. HVP Sequence

The HVP system was incorporated into the baseline model as seen in Figure 32. As discussed earlier in Chapter III, the HVP munitions were installed on the DDGs and CG with the intention to evaluate whether the SOI will improve warfighting capacity, flexibility and capability of legacy weapons systems. For this sequence, the HVP Engage switch connected to a database block, read in runs from the DOE which were associated to a mode status for the HVP system. When the HVP switch is ON and an enemy ship or ASCM is detected, the ship or land target goes to the equation block and from there it would be sent to the HVP Engage block. A logic check is performed to verify that the HVP system isn't overloaded, has enough ammunition, and is in range. If the target is no longer in range for the HVP, it would go to the ESSM because it has the longest distance. The target would be routed to the VLS/SM Engage sequence if the HVP system was overloaded. In the instance that a missile was missed, it must be re-engaged and would be set as a priority one in order to get queued back in first. If all the verification conditions are met, it will proceed to firing.

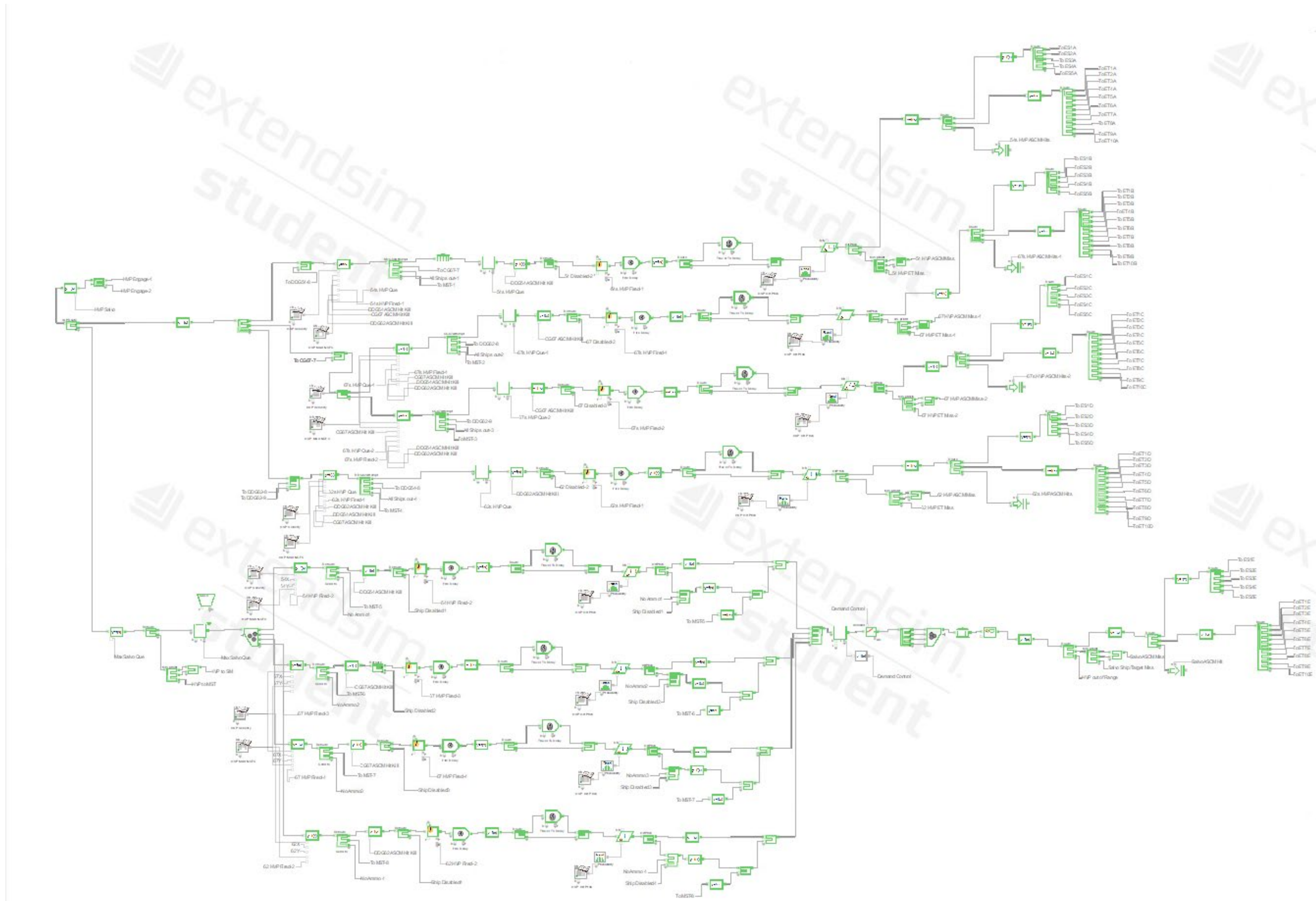

Figure 32. HVP Sequence

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LIST OF REFERENCES

"A Promising Future for US Navy: Vertical Launching Systems." DSIAC. July 08, 2020. https://www.dsiac.org/resources/articles/a-promising-future-for-us-navy-vertical-launching-systems/.

BAE Systems. n.d. "Advanced Gun System (AGS)." Accessed 01 22, 2021. https://www.baesystems.com/en-us/product/advanced-gun-system-ags.

———. 2016. "Mk 45 Naval Gun System - BAE Systems." https://www.baesystems.com/en/download-en/20160511180855/1434555687963.pdf.

"CG 47 Ticonderoga Class AEGIS Cruiser." AeroWeb. 2021. http://www.fi-aeroweb.com/Defense/AEGIS-Cruiser.html.

Clark, Bryan and Jesse Sloman. 2016. "New Operational Concepts for Amphibious Forces." *Advancing*

Beyond the Beach: Amphibious Operations in an Era of Precision Weapons (Winter): iii. https://csbaonline.org/research/publications/advancing-beyond-the-beach-amphibious-operations-in-an-era-of-precision-wea/publication/1

Clark, Bryan, and Mark Gunzinger. "Winning The Salvo Competition: Rebalancing America's Air And Missile Defenses." CSBA. May 20, 2016. https://csbaonline.org/research/publications/winning-the-salvo-competition-rebalancing-americas-air-and-missile-defenses.

Department of Defense. 2020. *DOD Dictionary of Military and Associated Terms.* June. https://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/dictionary.pdf.

Fiore, Eric. 2014. "A Promising Future for U.S. Navy Vertical Launching Systems." *DSIAC Journal* 1 (2) (Fall): https://issuu.com/dsiac/docs/dsiac-journal-fall-web.

Hitchins, Derek K. 2007. *Systems Engineering: A 21st Century Systems Methodology.* John Wiley & Sons.

"Hypervelocity Projectiles: A Technology Assessment." DSIAC. July 06, 2020. https://www.dsiac.org/resources/articles/hypervelocity-projectiles-a-technology-assessment/#:~:text=The high-velocity compact design,magazines and improved shipboard safety.

LaGrone, Sam. 2016. *PACFLT's Swift: Amphib USS Wasp Will Deploy with Surface Action Group in 2017.* Nov 23.

https://news.usni.org/2016/11/23/pacflts-swift-amphib-wasp-will-deploy-surface-action-group-2017.

LaGrone, Sam. 2019. Navy Quietly Fires 20 Hyper Velocity Projectiles Through Destroyer's Deckgun January 08, 2019. https://news.usni.org/2019/01/08/navy-quietly-fires-20-hyper-velocity-projectiles-destroyers-deckgun.

Larter, David B. 2020. *Navy DDG-51 and DDG-1000Destroyer Programs: Background and Issues for Congress.* No. RL32109. Washington, DC: Congressional Research Service. https://crsreports.congress.gov/product/pdf/RL/RL32109/215.

"Lockheed Martin to Upgrade Shipboard Electronics in Aegis Combat System aboard Navy-Burke-class Destroyers." Military Aerospace Electronics. April 16, 2021. https://www.militaryaerospace.com/sensors/article/14201472/shipboard-electronics-combat-system-upgrade.

MITRE. 2016. *Navy Future Fleet Platform Architecture Study.* Study, McLean, VA: U.S. Navy.

Mizokami, Kyle. "The U.S. Navy's Railgun Is Nearly Dead in the Water." Popular Mechanics. March 14, 2021. https://www.popularmechanics.com/military/navy-ships/a32291935/navy-railgun-failure/.

"MK 45 - 5-inch 54/62 Caliber Guns." MK 45 - 5-inch 54/62 Caliber Guns > United States Navy > Displayy-FactFiles. January 16, 2019. https://www.navy.mil/Resources/Fact-Files/Display-FactFiles/Article/2167864/mk-45-5-inch-5462-caliber-guns/.

O'Rourke, Ronald. 2020. *Navy Lasers, Railgun, and Gun-Launched Guided Projectile: Background and Issues for Congress.* Congressional Research Service Report, Washington: Congressional Research Service.

Trevithick, Tyler Rogoway and Joseph. "Here Is What Each Of The Navy's Ship-Launched Missiles Actually Costs." The Drive. December 11, 2020. https://www.thedrive.com/the-war-zone/38102/here-is-what-each-of-the-navys-ship-launched-missiles-actually-costs.

"Upcoming CSBA Report on Missile Defense." InsideDefense.com. September 29, 2020. https://insidedefense.com/insider/upcoming-csba-report-missile-defense.

U.S. Navy. n.d. *America's Navy.* Accessed October 2, 2020. https://www.navy.mil/Resources/Fact-Files/.

———. 2017a. "Our Navy's Mission: How the Surface Forces Fit In." *Surface Warfare* (56) (Fall) 11-14. https://issuu.com/comnavsurfpac/docs/swm_fall_final_102517

———. 2017b. *Fact File - Standard Missile.* January 30. https://www.navy.mil/navydata/fact_display.asp?cid=2200&tid=1200&ct=2.

———. 2018. *Fact File - Tomahawk Missile.* April 26. https://www.navy.mil/navydata/fact_display.asp?cid=2200&tid=1300&ct=2.

———. 2019a. *Dry Cargo/Ammunition Ships T-AKE.* Jan 09. https://www.navy.mil/Resources/Fact-Files/Display-FactFiles/Article/2211797/dry-cargoammunition-ships-t-ake/.

———.2019b. *Fact File - AEGIS Weapon System.* January 10, 2019. https://www.navy.mil/Resources/Fact-Files/Display-FactFiles/Article/2166739/aegis-weapon-system/.

———. 2019c. *Fact File - Amphibious Assault Ships - LHD/LHA(R).* Jan 16. https://www.navy.mil/Resources/Fact-Files/Display-FactFiles/Article/2169814/amphibious-assault-ships-lhdlhar/.

———. 2017a. *Fact File - Cruisers (CG).* January 9. https://www.navy.mil/navydata/fact_display.asp?cid=4200&tid=800&ct=4.

———. 2019d. *Fact File - Destroyers (DDG).* Aug 21. https://www.navy.mil/navydata/fact_display.asp?cid=4200&tid=900&ct=4.

———. 2019e. *Fact File - Evolved Seasparrow Missile Block 1 (ESSM).* January 17. https://www.navy.mil/navydata/fact_display.asp?cid=2200&tid=950&ct=2.

———. 2019f. *Fact File - MK 15 Phalanx Close-In Weapon Ssytem (CIWS).* January 15. https://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=487&ct=2.

———. 2019g. *Fact File - MK 41 Vertical Launching System (VLS).* January 15. https://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=550&ct=2.

———. 2019h. *Fact File - MK 45 5-Inch 54/62 Caliber Guns.* January 16. https://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=575&ct=2.

———. 2019i. *Fact File - SeaRam Close-In Weapon System (CIWS) Anti-Ship Defense System.* January 17. https://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=456&ct=2.

U.S. Navy. 2019. *USS Zumwalt arrives in British Columbia.* March 12. https://www.public.navy.mil/surfor/ddg1000/Pages/USS-Zumwalt-arrives-in-British-Columbia.aspx.

U.S. Navy CDR Leo J. Schneider Jr. 1987. VLS: A Challenge Met, An Old Rule Kept. April 1987. https://apps.dtic.mil/sti/pdfs/ADA183944.pdf

U.S. Navy MC3 Sawyer Haskins. 2020. *201006-N-KT825-1092.* Oct. 6. https://www.navy.mil/Resources/Photo-Gallery/igphoto/2002513367/.

U.S. Navy Petty Officer 2nd Class Natalie Byers. 2020. *Photo Gallery.* Oct. 13. https://www.navy.mil/Resources/Photo-Gallery/igphoto/2002516768/.

Vergun, David. 2020. *China, Russia Nearing Status as U.S. Nuclear Peers, Stratcom Commander Says.* July 30. https://www.defense.gov/Explore/News/Article/Article/2294574/china-russia-nearing-status-as-us-nuclear-peers-stratcom-commander-says/.

Wiederholt, Michael L. 2015. "Vertical Launch System Loadout Planner." Master thesis, Naval Postgraduate School. http://hdl.handle.net/10945/45273

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