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BRINGING HYPERSONIC MISSILE CAPABILITY TO THE FLEET

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SYSTEMS ENGINEERING CAPSTONE REPORT

BRINGING HYPERSONIC MISSILE CAPABILITY TO THE FLEET

by

Sebastian I. Banuchi, Thomas M. Hughes, Cole Rice,
and Thia N. Tank

September 2021

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Hypersonic glide body weapons represent a revolutionary change in offensive capabilities for militaries around the world. The U.S. Navy is developing a hypersonic glide body capability with the Conventional Prompt Strike Program, which has a scheduled initial operational capability of 2025. This capstone project has developed candidate systems that describe how the Army's Long Range Hypersonic Weapon (LRHW) system could be integrated onto various vessels to deliver a hypersonic glide body capability to the Navy before the Conventional Prompt Strike Program is operational. Research indicates that the LRHW is the most mature hypersonic glide body system developed by the United States, and integrating its use aboard Navy ships is the most likely path to success. This capstone describes the user concerns, system requirements, and concepts of operation through the development of systems engineering products that describe each of the candidate systems.

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ABSTRACT

Hypersonic glide body weapons represent a revolutionary change in offensive capabilities for militaries around the world. The U.S. Navy is developing a hypersonic glide body capability with the Conventional Prompt Strike Program, which has a scheduled initial operational capability of 2025. This capstone project has developed candidate systems that describe how the Army's Long Range Hypersonic Weapon (LRHW) system could be integrated onto various vessels to deliver a hypersonic glide body capability to the Navy before the Conventional Prompt Strike Program is operational. Research indicates that the LRHW is the most mature hypersonic glide body system developed by the United States, and integrating its use aboard Navy ships is the most likely path to success. This capstone describes the user concerns, system requirements, and concepts of operation through the development of systems engineering products that describe each of the candidate systems.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFATDS	Advanced Field Artillery Tactical Data System
ASW	Anti-Ship Weapon
AUR	All-Up-Round
C2	Command and Control
CAP	Combat Air Control
C-HGB	Common Hypersonic Glide Body
CPS	Conventional Prompt Strike
DEVCOM	Development Command Chemical Biological Center
DOD	Department of Defense
DoDAF	Department of Defense Architecture Framework
EFFBD	Enhanced Functional Flow Block Diagram
EPF	Expeditionary Fast Transport
ICBM	Intercontinental Ballistic Missile
IOC	Initial Operational Capability
LCAC	Landing Craft Air Cushion
LCS	Littoral Combat Ship
LPD	Amphibious Transport Dock
LRHW	Long-Range Hypersonic Weapon
MOEs	Measures of Effectiveness
MOPs	Measures of Performance
NSM	Naval Strike Missile
ONR	Office of Naval Research
OPNAV N95	Navy’s Resource Sponsor for Expeditionary Warfare
OPNAV N96	Surface Warfare Directorate
PEO IWS	Program Executive Office Integrated Warfare Systems
PEO Ships	Program Executive Office Ships
RAM	Rolling Airframe Missile
RIHMC	Rapid Integration of Hypersonic Missile Capability

SMWDC	Naval Surface and Mine Warfighting Development Center
TLAM	Tomahawk land attack missile
TTWCS	Tactical Tomahawk Weapons Control System
USFF	United States Fleet Forces Command
USNS	United States Naval Ship
VLS	Vertical Launching System.
VPM	Virginia Payload Module
VSTOL	Vertical/Short Takeoff and Landing

EXECUTIVE SUMMARY

The development of anti-missile defenses by U.S. adversaries has propelled the U.S. and the Department of Defense (DOD) to urgently research, test and deploy hypersonic glide body weapons. Hypersonic missiles represent a revolutionary change in offensive capabilities for militaries around the world. As of 2021, the U.S. does not have a hypersonic weapon in its arsenal to counter Chinese and Russian hypersonic weapons already deployed in the battlefield. The Naval Surface and Mine Warfighting Development Center (SMWDC) has proposed a study to examine multiple navy surface ship platforms and perform analysis of how to bring hypersonic missile capability to the surface Fleet by FY 2025.

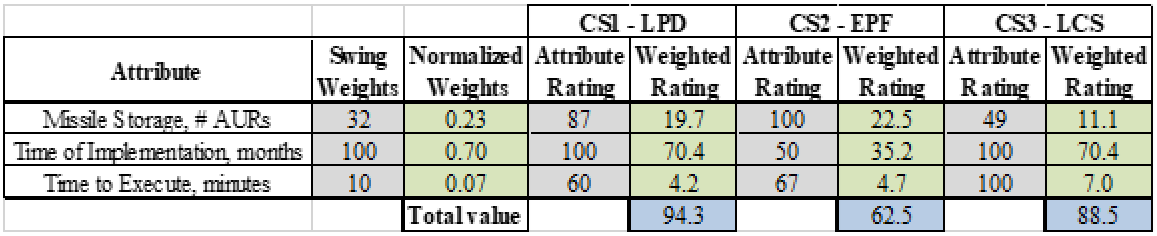
While the Navy is conducting ongoing testing of its version of a hypersonic missile, there is a need to examine alternative launch methods for these missiles from a variety of existing surface ships in the near future. The ability to successfully deploy and launch hypersonic anti-ship missiles, as well as potentially hypersonic missiles in support of land forces, could provide significant advantage to joint forces.

Research into the Army's Long Range Hypersonic Weapon (LRHW) system has shown that the LRHW is currently the most mature hypersonic glide body system developed by DOD and could potentially be integrated onto various vessels to deliver a hypersonic glide body capability to Navy surface ships. This Capstone project has developed three candidate systems that describe a possible integration of the Army's Long Range Hypersonic Weapon (LRHW) system before the Navy's Conventional Prompt Strike Program is operational.

The three types of vessels considered for the candidate systems were: 1) LPD Class Vessel, LRHW with trailer launch, 2) EPF Class Vessel, LRHW AUR with crane launch and 3) LCS Class Vessel, LRHW, with trailer launch. The primary attributes identified and analyzed were: 1) number of AURs stored; 2) time to implement hypersonic launcher on board vessel; and 3) time to execute launch.

Analysis

The system analysis was conducted using the Multi-Attribute Value Theory. This approach allowed the Capstone Team to assess all attributes with a combination of stakeholder preferences over conflicting attributes to discover alternatives with the highest value. The team started by determining the multiple attributes that would be used for measurement. Only the genuine distinctions between alternatives were used to make decisions. Focusing on the differences between our alternatives provided attributes that would offer the strongest justification during our decision evaluation. To appropriately measure three independent criteria within an additive model we determined a swing weight using the Parnell method. The team created a swing weight for each attribute which allows for the individual values to be measured together although they do not have similar units. These swing weights were then used to create the normalized weight for each attribute.



			CS1 - LPD		CS2 - EPF		CS3 - LCS	
Attribute	Swing Weights	Normalized Weights	Attribute Rating	Weighted Rating	Attribute Rating	Weighted Rating	Attribute Rating	Weighted Rating
Missile Storage, # AURs	32	0.23	87	19.7	100	22.5	49	11.1
Time of Implementation, months	100	0.70	100	70.4	50	35.2	100	70.4
Time to Execute, minutes	10	0.07	60	4.2	67	4.7	100	7.0
		Total value		94.3		62.5		88.5

Conclusion and Recommendations

After performing the swing weights analysis of all three attributes, Candidate system 1, LPD, scored highest when evaluated based on all three attributes. Close behind was Candidate system 3, LCS, while Candidate system 2, EPF, lagged behind considerably.

We recommend Candidate system 1, LPD, be considered as a possible ship platform for a future hypersonic glide body weapon system with additional in-depth studies, modeling, and analysis conducted to explore the use of box launchers, LPD trade-offs, and Fleet planning around the new hypersonic missile capability.

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I. INTRODUCTION

A. BACKGROUND

The DOD provides the president and our diplomats the military options that enable them to negotiate from a position of strength. As indicated in the National Defense Strategy of 2018, the U.S. "would generally deploy our forces when we wanted, assemble them where we wanted, and operate how we wanted. Today, every domain is contested-air, land, sea, space, and cyberspace" (Mattis 2018, 3). Since the end of World War II, the U.S. has engaged in several different wars and conflicts that have shown that our competitive military advantage has declined along with a pattern of deteriorating relations between many nations. China is a strategic competitor and has made huge advances in financial growth, military might, and technological development. Russia has continued its aggressive behavior throughout Europe and with Iran as an ally, instigate a great deal of instability in the Middle East. North Korea also continues with its rhetoric and actions even with United Nation's sanctions in place. Due to the current strategic environment, the assumption that the U.S. Navy will continue to maintain dominance at sea is not a foregone conclusion. A more lethal, innovative, and resilient U.S. Navy is necessary to maintain the capability and strong posture to prevail in case of conflict.

Since its creation nearly 250 years ago, the United States Navy has operated surface combatant vessels organized into Carrier Strike Groups, Amphibious Readiness Groups, and Surface Action Groups to keep access of the seas to all sea-worthy vessels and maintain U.S. interests according to U.S. foreign policy. But not since World War II has the U.S. engaged in major fleet combat. Therefore, it is uncertain whether the U.S. Navy can maintain sea control against modern-day adversaries. A recent report by the Center for Strategic and Budgetary Studies, Maritime Competition in a Mature Precision-Strike Regime concludes that since the last major U.S. Navy battle in World War II, "advances in maritime capabilities have been dramatic. Yet the data on the relative value of these new capabilities are meager, culled from minor conflicts that may stimulate as many false conclusions as useful insights" (Krepinevich 2014, 3). Recent maritime challenges include the Chinese Navy in the Western Pacific and Russian Navy in the Arctic, Baltic, and Black Seas. Considering the military and technological advances in hypersonic weapons development of the Chinese in recent years, the U.S. Joint Forces face a considerable challenge to counter with hypersonic weapons of their own. The Navy's conventional prompt strike currently does not include hypersonic weapons as part of its arsenal. This study is aimed at developing the architecture and the strategy for using hypersonic weapons in amphibious dock ships (LPD), Expeditionary Fast Transport (EPF) vessels or Littoral Combat Ships (LCS).

B. PROBLEM STATEMENT

The development and deployment of hypersonic missiles is a major priority for the U.S. Armed Forces. While the Navy has conducted testing of its version of the hypersonic missile, there is a need to examine alternative launch methods for these missiles from existing surface ships in the near future. The ability to successfully deploy and launch hypersonic anti-ship missiles, as well as potentially anti-surface missiles in support of land forces, could provide a significant advantage to joint forces, particularly in the Pacific region.

The objective of the Rapid Integration of Hypersonic Missile Capability (RIHMC) Capstone Team, as provided by the Naval Surface and Mine Warfighting Development Center (SMWDC) sponsor, was to develop a system of systems concept that would allow for vessel classes such as the Expeditionary Fast Transport (EPF) or the Amphibious Transport Dock Ship (LPD) to ultimately provide a launch platform for hypersonic missiles. The team's efforts were focused on providing an analysis of alternatives for adding a hypersonic missile strike capability to ships that are not currently able to launch such missiles. The results of the analysis were used to provide recommendations for how to add low-cost and versatile offensive capabilities to ships not yet equipped with a vertical launching system (VLS). A proof of concept for this approach resulted in a focus on available missiles such as the Tomahawk Land Attack Missile (TLAM)) with subsequent application to hypersonic missiles.

C. RESEARCH OBJECTIVES

The research questions that are addressed throughout this project can be broadly placed into three different categories:

1. Can a system be developed that safely, effectively, and efficiently stores, transports, and launches hypersonic missiles from existing Navy platforms using launch methods that are not currently employed? How can this system accommodate the use of other established missile systems?
2. Which design considerations of the alternative launching system are the most critical to the successful implementation of this offensive strike capability?
3. What are the strategic advantages offered to the fleet by the successful implementation of the offensive strike system described?

D. SYSTEMS ENGINEERING PROCESS

A four-phased system engineering process with a feedback mechanism was created to confirm a meticulous technical approach. Figure 1 illustrates these four phases and how the feedback loop allowed for the concerns, requirements, and architecture to be altered if results from a subsequent phase require the alteration. This agile mechanism permitted concurrent design while working to improve the clarity of our stakeholder's needs.

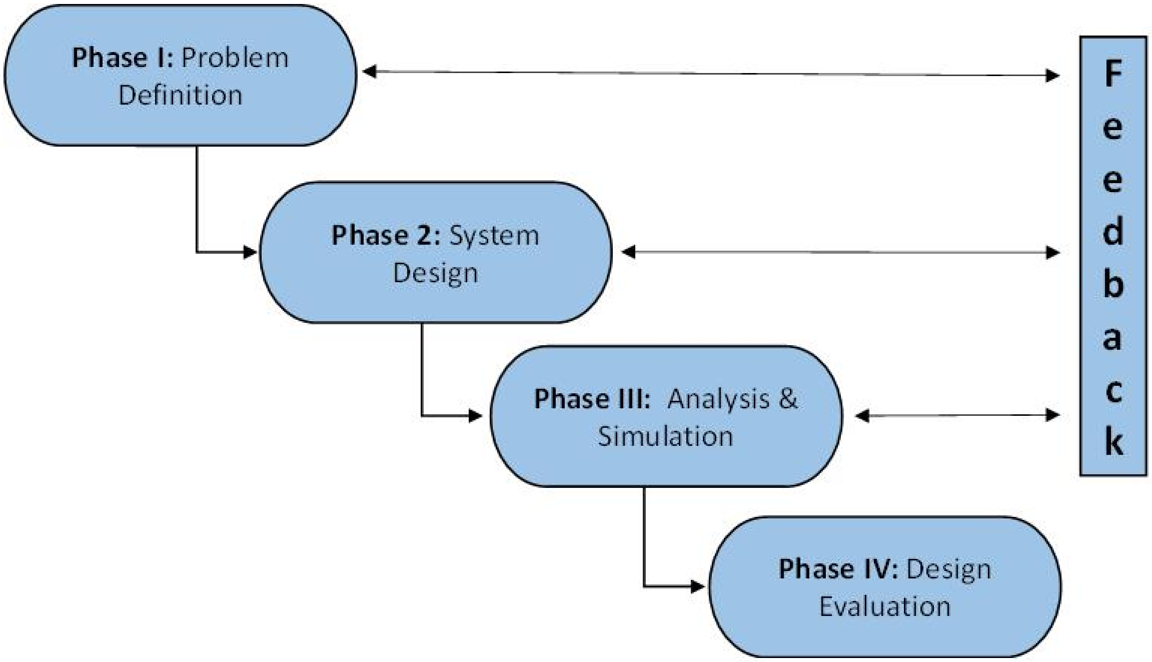

Figure 1. System engineering approach

In the problem definition phase, the problem has been defined and bounded by performing literature reviews and actively engaging with stakeholders to collect concerns about the potential system. These stakeholder concerns, paired with the literature review results, were used lockstep during the stakeholder analysis to create a higher probability that all needs of our stakeholders were going to be met. The use of the concern construct of the systems engineering software chosen for this effort, CORE, allows both requirements and functions, both functional and non-functional, to be developed from the input collected from stakeholders. The use of concerns as the entry point for stakeholder input into the model has also allowed this input to be captured as documenting the concern, and ultimately the derived requirements or functions. Phase I has contributed to both chapters one and two of this report.

In the system design phase, the concerns, requirements, and functions that have been collected in the first phase were turned into a solution-agnostic system architecture. Additionally, a series of measurements of effectiveness were created to assess the performance of the candidate systems during the later phases.

In the analysis and simulation phase, the potential solutions were mapped to the developed architecture. This phase included specific descriptions of potential solutions and how the components meet the requirements and perform the functions in the model. The ability of the candidate systems' characteristics and attributes to fulfill the functions and requirements of the architecture were determined. The results of this analysis were compared to the measurements of effectiveness that were determined in the previous phase.

Finally, the design evaluation included the design evaluation for each of the candidate systems and a set of recommendations for the next steps in the development of this system.

E. THESIS OUTLINE

This thesis will begin with a Literature Review to describe the classes of vessels available in the Navy for the integration of hypersonic missiles, current cruise missile technologies and capabilities, and both current and planned hypersonic glide body technologies and capabilities available to the DOD.

Next, the stakeholders in the rapid development of hypersonic missile capabilities on board Navy vessels are identified and their concerns regarding the capability are presented in the Architecture section. These concerns are organized into white box concerns and black box concerns – the former being concerns about the system that are dependent upon the manner in which the system is designed, and that latter being concerns about the system that are agnostic to the system's design. A system architecture to capture these concerns and develop requirements, measures of effectiveness (MOEs), measures of performance (MOPs), and guide system descriptions is also presented.

A generic hierarchy for a hypersonic launch is presented and used as the basis for each of the candidate systems described in the System Development section. Three distinct candidate systems are presented, each launching the Army LRHW from a different class of vessel. A detailed description of each candidate system is presented, along with enhanced functional flow block diagrams (EFFBDs) and DOD Architecture Framework (DoDAF) SV-5b matrices describing the operation of each system.

The Multi-Attribute Value Theory was used to perform an analysis of the three candidate systems to recommend the best system for development. Three attributes of the systems were chosen: Number of All-Up- Rounds (AURs) Stored, Time to Implement the candidate system, and Time to Execute a missile launch. These attributes were determined for each system through an analysis of each systems' components and simulation using the previously developed EFFBDs. Each attribute was associated with a linear piece-wise rating curve and swing weight in accordance with the Multi-Attribute Value Theory to arrive at relative scores for each system and each attribute. A sensitivity analysis was performed on these results.

Finally, a recommendation for which candidate system to pursue and a description of multiple areas for future research to support the rapid development of a hypersonic missile capability are presented in the Conclusions and Future Work section.

II. LITERATURE REVIEW

This project was conducted to determine the highest-ranking alternatives for rapidly providing hypersonic missile launching capabilities to the fleet by understanding current military technologies. These technologies include ship classes, missile launching systems, and different missile types. The history of ship modularity was also investigated to fulfill the stakeholder need for rapid implementation to the fleet.

A. SPEARHEAD-CLASS EXPEDITIONARY FAST TRANSPORT (EPF)

The Spearhead-class EPF, shown in Figure 2, is a rapid sealift vessel designed to allow rapid movement of cargo within theater. It is equipped with a catamaran hull that allows it to operate with a shallow draft in the littoral zone. The EPF can provide combatant commanders with a high-speed sealift capability. The EPF is not equipped with any offensive weapons systems and currently does not have any capability to contribute to an offensive strike.

The EPF can land up to a single CH-53 Sea Stallion helicopter on its flight deck but cannot place any aircraft into a hangar. The EPF has a mission bay that is located below the flight deck and opens to a deployable loading ramp and an extensible boom crane that can lift a maximum of 27,000 pounds when fully extended to 49 feet (Christopher DeWindt, email to author, January 15, 2021). The mission bay provides an 1,800 m^2 area for the storage and maneuvering of cargo (Vavasseur 2020). The EPF is not equipped with a magazine for the safe storage and munitions.

Figure 2. Spearhead-class EPF featuring the flight deck and extensible boom crane. Source: Vavasseur (2020).

B. SAN ANTONIO-CLASS LANDING PLATFORM, DOCK (LPD)

The San Antonio-class LPD, shown in Figure 3, is an amphibious transport vessel capable of launching rotary wing and vertical/short takeoff and landing (VSTOL) aircraft from a flight deck, as well as launching amphibious vehicles such as the Landing Craft Air Cushion (LCAC) from its well deck. The flight deck of the LPD is adjacent to a mission bay where aircraft are stored and prepared before being towed onto the flight deck for launching without the need for an elevator to bring the aircraft to the flight deck. The LPD has approximately 640 m^2 of area available in its hangar while 2,323 ft^2 of space available is available in the lower decks to store vehicles for the amphibious force being transported (Federation of American Scientists 2000). The LPD also features internal ramp systems that allow vehicles that are stored in the vessel to be transported to the mission bay, as shown in Figure 4. The LPD also has a volume of 708 m^3 available to store munitions in two separate ammunition magazines below decks.

Figure 3. A San Antonio-class LPD highlighting the mission bay adjacent to the flight deck. Source: Seaforce-online Naval Information (n.d.b).

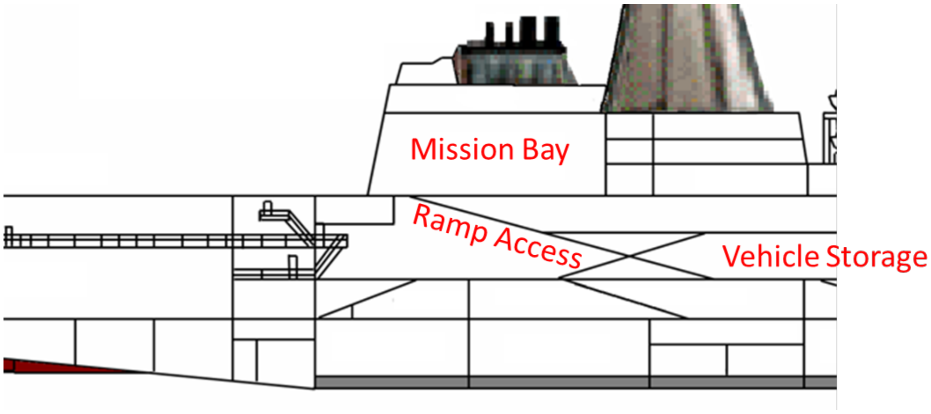

Figure 4. Cutaway diagram of San Antonio-Class LPD highlighting the mission bay access from storage via ramp. Image courtesy of Naval Warfare Studies Institute (2021).

C. INDEPENDENCE-CLASS LITTORAL COMBAT SHIP

The Independence-class littoral combat ship (LCS), shown in Figure 5, is a vessel designed to perform a multitude of combat roles while operating close to shore. The LCS is equipped with a flight deck and hangar space that can accommodate operations with a single MH-60 Seahawk helicopter alongside other unmanned aerial reconnaissance vehicles. The hangar of the Independence-class LCS provides an area of 351 m^2 while the cargo space located in the deck below the flight deck and hangar provides an area 1,410 m^2 for storage. This cargo area and the hangar are connected by an elevator with a length of approximately 20 feet (Seaforces-online Naval Information n.d.a). The bow of the Independence-class LCS can be equipped with box launchers that can currently accommodate missiles like the Naval Strike Missile. The LCS is equipped with magazine storage for ammunition only for its onboard weapons systems, not for any weapon systems that are carried as cargo.

Figure 5. Independence-class LCS highlighting the flight deck and bow missile launchers. Source: Seaforce-online Naval Information (n.d.a).

D. TOMAHAWK LAND ATTACK MISSILE

The Tomahawk land attack missile (TLAM) is a cruise missile that can currently be launched from the Mk 41 VLS or other established launching systems. The TLAM is a sub-sonic missile, with a top speed of about 500 miles per hour and a maximum range of approximately 1,000 miles and physical dimensions of 20 inches in diameter, 20.5 feet long, and 3,500 pounds (Missile Defense Project 2021). The newest block of the TLAM is equipped with a GPS enables targeting system that allows the missile to update its flight path during its travel to the target and to be able to loiter while waiting for additional assets to be available for an attack or a target to be available to attack. This allows the TLAM to approach from headings and angles that may not be expected by enemy defenses. With its relatively slow speed, the TLAM relies upon its low flight altitude to reduce its exposure to detection by enemy radar systems. According to Nicholls (2020), the slow airspeed of the TLAM makes individual TLAMs exceptionally vulnerable to active air defenses. In some scenarios, a combat air patrol (CAP) of four F-15 fighters equipped with air-to-air missiles would be able to successfully intercept an attack consisting of eight TLAMs (Nicholls 2020, 24). The number of TLAMs that are required to overwhelm the active defenses of a target will vary based on the number and types of defenses, however, it is unusual for dozens of TLAMs to be launched at a target to ensure that its defenses are penetrated, and the target destroyed. Figure 6 shows a TLAM being launched from a single cell of an Mk41 VLS while an additional 31 TLAMs could be loaded in the remaining cells of the VLS.

Figure 6. A TLAM being launched from a Mk 41 Launcher. Source: LaGrone (2020).

E. HYPERSONIC MISSILES

Hypersonic missiles can be broadly separated into two different categories: hypersonic glide body systems and hypersonic cruise missile systems. The hypersonic glide body system consists of a booster rocket with a hypersonic glide vehicle attached as a warhead. The booster rocket launches in a trajectory that starts like a standard intercontinental ballistic missile (ICBM) but releases the hypersonic glide vehicle early in the trajectory, allowing the glide vehicle to maneuver to its target while moving at Mach 5 or faster (Congressional Research Service 2021, 2). These hypersonic glide vehicles are not powered by a rocket motor but instead rely upon the kinetic energy imparted to them from the booster rocket to reach their target.

1. Common Hypersonic Glide Body

The U.S. Army and U. S. Navy have collaborated since 2018 to develop a common hypersonic glide vehicle, now known as the Common Hypersonic Glide Body (C-HGB), shown in Figure 7. The C-HGB takes the place of the warhead in a conventional ballistic missile and can be equipped with several different types of missiles. Two missile systems that have been equipped with the C-HGB, or precursors to the current glide vehicle, include the Minotaur IV rocket and Trident II missiles (Congressional Research Service 2020, 13). The use of the C-HGB on these missiles is important because of the size of the missiles; the Minotaur IV weighs 95 tons and is nearly 80 feet tall (Space Launch Report 2020) while the Trident II weighs 65 tons and is nearly 45 feet tall (Federation of American Scientists 1998). While the Minotaur IV is not intended for offensive strike missions, the Trident II is equipped on the Ohio-class nuclear ballistic missile submarine and could be equipped with a C-HGB warhead. While it may generally hold true that the more power a boost missile carrying a C-HGB has, the further the range of the C-HGB, it is not clear how the capabilities of the boost missile will directly affect the C-HGB's performance.

Figure 7. Common hypersonic glide body. Source: Jones-Bonbrest (2019).

2. U.S. Navy Conventional Prompt Strike

The U.S. Navy’s Conventional Prompt Strike (CPS) program is aiming to pair the C-HGB warhead with an intermediate-range ballistic missile to provide hypersonic missile capabilities to the Virginia-class submarine. A new booster is being developed for the CPS that will be able to launch the C-HGB from the recently developed Virginia Payload Module (VPM) (Congressional Research Service 2020, 22). The program is slated to have an FY2028 initial operational capability (IOC).

The VPM is an upgrade for the Virginia-class nuclear-guided missile submarine. The VPM will replace a number of the current missile launch tubes on the submarine and give the submarine a modular capability for increased mission flexibility (Eckstein 2017). The VPM will be able to accommodate the launch and retrieval of underwater unmanned vehicles, contain seven TLAM missiles, contain yet undetermined hypersonic cruise missiles, or house an intermediate-range missile capable of being equipped with a hypersonic glide vehicle. Regardless of the final configuration, the VPM represents a self-contained weapons platform that can meet a number of different missions, including the launch of a C-HGB equipped missile.

3. U.S. Army Long Range Hypersonic Weapon

The U.S. Army is developing a hypersonic glide body missile system under the Long-Range Hypersonic Weapon (LRHW) program, with an IOC of 2023 (Neil 2019). The LRHW consists of an AUR, a trailer for mounting the AURs, an M983A4 tractor for maneuvering the system, and an Advanced Field Artillery Tactical Data System (AFATDS) operations center (Trevithick 2021). The LRHW is a collaboration between the U.S. Army and the U.S. Navy that uses the C-HGB attached to a booster missile whose development has not yet been completed. The LRHW AUR, shown in Figure 8, consists of a canister that contains the booster and C-HGB in a state that is ready to be loaded onto the trailer and launched. The trailer system is a modified U.S. Army M870 trailer that can hold two AURs simultaneously.

Figure 8. An inert training AUR for the LRHW program. Source: Trevithick (2021).

The M870 trailer, shown in Figure 9 equipped with LRHW AURs, is 42 feet long, 8 feet wide, 5.5 feet tall and can carry up to 40 tons (Headquarters, Department of the Army 1999). The individual weights of the AUR's are not known, but the fact that the M870 can carry two simultaneously gives an upper bound of 20 tons for an individual AUR.

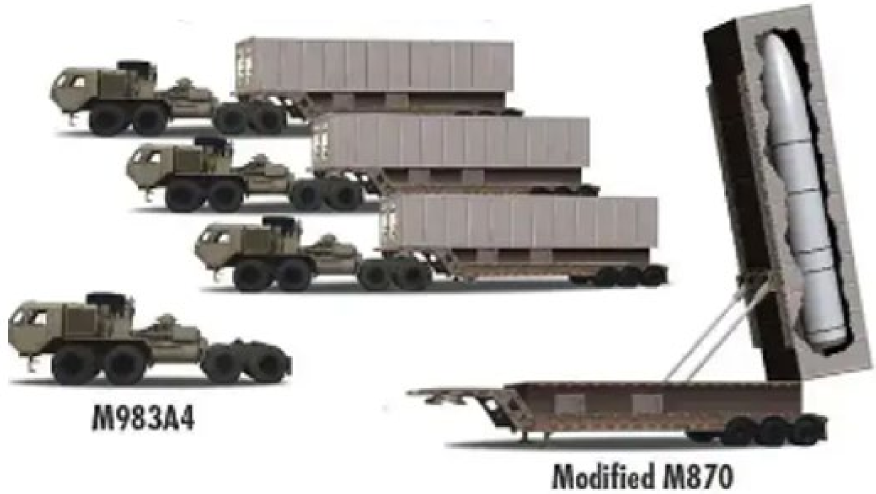

Figure 9. M870 trailers equipped with two LRHW AURs each. Source: Thurgood (2019).

F. VESSEL MODULARITY

J. Schank articulates the concept of modularity and flexibility to build adaptable ships to reduce cost and time in the book *Design Adaptable Ships: Modularity and Flexibility in Future Ship Designs* (Schank 2016). He provides insight into the different definitions of modularity that currently exist in the infrastructure of ships and how these definitions can be used to keep the Navy ships progressing in a modular dynamic. These definitions are broken out into three different concepts.

First Schank describes common modules used across multiple class ships as structural pieces that are built and tested in factory-like environments (Schank 2016). Second, he describes the next concept as self-contained modules that provide a plug-and-play capability. He uses the example of a vertical launch system as being designed on a specific class ship but providing a specific interface and functionality of missile launching. His last concept is explained as structure and services that can be interchanged or installed as needed. These modular installations provide a ship with flexibility although the interfaces have much broader boundaries.

The concept of modifying the original design or even the mission of a ship is not new in the U.S. Navy. For instance, the Navy has been interested in enhancing the original mission and capabilities of the LPD since 2016 (Harper 2016).

These exchanges with Huntington Ingalls Industries contributed to the award of a cost-plus-fixed-fee contract for life cycle engineering and support services of the LPD (Huntington Ingalls Industries, Inc. 2021). Huntington Ingalls Industries has realized the necessity to adapt current ships to have new capabilities, stating "We look forward to supporting these ships as they evolve to meet the changing environment" (Huntington Ingalls Industries, Inc. 2021). Services to supply the Navy with system engineering and integration are highlighted in the news release titled Ingalls Shipbuilding Awarded Life-Cycle Engineering Contract on U.S. Navy's LPD Program (Huntington Ingalls Industries Inc, 2021).

Another supporter of the idea of flexible ships is Glen Sturtevant, Director for Science and Technology for the Navy Sea Systems Command. In a brief entitled, "Flexible Ships" Sturtevant (2015) discusses the benefits of providing modifications to, "Provide the warfighting requirements that will drive flexible, common, and open architectures into our ship designs and acquisitions." Such an approach could bring hypersonic missile launching capability to the fleet rapidly.

Due to the recent interest within the Navy to pursue a surface ship launch platform for a hypersonic glide missile, modifying ships such as the LPD and EPF by installing a missile launch capability may offer a cost-effective and rapid solution.

G. LITERATURE REVIEW CONCLUSION

The literature review for this project focused on describing the current capabilities and attributes of the ships that could be used or modified to achieve additional hypersonic missile capabilities, the current capabilities of the non-hypersonic missile systems that these vessels are equipped with, and finally the likely attributes of the hypersonic missiles that could be equipped on the vessels. The vessels and hypersonic missiles were combined in a variety of ways to create candidate systems for achieving the hypersonic missile capability. The non-hypersonic missile capabilities were presented to establish the current state of missile strike capabilities and provide the background for a comparison of the potential hypersonic missile capability of each candidate system.

The research performed on the vessels and weapons systems that could be used to achieve the goal of rapidly equipping a surface vessel with a hypersonic strike capability, indicates that there is the potential for several different combinations of candidate systems. Several generalizations can be made about the state of hypersonic missiles on surface vessels:

1. None of the vessels studied have a current ballistic missile launching capability or an obvious way to install a ballistic missile launching capability. The same holds true for traditional sub-sonic cruise missile capabilities. Significant modification of the vessels or the use of missile launching systems not permanently installed on the vessels will be needed.
2. The exact physical configuration of a boost missile equipped with a C-HGB is still unknown. While the LRHW AUR provides a reasonable definition for the size and weight requirements to launch the C-HGB, it is possible that a smaller boost missile could be used or that a larger boost missile would be required for the mission at hand. This size requirement precludes the use of current launching systems like the Mk 41 VLS for launching C-HGB equipped ballistic missile, but it does not necessarily preclude hypersonic scramjet equipped cruise missiles from being fit into current systems like the Mk 41 VLS.
3. There are no programs for launching the C-HGB that are more mature than the LRHW. While the Navy’s CPS program will equip the Virginia-class submarine with a hypersonic glide vehicle strike capability, it is not slated for IOC until 2028. The boost missile system that will be used for this capability is not yet clear and no information could be found on it. This iteration of the C-HGB equipped missile will have to fit either in the standard missile tubes currently equipped or the upgraded VPM. It is

reasonable to assume that the VPM will be able to accommodate the equipping and use of a C-HGB equipped ballistic missile.

III. ARCHITECTURE

A simple architecture was developed to allow the concerns of identified stakeholders to be captured. These concerns are recorded as white box concerns or black box concerns. The concerns result in the development of requirements, MOEs, and MOPs that will later help to guide the development of the candidate systems.

A. ARCHITECTURE DESCRIPTION

The Hypersonic Missile Launching System architecture design aimed to document stakeholder concerns and requirements and map them to the functions and components of the candidate systems. The architecture starts with stakeholders providing concerns about the potential system. A requirements analysis results in requirements from these concerns to address the issues or questions that the stakeholders have raised. Finally, a functional analysis translates system requirements into design criteria and identification of the resources required for the system to operate (Fabrycki 2011, 86). Figure 10 shows this schema, which is derived from the CORE DoDAF v2.02 Schema.

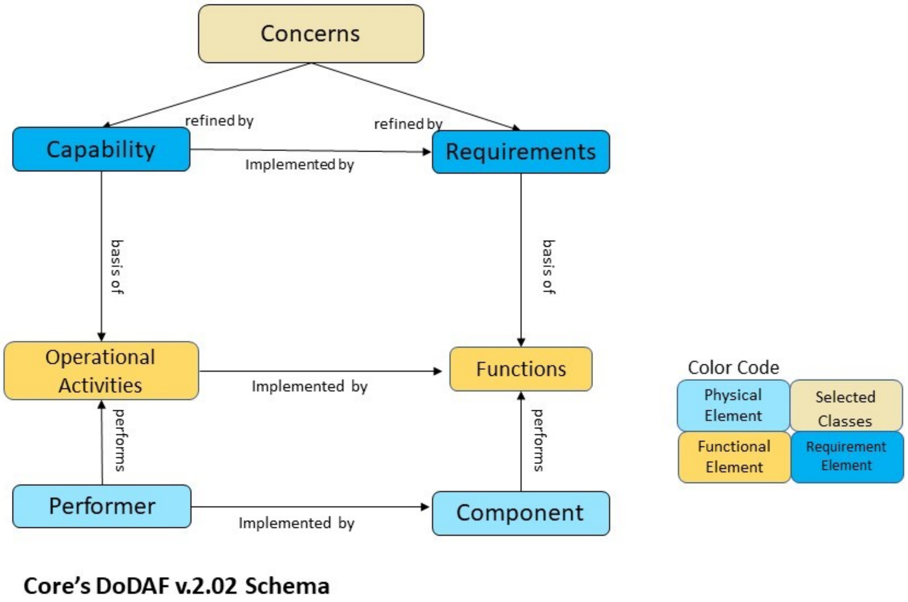

Figure 10. Architecture schema

B. STAKEHOLDER IDENTIFICATION

Performing stakeholder analysis facilitates delivering a high-quality product. This analysis allowed the RIHMC Capstone Team to identify key concerns that our stakeholders might have as well as understand their impact on our system. Actively engaging with all stakeholders, produces a higher probability that the finished product will meet the users' needs and requirements and perform as expected. The RIHMC Capstone Team has researched the mission of each stakeholder to support the determination of the primary concerns for each stakeholder represented in Table 1. These concerns are the first tier of the hypersonic missile launching architecture and are described in more detail in Tables 2 and 3.

Table 1. Stakeholder primary concerns

Stakeholder	Primary Concerns
Surface Warfare Directorate (OPNAV N96)	Con.2.3-How does the new hypersonic missile system impact other weapon systems in other combat ships? Con.1.1.1-What training will be required for the personnel to operate the hypersonic missile launching system? Con.1.5 -What targeting features will the system have? Con 1.3.1 -How many missiles will the system be able to launch?
Navy's Resource Sponsor for Expeditionary Warfare (OPNAV N95)	Con.1.1-How would the new missile launching capabilities on the LPDs and EPFs impact personnel manpower and training to be able to maintain readiness? Con.1.5 -Is the missile launching system targeting reliable?

Stakeholder	Primary Concerns
Office of Naval Research (ONR)	Con.2.5-What research still needs to be conducted to obtain an effective hypersonic missile within a few years? Con.2.5-What measurements of effectiveness were applied to the candidate systems? Con.1.4-How will the missile be stored?
Naval Surface and Mine Warfighting Development Center (SMWDC)	Con.2.3-Is the hypersonic missile launching system suitable for LPD and EPF vessels? Con.1.3-What is the impact to the operational mission of the Amphibious Task Force with this new missile launching capability?
United States Fleet Forces Command (USFF)	Con.1.3-How does the hypersonic missile system contribute to the fleet's capabilities and mission sets? Con.1.1-What personnel will be required on the vessel to operate the hypersonic missile launching system?
Program Executive Office Integrated Warfare Systems (PEO IWS)	Con.2.4-How long would the hypersonic missile launching system implementation take?
Program Executive Office Ships (PEO Ships)	Con.1.2-What operational changes need to be made to the LPD or EPF to accommodate the launching system?

OPNAV N95 is the Navy's resource sponsor for expeditionary warfare. "The organization establishes requirements, sets priorities, and directs overall planning and programming for expeditionary warfare systems and related manpower, training, and readiness" (Campbell 2018). OPNAV N95 concerns are personnel, training, and planning required for the successful integration of the hypersonic missile launching system.

"OPNAV N96, the Surface Warfare Directorate, is responsible for the determination of force levels, shipboard and related support requirements, and major features of programs involving weapon systems, cruisers, destroyers, frigates, command ships, patrol craft, and littoral combat ships" (Campbell 2018).

The Office of Naval Research (ONR) is a branch of the United States Department of the Navy that focuses on the Navy's and Marine Corps' research and technology projects. The aim of the Office of Naval Research is to outline and develop scientific research to preserve future naval strength and ensure national security. (Welcome Aboard 2021)

The Naval Surface and Mine Warfighting Development Center (SMWDC) provides sponsorship to the Naval Postgraduate School (NPS) for scientific research and investigations.

One mission of the United States Fleet Forces Command (USFF) is to "Train, certify and provide combat-ready Navy forces to combatant commanders that are capable of conducting prompt, sustained naval, joint and combined operations in support of U.S. national interests." (Commander, U.S. Fleet Forces Command 2021).

> Program Executive Office Integrated Warfare Systems (PEO IWS) and PEO Ships are responsible for the development, delivery, and sustainability of operationally dominant combat systems for Sailors. The Program Executive Office Ships manages the acquisition and complete life-cycle support for all U.S. Navy non-nuclear surface ships. These ships range from frontline combatants to amphibious ships that transport Marines and their equipment to supply and replenish cargo ships. For these and all other non-nuclear surface craft, PEO Ships maintains "cradle to grave" responsibility including research, development, acquisition, systems integration, construction, and lifetime support. (Commander Naval Sea Systems Command 2021)

PEO stakeholders would be concerned with the steps necessary for implementation as well as additional research that may need to be conducted for rapid but successful execution of this system within the vessels.

C. STAKEHOLDER ANALYSIS

For any systems engineering process, the needs analysis identifies the goals and stakeholders of each user and records them. Due to the complexity of the system, the solution-independent needs are fundamental in having a complete scope of the system. The concerns generated by the stakeholder's analysis have been distributed into the design of the hypersonic missile launching system architecture. The RIHMC Team established an architectural development approach consistent with Aleksandraviciene and Morkevicius (Aleksandraviciene 2018).

There are two categories that stakeholder concerns can fall into white box concerns and black box concerns. White box concerns are concerns that deal with the mechanisms of how the system will operate and what its components are. In the context of this project, an example of a white box concern would be the ability to store the LRHW AUR safely onboard a vessel. This concern would result in a requirement that would need a component or sub-system of the system to be designed or operated in a specific way.

Table 2. White box concerns

Number	Element	Description
Con.1.1	Personnel Required for Missile Launch Mission	There will need to be a group of personnel that are trained in the use of the LRHW. The extra burden of this Army-based training that would normally be done by an artillery group could be significant.
Con.1.2	Personnel Required to Authorize Attack	An officer with the ability to authorize an offensive first strike must be present on the vessel
Con.1.3	Operational Area Concerns	The new system will need to fill a capability gap
Con.1.4	Vessel Mission Concerns	Converting some of a vessel's capabilities to a missile capability may alter the vessel's mission significantly
Con.1.5	Onboard Missile Storage	The missiles must be able to be stored safely on board the vessel
Con.1.6	Onboard Missile Movement	The missiles must be able to be moved around the vessel to be prepared for launch. This concern is

Number	Element	Description
		not valid if the missiles are loaded into a dedicated launcher
Con.1.7	Missile Targeting Concerns	The missiles must get targeting information from somewhere.
Con.1.8	Meteorological Events Affecting Launch	The weather may affect the ability to launch missiles.
Con.1.9	Sea State Affecting Launch	The sea state may affect the ability to launch missiles.
Con.1.10	Missile Launch Damaging Vessel	The exhaust of the missile must not cause damage to the surface of the ship it is being launched from

Black box concerns are concerns that exist agnostic of the internal mechanisms of the system. An example of a black box concern would be the effect of the system's capability on fleet planning. In this example, the capability of launching the hypersonic missile is what is critical to the concern while how the hypersonic missile is launched is unimportant. Concerns will be generated in one of these two categories and presented in separate hierarchies.

Table 3. Black box concerns

Number	Element	Description
Con.2.1	External Communications Concerns	Concerns regarding communication
Con.2.1.1	Voice Communications Concerns	LOS or satellite radio and voice data communications with Command and Control
Con.2.1.2	Mission Operations Data Concerns	Link 16 network communication and exchange of sensor information, creating a common operating picture (COP)
Con.2.2	Vessel Environment Concerns	Concerns regarding the environment the vessel will operate in
Con.2.2.1	Meteorological Data Concerns	Ability to accurately receive GMDSS data or predictive weather data such as barometric pressure

Number	**Element**	**Description**
Con.2.3	Existing System Integration	The system must have integrability with existing systems.
Con.2.4	Rapid Implementation	Concerns about how quickly the system can be implemented
Con.2.5	Testing & Research Concerns	Concerns about what testing and research has been completed
Con.2.6	Cost Concerns	How much will this cost

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IV. SYSTEM DEVELOPMENT

The candidate systems were developed by collecting concerns, mapping requirements to concerns, developing MOEs and MOPs, and then proposing mechanisms to launch the LRHW from several different Naval vessels. The concerns, requirements, MOEs and MOPs, and a description of each candidate system, including several systems engineering views, were recorded in the model-based systems engineering tool CORE. This section of the paper describes the process of developing the candidate system from concern to EFFBD.

A. REQUIREMENTS ANALYSIS

System requirements are requirements that describe the functions that the system should complete to satisfy stakeholder concerns and are stated in a collection of statements, views, and non-functional requirements. The non-functional requirements of the system reflect the levels of safety, availability, dependability, and other factors that the system will need to achieve (Faisandier 2021). After concerns and technical approach have been identified the translation of requirements is generated to help identify areas of the system that may be inconsistent, incomplete, or unrealistic (Kossiakoff et al. 2020). Figure 11 is a visual representation of the hierarchy of stakeholder concerns identified in the stakeholder analysis which result in requirements of the hypersonic missile launching system.

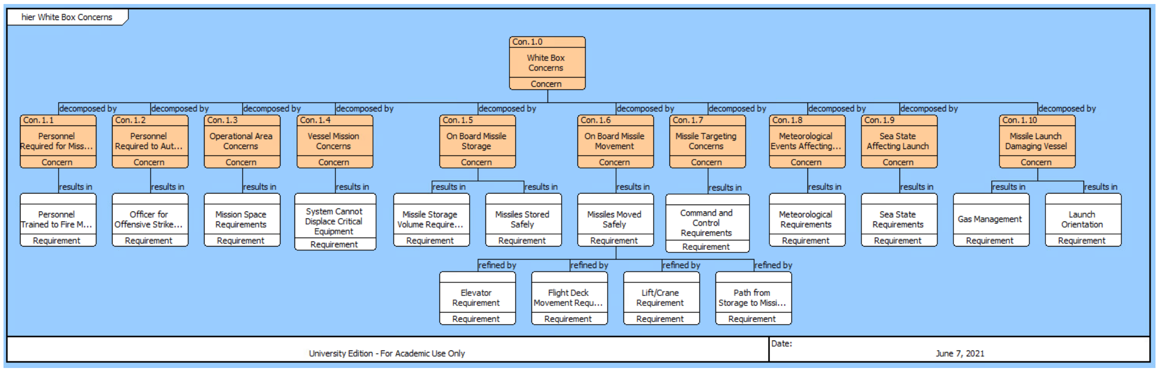

Figure 11. A diagram of concerns resulting in requirements

B. OPERATIONAL SCENARIO

The following scenario is intended to provide the means to evaluate MOPs and MOEs for two very different types of surface ships modified to launch hypersonic glide missiles, each ship type offering unique operational advantages.

> Country Red is installing a modern ICBM launch site on its mainland. This site could launch ICBMs (intercontinental ballistic missile) capable of reaching Country Blue's major cities/military bases as well as military bases and partner nations in the Azure Ocean. Country Blue has equipped five surface vessels (three near-ashore/littoral class ships; one blue-water large deck amphibious class ship) with the ability to launch hypersonic missiles. Each near-ashore/littoral type ship can carry one such missile; the large deck amphibious ship can carry five such missiles. All of these missiles would have the range to strike Country Red's ICBM launch site based upon the launch vessel's assigned operating area. Country Red has sophisticated ISR capability and could be expected to strike any ship launching such a missile. The likelihood is that it would take more than one hypersonic missile to eliminate the ICBM launch site.

Figure 12 shows the three littoral class ships firing their single hypersonic missile and the blue water ship firing its three hypersonic missiles at the hypothetical ICBM site. Country Red's anti-ship weapon (ASW) sites are shown returning fire on the vessels that carried out the hypersonic missile strike with anti-ship missile systems located further inland, but not with direct fire from shore batteries.

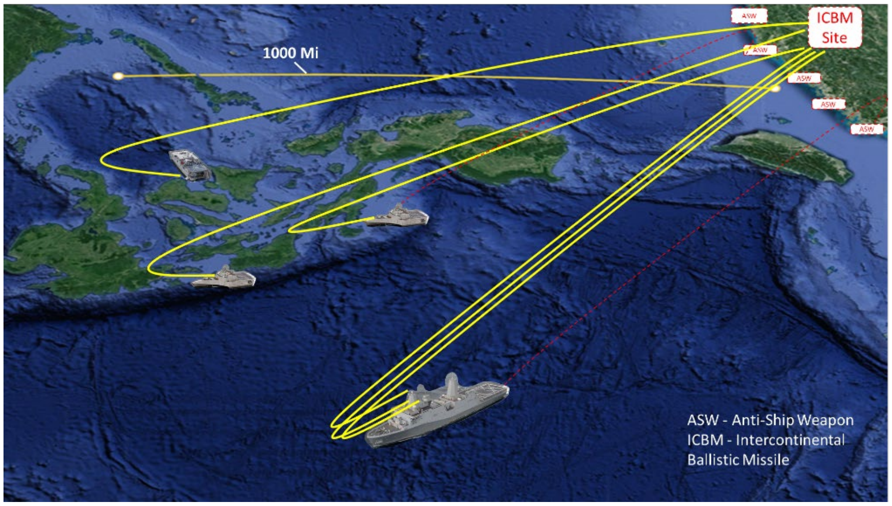

Figure 12. OV-1 of the operational scenario presented

C. MEASURES OF EFFECTIVENESS AND PERFORMANCE

The MOEs of a system are defined by the Defense Acquisition University to be "The data used to measure the military effect (mission accomplishment) that comes from using the system in its expected environment." The MOPs of a system are defined by Green to be "measures derived from the dimensional parameters (both physical and structural) and measure attributes of system behavior." Other examples of performance parameters that are MOPs include speed, weight, range, or rate of fire. Table 4 shows MOEs and MOPs that are derived from the white box concerns developed earlier in the model and Table 5 shows MOEs and MOPs that are derived from black box concerns.

Table 4. MOEs and MOPs derived from model white box concerns

Measure of Effectiveness	**Measure of Performance**	**Model Concern**
Crews can launch the missile		Con.1.1 Personnel Required for Missile Launch Con.1.2 Personnel Required to Authorize Launch
System can be used while vessel deployed		Con.1.3 Operational Area Concerns
		Con.1.4 Vessel Missile Concerns
No degradation of other vessel missions		Con.1.4 Vessel Missile Concerns
Missile can be stored on the vessel	Number of AURs a vessel can store	Con.1.5 On Board Missile Storage
Missile can be moved throughout the vessel	Time required to move missile from storage to ready-to-launch state	Con.1.6 On Board Missile Movement
Missile system's C2 system is compatible with the vessel's C2 systems by launching missile	Time required to apply mission data package	Con.1.7 Missile Targeting Concerns
Authorization to fire can be received		Con.1.7 Missile Targeting Concerns
Missile can be launched	Maximum wind speed missile can be launched under Maximum sea state missile can be launched under Missile launch rate Time required to launch missile from neutral vessel state.	Con.1.8 Meteorological Events Affecting Launch Con.1.9 Sea State Affecting Launch
Missile launching is compatible with the type of vessel	Chance of damaging vessel with launch	Con.1.10 Missile Launch Damaging Vessel

Table 5. MOEs and MOPs derived from model black box concerns

Measure of Effectiveness	**Measure of Performance**	**Model Concern**
Crews and the missile launcher can communicate with Command and Control		Con.2.1.1 Voice Communications Concerns
Crews and the missile launcher can communicate with Command and Control		Con. 2.1.2 Mission Operations Data Concerns
System can be used while vessel deployed		Con. 2.2 Vessel Environment Concerns
System can be used while vessel deployed		Con. 2.2.1 Meteorological Data Concerns
System can be integrated into the vessel and the Fleet		Con.2.3 Existing System Integration Concerns
System can be implemented into fleet vessel	Number of years until operation	Con.2.4 Rapid Implementation Concerns
Field testing have yielded satisfactory results		Con 2.5 Testing & Research Concerns

D. FUNCTIONAL ANALYSIS

The four primary areas of operational activity that have been identified for the system are:

- Storing the missiles – this includes the logistical front end of getting both the missiles and whatever launching system that will exist into ship storage.
- Preparing the missiles for launch – this includes setting up the missile launching system, moving the missiles to the launcher, and loading the missiles.
- Launching the missiles – this includes providing the missiles with targeting information, launching the missile, and recovering the launcher to be able to fire again if the ship will have multiple missiles.
- Retrograding the launcher – this includes breaking down the launcher for storage and returning the ship to a state where it can conduct its other missions.

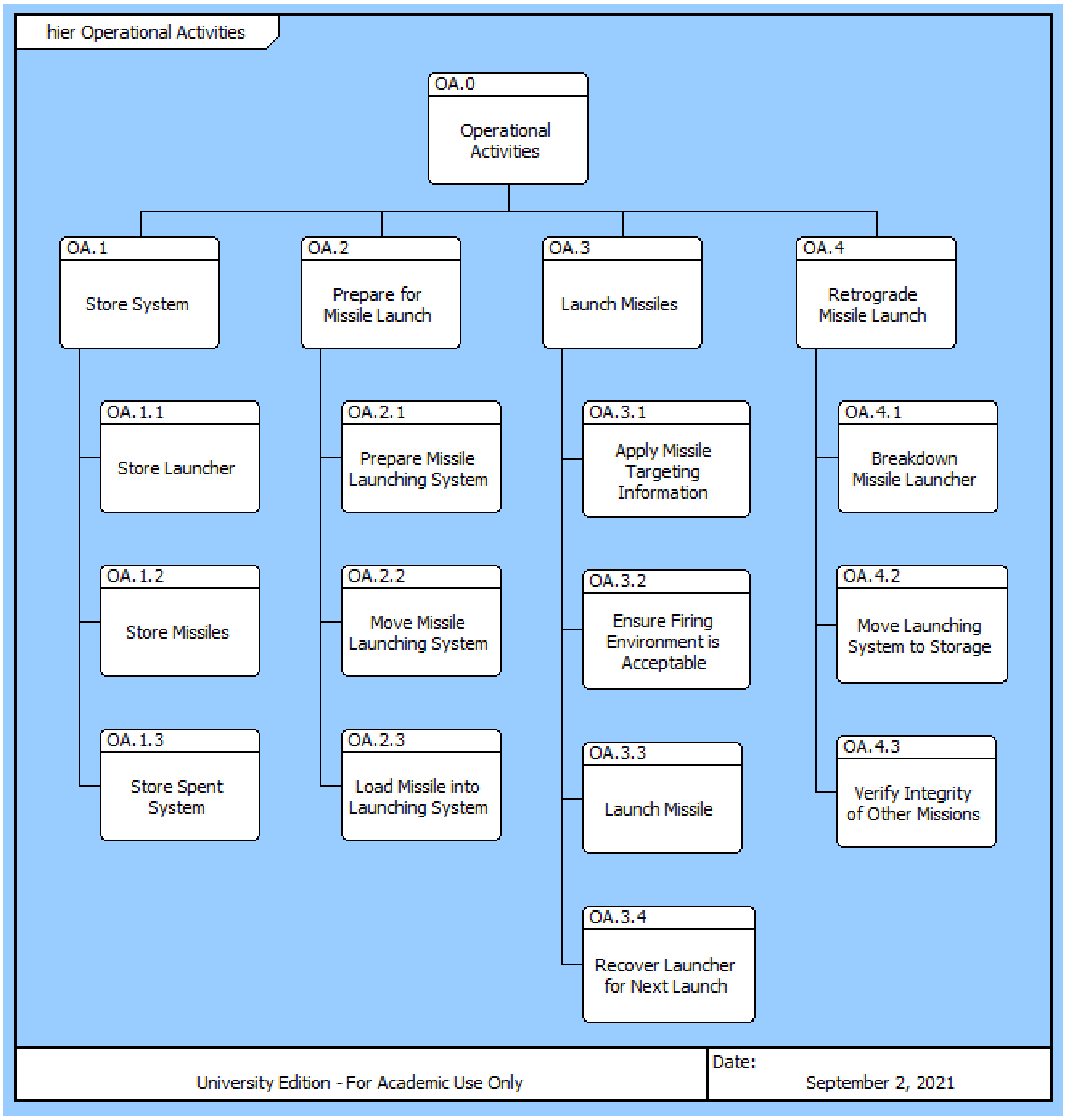

Figure 13. Generic operational activity hierarchy.

These solution-agnostic activities, shown in Figure 13 are required to be able to launch missiles from a ship that is not currently equipped with a missile launching capability. These functions provide the framework through which the analysis of the missile system and vessel combinations was completed.

E. ALTERNATIVE GENERATION

1. LPD Class Vessel, LRHW, Trailer Launch

This candidate system will launch the Army LRHW AUR directly from the M870 trailer. The M870 trailer, the AURs, and potentially the AFATDS will be stowed aboard the LPD until the missile launch is needed. All guided hypersonic missiles should be stored in accorance with the Navy's explosives safety afloat regulations, detailed in NAVSEA OP 4, Twelfth Revision of 15 July 2019. When the need for a hypersonic missile launch becomes apparent, the M870 and LRHW AURs will be transported from the below deck storage into the mission bay adjacent to the flight deck. In the mission bay, the AURs will be loaded onto the M870 trailers and any connections to power or data sources will be made. Once the AUR and the M870 are prepared to fire, they will be transported to the flight deck. The most effective orientation concerning the LPD flight deck and the sea state requirements for the launch of the missile are unknown. The LRHW will be fired using standard procedures developed for launching on land. Figure 14 shows a conceptual drawing of the system launching an LRHW from an LPD flight deck.

Figure 14. Rendering of LPD/LRHW concept. Adapted from Seaforces-Online Naval Information (n.d.b).

After launching the missile, or missiles, from the M870, the trailer will be recovered and transported back into the mission bay. Further launches will be determined by the ability to acquire additional targets, the number of AURs available to be loaded, and the state of the M870 trailer after the initial launch.

a. Candidate System 1 Sub-system and SV-5b

A DoDAF SV-5b Operation Activity to Systems Traceability Matrix diagram for candidate system 1 is shown in Figure 15.

Number	**Operational Activity**	**LPD**	**Trailer**	**Tractor**	**Mission Bay Lift**	**C2**
OA.1.1.1	CS1 Store Missiles	X				
OA.1.1.2	CS1 Store Launcher	X				
OA.1.1.3	CS1 Move Launcher to Mission Bay			X		
OA.1.1.4	CS1 Move Missiles to Mission Bay	X				
OA.1.2.1	CS1 Load Missile into Launching System				X	
OA.1.2.2	CS1 Move System to Flight Deck			X		
OA.1.3.1	CS1 Receive Notice to Start Mission					X
OA.1.3.2	CS1 Acquire Targets					X
OA.1.3.3	CS1 Apply Missile Targeting Information					X
OA.1.3.4	CS1 Ensure Firing Environment is Acceptable	X				
OA.1.3.5	CS1 Launch Missile		X			
OA.1.4.1	CS1 Move Spent System to Mission Bay			X		
OA.1.4.2	CS1 Breakdown Missile Launcher				X	
OA.1.4.3	CS1 Move Launcher to Storage			X		
OA.1.4.4	CS1 Move Spent AUR to Storage	X				
OA.1.4.5	CS1 Verify Integrity of Other Missions	X				

Figure 15. Candidate system 1 SV-5b

In this SV-5b, the systems and sub-systems required for the operation of the LRHW onboard the LPD are identified and linked to the operational activities that they perform. These systems include:

1. LPD – see below for a full explanation.
2. Trailer – this is the M870 trailer that the LRHW AURs will be launched from
3. Tractor – this is the mechanism by which the trailer will be conveyed. It will either be a native LPD capability or the M983A4 that is currently included in the terrestrial LRHW system.
4. Mission Bay Lift – this mechanism could either be some sort of crane or lift that is already in place in the mission bay, or an additional component of the system to perform the lifting like a Kalmar RT240 shown earlier.
5. C2 – this is the command-and-control system that will be used to receive mission packages, launch authorizations, and transfer mission data to the LRHW AUR prior to launching. In the LPD this system will either be the AFATDS that is included in the terrestrial LRHW system or the Tactical Tomahawk Weapons Control System (TTWCS).

The system labeled "LPD" is intended to be an overarching group of capabilities that are provided by the host vessel. The sub-systems that are included in this category are:

1. The munition storage system, to include meeting requirements outlined in OP-4.
2. The launcher storage location.
3. A system that can safely move the LRHW AURs from storage to the mission bay.
4. Vessel procedures and personnel are required to make statements about the state of the vessel, (i.e., whether it is safe to launch the missile and whether the vessel has been appropriately retrograded and is ready to conduct its other missions).

b. Operational Activities and EFFBD

Figure 16 shows the enhanced functional flow block diagram for the candidate system comprised of the LPD and LHRW using an M870 trailer as the launching platform. The EFFBD describes the operational activities, outputs, and triggers that are needed to conduct the successful launching of a single load of hypersonic missiles onto an M870 trailer. This EFFBD does not consider the potential for a misfire requiring remediation or reloading the M870 trailer to launch additional missiles.

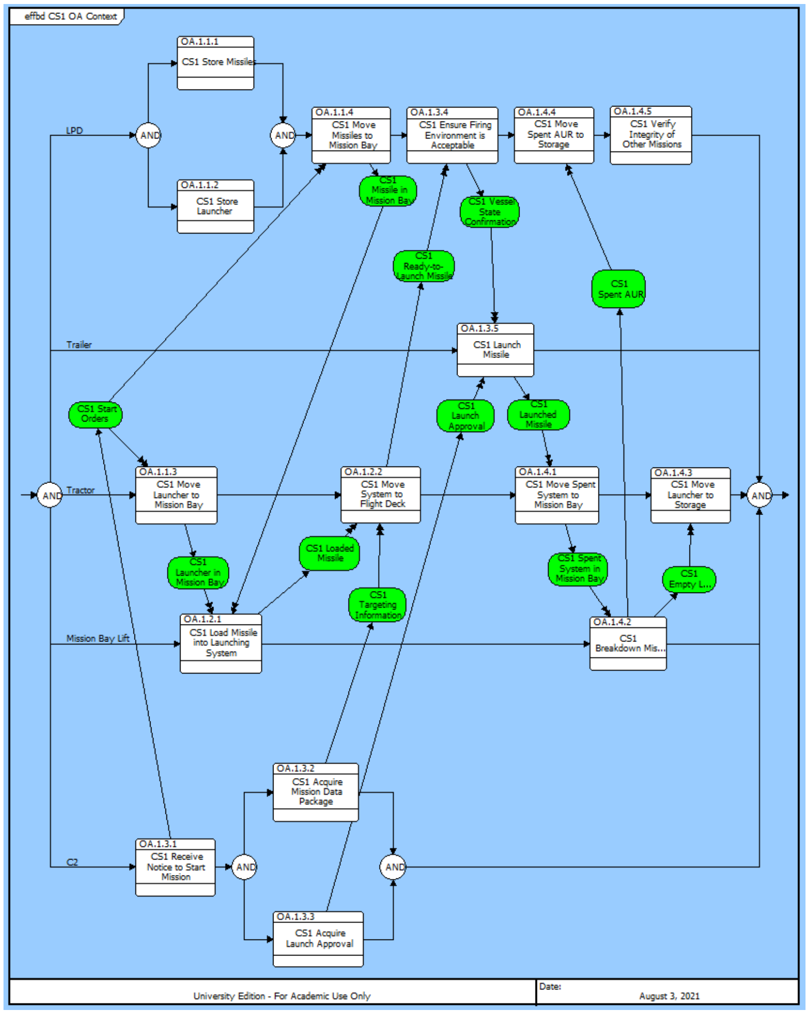

Figure 16. EFFBD for trailer launch of LRHW from an LPD.

OA.1.1.0 Store Missile System: The missile system must be safely stored on the LPD. The M870 trailer is comparable to other vehicles that the LPD normally carries in its hold and can be treated as such. The AURs for the LRHW will need to be stored in a safe location within the hold of the ship, most likely in the same place that the munitions for the embarked assault force are stored.

OA.1.1.1 Store Missiles: The missiles will be stored as AURs. The total number of missiles that can be stored for use will depend on the exact dimensions of the missiles, the exact dimensions of the storage space, and the number of other munitions that will need to be removed to accommodate the storage of the AURs.

OA.1.1.2 Store Launcher: The M870 trailer will be stored in the same hold as the vehicles for the embarked assault force.

OA.1.1.3 Move Launcher to Mission Bay: The M870 trailer will be moved to the mission bay using the elevator connecting the lower holds to the mission bay. The dimensions of the mission bay elevator must be able to accommodate the size and weight of the M870 trailer.

OA.1.1.4 Move Missiles to Mission Bay: The AURs will be removed from their storage location and moved into the mission back using the mission bay elevator in the same manner that the M870 trailer was moved.

OA.1.2.0 Prepare Missile for Launch: After the launcher and missile are collocated, they must be configured to prepare for launch.

OA.1.2.1 Load Missile into Launching System: The AUR or AURs in the mission bay will be loaded onto the M870 trailer using the mission bay lift.

OA.1.2.2 Move System to Flight Deck: Once the M870 trailer has been loaded with the AURs and the targeting information has been provided to the missiles, the ready-to-launch system will be transported to the flight deck. The entire process of transportation is not fully understood, but the most desirable method would be to use a tractor that is currently used on the LPD to move aircraft in and out of the mission bay. If this tractor is not capable of moving the loaded M870, then another vehicle will need to be added to the system to accomplish this function.

In addition to the M870 trailer that will need to move onto the flight deck, a blast shield will need to be placed on the flight deck to protect the surface from the hot exhaust gases of the LRHW launching. This blast shield is not a part of the LHRW system and has not yet been designed. This will address Concern 1.6.3

OA.1.3.0 Launch Missiles: The steps that are required to start the launching process and launch the missile at the target.

OA.1.3.1 Receive Notice to Start Mission: The portion of the command-and-control center that is responsible for receiving orders to conduct offensive strikes will initiate the launch process by receiving the orders to launch the missile. The personnel who are responsible for receiving and disseminating the orders will notify the chain of command that a hypersonic missile launch is being.

OA.1.3.2 Acquire Mission Data Package: The mission data package for the hypersonic missile strike be provided from a system external to the LPD, likely a satellite connection to a Naval Operations center. The need for the AFATDS to be included in the system will depend upon the ability of the LPD's current fire control systems to either provide the information required in their current state or be modified and upgraded to be able to provide the required information. If the LPD's fire control systems are going to be used to perform this function, there will likely need to be software development to provide a system that can translate the output of the LPD's fire control systems to a format compatible with the input required for the LRHW. The most likely system to upgrade the LPD's native fire control system would be the Tactical Tomahawk Weapons Control System (TTWCS). If the AFATDS is used for this function, its storage, transportation, setup, and use will need to be accounted for in the system.

OA.1.3.3 Acquire Launch Approval: In addition to the mission data package, the command approval to launch the LRHW will also be acquired.

OA.1.3.4 Ensure Firing Environment is Acceptable: After the system is in place on the flight deck an assessment of the firing environment will be made. This includes final checks on the readiness of the system and safety considerations regarding the personnel and equipment on or near the flight deck.

OA.1.3.5 Launch Missile: After the firing environment has been determined to be acceptable the missiles will be launched at their target. This function is entirely determined by the missile launching process determined by the LHRW system.

OA.1.4.0 Retrograde Missile Launcher: After the missile launch has occurred additional steps will be taken to recover the spent launcher and prepare for the vessel to conduct its other missions.

OA.1.4.1 Move Spent System to Mission Bay: After the missile has been successfully launched, the M870 trailer will be returned to the mission bay using the same manner of transportation that was used to get the M870 trailer onto the flight deck.

OA.1.4.2 Breakdown Missile Launcher: Once the system is back in the mission bay, the launcher will be disassembled by removing the AUR using the same lift system that was used to put the AUR onto the trailer.

OA.1.4.3 Move Launcher to Storage: The launcher will be assessed, prepared for storage, and moved back to the lower decks using the elevator.

OA.1.4.4 Move Spent AUR to Storage: The spent AUR case will be moved into storage.

OA.1.4.5 Verify Integrity of Other Missions: After the system has been fully retrograded the vessel's ability to perform its other functions will be restored. Procedures designed to confirm the vessel's successful retrograde will be conducted.

2. EPF Class Vessel, LRHW AUR, Crane Launch

This candidate system will launch the Army LRHW AUR from a cradle system that will be suspended from the boom crane. Unlike the LPD, the EPF cannot easily move a loaded M870 trailer from a storage location to the flight deck. Instead, the EPF will take advantage of its 27-ton crane that is located at the mouth of the mission bay, shown in Figure 17. The cradle will perform the functions of securing the AUR on the crane and orienting the AUR in an appropriate configuration before launching. This cradle system is not part of any of the existing components of the candidate system and will have to be developed in a separate effort. The fact that this cradle and crane launching concept has not been used before means there is a significant amount of risk associated with the successful development of the cradle.

After moving both the cradle and the AUR to the mission bay from storage, the AUR will be loaded into the cradle system and given its targeting information. The loaded system will be moved to the mouth of the mission bay where it will be hoisted by the crane. Once the missile system is in place on the crane the system will be ready to launch.

After launching the missile, the spent AUR and cradle will be released from the crane at the mouth of the mission bay and moved back into the mission bay to be disassembled and either loaded with another fresh AUR or sent back to storage.

Figure 17. Rendering of EPF/LRHW AUR concept. Adapted from Vavasseur (2020).

a. *Candidate System 1 Sub-system and SV-5b*

A DoDAF SV-5b Operation Activity to Systems Traceability Matrix diagram for candidate system 2 is shown in Figure 18.

Number	Operational Activity	EPF	Crane	Mission Bay Lift	C2
OA.2.1.1	CS2 Store Missiles	X			
OA.2.1.2	CS2 Store Cradle	X			
OA.2.1.3	CS2 Move Cradle to Mission Bay	X			
OA.2.1.4	CS2 Move Missiles to Mission Bay	X			
OA.2.2.1	CS2 Load Missile into Cradle			X	
OA.2.2.2	CS2 Hoist Cradle		X		
OA.2.2.3	CS2 Ensure Firing Environment is Acceptable	X			
OA.2.2.4	CS2 Launch Missile		X		
OA.2.3.1	CS2 Receive Notice to Start Mission				X
OA.2.3.2	CS2 Acquire Mission Data Package				X
OA.2.3.3	CS2 Acquire Launch Approval				X
OA.2.4.1	CS2 Release Cradle		X		
OA.2.4.2	CS2 Breakdown Cradle			X	
OA.2.4.3	CS2 Move Cradle to Storage	X			
OA.2.4.4	CS2 Move Spent AUR to Storage	X			
OA.2.4.5	CS2 Verify Integrity of Other Missions	X			

Figure 18. Candidate system 2 SV-5b

In this SV-5b, the systems and sub-systems required for the launching of the LRHW AUR from the EPF crane are identified and linked to the operational activities that they perform. These systems include:

1. EPF – see below for a full explanation.
2. Crane – this is the crane that is present on the stern of the EPF outside of the mission bay. The crane itself will not be modified, but a sub-

component cradle that secures the LRHW AUR and is hoisted by the crane will need to be designed, built, and tested.

3. Mission Bay Lift – this is the native materiel lifting capability inside the mission bay of the EPF. This lifting capability will need to be able to lift the LRHW AUR and place it into the cradle.
4. C2 – this is the command-and-control system that will be used to receive mission packages, launch authorizations, and transfer mission data to the LRHW AUR prior to launching. In the EPF this system will be the AFATDS that is included in the terrestrial LRHW system because the EPF lacks any native C2 capabilities for missile fire control.

The system labeled “EPF” is intended to be an overarching group of capabilities that are provided by the host vessel. The sub-systems that are included in this category are:

1. The munition storage system, to include meeting requirements outlined in OP-4.
2. Cradle storage.
3. A system that can safely move the LRHW AURs from storage to the mission bay.
4. Vessel procedures and personnel are required to make statements about the state of the vessel, i.e., whether it is safe to launch the missile and whether the vessel has been appropriately retrograded and is ready to conduct its other missions.

b. Operational Activities and EFFBD

Figure 19 shows the enhanced functional flow block diagram for the candidate system comprised of the EPF and LRHW AUR using the EPF crane and a custom missile cradle as the launching platform. The EFFBD describes the operational activities, outputs, and triggers that are needed to conduct the successful launching of a single LRHW AUR from the EPF crane. This EFFBD does not consider the potential for a misfire requiring remediation or reloading the crane to launch additional missiles.

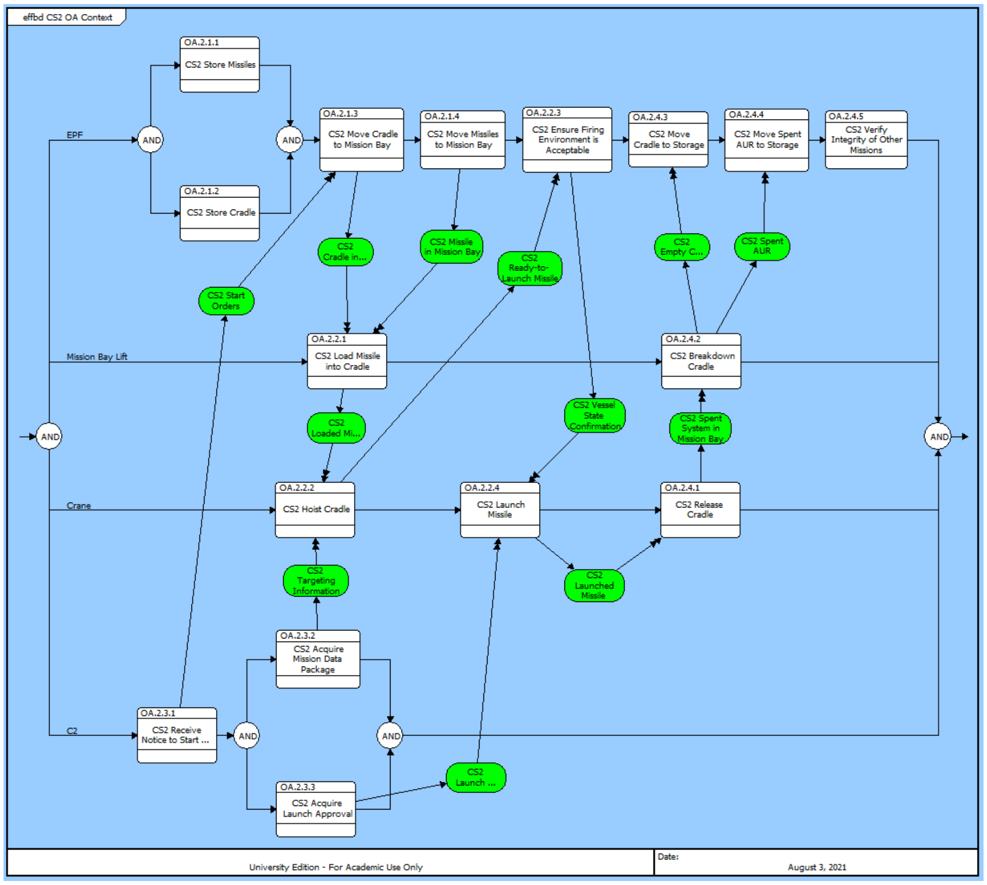

Figure 19. EFFBD for crane launch of LRHW AUR from an EPF

OA.2.1.0 Store Missile System: The missile system must be safely stored on the EPF. The EPF does not natively have a location on the ship that is designed to hold.

OA.2. 1.1 Store Missiles: The missiles will be stored as AURs. The total number of missiles that can be stored for use will depend on the exact dimensions of the missiles, the exact dimensions of the storage space, and the number of other munitions that will need to be removed to accommodate the storage of the AURs.

OA.2. 1.2 Store Cradle: The cradle will be stored in an accessible location inside the EPF. The size and weight of the cradle are not predicted to be a significant burden to move throughout the storage compartments and mission bay of the EPF.

OA.2.1.3 Move Cradle to Mission Bay: The cradle will be moved to the mission bay using onboard forklifts or overhead crane systems.

OA.2.1.4 Move Missiles to Mission Bay: The AURs will be removed from their storage location and moved into the mission bay the same way as the cradle.

OA.2.2.0 Prepare Missile for Launch: After the launcher and missile are collocated, they must be configured to prepare for launch.

OA.2.2.1 Load Missile into Cradle: The AUR or AURs in the mission bay will be loaded into the cradle system. The mechanism used to accomplish this step could either be some sort of crane or lift mechanism that is already in place in the mission bay. The design of the cradle system will contribute greatly to the operation of loading the AUR into the cradle.

OA.2.2.2 Hoist Cradle: Once the cradle has been loaded with the AUR and the targeting information has been provided to the missiles, the ready-to-launch system will be transported to the mouth of the mission bay using the forklift or equivalent mechanism provided by the native capabilities of the EPF. The cradle will be connected to the crane and hoisted into position.

OA.2.3.0 Launch Missiles: The steps that are required to start the launching process and launch the missile at the target.

OA.2.3.1 Receive Notice to Start Mission: The portion of the command-and-control center that is responsible for receiving orders to conduct offensive strikes will initiate the launch process by receiving the orders to launch the missile. The personnel who are responsible for receiving and disseminating the orders will notify the chain of command that a hypersonic missile launch is being.

OA.2.3.2 Acquire Mission Data Package: The targeting information for the hypersonic missile strike will be provided from a system external to the EPF. There are currently no systems onboard the EPF that can provide the command and control needed to target and launch the LRHW AUR. This means that the AFATDS that is currently used on the terrestrial LRHW system will likely be needed to be available on the EPF to provide command and control. Therefore, the AFATDS's storage, transportation, setup, and use will need to be accounted for in the system.

OA.2.3.3 Acquire Launch Approval: In addition to the mission data package, the command approval to launch the LRHW will also be acquired.

OA.2.3.4 Ensure Firing Environment is Acceptable: After the system has been hoisted by the crane, an assessment of the firing environment will be made. This includes ensuring the AUR is secured in the cradle, oriented correctly, and final checks on the readiness of the system and safety considerations regarding the personnel and equipment on or near the mission bay and upper flight deck.

OA.2.3.5 Launch Missile: After the firing environment has been determined to be acceptable the missiles will be launched at their target.

OA.2.4.0 Retrograde Missile Launcher: After the missile launch has occurred additional steps will be taken to recover the spent launcher and prepare for the vessel to conduct its other missions.

OA.2.4.1 Release Cradle: After the missile has been successfully launched, the cradle and spent AUR will be returned to the mouth of the mission bay and moved into the mission bay with the forklift or equivalent mechanism.

OA.2.4.2 Breakdown Cradle: Once the system is back in the mission bay, the cradle will be disassembled by removing the AUR using the same lift system that was used to put the AUR into the cradle.

OA.2.4.3 Move Cradle to Storage: The cradle will be assessed, prepared for storage, and moved back to storage.

OA.2.4.4 Move Spent AUR to Storage: The spent AUR case will be moved into storage.

OA.2.4.5 Verify Integrity of Other Missions: After the system has been fully retrograded the vessel’s ability to perform its other functions will be restored.

3. LCS Class Vessel, LRHW AUR, Trailer Launch

The greatest limiting factor for the LCS to be able to accommodate the launch of the LRHW is the fact that the elevator connecting the bulk of the storage area available in the LCS to the hangar and flight deck is not large enough to transport either the M870 trailer or individual LRHW AURs. This means that in order to launch LRHW AURs, the hangar space of the LCS will need to be reserved for the storage, arming, movement, and recovery of the LRHW system being used. The flight deck will still be able to be land helicopters, but there will be no hangar facilities available for helicopter storage or service. The limited space in the hangar means that the AURs will likely need to be stored directly on the M870 trailers because there will not be enough space for separate storage for the AURs, M870s, AFATDS, and a mechanism for loading the AURs onto the M870s.

The launching of the LRHW from the LCS will be essentially identical to the launching of the LRHW from the LPD: the M870 trailer equipped with LRHW AURs will be prepared with the mission data package in the hangar space, towed onto the flight deck, and launched directly from the M870 trailer.

a. Candidate System 1 Sub-system and SV-5b

A DoDAF SV-5b Operation Activity to Systems Traceability Matrix diagram for candidate system 3 is shown in Figure 20.

Number	Operational Activity	LCS	Trailer	Tractor	C2
OA.3.1.1	CS3 Store Missiles	X			
OA.3.1.2	CS3 Store Launcher	X			
OA.3.2.1	CS3 Move System to Flight Deck			X	
OA.3.2.2	CS3 Ensure Firing Environment is Acceptable	X			
OA.3.2.3	CS3 Launch Missile		X		
OA.3.3.1	CS3 Receive Notice to Start Mission				X
OA.3.3.2	CS3 Acquire Mission Data Package				X
OA.3.3.3	CS3 Acquire Launch Approval				X
OA.3.4.1	CS3 Move Spent System to Hangar			X	
OA.3.4.2	CS3 Verify Integrity of Other Missions	X			

Figure 20. Candidate system 3 SV-5b

In this SV-5b, the systems and sub-systems required for the launching of the LRHW AUR from the LCS flight deck are identified and linked to the operational activities that they perform. These systems include:

1. LCS – see below for a full explanation.
2. Trailer – this is the M870 trailer that the LRHW AURs will be launched from
3. Tractor – this is the mechanism by which the trailer will be conveyed. It will either be a native LCS capability or the M983A4 that is currently included in the terrestrial LRHW system.
4. C2 – this is the command-and-control system that will be used to receive mission packages, launch authorizations, and transfer mission data to the LRHW AUR prior to launching. In the LCS this system will likely be the AFATDS that is included in the terrestrial LRHW system unless a suitable alternative is natively available on board the LCS.

The system labeled "LCS" is intended to be an overarching group of capabilities that are provided by the host vessel. The sub-systems that are included in this category are:

1. The munition storage system, to include meeting requirements outlined in OP-4. It is unclear whether the requirements outlined in OP-4 will be able to be met with the need to store LRHW AURs inside the LCS hangar.
2. Vessel procedures and personnel are required to make statements about the state of the vessel, i.e., whether it is safe to launch the missile and whether the vessel has been appropriately retrograded and is ready to conduct its other missions.

b. Operational Activities and EFFBD

Figure 21 shows the EFFBD for the candidate system comprised of the LCS and LRHW using the LCS flight deck and M870 trailer as the launching platform. The EFFBD describes the operational activities, outputs, and triggers that are needed to conduct the successful launching of a single load of LRHW AURs from the M870 trailer. This EFFBD does not consider the potential for a misfire requiring remediation or reloading the trailer to launch additional missiles.

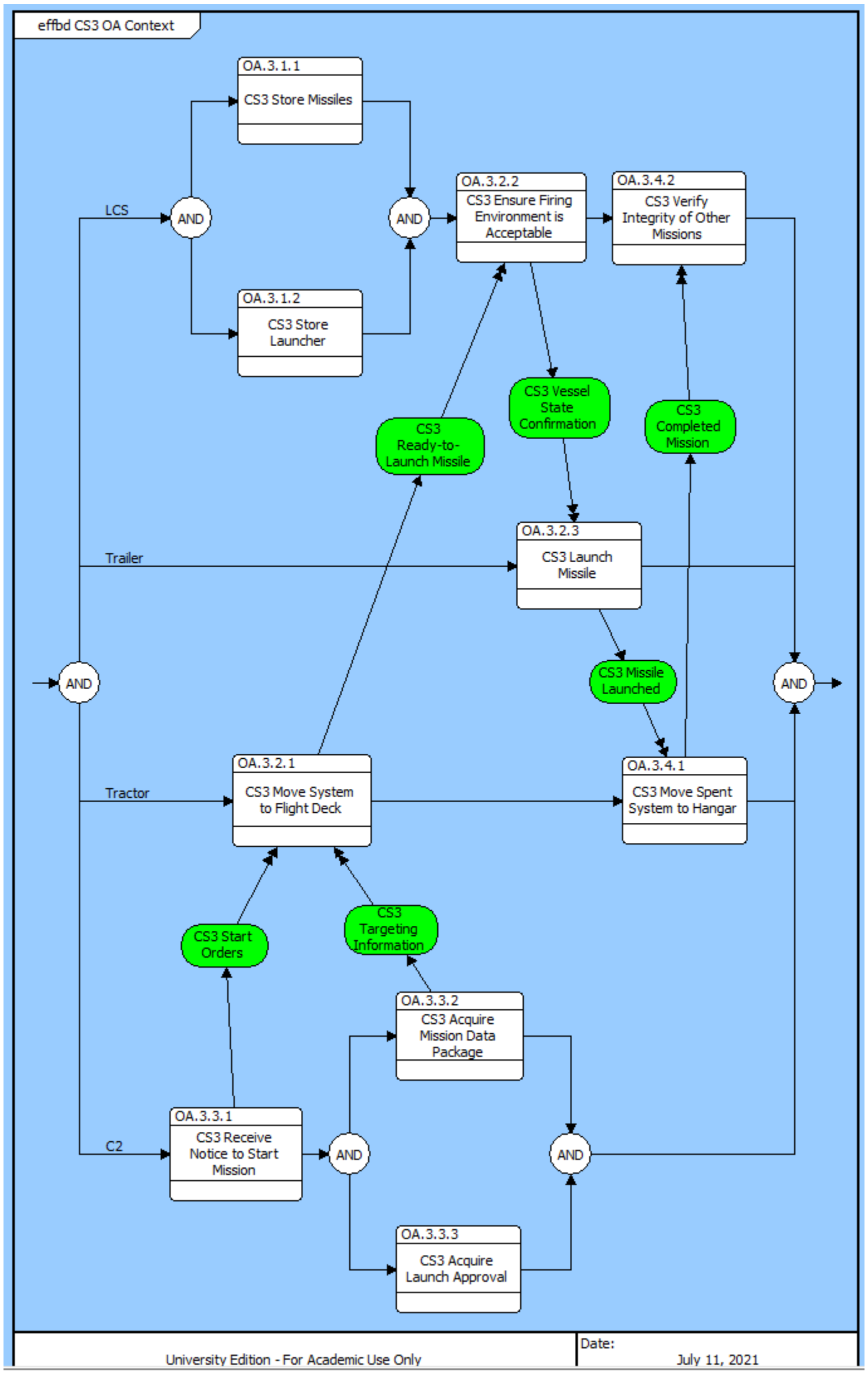

Figure 21. EFFBD for crane launch of LRHW AUR from an EPF

OA.3.1.0 Store Missile System: The missile system must be safely stored on the LCS. As described earlier, the LCS has no mechanism that can physically transport M870 trailers or LRHW AURs from the lower mission bay and cargo storage to the hangar and subsequently the flight deck. This means that the hangar will need to be converted into a space to store and service the LRHW system, including the M870 trailer, the AURs, the AFATDS, and the mechanism that will be used to move the M870 trailer to and from the flight deck.

OA.3.1.1 Store Missiles: The missiles will be stored as AURs preloaded onto the M870 trailer.

OA.3.1.2 Store Launcher: The M870 trailer will be stored in the hangar with AURs already loaded onto it.

OA.3.2.0 Prepare Missile for Launch: After the mission has been started, the mission package data will be uploaded to the LRHW system and the trailer will be moved to the flight deck.

OA.3.2.1 Load Missile into Cradle: Once the targeting information has been provided to the missiles, the ready-to-launch system will be transported to the flight deck. The entire process of transportation is not fully understood, but the most desirable method would be to use a tractor that is currently used on the LCS to move aircraft in and out of the mission bay. If this tractor is not capable of moving the loaded M870, then another vehicle will need to be added to the system to accomplish this function.

In addition to the M870 trailer that will need to move onto the flight deck, a blast shield will need to be placed on the flight deck to protect the surface from the hot exhaust gases of the LRHW launching. This blast shield is not a part of the LHRW system and has not yet been designed.

OA.3.3.0 Launch Missiles: The steps that are required to start the launching process and launch the missile at the target.

OA.3.3.1 Receive Notice to Start Mission: The portion of the command-and-control center that is responsible for receiving orders to conduct offensive strikes will initiate the launch process by receiving the orders to launch the missile. The personnel who are responsible for receiving and disseminating the orders will notify the chain of command that a hypersonic missile launch is being.

OA.3.3.2 Acquire Mission Data Package: The targeting information for the hypersonic missile strike will be provided from a system external to the LCS. There are currently no systems onboard the LCS that can provide the command and control needed to target and launch the LRHW AUR. This means that the AFATDS that is currently used on the terrestrial LRHW system will likely be needed to be available on the LCS to provide command and control. Therefore, the AFATDS's storage, transportation, setup, and use will need to be accounted for in the system.

OA.3.3.3 Acquire Launch Approval: In addition to the mission data package, the command approval to launch the LRHW will also be acquired.

OA.3.3.4 Ensure Firing Environment is Acceptable: After the system is in place on the flight deck an assessment of the firing environment will be made. This includes final checks on the readiness of the system and safety considerations regarding the personnel and equipment on or near the flight deck.

OA.3.3.5 Launch Missile: After the firing environment has been determined to be acceptable the missiles will be launched at their target. This function is entirely determined by the missile launching process determined by the LHRW system.

OA.3.4.0 Retrograde Missile Launcher: After the missile launch has occurred additional steps will be taken to recover the spent launcher and prepare for the vessel to conduct its other missions.

OA.3.4.1 Move Spent System to Hangar: After the missile is launched from the flight deck, the spent system will be transported back into the hangar. The lack of additional storage for the spent AURs in the hangar means that it is likely the spent AURs will remain loaded on the M870 until the whole system is removed at port.

OA.3.4.2 Verify Integrity of Other Missions: After the system has been fully retrograded the vessel's ability to perform its other functions will be restored.

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V. SYSTEM ANALYSIS

The system analysis was conducted using the Multi-Attribute Value Theory. This approach allowed the RIHMC Capstone Team to assess all attributes with a combination of stakeholder preferences over conflicting attributes to discover alternatives with the highest value. (Buede 2016, 400) The team started by determining the multiple attributes that would be used for measurement. Only the genuine distinctions between alternatives should be used to make decisions. (Fabrycky 2011) Focusing on the differences between our alternatives provided attributes that would offer the strongest justification during our decision evaluation. To appropriately measure three independent criteria within an additive model we determined a swing weight using the Parnell method. Creating a swing weight for each attribute allows for the individual values to be measured together although they do not have similar units. These swing weights were then used to create the normalized weight for each attribute. This step is important as it allows specific measures to have more weight on the value of an alternative depending on the preference of our stakeholders. The last step was evaluating the value functions with each swing weight.

A. DEFINING ATTRIBUTES AND DELINEATE VALUE FUNCTION

1. Number of AURs Stored

Table 6 shows a summary of the diverse types of storage space available for the three types of vessels considered for the candidate systems. The physical space available in each of these types of storage was considered along with the dimensions of the LRHW AURs and other details of the vessels to determine the maximum number of AURs each candidate system could hold. It is assumed that the AURs can be stacked two high with some sort of rack or spacing mechanism that would be available from the LRHW program office. The footprint of an AUR is assumed to be 13 meters long and 2 meters wide.

Table 6. Storage spaces for each vessel type

	EPF	**LCS**	**LPD**
Cargo Space	1800 m^2	1410 m^2	2323 m^2
Mission Bay/Hangar Space	N/A	351 m^2	640 m^2
Magazine Space	N/A	N/A	708 m^3

a. LPD Storage

The LPD has the most storage space available for the M870 trailer system and is the only ship with a dedicated magazine that will meet all the munition requirements set forth by the OP-4. The LPD concept uses a single M870 trailer that is loaded with separate AURs, so there only needs to be space for a single M870 reserved. With a beam of 32 meters, the LPD magazine would also hold the AURs with their long dimension across the vessel. If one-half of the 708 m^2 magazine is reserved for LRHW AURs, this means that the AURs can be stored two wide, five deep, and two high for a total of 20 AURs available onboard a single LPD. If instead one-quarter of the magazine is reserved for LRHW AURs, a total of ten AURs would be available.

The amphibious assault mission of the LPD means that every component of the hypersonic missile launching system that needs to be added to the LPD must correspond to the removal of some component of the amphibious assault package. The impact of the single M870 trailer and AFATDS system in the vehicle storage is minimal to the amphibious assault mission because only a single trailer must be accounted for. The storage of the AURs in the magazine has a much bigger impact – in the example given one half of the storage that was available to the amphibious force is now reserved by the AURs. Depending on the mission requirements for the hypersonic missile capability, carrying fewer AURs to maximize space for ammunition for the amphibious force may be necessary. The ten AUR option would likely be preferable in order to achieve the lowest impact on the other missions of the LPD.

b. EPF Storage

The EPF's cargo space of 1,800 m^2 represents the usage of the entire hold of the EPF for the mission of launching LRHW missiles. If half of the hold is reserved for maneuvering the AURs into firing position, maneuvering spent AURs after they come off the crane, storing the AFATDS, storing the cradle system, and storing other equipment that will be used to move AURs, 900 m^2 remains to be filled with AURs.

The beam of the EPF is 28.5 meters which means that two AURs can likely fit across the width of the cargo space. To achieve a balanced payload, half of the cargo hold would be filled two AURs across. This means that the 900 m^2 area can hold 31.5 meters deep worth of AURs. At 2 meters deep, this is enough for the footprint of 30 AURs. When the AURs are stacked 2 high, this means there is room for 60 AURs onboard a single EPF.

The practicality of this number of AURs onboard the EPF is questionable. There is no good estimate for the weight of the AUR, so 60 AURs may be too heavy for the EPF to hold. The danger associated with holding this amount of ordnance, especially in a generic cargo hold and not a magazine, may introduce too much risk to the operation of the ship. It is also unlikely that the mission this EPF launching system would fill would require 60 LRHW AURs to complete. Finally, at an estimated cost of between \$30 and \$50 million each, a load of 60 AURs represents a \$2 to \$3 billion cost to carry this many AURs.

c. LCS Storage

The LCS's cargo space of 1,410 m^2 is inaccessible for use as storage for M870 trailers or LRHW AURs because the elevator connected the storage space to the hangar and flight deck cannot accommodate the 40-foot length of each component. This means that the entire LRHW system used for this capability will need to be permanently stored in the hangar location.

The beam of the LCS is 32 meters, which means that the 351 m^2 is only 11 meters deep. The M870 trailer is 12.8 meters long by 2.4 meters wide and would need to be stored with its long dimension across the beam of the LCS. Two M870 trailers would take up an area approximately 15 meters wide by 6 meters deep in the LCS hangar. The remainder of the hangar would be reserved for maneuvering the trailers, the AFATDS, and the tractor system required to move the trailers. Each M870 trailer would have two AURs loaded on them as described earlier in the candidate system 3 section. This means that a total of four LRHW AURs are available onboard a single LCS.

This system requires the entire hangar of the LCS to be reserved for the M870 trailers and AURs. The flight deck will still be able to land and launch helicopters when the LRHW is not being fired, but there will no longer be a space to service aircraft on the LCS.

d. *Number of AURs Stored Rating Curve*

Figure 22 shows the linear piece-wise rating curve developed for the number of AURs stored attribute.

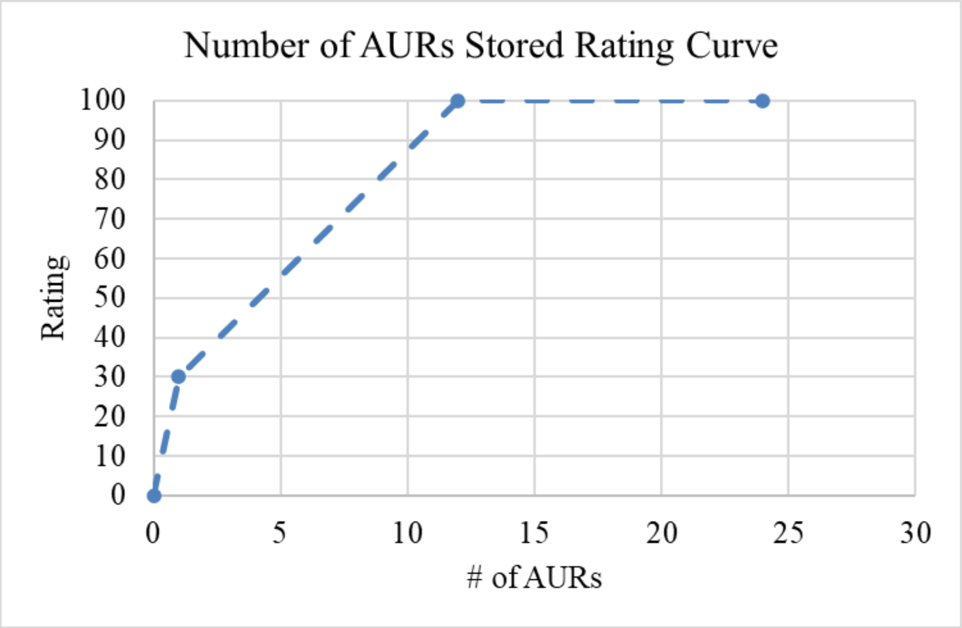

Figure 22. Linear piece-wise rating curve for number of AURs stored attribute.

The rating starts at 0 for no missile storage because the system would not be operational without AUR storage. The curve starts at a rating of 30 for a single AUR stored and increases to a rating of 100 linearly until 12 AURs are stored.

The literature review section describes the manner in which TLAM cruise missiles must be launched in salvos as large as 16 missiles to defeat a target with active defense. Due to its exceptional speed, maneuverability, and low flight path, a single hypersonic glide body missile is likely to be able to overcome an active defensive system that could defeat even a salvo attack of TLAMs. An Arleigh Burke-class destroyer is equipped with 96 TLAMs, or six salvo attacks of 16 missiles each. This means that a vessel equipped with 12 hypersonic missiles can attack as many actively defended targets as two Arleigh Burke-class destroyers firing 16-missile salvos. 12 AURs was chosen as the highest rating for this attribute because it represents the offensive equivalent of two entire vessels in the scenario where an actively defended target is being attacked. While additional hypersonic AURs on board a vessel does represent the ability to attack more targets, there are other considerations, such as cost or effect on other vessel missions, that prevent additional AURs beyond 12 from increasing the rating of this attribute. Table 7 summarizes the number of AURs that each candidate system can store.

Table 7. Results of # of AURs stored attribute

Measure	CS1 - LPD	CS2 - EPF	CS3 - LCS
# of AURs Stored	10	20	4

2. Time to Execute Launch

The time to execute launch attribute was calculated using the discrete event simulation tool COREsim. The EFFBDs presented in the candidate system section were used to simulate the estimated time it would take for each of the candidate systems to start from a fully stowed configuration and complete the activities required to launch the hypersonic missile. Normal distributions were used for each activity and each simulation was run 30 times. Mean values and 95% confidence intervals are reported for each candidate system. Assumptions regarding the duration and distribution time that each activity would require were made, and while the assumptions may not be absolutely accurate, they are consistent across the three candidate systems. This means that the final values determined for the time to execute a launch from each candidate system may be unrealistic, but a comparison of the relative times required for each candidate system is likely to be useful in rating the systems for further analysis.

a. LPD Time to Execute Launch

Table 8 shows the durations and standard deviations used for the simulation of candidate system 1.

Table 8. Candidate system 1 LPD activity timing

Number	Operational Activity	Time, min	SD, min
OA.1.1.1	CS1 Store Missiles	0	0
OA.1.1.2	CS1 Store Launcher	0	0
OA.1.1.3	CS1 Move Launcher to Mission Bay	10	1
OA.1.1.4	CS1 Move Missiles to Mission Bay	10	1
OA.1.2.1	CS1 Load Missile into Launching System	10	1
OA.1.2.2	CS1 Move System to Flight Deck	2	0.5
OA.1.3.1	CS1 Receive Notice to Start Mission	0	0
OA.1.3.2	CS1 Acquire Mission Data Package	1	0.25
OA.1.3.3	CS1 Acquire Launch Approval	1	0.25
OA.1.3.4	CS1 Ensure Firing Environment is Acceptable	3	0.5
OA.1.3.5	CS1 Launch Missile	1	0.25
OA.1.4.1	CS1 Move Spent System to Mission Bay	2	0.5
OA.1.4.2	CS1 Breakdown Missile Launcher	5	1
OA.1.4.3	CS1 Move Launcher to Storage	10	1
OA.1.4.4	CS1 Move Spent AUR to Storage	10	1
OA.1.4.5	CS1 Verify Integrity of Other Missions	10	1

The simulation resulted in a mean execution time of 53.9 minutes with a 95% confidence interval from 53.2 minutes to 54.7 minutes.

b. EPF Time to Execute Launch

Table 9 shows the duration and standard deviations used for the simulation of candidate system 2.

Table 9. Candidate system 2 EPF activity timing

Number	Operational Activity	Time, min	SD, min
OA.2.1.1	CS2 Store Missiles	0	0
OA.2.1.2	CS2 Store Cradle	0	0
OA.2.1.3	CS2 Move Cradle to Mission Bay	5	1
OA.2.1.4	CS2 Move Missiles to Mission Bay	5	1
OA.2.2.1	CS2 Load Missile into Cradle	10	1
OA.2.2.2	CS2 Hoist Cradle	5	1
OA.2.2.3	CS2 Ensure Firing Environment is Acceptable	2	0.5
OA.2.2.4	CS2 Launch Missile	1	0.25
OA.2.3.1	CS2 Receive Notice to Start Mission	0	0
OA.2.3.2	CS2 Acquire Mission Data Package	1	0.25
OA.2.3.3	CS2 Acquire Launch Approval	1	0.25
OA.2.4.1	CS2 Release Cradle	2	0.5
OA.2.4.2	CS2 Breakdown Cradle	5	1
OA.2.4.3	CS2 Move Cradle to Storage	5	1
OA.2.4.4	CS2 Move Spent AUR to Storage	5	1
OA.2.4.5	CS2 Verify Integrity of Other Missions	5	1

The simulation resulted in a mean execution time of 49.9 minutes with a 95% confidence interval from 49.3 minutes to 50.5 minutes.

c. LCS Time to Execute Launch

Table 10 shows the duration and standard deviations used for the simulation of candidate system 2.

Table 10. Candidate system 3 LCS activity timing

Number	Operational Activity	Time, min	SD, min
OA.3.1.1	CS3 Store Missiles	0	0
OA.3.1.2	CS3 Store Launcher	0	0
OA.3.2.1	CS3 Move System to Flight Deck	5	1
OA.3.2.2	CS3 Ensure Firing Environment is Acceptable	5	1
OA.3.2.3	CS3 Launch Missile	1	0.25
OA.3.3.1	CS3 Receive Notice to Start Mission	0	0
OA.3.3.2	CS3 Acquire Mission Data Package	1	0.25
OA.3.3.3	CS3 Acquire Launch Approval	1	0.25
OA.3.4.1	CS3 Move Spent System to Hangar	5	1
OA.3.4.2	CS3 Verify Integrity of Other Missions	5	1

The simulation resulted in a mean execution time of 21.9 minutes with a 95% confidence interval from 20.9 minutes to 22.9 minutes.

d. Time to Execute Launch Rating Curve

Figure 23 shows the linear piece-wise rating curve developed for the time to execute launch attribute.

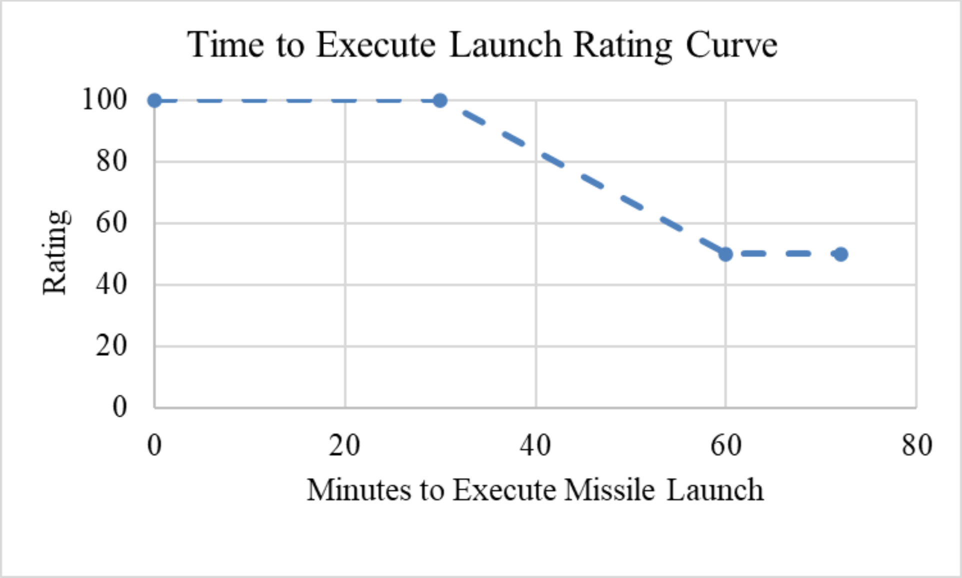

Figure 23. Linear piece-wise rating curve for time to execute launch attribute

The piece-wise linear rating curve for the time to launch attribute was constructed to give a full rating if the hypersonic missile can be launched in 30 minutes or less. The rating decreases to 50 as the launch takes up to an hour. This relatively high rating floor represents the fact that a launch from this system will likely be planned well ahead of execution rather than be needed immediately. Table 11 summarizes the time it takes each candidate system to launch a missile with a 95% confidence interval.

Table 11. Results of time to execute launch attribute

Measure	**CS1 - LPD**	**CS2 - EPF**	**CS3 - LCS**
Time to Execute, minutes	53.9 ± 0.7	49.9 ± 0.6	21.9 ± 1.0

3. Time to Implement

The time to implement attribute was determined using information available from the LRHW and VPM programs. The LRHW is currently scheduled for an FY23 IOC while the VPM is currently scheduled for an FY28 IOC. This means that the earliest possible time a vessel could be equipped with an LRHW or LRHW AUR is 24 months from July

2021. If a vessel is not equipped with a hypersonic capability by FY28, it is likely that the capability that will be available to the fleet through the use of the VPM will surpass the candidate systems presented here, rendering the implementation of the candidate system obsolete.

a. LPD Time to Implement

The proposed design of candidate system 1 does not require any significant modification of the LPD and so the implementation of candidate system 1 is entirely reliant on the availability of the LRHW system. Assuming that the planning for candidate system 1 can begin immediately, it can be assumed that once the LRHW systems are available there will be very little delay in their integration onto the LPD. Therefore, the predicted time to implement candidate system 1 is 24 months.

b. EPF Time to Implement

The crane launching concept used in candidate system 2 necessitates the use of a cradle system to secure the LRHW AUR in place on the crane before firing. This concept of launching missiles from a naval vessel is not currently implemented and the cradle system does not exist. An engineering design and manufacturing team at the U.S. Army Combat Capabilities Development Command Chemical Biological Center (DEVCOM CBC) was asked to provide an estimate for the design, build, and test of the crane system described in candidate system 2. The engineering team determined that an estimated 18 months would be needed to develop, build, and test the cradle system after the final configuration of the LRHW AURs was known and available to be worked with. This means that the final estimate for the implementation of candidate system 2 is 18 months after the delivery of the LRHW, or 42 months from July 2021.

c. LCS Time to Implement

The proposed design of candidate system 3 aboard the LCS utilizes identical LRHW system hardware as the candidate system 1 design. Therefore, the 24-month time to implement the LRHW system aboard the LCS is identical to the time to implement aboard the LPD.

d. Time to Implement Rating Curve

Figure 24 shows the linear piece-wise rating curve developed for the time to implement attribute.

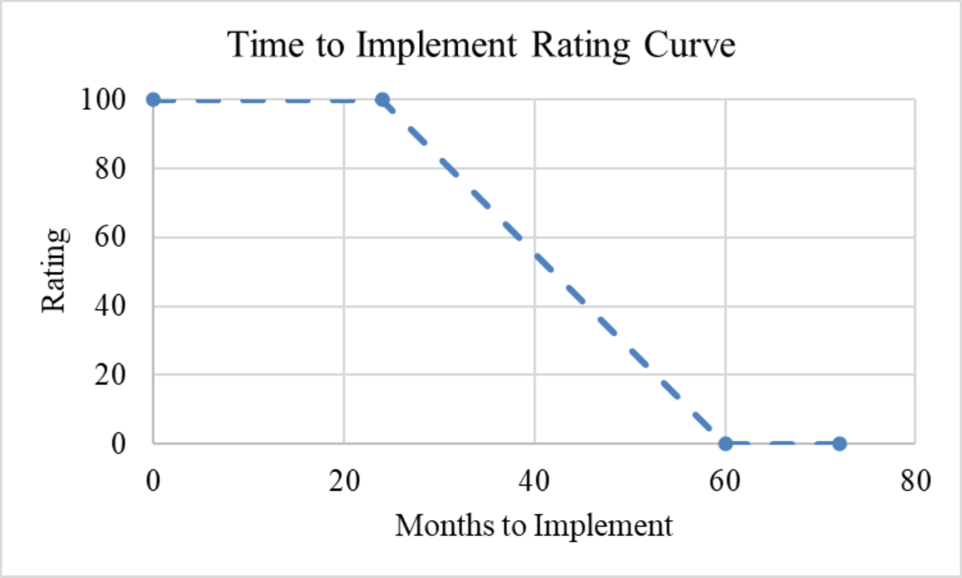

Figure 24. Linear piece-wise rating curve for time to implement attribute

The piece-wise linear rating curve for the time to implement attribute was constructed to give a full rating if the hypersonic missile system can be implemented aboard the vessel in 24 months or less. The rating decreases to 0 as the time to implement reaches 60 months. This rating floor of 0 represents the fact that other systems to launch hypersonic missiles from naval will be available in this time frame, and likely be more intentionally designed for their applications to provide superior capability to the candidate systems described here. Table 12 summarizes the time it will take for each candidate system to be implemented.

Table 12. Results of time to implement attribute

Measure	CS1 - LPD	CS2 - EPF	CS3 - LCS
Time of Implementation, months	24	42	24

B. ASSESSING WEIGHTS

Once the three criteria were defined a swing weight was extracted using the Parnell Method (Parnell 2016). The swing weight was determined by the variation in each attribute as well as the level of importance each attribute has to the alternative solution. The assignment of swing weights did require a level of judgment based on stakeholder's needs and preferences. We assigned the original stakeholder concern for rapid implementation 100 as the main measure of performance for this project is to provide rapid hypersonic missile launching capability to the fleet. We then assessed the remaining differences between our alternatives and how their variation and importance impacted the needs of our stakeholders, leaving missile volume with 32 swing weight and time to execute functions with 10. These swing weights provide a normalized weight for the three independent criteria to be measured together although their measurements and impact may be different. The swing weight benefits the analysis by allowing a measure that is critical to the decision problem to be given more weight than a measure that is less critical. Table 13 is the completed swing weight matrix, with the swing weight shown in bold for each attribute.

Table 13. Swing weight matrix

		Level of Importance of the Value Measure		
		Project Critical	Project Enabling	Project Enhancing
Variation in Measure Range	Large Capability Gap	Con 2.4 - Rapid Implementation **100**		
	Significant Capability Gap		Con 1.5 - Onboard Missile Storage **32**	
	Small Capability Gap			Con 1.6 - Onboard Missile Movement **10**

C. SCORING ALTERNATIVES

An additive model calculation, that includes the value functions and normalized weights, was used to provide a quantitative score for each alternative. The RIHMC Team utilized these scores to accomplish further analysis and aid in decision-making. We utilized the Ideal Range Method which establishes a best and worst range creating scoring measurements that apply more directly to the decision evaluation. The main purpose of utilizing this method is that it produces a flexible analysis that would allow for future alternatives to be considered. The final decision matrix can be seen in Table 14.

Table 14. Final scores for candidate systems.

			CS1 - LPD		**CS2 - EPF**		**CS3 - LCS**	
Attribute	**Swing Weights**	**Normalized Weights**	**Attribute Rating**	**Weighted Rating**	**Attribute Rating**	**Weighted Rating**	**Attribute Rating**	**Weighted Rating**
Missile Storage, # AURs	32	0.23	87	19.7	100	22.5	49	11.1
Time of Implementation, months	100	0.70	100	70.4	50	35.2	100	70.4
Time to Execute, minutes	10	0.07	60	4.2	67	4.7	100	7.0
		Total value		94.3		62.5		88.5

D. ANALYSIS RESULTS

We scored all three alternatives using value measurements to give our stakeholders a value that represented the performance in fulfilling each criterion. We used Microsoft Excel to create a model that would calculate the alternatives score based on each alternatives value function and each attributes swing weights. Candidate system 1 scored highest when evaluated based on all three attributes.

1. Sensitivity Analysis

We executed a sensitivity analysis on our normalized weights to assess the validity of our results. The purpose of a sensitivity analysis is to determine how possible changes in parameter values affect model outputs (Rappaport 2021). Since our scores are a calculation of swing weight and value function for each candidate system, we needed to determine what changes in the swing weights would change the results of our scores. Conducting a sensitivity analysis also helps identify the relationship between independent parameters on dependent parameters.

We determined the sensitivity of each swing weight by adjusting each attribute to either zero or one then log the difference in scoring for each attribute. After each adjusted score was calculated, we plot the existing and adjusted scores to compare the differences.

The sensitivity analysis performed on the attribute of Number of AURs, shown in Figure 25, reveals that the weight of this attribute would need to be raised significantly from 0.23 to 0.8 for the threshold to flip the decision scoring the EPF higher than the LPD. Another observation from the sensitivity analysis shows that the normalized weight of this attribute would need to decrease below 0.1 to flip the decision point that would cause the LCS to score higher than the LPD. Both of these results show that the result from this analysis is not sensitive to a moderate change in the weight assigned to Number of AURs.

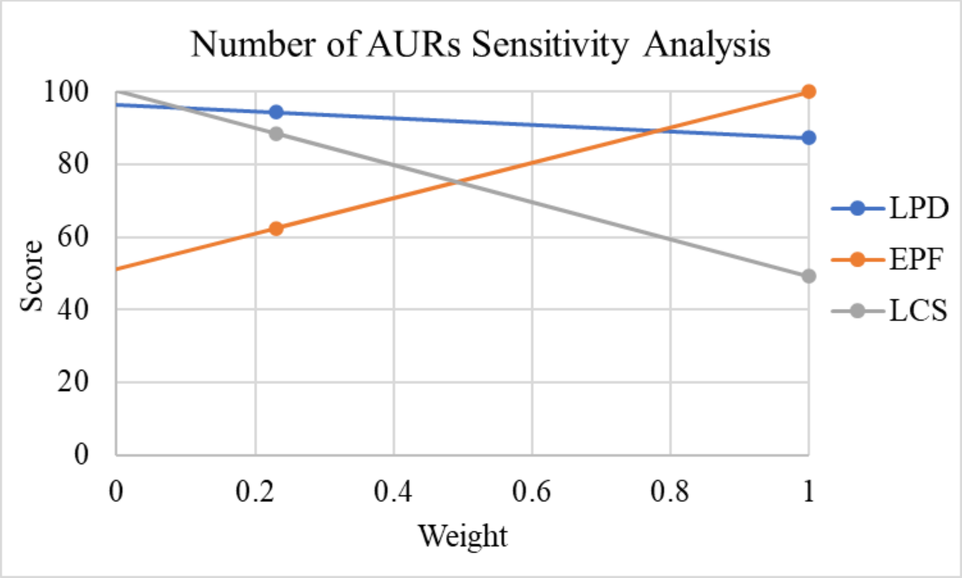

Figure 25. Candidate system scores by varied Number of AURs weight

The sensitivity analysis performed, shown in Figure 26, on the attribute Time to Implement illustrates that the weight for both LPD and LCS are identical. This tells decision makers that no matter what the change is in weight both alternatives will score the same. The most important observation from the sensitivity analysis shows that the normalized weight of this attribute would need to decrease by 80 percent for the decision to flip causing the EPF to score higher.

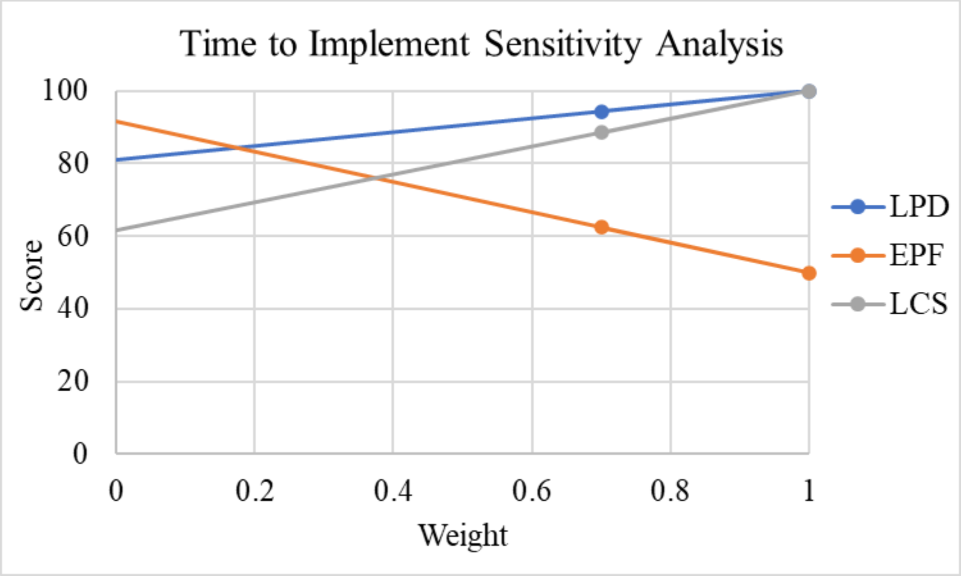

Figure 26. Candidate system scores by varied Time to Implement weight

The third sensitivity analysis performed was on the attribute Time to Execute, shown in Figure 27. This analysis identified that there would need to be a significant change in weight for the threshold to cause the EPF to score higher than the LPD, however, not much change would be necessary for LCS to score higher compared to the LPD alternative.

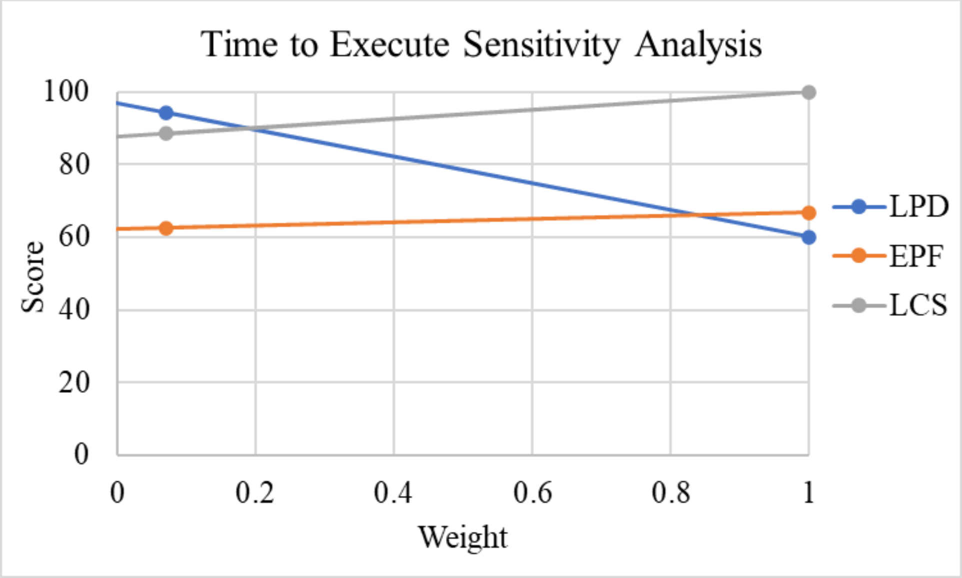

Figure 27. Candidate system scores by varied Time to Execute weight

While each attribute’s sensitivity analysis identifies the point at which the decision would flip from one alternative to another the analysis also helps decision makers identify which parameter values have a substantial influence on metrics and therefore should be carefully modeled (Law 2014).

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VI. CONCLUSION AND FUTURE WORK

The RIHMC Capstone Team was tasked to examine how to integrate a hypersonic glide body system and integrate it into a U.S. Navy surface vessel. This Capstone project describes the possible integration of the Army's Long Range Hypersonic Weapon (LRHW) system into three types of vessels considered as candidate systems: the San Antonio-class LPD, the Spearhead-class EPF, and the Independence-class LCS. A systems engineering approach was used to collect concerns, identify requirements, derive MOEs and MOPs, and perform a functional analysis to ultimately describe how each of the candidate systems would be implemented on board each vessel. The Multi-Attribute Value theory was used in conjunction with the Parnell method to measure three independent criteria and apply swing weights for each criteria based to allow the disparate attributes of the systems to be normalized into a single measurement.

A. CONCLUSIONS

(1) Number of AURs Stored

One of the research objectives of this study was to examine if a hypersonic missile system could be developed that could safely, effectively, and efficiently store, transport, and launch hypersonic missiles from existing Navy platforms. After evaluating all candidate system, we determined that the LPD has the most storage space available for the required components of the LRHW and is the only candidate ship with a dedicated magazine that will meet all the munition requirements set forth by the Navy's Ammunition and Explosives Safety Afloat Manual, the OP-4. In terms of mission bay or hangar space availability, the LPD is the best candidate vessel to be able to safely carry the AURs and not compromise the vessel's hangar space and its ability to service aircraft.

(2) Time to Execute Launch

Another research objective was to determine which design considerations of the alternative launching system are the most critical to the successful implementation of this offensive strike capability. During offensive maritime operations, time to execute launch is a critical requirement for mission success. The time to execute obtained averaged 53.9 minutes for the LPD, 49.9 minutes for the EPF, and 21.9 minutes for the LCS. The LCS vessel was modeled as the candidate system with the fastest time to execute launch particularly due the fact that the AURs and the M870 trailer will have to be permanently stored in the hangar adjacent to the flight deck due to the inability to move LRHW AURs via the hangar elevator.

(3) Time to Implement

A third research objective was to determine the time of implementation of candidate the hypersonic missile system into the Fleet. In order to keep up strategically with Chinese and Russian hypersonic offensive capabilities, the Navy has proposed to implement a hypersonic missile weapon system to the surface Fleet by FY 2025. We determined 24 months for time of implementation for the LPD, 42 months for the EPF and 24 months for the LCS. The LPD and LCS have identical time to implement because they both take advantage of the M870 trailer for launching hypersonic missiles and will not require significant deviation from the standard operation of the LRHW system. The EPF has a longer time to implement because it will require significant engineering and manufacturing efforts to develop the crane launching cradle and method.

B. RECOMMENDATIONS

After performing the swing weights analysis of all three attributes, candidate system 1, the LPD, scored highest when evaluated based on all three attributes. Close behind was candidate system 3, LCS, while candidate system 2, EPF, lagged behind considerably. We recommend candidate system 1, the San Antonio-class LPD launching the LRHW from its flight deck, be considered as a possible ship platform for a future hypersonic glide body weapon system.

C. FUTURE WORK

(1) LRHW AUR Safety Considerations

The requirements for magazines that must hold missiles with rocket motors can be found in NAVSEA OP 4, Ammunition and Explosives Safety Afloat. Each of the candidate systems describes storing the LRHW AURs somewhere onboard the vessels – in an ammunition magazine on the LPD, in the cargo hold on the EPF, and in the hangar on the LCS. It is unlikely that all of these storage locations will meet the requirements set forth in OP 4 and further analysis of the requirements to modify each of these spaces or to develop procedures that are acceptable to be able to store the AURs in these spaces. This represents a significant risk to the implementation of the LRHW as a rapid solution for hypersonic missile capability.

One solution that was presented by the Sponsor was to permanently store the LRHW system including the AURs and AFATDS on the flight deck of the various vessels. For example, Figure 28 shows highlights an area of the EPF deck that could be used to permanently store an LRHW trailer with two AURs loaded onto it.

Figure 28. Potential on deck storage on the Spearhead-class EPF. Source: Vavasseur (2020).

The team believes that hypersonic weapons could be used in this deck-stored configuration, however more research into the ability of the LRHW to remain reliable after being stored for extended periods of time in an unprotected maritime environment may be necessary. Additionally, it is unlikely that weather or sea states will be such that the systems can be truly permanently stored on the open flight deck. Therefore, it is necessary to understand the requirements for even temporary storage in the portions of the vessels that will be unprotected from the elements.

(2) Feasibility of EPF Offensive Launches

The Spearhead-class EPF is a United States Naval Ship (USNS) vessel, which means that it is non-commissioned and serviced by a civilian crew. The ability to perform offensive missile strikes from a non-commissioned vessel represents a significant risk to the operation of the candidate system. Concerns 1.1 Personnel Required for Missile Launch and 1.2 Personnel Required to Authorize Launch reflect the need for the appropriate personnel and permissions to be available on the vessel that is performing the offensive launch. In the case of the EPF, it may be possible for a small contingent of enlisted sailors to be onboard the vessel to perform the missile launch. If the candidate system based on the EPF is to be pursued, additional work must be performed to define how the appropriate personnel and permissions will be put in place.

(3) Understanding LPD Trade-offs

The analysis of the number of AURs that can be carried on the LPD described a scenario where storage for vehicles that were part of the amphibious assault force in the vehicle storage locations on board the LPD would be displaced by the M870 trailer required to launch the LRHW missiles. It also described displacing munitions for the amphibious assault force in the magazine storage to store LRHW AURs. The displacement of equipment required for other missions to be conducted on board is the basis of Concern 1.3 Vessel Mission and the impact of adding a hypersonic missile capability on the amphibious assault mission must be understood. It is recommended that experts on the operation of the LPD and on the planning and execution of amphibious assault missions be consulted to determine how best to modify the LPD’s cargo to meet both missions.

(4) Understanding LCS Hanger Trade-offs

Similar to the concern described previously for the LPD, the candidate system that uses the LCS would prevent the hangar space from being used on the LCS from being used to house and service helicopters. The flight deck will still be available for helicopters to operate from unless the LRHW is being prepared to fire. The implications to the capabilities of the LCS not being able to use its hangar needs to be understood to address Concern 1.3 Vessel Mission.

(5) Exploring Box Launchers

In Appendix A, the Sponsor describes how box launchers for cruise missiles or defensive missiles are currently employed throughout the fleet. The advantages described include superior gas management systems and offensive strikes capability that is available in a fraction of the time that the candidate systems described in this paper require. While there are currently many weapons systems that are contained in box launchers, none of them approach the size of the LRHW. For example, the Naval Strike Missile (NSM) described by the sponsor is 13 feet long, approximately one third the size of the LRHW AUR. Development of a box launcher that would accommodate the LRHW missile in an LRHW AUR-like box launcher represents a significant deviation from the size and configuration of currently deployed box launchers. Missile launching characteristics of the larger LRHW may also preclude the use of launchers that do not start in a vertical or close to vertical configuration.

Any development of box launching systems for hypersonic glide body equipped missiles that would be a direct replacement for currently deployed box launching systems on vessels like the Independence-class LCS would require a significant amount of time. This study did not consider their employment because of the significant difference between the date of availability of the LRHW fired from the M870 trailer compared to the LRHW missile being launched from a box launcher.

Further development of a C-HGB-equipped missile that can be loaded in the VPM by the Navy will likely result in a hypersonic glide body missile capability in a smaller missile form factor. There may be a higher chance of success developing a hypersonic glide body box launcher for launching this smaller missile from surface vessels. Monitoring of the progress of these smaller missiles and considering their use in a box launcher is recommended.

(6) More Advanced Modeling

A large number of assumptions went into the times assigned to each of the steps in the EFFBDs describing the operation of each candidate systems. Comparable steps across the different candidate systems were assigned similar or even identical times to allow the results of each simulation to be compared to each other. This allowed the relative comparison between candidate system to be made and ratings to be assigned for the system analysis. In order to more accurately determine the actual time to launch for each of the candidate systems, it is recommended that both personnel who are familiar with the operation of the LRHW and the operation of the different vessels used in the candidate systems are consulted to determine more accurate timings for each of the steps. By determining more accurate timings for each of the steps, simulation of the operation of the candidate systems will have higher fidelity results and could be used to provide greater differentiation between the candidate systems. Additionally, as more characteristics of the hypersonic missile become known or unclassified, modeling that takes into account the performance of the missiles could be completed to help determine the optimal number of missiles required for a mission set, potentially altering the weight of the Number of AURs scored attribute.

(7) Fleet Planning Around New Hypersonic Missile Capability

The discussion of AUR storage and the conclusion that 12 AURs likely represents the "full" capability that would be needed from this system was based around the idea of a single AUR replacing as many as 16 TLAMs. As the Sponsor describes in Appendix A, TLAMs that are currently equipped on surface ships can be viewed as displacing missiles that might be used in anti-aircraft or anti-submarine missions. The potential for a single AUR to free as many as 16 vertical launch system tubes to allow missiles that conduct other missions to be loaded onto vessels would increase the flexibility of the vessels when it comes to planning their missile armament. It should be noted that the stated 16-to-1 ratio of TLAMs to hypersonic missiles only applies in the mission where a target with active defenses is being attacked. In a scenario in which the target is not being actively defended, it may be beneficial to have more TLAMs available than to have a single hypersonic missile. The availability of more space for alternate armaments in vertical launch systems and the strengths and weaknesses of the TLAMs versus hypersonic glide body missiles will need to be studied and considered by fleet planners when hypersonic glide body missiles become available to surface vessels.

This additional research, applied to the descriptions and analysis of the candidate systems presented in this study, will help to further refine system concerns, requirements, activities, and components that will be necessary to successfully deploy a hypersonic glide body equipped missile system on a Naval surface vessel in the near future.

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APPENDIX

NPS-21-N188, How to Rapidly Bring Hypersonic Missiles to the Fleet, Sponsor Input

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Sponsor Note

I really appreciate the Naval Postgraduate School (NPS) pursuing the topic of how to rapidly bring hypersonic missiles to the fleet. The ideas that will be explored in this thesis have deep personal meaning and the potential to solve operational problems and gain tactical advantage. These ideas percolated during 28-years of operational, staff and academic experience throughout the world.

The goal of this project is to:

Help our Navy and joint force incorporate hypersonic missiles as rapidly as possible.

Note: Hypersonic missiles are too large to fit in and their exhaust would overwhelm existing internal launching systems like the MK41 VLS.

A byproduct of this project is hopefully:

The ability to rapidly and inexpensively expand the number of ships able to contribute offensive fires.

- Existing ships well suited for this capability and mission upgrade include EPF, LCS, LPD and LSD.

- Emerging ships well suited for this capability are the *Constellation* class frigate and medium and large unmanned surface vessels (MUSV and LUSV).

Note: Modifications should have no or minimal required structural changes and any modifications should be transparent to the primary vessel tasks or easily removable when the vessel is not engaged in hypersonic missile employment.

Hypersonic Missile Demand Signal

Hypersonic weapons are attractive because of their short response time and how difficult they are to counter. I can personally vouch for the higher headquarters desire to be able to employ these weapons as soon as possible.

Long Range and Support Fires Demand Signal

On the SEVENTH Fleet staff, my job was executive officer (XO) of their Naval and Amphibious Liaison Element (NALE). The NALE integrates naval forces into joint fires at the Air Operations Center (AOC). One of the biggest issues was the demand for land attack missiles like the *Tomahawk Land Attack Missile* (TLAM). There are far more targets than TLAMs, especially if the conflict is a surprise and friendly forces are not already in place. The platforms that currently fire TLAM, destroyers, cruisers, attack submarines and guided missile submarines often have competing priorities and flexibility issues. Destroyers and cruisers are protecting themselves and the carrier or amphibious groups by doing anti-submarine, anti-air and anti-ship warfare. Every TLAM in their magazines is an anti-air or anti-submarine weapon not carried. The 96 MK41 VLS cells on a destroyer and 128 and a cruiser could be completely filled with anti-air missiles and may be inadequate for extended engagements with enemy aircraft, ships, submarines, and land based anti-ship forces, especially when decoys are employed. Additionally, it may take several TLAMs to service a larger target and especially one protected by an air defense system. In addition to TLAM appropriate targets ashore, we have a huge unsatisfied demand for fires in support of amphibious landings and friendly land forces.

Crane Launching

The crane launching idea originated when I was XO of HSV-2 *Swift* 2006–2008. *Swift's* charter was to be the risk reduction platform for the Littoral Combat Ship (LCS). *Swift's* core crew was the same number as the original LCS core crew and the ship had six stations in its mission bay capable of embarking and testing the various mission package options LCS was designed to carry. The commercial crane had a 14–20ton capability depending on extension to ensure it could handle 11-meter RHIBs, SEAL delivery vehicles, the WLD-1 Remote Mine-hunting System and other anticipated or possible mission package items. We also had a flight deck and hangar for two SH/MH-60 helicopters as LCS was expected to embark either a helicopter or hybrid helicopter and unmanned aerial vehicle (UAV) detachment. I joined *Swift* after the testing phase and the ship operated as a small, flexible amphibious ship, working for every numbered fleet and circumnavigating the globe during the final 30-months of its 5-year lease.

Shortly after joining the ship in Portsmouth, UK, *Swift* was the flag ship and afloat forward staging base for a combined Royal Navy and Royal Norwegian Navy mine countermeasure force during exercise COLD RESPONSE 2006. The only weapons *Swift* had were a 25mm cannon/40mm automatic grenade launcher system on the bow like those installed on the U.S. Patrol Combatants (PC), and some .50caliber machineguns. It was frustrating to be a sitting duck for any gunboat, helicopter or aircraft simulating an enemy. It would have been nice to have a missile system to give them pause. As a leased vessel, making significant changes to the superstructure to incorporate a launching system was not practical. As the entire ship was aluminum, no missile could safely exhaust on the hull and there were no areas to install a box-launcher system other than the flight deck and the ship only had one landing spot. The only option to non-invasively arm the ship on short notice would be to utilize the crane to hold a missile launcher. The initial idea was the 8-cell *Harpoon* launcher found on U.S. destroyers and cruisers and the X-shape would make it easy to hold the launcher tight against the crane with a simple saddle. A control cable back to a fire control computer would run on the underside of the crane into the mission bay. The missiles would exhaust over the water when the crane was rotated 180-degrees from the bow (front) of the ship. The crane being along the same axis of the ship and the missiles firing at an upward trajectory perpendicular to the ship's course, the same orientation if on a destroyer or cruiser, would make fire control inputs easier. The *Harpoon* launcher could accommodate SM-1 and SM-2 surface to air missiles, which also have an anti-ship capability and SM-1s had been test fired from that launcher on older ships. Several 8-cell *Harpoon* launchers could be stored in the mission bay and moved to the crane via the organic forklift. The launcher would be plugged into the fire control system when being lifted up into firing position.

When *Swift* was supporting GLOBAL FLEET STATION Central America in 2007, the ship visited Port Canaveral and a NASA group asked for a tour. They started measuring the flight deck and asking about available electrical power because the ship they used to track Space Shuttle launches was having engineering problems and they were looking for a back-up as the radar was portable. NASA fixed their ship, but *Swift* could have supported their portable radar. Following that line of thinking, there are portable domestic ballistic missile tracking radars and fire control systems that could be plugged into SM-3 or SM-6 missiles in a launcher suspend from *Swift's* crane that would provide a similar capability to destroyers we currently assign ballistic missile defense duties. As Japan based destroyers are heavily/over tasked, being able to execute single task missions like BMD with EPFs would significantly ease their burden and provide the fleet commander with more flexibility. Additionally, *Swift* or an EPF with a modular BMD system would be more easily upgradeable as the radar system is easily removable and larger missiles would only require larger boxes.

As the only limit to the size and number of missiles that could be fired in one salvo is crane capacity, this capability is well suited to shore bombardment systems like the Army/Marine Corps Army Tactical Missile System (ATACMS) and Guided Multiple Launch Rocket System (GMLRS). 2 ATACMS and 12 GMLRS were carried on the mobile Multiple Launch Rocket System (MLRS) and half those numbers on the High Mobility Artillery Rocket System (HIMARS). *Swift* could hold several of the missile boxes that fire those missiles from MLRS and HIMARS in the mission bay and launch them from the crane with appropriate saddle attachments. *Swift* or EPF can be quickly converted to do the shore bombardment/fire support mission we have neglected since the Vietnam War.

Longer range targets could be serviced by *Tomahawk* Land Attack Missiles (TLAM) with slightly elongated *Harpoon* tubes. TLAM and ATACMS became the focus of my efforts to make crane launching from *Swift's* replacement, EPF (formerly JHSV) a reality while XO of SEVENTH Fleet's Naval and Amphibious Liaison Element (NALE) 2010–2013 and 2016–2019 as there is an almost unlimited appetite for long-range precision fires in the Far East. TLAMs are now sourced from destroyers, cruisers and submarines that have other missions. Every TLAM loaded onto a cruiser or destroyer displaces an air-defense missile or anti-submarine rocket (ASROC). The requirement to provide TLAM fires on short notice affects the operational flexibility of these ships and submarines. An EPF in Korea with a mission bay full of TLAMs able to be launched by its crane would significantly reduce the TLAM strike burden on SEVENTH Fleet forces.

While attending the 2020 Air Force Weapons and Tactics (WEPTAC) conference, I enquired about the supersonic *Ratlers* missile displayed on the *Lockheed Martin* table during Industry Night. The good salesman, who turned out to be the INDOPACOM exercise funding point of contact I had worked with via email but never met when managing exercises for CTF73, said that 'supersonic is so last millennium, what you really want is hypersonic.' After his pitch I asked if his hypersonic missile will fit in a MK41 VLS and he said it wouldn't by quite a bit but that the dimensions were proprietary and he couldn't tell them to me. At that point I did a bar napkin sketch of the EPF crane launching idea and explained its scalability. He sent that to his boss and I had an appointment to visit the famed *Lockheed Martin Skunk Works* in Palmdale, California. When I briefed my command after the conference and ran the proposed *Skunk Works* visit by our JAG, the JAG recommended against the visit because I was on active duty and not directly involved in acquisitions.

Shortly after not being able to visit the *Skunk Works,* the Naval Surface and Mine Warfighting Development Center (SMWDC), the command I work for, Science Advisor put out a call for NPS thesis topic proposals. I submitted a proposal for "How to Rapidly Bring Hypersonic Missiles to the Fleet" and mentioned firing them from the crane of an EPF as an idea. Some who had a say or knew people who had a say in the ranking and funding of NPS thesis topic proposals at COMNAVSURFPAC and U.S. Fleet Forces Command had heard of my crane firing idea and understood that the scalability would solve the hypersonic missile size problem, so this thesis topic was the #1 ranked and thus funded NPS thesis topic for FY21.

Note: Current *San Antonio* class LPDs don't have the large cargo crane (30-ton capacity) of the LPDs they replaced and the soon to be retired LSDs.

Shipping Container Launchers

In the fall of 2020, while NPS was putting together this thesis team, *Lockheed Martin* visited SMWDC and briefed their proprietary hypersonic missile launching system alternative to the program of record internal launcher for DDG1000 that is still in development. Their alternative, which could be placed on the flight deck of their version of the LCS, was a 40-foot shipping container that housed a hypersonic missile on an automatically erectable launcher with its own gas management (blast ducting) that would not require any ship modification. The fire-control, communications and operations were contained in a 20-foot shipping container attached to the missile container by a cable. I connected the NPS thesis team to the *Lockheed Martin* representative that briefed SMWDC to show the team that a modular fire control and communications system for EPF or other non-traditional missile firing platforms was not a significant issue to be overcome. The limitation of this system is that only two missiles could be carried on the flight deck of either LCS version or an EPF. This system would be ideal for the proposed medium unmanned surface vessel as it is being designed to simultaneously support a 40 and 20-foot shipping container mission package.

Box Launchers

A fixed box launcher on the outer edge of a ship where the missile exhausts into open air instead of on the ship's hull is the simplest, provides the most reliable method of having a hypersonic missile ready for launch on short notice and is scalable. A bigger missile gets a bigger box. This configuration can be seen with the Naval Strike Missiles (NSM) on the narrow bow of the trimaran LCS and missile deck of the *Constellation* class frigate being designed. This could also be applied to flight deck edges on ships without "catwalks" and after removing the flight deck safety nets. Removal of flight deck nets is a simple unbolting of the nets, but re-installation would require a weight test and re-certification before that flight deck spot could be used. This is not a major issue for LCS and EPF as those ships were designed and conceived as single mission platforms. Hypersonic weapons employment would be the mission of those platforms when box launchers are installed on the port and starboard edges of their flight deck. LPDs and LSDs have flight decks large enough for two large helicopters like a CH-53 or four MH-60 sized helicopters. The forward large and small spots could remain available and aircraft could be easily moved to and from the hangar if the aft spots were reserved for box launchers. The current LPDs and LSDs do not have "catwalks" that would be affected by missile exhaust like their predecessors would have.

Box launchers are very common on naval vessels world-wide, especially smaller combatants that do not have internal volume for launchers and exhaust ducting. The Soviets expedited the employment of new systems by utilizing fixed box launchers unique to the new missile system. Most Western anti-ship cruise missiles have their own unique fixed box launchers too.

Vehicle Launchers

The October 2017 HIMARS missile launch from USS *Anchorage* (LPD 23) validated an idea I had been kicking around since my time on USS *Ogden* (LPD 5) 1996–1998. https://news.usni.org/2017/10/24/marines-fire-himars-ship-sea-control-experiment-navy

Prior to *Ogden's* 1997 deployment, the Marines had to do ship trials for the then new M777 155mm howitzer. Having an interest in cannons and knowing the need for fire support, I asked one of the civilian technicians if anyone had ever fired an infantry cannon from the flight deck of a ship. He said it was tried during the Vietnam War, but that the recoil was too severe and broke the flight deck aircraft tie-down pad-eyes used to hold the cannon in place. With cannons out of the question, the next idea was the Army multiple launch rocket system (MLRS), essentially an armored personnel carrier with two missile pods where the troops normally were and a laptop fire control system in the cab. Each pod could hold either one ATACMS or six GMLRS. The downfall of this idea was that one or both of the large helicopter landing spots would need to be sacrificed, depending on the number of vehicles firing. While the aircraft tie-down pad-eyes survived the 2017 shot, a $1million blast pad had to be installed to protect the flight deck.

The Army has a near-term, FY23, solution to rapidly launch a hypersonic missile from a ship. They are planning to use a modified *Patriot* missile transporter/erector/launcher (TEL) trailer. This could easily operate from a helicopter landing spot, giving an initial salvo of two from an LPD or LSD and one from an EPF and LCS. EPF and LCS could have a reload stored in the helicopter parking spot, EPF, or hangar, LCS. The LPD or LSD could have multiple spare TELs on their forward flight deck. The LPD could have additional TELs stored in its hangar and possibly additional TELs internally stored if able to transit the ramps. The LSDs could hold a significant number of TELs in their well deck and use their crane to move them to the flight deck.

Sponsor Bio

CDR Brodie is a 1993 graduate of the U.S. Naval Academy with a Bachelor of Science in History. He earned his Master of Arts in National Security Affairs (Western Hemisphere) and Joint Professional Military Education Phase I from the Naval Postgraduate School.

Sea duty assignments include Executive Officer (XO), USS FITZGERALD (DDG 62); XO, HSV-2 SWIFT; 1st Lieutenant, USS CORONADO (AGF 11); Combat Systems Officer USS GEORGE PHILIP (FFG 12); Navigator and Admin Officer, USS OGDEN (LPD 5); Damage Control Assistant and Electronics Materiel Officer, USS GARY (FFG 51). He operated at sea in every numbered fleet area of responsibility. Deployments include Far East Forward Deployed Naval Forces (twice), Africa Partnership Station, Global Fleet Station Central America, WESTPAC/JTF 515, EUCOM/CENTCOM, Cooperation Afloat Readiness And Training, Counter-Narcotics, Middle East Amphibious Ready Group, and Arabian Gulf Surface Action Group.

Ashore, CDR Brodie was “by named” back to Fleet Coordinating Group (FCG) Yokosuka, Japan/SEVENTH Fleet Naval and Amphibious Liaison Element (NALE) as XO; “by named” to Deputy N3/5/7, Commander, Logistics Group Western Pacific/CTF73 in Singapore; XO, FCG/C7F NALE; and Flag Secretary for Commander Amphibious Group ONE/CTF76 in Okinawa, Japan.

In addition to being the Doctrine and Concepts of Operations Lead for SMWDC HQ, he is the sponsor for the #1 FY21 U.S. Fleet Forces Command ranked and funded Naval Postgraduate School study, “How to Rapidly Bring Hypersonic Missiles to the

Fleet," NPS-21-N188, NPS-22-090, "Develop a database of biologic bioluminescence signatures," and Naval Warfare Development Command Fleet Battle Problem Experiment FIMS#15993, "Visual Anti-Submarine Warfare via UAV."

CDR Brodie's published articles:
https://www.usni.org/magazines/proceedings/2021/february/high-speed-ferries-surface-and-amphibious-warfare
https://www.usni.org/magazines/proceedings/2020/april/make-mine-warfare-team-sport
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