NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

LITTORAL COMBAT VESSELS: ANALYSIS AND COMPARISON OF DESIGNS

by

Bryan J. Christiansen

September 2008

Thesis Advisor:	Wayne P. Hughes
Second Reader:	Thomas Lucas

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2008	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE Littoral Combat Vessels: Analysis and Comparison of Designs			**5. FUNDING NUMBERS**
6. AUTHOR(S) Bryan J. Christiansen			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

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14. SUBJECT TERMS Littoral Combat Ship, National Security Cutter, Sea Lance, Combat Patrol Craft, Chinese Type 022 Houbei, missile combat, salvo model, leakers			**15. NUMBER OF PAGES** 84
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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LITTORAL COMBAT VESSELS:
ANALYSIS AND COMPARISON OF DESIGNS

Bryan J. Christiansen
Lieutenant, United States Navy
B.S., San Diego State University, 2002

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 2008

Author: Bryan J. Christiansen

Approved by: Wayne P. Hughes
Thesis Advisor

Thomas Lucas
Second Reader

James N. Eagle
Chairman, Department of Operations Research

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ABSTRACT

The introduction of new technologies force navies to adapt and the introduction of surface-to-surface anti-ship cruise missiles from a large number of small coastal combatants created vulnerability in the Navy's force structure of large, expensive, nonexpendable warships. To counter this threat, the adoption by the U.S. Navy of small, inexpensive, missile bearing vessels is recommended. Four alternative candidate vessels are evaluated using a mathematical simulation. The candidates are a Littoral Combat Ship with a surface warfare module, a National Security Cutter augmented with offensive and defensive weaponry, a "Sea Lance" inshore combat vessel, and a Combat Patrol Craft, a variant of the Cyclone class patrol craft augmented with offensive and defensive weaponry. Equal cost force structures for the four candidate vessels are developed, and then these forces are "fought" in simulated battles against a missile-firing opponent force of variable strength. Additional roles such as maritime interdiction and theater security cooperation are considered and the candidate vessels are qualitatively compared for their ability to perform in these missions. Sea Lance is demonstrated to be the most effective and lowest cost candidate vessel. The driving force behind this is the large number of vessels the equal-cost Sea Lance squadron makes possible by its low procurement and operating costs, a result predicted by Lanchester and Hughes because in naval combat, numerical superiority is the single most important factor in determining the outcome of a battle.

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EXECUTIVE SUMMARY

Throughout history, the introduction of new tactics and technology has forced navies to adapt or suffer the consequences. A handful of technologies have required a paradigm shift in force structure. One was the advent of aircraft before World War II, which pushed naval force structures to be centered on the aircraft carrier instead of the battleship. Another such technology is the surface-to-surface anti-ship missile, particularly when carried aboard small, inexpensive vessels operating close to shore. Against a force of such vessels, a blue water navy of all big, expensive ships is very vulnerable. In addition to this new threat, evolving needs in security patrol, theater security cooperation, maritime interdiction, and other operations require that a navy adapt by procuring its own small, inexpensive, missile bearing craft, as many nations have done.

The current U.S. Navy force can be characterized as an all big ship fleet designed for blue water and force projection operations against opponents such as the former Soviet Union. Recent developments have suggested that operations against smaller navies composed of small, inexpensive, missile bearing vessels are far more likely, such as a conflict against Iran, North Korea, or China. The Navy's current inventory of relatively small numbers of large, expensive ships is not well equipped to confront such threats. Because of this, the Navy may not be willing or able to put these ships at risk because their loss would be unacceptable.

The thesis postulates that the Navy must identify and adopt a small, inexpensive, missile-bearing vessel that can be exposed to combat risks without posing unnecessary risk to the big navy force structure. This study compares four candidate vessels to fill this role: a Littoral Combat Ship (LCS) with an adapted surface combat module, a National Security Cutter (NSC) outfitted with additional offensive and defensive weaponry, a "Sea Lance" near shore combat vessel designed by the faculty and students at the Naval Postgraduate School, and a Combat Patrol Craft (PC), which is an adaptation of the Cyclone class PC with added offensive and defensive weaponry.

Utilizing the Salvo Model developed by Captain Wayne Hughes, USN (Retired) of the Naval Post Graduate School, the four candidate vessels were compared in a mathematical simulation of combat scenarios. In a base case scenario against a force of up to forty Chinese Type 022 Houbei coastal missile craft, the Sea Lance is demonstrated to be the most effective. Although the PC is the least expensive alternative, it is demonstrated to be wholly ineffective, making Sea Lance the least expensive, most attractive viable candidate. An additional case is considered in which defenses are imperfect, introducing the concept of leakers, missiles which penetrate defenses. The Sea Lance again is the most effective, least expensive alternative. In both cases, NSC is second to Sea Lance, followed by LCS and finally by the PC. The thesis also looks at additional factors, such as accounting for imperfections in scouting on either side, and the inclusion or exclusion of chaff and decoys. No variation changes the cost-effective choice. Doubling the staying power of the significantly larger LCS and NSC also does not alter the outcome. In every case Sea Lance is demonstrated to be the best choice. The driving force behind this is the large number of vessels the equal-cost Sea Lance squadron makes possible by its low procurement and operating cost, a result predicted by Lanchester and Hughes because in naval combat, numerical superiority is the single most important factor in determining the outcome of a battle.

In addition to the missile combat scenarios, non-combat roles such as maritime interdiction, theater security cooperation, and homeland security, impose taxing roles on the current Navy structure. The addition of a large group of small, inexpensive vessels such as Sea Lance relieves the stress placed on the current Navy, freeing up the large ships to carry out the roles for which they were designed, which are power projection and blue water operations. Their small size and low cost makes Sea Lance much better suited for interactions with coastal navies and allows them to be supported by relatively modest sea or shore facilities in places at minimal risk to the Navy.

The conclusion of this study is that a small vessel such as Sea Lance is the ideal choice for the Navy, and a superior choice to the alternatives proposed.

ACKNOWLEDGMENTS

First I would like to thank my thesis advisor, Professor Wayne Hughes. Without his guidance, extensive knowledge and experience, and dedication to the success of his students, this thesis might never have been completed. The time he dedicated towards ensuring I produced the most accurate and thorough product possible is greatly appreciated. The gentle “calls to task” returned my attention and focus to where it needed to be to complete this thesis on time. I would also like to thank Professor Thomas Lucas for taking time out of his extremely busy schedule to be my second reader and provide feedback to ensure the accuracy and quality of my work.

Special thanks to Professor Jeff Kline for providing a sounding board for ideas and an alternative perspective to thesis students otherwise not directly under your advisement. Meetings including Professor Kline were always informative and generated new ideas. I would also like to thank the professors who aided me in my search for a thesis topic and eventually led me to Professor Hughes’ door: Professor Alderson, Professor Brown, Professor Meyer, and Professor Salmeron, as well as all the other professors and staff members at the Naval Postgraduate School for ensuring that I had the knowledge necessary to complete this thesis.

Finally I must thank my family, and especially my wonderful wife Shauna for providing the encouragement and support necessary to make it through this process. Without her interminable understanding and countless hours of quiet alone time at my computer, I never would have finished, and for that I forever owe a debt of gratitude.

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I. INTRODUCTION

A. BACKGROUND – WHY THE ANALYSIS WAS PERFORMED

On January 6, 2008, a column of three United States Navy warships was brought to a standstill in the Straight of Hormuz by a group of five marauding Iranian gunboats[1]. The Iranians did not fire on the Americans. They simply closed in close aboard, appeared to drop objects in the water, and verbally threatened the warships over the radio. The response of the Americans, or lack thereof, illustrates clearly the point this paper will demonstrate mathematically: the current U.S. Navy is highly capable, but its vessels are too large and too expensive to risk losing in combat, and such large, expensive vessels simply are not necessary for the missions they are often tasked to perform. It is necessary that smaller, combat worthy but less expensive vessels be added to the inventory to fill this role (as well as many other roles). We will sometimes refer to these small, lethal inshore combatants as "street fighters," an apt name that is no longer in vogue.

F.W. Lanchester first published his "Square Law" mathematical model for military combat in 1914.[2] Although it was initially developed to help predict the impact of aircraft in World War I, it was found to be effective at modeling many types of combat, including ground combat and naval warfare. J.V. Chase developed a similar model for naval warfare in 1902,[3] but his work was classified until 1972, and as a result Lanchester's Square Law is a commonly accepted base model for modern combat. One common outcome that was found by both Lanchester and Chase was that the most dominant factor in predicting the outcome of a battle is the number of combatants, and this still tends to hold true today. Although terms are included for analyzing the effectiveness of individual combatants in even the most basic models, and these other factors certainly do play a role, the models are most sensitive to changes in the number of combatants involved in the battle.

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[1] Shanker and Knowlton, 2008.

[2] Lanchester, 1916.

[3] Chase, 1902.

Problems with the Lanchester model arose with the introduction of certain force multipliers and particularly the introduction of missiles into naval combat scenarios. When a single vessel carries a large number of missiles, the offensive combat potential of that single vessel rises dramatically. For the first time in naval combat the possibility of defensive countermeasures also enters into the equations. Thirdly, the previous models assume continuous rates of fire until a firepower kill is achieved, where as missiles tend to be fired in groups, or salvos, after which the effectiveness of the salvo is assessed prior to the firing of another salvo. To address these problems, Captain Wayne Hughes USN (Retired) of the Naval Postgraduate School developed the salvo equations as a modern extension of Lanchester's work.[4] In the salvo equations, the importance of the number of combatants becomes even greater and the equations reveal why. Hughes introduced terms that accounted for not only offensive effectiveness, but also defensive effectiveness and staying power (defined later). Prior to the introduction of missiles in naval combat, it was believed that the combat effectiveness of a naval vessel could be measured by the number of guns that it carried. For example, a ship of the line with three gun decks was considered equivalent to two ships of the line each with two gun decks. Hughes demonstrated that for modern salvo warfare at sea this is no longer the case. For example, to make a single vessel the equivalent of two adversaries, the single vessel must have double the offensive, the defensive, and the staying power of each of the two ships. Roughly speaking, to double the combat potential of a vessel, its overall capabilities must be increased by a factor of eight, often times at a comparable cost increase as well.

The result is what we see in the United States Navy today; warships which cost well over a billion dollars apiece can be overwhelmed by a group of small, inexpensive, missile bearing vessels (street fighters), such as those possessed by potential adversary nations like Iran, North Korea, and China. This fact was illustrated in 1967 when an Israeli destroyer was sunk by a pair of much smaller, and seemingly less capable, Egyptian missile boats carrying only two missiles each. It is true that in such a conflict against a modern U.S. warship, the group of small vessels would likely be destroyed in the battle. But if the adversary nation trades fifty million dollars worth of small vessels

[4] Hughes, 1995.

and a few dozen lives to succeed in sinking, or at least disabling or crippling, a two billion dollar United States warship, that is quite an effective return on its investment and a victory for its cause. Later this factor will be referred to and defined as favorable attrition. Recent experience in the Global War on Terror has clearly demonstrated that there is no shortage of individuals willing to go into combat against the United States knowing there is no hope of survival. This was demonstrated by the attack on the USS Cole on October 12, 2000.[5] It is reasonable to assume that such small vessels crewed by such individuals would willingly sacrifice themselves if they believed the destruction of a large adversary could be achieved. This is a very dangerous prospect for the U.S. Navy's current inventory of relatively few, very large, very expensive vessels. When the U.S. Army goes into combat with Abrams tanks and Bradley fighting vehicles, they do so expecting that not all of those tools will remain when the fighting is done. Their combat vehicles are expensive, but not so much so that they cannot afford to loose some of them in combat. Current navy planning does not reflect the reality that in modern missile combat, vessels *will* be lost, and the Navy does not possess any vessels which can be likened to the Army's tanks and other vehicles which can be sent into combat expecting that some will not survive.

B. POTENTIAL SCENARIOS

There is no shortage of potential scenarios throughout the world which could lead to a confrontation between the United States and an adversary possessing relatively large numbers of street fighters. This adversary does not need to defeat the entire U.S. Navy, but only to defeat the vessels that we have in the area at the time. Our presence can range anywhere from a single Arleigh Burke class destroyer to an entire carrier strike group. The loss of an Arleigh Burke to a country which was previously thought to pose no real danger to the United States would certainly give the Navy, and indeed the entire country, cause for alarm and would require a pause to consider the implications and response, as it did in Yemen in 2000. A successful attack would also send a message to the world that the U.S. Navy no longer reigns supreme over the high seas.

[5] Burns and Myers, 2000.

An obvious scenario which can be played out is the one mentioned in the beginning of this paper, a confrontation between Iran and the United States. Although the vessels encountered in January of 2008 were not carrying anti-ship missiles, they very easily could have been. In May of 2002 reports circulated that Iran had purchased a number of Chinese made C-14, or "China Cat," missile attack boats, which are small, light, and fast, and carry up to eight short range anti-ship missiles.[6] Vessels of this type have been observed in Iranian naval ports.[7] To counter such vessels the U.S. has always counted on a range advantage, out scouting and defeating adversaries before entering into range of their weapons, but in the Persian Gulf, and particularly in the Strait of Hormuz, the range advantage is nullified. Whichever side fires first is most likely to win the exchange of fire. In the January 2008 case, if the Iranians had been carrying missiles and had fired them, even if the U.S. warships were able to see the missiles launch and fire their own missiles in return, the likelihood of the three U.S. vessels surviving a barrage of forty (five boats firing eight missiles each) incoming missiles is very small. The Iranian vessels may have all been destroyed as well, but trading five twenty-ton missile boats[8] for a Ticonderoga class cruiser or Arleigh Burke class destroyer gets at the heart of favorable attrition. If the U.S. mission in the Gulf could be accomplished by smaller, far less expensive vessels, the exchange outlined here might not be prevented, but it certainly levels the playing field, and reduces the exchange to either mutual attrition, or even favorable attrition on the side of the U.S. In any case, the lives of far fewer American sailors and the integrity of far less expensive military assets would be put in jeopardy.

Another possible scenario can be found in the Sea of Japan. The U.S. routinely conducts naval exercises and port visits around Japan and South Korea. Recent activities in North Korea (attempts to obtain nuclear weapons, for example) have given rise to concerns about the possibility of a confrontation between the United States and North Korea. Also, since the cease fire was signed which ended the Korean War; there have been concerns about North Korea launching an offensive into South Korea, in which case

[6] Pike, "C-14 China Cat Class Fast Attack Craft, Missile."

[7] Gertz and Scarborough, "Iran's Missile Boats."

[8] Pike, "C-14 China Cat Class Fast Attack Craft, Missile."

the U.S. Navy would undoubtedly support South Korea to the greatest extent possible. North Korea does possess vessels equipped with anti-ship missiles[9], and in such a scenario would likely not hesitate to use them, which leads to a situation similar to the one laid out in the previous paragraph.

There are any number of additional scenarios which can be played out in which the U.S. could become entangled in naval combat, including a conflict in the Caribbean between Venezuela and Columbia, or between the Greeks and Turks in the Aegean Sea, but it is not necessary to discuss all of them here. The primary scenario to be considered, and the core of the analysis to follow, is the possibility of a direct confrontation between the People's Liberation Army Navy (PLAN) and the United States Navy. It is not a stretch to imagine an armed attempt by the People's Republic of China (PRC) to retake Taiwan, which they see as a rogue province, not an independent nation. The United States has pledged to support the Republic of China (ROC) on Taiwan in such a scenario, and would find itself facing a large naval force possessing a large number of small, high-speed catamaran-type vessels, such as the Type 022 Houbei class, each carrying eight medium-range anti-ship missiles.[10] In such a scenario, even a carrier battle group would likely find itself in jeopardy in proximity to the Taiwan Straight. The air cover provided by the carrier aircraft would likely be nullified by Chinese land-based aircraft, and airborne scouting effectiveness would be severely attenuated due to the conflict in the skies overhead. Therefore, U.S. Naval vessels would most likely be required to deal with the Chinese surface combatants ship to ship in a missile duel. This is a prospect that puts the current U.S. fleet at a grave disadvantage when facing off, for example, against forty or more Houbei class missile boats.[11]

There is no quick and easy answer to the vulnerability of an all big ship navy described above, but there are solutions. This paper addresses the problem by proposing that an alternative to big ships be considered for construction, an alternative which the Navy *can* afford to expose to combat and risk. Four candidate vessels are compared in a

[9] Pike, "Navy of the Democratic People's Republic of Korea (DPRK)."

[10] Sinodefence.com, "Type 022 Houbei Class Fast Missile Attack Craft."

[11] Sinodefence.com, "Surface Combatants."

mathematical combat simulation which not only contrasts the attributes of the candidate vessels, but also “fights” groups of candidate vessels against an adversary force of varying size. The combination of subjective review of the attributes of the candidate vessels coupled with the analytical results of the combat simulation is used to determine which vessel is superior and therefore recommended for adoption by the Navy.

II. THE MODEL AND CANDIDATES

A. DEFINITIONS

To explain the mathematical model that was used to analyze the performance of various candidate naval platforms against an adversary force such as the Chinese Type 022 Houbei, it is necessary to define some terms. For additional information on the terms and their mathematical definitions, see Hughes 1995 unless otherwise indicated.

Favorable Attrition – the exchange of vessels of one's own force for vessels of greater value or combat potential of an opposing force, such that the exchange favors one's own force.

Staying Power (a_1, b_1) – the number of missile hits required to put a unit out of action.

Defensive Power (a_3, b_3) – the number of well-aimed incoming missiles destroyed by each unit's defensive systems.

Offensive Power (α, β) – the number of well-aimed missiles fired by each individual unit on average.

Distraction Chaff (ρ_A, ρ_B) – missile countermeasure (chaff or decoy) used to draw off an otherwise good shot before it enters the targeting phase and before counter-fire. Ineffective chaff has an effectiveness value of 1; perfect chaff has an effectiveness value of 0 (because it acts to degrade the number of incoming ASCMs).

Seduction Chaff (δ_A, δ_B) – missile countermeasure (chaff or decoy) used to draw off an otherwise good shot after it enters the targeting phase and after counter-fire. Ineffective chaff has an effectiveness value of 1; perfect chaff has an effectiveness value of 0 (because it acts to degrade the number of incoming ASCMs).

Scouting Effectiveness (σ_A, σ_B) – diminishment of offensive power due to less than perfect targeting and distribution of fire, a number between zero and one.

Lethality – condition defined by Armstrong[12] (low, moderate, or high) which characterizes the nature of a missile combat scenario based on the force ratios and the armaments of those forces.

B. THE MODEL

The salvo model[13] used for this study deterministically calculates the number of surviving units following an exchange of missiles between two opposing forces. The terms in the model allow the opposing forces to be of varying size and allow the exploration of the effects of changing many different vessel characteristics. Not all of the characteristics incorporated into the salvo model were explored in the cost effectiveness comparison of the four candidates; the terms considered by this analysis are included in the definitions section above. The model assumes that each force is homogeneous, fire received by a force is distributed evenly across that force, and a missile salvo occurs within a discrete time step. For additional information on the salvo model and assumptions, see Appendix and Hughes, 1995.

The basic salvo model equations determine the change in strength of a force (ΔA, ΔB) after an exchange of a single salvo, (see Equation 1). The change in strength of a candidate force is directly proportional to the opponent force's initial force strength (B) and offensive power (β) minus the candidate force's defensive power (a_3) and force strength (A), and is inversely proportional to the candidate force's staying power (a_1). The reverse is true for the opponent force's change in force strength.

$$\Delta A = \frac{\beta B - a_3 A}{a_1} \qquad \Delta B = \frac{\alpha A - b_3 B}{b_1}$$

Equation 1 – Basic Salvo Model

Naval combat simulations were performed using the salvo model programmed into Microsoft Excel (see Appendix for more information). All inputs may be varied, but the effects of those variables defined above were the only ones explored in this study.

[12] Armstrong, 2003.

[13] Hughes, 1995.

The model determines the remaining forces from each side and displays them graphically. A separate graph was used for each of the four candidate vessels. The opposition force strength was used as the independent variable on the X-axis, varying from zero to forty, and the remaining vessels from both forces were the dependent variables displayed on the Y-axis. This allowed for a graphical determination of how a candidate force of a fixed number of vessels would fare in a combat scenario against a homogeneous opposition force varying in size from zero to forty. Forty was chosen because open sources suggest this is the approximate number of Houbei the PLAN intends to build.[14] The model also allows for an instantaneous calculation in which a fixed number of both a candidate vessel and the opposition are input, and the model determines the remaining forces from both sides following a single salvo exchange. This allows for manipulation and exploration of specific regions which appear to be interesting on the graphical output, and determines the precise impact varying an individual variable has on the outcome of a combat scenario.

Actual open source data for the vessels under consideration was used to the greatest extent possible to determine values of the model inputs, but in some cases approximation was required due to the lack of availability of data in the unclassified forum. Detailed descriptions of the characteristics used in the simulations will be discussed later in the vessel descriptions section. The Chinese Type 022 Houbei was used as the opponent in all simulations to provide a consistent basis of comparison, and because it is the most capable opponent likely to be encountered in the scenarios under consideration, that is to say, a littoral combat environment.

C. VESSEL DESCRIPTIONS

Each vessel considered is evaluated based on equal program procurement costs. We assume that a fixed budget of twenty billion dollars is available for the purchase of all units and support vessels (if required) of a candidate force. Squadron sizes and total number of vessels within a program are based on this budget, as well as the estimated

[14] Sinodefence.com, "Type 022 Houbei Class Fast Missile Attack Craft."

limitations of the envisioned support vessel; more information can be found in the candidate and support vessel descriptions below.

1. Littoral Combat Ship

As it was originally conceived, the Littoral Combat Ship (LCS)[15] was to be a formidable inshore combatant which would likely have filled the role being explored by this study quite effectively. In his 2003 thesis for the Naval Postgraduate School, LCDR David Rudko, USNR, conceived the LCS as "an affordable, small, multi-mission ship capable of independent, interdependent and integrated operations inside the littorals."[16] At three thousand tons and four hundred feet long, the LCS is no longer small, nor is it particularly affordable with a price tag of about five hundred million dollars, once the cost of the mission module is included. It is, however, still expected to be a highly capable warship, and therefore is being considered by this study. The surface combat module considered for this study is assumed to incorporate around eight medium range surface-to-surface, anti-ship cruise missiles (ASCMs), an Evolved Surface-to-Surface Missile (ESSM) pack of multi-purpose short range missiles, Close in Weapons System (CIWS), thirty millimeter gun system, and both distraction and seduction chaff or other decoys. It is understood that the LCS surface warfare mission module is currently being designed to utilize the Non-Line-of-Sight Launch-System (NLOS-LS), but due to the limited range of NLOS-LS (forty to sixty kilometers)[17] compared to the YJ-83 missiles (one hundred twenty kilometers)[18] carried by the opponent vessel, this study assumes that the surface warfare mission module is equipped with about eight longer range ASCMs. It is assigned a top speed of forty-five knots and combat crew of seventy-five. Although its range is expected to be forty-five hundred miles when cruising at low speeds, a range limitation of fifteen hundred miles when sprinting at tactical speeds for combat operations in addition to the requirement that additional mission modules be carried in

[15] Pike, "Littoral Combat Ship (LCS)."

[16] Rudko, 2003.

[17] Pike, "Non-Line-Of-Sight Launch System (NLOS-LS)."

[18] SinoDefence.com, "C-802 / YJ-83 Anti-Ship Missile."

theater will require the presence of a nearby support vessel or facility for replenishment of fuel and for the storage and change out of mission modules.

Figure 1. Photo – Littoral Combat Ship (Courtesy of Lockheed Martin)

Based on these characteristics, the LCS was given an offensive power of six (this assumes that seventy-five percent of missiles available will be "good shots") and a staying power of one. Based on its considerable size, a staying power of two was explored in the analysis, but historically a vessel of three thousand tons will have a staying power closer to one[19] and so one is used for the base case. The defensive power was set at twelve, the highest of any vessel considered, ten for the ESSM (assuming that a significant portion of the missiles carried will be configured for anti-air defense, more than one missile may be required to defeat each incoming ASCM, and greater than ten incoming targets will overwhelm either the missile launcher or targeting system), one for the CIWS, and one for maneuverability given a tactical speed of forty-five knots which may allow it to evade one incoming missile. We assume that distraction and seduction chaff (or other decoys) would appear to an incoming missile with a radar signature very similar to the vessel being targeted. In the base case an incoming missile will have a fifty percent chance of targeting either the decoy, or targeting the vessel. Therefore, for having both distraction and seduction chaff launchers, the LCS is assumed to have fifty percent

[19] Hughes, 2000.

effectiveness for distraction and seduction chaff, that is, an incoming missile will have a fifty percent chance of correctly targeting the LCS over the decoy before counter fire, and will also have a fifty percent chance of targeting the LCS following counter fire if the counter fire is ineffective.

An LCS squadron is determined to comprise four LCS and a support vessel, based on the limitations of the support vessel. This results in a squadron procurement cost of three billion dollars (two billion for four LCS, one billion for the support vessel), and a manpower requirement of seven hundred (three hundred of which would be in harms way in combat). For a twenty billion dollar budget we can fund the procurement of just under seven squadrons, with a total of twenty-six LCS and a total manpower requirement of just over forty-three hundred. The values discussed in this section are summarized in Table 1.

2. National Security Cutter

Similar in size to the LCS is the National Security Cutter (NSC)[20] originally designed for the U.S. Coast Guard. As a coast guard patrol vessel, it does not carry the armament required for consideration by this study as it was originally designed. According to Naval Ships Systems personnel at the Naval Postgraduate School, outfitting the NSC with an armament comparable to that described for the LCS is feasible. The organic NSC is expected to cost roughly four hundred million dollars and have a crew around one hundred twenty five. For the purposes of this study it is estimated to have a procurement cost of five hundred million dollars once offensive and defensive armament is incorporated, and have a crew of one hundred fifty, once personnel to operate the increased armament are included. The NSC is slightly longer than the LCS at four hundred eighteen feet and tips the scales at four thousand three hundred tons. The significant advantage the NSC gains over the LCS is in its range, estimated to be in excess of twelve thousand miles, relieving it of the requirement for a nearby support vessel or facility, except as required for replenishing ammunition. The NSC pays for this advantage with a disadvantage in speed, expected to top out at twenty eight knots. As stated previously, the armament of the adapted NSC is assumed to be comparable to the

[20] Pike, "Maritime Security Cutter, Large (WMSL) / National Security Cutter (NSC)."

LCS, with eight medium range surface to surface anti-ship missiles, an ESSM pack of multi-purpose short range missiles, CIWS, thirty millimeter gun system, and distraction and seduction chaff or decoy launchers.

Figure 2. Photo – National Security Cutter (Courtesy of Northrop Grumman)

As a result of the similarities between the LCS and NSC, the vessel characteristics used for analysis are very similar as well. Please see the LCS description for further explanations of the derivation of these values. The offensive power is set at six and staying power is set at one, as with the LCS. Slightly different from the LCS is the defensive power, set at eleven vice twelve due to the lower speed of the NSC. The distraction and seduction chaff/decoy are given an effectiveness of fifty percent, also as with the LCS.

Due to the requirement of the support vessel being removed for the NSC and a unit cost similar to the LCS, the squadron size is found to be six vessels. Thus, the squadron costs for both vessel types are the same at three billion dollars, with a manpower requirement of nine hundred (all of whom will be in harms way in combat). The result is the same number of squadrons being created, just under seven, but unlike the LCS a total of forty vessels can be procured within the twenty billion dollar budget, with a total manpower requirement of six thousand. The values discussed in this section are summarized in Table 1.

3. Sea Lance

In January, 2001, the Naval Postgraduate School published a technical report titled "Sea Lance – Littoral Warfare Small Combatant System."[21] The Sea Lance, as described in this report, is a logical progression of the Street Fighter concept and is similar to the LCS as it was originally conceived, and as LCDR Rudko defined it in his thesis (quoted above). The Sea Lance is small, fast, formidable, and relatively affordable. As conceived, it would be two hundred feet long, displace five hundred tons, and carry a total crew of twenty five, only twelve of whom would be onboard when combat operations are expected. Each vessel is estimated to have a procurement cost of one hundred million dollars (the cost was under eighty million dollars when the original study was performed, but for this study it is increased to account for inflation and additional costs), a top speed of fifty knots, and an operational range of twenty five hundred miles.[22] Thus, the Sea Lance is smaller, faster, and less expensive than LCS, but is more limited in range and armament. Due to its reduced size, it is only expected to carry four medium range ASCMs and will not have CIWS, but does carry the same ESSM pack and distraction and seduction chaff or decoy launchers as the LCS and NSC.

Please see the LCS description for a more detailed explanation of how the following vessel characteristics were derived. Due to the number of ASCMs being reduced from eight to four, the Sea Lance is given an offensive power of three, and due to its diminutive size it is given a staying power of only one. For defensive power, it lacks the CIWS carried aboard the larger combatants, but due to its high speed capability and ESSM pack it is assigned a defensive power of eleven. Like the LCS and NSC, the distraction and seduction chaff/decoy launchers are given fifty percent effectiveness.

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[21] Byers et al., 2001.

[22] Pike, "Sea Lance."

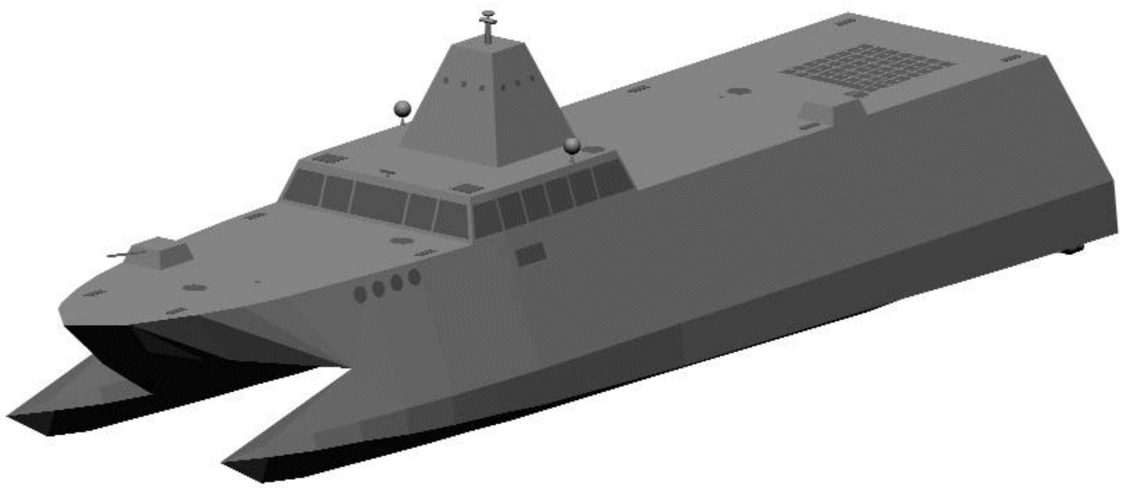

Figure 3. Rendered Isometric – Sea Lance[23]

Due to its limited range and number of missiles, Sea Lance will rely upon a support vessel for refueling and rearming. The support vessel will also house the portion of the crew that is not on board when combat is anticipated. It is assumed that the support vessel cannot effectively support more than twelve vessels of any size (see the support vessel description below for more information), so the squadron size is set at twelve, with a squadron procurement cost of two point two billion dollars, well under the squadron procurement cost of the LCS. The squadron manpower requirement is seven hundred, the same as LCS, but only one hundred forty four personnel are placed in harms way when the squadron goes into combat, compared to three hundred for LCS. The lower squadron cost allows for just over nine Sea Lance Squadrons to be procured within the twenty billion dollar budget, with a total of one hundred nine units (compared to twenty six LCS), and a total personnel requirement of just over six thousand three hundred. The values discussed in this section are summarized in Table 1.

4. Combat Patrol Craft

A variant of the Cyclone class Patrol Coastal craft (PC)[24], like the NSC it is an existing hull not originally designed for this purpose which is being adapted for missile

[23] Byers et al., 2001.

[24] Pike, "PC-1 Cyclone Class Patrol Coastal Craft."

combat in this study. A very low cost alternative, the PC is expected to cost only sixty million dollars, with a length under one hundred eighty feet and displacement of only four hundred tons. The reduced cost is achieved by using an existing hull, a reduced top speed of thirty five knots (the current Cyclone class top speed)[25], and a significantly reduced armament, which is also necessary due to its diminutive size. The Cyclone class has an approximate range of twenty five hundred miles and a crew of thirty, numbers which are maintained the same for this variant. The reduced armament allows for only two medium range surface to surface anti-ship missiles and one set of chaff/decoy launchers, in this case seduction chaff. Seduction chaff was chosen vice distraction chaff because it stands to reason that if only one type of chaff can be carried, and in limited quantity, a vessel will want to be sure that the incoming missile is in fact targeting that vessel before utilizing countermeasures. Distraction chaff is used before the missile acquires the target. Using seduction chaff allows the vessel the chance to evade without countermeasures before target acquisition occurs, then use countermeasures if the missile still manages to acquire the vessel. Unlike the other vessels above, our combat PC does not have the ESSM launcher, CIWS, or distraction chaff, and due to its limited range and habitability would require the support vessel.

Due to its lack of defensive systems, the PC is assigned a defensive power of one, achieved through the assumption that its top speed of thirty-five knots can effectively defend against one incoming missile through evasion. Due to its size, its staying power is also one, and its offensive power is two. The other candidate vessels were charged a penalty of twenty-five percent to account for missiles launched that were not "good shots." Because the PC only carries two missiles, as outlined here, it is given credit for both being good shots to make it more competitive with the other candidate vessels. As with the other vessels, the seduction chaff (or other decoys) is assumed to have an effectiveness of fifty percent.

[25] U.S. Navy, "Patrol Coastal Craft – PC."

Figure 4. Photo – PC1 Cyclone (Courtesy of GlobalSecurity.org)

Due to the larger crew and limitations on crew support capability of the support vessel, the squadron size for the PC is ten, with a procurement cost of one point six billion, barely half the procurement cost of the LCS squadron, and with a manpower requirement of seven hundred (three hundred of whom are in harms way during combat operations). This reduced cost allows for the procurement of twelve and a half squadrons, greater than all the others, with a total of one hundred twenty five units, and a total manpower requirement of over eighty five hundred, the largest total of any vessel type. The values for the PC are also summarized in Table 1.

5. Support Vessel

For the purpose of this study, the support vessel is envisioned to be a simplified variant of the San Antonio class LPD. The advantages of using this concept is that it utilizes an existing hull with air support capability (for the inclusion of Unmanned Aerial Vehicles, or UAVs, to improve scouting and helicopters for personnel recovery) and is already designed to support a large number of personnel in addition to the organic crew as well as interface with smaller seaborne vessels. This is particularly advantageous to the Sea Lance. With its small draft and size, it is even conceivable that the Sea Lance could dock with the support vessel inside the well deck, where replenishment, crew rotation, and maintenance could be accomplished in a relatively sheltered environment. Loosely based on the vessel characteristics of the San Antonio class, it is estimated to have a procurement cost of roughly one billion dollars and an organic crew of four hundred.[26] The San Antonio class is expected to cost more than this, but the support mission envisioned by this study requires fewer capabilities than a standard San Antonio class, which should allow the support vessel to be produced at a lower cost. Other characteristics, such as range, armament, displacement, and speed are not important for this study; it is sufficient to assume that it can be in the area of operation within reach its dependent vessels.

Figure 5. Photo – LPD 17 (Courtesy of flickr.com)

The following limits are placed on the support vessel for squadron sizing purposes: it is assumed to have a maximum support capability of twelve vessels, three hundred crew members, or twelve thousand tons of combined displacement of dependent vessels, whichever limit is reached first. The vessel number limit is set due to limitations on the support vessel's ability to rotate through servicing its dependent vessels. The crew limit is set based on providing relatively comfortable long term berthing onboard the LPD in excess of the organic crew, giving consideration for additional personnel required

[26] Pike, "LPD-17 San Antonio Class (Formerly LX Class)."

for maintenance, crew rotation (berthing for two full crews for each dependent vessel may be needed if frequent rotations are required), and other specialties in addition to supporting the dependent vessel crews. The displacement limit is set based on the assumption that larger vessels use more fuel and larger crews require more stores, therefore taxing the replenishment capabilities of the support vessel if too many or too large dependent vessels are assigned. In the case of LCS the tonnage limit is reached first, in the case of PC the crew limit is reached first, and in the case of Sea Lance the vessel number limit is reached first.

6. Chinese Type 022 Houbei

The opposition force for this study is comprised of varying numbers of the Chinese Type 022 Houbei Missile Fast Attack Craft. This particular vessel was chosen due to the primary scenario being set in the Taiwan Strait. In addition, the Houbei is the most capable missile combatant possessed by any potential adversary in the envisioned scenarios. As a result, the conclusions drawn from analysis against the Type 022 can be readily applied to virtually any other theater with any other opposition force.

The Houbei is smaller than the other vessels being considered, measuring only one hundred forty feet long, drawing two hundred fifty tons, and with a crew of twelve.[27] What it lacks in size it makes up for in performance. It is estimated to have a top speed in excess of forty knots, and though it may be limited in range, even a range of only one thousand miles is more than sufficient to carry out the mission of sea denial in the Taiwan Strait while being supported from land bases in mainland China. The Houbei's offensive capability is formidable, carrying eight YJ-83 type medium range surface-to-surface, anti-ship missiles. Its defenses are less considerable, as it does not appear to carry any anti-air missile defense system, but rather depends upon a close in weapon system and either seduction or distraction chaff/decoy launchers (seduction chaff assumed for the purpose of this study). The procurement cost of the Houbei is unknown; open sources indicate that China is planning to build in excess of forty vessels.[28]

[27] SinoDefense.com, "Type 022 Houbei Class Missile Fast Attack Craft."

[28] SinoDefense.com, "Type 022 Houbei Class Missile Fast Attack Craft."

Figure 6. Photo – Chinese Type 022 Houbei (Courtesy of SinoDefence.com)

For its speed and rapid fire gun defense, the Houbei is given a defensive power of two, and due to its size it is given a staying power of one. Its offensive power, diminished as with the other vessels by the assumption that not all shots are good shots, is set at six. Also as with the other vessels in this study, the seduction chaff launchers are estimated to have an effectiveness of fifty percent. As with the PC, seduction chaff was chosen in lieu of distraction chaff for the reasons stated in the PC description. The characteristics assigned to the Houbei for this study are not as important as those assigned to the other vessels. It appears that small changes to these characteristics would not significantly impact the overall outcome of the study, as it would affect each U.S. candidate force proportionally when combat modeling is conducted. The Houbei is simply used as a consistent adversary for comparisons. The values discussed in this section are summarized in Table 1.

Table 1. Summary of Vessel Characteristics and Model Inputs

Vessel Characteristics	LCS	NSC	Sea Lance	PC	Type 022 Houbei
Length	400	418	200	179	140
Displacement	3000	4300	500	400	250
Crew	75	150	25	30	12
Combat Crew	75	150	12	30	12
Unit Cost ($M)	500	500	100	60	
Sprint Range	1500		1000		
Cruise Range	4500	12000	2500	2500	
Top Speed	45	28	50	35	40
# ASCMs	8	8	4	2	8

Defensive Missiles	ESSM	ESSM	ESSM	No	No
Guns	CIWS 30mm	CIWS 30mm	30mm	25mm	CIWS*
Distraction Chaff	Yes	Yes	Yes	No	No
Seduction Chaff	Yes	Yes	Yes	Yes	Yes
Support Vessel	Yes	No	Yes	Yes	Port

Model Inputs

Staying Power (a1)	1	1	1	1	1
Defensive Power (a3)	12	11	11	1	2
Offensive Power (α)	6	6	3	2	6
Scouting Effectiveness (σA)	1	1	1	1	1
Seduction Chaff (a4)	0.5	0.5	0.5	0.5	0.5
Distraction Chaff (ρA)	0.5	0.5	0.5	1	1

Sqdn Size	4	6	12	10
Sqdn Cost ($M)	3000	3000	2200	1600
Sqdn Manpower	700	900	700	700
# Sqdns	6.67	6.67	9.09	12.50
Program Manpower	4350	6000	6325	8550
Max Number	26	40	109	125
Combat Cost Risk ($M)	2000	3000	1200	600
Combat Crew Risk	300	900	144	300

* The CIWS abbreviation is typically used to describe a specific U.S. Close In Weapons System; in this case it is describing an equivalent rapid fire hard kill defensive weapons system.

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III. ANALYSIS

A. BASE CASE

The paragraphs that follow are a discussion of how each of the candidate vessels performed in the previously described model in a very basic scenario. A squadron of candidate vessels is "fought" against a small squadron of up to ten opponent vessels (Chinese Type 022 Houbei), and then fought against a variable force of up to forty opponent vessels. If the squadron of candidate vessels does not survive the squadron engagement, the force engagement is omitted. Following the discussion of all the candidates' performance is a summary comparison of their overall performance in the simulations. In each case, the two forces expend all missiles in a single salvo, with outcomes that may range from both forces being completely annihilated, to neither force taking any casualties. Whichever force emerges from this exchange with a lower loss rate will be considered victorious. The base case does not account for factors such as leakers (incoming missiles that slip through otherwise perfect defenses) which would impact the attrition rate of the combatants, and does not account for scouting effectiveness as it is assumed in this case that both forces are within detection and engagement range of each other. These factors will be explored later insofar as how they impact the selection of the "best" candidate vessel. Also assumed is even distribution of fire, which may not be a realistic assumption, but should impact each candidate's performance proportionally.

1. Littoral Combat Ship

In combat against the opponent squadron, the LCS is clearly superior (see Figure 7). When given equal numbers of vessels, the LCS eliminates all of its opponents without taking any casualties. Even when outnumbered two to one, the LCS also does not take any casualties, and reduces the opponent force by half. Although both the LCS and the Houbei carry the same number of ASCMs (eight), this off-balanced result in favor of the LCS can be attributed predominantly to the ESSM system, which gives the LCS a large advantage in defensive power. Additional defensive hard and soft kill systems do impact the outcome on both sides, but the impact of these systems is relatively small compared to the impact of the ESSM system. Once all ASCMs are expended, one or both forces would likely withdraw to rearm, or the battle would be decided by short range weaponry. In this case the LCS would also have the advantage, as it is equipped with short range surface warfare weapons systems such as thirty millimeter guns and ESSM. Any missiles in the ESSM system not utilized in anti-air defense can be reconfigured for short range surface warfare applications. The Houbei, by comparison, is armed only with a Close In Weapons System, which is not designed for or particularly effective in ship to ship combat.

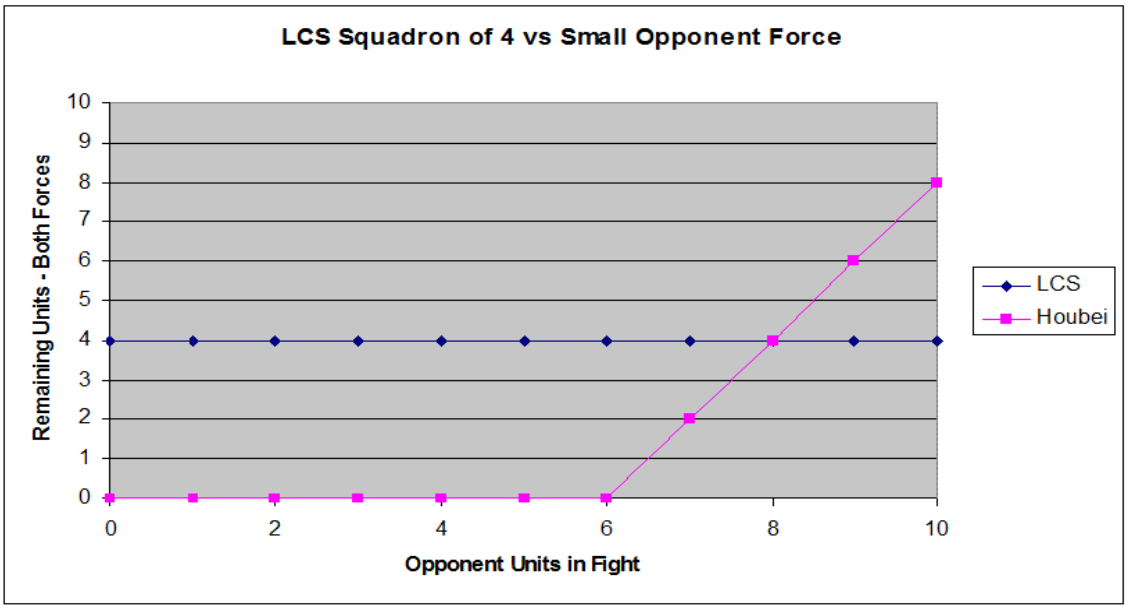

Figure 7. LCS Squadron vs. Chinese Type 022 Squadron Sized Force

As might be expected, in the large scale engagement (ranging up to forty opponents, see Figure 8), the LCS squadron is eventually overwhelmed by both the combined defensive power of the opponent force, and also by the combined offensive force. It can be argued that four against forty is not a fair engagement, but all candidates will be subjected to the same scenario and the outcomes will be discussed for comparison purposes. Four significant break points in the scenario are worth noting. The first is when the opponent force reaches six vessels, at which point the opponent force is no longer completely destroyed. The second is when the opponent force reaches twelve vessels, and their combined defensive power is sufficient that incoming missiles are no longer able to penetrate (as stated previously, this assumes even distribution of fire and no leakers). The result is a stalemate, in which neither side achieves any hits against the other. In the discussion of lethality conditions, this outcome demonstrates that this scenario is moderately lethal.[29] The third break point is when the opponent force reaches sixteen, after which the opponent begins to score hits on and attrite the LCS force. It is worth pointing out that at this point the LCS force is outnumbered four to one, before taking casualties. After this point, as the opponent force increases, the LCS squadron takes additional casualties until the force is completely eliminated when the opponent force reaches nineteen vessels (the fourth break point). At this point the opponent is taking no losses, and the U.S. losses could potentially reach two billion dollars in vessel procurement costs and three hundred lives (if vessels are sunk with all hands vice firepower kill with survivors). Of note, additional calculations showed that to completely destroy an opponent force of forty Houbei, a force of twenty-seven LCS would be required (procurement cost for twenty-seven LCS and the appropriate number of support vessels is over twenty billion dollars).

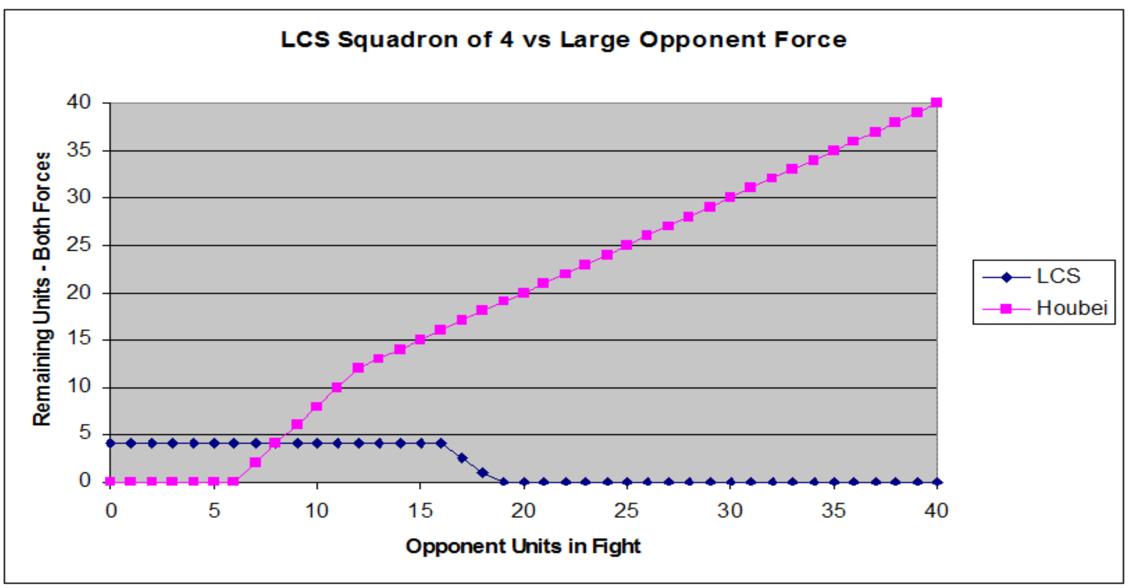

Figure 8. LCS Squadron vs. Chinese Type 022 Fleet Sized Force

29 Armstrong, 2003.

2. National Security Cutter

Due to the similarities between the offensive and defensive armaments carried by the LCS and the NSC, it is not surprising that the NSC achieved a similar performance to that of the LCS (Figure 9). The results were similar, but in this case the NSC was the superior performer. Because the NSC does not require the presence of a support vessel in theater, its squadron size is fifty percent larger, therefore bringing fifty percent more missiles to the fight. As an expected result, the opponent has to bring fifty percent more vessels, or nine, to the fight, before reaching the point where any of his force survives the exchange (the first break point). This leaves the NSC with far fewer opponent vessels to deal with in short range combat after the missile exchange in which all missiles are expended, giving it an advantage over LCS, particularly when considering the numerical superiority of the NSC force. However, the sprint speed of the LCS might allow it to run down and destroy a withdrawing opponent, while the NSC would likely find itself lagging behind due to its slower speed, making the initial missile exchange the only opportunity the NSC squadron would get to engage the enemy. As with the LCS, the performance advantage over the opponent force is predominantly attributed to the performance of the ESSM system.

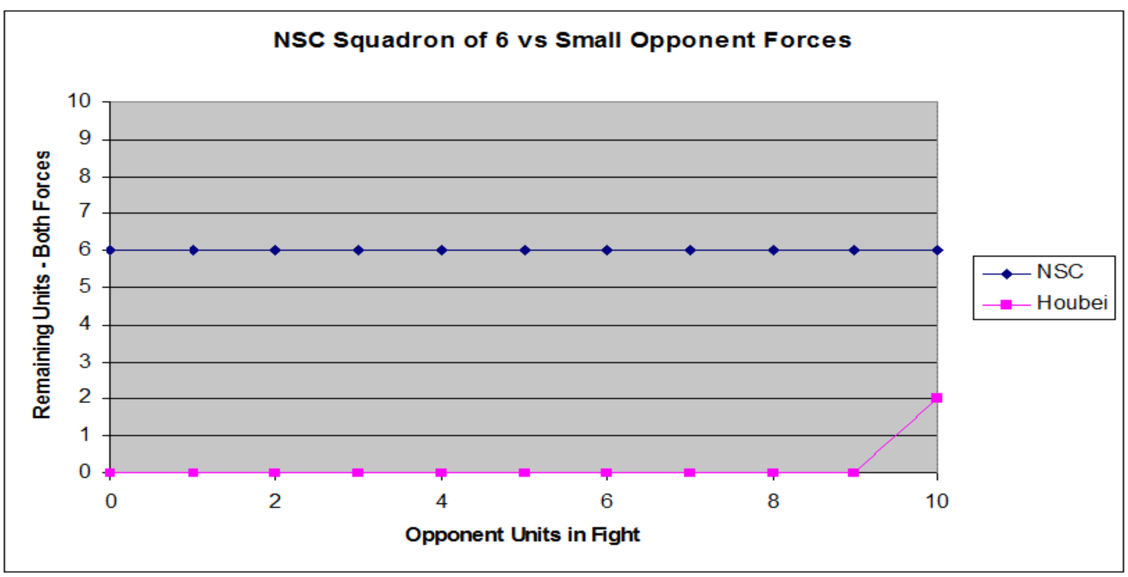

Figure 9. NSC Squadron vs. Chinese Type 022 Squadron Sized Force

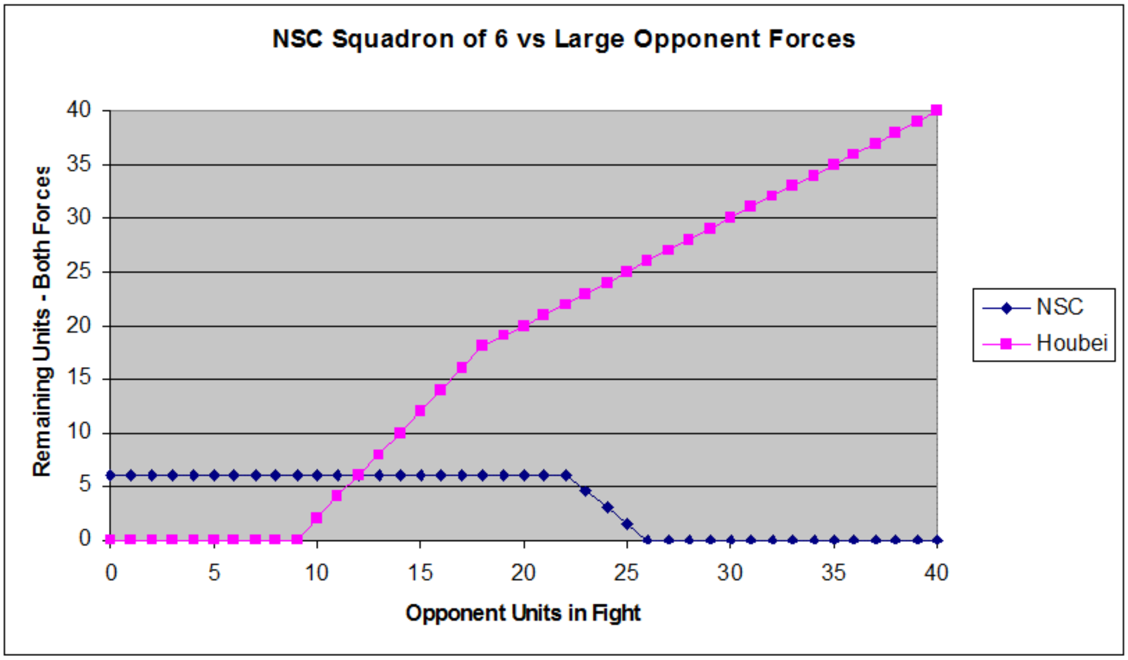

Figure 10. NSC Squadron vs. Chinese Type 022 Fleet Sized Force

In the large scale engagement scenario, the NSC again resulted in a performance very similar to but superior to the LCS (Figure 10). The results are nearly identical, but with different break points. The first break point was identified above at nine Houbei. The second break point occurs when the opponent force reaches eighteen, at which point a stalemate is achieved because neither force can penetrate the other's defenses, again exhibiting the behavior of moderate lethality[30]. As a comparison note, the LCS started taking casualties after the opponent force reached sixteen. The NSC squadron does not start taking casualties until the third break point, when the opponent force is greater than twenty-two. The fourth break point, when the NSC squadron is put completely out of action, does not occur until the opponent force reaches twenty-six. While this outcome is superior to the outcome achieved by the LCS, it should be noted that the complete loss of an NSC squadron could result in U.S. losses of as much as three billion dollars in vessel procurement costs and nine hundred lives (if vessels are sunk with all hands vice firepower kill with survivors). This is a significantly larger loss than the loss of an LCS squadron, but up to the second break point the opponent force would take significantly

[30] Armstrong, 2003.

greater losses as well, demonstrating the basic axiom that greater risk brings greater reward. As with LCS, to completely eliminate an opponent force of forty Houbei, a force of twenty-seven NSC would be required, the procurement cost for twenty-seven NSC being over thirteen billion dollars.

3. Sea Lance

For the Sea Lance, the squadron size engagement resulted in exactly the same result as for the NSC (Figure 11); the opponent force is completely destroyed until it reaches ten vessels, at which point two vessels survive (the first break point at nine). This should be expected, as the Sea Lance carries half the number of missiles as the NSC, but the Sea Lance squadron has twice the number of vessels. Unlike the NSC, however, with its superior speed, the Sea Lance has the capability to chase down a withdrawing opponent (if necessary) and finish the fight in short range combat with the thirty-millimeter gun and remaining ESSMs.

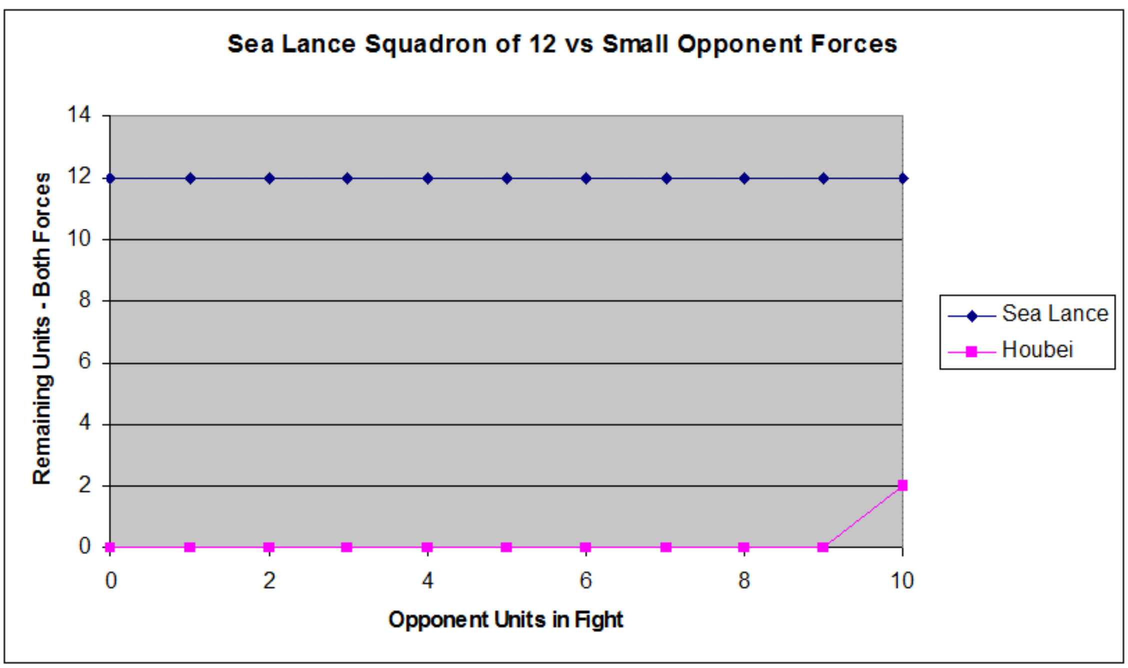

Figure 11. Sea Lance Squadron vs. Chinese Type 022 Squadron Sized Force

The large-scale force scenario results were different for Sea Lance than for the other two candidates already considered (Figure 18). The second break point occurs when the opponent force reaches nine vessels, and the number of survivors increases linearly as more vessels are added to the fight, like NSC. The third break point occurs when the opponent force reaches eighteen vessels, again like NSC, and a stalemate is achieved. The fourth break point, now unlike NSC, never occurs within the range being considered. As the opponent force grows, finally reaching forty vessels, the combined defensive power of Sea Lance squadron of twelve is still able to defeat the incoming salvo without taking any casualties. This is a low lethality condition[31], because neither side is capable of penetrating the other's defenses. This suggests that perhaps in this scenario a better balance between offensive and defensive power has been achieved than in the other cases. Additional calculations showed that the first casualties suffered by the Sea Lance squadron would not occur until the opponent force reached forty-five vessels. This result overturns the previously stated axiom that greater risk brings greater reward. The Sea Lance squadron only risks one point two billion dollars in vessel procurement costs and one hundred forty-four lives when going into combat, significantly lower than either of the other two vessels discussed, but it achieves greatly improved results. Additional calculations showed that to *completely eliminate* an opponent force of forty Houbei, a total of fifty-four Sea Lance would be required (procurement cost for fifty-four Sea Lance and appropriate number of support vessels is ten point four billion, the least expensive alternative thus far).

[31] Armstrong, 2003.

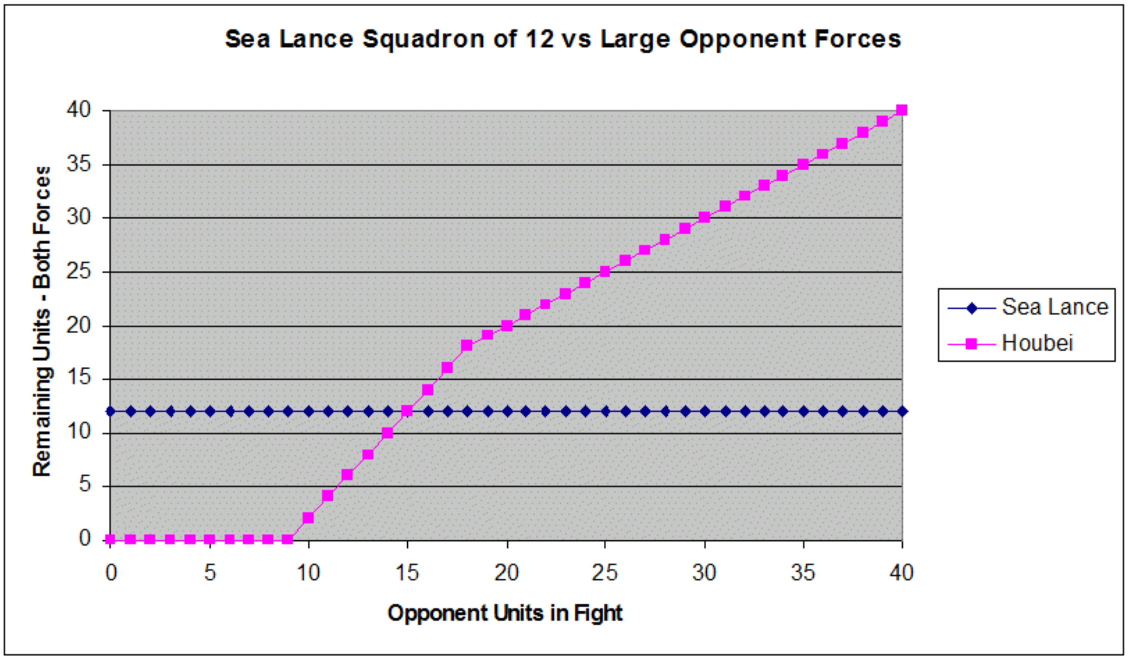

Figure 12. Sea Lance Squadron vs. Chinese Type 022 Fleet Sized Force

4. Combatant Patrol Craft

As might be expected in the case of the PC, the lack of offensive and defensive armament left it ill prepared for the mission of defeating even a small opponent force. A combatant PC squadron might be effective in the mission of deterrence, but not direct combat (Figure 13). Only when facing a single opponent was the PC squadron able to emerge without taking any casualties, due to the high lethality condition of this combat scenario (in which both forces are capable of annihilating each other in a single salvo).[32] In this scenario there was only one break point of interest, when the opponent squadron numbered five vessels against our ten. At this point, both forces were completely put out of action. For this case only the Fractional Exchange Ratio (FER) was included in Figure 13. The FER is defined as the number of vessels in one force exchanged for an opponent's vessels, is only defined for a region where both forces take losses, and is effective at illustrating the concept of favorable attrition (FER was excluded from the other force discussions because the stalemate regions in the middle of each scenario

[32] Armstrong, 2003.

prevented the FER from ever being defined in those cases, as there was no point where both forces took losses). In the PC case the FER demonstrates the favorable attrition achieved by the PC squadron early on, trading a single PC for two Houbei, but it quickly drops to zero as the opponent force grows.

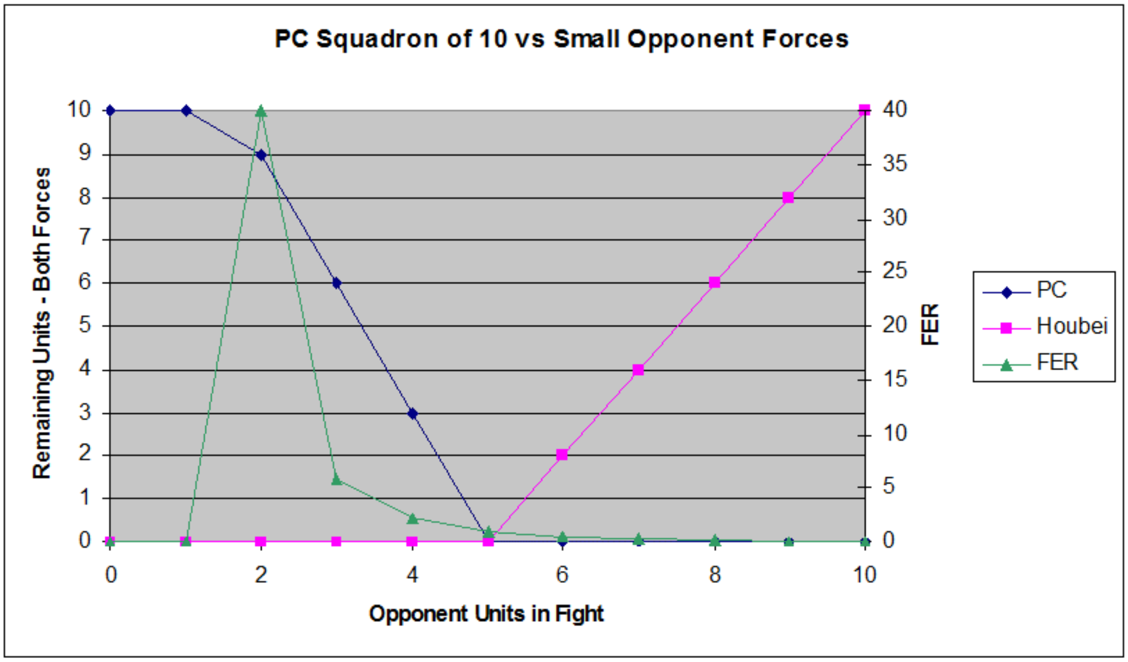

Figure 13. PC Squadron vs. Chinese Type 022 Squadron Sized Force

The discussion of the full force combat scenario is omitted because the entire PC squadron is destroyed when the opponent force reaches just five vessels. Additional calculations showed that to eliminate a force of forty Houbei, the PC force would require eighty vessels, all of which would also be put out of action, at a potential loss of four point eight billion dollars in procurement costs and twenty-four hundred lives (if vessels are sunk with all hands vice firepower kill with survivors). Such a force would also require eight support vessels, for a total procurement cost of nearly thirteen billion dollars, less expensive to replace than the LCS or NSC, but far more costly in losses than any of the other alternatives, making the PC a non-viable option.

5. Summary Comparison of Basic Case

A close examination of the discussion points and figures above is not required to determine that one candidate force outperformed the other three. The Combat PC is summarily eliminated in this case, as it took the most losses while inflicting the least amount of damage. The LCS and NSC achieved similar performance, however the NSC mathematically performed better due solely to the fact that an NSC squadron is composed of more vessels, and therefore more offensive and defensive missiles, making it more survivable and more potent offensively. The best performer was the Sea Lance, due largely to the higher number of vessels in the squadron as well as the lower cost and manpower requirements, which makes losses more acceptable when they must be accrued. To be fair to the larger LCS and NSC, the model was also run using staying power of two for both vessels, which improved both candidates' performance, but did not alter the outcome of the analysis. Table 2 summarizes the results of this analysis.

Table 2. Summary of Analysis for Base Case Scenario

	LCS	NSC	Sea Lance	PC
Performance Ranking	3	2	**1**	4
Break Point 1	6	**9**	**9**	5
Break Point 2	12	**18**	**18**	10
Break Point 3	16	22	**44**	1
Break Point 4	19	26	**52**	5
Lethality Condition	Moderate	Moderate	Low	High

Candidate requirements to eliminate 40 Houbei:

	LCS	NSC	Sea Lance	PC
# Vessels Required	27	27	54	80
# Vessels Lost	0	0	0	80
Procurement Cost	$20.5 Billion	$13.5 Billion	**$10.4 Billion**	$12.8 Billion

Notes:

All break points are defined by the number of vessels in the opponent Houbei force

Break Point 1 - Number above which the Houbei force is no longer completely eliminated

Break Point 2 - Number above which the Houbei force no longer takes any casualties

Break Point 3 - Number above which the candidate force will start taking casualties

Break Point 4 - Number at which the candidate force is completely eliminated

Procurement cost includes the appropriate number of support vessels

B. CONSIDERATION OF LEAKERS

Following the basic case, the model and scenario were adapted to allow for the incorporation of "leakers," or incoming ASCMs which are good shots and would otherwise be stopped by perfect defenses, but have some probability of penetrating those defenses because no defense is actually perfect. This adds more realism to the model, as historically missile defense systems have not been perfect. In previous cases of missile combat, the incidence of leakers has tended to have a bimodal distribution, either no leakers occur, or a large number of ASCMs hit their targets.[33] To account for this in a way which is relatively easy to model and easy to understand, a fixed percentage of incoming missiles are assumed to leak through both candidate and opponent defenses, in this case twenty percent, which is close to the historical average leakage rate through missile defense systems, defined as the leakage factor (L). For both the candidate and opponent forces, a term was added which multiplies together the total number of a force's vessels (A, B), the offensive power (α, β), and the introduced leakage factor, divided by the staying power, and then this value is added to the ΔA and ΔB terms (see Equations 2 and 3). The effect is that some additional losses occur to both sides in every case, the value of which is linearly dependent on the total number of missiles carried by a squadron and the leakage factor, and inversely proportional to the staying power.

$$\Delta A = \frac{\beta B - a_3 A}{a_1} \qquad \Delta A_L = \Delta A + \frac{B\beta L}{a_1}$$

$$\Delta B = \frac{\alpha A - b_3 B}{b_1} \qquad \Delta B_L = \Delta B + \frac{A\alpha L}{b_1}$$

Equation 2 – Basic Salvo Model

Equation 3 – Salvo Model Adaptation for Consideration of Leakers.

The impact on the outcome of the scenarios described above was surprising in some aspects, not surprising in others. A primary effect which was significant across all the models was the breaking of the stalemates. In all cases, the stalemate region in which neither force can penetrate the other's defenses disappeared, leaving instead an open

[33] Hughes, 2000.

region where both forces can be completely put out of action, shifting the scenarios to high lethality combat.[34] This is an expected result, since by definition the leakage term eliminates the perfect defense, and therefore casualties will be accrued by both sides in every exchange. An unanticipated but also logical result was that even in the cases where one force is greatly outmatched or outnumbered (i.e., PC versus Houbei Fleet), some casualties were inflicted on the opponent force regardless of its superiority, due again to the fact that the defenses are no longer able to perform in a perfect manner. It is logical to assume that an incoming missile will only be engaged by one or two vessels in a force, and if the particular vessel that engages is unsuccessful for any reason, then casualties will occur regardless of the overall force size.

1. Littoral Combat Ship

Due to the littoral combat ship having only four vessels in a squadron, it was perhaps impacted the most by the introduction of leakers. Since a single opponent vessel has an offensive power of six, assuming twenty percent leakage, the LCS squadron strength is reduced by thirty percent. The result is that the LCS squadron can be nearly eliminated by as few as three opponents (Figure 14). Alternatively, the LCS squadron can completely eliminate an opponent force of up to eight vessels. The next break point is when the opponent force strength reaches the point where only leakers are able to penetrate, at which point the LCS squadron inflicts five casualties on an opponent force of any size.

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[34] Armstrong, 2003.

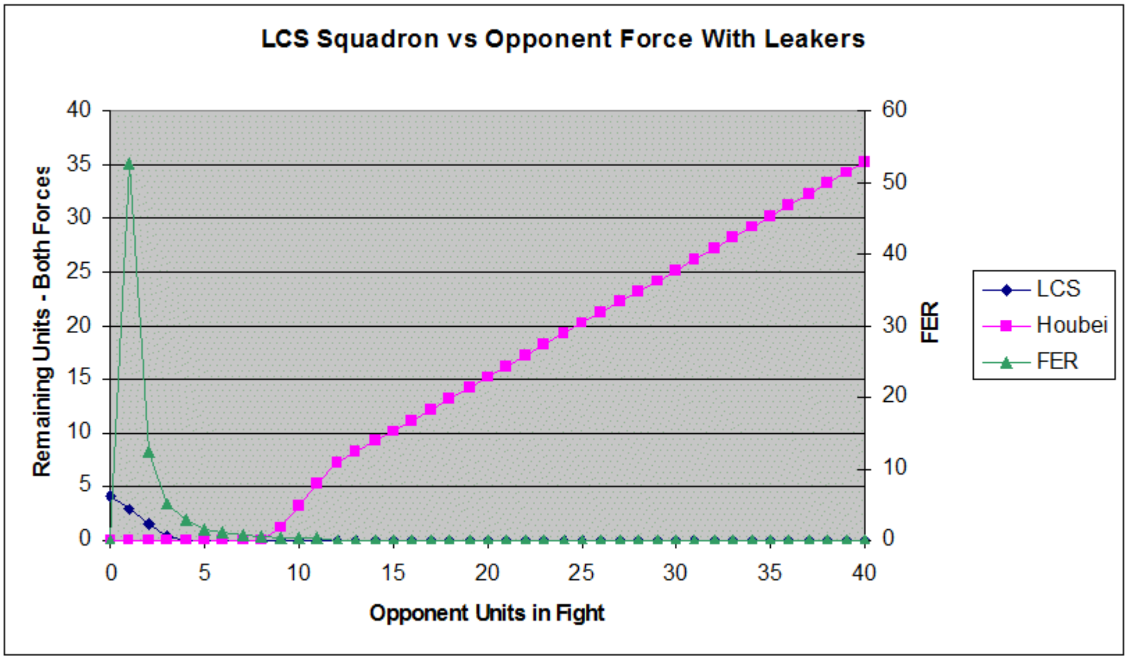

Figure 14. LCS Squadron vs. Chinese Type 022 Force with Leakers

2. National Security Cutter

The impact on the NSC of the introduction of leakers was similar to the impact on the LCS, but less severe due to the larger number of vessels in the squadron. Like the LCS, the NSC squadron begins taking casualties with the introduction of a single opponent, but the NSC force is not completely eliminated until the opponent force strength is five (Figure 15). The NSC squadron is also able to completely eliminate an opponent force up to twelve vessels, an improvement over the eight achieved by the LCS squadron, and continues to eliminate seven vessels on an opponent force of any size once leakers are the only missiles penetrating the opponent defenses.

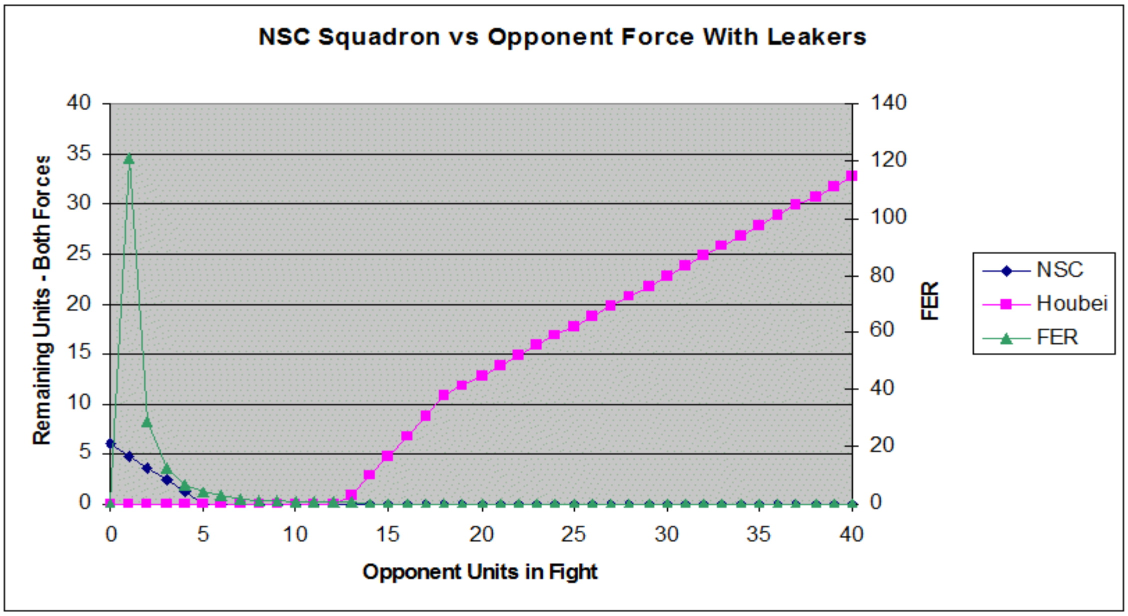

Figure 15. NSC Squadron vs. Chinese Type 022 Force with Leakers

3. Sea Lance

The impact of leakers was substantial on the Sea Lance squadron. Previously, the Sea Lance squadron appeared completely invulnerable to enemy attack, because the large number of vessels and high defensive power of each vessel made the Sea Lance squadron's defenses impenetrable unless the opponent force was extremely large. The introduction of the leakage term removes that invulnerability and allows the Sea Lance squadron to suffer attrition, but due to the large number of vessels in the squadron, it still survives longer than the LCS or the NSC, requiring an opponent force of ten vessels to completely wipe out the squadron (Figure 16). The Sea Lance squadron is also able to inflict more damage than LCS but equal to NSC, completely eliminating an opponent of up to twelve vessels, and continuing to eliminate seven vessels on an opponent force of any size. The similarity to the NSC is expected because the Sea Lance squadron carries the same total number of missiles as the NSC squadron, and the leakage rate against the opponent force is dependent on the total number of candidate squadron missiles, the leakage factor, and the staying power of the opponent, all of which are the same for the NSC and the Sea Lance.

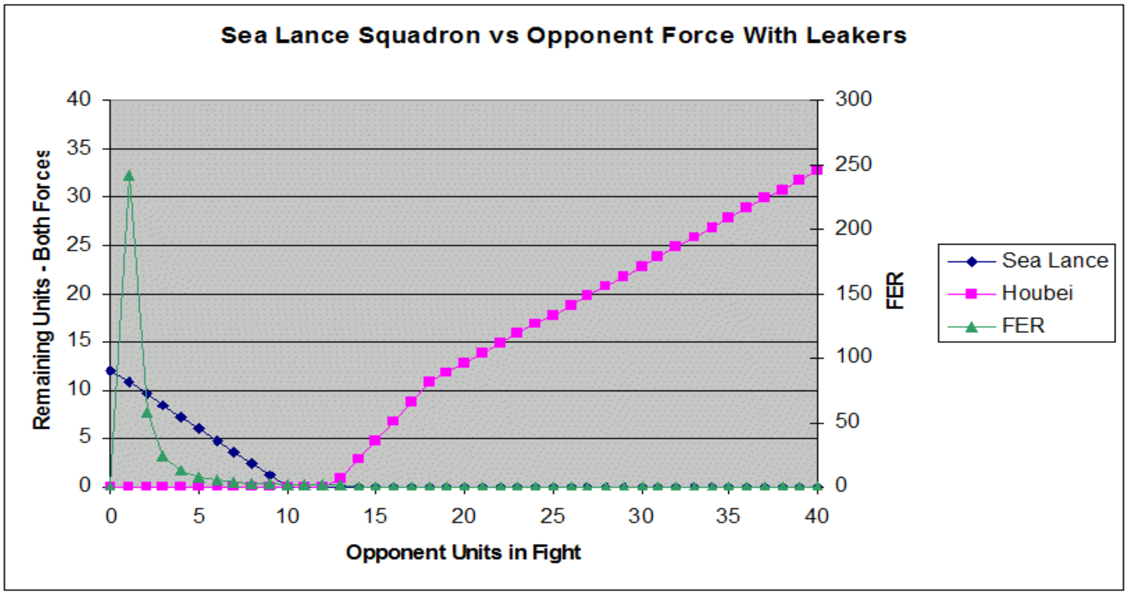

Figure 16. Sea Lance Squadron vs. Chinese Type 022 Force with Leakers

4. Combat Patrol Craft

One of the surprising outcomes of the introduction of leakers was how it impacted the performance of the PC squadron, as it actually improved the PC's performance. In the basic case the PC squadron was put out of action by such a small number of opponent vessels and the opponent force was able to completely block all incoming missiles so early in the model that the PC squadron was only effective against a very small opponent force, and large casualties were expected. With the introduction of leakers, the combat PC squadron continues to take large casualties, but is only put out of action slightly sooner in the model, whereas because the PC squadron's missiles achieve leaker hits as well, larger opponent forces are put out of action than in the basic case (Figure 17). The result is that in some respects the PC squadron outperforms the LCS. An opponent force of four vessels eliminates the PC squadron, where only three were required to eliminate the LCS squadron. Once the opponent squadron is large enough so that only leakers penetrate its defenses, the PC squadron achieves nearly the same number of hits as the LCS squadron, and the loss of a PC squadron represents substantially lower losses in procurement costs.

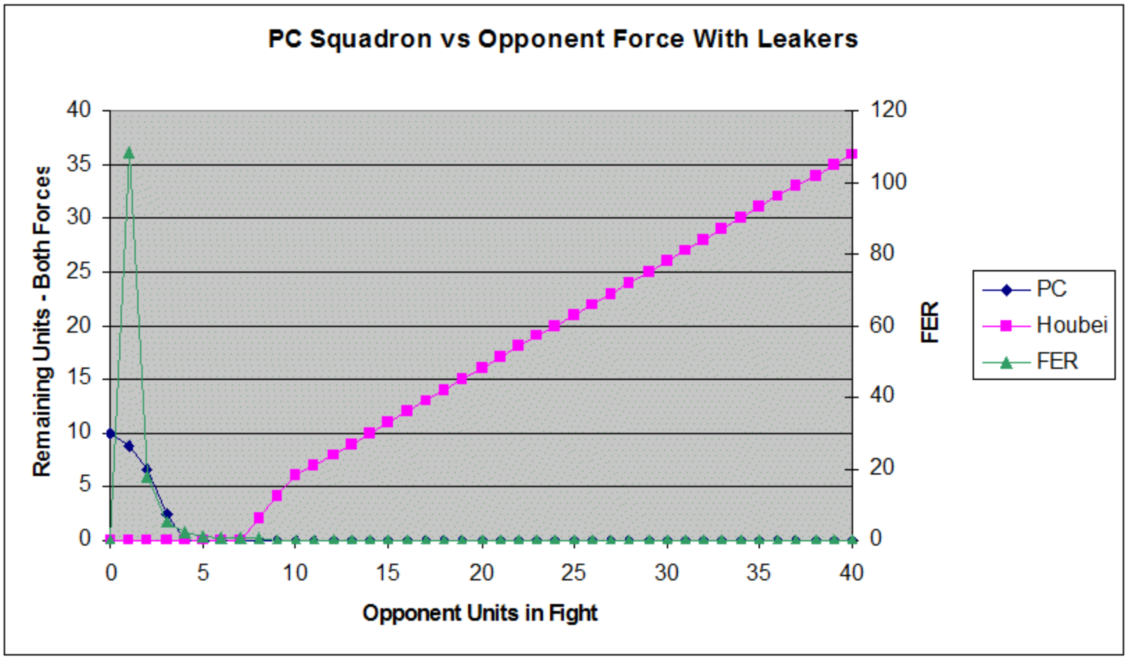

Figure 17. PC Squadron vs. Chinese Type 022 Force with Leakers

5. Summary Comparison when Leakers are Considered

The superior performance of the Sea Lance squadron due to its lower cost and numerical superiority is again reflected in this case, as it inflicts the most damage and the losses are stretched over the largest span in the model. The NSC again achieved similar but superior results to the LCS, due to the larger number of vessels in the squadron. The PC performed better than in the basic case, and also outperformed the LCS in some respects, placing the LCS squadron and PC squadron on par when leakers are introduced into the model. The poor performance of the LCS can be attributed to the simple fact that four vessels cannot absorb an attack that includes leakers. Once the squadron begins taking casualties, it is put out of action very quickly. The firepower advantage of the NSC offset its numerical inferiority when compared to the PC squadron, but the firepower advantage of the LCS was not enough to offset its numerical inferiority. As with the basic scenario, to be fair to the significantly larger LCS and NSC, the analysis was also performed using a staying power of two for these vessels. With the staying power of both vessels set at two, the LCS is still outperformed by the Sea Lance and NSC, but regains its position above the PC, with the squadron not being completely eliminated until seven opponents are engaged. The NSC performance with staying power of two becomes equal to the Sea Lance squadron, because it carries the same number of offensive weapons, and then requires the same number of leaker hits to be destroyed, but at a much higher cost if the squadron is lost. Table 3 summarizes the results of the analysis with consideration for the effects of leakers.

Table 3. Summary of Analysis for Scenario Including Leakers

	LCS	NSC	Sea Lance	PC
Performance Ranking	3	2	**1**	4
Break Point 1	8	**12**	**12**	7
Break Point 2	12	**18**	**18**	10
Break Point 3	0	0	**0**	0
Break Point 4	3	5	**10**	4
Lethality Condition	High	High	High	High

Candidate requirements to eliminate 40 Houbei:

	LCS	NSC	Sea Lance	PC
# Vessels Required	19	19	38	57
# Vessels Lost	19	19	38	57
Procurement Cost	$14.5 Billion	$9.5 Billion	**$7.8 Billion**	$9.4 Billion

Notes:
All break points are defined by the number of vessels in the opponent Houbei force
Break Point 1 - Number above which the Houbei force is no longer completely eliminated
Break Point 2 - Number above which the Houbei force no longer takes any casualties
Break Point 3 - Number above which the candidate force will start taking casualties
Break Point 4 - Number at which the candidate force is completely eliminated
Procurement cost includes the appropriate number of support vessels

C. MODEL PERFORMANCE

1. Strengths

The greatest strength of the model used for this analysis is the enormous flexibility and ease with which it can be understood. The equations are straight forward and relatively intuitive, making the outcomes of the analysis equally straight forward and intuitive. The model provides a basis for comparison which numerically and graphically demonstrates how each candidate vessel force compares with the others when fought in identical scenarios. The outcomes of the scenarios are also repeatable, because the model is deterministic, so there is no randomness in the results. The ability to explore how each factor impacts each candidate force and compare those impacts across the forces was instrumental in the performance of this study.

2. Impact of Additional Variables

The model is very consistent. When variables are changed which should effect all candidates proportionally (i.e., changing the opposition vessel characteristics) the outcome of the analysis and ranking does not change, which is a desirable result for the decision maker. To verify this, several factors of interest not previously introduced into the analysis were explored, including the removal of chaff from all vessels, the impact of scouting, and increasing staying power for the larger LCS and NSC. When chaff was removed from the model, the ranking of the candidates remained the same, but the gap between each vessel widened, making Sea Lance stand out farther ahead of the other candidates, followed by NSC, LSC, and PC.

The impact of scouting effectiveness also did not alter the outcome of the analysis. Scouting effectiveness acts as a degradation factor. In the previous analysis, the scouting factor was set at one, implying perfect scouting on both sides. When the scouting effectiveness of the candidate forces were degraded, the candidates scored fewer hits but took the same number of casualties (because the number of hits against the candidates is dictated predominantly by their defensive power). When the scouting effectiveness of the opponent force was degraded, the candidate forces scored the same number of hits against the opponent force, but took fewer casualties. In both cases the overall ranking of the candidate vessels remained the same.

Increasing the staying power of the LCS and NSC also does not alter the ranking order, because it only affects the region between when the first hit is scored against the candidates to when the last candidate is destroyed. It doubles the number of opponent vessels required to cross this region. If the candidates being compared were very close in comparison, this increase could impact the outcome, as it did in the case of the NSC and Sea Lance when leakers were being considered, bringing the NSC force on par with the

Sea Lance in performance. But in general, the performance of the candidate vessels were varied sufficiently that changing the staying power of the larger candidates did not alter the outcome. In both the basic model and the model with consideration for leakers, the ranking remains the same.

3. Weaknesses

The most significant weakness of the model is the artificiality presented by the lack of randomness. Historical battles have shown that combat is not deterministic, but stochastic,[35] and the salvo model does not account for this. Ideally, factors such as the leakage rate should be modeled randomly, which can be accomplished with some additional work, but this was beyond the scope of this study and would likely not alter the ranking. An additional weakness of the model is that it only accounts for a single salvo in each scenario, when in reality a force would likely fire only a portion of their offensive missiles, wait to assess the results, and then fire an appropriate number of the remaining missiles to finish the job. This can be incorporated into the model by modeling the first exchange with a reduced offensive power to simulate a force withholding a portion of its missiles, determining the outcome, then repeating for the remaining missiles held by the remaining forces, but this cannot be easily accomplished in a way that allows the graphical demonstration of the effects of altering the size of an opponent force as was done here.

[35] Hughes, 2000.

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IV. EXPANSION OF ANALYSIS

A. ALTERNATIVE SCENARIOS AND ENVIRONMENTS

Up to this point the analysis performed in this study has examined only one scenario, missile combat in the Taiwan Strait against a force of Chinese Type 022 Houbei, and determined the best candidate vessel for that scenario. This section will explore some of the other roles that a vessel designed for littoral combat might be expected to fill with a qualitative discussion of how well the candidate vessels might perform in those roles. Some of the alternative scenarios mentioned in the introduction will also be addressed with a determination of the impact of different scenarios on the vessel rankings established in the analysis.

1. Theater Security Cooperation

In 2008, the RAND Corporation released “Small Ships in Theater Security Cooperation” which examined the interactions between foreign navies which are potential partners in Theater Security Cooperation (TSC) and small vessels being considered for adoption by the U.S. Navy.[36] The ultimate conclusion of the study was that additional research was required to determine many of the requirements and roles which would be performed by a small vessel both inside and outside the realm of TSC. It also stated that the PC-1 Cyclone class, while not an ideal choice, could fill the role if properly adapted and supported by a larger vessel. Prior to the release of the RAND study, the Center for Naval Analyses (CNA) released “Next-Generation Navy Green Water Craft” which addressed many of the same issues identified by the RAND study.[37] An interesting concept postulated by the CNA study and supported by real world examples is the “rule of two” which states “that a given vessel can operate effectively with a vessel from twice its size to half its size.”[38]

[36] Button et al., 2000.

[37] Cox and Potashnik, 2007.

[38] Cox and Potashnik, 2007.

To perform effectively in theater security cooperation, a U.S. Navy vessel must be able to work well with partner nations, a concept which President George W. Bush refers to as the thousand ship navy. The CNA study tabulated vessels from numerous countries in different parts of the world, finding that in areas of the world such as the Gulf of Guinea, Latin America, and Southeast Asia, the average vessel used by national navies was roughly one hundred to one hundred fifty feet long, with speed capabilities up to fifty knots.[39] By the rule of twos, to effectively work with the majority of vessels in these navies a U.S. Navy ship should not be greater in length than roughly two hundred feet. This eliminates the LCS (four hundred feet) and NSC (four hundred eighteen feet) as too large, leaving only the Sea Lance and PC. The RAND study also suggested that in TSC, having a larger number of small vessels was advantageous over a small number of large vessels due to the nature of the mission requiring force dispersion, even when considering the requirement for a support vessel, again edging out the LCS and NSC due to their high procurement cost making large numbers of vessels infeasible.

Although the original Sea Lance design did not include a Rigid Hull Inflatable Boat (RHIB),[40] the catamaran design could be easily adapted to include a launch and recovery system between the hulls, matching its capabilities to those of the PC in TSC. The added bonus of the Sea Lance is the top speed of fifty knots, which would allow it to keep up with all but the fastest of vessels possessed by other nations. The rapidly changing environments in which forward deployed vessels employed in TSC can expect to operate requires that a vessel be capable of multiple missions, because it is never known when it may be called into action. Once in a combat role, the previous analysis demonstrated that the PC is at a serious disadvantage, suggesting that the Sea Lance is the ideal choice. In addition, the shallow draft due to its catamaran design would allow it to enter into shallow mini-harbors and inlets where the PC would not be able to enter.

[39] Cox and Potashnik, 2007.

[40] Byers et al, 2001.

2. Interdiction

Interdiction operations are nothing new for the Navy, and are not expected to disappear from the Navy's task list in the near future. Between the war on drugs in the Caribbean, economic sanctions against Iran, Homeland Security, anti-piracy in the Malacca Strait, etc, the requirement for the Navy to support the Coast Guard in interdiction operations, or perform its own interdiction operations, is continuing to increase. In the majority of cases, the size of the vessel performing an interdiction operation is not of particular importance, as an armed Navy vessel of virtually any size is intimidating enough to force a civilian vessel to heed to. What is important is that the intercepting vessel be capable of finding, and then catching the vessel of interest, a particular problem in the war on drugs, and when countering piracy.

In the Caribbean, one popular tactic used by drug runners is the use of very fast vessels (known as go-fasts) which can outrun a standard Coast Guard patrol vessel, and would be able to outrun the NSC, and likely the PC as well. Sea Lance and LCS, however, would be much more capable of catching one of these fast vessels. Another problem currently faced in the Caribbean is the growing use of semi-submersible vessels, which are extremely difficult to locate. Because of this, to effectively search for these vessels a large number of interceptors would be required, which places Sea Lance ahead of LCS due to the large procurement cost of LCS.

In general, when performing interdiction operations of any kind it is not necessary to employ large vessels. Most boarding operations are performed from a RHIB, the smallest of vessels employed by the Navy. It is far more useful to have a large number of vessels (carrying RHIBs) which are capable of operating independently or interconnected, intercepting a vessel and sending personnel aboard it, a role for which the Sea Lance and PC are both better suited than either the NSC or LCS. Given the smaller size and greater maneuverability of the Sea Lance and PC, they would also be more ideally suited to operations in the Persian Gulf, where numbers of vessels performing intercepts is particularly important because of the extremely large quantity of vessel traffic in the area.

3. Export to Partner Nations

To work effectively with other nations, whether it is for theater security operations, interdiction operations, or assisting a partner nation in protecting itself against a potentially hostile neighbor (e.g. South Korea), it is important that the Navy possess a vessel which can work well with those nations' existing forces as well as a vessel which can be exported to those countries. Because of their high cost, LCS and NSC are not well suited to this role. Because of its limited combat potential, the PC is also not very well suited to this role. The highly capable and flexible Sea Lance is a better option, as it is more affordable and its size fits the needs of smaller countries with small boat navies.

It cannot be argued that the requirement for a support vessel might make the Sea Lance less attractive to other countries, because the majority of nations to which such a vessel might be exported are more interested in the security of their own shores rather than projecting power around the world. The vessels can be supported from local bases, eliminating the need for a support ship. Even in the Taiwan Strait scenario the support vessel requirement can be reconsidered, as a squadron of Sea Lance can draw the support they need from the Island of Taiwan. The much larger NSC and LCS are less well suited to entering many of the small ports and inlets, making support and forward deployment more difficult.

B. SUMMARY

For a century the U.S. Navy has been a blue water force, concentrating on large combat vessels capable of operating anywhere in the world. The environments in which the Navy is now being called upon to operate in, such as the Persian Gulf and Caribbean, do not favor the large vessels, but rather a large group of small vessels. For the widest flexibility, particularly where shore support is available (Persian Gulf, Caribbean, Sea of Japan, Taiwan Strait, South China Sea, etc), large, long range vessels aren't necessary, and instead may become more inviting targets, particularly when visiting foreign ports (i.e., USS Cole in Yemen). Whether for theater security cooperation, interdiction operations, export to other nations, homeland defense, or one of many other missions, the experts generally agree (RAND and CNA among others) that numbers and affordability outweigh size and advanced weaponry. Hence, Sea Lance is preferable to both NSC and LCS, while its greater combat potential makes it preferable to the combat PC.

C. ADDITIONAL STUDY RECOMMENDATIONS

In the performance of this study, several areas were identified which would benefit from closer examination and additional study. The goal of this study was to compare and contrast the candidate vessels being considered. Factors which likely would not change the outcome of the comparison were not considered, or were handled qualitatively. It is not believed that such other factors would alter the outcome of this study, but are worth additional exploration (perhaps with simulation).

1. Stochastic vs. Deterministic Modeling

As stated in the weaknesses section above, the salvo model used for this study is deterministic; there is no randomness in the model. While this is beneficial for clear comparison, because the results of any change to the inputs will always be the same, it is not particularly realistic because of the randomness in any real world combat scenario. Introducing stochastic variables can add additional insights. In this study all candidates (except PC) had their missile inventory reduced by twenty five percent in the determination of their combat power. A random reduction factor within some fixed range to account for misfires, unexpected interference, and other unpredictable factors, could be enlightening. The leakage factor was fixed, where twenty percent of good shots were assumed to leak past defenses. This factor is also likely to be far more random in a real scenario. Scouting effectiveness due to weather effecting one side more than the other, chaff and decoy effectiveness due to unpredictable adverse or favorable surface conditions, many of the terms used in the salvo model can be subjected to randomness. For the purpose of this study fixed values were either determined or assumed, equivalent to the mean value expected to be found if a series of stochastic simulations were performed, but to completely determine the effect of randomness on the model and the candidate selection process, further study would be required.

2. Incorporation of Leakers

Leakers, or incoming ASCMs which should be stopped by defensive systems but "leak" through due to imperfections in the defensive system, are incorporated into the model, but only in a very coarse manner. In this study, the effect of leakers is determined to be an addition term added to the change in force strength which is proportional to the combined offensive power of a squadron and inversely proportional to the combined staying power of the opposition squadron. Although it is useful in illustrating the effect leakers have for candidate comparison purposes, it is not necessarily the most accurate manner with which to incorporate leakers into the salvo model. Ideally, leakage terms should be incorporated into the primary salvo equations themselves, rather than simply adding an addition term. The determination of exactly how to modify the salvo equations to properly incorporate leakers was beyond the scope of this study, although there is no evidence that incorporating leakers in a different manner would alter the conclusions reached here.

3. Additional Unexplored Variables

Many of the variables included in the salvo model were used in the performance of this study, but several variables with the potential for significant impact were excluded, and therefore additional exploration of these variables might be beneficial. Scouting effectiveness was only explored insofar as how an advantage in scouting affected the outcome of the comparison results. No attempt was made to realistically estimate the impact of satellite imagery, UAVs, other aerial surveillance, or any other scouting method on scouting effectiveness. These factors were assumed away initially with the statement that an aerial battle could be expected to nullify scouting abilities. The impact of the seduction and distraction chaff and decoy was also not explored in detail, but was set at a fixed number for both sides. Further study to determine the actual effectiveness of chaff or decoys for vessels of varying size might alter the outcome of this study, although it can be reasonably expected that a smaller vessel with a smaller radar cross section would benefit more from chaff and decoys, and therefore would give an even greater advantage to the smaller candidates (i.e., Sea Lance). Seduction and distraction chaff were also assumed to have the same effectiveness, which might not be realistic, and the choice of seduction chaff only for the Houbei and PC could be re-evaluated if further examination of the impact of this variable is performed. Two other variables in the embellished salvo model, defender alertness and training effectiveness, were left out of this study entirely. It is not believed that these variables would impact the outcome of this study, as they would probably affect each of the candidate vessels in the same manner, but further study may be warranted.

4. Additional Candidates

The range of candidates considered by this study was limited to four, looking only at a handful of existing or proposed domestically produced vessels. As the U.S. Navy is primarily a big ship navy, the number of small vessels available for comparison is limited. However, a number of other countries are already producing formidable street fighter type vessels, such as the Swedish Visby Class Corvette[41] and the Norwegian Skjold Class Missile Patrol Boat[42]. After an analysis similar to this one of some of the other vessels available internationally, the results could be compared to the results of this study to contrast domestically produced and internationally produced vessels, and would be a significant benefit and a logical progression of this analysis.

5. Tactics

An important consideration which was left out of this study was the incorporation of tactics, and how tactics impact the outcome of a combat scenario. Tactics are inherently difficult to model, and the focus of this study was on the analytical comparison of candidate vessels in an intuitive model. The large variation in the sizes of the combat forces being considered (i.e., four LCS in a squadron vice twelve Sea Lance in a squadron) and in the capabilities of the candidates (i.e., top speed of NSC is twenty eight knots vice top speed of Sea Lance is fifty knots) gives rise to questions of tactics which may be available to some candidates but not available to others. Exploration of tactics

[41] SPG Media Limited, “Visby Class Corvettes, Sweden.”

[42] SPG Media Limited, “Skjold Class Missile Fast Patrol Boats, Norway.”

which are available, how they might impact the performance of a candidate in the scenarios being considered, and of particular importance how they might impact the ranking of candidates would be a beneficial extension to this study. It is expected that most tactics which might be considered would give the advantage to the faster and more numerous vessels, and as such it is reasonable to assume that the addition of tactics would not alter the overall conclusion that the Sea Lance is the top performer, but further analysis is necessary to verify this conclusion.

V. CONCLUSION

The Navy's current inventory of relatively few, large, expensive, vessels is very capable, particularly when considering efficient projection of power scenarios. This study has explored a critical weakness in this force structure, which is the vulnerability of big warships when conducting operations near shore against an opponent who possesses relatively large numbers of small, missile bearing vessels. Numerous historical examples have shown that the introduction of missiles into modern naval combat requires a balanced approach to ship design, balancing offensive power, defensive power, staying power, and force numbers.[43] Without this balance, high lethality combat conditions can exist[44] in which each side is able to completely eliminate the other with a single salvo. This gives rise to the realization that a small force of inexpensive vessels, in a missile combat scenario, can be victorious over a much larger and more expensive adversary vessel or group of vessels, achieving favorable attrition.

Combat models introduced by Lanchester, Chase, and later Hughes, all demonstrate that in naval combat scenarios the number of vessels participating is the single most important factor in determining the outcome of a battle. With the introduction of missile combat and the salvo model, the number of participating vessels became even more important. To remain competitive in an evolving world in which small, inexpensive, missile bearing craft, or street fighters, reign supreme over the littoral waters, the Navy must develop and adopt its own small and inexpensive warships so that it can be exposed to the dangers of combat operations without representing too great a risk to the naval force structure.

Four potential candidates were introduced for consideration to fill this role: the Littoral Combat Ship with surface warfare module (LCS), the National Security Cutter with the addition of offensive and defensive armament (NSC), the newly conceived and designed Sea Lance inshore combat vessel, and a "beefed up" Combat Patrol Craft (PC),

[43] Hughes, 1995.

[44] Armstrong, 2003.

an adaptation of the Cyclone class patrol craft with additional offensive and defensive weapons. Of the four vessels described, only Sea Lance is specifically designed to fill the role being explored. The NSC was developed for the Coast Guard, and would require significant augmentation. The PC was designed for patrol, not missile combat, and for this study required significant adaptation. The surface warfare module for LCS is designed for combat against other surface ships, but the vessel itself is designed to be far more multi-purpose, and is too large and expensive, making it not as ideally suited to this role. While specifically designed to fill the role described here, Sea Lance is also a flexible platform capable of filling many other roles (such as patrol, interdiction, security, etc). With only minor adaptations, its moderate cost makes the procurement of large numbers of them more feasible than can be achieved with larger vessels, making a Sea Lance force even more effective in these roles than the alternatives. To be fair it should also be noted that in non-combat roles, such as patrol and security, even Sea Lance is more ship than is really needed. The Center for Naval Analyses introduced a concept of "Big Brother" and "Little Brother"[45] for which Sea Lance would be well suited to fill the role of big brother, but an even smaller, lightly armed and far less expensive (less than ten million dollars apiece, for example) craft could perform many of the same functions so long as shore based support is readily available. Even given this consideration, Sea Lance is far better suited than the other candidates considered here. When considering frequency of operations, the Navy finds itself performing interdiction and patrol operations far more often than missile combat, which means any vessel adopted by the Navy should be a strong performer in these areas, as Sea Lance has been demonstrated to be.

The comparison of the four candidate vessels in the base case missile combat scenario demonstrated that the generally accepted axiom of greater risk brings greater rewards is not necessarily true. A squadron of Sea Lance costs significantly less than a squadron of either LCS or NSC yet outperformed both of those candidates, due largely to the large number of vessels in the Sea Lance squadron, which compounds the defensive power to make the squadron more survivable. The NSC outperformed the LCS due to the

[45] Cox and Potashnik, 2007.

larger number of vessels, made possible by removing the requirement for a support vessel. The combat PC squadron is cheaper than the other squadrons, and might be well suited to performing the alternative roles described above, but is not suited to missile combat and would be quickly defeated with heavy casualties. To perform the same mission of eliminating a force of many Houbei in order to establish Sea Control in a region, the Sea Lance squadron is the least expensive alternative, and exposes the fewest number of personnel to combat risks.

When the concept of leakers is introduced into the model (leakers being good shots which penetrate otherwise perfect defenses due to the fact that real defenses aren't perfect) the overall outcome remains the same. The Sea Lance squadron continues to outperform the LCS and NSC because of the number of vessels in the squadron. It achieves the same number of hits against the opponent as the NSC squadron (because the Sea Lance and NSC squadrons carry the same number of missiles), but survives assaults by larger opponent forces. The surprising result was the improvement in performance of the combat PC when leakers were introduced due to the ability to absorb more hits because of the size of the PC squadron. It still lags behind the other candidates, but is raised on par with the LCS because the small number of vessels in the LCS squadron simply cannot absorb any hits without being significantly depleted, allowing it to be eliminated by very few opponents. As with the base case, to accomplish the same mission of eliminating a force of up to forty Houbei, the Sea Lance squadron is the least expensive alternative. More importantly in this case than in the base case because the candidate force is completely eliminated for all candidates, the Sea Lance squadron exposes the fewest number of personnel to combat by a factor of more than three when compared to the next closest competitor (LCS).

The exploration of other factors did not change the vessel ranking. The exclusion of chaff from all candidates reduced each of their performance proportionally. The consideration of scouting effectiveness impacted all of the candidates, whether the scouting advantage was given to the opponent, or to the candidates. To give further consideration to the size of LCS and NSC when compared to Sea Lance and PC, the staying power of these two candidates was increased from one to two (historical data indicating that their staying power should be just over one).[46] Despite this advantage, the Sea Lance squadron still remained ranked as the top performing candidate, though the NSC squadron partially closed the gap, with LCS still trailing behind.

Each aspect approached by this study compared the four candidates either quantitatively or qualitatively, and in each comparison the result was the same. When considering a vessel for adoption that is capable of performing in multiple roles and environments in the littorals, as well as fighting in missile combat against a potential adversary possessing small missile bearing combatants, the best performing and least expensive alternative is a force of small, relatively inexpensive, missile bearing vessels such as Sea Lance. Because of their lower cost, they can be procured in much greater numbers, and because of their small size they gain a great deal of flexibility for inshore operations as well as their ability to be supported by bases ashore or by support vessels. In addition, the low cost and small crews associated with these small vessels generate the least amount of risk when combat occurs.

[46] Hughes, 2000.

APPENDIX – MODEL CONSTRUCTION

The model used for simulations in this study was developed using Microsoft Excel using adaptations of the equations found in the Salvo Model.[47] This appendix is a description of how the model was created to allow the reader to recreate this work to more easily facilitate further study of the conclusions reached herein. A screen capture of the working page of the model with sample inputs is included as Figure 18. Variables which are available for manipulation are indicated in blue.

The basic, unembellished salvo model was created first, by simply creating a cell for each of the A force and B force variables (A, a_1, a_3, α and B, b_1, b_3, β). The basic definitions of these terms are annotated in Figure 18. Scroll bars were used to control the values of these variables and ensure that only integer values could be used, but are not necessary. The equations from the basic salvo model (see equation 4) were then entered into separate cells to determine the change in each force level after a single salvo exchange (ΔA, ΔB) and the final force levels (A_f, B_f), which are simply the change in force term (ΔA, ΔB) subtracted from the initial force level (A, B). In Figure 18 these results are shown under the "Basic Values" heading.

$$\Delta A = \frac{\beta B - a_3 A}{a_1} \qquad \Delta B = \frac{\alpha A - b_3 B}{b_1}$$

Equation 4 – Basic Salvo Model

The salvo equation "embellishment" terms (labeled Additional Terms in Figure 18) were added to allow for the exploration of the effects of additional factors, such as seduction and distraction chaff and scouting effectiveness. Not all of the terms included in the model were explored in this study. For the sake of simplicity, the calculations were broken down in the same matter as in Hughes, 1995. It would be a relatively simple matter to combine calculations into fewer cells, but would have made the model less transparent and more difficult to diagnose if problems were encountered. The terms

[47] Hughes, 1995.

altered by the embellishments are a_3, α, b_3, and β, the embellished forms being annotated as a_3', α', b_3', and β' under the Calculated Values heading in Figure 18. The Equations used to calculate these are included as Equations 5 and 6. The final values of the change in force levels (ΔA, ΔB) and final force levels (A_f, B_f) were then recalculated and appear under the Embellished Values heading on Figure 18; the equations used are included as Equation 7. The basic definitions of the embellishment terms are annotated on Figure 18.

$$\alpha' = \sigma_A \tau_A \rho_B \alpha \qquad\qquad a_3' = \delta_A \tau_A a_3$$

$$\beta' = \sigma_B \tau_B \rho_A \beta \qquad\qquad b_3' = \delta_B \tau_B b_3$$

Equation 5 – α and β Embellishments   Equation 6 – a_3 and b_3 Embellishments

$$\Delta A = \frac{(\beta' B - a_3' A) a_4}{a_1} \qquad \Delta B = \frac{(\alpha' A - b_3' B) b_4}{b_1}$$

Equation 7 – Salvo Equations Using Embellishment Terms

The final calculation performed for the model, the non-graphical portion that is, was the determination of the Fractional Exchange Ratio. The equation used is included as Equation 8 and was programmed into separate cells. The calculation was performed twice, using both the basic force change terms and the embellished force change terms for comparison purposes.

$$FER = \frac{\Delta B / B}{\Delta A / A}$$

Equation 8 – Fractional Exchange Ratio

One additional block shows up on the model worksheet, which is the Lethality Condition.[48] This was calculated using the equations developed by Armstrong to define the lethality conditions. A lookup table was created on a separate calculations page which used three “IF” statements to calculate a binomial for each of the three Lethality conditions, the binomial having a value of one for true and zero for false. Quasi-code for

[48] Armstrong, 2003.

the lookup table is included as Table 4. To list the lethality condition on the model worksheet, the VLOOKUP function was used, using the quasi-code: "=VLOOKUP(1, Lookup Table Range, 2, False)" which then displayed the lethality condition which corresponded to the row having a value of one indicating true. Note that the Medium Lethality condition is determined by checking whether Low or High lethality has been determined true. This was done to help prevent multiple conditions from indicating true (which should not happen unless an error has occurred) and because the conditions used for determining Medium Lethality are more complicated than Low or High (See Armstrong, 2003).

Table 4. Quasi-Code for Lookup Table for Lethality Condition

Lethality Condition	
= IF (α / b_3 <= a_3 / β, 1, 0)	Low
= IF (above = 0, IF (below = 0, 1, 0), 0)	Medium
= IF (α / (b_3 + b_1) >= (a_3 + a_1) / β, 1, 0)	High

The next step in generating the model worksheet was the creation of the graph displayed in Figure 18, which was used as the basis for many of the figures which appear throughout this study. A separate worksheet was used to calculate all the values used in the generation of the graph. The first column was simply numbered from one to forty to represent the variable number of Houbei in the opposition force. The second column calculated ΔA for each row, using the embellished constants on the model worksheet page and the value in the first column of the same row for the B term. In the same manner, the third column calculated A_f, the fourth column ΔB, the fifth column B_f, and the sixth column FER using Equation 7 above. Note that the value of A was fixed, and obtained from the model worksheet page. Quasi-code for these calculations is included in Table 5. Cell references should be substituted for the variable names which appear in the quasi-code. Although arranged horizontally in the calculations worksheet for the model, the variables are listed vertically here due to space consideration. In each of the calculations, "IF" statements were used because the salvo model equations allow for negative numbers to result; this wouldn't be appropriate for the graph generation. The "IF" statements ensure that all values are either zero or positive as appropriate.

Table 5. Quasi-Code for Calculations Used to Generate Graphs.

Column	Equation in Quasi-Code
B	Integers ranging from 1 to 40
ΔA	$= IF ((\beta' * B - a_3' * A) * a_4 / a_1 > 0, (\beta' * B_2 - a_3' * A) * a_4 / a_1, 0)$
A_f	$= IF (A - \Delta A > 0, A - \Delta A > 0, 0)$
ΔB	$= IF ((\alpha' * A - b_3' * B) * b_4 / b_1 > 0, (\alpha' * A - b_3' * B) * b_4 / b_1, 0)$
B_f	$= IF (B - \Delta B > 0, B - \Delta B > 0, 0)$
FER	$= IF (\Delta A / A = 0, \#NULL!, ((\Delta B / B) / (\Delta A / A))$

The graph is an XY Scatter with data points connected by non-smoothed lines. Three series of data are plotted on the graph, all with variable B as the X variable (from the B column on the calculations worksheet). The first series is the A force remaining, using the A_f column in the calculations worksheet. Throughout the study this data series was used to plot of the candidate vessels remaining as a function of the opponent force initial strength. The second series is the B force remaining, using the B_f column in the calculations worksheet. Throughout the study this data series was used to plot the opponent force remaining as a function of the opponent force initial strength. The third series is the Fractional Exchange Ratio, using the FER column in the calculations worksheet. Note that this data series requires the additional of a second Y-axis due to the wide variability in the values of FER. To maintain flexibility while exercising the model, leaving the range of the secondary Y-axis in automatic is strongly recommended.

The incorporation of leakers into the model required relatively minor changes. A leakage rate term (designated L) was added to the model worksheet with possible values ranging from zero to one. On the calculations worksheet, the ΔA term was modified by adding " + $B_3*\beta*L / a_1$" to the quasi-code listed above in Table 5, and the ΔB term was modified likewise by adding " + $A_3*\alpha*L / b_1$" to the quasi-code listed above in Table 5.

The result is that when L has a value of zero, the graphical output appears exactly the same as before the leakage term was incorporated. Any value other than zero (only positive numbers between zero and one are permitted) degrades both forces according to the newly incorporated terms.

Basic Terms

A terms	Value	B terms	Value	Term defined
A	5	B	7	Number of units
a1	2	b1	1	Unit staying power
a3	2	b3	1	Unit defensive power
α	4	β	2	Unit offensive power

Additional Terms

A terms	Value	B terms	Value	Term defined
σA	1	σB	1	Scouting effectiveness
δA	1	δB	1	Defender alertness / readiness
a4	0.8	b4	1	Seduction chaff effectiveness
ρA	0.8	ρB	1	Distraction chaff effectiveness
τA	1	τB	1	Training effectiveness

Calculated values

a3'	2	b3'	1	Defensive pwr adj for training & alertness
α'	4	β'	1.6	Offensive power adjusted for scouting, training, & distraction chaff

Basic Values

ΔA	2	ΔB	13	Units out of action from opposing salvo
Af	3	Bf	-6	
FER	4.642857			

Embellished Values

ΔA	0.48	ΔB	13
Af	4.52	Bf	-6
FER	19.34524		

Lethality Condition:	High

Leakage Rate
0

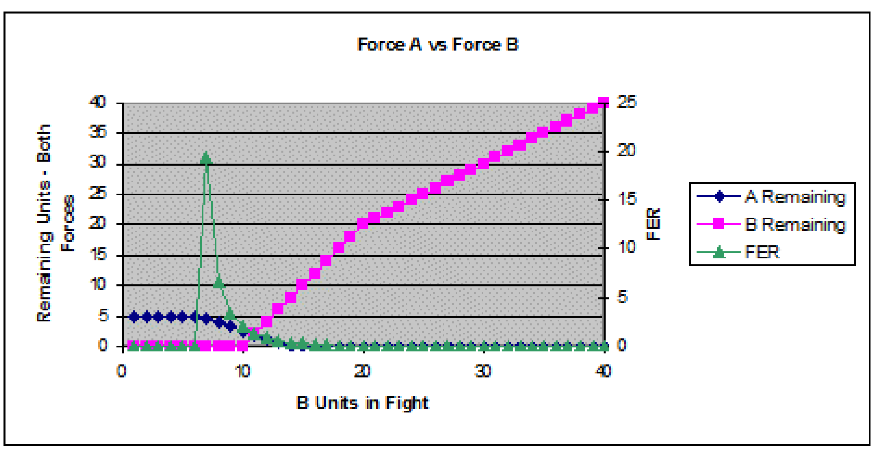

Figure 18. Screen Capture of the Model Worksheet with Sample Data

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