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THESIS

LOGISTICAL ANALYSIS OF THE LITTORAL COMBAT SHIP

by

David D. Rudko

March 2003

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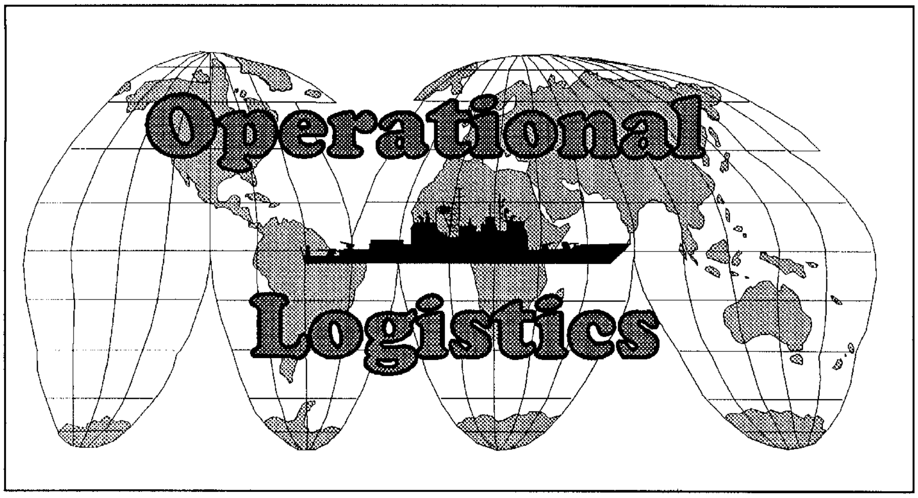
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The purpose of the Littoral Combat Ship is to provide the Navy with an affordable, small, multi-mission ship capable of independent, interdependent and integrated operations inside the littorals. The Littoral Combat Ship will be designed to replace high-value Naval assets when conducting high-end missions such as littoral Anti-Submarine Warfare (ASW), Mine Warfare (MIW) and Anti-Surface Warfare (ASuW) as well as perform low-end missions such as Humanitarian Assistance (HA), Non-combatant Evacuation Operations (NEO) and Maritime Intercept Operations (MIO). In order to accomplish these missions and successfully counter the enemy's littoral denial strategy, the Navy has stated the Littoral Combat Ship must incorporate endurance, speed, payload capacity, sea-keeping, shallow-draft and mission reconfigurability into a small ship design. However, constraints in current ship design technology make this desired combination of design characteristics in small ships difficult to realize at any cost. This thesis (1) analyzes the relationship between speed, endurance, and payload to determine the expected displacement of the Littoral Combat Ship, (2) determines the impact of speed, displacement and significant wave height on Littoral Combat Ship fuel consumption and endurance, and (3) analyzes the implication of findings on Littoral Combat Ship logistics.

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LOGISTICAL ANALYSIS OF THE LITTORAL COMBAT SHIP

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ABSTRACT

The purpose of the Littoral Combat Ship is to provide the Navy with an affordable, small, multi-mission ship capable of independent, interdependent and integrated operations inside the littorals. The Littoral Combat Ship will be designed to replace high-value Naval assets when conducting high-end missions such as littoral Anti-Submarine Warfare (ASW), Mine Warfare (MIW) and Anti-Surface Warfare (ASuW) as well as perform low-end missions such as Humanitarian Assistance (HA), Non-combatant Evacuation Operations (NEO) and Maritime Intercept Operations (MIO). In order to accomplish these missions and successfully counter the enemy's littoral denial strategy, the Navy has stated the Littoral Combat Ship must incorporate endurance, speed, payload capacity, sea-keeping, shallow-draft and mission reconfigurability into a small ship design. However, constraints in current ship design technology make this desired combination of design characteristics in small ships difficult to realize at any cost. This thesis (1) analyzes the relationship between speed, endurance, and payload to determine the expected displacement of the Littoral Combat Ship, (2) determines the impact of speed, displacement and significant wave height on Littoral Combat Ship fuel consumption and endurance, and (3) analyzes the implication of findings on Littoral Combat Ship logistics.

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EXECUTIVE SUMMARY

According to the United States 2002 Defense Planning Guidance, the Navy must develop the capability to maintain an Aircraft Carrier Operating Area clear of submarine-delivered and floating mines, improve the capability to destroy or evade large numbers of submarines operating in the littorals and develop the capability to destroy large numbers of small anti-ship cruise missile-armed combatants or armed merchant vessels in the littoral areas, without relying on carrier based air. Currently, sensors and weapons in the littoral environment have limited ranges due to environmental conditions and the clutter of maritime traffic. In addition, the proliferation of high-tech weapons and sensors potentially provides the enemy with the tools necessary to exploit the vulnerabilities of our current Naval force when operating inside the littorals. As a result, the Navy's current ability to counter enemy submarines, small craft and mines in the littoral environment is limited. It is for these reasons the Navy has stated the need for the Littoral Combat Ship.

The purpose of the Littoral Combat Ship is to provide the Navy with an affordable, small, multi-mission ship capable of independent, interdependent and integrated operations inside the littorals. In order to accomplish these missions and successfully counter the enemy's littoral denial strategy, the Navy has stated the Littoral Combat Ship must incorporate endurance, speed, payload capacity, sea keeping, shallow-draft, and mission reconfigurability into a small ship design. However, constraints in current ship design technology make this desired combination of design characteristics in small ships difficult and potentially costly, and may compromise supportability and sustainability. This thesis (1) analyzes the relationship between speed, endurance, and payload to determine the expected displacement of the Littoral Combat Ship, (2) determines the impact of speed, displacement and significant wave height on Littoral Combat Ship fuel consumption and endurance, and (3) analyzes the implication of these findings on Littoral Combat Ship logistics. While various hull forms are being considered for the Littoral Combat Ship (including, but not limited to the Surface Effect

Ship, Trimaran, SWATH technology and monohull), the JOINT VENTURE high-speed, wave-piercing catamaran is currently being tested by the military as a surrogate Littoral Combat Ship. As a result, the Littoral Combat Ship modeled in this thesis is based on the JOINT VENTURE seaframe.

The thesis demonstrates that speed, displacement, and significant wave height all result in considerable increases in fuel consumption, and as a result, severely limit Littoral Combat Ship endurance. When operating in a significant wave height of six feet, regardless of the amount of fuel carried, the maximum endurance achieved for a Littoral Combat Ship outfitted with all modular mission packages is less than seven days. Especially noteworthy is that when restricted to a fuel reserve of 50% and a fuel carrying capacity of Day tanks, the maximum achieved endurance is only 4.8 hours when operating at a maximum speed of 48 knots. Refueling, and potentially rearming, will require the Littoral Combat Ship to leave littoral waters and transit to Combat Logistics Force ships operating outside the littorals for replenishment. Given the low endurance of the Littoral Combat Ship, its time on station is seriously compromised. This not only limits the Littoral Combat Ship's ability to conduct independent operations, but restricts interdependent operations as part of a littoral operations force and integrated operations with Carrier and Expeditionary Strike Groups as well.

Significant wave height not only has a considerable negative impact on fuel consumption and endurance, but also has the potential for devastating impact on Littoral Combat Ship operations and crew effectiveness. The anticipated inability of the Littoral Combat Ship to effectively operate in ocean conditions beyond sea state 6 coupled with the real possibility of experiencing sea states 7 and beyond demonstrates the potential for the Littoral Combat Ship to be forced to either delay or abandon assigned missions. With regard to crew effectiveness, of the twenty-two personnel that were given a questionnaire regarding seasickness during joint Navy and Marine Corps testing of the JOINT VENTURE, 70% of those surveyed experienced dizziness, 65% experienced nausea and 30% actually became seasick when operating in sea state 4 and below.

The Littoral Combat Ship can achieve high speeds; however, this can only be accomplished at the expense of range and payload capacity. The requirement for the Littoral Combat Ship to go fast (forty-eight knots) requires a seaframe with heavy propulsion systems. The weight of the seaframe, required shipboard systems (weapons, sensors, command and control, and self-defense) and modular mission packages accounts for 84% of the full displacement, and as a result, substantially limits total fuel carrying capacity. Since initial mission profiles required the high-speed capability at most five percent of the time, the end result is a Littoral Combat Ship that has very little endurance and a high-speed capability it will rarely use. The pursuit for high speed itself demonstrates an inherent bias toward the attribute of speed and the neglect of range and payload requirements. Regardless of which hull form is selected for the Littoral Combat Ship, this thesis demonstrates the price that must be paid for speed as the tradeoffs between speed, endurance, and payload, in general, apply to any ship design.

I. INTRODUCTION

A. BACKGROUND

In the late 19th century, the world was introduced to the torpedo boat. These small, swift craft were able to race in close to larger ships, fire their torpedoes and quickly get away without suffering any damage. In 1894, they demonstrated their abilities with overwhelming effectiveness in the Chilean Civil War and Sino-Japanese War. By the mid-1890s, the United States recognized the need for a Naval asset to counter the torpedo boat and in 1902, the first U.S. destroyer, *USS Bainbridge* (DD 1), was commissioned.

During the past century, advances in technology have lead to the creation of a new breed of fast, shallow-draft ships that operate in regions in which our Navy is not designed to operate. Missile Frigates, Corvettes, Fast Patrol Crafts and Fast Attack Missile Boats, all of which are capable of speeds ranging from 30-50+ knots, have become standard equipment in many of the world's Navies. Even though the United States destroyer has evolved into a very capable and survivable Naval asset, its speed is only 30 knots and its draft of approximately 30 feet limit its ability to operate in shallow waters. As a result, the United States is once again faced with developing a ship capable of countering threats with speed, maneuverability and lethality in waters far from our nation's homeland. "Today, the United States is master of the seas. Unless we adapt our Navy for future war fighting in contested, close-in waters, however, we risk our ability to influence events." (Cebrowski and Hughes, 1999). The response to this is Sea Power 21: the new vision to transform the Navy in order to meet the challenges that lie ahead. (Bucchi and Mullen, 2002)

B. PROBLEM DEFINITION

The first fundamental concept and core element of Sea Power 21 is Sea Shield. One of the major components of Sea Shield is the concept of forward littoral dominance. According to the United States 2002 Defense Planning Guidance, the Navy must develop the capability to maintain an Aircraft Carrier Operating Area clear of submarine-delivered and floating mines, improve the capability to destroy or evade large numbers of submarines operating in the littorals and develop the capability to destroy large numbers of small anti-ship cruise missile-armed combatants or armed merchant vessels in the littoral areas, without relying on carrier based air. (Navy Warfare Development Command, 2003)

Currently, sensors and weapons in the littoral environment have limited ranges due to environmental conditions and the clutter of maritime traffic. (Bucchi and Mullen, 2002) In addition, the proliferation of high-tech weapons and sensors potentially provides the enemy with the tools necessary to exploit the vulnerabilities of our current Naval force when operating inside the littorals. As a result, the Navy's current ability to counter enemy submarines, small craft and mines in the littoral environment is limited. It is for these reasons the Navy has stated the need for the Littoral Combat Ship.

> The challenge of access and the requirements to perform missions across the operational spectrum – including logistics, medical support, humanitarian assistance in inhospitable areas, non-combatant evacuation operations, force protection, and maritime interception / SLOC patrols – suggest that new capabilities may be needed to rebalance the fleet. The Navy could task the current force structure with these new littoral missions – but there are significant risks and costs associated with using expensive, high-end, power projection platforms against the enemy's fairly inexpensive air, surface, and undersea platforms with their associated combat and information technologies. Current fleet assets are sized for, and tasked with high-end missions and the associated training requirements to prepare for them. Declining force numbers further impair the ability of our capital ships to perform additional access missions. Further, it is unlikely that we would, in the foreseeable future, be able to afford the numbers of multi-mission, high end ships it would take to fill the gaps in needed littoral capabilities. (Navy Warfare Development Command, 2003)

As a result, the Navy has turned toward the development of the Littoral Combat Ship (LCS). The purpose of the Littoral Combat Ship program is to provide the Navy with an affordable, small, multi-mission ship capable of independent, interdependent and integrated operations inside the littorals. In order to accomplish these missions and successfully counter the enemy's littoral denial strategy, the Navy has stated the Littoral Combat Ship must incorporate endurance, speed, payload capacity, sea-keeping, shallow-draft, and mission reconfigurability into a small ship design (Navy Warfare Development

Command, 2003). However, constraints in current ship design technology make this desired combination of design characteristics in small ships difficult and potentially costly, and may compromise supportability and sustainability.

The Littoral Combat Ship must be able to operate long distances from home while remaining combat effective. Some of the Littoral Combat Ship logistics requirements, such as fuel, food, stores, provisions and basic supplies, are common to most of the Navy's high-value, blue-water ships. However, since the Littoral Combat Ship is a modular design, it will also require a suite of modular weapon systems and associated support equipment capable of being configured to successfully achieve its operational tasking. Currently, there exist a limited number of Combat Logistics Force (CLF) ships that can be utilized for replenishing Navy ships at sea. Since there is no indication a logistics support ship will be built specifically for the Littoral Combat Ship, the addition of the Littoral Combat Ship fleet is going to place an added strain on the already burdened CLF fleet. Even though the CLF ships are capable of replenishing basic logistics requirements, they do not possess the capability to support modular reconfiguration. In addition, to ensure the protection of the CLF ships, they often operate with high-value, blue-water units located outside the littoral environment. These considerations raise the question of whether or not current replenishment capabilities are sufficient to effectively support sustained Littoral Combat Ship operations inside the littorals.

Through the use of a model developed in Microsoft Office Excel, this thesis (1) analyzes the relationship between speed, endurance, and payload to determine the expected displacement of the Littoral Combat Ship, (2) determines the impact of speed, displacement and significant wave height on Littoral Combat Ship fuel consumption and endurance, and (3) analyzes the implication of these findings on Littoral Combat Ship logistics.

C. SMALL SHIP DESIGN CONSIDERATIONS

Ideally, a small warship would be inexpensive and fast, carry a large payload and have high endurance and good sea keeping. Unfortunately, the current state of technology prevents this combination. As the offensive and defensive capabilities of a ship increase, so must the size and cost of the ship, therefore, tradeoffs must be considered between speed, endurance, and payload during the design process.

1. Definitions

Size is physical magnitude, extent or bulk. It is measured as the full displacement of the ship.

Speed is the rate of motion. It is achieved through the use of large, powerful engines.

Endurance is the ability to sustain a ships mission. It is measured by a ship's range, sea keeping, fuel storage and consumption rate, and ordnance storage and delivery rate.

Range is the maximum distance a ship can travel at "best speed" without refueling. It is a combination of fuel capacity, fuel consumption rate and ships speed.

Sea keeping is the effect of sea states on crew effectiveness.

Survivability is the ability of a ship to avoid and/or withstand an enemy attack. It is a combination of speed, maneuverability, stealth and/or strength of design materials.

Payload is the number of weapons systems and their sensors capable of delivering ordnance on target. It is related to speed and endurance by space and weight.

(Kelley, 2002 and Merriam-Webster, 2003)

The United States currently possesses the technology to outfit the Littoral Combat Ship with engines capable of producing ship speeds in excess of 60 knots. However, these engines are large and increase the overall weight and displacement of the ship, thereby increasing fuel consumption and decreasing endurance. Fuel capacity in itself is an opportunity cost; the more space and weight that are dedicated to it, the less that can be allocated to payload. Typically, a modern warship's mission payload makes up ten to fifteen percent of its full displacement; to increase it much beyond this, speed, range or survivability would have to be sacrificed. (Kelley, 2002) Currently, shipboard systems critical to survivability and combat effectiveness, such as the Aegis Combat System, ballistic defense missiles and large guns, cannot fit aboard small ships. "A ship of less than about 4,500 tons displacement would not be able to carry most of the major systems used for critical Navy missions, severely limiting its usefulness." (Kelley, 2002) In order for the Littoral Combat Ship to achieve success as a small, multi-mission ship, these constraints in small ship design must be overcome.

Figure 1 depicts the tradeoffs between ships speed, range, and payload with respect to the projected impact of future technology on ship performance.

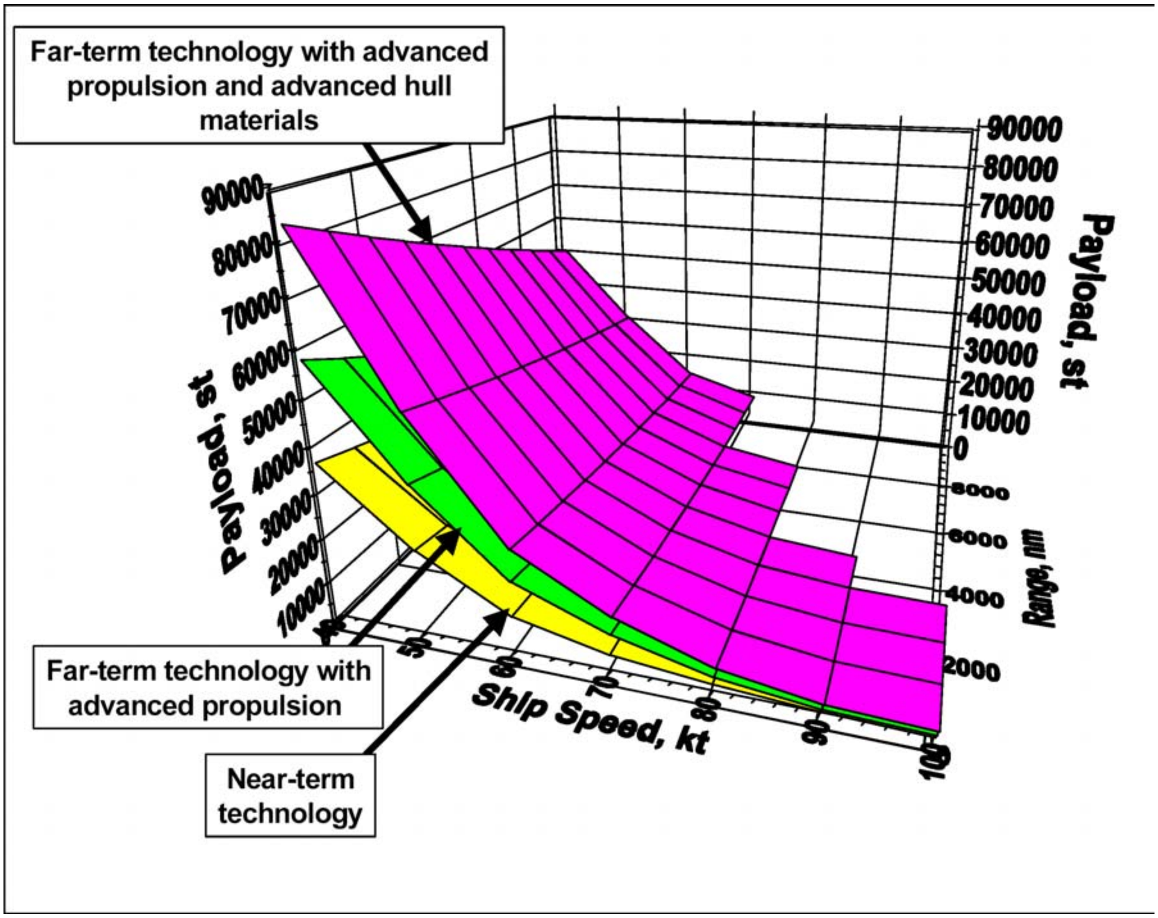

Figure 1. Predicted Impact of Technology on Ship Performance

It represents the maximum mission performance associated with the technology projections made by the Naval Surface Warfare Center's Carderock Division High-Speed Sealift Innovation Cell project team. Their work was conducted from May 2000 through August 2001, and the purpose of the project was to define the technology investments required to enable development of the high-speed commercial and military ships needed to provide realistic future mission capabilities. It shows that significant capabilities are scientifically possible using such technology projections in the near-term and the far-term, where the near-term relates to technology that will be available in 5 years and the far-term, 10 years. Full realization of capabilities shown in Figure 1 requires engineering development, particularly in packaging propulsion technology, advanced seaframes, and advanced materials and structures. (Naval Surface Warfare Center, 2002)

D. STUDY PLAN

Since the 1960s, the Navy has built three small, high-speed ship classes: patrol gunboats during the 1960s, missile hydrofoils during the 1980s and patrol coastal ships during the 1990s. Chapter II of this thesis considers these three small ship design programs and discusses the reasons for their limited operational usefulness.

In Chapter III, the Littoral Combat Ship concept of operations is discussed and a model is designed to estimate the Littoral Combat Ship displacement. According to a senior Navy official, the Littoral Combat Ship will be a non-traditional seaframe capable of high speeds (Koch, 2002). Currently, the JOINT VENTURE (HSV-X1) high-speed, wave-piercing catamaran is being leased by the Army, in cooperation with the Navy, Marine Corps and Coast Guard, from Australia’s Incat International for testing high-speed catamaran capabilities, potential operational impact and technologies. The Joint Venture successfully took part in the Millennium Challenge ’02 experiment and performed well in support of Operations Allied Force and Enduring Freedom. (Baumgardner, 2002) As a result, the Joint Venture high-speed, wave-piercing catamaran is utilized in this thesis as the Littoral Combat Ship seaframe to demonstrate the logistical implications of the speed, endurance, and payload tradeoffs with respect to the modular design of the Littoral Combat Ship. The weight and space requirement of each onboard and modular system is determined and added to that of the JOINT VENTURE seaframe. Factors considered for full displacement calculations include the base seaframe; installed weapons systems, command and control systems and sensors; personnel and supply load levels; fuel storage capacity; ordnance load levels and modular systems (embarked manned and unmanned air and sea vehicles). The number and types of systems installed and amount of load-out ordnance varies based on the mission for which the modular ship is configured. Hull design, fuel carrying capacity and supply load levels are derived from the JOINT VENTURE design. Factors considered for endurance calculations include displacement, fuel storage levels, fuel consumption rates, speed and sea state.

In Chapter IV, the impact of speed, displacement and significant wave height on Littoral Combat Ship fuel consumption and endurance is analyzed and the implication of these relationships with regard to Littoral Combat Ship logistics is discussed. An analysis of Littoral Combat Ship off-station time due to required replenishment is conducted by determining the required frequency of replenishments and estimating how far the Littoral Combat Ship will have to transit to the replenishment ship. Littoral Combat Ship replenishment requirements are compared with the current size and replenishment capabilities of the Combat Logistics Force in order to determine the overall impact of the added Littoral Combat Ship requirements.

In Chapter V, a conclusion of the Littoral Combat Ship analysis is provided along with associated recommendations. While this thesis based the design of the Littoral Combat Ship around the JOINT VENTURE hull form, the methodology followed applies to any high-speed ship as the tradeoff between speed, endurance, and payload must be acknowledged during the ship design process.

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II. USN HISTORY OF HIGH SPEED SHIPS

Throughout history, the United States Navy has invested a considerable amount of time and money in the development of high-speed ships. Since World War Two, three high-speed ship classes have been commissioned and tested in hopes of achieving great military usefulness: the ASHEVILLE class patrol gunboats during the 1960s, the PEGASUS class missile hydrofoils during the 1980s and the CYCLONE class patrol coastal ships during the 1990s. However, each class failed to capitalize on the speed they were designed for and, as a result, failed to achieve the missions for which they were intended. This chapter will provide an overview of these three small ship design programs and discuss the reasons for their limited operational usefulness. Most of the historical information for the ASHEVILLE and PEGASUS class contained in this chapter was obtained from Norman Friedman's book *U.S. Small Combatants, Including Pt-Boats, Subchasers, and the Brown-Water Navy: An Illustrated Design History* (1987).

A. ASHEVILLE CLASS PATROL GUNBOATS (PG)

In May 1961, the Ship Characteristics Board (SCB) asked for cost and feasibility studies for a small combatant designed primarily for surveillance, blockade, operations against other small crafts in coastal waters, and limited support of troops ashore. Tentative ship design characteristics included a length of 95 to 125 feet, a maximum draft of 8 feet (to allow for coastal operations), a speed of 30 knots, and an endurance of 1,500 nautical miles at 17 knots. A representative from the Long-Range Objectives (LRO) Group, an organization that determines naval requirements based on U.S. national strategy, determined that "in the future, there would be a place for small, relatively inexpensive, lightly manned coastal patrol craft aimed primarily at possible requirements in support of limited wars." (Friedman, 1987) The LRO went on to describe the patrol gunboat as being suitable for destroyer-type missions in waters where destroyers could not go or could not be risked.

In March 1962, Secretary of Defense McNamara specifically called for a navy program of patrol gunboats to deal with Cuban-based covert aggression in South America. Shortly thereafter, fleet commanders were asked for their own patrol gunboat force goals. The Commander-in-Chief Atlantic Fleet (CINCLANTFLT) asked for a total of eight, which were to be used for contingency readiness and cold war operations in the Caribbean, South Atlantic, and Indian Oceans, while the Commander-in-Chief Pacific Fleet (CINCPACFLT) asked for a total of twenty-seven, which were to be used in waters off of South Vietnam, Cambodia, China, and South Korea. Initially, a total of eight ASHEVILLE class patrol gunboats were approved for construction (one per year in fiscal years 1963-1970), however, that figure was later increased for a planned total of twenty-four at a cost of $1 million dollars each.

Design work on a small (length of 95 feet) ship, which began in June 1961, was already running into problems. The Bureau of Ships (BuShips) determined that, keeping within the previous stated ship design limits, they could achieve the desired speed but not the desired range due to the fact that the weight of the powerful diesel engines prevented the ship from carrying the necessary amount of fuel. Additional problems began to surface. Unimpressed with the performance of the 40 mm gun, they turned to the larger, and heavier, 3-inch/.50-caliber gun. With the addition of the new gun, BuShips was now not only unable to obtain the desired range, but also could not achieve the desired speed. As a result, BuShips considered gas turbines as the only method of propulsion that could potentially yield the desired speed, endurance, and payload combinations. In order to accommodate the gas turbine, it was determined the 3-inch/.50-caliber gun had to be moved aft and the length of the ship had to be increased.

As the design process continued, BuShips engineers increasingly struggled with the tradeoffs between speed, payload and range. They quickly realized that in order to achieve the combination they were looking for, they would have to increase the size of the ship. Table 1 contains the first five patrol gunboat design proposals submitted by BuShips. (Friedman, 1987) It includes the ship characteristics for each proposal along with associated costs in both fiscal year 1961 and, for current spending comparison, fiscal year 2003.

	Proposal 1	Proposal 2	Proposal 3	Proposal 4	Proposal 5
Length (ft)	95.0	95.0	115.0	161.0	161.0
Beam (ft)	19.8	22.0	24.2	25.0	24.0
Draft (ft)	6.3	6.5	8.1	7.0	7.0
Full Load (tons) [1]	107.3	124.1	209.9	225.0	225.0
Max Speed (kts)[2]	30	28	27	30	30
Endurance (nm / kts)	1,150 / 12	600 / 12	1,300 / 17	1,700 / 16	1,700 / 16
Estimated Cost FY 1961	\$1.00 M	\$1.20 M	\$1.50 M	\$1.70 M	\$1.90 M

Table 1. Patrol Gunboat Designs, October 1961

Notes: 1. Includes the following armament:

Forward	Single .50-caliber gun
Aft:	Twin .50 caliber guns
Amidships:	Two single .50 caliber guns (port and starboard)
	3-inch/.50-caliber gun
	Two 81 mm mortars at centerline

2. Maximum speed at 50% fuel level.

As BuShips proposals continued into 1962 none contained the answer senior officials were looking for. In July, under a great deal of pressure, BuShips finally proposed it’s preliminary design, which measured 166.2 feet; however, that proposal was discarded the following month. As BuShips continued the design process, costs continued to increase. BuShips was able to design a ship that achieved a range of 1,900 nautical miles at 16 knots; however, the cost to produce this ship rose to \$2.7 million (\$3.9 million for the lead ship). The total for the first two ships, \$6.6 million, exceeded the \$4.1 million that was authorized in the fiscal year 1963 budget, and as a result, officials realized the allocated budget would only be sufficient to purchase the lead ship vice the first two ships of the ASHEVILLE class.

After two years of efforts, speed was still driving the ship design process. The desired speed eventually increased to 40 knots; however, this idea was abandoned after it became clear the ship would not be able to carry the necessary payload at that speed. As a result, the speed requirement was finally dropped to 37 knots. In 1963, the lead ASHEVILLE class ship was finally approved. Table 2 contains the ASHEVILLE class ship specifications (Pike, 2002) and Table 3 contains ASHEVILLE class payload (Donaldson, 2003).

Length (feet)	**Beam (feet)**	**Draft (feet)**	**Displacement (long tons)**	**Maximum Speed (knots)**	**Range (nm / kts)**	**Crew**
165	24	10.5	240	37	2,300 / 13	28

Table 2. ASHEVILLE Class Specifications

Mission Profile	**Armament**
Anti-Surface Warfare	- One 40 millimeter Gun - One 3-inch/.50-caliber Rapid Fire Gun - Two twin .50 caliber Machine Guns - M60 Machine Guns - M79 Grenade Launchers - Two Missile Launchers[1]
Anti-Air Warfare	None
Anti-Submarine Warfare	None

Table 3. ASHEVILLE Class Payload

Note: 1. Replaced 40 millimeter Gun aboard USS ANTELOPE (PG 86) and USS READY (PG 87) only.

Upon their entrance into the fleet, the ASHEVILLE class ships quickly received a reputation as poor sea-keepers. They would often experience 45 to 65 degree rolls each way in waves up to eight feet and pounding fore-to-aft motion of the ship's bow in up and down angles of 15 to 25 degrees. Resting, sleeping and eating were extremely difficult under these conditions and fatigue overwhelmed even the most seasoned sailors. Crews riding out 10-foot waves for more than 72 hours would become badly fatigued, so maximum ship speeds would generally be reduced from 37 to 20 knots. Logistics was also a limiting factor. The patrol gunboats could spend two weeks at sea without any replenishment if necessary; however, underway time was usually limited to a few days between port visits. Food and fuel could be re-supplied by underway replenishment (UNREP), but the major limiting factor was in the quantity of freshwater that could be made onboard. Even though the gunboat crews were small, the ships evaporators could not keep the crew adequately supplied; a particularly troubling problem. (Donaldson, 2003)

In Vietnam, the ASHEVILLE class became an effective river gunboat; however, it found little use for its high speed. In 1971, the Chief of Naval Operations, Admiral Elmo Zumwalt, directed Project Sixty, a quick look at new ways of using U.S. warships. One of the conclusions was to use the ASHEVILLE class ships to trail Soviet naval formations in the Mediterranean, even though they did not carry enough armament to successfully protect themselves against the Soviet ships. Efforts were undertaken to increase the payload; however, the outcome was a loss of three to four knots in speed. As a result, only four of the seventeen ships built remained in this role. Three ships were moved to the Naval Base at Little Creek, Virginia, three ships were transferred to U.S. allies, and the remaining seven were assigned to gunboat duty patrolling the Marianas trust territory from Guam. By the early 1980s, all of the ASHEVILLE class ships were either decommissioned or transferred to U.S. allies.

The ASHEVILLE class experienced many problems throughout its life cycle. In the design process, the tradeoff between speed, payload and range was a great source of debate and resulted in delayed construction. Each ship cost approximately $5 million, five times greater than the initial $1 million projection, and high maintenance costs made them expensive to operate once commissioned. Additionally, sea keeping problems prevented them from capitalizing on the high speeds for which they were designed. The changes in missions they experienced throughout their service life demonstrated their inability to successfully fulfill the primary mission for which they were designed. Even though the majority of them did end up on gunboat patrol missions based out of Guam, the Navy was already looking at a cheaper and more effective replacement: the PEGASUS class missile hydrofoils.

B. PEGASUS CLASS MISSILE HYDROFOILS (PHM)

Once it was determined the ASHEVILLE class ships were too expensive and unable to satisfactorily perform their required missions, the Navy immediately turned their research efforts toward the development of a new small combatant that would replace the expensive patrol gunboats. The goal was to develop a high-speed ship with improved all weather performance, reduced maintenance costs, good sea keeping ability and increased operational availability. By the late 1960s, missile technology provided new hope that a large amount of anti-ship firepower could be generated from aboard a small ship. Due to its projected small size, good sea keeping ability and sustained rough water speed, it was believed these small ships could lie in wait, conduct a quick attack and retreat at high speeds. As a result, they would be able to successfully perform blockades, intercept missions and offshore patrols as necessary.

The missile hydrofoil was initially turned to in the late 1960s as an attractive replacement for the ASHEVILLE class gunboat, particularly in the Mediterranean. The initial concept was to establish a squadron of missile hydrofoils, each carrying a different modular weapons package, capable of functioning collectively as one multi-mission conventional warship. In May 1967, the Naval Ship Systems Command (NavShips) was asked to research a hydrofoil design capable of protecting coastal installations, surface shipping, and amphibious operations against fast-attack boats and conducting covert operations, reconnaissance and surveillance. By November 1968, even though nobody knew how hydrofoils would perform in realistic environments, the Navy was considering a 100-150 ton missile hydrofoil capable of achieving 45 knots sustained in sea state 5. Ship design was focused on high speed, a small crew and reduced life cycle costs; however, the total cost per ship was already estimated at $10.2 million ($18 million for the prototype). Compared to the cost of the ASHEVILLE class ships, this was an increase of more than 100%, however, the Navy believed they would see the savings in operating costs.

In November 1969, operations and technical personnel from eleven North Atlantic Treaty Organization (NATO) nations met to devise a joint fast patrol boat program with the goal of designing a ship that would offer a significant speed advantage over the large Soviet missile ships when operating in rough weather. Admiral Zumwalt made the missile hydrofoil an important element of his Project Sixty program, and in 1970 NavShips received authorization from the Secretary of Defense to continue the design process. At this time, however, NavShips was still far from a prototype as problems were being encountered with regards to the tradeoffs between speed, endurance, and payload. Since the limited size of the ship restricted the weight of the weapon systems to only 18 tons, it was determined that a modular weapons package concept would still be required in order to achieve a foil-borne range of 600 nautical miles and a hull-borne range of 2,000 nautical miles. Table 4 contains proposals for the various missile hydrofoil modular mission payload systems. (Friedman, 1987)

Modular Weapons Package	**Payload**
Electronic Warfare	Demountable deckhouse with required equipment
Anti-Surface Warfare (Coastal)	Sonobuoys and torpedoes, with a high-speed, two-mode sonar to be developed later.
Anti-Surface (Gun) Warfare	OTO-Melara 76mm gun, with a lightweight 3-inch/.50-caliber gun as a fallback
Anti-Surface (Missile)	6 Standard or Harpoon missiles in fixed launchers
Anti-Air Warfare	15 Sparrows in fixed launchers
Special Operations	Deck-mounted module for 14 SEALS
NATO	Undetermined gun plus missile combination

Table 4. Proposed Missile Hydrofoil Modular Mission Payload Systems

In mid-1970, the Secretary of Defense decided the United States would lead the NATO fast patrol boat program, and in November the United States formally offered a 142-ton hydrofoil with a maximum speed of 48 knots at sea state 0 and a range of 860 nautical miles foil-borne or 1,500 nautical miles hull-borne. Based on a forty-two ship purchase, the estimated cost was only \$3.2 million per ship (\$6.9 million for the lead ship). In March 1971, the United States announced that the initial purchase would consist of eight missile hydrofoils with an additional thirty being purchased between fiscal years 1973-1977. The problem was that the modular design was discarded. Therefore, the single hull now had to accommodate a variety of weapons systems. As a result, the ship had to be made larger and in turn, required more fuel and power. By late 1971, the missile hydrofoil grew to a displacement of 160 tons while total armament weight had increased from 18 to 21 tons. Its 40 tons of fuel resulted in a foil-borne range of 750 nautical miles and hull-borne range of 1,500 nautical miles. Since many conventional ships outgrow the future growth margins designed into them, the gradual growth of the missile hydrofoils was a concern since foil-borne operations provided for a relatively small growth margin. As a result, the Navy quickly realized their desire to outfit the missile hydrofoils with the Harpoon Missile System, 76 millimeter anti-destroyer gun and the Sea Sparrow Missile System was going to be a problem.

In order to save time and money, the Navy chose sole-source procurement, and a contract was awarded to Boeing in November 1971. In 1972, letters of intent were received from Italy and Germany; however, all other NATO participants dropped out of the program or reverted to observer status. While the Naval Ship Engineering Center (NAVSEC) completed a feasibility study of a 150-160 ton missile hydrofoil in May 1972, Boeing's design, aimed at both U.S. and German markets, turned out to be much larger. NAVSEC argued that the Boeing proposal, with its relatively short range, large payload and high cost (approximately 25-35 percent more than that of their 160-ton design) was too large for the Navy. In the end, it was the Boeing design, the PEGASUS class missile hydrofoil, which was selected, mainly for its greater growth margins. Table 5 contains PEGASUS class ship specifications (Pike, 2002 and Friedman, 1987) and Table 6 contains PEGASUS class payload. (Pike, 2002)

	Length (feet)	Beam (feet)	Draft (feet)	Displacement (long tons)	Maximum Speed (knots)	Range (nm / kts)	Crew
Hull-borne	145	28	23.2[1]	255	12	1110 / 10	25
Foil-borne	133	28	8.8	255	50	400 / 50	25

Table 5. PEGASUS Class Ship Specifications

Note: 1. With foils extended. Hull-borne draft with foils retracted is 6.2 feet.

Mission Profile	Armament
Anti-Surface Warfare	- Eight Harpoon Missiles - One 76 millimeter Rapid Fire Gun
Anti-Air Warfare	None
Anti-Submarine Warfare	None

Table 6. PEGASUS Class Payload

By 1974, the PEGASUS class program encountered severe cost overruns and a decision was made to reduce the number of ships in the program from thirty to twenty-five. The following year brought more funding problems for the PEGASUS class, and a decision was made to further reduce the number of ships in the program to six. In 1976, construction on the USS HERCULES (PHM-2) was suspended in order to obtain enough money to complete the lead ship, USS PEGASUS (PHM-1). By 1977, the PEGASUS program incurred such a cost growth ($13.2 million) that the last of the six ships, USS GEMINI (PHM-6), had to be built without armament. (Jenkins, 1995)

As the ships were commissioned in the late 1970s and early 1980s, the Navy made numerous attempts at a trial deployment to the Mediterranean; however, these were prevented by frequent system failures and a long lead-time for repair parts. Since the PEGASUS class was too small to support itself and mobile logistics support was unavailable, it could not operate in waters far from home. Just as USS GRAHAM COUNTY (LST 1176) was modified to provide necessary logistics support for the

ASHEVILLE class, USS WOOD COUNTY (LST 1178) was considered essential for logistics support of the PEGASUS class ships if their deployment to the Mediterranean was going to be successful. While the fiscal year 1978 budget provided the necessary funding ($42.8 million) for the conversion, the poor condition of USS WOOD COUNTY's propulsion plant was not taken into consideration. After reviewing the proposal, it was determined the cost of plant replacement plus modification was excessive, and as such, the conversion was cancelled, even though it was previously determined that a logistics support ship was vital for the success of the PEGASUS class. As a result, hopes for a Mediterranean deployment were abandoned and operations beyond the Caribbean were never scheduled. Even though funding was the official basis for cancellation, it seems more likely that the program had lost support and was destined for failure. (Jenkins, 1995)

As with the ASHEVILLE class, it seemed once again the strategic requirements of the United States Navy were not met with the development of the missile hydrofoils. Due to the inability to incorporate a modular weapons capability into the missile hydrofoil design, the squadron concept never came to fruition and the missile hydrofoils limited role was not in keeping with the Navy's emphasis on multi-purpose ships that were more adaptable to the full spectrum of naval operations. On July 30, 1993, the PEGASUS class program came to an end as all six were decommissioned.

C. CYCLONE CLASS PATROL COASTAL SHIPS (PC)

In 1990, the Navy awarded a contract to Bollinger Shipyards Incorporated for construction of eight patrol coastal ships. A follow-on contract for five additional ships was awarded in July 1991; in October 1997 Bollinger was awarded a contract to build a fourteenth patrol coastal ship. Construction of the ships was funded by the United States Special Operations Command (USSOCOM), and as such, the ships were assigned to the Naval Special Warfare Command under the cognizance of Special Boat Squadron ONE (Coronado, CA) and Special Boat Squadron TWO (Little Creek, VA). The initial mission of the patrol coastal ships was to conduct Maritime Special Operations, to include maritime interdiction operations, forward presence, escort operations, noncombatant evacuation, foreign internal defense, long-range Special Operations Forces

(SOF) insertion/extraction, tactical swimmer operations, reconnaissance, intelligence collection, operational deception, and SOF support as required. (Matyas, 2003) Table 6 contains CYCLONE class ship specifications and Table 7 contains CYCLONE class payload.

	Length (feet)	**Beam (feet)**	**Draft (feet)**	**Displacement (long tons)**	**Maximum Speed (knots)**	**Range (nm / kts)**	**Crew**
PC 1 - PC 13	170	25	7.9	341	35	2000	39
PC 14	179	25	8.5	392	35	2900	39

Table 7. CYCLONE Class Ship Specifications

Mission Profile	**Armament**
Anti-Surface Warfare	- 25mm Machine Guns - Five .50-caliber Machine Guns - Two 40mm automatic grenade launchers - Two M-60 machine guns.
Anti-Air Warfare	Stinger Missiles
Anti-Submarine Warfare	Sonar transducer retracted within the hull at speeds above 14 knots

Table 8. CYCLONE Class Payload

The goal of the CYCLONE class program was to produce ships that provided the Navy with a fast, reliable platform that was able to respond to emergent requirements in a shallow-water environment. However, the Navy quickly realized they had once again embarked upon another problematic high-speed ship program. As with the previously discussed high-speed ship designs, the full displacement grew during construction. The focus on speed during the design process resulted in damaging tradeoffs to range and payload. Even though the patrol coastal ships are much larger than their predecessors, they only carry about the same payload and their combat systems and ammunition allowance do not compare well with similar ships in most other navies. Even though they are capable of refueling at sea using astern refueling rigs, they only have a 10-day endurance, which is extremely limited for a ship its size. In order to support the few deployments they made to the Mediterranean, they require a temporarily shore-based Maintenance Support Team that pre-deployed with three 20-foot vans for spare parts and repair work. If these problems weren't bad enough, it was later discovered that they were too large for the close inshore work for which they were intended.

Due to the inability to successfully fulfill the missions for which they were designed, plans to build three additional patrol coastal ships (PC 15 through PC 17) were terminated and the CYCLONE class ships were slated for decommissioning in 2002. However, after the September 11th attacks on New York and Washington, D.C., there appeared to be a need for these ships in providing homeland defense. On November 5, 2001, it was announced that under OPERATION NOBLE EAGLE, five CYCLONE class ships were to be used for U.S. coastal patrol and maritime homeland security operations under the tactical control of the Coast Guard. As a result, they were tailored for maritime homeland security missions and have been employed jointly with the U.S. Coast Guard to assist in protecting U.S. coastlines, ports and waterways against potential terrorist attacks. The lead ship of the class, USS CYCLONE (PC 1), was decommissioned and turned over to the U.S. Coast Guard on February 28, 2000. As of now, no decisions have been made as to the decommissioning dates for the remaining CYCLONE class ships.

D. VALUE AND LIMITATION OF SPEED

Throughout Naval history, the development of small combatants in the United States has been driven by two factors: national strategy and technology, particularly the technology of high speed. (Friedman, 1987) While it is clear small ship design should be driven by national strategy, the concept of speed has always been a source of great debate.

> It must be plain to everyone who has ever taken part in any discussion on speed…that those who favour very high speed…are extremely sensitive on those points, and are usually ready to meet even a historical and undisputed statement with a vigorous rejoinder, as though an appeal to history were regarded as a controversion of their opinions. This deserves a good deal of consideration. (The Institution of Naval Architects, 1905)

Those who believe speed is critical to successful Naval operations argue high speed enables ships to arrive in theater faster and increase maneuverability within the assigned operating area. On station, some of the tactical benefits of high speed would seem to include decreased Special Operations Forces insertion and extraction times, increased flexibility in supporting Ship-to-Shore and Ship-to-Objective Maneuver operations, quick attacks against an enemy. and increased ability to evade enemy ships and weapons. Some proponents of speed may refer to war games and computer simulations as proof that speed is, in fact, a tactical advantage when it comes to Naval operations.

> Speed has always been of value in warfare, and daily it is being revalued yet further. If the value of speed is increasing, then those factors, sectors or forces which slow us down must either change or cease to exist. (Cebrowski, 1998)

Others argue high speed is not a tactical advantage. They state history has shown that high speed often appears so attractive that the possibility of obtaining it, even at great expense, seems to alone justify the construction of high-speed, small combatants. Often these proposals for new high-speed ships demonstrated the conflict between an attractive technology and naval requirements and turned out to be nothing more than solutions seeking problems. (Friedman, 1987) The lessons learned from the ASHEVILLE, PEGASUS and CYCLONE classes seem to support this idea.

Whether or not speed is tactically useful may not be the right question to ask. Perhaps, the more appropriate question is whether or not it is possible to overcome the limitations which have, throughout history, prevented previous high-speed ship designs from successfully capitalizing on any value that speed potentially offers. One reason the ASHEVILLE, PEGASUS and CYCLONE classes were all unable to meet the high-speed mission requirements for which they were designed was due to poor sea keeping in rough waters. Figure 2 demonstrates the impact of wave height on speed: as wave height increases, speed significantly decreases. (Lockheed Martin, 2002) While wave height has proven itself to be a major limitation on speed, it is not the only one. The need for the U.S. Navy to operate in potentially hostile waters far from home requires that ships be capable of long range, high endurance, and delivery of ordnance on target when necessary. Considering the small size of these previous high-speed ships and existing constraints in technology, range and payload were always sacrificed in order to achieve high speeds. With endurance rarely exceeding fourteen days, frequent replenishment was necessary if these ships were to remain mission capable. Since the U.S. Navy did not have mobile logistics assets capable of resupplying these ships as often as needed, it made it nearly impossible to support them in their operating areas.

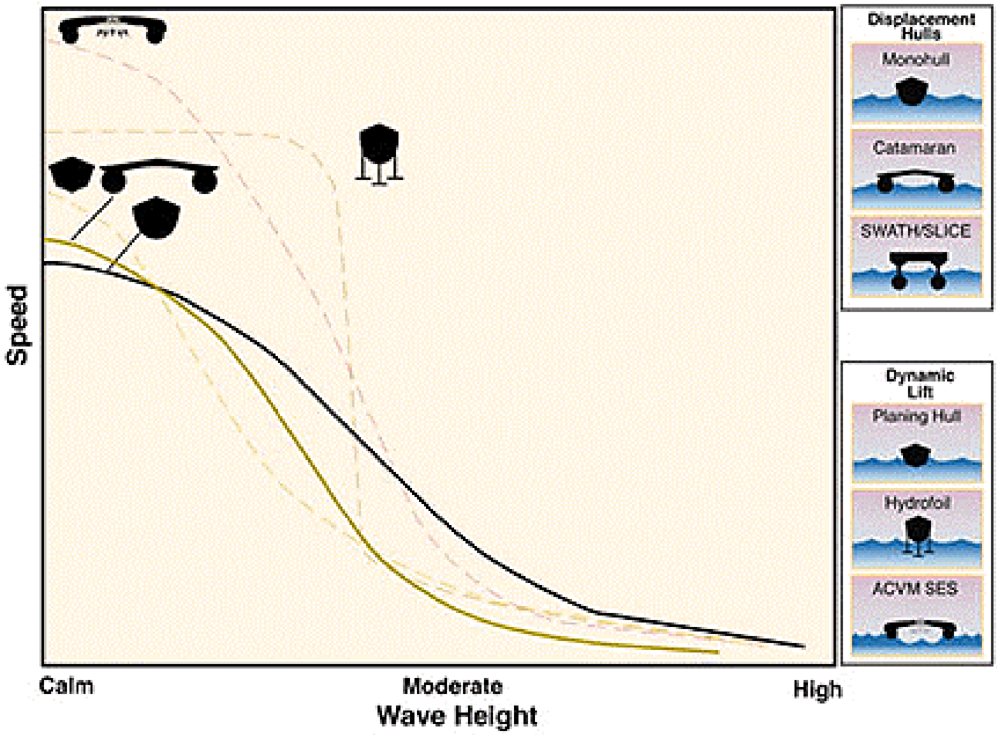

Figure 2. Impact of Wave Height on Ship Speed

> We now stand, according to Sir Reginald Custance, in the position that there is no absolute proof of the value of speed. He is an officer of the largest experience in the handing of fleets, and he tells us that the experiments so far made have not conclusively established one view or the other, and that he considers it is possible to reach a definite conclusion by properly conducted and well arranged, exhaustive experiments. (The Institution of Naval Architects, 1905)

From the ASHEVILLE, PEGASUS and CYCLONE class high-speed ship programs, we have learned there are, in fact, limitations to speed; however, the question regarding the value of speed, relative to the factors one must sacrifice to obtain it, remains. War games and simulation may provide insights into the value of speed; however, the true value of speed will not be determined until the limitations of speed can be eliminated.

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III. LITTORAL COMBAT SHIP MODEL DEVELOPMENT

The Littoral Combat Ship is scheduled to be a member of the family of future surface combatants in support of the Sea Shield component of Sea Power 21. Its proposed contribution to Sea Shield is through its high-speed capability coupled with its ability to conduct a variety of peacetime and combat missions. In addition, the Littoral Combat Ship is proposed to be an enabler of Sea Basing by providing security for Joint assets and by acting as a logistics element for joint mobility and sustainment. The Littoral Combat Ship is envisioned to be a seaframe, serving much the same purpose as an airframe for a reconfigurable aircraft. It will serve as a platform for modular mission packages that can be changed, modified or removed in a short period of time. Logistics support will be self-contained and possess the capability of supporting additional personnel to augment the core crew as required for modular mission package support and additional tasks such as messing, administration and medical support.

In this chapter, the Littoral Combat Ship concept of operations is discussed, critical design parameters are listed and a model is created to estimate the Littoral Combat Ship size and endurance. Information regarding Littoral Combat Ship operations was obtained from the Naval Warfare Development Command Littoral Combat Ship Concept of Operations. (Navy Warfare Development Command, 2003)

A. CONCEPT OF OPERATIONS

The Littoral Combat Ship is designed to accomplish missions inside the littorals in order to support the national strategy tenet of littoral dominance. It will effectively operate throughout the continuum of operations as part of a distributed force. It is networked to off-board systems and to power projecting elements, from Carrier Strike Groups (CSG) and Expeditionary Strike Groups (ESG) to other Service capabilities for influencing events at sea and shore. Effective operations in the littorals are characterized by speed, agility, and integration with off board modular systems, survivability and signature control.

In order to operate effectively, the Littoral Combat Ship must be capable of limited independent operations, interdependent operations as part of a littoral operations force or integrated operations with multi-mission fleet forces such as Carrier and Expeditionary Strike Groups. In the self-deployable mode, a single forward deployed Littoral Combat Ship will be capable of responding rapidly and conducting a wide range of mobility missions such as Special Operations Forces (SOF) support, logistics (LOG), Anti-Terrorism/Force Protection (AT/FP), Maritime Intercept Operations (MIO), Sea Line of Communication (SLOC) patrols, Non-Combatant Evacuation Operations (NEO), Humanitarian Assistance (HA), and Medical Support (MED). The Littoral Combat Ship must be capable of transiting to the assigned operating area without having to rely on valuable and scarce Combat Logistic Force (CLF) ships or an ever-present logistics support ship. A self-deployment range of at least 3,500 nautical miles is desired as it would ensure a quick transfer to and from the theater of operations. In the interdependent operations mode, a number of Littoral Combat Ships would be forward deployed to maintain a continuous presence in critical theaters of operations. They will build the situational awareness in the littorals in anticipation of sanction enforcement, forced entry, information operations, strike operations and land warfare. In the integrated operations mode, several Littoral Combat Ships, with tailored mission configurations, will deploy with a CSG or ESG to provide vanguard scouting, pouncing support, and other tasking as directed.

The two primary mission categories for the Littoral Combat Ship are Focused Missions and Continuing Missions. During Focused Missions, the Littoral Combat Ship will employ reconfigurable modules tailored to specific missions such as littoral Anti-Submarine Warfare, Mine Warfare and Anti-Surface Warfare. As the Littoral Combat Ship will generally operate as part of a distributed force of many Littoral Combat Ships, groups of ships may be discretely configured so that more than one mission is conducted throughout the force. An additional Focused Mission is formalized logistics, which would include inter-theater and intra-theater lift and other joint logistics missions. Table 9 contains the Littoral Combat Ship focused mission profile and associated payload.

Mission Profile	Armament
Anti-Submarine Warfare	- MH-60 R/S Multi-Mission Helicopter - SPARTAN USV
Mine Warfare	- MH-60R/S Multi-Mission Helicopter - SPARTAN USV - RMS USV - LMRS UUV
Anti-Surface Warfare	- MH-60R/S Multi-Mission Helicopter - AH-58D Army Attack Helicopter [1] - SPARTAN USV
Anti-Air Warfare	- AH-58D Army Attack Helicopter
Self Defense	- Four .50-caliber M2 Machine Guns - Four M-60 Machine Guns

Table 9. Littoral Combat Ship Focus Mission Profile and Payload

Note: 1. The Army AH-58D Warrior aircraft is a version of the Army OH-58D Kiowa Warrior with air-to-air and air-to-surface armament installed.

During Continuing Missions, the Littoral Combat Ship will conduct intelligence, surveillance and reconnaissance (performed by the Fire Scout VT-UAV) or participate in any of the previously listed mobility missions while providing for its own self-defense. The core capabilities of the Littoral Combat Ship (sensing; command, control and communications; processing capability; and modular weapons) will support these continuing missions, which may or may not be conducted in a distributed manner.

The Littoral Combat Ship will contain mission systems and weapons that provide both core self-defense capabilities and the necessary compatibility with off-board sensors and networks. The mission systems will have four components: the host Littoral Combat Ship platform, its organic associated mission systems (installed seaframe systems), its networking capability, and the off-board sensors/vehicles (modular mission packages). Elements of mission modules will be designed to overlap in their applicability, and reconfiguration is anticipated to be a relatively simple and rapid task conducted at sea via Conventional Replenishment (CONREP) or Vertical Replenishment (VERTREP), in port or in a shipyard type environment. Replacement or replenishment modules may be flown in or pre-staged in theater as necessary.

B. CRITICAL DESIGN PARAMETERS

Table 10 contains the Littoral Combat Ship critical design parameters listed in the Surface Warfare Directorate Ship Systems Division Preliminary Design Interim Requirements Document. (Surface Warfare Directorate, 2003)

Category	Threshold Level	Objective Level
Total Price per Ship	Seaframe: $220 M Mission Packages: $180 M	Cost less than threshold
Hull Service Life	20 Years	30 Years
Draft at Full Displacement	20 feet	10 feet
Sprint Speed at Full Displacement	40 knots in Sea State 3 [1]	50 knots in Sea State 3
Range at Sprint Speed [2]	1,000 nautical miles	1,500 nautical miles
Range at Economical Speed [2]	3,500 nautical miles, speed greater than 18 knots	4,300 nautical miles, speed greater than 20 knots
Aviation Support	Embark and hangar one MH-60R/S and VT-UAVs	Embark and hangar one MH-60R/S and VT-UAVs
Aircraft Launch/Recover	Sea State 4	Sea State 5
Watercraft Launch/Recover	Sea State 3 within 45 minutes	Sea State 4 within 15 minutes
Mission Package Boat Type	11 Meter RHIB	40-foot High Speed Boat
Time for Mission Package Change-Out to full operational capability	4 days	1 day
Provisions	336 hours (14 days)	504 hours (21 days)
Underway Replenishment Modes	CONREP/VERTREP/RAS	CONREP/VERTREP/RAS
Mission Package Payload [3]	177.2 long tons	206.7 long tons

Core Crew Size	50	15
Accommodations (crew and embarked personnel)	75	75
Operational Availability	0.85	0.95

Table 10. Littoral Combat Ship Critical Design Parameters

Note: 1. Sea State parameters are defined in Appendix A.

2. Includes payload for required range.

3. Includes the weight of fuel required to operate the mission package.

C. MODEL DESCRIPTION AND FORMULATION

The purpose of the model is to calculate the estimated size and endurance for the Littoral Combat Ship in order that the logistical implications of speed, endurance, and payload tradeoffs can be studied. Since the Littoral Combat Ship is still in the conceptual phase, a seaframe suitable for conducting missions listed by the Navy Warfare Development Command (NWDC) in the Littoral Combat Ship Concept of Operations had to be utilized. (Navy Warfare Development Command, 2003) The lack of logistical analysis for non-traditional hull forms coupled with current military testing of and data availability for the Joint Venture (HSV-X1) high-speed, wave-piercing catamaran resulted in the selection of the Joint Venture as the Littoral Combat Ship surrogate for model development. The model is developed using Microsoft Office EXCEL. It is subdivided into seven sections: Seaframe Data, Seaframe Systems, Modular Mission Packages, Ship's Gear Weight, Full Displacement Calculation, Endurance Calculation and Fuel Replenishment Requirement Calculation. Tables 11 through 13 contain conversion factors used throughout the model.

Weight Conversion Factors:		
1 kilogram (kg) =	2.2046	pounds
1 long ton (lt) =	2240	pounds
kg to lt conversion factor =	0.000984	
Marginal Growth Factor =	1.20	

Table 11. Weight Conversion Factors

Storage Area Conversion Factors:		
1 square meter (sq m) =	1.196	sq yards
1 square yard (sq yd) =	9.000	sq feet
sq m to sq ft conversion factor =	10.764	
Marginal Growth Factor =	1.10	

Table 12. Storage Area Conversion Factors

Full Displacement Calculation Conversion Factors:		
1 gallon =	3.7854	liters
1 ounce =	0.0078125	gallons
1 pound =	16	ounces
1 short ton =	2000	pounds
1 long ton =	2240	pounds
1 short ton =	1.12	long tons
Crew Member / Embarked Personnel =	0.15	short ton
Ship Growth Margin per Person =	3	long tons / person
Payload Weight Factor =	15%	

Table 13. Full Displacement Calculation Conversion Factors

1. Seaframe Data

Ship specifications for the Joint Venture include length, beam, draft, seaframe and maximum displacement, speed, maximum range, and storage area. Seaframe displacement is defined as the weight of the hull, self-defense machine guns (total of eight), and all installed propulsion systems. It excludes installed seaframe systems (weapons systems, sensors, command and control systems) and deadweight. Deadweight is defined as the total weight of the crew, embarked personnel and their effects; fresh water; stores and provisions; fuel; ordnance; modular mission packages; and any additional items of consumable or variable load. Maximum displacement is defined as the maximum weight of the ship, which includes the seaframe and its installed systems and all deadweight. Storage area is defined as the amount of space available for installed seaframe systems and modular mission packages. Military useful storage area was determined based on the Transportability Analysis conducted by the Military Traffic Management Command's Transportation Engineering Agency. (Atwood and Delucia, 2002) Since all seaframe and modular mission package systems listed in the Navy Warfare Development Command Littoral Ship Concept of Operations are of a height less than that of the Joint Venture storage decks, storage areas are calculated in square feet for area vice cubed feet for volume. Table 14 contains JOINT VENTURE ship specifications.

Length (feet)	**Beam (feet)**	**Draft (feet)**	**Seaframe Displacement (long tons)**	**Maximum Displacement (long tons)**	**Maximum Speed (knots)**	**Maximum Range (nm / kts)**	**Crew**	**Maximum Storage Area (square feet)**
313.2	87.3	12.1[1]	922.3	1671.4	48	2400 / 35	30	12114[2]

Table 14. JOINT VENTURE Ship Specifications

Notes: 1. Maximum draft is 13 feet.
2. Storage area with the Portable Stern Ramp (562 square feet) onboard is 11,552 square feet.

2. Seaframe Systems

The seaframe systems consist of all weapon systems, sensors, and command and control systems that have been used by the Navy as surrogate systems to be permanently installed aboard the Littoral Combat Ship. (Navy Warfare Development Command, 2002) This section contains the number of proposed systems, unit weight and unit area for each system. The total weight and area for each system are calculated and added to determine the total weight and storage area of all seaframe systems. During ship design and construction, growth margins are included to allow for unknowns, inaccuracy of assumptions, and additional unforeseen factors. Allowances, which are excesses of some characteristic beyond known needs, are intentionally built into the ship to be consumed during its life. Figure 3 demonstrates margins and allowances over the life cycle of a ship. (Calvano, 2003) In order to account for these margins and allowances in the model, a marginal growth of 20% for system weight and 10% for system area are added to seaframe system weight and area totals.

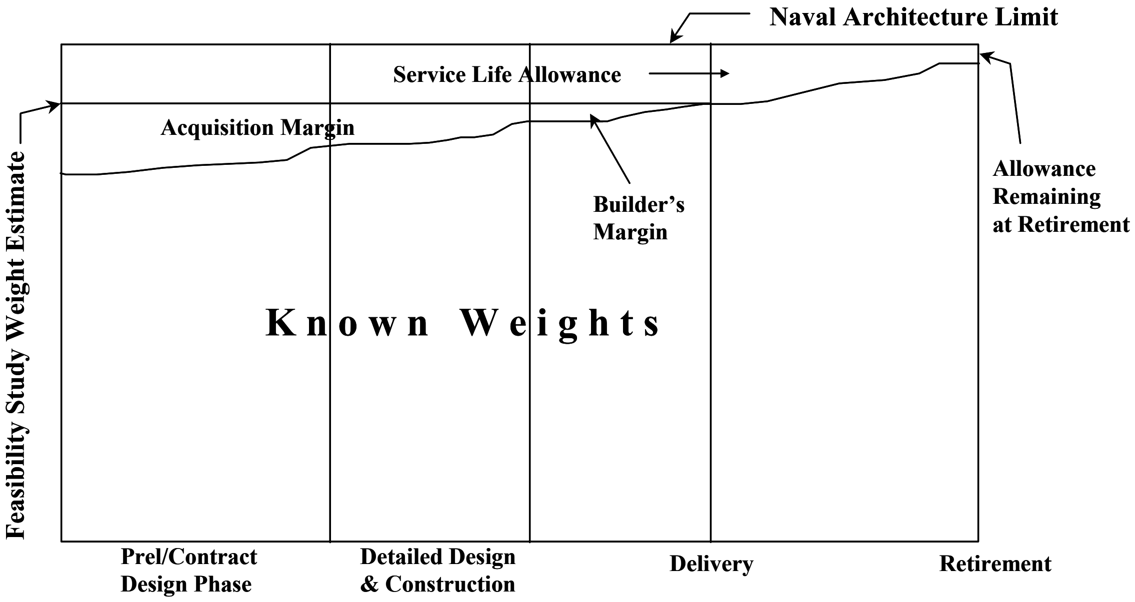

Figure 3. Margins and Allowances Over Ship Life Cycle

Table 15 contains a list of the proposed Littoral Combat Ship seaframe systems and their associated weight and storage area.

The following formulation is used to determine total weight and space requirements for all seaframe systems:

$$Total\ Weight_{Seaframe\ Systems} = \sum Number\ of\ Systems_i * Unit\ Weight_i$$
$$Total\ Storage\ Area_{Seaframe\ Systems} = \sum Number\ of\ Systems_i * Unit\ Area_i$$
$$\forall i, i \in \{Weapon\ Systems, Sensors, Command\ \&\ Control\ Systems\}$$

Weapon Systems, Sensors and Command & Control Systems	Number	Total Weight (long tons)	Total Weight including Marginal Growth (long tons)	Total Storage Area (square feet)	Total Storage Area including Marginal Growth (square feet)
Mk 15 CIWS Block 1B Gun Mount	1	6.47	7.8	131.3	144.5
CIWS Support	1	0.86	1.0	117.3	129.1
Mk 31 RAM Guided Missile System					
Launcher, above deck	1	5.11	6.1	103.3	113.7
RAM, below deck	1	0.89	1.1	10.8	11.8
Mk 53 Mod 4 Decoy Launch System (4 NULKA-SRBOC & 2 SRBOC launchers)	1	10.00	12.0	158.2	174.1
Advanced Surface / Air Search Radar	1	1.00	1.2	20.0	22.0
Electro Optical Sight System	1	1.00	1.2	20.0	22.0
Link 16 (CDLMS & JTIDS)	1	1.60	1.9	45.2	49.7
AN/USG-2(V) Co-operative Engagement Capability (CEC) (Receive Only)	1	1.57	1.9	58.1	63.9
		TOTAL:	**34.2**	**TOTAL:**	**730.7**

Table 15. Proposed Littoral Combat Ship Seaframe Systems

3. Ship's Gear Weight

Ship's gear consists of items necessary for support of the seaframe. Table 16 contains a list of ship gear aboard JOINT VENTURE and its associated weight.

Ship's Gear Item	Number	Unit Weight (long tons)	Total Weight (long tons)
Caterpillar Container:	1	3.6	3.6
Incat Container:	1	4.5	4.5
Portable Ramp:	1	6.6	6.6
ISU-90 W-Locker:	1	2.1	2.1
ISU-90 A-Locker:	1	2.1	2.1
Oil drums, misc items:	1	8.9	8.9
Incat Support Van:	1	2.7	2.7
Forklift:	1	6.4	6.4
GUV	1	0.6	0.6
Generator Set:	2	2.0	3.9
RHIB:	1	0.7	0.7
		TOTAL:	**42.2**

Table 16. JOINT VENTURE Ship's Gear

The following formulation is used to determine the total weight of all ship's gear items:

$$Total\ Weight_{Ships\ Gear} = \sum Number\ of\ Item_j * Unit\ Weight_j$$
$$\forall j,\ j \in \{Ship's\ Gear\ Items\ Listed\ in\ Table\ 10\}$$

4. Modular Mission Packages

Modular mission packages consist of all manned and unmanned vehicles that are not permanently installed in the seaframe. These systems are designed to support the modular architecture of the Littoral Combat Ship. They provide flexible mission capability to meet different primary, secondary or alternate missions and the future ability to incorporate new technology for given mission functions. This section contains the number of proposed modular mission package systems, unit weight and unit area for each system. The total weight and area for each system are calculated and added to determine the total weight and storage area of all modular mission systems. As previously applied to the seaframe systems, a marginal growth of 20% for system weight and 10% for system area are added to the modular mission package weight and area totals in order to account for modular mission package margins and allowances. Data regarding the five modular mission packages used in the model was obtained from the NWDC Littoral Combat Ship Concept of Operations draft and Surface Warfare Directorate Ship Systems Division Preliminary Design Interim Requirements Document. (Navy Warfare Development Command, 2002 and Surface Warfare Directorate, 2003). They include the MH-60R/S Multi-Mission Helicopter (MMH), AH-58D Warrior Helicopter, Fire Scout Vertical Takeoff-Unmanned Aerial Vehicle (VT-UAV), Remote Mine-hunting System (RMS), Spartan Unmanned Surface Vehicle (USV), and Long-term Mine Reconnaissance System (LMRS). Table 17 contains proposed Littoral Combat Ship modular mission packages, and Table 18 provides the weight and storage area of each modular mission package. The total storage area of all seaframe systems, all modular mission packages, and the onboard ramp is 8,769 square feet, which falls below the maximum storage area of 12,114 square feet listed in Table 14.

MH-60R/S	AH-58D	Fire Scout VT-UAV	RMS	Spartan USV	LMRS
- Support for 1 - Payload - Fuel	- Support for 2 - Payload - Fuel	- Support for 3 - Payload - Fuel	- Launch, Recovery and Stow System - Support for 1 - Payload - Fuel	- Launch, Recovery and Stow System - Support for 1 - Payload - Fuel	- Launch, Recovery and Stow System - Support for 2 - Payload - No fuel required (battery powered)

Table 17. Proposed Littoral Combat Ship Modular Mission Systems

Modular Mission Package	**Number**	**Total Weight (long tons)**	**Total Weight including Marginal Growth (long tons)**	**Total Storage Area (square feet)**	**Total Storage Area including Marginal Growth (square feet)**
MH-60R/S	1	75.2	90.2	1551.6	1706.8
AH-58D	2	22.0	26.4	2095.5	2305.1
Fire Scout VT-UAV	3	13.5	16.2	1505.9	1656.5
RMS	1	27.6	33.1	398.3	438.1
SPARTAN USV	1	35.8	43.0	1083.9	1192.3
LMRS	2	7.4	8.9	161.5	177.6
		TOTAL:	**217.8**	**TOTAL:**	**7476.3**

Table 18. Modular Mission Package Weights and Storage Areas

The following formulation is used to determine total weight and space requirements for all modular mission packages:

$$Total\ Weight_{Modular\ Mission\ Packages} = \sum Number\ of\ Modular\ Mission\ Packages_k * Unit\ Weight_k$$

$$Total\ Storage\ Area_{Modular\ Mission\ Packages} = \sum Number\ of\ Modular\ Mission\ Packages_k * Unit\ Area_k$$

$$\forall k, k \in \{MH-60R/S, AH-68D, Firescout\ VT-UAV, RMS, Spartan\ USV, LMRS\}$$

5. Full Displacement Calculation

This portion of the model calculates the full displacement of the proposed Littoral Combat Ship by adding the deadweight to the light displacement. The light displacement is calculated by adding the displacement of the seaframe and all seaframe installed systems. The deadweight is calculated by adding the weight of the crew, embarked personnel and their effects; fresh water; stores and provisions; fuel; lube oil; ship's gear; ordnance; and all modular mission packages installed aboard the seaframe (this varies depending on the assigned mission). The weight of the crew and embarked personnel is calculated by multiplying the total number of crew and embarked personnel by the average weight per person. According to the critical design parameters, there will be between fifteen and fifty crewmembers aboard the Littoral Combat Ship. During the Navy's testing of the JOINT VENTURE, there were a total of thirty-one crewmembers. However, the lessons learned stated the fast pace of JOINT VENTURE testing operations along with duty and watch-standing requirements were too demanding for the current crew size, and as such, recommended a crew size of forty. (Beierl, 2002) Since it appears these added demands were due to the Navy testing a ship that wasn't specifically designed for Littoral Combat Ship operations, it seems reasonable the majority of these problems will be resolved during the actual design process. As a result, a crew size of thirty-five is used as it provides an additional four personnel to compensate for any unforeseen manning requirements. The critical design parameters state the Littoral Combat Ship will be able to provide accommodations for up to seventy-five personnel, which includes personnel to support the various modular mission systems and other passengers as a result of the assigned Littoral Combat Ship mission (examples include Non-Combatant Evacuation Operations, Humanitarian Support and Medical Support). Since the number of personnel required to support all modular mission systems has not been determined, it is assumed to be approximately 25% of the total number of passengers. As a result, 18 personnel are used as the number of embarked personnel in the model full displacement calculation. Adding the number of crewmembers and embarked personnel results in a total of 53 personnel assigned onboard the Littoral Combat Ship. The weight of crew and embarked personnel effects; fresh water; and stores and provisions is calculated by multiplying the total number of crew and embarked personnel by the ship growth margin per person.

The weight of fuel depends on the amount being carried onboard. The JOINT VENTURE has four Day tanks and two Long-Range tanks, for a total carrying capacity of 567,580 liters. Fuel weight is calculated by converting the amount of fuel being carried in liters to tons. Table 19 contains data for the Littoral Combat Ship fuel capacity and weight.

	Fuel Capacity (liters)	**Fuel Weight** (pounds)	**Fuel Weight** (long tons)
4 Day Tanks:	174880	369588.42	164.99
2 Long-Range Tanks:	392700	829925.50	370.50
Combined Tanks:	567580	1199513.92	535.50

Table 19. Littoral Combat Ship Fuel Capacity and Associated Weight

The weight of lube oil and ship's gear is obtained from the Transportation Engineering Agency Transportability Analysis. (Atwood and Delucia, 2002)

The amount of ordnance depends on the installed weapon systems and mission profile for which the Littoral Combat Ship is being configured. Typically, the weight of a modern warship's mission payload (consisting of armament and ordnance) makes up ten to fifteen percent of its full displacement. (Kelley, 2002) As a result, the total payload weight is calculated by multiplying the maximum displacement by fifteen percent. Since the ordnance required for modular missions is included in each mission package, the objective level weight for mission module payload, contained in Table 9, is used for the total weight of modular mission packages. The weight of ordnance for seaframe systems is determined by subtracting the weight of all seaframe systems and modular mission packages from the total payload weight.

The following formulation is used to determine the full displacement of the Littoral Combat Ship:

$$
\begin{aligned}
&\mathit{Light\ Displacement}_{LCS} = \mathit{Total\ Weight}_{Seaframe} + \mathit{Total\ Weight}_{Seaframe\ Systems}\\
&\mathit{Weight}_{Crew} = \mathit{Number\ of\ Crew\ Members} * \mathit{Unit\ Weight}_{Crew\ Member}\\
&\mathit{Weight}_{Embarked\ Personnel} = \mathit{Number\ of\ Embarked\ Personnel} * \mathit{Unit\ Weight}_{EmbarkedPersonnel}\\
&\mathit{Total\ Number\ of\ Personnel} = \mathit{Number\ of\ Crew\ Members} + \mathit{Number\ of\ Embarked\ Personnel}\\
&\mathit{Weight}_{Effects,\ Stores,\ Provisions} = \mathit{Total\ Number\ of\ Personnel} * \mathit{Ship\ Growth\ Margin\ Per\ Person}\\
&\mathit{Weight}_{Fuel} = \mathit{Amount\ of\ Fuel\ Carried\ Onboard} * \mathit{Fuel\ Weight\ Conversion\ Factor}\\
&\mathit{Weight}_{Lube\ Oil} = 0.8929\ \mathit{long\ tons}\\
&\mathit{Weight}_{Payload} = \mathit{Maximum\ Displacement} * \mathit{Payload\ Weight\ Factor}\\
&\mathit{Weight}_{Ordnance} = \mathit{Weight}_{Payload} - \mathit{Weight}_{Seaframe\ Systems} - \mathit{Weight}_{Modular\ Mission\ Packages}\\
&\mathit{Deadweight}_{LCS} = \mathit{Weight}_{Crew} + \mathit{Weight}_{Embarked\ Personnel} + \mathit{Weight}_{Effects,\ Stores,\ Provisions} + \mathit{Weight}_{Fuel} +\\
&\qquad\qquad \mathit{Weight}_{Lube\ Oil} + \mathit{Weight}_{Ships\ Gear} + \mathit{Weight}_{Ordnance} + \mathit{Weight}_{Modular\ Mission\ Packages}\\
&\mathit{Full\ Displacement}_{LCS} = \mathit{Light\ Displacement}_{LCS} + \mathit{Deadweight}_{LCS}
\end{aligned}
$$

6. Endurance Calculation

In order to calculate the estimated endurance of the Littoral Combat Ship, a fuel consumption equation is required. Table 20 contains JOINT VENTURE fuel consumption data. (Beierl, 2002)

Fuel Consumption Rate (liters / hour)	Displacement (long tons)	Ship Speed (knots)	Significant Wave Height (feet)
1320	1500	15	6
5940	1450	33	7
1445	1350	17	7
5760	1300	36	5
6800	1600	34	7
6600	1300	40	3.5

Table 20. JOINT VENTURE Fuel Consumption Data

In order to obtain the required fuel consumption equation, fuel consumption rate is regressed against various combinations of displacement, ship speed and significant wave height raised to the first, second and third powers. Significant wave height is defined as the average of the highest one-third of the waves. (National Oceanic and Atmospheric Administration, 2003) The regression of fuel consumption rate against displacement, ship speed^3 and significant wave height is selected as the preferred regression due to the fact that it is statistically sound and yields the most realistic fuel consumption equation with regard to JOINT VENTURE actual range and endurance data. Since ship power requirements for displacement hulls increase roughly with the cube of speed, this further supports the regression selected for use in the model. (Beierl, 2002) Table 21 contains the fuel consumption rate regression statistics.

Regression Statistics	
Multiple R	0.998
R Square	0.996
Adjusted R Square	0.991
Standard Error	247.896
Observations	6

ANOVA

	df	SS	MS	F	Significance F
Regression	3	32559016.000	10853005.333	176.608	0.006
Residual	2	122904.833	61452.417		
Total	5	32681920.833			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-7997.867	1437.562	-5.563	0.031	-14183.203	-1812.531
Displacement	3.281	1.217	2.695	0.114	-1.956	8.518
Speed^3	0.129	0.006	20.867	0.002	0.102	0.155
Significant Wave Height	647.403	128.246	5.048	0.037	95.605	1199.201

Table 21. Fuel Consumption Rate Regression Statistics

The regression demonstrates that increases in displacement, speed and significant wave height result in increases in fuel consumption. This finding is confirmed by the fuel consumption discussion in the Navy's JOINT VENTURE "lessons learned" as it was noted fuel consumption increased dramatically when both displacement and significant wave height increased. (Beierl, 2002) Fuel consumption rates are calculated by adding the intercept coefficient to the sum of the products of the displacement, speed^3, and significant wave height coefficients obtained from the regression and their respective inputs. In reality, the weight of fuel decreases as it is consumed during ship operations.

As a result, full displacement of the ship decreases as well. However, this model uses a constant fuel weight during calculations. The result is a lower bound on endurance since fuel consumption would actually decrease as the ship becomes lighter, thereby, increasing range.

The following formulation is used to estimate Littoral Combat Ship endurance:

$$\begin{aligned}
&\mathit{Fuel\ Consumption\ Rate} = -7997.87 + 3.28 * \mathit{Full\ Displacement} + \\
&\qquad 0.13 * (\mathit{Ship\ Speed})^3 + 647.40 * \mathit{Average\ Wave\ Height} \\
&\mathit{Endurance} = \mathit{Amount\ of\ Fuel\ Carried\ Onboard} \,/\, \mathit{Fuel\ Consumption\ Rate} \\
&\mathit{Total\ Fuel\ Consumed} = \sum \mathit{Fuel\ Consumption\ Rate}_l * \mathit{Operating\ Time}_l \\
&\quad \forall l, l \in \{\mathit{Mission\ Profile\ Speeds}\}
\end{aligned}$$

7. Fuel Replenishment Requirement Calculation

Fuel replenishment requirements depend on the amount of fuel carried onboard, the rate at which it is consumed, and reserve level dictated. On-station speeds and length of time on station both depend upon the mission profile for which the Littoral Combat Ship is assigned. Once a minimum fuel level is reached, the ship must break from assigned operations in order to replenish its fuel before dropping below the pre-determined fuel reserve. For comparison purposes, this thesis uses both 50% and 20% fuel reserves during the analysis. While fuel tanks aboard Navy ships are normally filled to 95% capacity, the analysis in this thesis uses a 100% capacity since future Littoral Combat Ship fuel tank filling capacity is unknown.

The amount of fuel available is determined by multiplying the fuel carrying capacity by the percent of fuel available for assigned operations, which is calculated by subtracting the fuel reserve from 100%. The total amount of fuel consumed is calculated by summing the products of total operating time and fuel consumption rate for each on-station speed as listed in the mission profile. The number of required fuel replenishments is calculated by dividing the total amount of fuel consumed during a specified mission of a set duration by the amount of fuel carried onboard the ship minus the fuel reserve amount. Maximum time on-station is determined by dividing the mission duration by the number of required fuel replenishments. The fuel capacity depends on the mission profile and how much weight has been allocated to fuel with regard to total deadweight capacity; a tradeoff between the amount of fuel (range) and the amount of modular mission packages and ordnance (payload) carried onboard.

The following formulation is used in estimating the number of required fuel replenishments and maximum time on-station for the Littoral Combat Ship:

$$\begin{array}{l}
\mathit{Amount\ of\ Fuel\ Available\ for\ Use} = \mathit{Fuel\ Carrying\ Capacity} * (100\% - \mathit{Fuel\ Reserve}) \\
\mathit{Number\ of\ Fuel\ Replenishments\ Required} = \\
\qquad \mathit{Total\ Amount\ of\ Fuel\ Consumed} / \mathit{Amount\ of\ Fuel\ Availble\ for\ Use} \\
\mathit{Time\ On} - \mathit{Station} = \mathit{Duration\ of\ Mission} / \mathit{Number\ of\ Fuel\ Replenishments\ Required}_{\mathit{Assigned\ Mission}}
\end{array}$$

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IV. ANALYSIS

In this chapter, the model developed in the previous chapter is used to study the implications of speed, endurance, and payload tradeoffs through an analysis of the impact of speed, displacement and significant wave height on fuel consumption and endurance. In addition, logistics requirements are identified and a discussion of their impact on Littoral Combat Ship operations is provided.

A. FULL DISPLACEMENT ANALYSIS

Table 22 contains the total weight of each modular mission package and its respective percentage of the total modular mission package weight. The total weight of all modular mission packages is listed in bold italics.

Modular Mission Package	Number of Modular Mission Packages	Total Weight (long tons)	Percent of Total Modular Mission Package Weight
MH-60R/S	1	90.2	41.4%
AH-58D	2	26.5	12.2%
Fire Scout VT-UAV	3	16.2	7.4%
RMS	1	33.1	15.2%
SPARTAN USV	1	43.0	19.8%
LMRS	2	8.8	4.0%
TOTAL		***217.8*** [1]	***100%***

Table 22. Modular Mission Package Weights and Percentages

Notes: 1. The total modular mission package weight exceeds both the threshold and objective levels in the Littoral Combat Ship critical design parameters listed in Table 9.

Currently, due to the applicability of the MH-60R/S, Fire Scout VT-UAV and SPARTAN USV to the majority of Littoral Combat Ship missions, there is a desire by some Navy officials to permanently embark one of each of these modular mission packages aboard every Littoral Combat Ship. Considering this accounts for 65.23% of the total weight of all modular mission packages, it seems to significantly reduce the benefit of incorporating the modular concept into the Littoral Combat Ship design and further reduces the amount of weight allocated to carrying additional fuel. Due to this information and the desire to obtain upper bounds on fuel consumption and lower bounds on endurance, all modular mission packages are included in the model when calculating full displacement. As such, changes in full displacement are only achieved by varying the amount of fuel carried onboard. Table 23 lists the two Littoral Combat Ship fuel storage profiles that are used for Littoral Combat Ship endurance analysis.

Weight Component	Displacement at 174,880-liter Carrying Capacity Day Tanks Only (long tons)	Displacement at 281,730-liter Carrying Capacity Day Tanks plus Partial Fill of Long-Range Tanks (long tons)
Fuel	165.0	265.8
Deadweight (Excluding fuel)	231.3	231.3
Modular Mission Packages	217.8	217.8
Light Displacement	956.5	956.5
Full Displacement	1570.6	1671.4

Table 23. Littoral Combat Ship Fuel Storage Profiles

Table 24 contains the estimated weight of each component of the Littoral Combat Ship and the associated light displacement, deadweight and full displacement (listed in bold italics). It includes configurations with and without all modular mission packages installed and uses the fuel profiles listed in Table 23. Without the modular mission packages (the mode in which the Littoral Combat Ship can be expected to transit), the full displacement is 1352.8 long tons. This leaves 318.6 long tons of deadweight for additional fuel, which is not enough to fill the Long-Range tanks capable of holding a total of 370.5 long tons. With all modular mission packages embarked, only 100.8 long tons of deadweight remain for additional fuel, which again is not enough to fill the two long-range tanks. As a result, even though the full displacement included in the first two profiles falls below the Littoral Combat Ship maximum displacement of 1671.4 long tons, the Littoral Combat Ship is unable to use the maximum fuel carrying capacity (both Day and Long-Range Tanks). The third profile includes a Littoral Combat Ship with all modular mission packages embarked and fuel weight of 265.8 long tons. This results in a fuel level of 281,730 liters and full displacement of 1671.4 long tons.

Littoral Combat Ship Component	Weight without Modular Mission Packages and Fuel Capacity of 174,880 liters (long tons)	Weight with all Modular Mission Packages and Fuel Capacity of 174,880 liters (long tons)	Weight with all modular Mission Packages Embarked and Fuel Capacity of 281,730 liters (long tons)
Sea frame	922.3	922.3	922.3
Onboard Systems	34.2	34.2	34.2
Light Displacement	***956.5***	***956.5***	***956.5***
Number of Crew	4.7	4.7	4.7
Number of Embarked Personnel	2.4	2.4	2.4
Crew effects, Fresh Water, Stores and Provisions	142.0	142.0	142.0
Fuel	165.0	165.0	265.8
Lube Oil	0.9	0.9	0.9
Ship's Gear	42.2	42.2	42.2
Ordnance	39.2	39.2	39.2
Modular Mission Packages	0.0	217.8	217.8
Total Deadweight	***396.3***	***614.1***	***714.9***
Full Displacement	***1352.8***	***1570.6***	***1671.4***

Table 24. Littoral Combat Ship Full Displacement

Table 25 demonstrates the impact of fuel weight on the Littoral Combat Ship full displacement both with and without all modular mission systems installed. It shows that when all onboard fuel tanks are filled to maximum capacity, the full displacement of the Littoral Combat Ship exceeds the maximum displacement even when no modular mission packages are embarked. The implication of this is that while the modular design does provide an increase in the amount of fuel that can be carried onboard, the Littoral Combat Ship will be unable to use its maximum fuel carrying capacity regardless of the mission profile because its maximum displacement is only 1671.4 long tons.

Fuel Tanks	Fuel Storage (liters)	Fuel Weight (long tons)	Full Displacement with Modular Mission Packages (long tons)	Full Displacement without Modular Mission Packages (long tons)
Day Tanks	174880	165.0	1592.0	1352.8
Combined Day and Long-Range Tanks	567580	535.5	1962.5	1723.3

Table 25. Impact of Fuel Weight on Full Displacement

B. FUEL CONSUMPTION AND ENDURANCE ANALYSIS

This section analyzes the impact of speed, displacement and significant wave height on fuel consumption and endurance. Since the model uses a fixed displacement and significant wave height for fuel consumption calculations, the displacement and significant wave height parameters are changed individually in order to determine the impact of that individual parameter on overall fuel consumption and endurance.

1. Mission Profiles

In the NWDC Littoral Combat Ship Concept of Operations draft, two potential Littoral Combat Ship mission profiles were originally provided: a 5-day Focused Mission profile and a 21-day Continuous Mission profile. These mission profiles are provided in Table 26 and Table 27 respectively. However, the sprint speed of 55 knots as contained in the Concept of Operations draft was replaced in the model with the JOINT VENTURE maximum speed of 48 knots. Of interesting note is the column containing the percent of time at speed. In the Focused Mission profile, sprint speed is only used 4.17% of the time while in the Continuous Mission profile, sprint speed is used only 0.40% of the time. Since the original Concept of Operations draft, these profiles have been eliminated, although the percent of time when the ships high-speed capability is used argues against the many compromises necessary to achieve this capability.

Focused Mision Profile		5 Days	
Speed (knots)	Op-Time (hours)	Range (nm)	Percent of Time at Speed
10	115	1150	95.83%
48	5	240	4.17%
Totals:	120	1390	

Table 26. 5-Day Littoral Combat Ship Focused Mission Profile

Continuous Mission Profile		21 Days	
Speed (knots)	Op-Time (hours)	Range (nm)	Percent of Time at Speed
8	502	4016	99.60%
48	2	96	0.40%
Totals:	504	4112	

Table 27. 21-Day Littoral Combat Ship Continuous Mission Profile

Table 28 lists an alternate 14-day Littoral Combat Ship mission profile that is created for model analysis.

Analysis Mission Profile				14 Days	
Speed (knots)	Op-Time (hours)	Range (nm)	Fuel Consumed (liters)	Percent of Time at Speed	Percent of Total Fuel Consumed
15	268	4020	483507.24	79.76%	51.29%
27	34	918	132677.75	10.12%	14.07%
40	34	1360	326536.83	10.12%	34.64%
Totals:	336	6298	942,721.82		

Table 28. 14-Day Littoral Combat Ship Analysis Mission Profile

Since the fuel consumption data obtained from the Navy's JOINT VENTURE lessons learned only included a range of speeds from 15 to 40 knots, the selected mission profile speeds are restricted to this range. In addition, the lessons learned stated that speeds between fifteen and seventeen knots obtain the best fuel consumption rates. This information is consistent with the findings of this thesis as Figure 4 demonstrates the impact of speed on range.

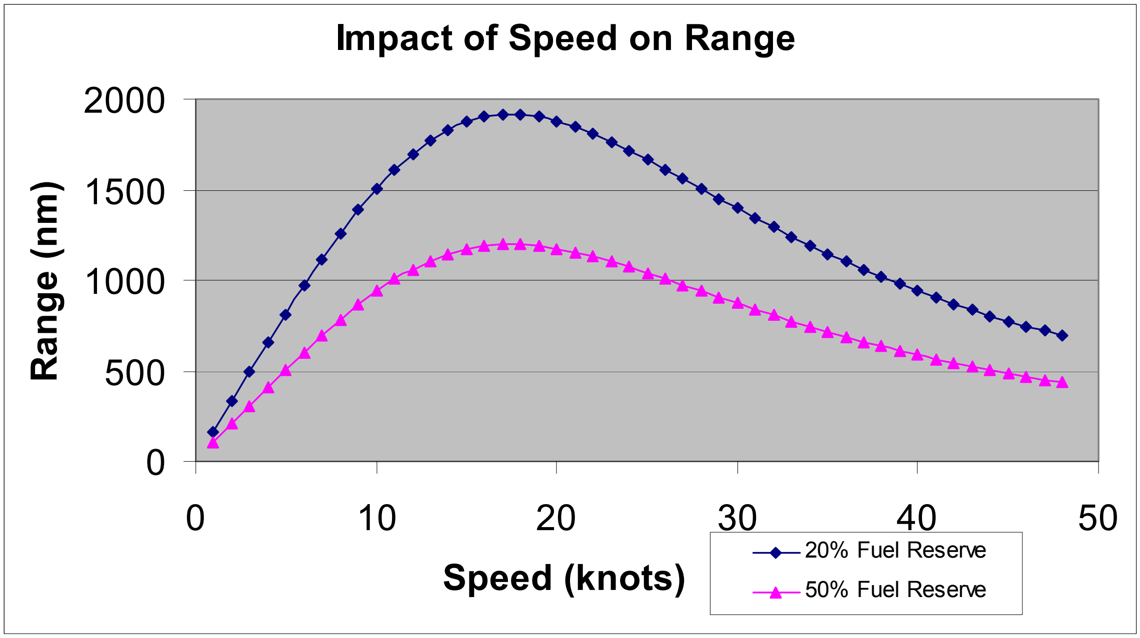

Figure 4. Impact of Speed on Range at 1671.4 long tons Full Displacement, 6-Foot Significant Wave Height and 281,730 liters Fuel Carrying Capacity

As a result, fifteen knots was chosen as the base operating speed as it was estimated the Littoral Combat Ship would operate at these speeds approximately 80% of the time. A moderate speed of twenty-seven knots and a sprint speed of forty knots were estimated operating speeds for approximately 10% of the time each. By comparing the percent of time at and the percent of total fuel consumed for a given speed, one can see the large impact ship speed has on fuel consumption. Even though the Littoral Combat Ship operates at fifteen knots for almost 80% of the time, these operations only account for 51.29% of the fuel consumed while only 10.12% of operating time at forty knots results in 34.64% of total fuel consumed. This is an important finding that is further analyzed later in this chapter.

2. Impact of Significant Wave Height

Significant wave height is a limiting environmental condition that was identified by the Navy during JOINT VENTURE operations as having a considerable impact on ship operations with regard to ship speed, fuel consumption and crew. Table 29 contains the Littoral Combat Ship sea state operating requirements as listed in the Littoral Combat Ship Preliminary Design Interim Requirements Document. (Surface Warfare Directorate, 2003)

Condition	Significant Wave Height (feet)	Requirement
Sea State 5	12.1	Full capability for all systems
Sea State 6	18.0	Continuous efficient operations
Sea State 8 and above	58.1	Best heading survival without serious damage to mission essential subsystems

Table 29. Littoral Combat Ship Sea State Operating Requirements

Beyond sea state 5, the Littoral Combat Ship can expect to encounter considerable restrictions to ship operations as significant wave heights exceed twelve feet. Even though probability distributions have been generated to estimate significant wave heights in various regions of the world, actual significant wave heights can vary greatly. Figures 5, 6 and 7 contain global significant wave heights for September 2, 2002, February 24, 2003 and March 1, 2003 respectively. (Colorado Center for Astrodynamics Research, 2003) Looking at Figures 5 and 7, it can be seen that significant wave heights in various regions of the world differ depending on the season (summer versus winter in these figures). However, comparing Figure 6 and Figure 7 demonstrates that significant wave height can also vary considerably from week to week. It is for this reason that significant waves heights can be a severe limiting factor when it comes to Littoral Combat Ship operations. If a Littoral Combat Ship had been assigned to conduct an independent 2-week mission off the east coast of Japan beginning February 24, 2002, it would have been able to conduct operations as wave heights were only approaching sea state 5. However, by March 1, significant wave heights increased to more than 20 feet. As a result, the assigned mission would have been interrupted and the Littoral Combat Ship would likely have been required to find calmer waters in order to protect mission essential systems and reduce the consequences of the increased sea state on crew effectiveness. Even if probability distributions can be used to predict regional significant wave heights with a fair amount of accuracy, military missions cannot always wait for calm waters. The anticipated inability of the Littoral Combat Ship to effectively operate in water conditions beyond sea state 6 demonstrates it may find itself having difficulties operating in the right place at the right time.

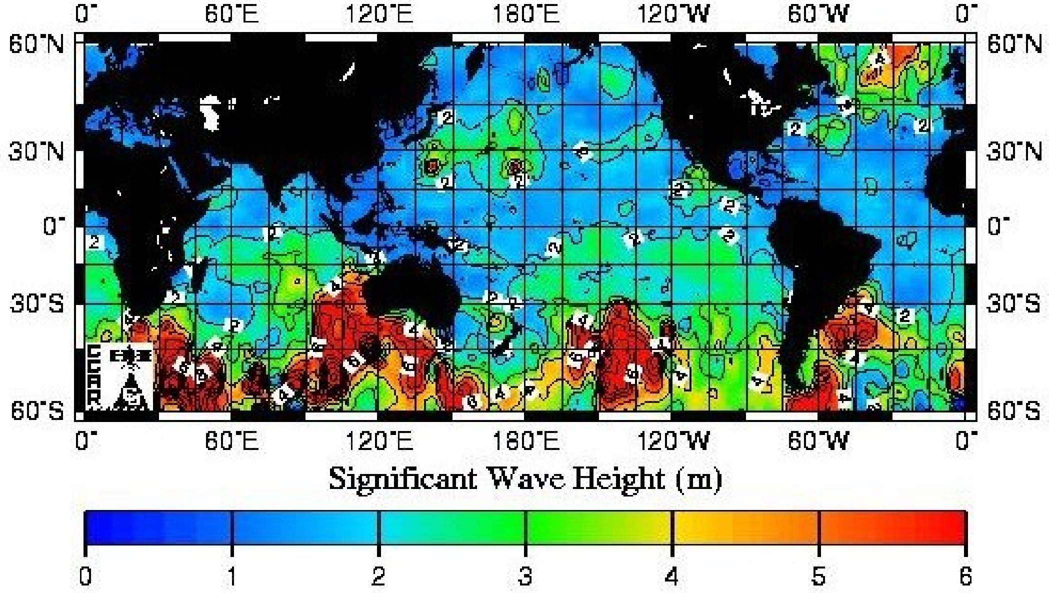

Figure 5. Global Significant Wave Heights for September 2, 2002

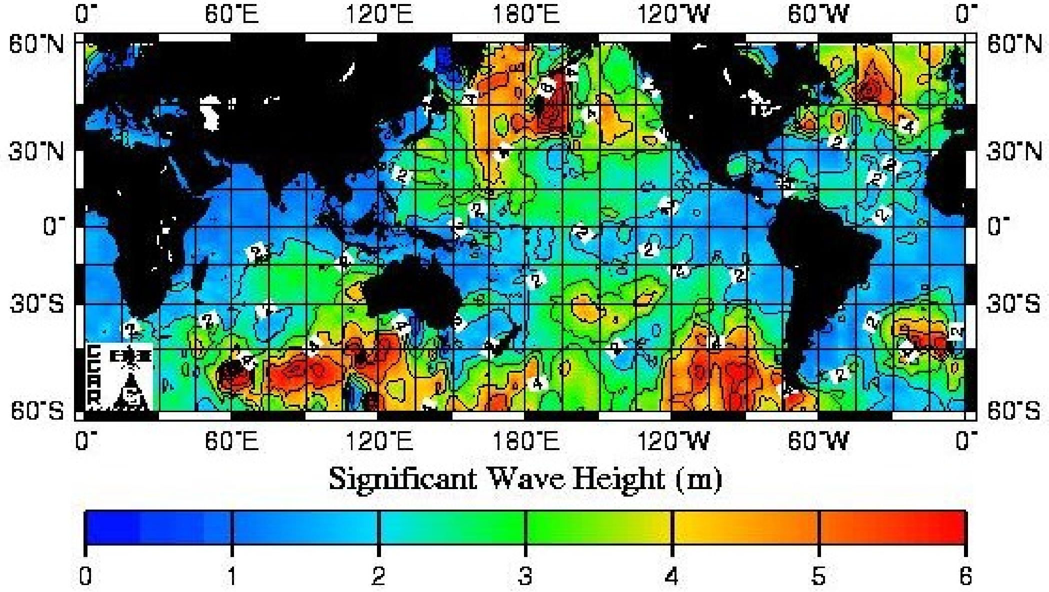

Figure 6. Global Significant Wave Heights for February 24, 2003

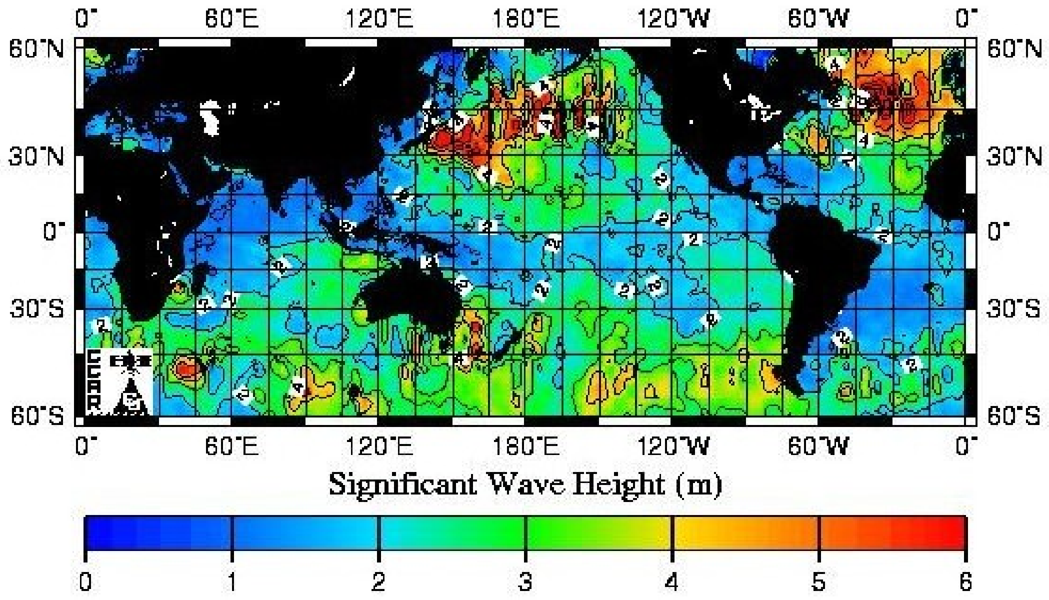

Figure 7. Global Significant Wave Heights for March 1, 2003

In addition to the considerable impact significant wave height has on Littoral Combat Ship operations, it also demonstrates devastating impact on crew effectiveness. Of the twenty-two personnel that were given a questionnaire regarding seasickness during joint Navy and Marine Corps testing of the JOINT VENTURE, 70% of those surveyed experienced dizziness, 65% experienced nausea and 30% actually became seasick. Of those experiencing dizziness, nausea and/or seasickness, 100% of them desired outside visibility and 80% desired weather-deck access in order to ease their symptoms. (Marine Corps Warfighting Laboratory, 2002) While the study did not specify the significant wave height at the time of the survey, it is fair to assume conditions were below sea state 5 since the data range of significant wave height generated during this time for fuel consumption was between 3.5 and 7 feet. Considering the Littoral Combat Ship is expected to operate in wave heights beyond eighteen feet, this is a problem that is certain to have a substantial negative impact on crew effectiveness and endurance.

3. Fuel Consumption Analysis

In order to study the impact of speed on fuel consumption, the model is set with a fixed displacement and significant wave height, and fuel consumption rates are calculated for speeds between one and forty-eight knots. A Littoral Combat Ship with a displacement of 1570.6 long tons (includes all modular mission packages and the use of Day tanks only) is used along with a significant wave height of six feet (the average of the significant wave height data used during regression analysis). Figure 8 demonstrates the relationship between speed and fuel consumption in the Littoral Combat Ship: fuel consumption increases with the cube of speed. The relationship produces a fuel consumption curve typical of diesel engines, which is appropriate considering the JOINT VENTURE is equipped with four Caterpillar Marine Propulsion Diesel engines.

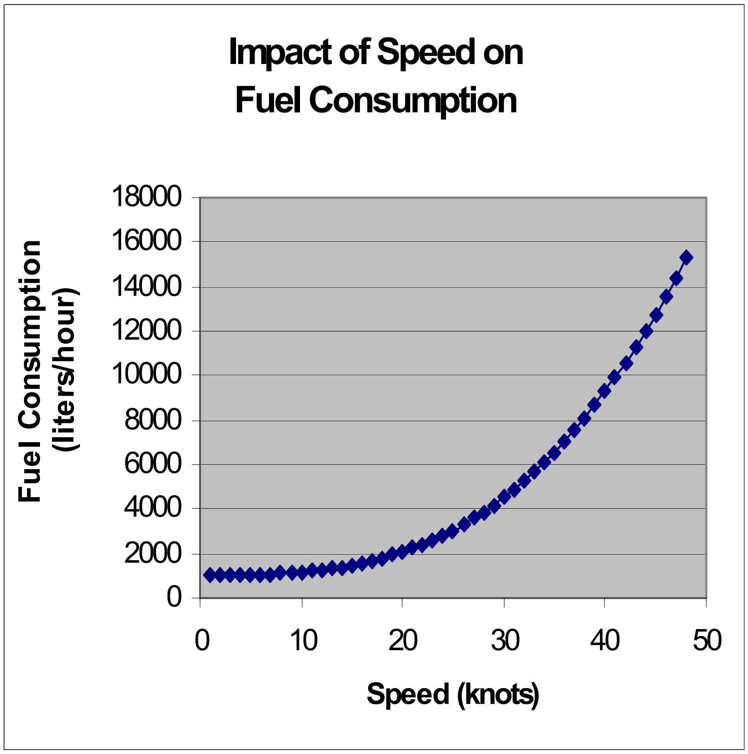

Figure 8. Impact of Speed on Fuel Consumption at 1570.6 long tons Full Displacement and 6-foot Significant Wave Height

To determine the impact of displacement on fuel consumption, a fixed speed of fifteen knots, fixed significant wave height of six feet and varying full displacements are used. Displacements between 1352.8 and 1671.4 long tons are used since the previous full displacement analysis indicated this was the feasible full displacement range for the Littoral Combat Ship. Figure 9 demonstrates the impact of displacement on fuel consumption for the Littoral Combat Ship at an operating speed of fifteen knots (the analysis mission profile base operating speed). Since displacement is a linear term in the fuel consumption equation, increases in displacement result in the same increase in fuel consumption for any given speed. Figure 9 shows that as the displacement of the Littoral Combat Ship is increased from the minimum feasible displacement (1352.8 long tons) to the maximum displacement (1671.4 long tons), fuel consumption increases by 137.73% (from 758.9 to 1804.1 liters per hour).

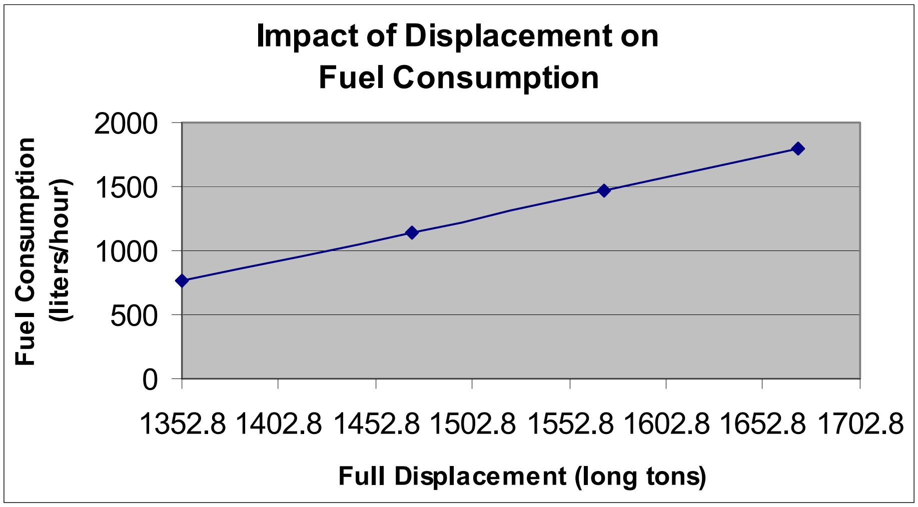

Figure 9. Impact of Displacement on Fuel Consumption at 15 knots and 6-foot Significant Wave Height

Considering the previous discussion to permanently install one MH-60R/S, one Fire Scout VT-UAV and one SPARTAN USV (which combined has a weight of 118.35 long tons), the minimum feasible displacement of the ship increases by 8.77% (1352.8 to 1471.15 long tons) and fuel consumption increases by 51.16% (758.9 to 1147.2 liters per hour). As a result, at fifteen knots and a significant wave height of six feet, a 1% increase in displacement increases fuel consumption by 5.83%. This finding demonstrates the importance of the modular concept with respect to the Littoral Combat Ship.

Since the significant wave height data utilized in the regression only provides a range between 3.5 and 7 feet, the model could not be used to study the impact of sea states 5 and beyond on Littoral Combat Ship operations. However, the analysis is able to conclude that even when operating in wave heights below sea state 5, significant wave height has a substantial impact on fuel consumption. This is determined using the most economical speed of fifteen knots, fixed displacement of 1671.4 long tons (includes all modular mission packages and the maximum fuel carrying capacity) and varying significant wave heights between 3.5 and 7 feet. Figure 10 demonstrates the impact of significant wave height on fuel consumption at fifteen knots.

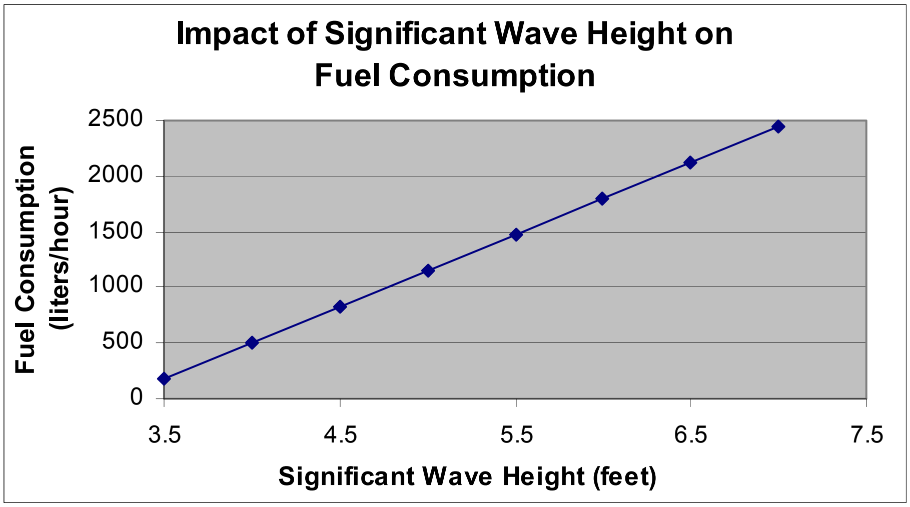

Figure 10. Impact of Significant Wave Height on Fuel Consumption at 15 knots and 1671.4 long tons Full Displacement

As in the previous case with displacement, since significant wave height is a linear term in the fuel consumption equation, increases in significant wave height result in the same increase in fuel consumption for any given speed. Figure 10 shows that as the significant wave height increases from 3.5 to 7 feet (a 100% increase in significant wave height), fuel consumption increases by 1220.69% (from 185.6 to 2451.53 liters per hour). As a result, at fifteen knots and a full displacement of 1671.4 long tons, a 1% increase in significant wave height increases fuel consumption by 12.2%. This finding demonstrates that even though the Littoral Combat Ship will be able to operate in conditions up to sea state 7, the amount of fuel required during these operations increases quickly as significant wave height increases.

4. Endurance Analysis

The impact of speed on endurance is analyzed by first determining the endurance for a Littoral Combat Ship with all modular mission packages installed (full displacement of 1570.6 long tons) and a minimum fuel storage capacity (use of Day tanks only). Then, the Littoral Combat Ship is modified by increasing the amount of fuel stored until the maximum displacement is attained (increase in full displacement from 1570.6 to 1671.4 long tons). This results in a maximum fuel carrying capacity of 281,730 liters. In both scenarios, significant wave height is held constant at six feet. Figure 11 demonstrates the impact of speed on Littoral Combat Ship endurance.

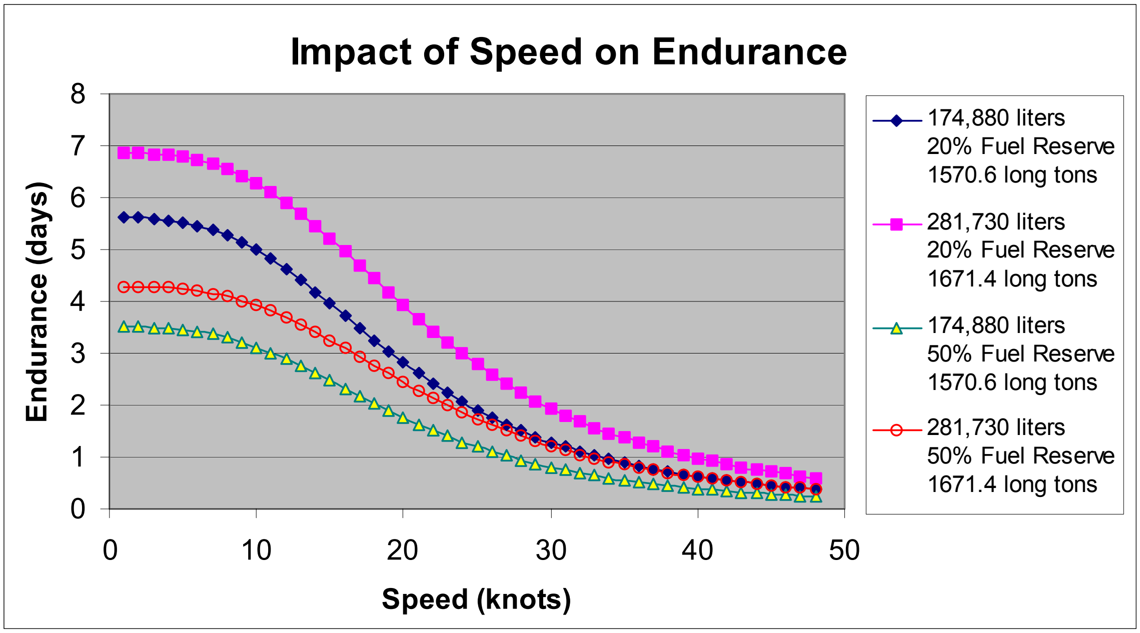

Figure 11. Impact of Speed on Littoral Combat Ship Endurance at 6-foot Significant Wave Height

Currently, Navy ships utilize a 50% fuel reserve, however, the Navy's JOINT VENTURE lessons learned discusses the penalty paid in fuel economy for carrying excess fuel (this further validates the previous discussion with regard to the relationship between displacement and fuel consumption). As a result, it is recommended that only the fuel required for the mission at hand should be carried unless readiness to meet contingencies dictates otherwise. (Beierl, 2002) Considering this penalty and the use of a 20 percent fuel reserve during JOINT VENTURE maximum range testing, fuel reserve levels of both 20% (top two curves) and 50% (bottom two curves) are used in the analysis. As fuel is consumed, the weight of fuel decreases and as a result, full displacement and fuel consumption decrease as well. By utilizing a 20% vice 50% fuel reserve, the Littoral Combat Ship is able to capitalize on this relationship.

At all speeds, increasing the fuel reserve from 20% to 50% results in a 60% decrease in endurance. However, the same relationship does not hold for increases in fuel carrying capacity. At the base operating speed of fifteen knots, increasing the fuel carrying capacity from 174,880 to 281,730 liters results in an increase of endurance by

31.67%. At a sprint speed of forty knots, the same increase in fuel carrying capacity results in an increase of endurance by 55.57%. This shows that as speed increases, increasing the fuel carrying capacity provides a greater impact on endurance. Figure 11 reveals the two most important findings. *Regardless of the fuel reserve or fuel carrying capacity, the maximum endurance achieved for a Littoral Combat Ship outfitted with all modular mission packages is less than seven days. In addition, when the Littoral Combat Ship is outfitted with all modular mission packages and operated continuously at its maximum speed of forty-eight knots, the maximum achieved endurance is only 14.4 hours. While this endurance is achieved utilizing a 20% fuel reserve and maximum fuel carrying capacity, increasing the fuel reserve to 50% and restricting the fuel carrying capacity to Day tanks results in a maximum endurance of only 4.8 hours.* These findings demonstrate the considerable impact ship speed has on Littoral Combat Ship endurance.

Figure 12 illustrates the impact of displacement on endurance. It is based on the speeds and operating times included in the 14-day mission profile (Table 28) and uses a fixed significant wave height of 6 feet and a maximum fuel carrying capacity. As displacement increases, endurance decreases. However, once again the critical finding is that the maximum obtainable time on-station is only a little more than 5 days (less than 40% of the desired 14-day mission requirement) using a 20% fuel reserve. The implication of this is that the Littoral Combat Ship would require at least two fuel replenishments if it was going to complete the assigned 14-day mission. If the Littoral Combat Ship was required to maintain a 50% fuel reserve, the maximum obtainable endurance would be just over 3 days (less than 25% of the desired 14-day mission requirement), and the Littoral Combat Ship would require at least four fuel replenishments in order to complete its assigned mission.

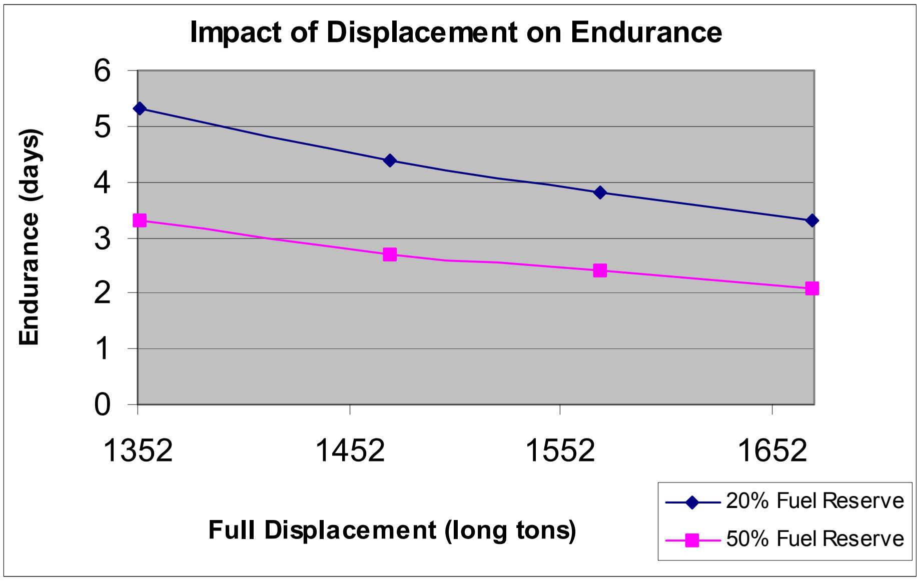

Figure 12. Impact of Displacement on Endurance at a 6-foot Significant Wave Height and Maximum Fuel Carrying Capacity of 281,730-liters

Figure 13 illustrates the impact of significant wave height on endurance. It is based on the speeds and operating times included in the 14-day mission profile (Table 28) and utilizes a fixed displacement of 1671.4 long tons and a maximum fuel carrying capacity. As with displacement, when significant wave height increases, endurance decreases. With a significant wave height of 3.5 feet and a fuel reserve of 20%, the Littoral Combat Ship is able to achieve an endurance of only eight days and is required to receive one fuel replenishment in order to complete the 14-day mission. By switching to a 50% fuel reserve, the endurance drops to approximately five days, thereby increasing the number of required fuel replenishments to two. As seen earlier with the impact of speed on endurance, as significant wave height increases, the 20% and 50% fuel reserve curves begin to converge. This demonstrates the considerable impact significant wave height has on Littoral Combat Ship endurance.

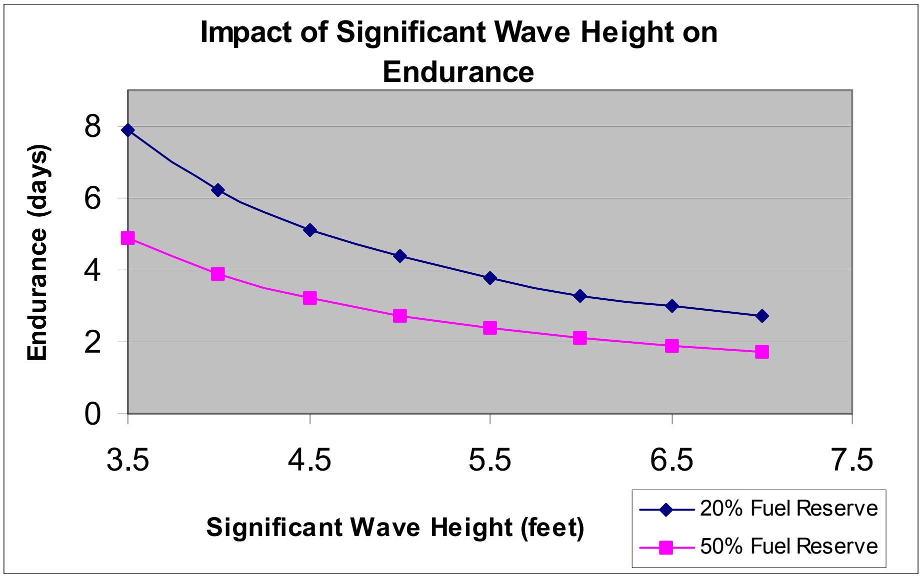

Figure 13. Impact of Significant Wave Height on Endurance at 1671.4 long tons Full Displacement and Maximum Fuel Carrying Capacity of 281,730-liters

C. IMPLICATION ON LITTORAL COMBAT SHIP LOGISTICS

In order for the Littoral Combat Ship to be an effective asset, it must not only possess the endurance necessary to keep pressure on the enemy without having to disengage often for replenishment, but it must also possess adequate sea keeping characteristics to permit open-ocean transits and extended operations in the world's littorals. Throughout the analysis, it is shown that increases in speed, displacement and significant wave height all result in a considerable increase to fuel consumption and severely limit Littoral Combat Ship endurance. As seen when using the 14-day mission profile, the Littoral Combat Ship requires at least one fuel replenishment in order to complete its assigned two-week mission. In order to receive the required replenishments, the Littoral Combat Ship must transit to a Combat Logistics Force ship off-station. Even though the Navy does not officially define the extent of the littorals by an actual distance from shore, the littorals can be defined as the waterways within 100 miles of the coastline. (Boeing, 2003) Typically, Combat Logistics Force ships operate outside the littorals near high-value, blue water assets. As a result, the Littoral Combat Ship would be required to leave its assigned operating area and transit at least 100 miles to the Combat Logistics Force ship in order to rendezvous for the required refueling at sea. Assuming the Littoral Combat Ship utilizes its base operating speed of fifteen knots during the transit and the Combat Logistics Force ship operates at a safe distance of 150 nautical miles from the shore, it would take the Littoral Combat Ship ten hours to transit each way. Including an estimated two hours for the actual replenishment, total off-station time for the Littoral Combat ship would be 22 hours (6.5% of the total 14-day assigned mission). Table 30 demonstrates the relationship between Littoral Combat Ship replenishment requirements and time off-station.

Number of Replenishments Required	Total Time Off-Station (days)	Percent of Time Off-Station During 14-Day Mission
1	0.92	6.5%
2	1.83	13.1%
3	2.75	19.6%
4	3.67	26.2%
5	4.58	32.7%

Table 30. Relationship Between Replenishment Requirements and Time Off-Station

Not only does the requirement for replenishments decrease time on-station and availability of the Littoral Combat Ship, it places an increased strain on an already over burdened Combat Logistics Support force. Since the critical design parameters require that the Littoral Combat Ship be able to conduct both conventional and vertical replenishment, the Littoral Combat Ship will rely on the Combat Logistics Force for the necessary logistics support. The deployment of Naval forces in support of OPERATION ENDURING FREEDOM resulted in significant increases in Combat Logistics Force requirements. Increases in Fifth Fleet requirements, which were substantial to begin with, were so dramatic that Seventh Fleet and Third Fleet were both required to provide additional Combat Logistics Force ships in order to satisfy the high demand within the Fifth Fleet operating area. (Haynes, 2002) The situation has become so drastic that some ships have been denied Combat Logistics Force support. As a result, the ships have been forced into port in order to refuel. Not only does this increase costs, it also places an added security risk considering the in-port attack on the USS COLE. Additionally, Combat Logistics Force ships do not receive maintenance while in Fifth Fleet. The negative impact of this has already been demonstrated as the USNS PECOS post-deployment maintenance put her out of service for several months. (Haynes, 2002) The addition of a fleet of Littoral Combat Ships that will potentially require frequent replenishment is only going to make the Combat Logistics Force problem worse.

D. ADDITIONAL LOGISTICS CONSIDERATIONS

Even though reconfiguration is not studied in this thesis, modular mission capability, which is the cornerstone of the Littoral Combat Ship design (Katz and Mustin, 2003), has already been identified as the biggest challenge. The critical design parameter for reconfiguration requires that the Littoral Combat Ship must be able to complete reconfiguration within four days and establishes a reconfiguration goal of only one day. This is ambitious considering the capability currently does not exist at sea. While the handling and stowage of modular mission packages in port would not be a problem, completing reconfiguration at sea would be a much greater challenge as it requires good sea keeping. Considering the previous discussion and illustrations regarding the impact of significant wave height on Littoral Combat Ship operations, it is clear the Littoral Combat Ship will not always have the benefit of calm seas to reconfigure modular mission packages when required. Even if reconfiguration is achievable at sea, the logistics required for reconfiguration is complex. Questions such as where will the modular mission packages be stored and how will they be transported and transferred to the Littoral Combat Ship remain unanswered. If for any reason the Littoral Combat Ship is unable to reconfigure for a specific mission while at sea, it would be required to leave its assigned operating area and find a port or shipyard-like environment in which it can be reconfigured. This not only places an additional strain on Littoral Combat Ship logistics but also increases time off-station.

In Chapter I, endurance was defined as the ability to sustain a ship's mission. While for analysis purposes this thesis calculates endurance only using speed and fuel consumption rates, in reality it is also measured by ordnance delivery rates and crew effectiveness. The amount of ordnance consumed depends upon the assigned Littoral Combat Ship mission, the frequency in which ordnance is required to support the mission, and the rate at which it is delivered. While a Littoral Combat Ship conducting a Continuous Mission would most likely have little need for ordnance, one conducting littoral Mine Warfare or Anti-Surface Warfare would, of course, have an ordnance requirement. Just as ship speed, displacement, and significant wave height impacts endurance, the same holds true for ordnance. As the delivery rate of ordnance increases, the need for replenishment increases as well, thereby potentially further reducing Littoral Combat Ship time on-station.

Crew effectiveness has just as much, if not more, impact on endurance as fuel and ordnance. While earlier discussion of dizziness, nausea and seasickness aboard JOINT VENTURE demonstrates the severe negative impact crew effectiveness has on endurance, logistics factors such as fresh water, provisions, stores and laundry also have a major impact on crew effectiveness. While current advances in technology have helped ease the potential negative impact these logistics factors have on crew effectiveness, they cannot be forgotten as they play an important part in crew morale.

The final, and perhaps most important, questions that need to be addressed are where does the Littoral Combat Ship originate from and where does it go back to at the conclusion of its mission. While the Littoral Combat Ship will be required to possess a blue-water transit capability, operations are designed for missions of fixed duration inside the littorals. Discussions of 5-day, 14-day and 21-day mission profiles are provided, however, there has been no indication as to where the Littoral Combat Ship will transit to between missions. While the shallow draft increases the number of ports available for the Littoral Combat Ship to operate out of, they may or may not be friendly. Not only is this an important issue with regard to reconfigurability, it also plays an important role with regard to logistics support and crew effectiveness. While it should be noted that one of the proposed missions of the Littoral Combat Ship is Logistics Support, a Littoral Combat Ship configured for a logistics mission still has the same operating constraints with respect to fuel consumption and endurance as one those studied in this thesis. Without a designated port to base out of, the Littoral Combat Ship endurance problem can only get worse.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

"For the 29-year period ending 1999, almost 60 percent of the missions conducted by ships were mobility related missions." (Navy Warfare Development Command, 2003) These continuous missions, all of which are listed as potential future Littoral Combat Ship requirements, typically require a platform with long endurance, high speed, considerable payload capacity, and excellent sea keeping. Just as the ASHEVILLE, PEGASUS and CYCLONE class ships were constrained in their operations due to low endurance and limited capability, the output from the Littoral Combat Ship model yields similar problems.

The thesis demonstrates that speed, displacement, and significant wave height all result in considerable increases in fuel consumption, and as a result, severely limit Littoral Combat Ship endurance. When operating in a significant wave height of six feet, regardless of the amount of fuel carried, the maximum endurance achieved for a Littoral Combat Ship outfitted with all modular mission packages is less than seven days. Especially noteworthy is that when restricted to a fuel reserve of 50% and a fuel carrying capacity of Day tanks, the maximum achieved endurance is only 4.8 hours when operating at a maximum speed of 48 knots. Refueling, and potentially rearming, will require the Littoral Combat Ship to leave littoral waters and transit to Combat Logistics Force ships operating outside the littorals for replenishment. Given the low endurance of the Littoral Combat Ship, its time on station is seriously compromised. This not only limits the Littoral Combat Ship's ability to conduct independent operations, but restricts interdependent operations as part of a littoral operations force and integrated operations with Carrier and Expeditionary Strike Groups as well.

Significant wave height not only has a considerable negative impact on fuel consumption and endurance, but also has the potential for devastating impact on Littoral Combat Ship operations and crew effectiveness. The anticipated inability of the Littoral Combat Ship to effectively operate in ocean conditions beyond sea state 6 coupled with the real possibility of experiencing sea states 7 and beyond demonstrates the potential for the Littoral Combat Ship to be forced to either delay or abandon assigned missions. With regard to crew effectiveness, of the twenty-two personnel that were given a questionnaire regarding seasickness during joint Navy and Marine Corps testing of the JOINT VENTURE, 70% of those surveyed experienced dizziness, 65% experienced nausea and 30% actually became seasick when operating in sea state 4 and below.

The Littoral Combat Ship can achieve high speeds; however, this can only be accomplished at the expense of range and payload capacity. The requirement for the Littoral Combat Ship to go fast (forty-eight knots) requires a seaframe with heavy propulsion systems. The weight of the seaframe, required shipboard systems (weapons, sensors, command and control, and self-defense) and modular mission packages accounts for 84% of the full displacement, and as a result, substantially limits total fuel carrying capacity. Since initial mission profiles required the high-speed capability at most five percent of the time, the end result is a Littoral Combat Ship that has very little endurance and a high-speed capability it will rarely use. The pursuit for high speed itself demonstrates an inherent bias toward the attribute of speed and the neglect of range and payload requirements. Regardless of which hull form is selected for the Littoral Combat Ship, this thesis demonstrates the price that must be paid for speed as the tradeoffs between speed, endurance, and payload, in general, apply to any ship design.

B. RECOMMENDATIONS

As this thesis concludes a Littoral Combat Ship similar in size to the JOINT VENTURE would not have the endurance necessary to effectively operate in the littorals, it would appear the only plausible recommendations would be to either relax the high-speed requirement or increase the size of the Littoral Combat Ship. Recently, Norman Polmar, author of *Ships and Aircraft of the U.S. Fleet*, wrote about the Navy's current Littoral Combat Ship program. Comparing the efforts to the Israeli 1,275-ton Sa'ar V-class corvette and the German 1,690-ton Type 130 corvette (which is currently under construction), he states the Navy will likely opt for a larger and more expensive Littoral Combat Ship. Despite the plans to utilize a modular design, he believes the Navy's desire for larger, multipurpose ships will result in the proposal of a large (frigate size) Littoral Combat Ship. (Polmar, 2002) According to the Navy's latest documentation, he appears to be correct, as the Littoral Combat Ship is no longer being pursued as a small ship, rather one that weighs approximately 3,000 tons. (Stewart, 2003) Whereas the proposed increase in size of the Littoral Combat Ship indicates the Navy has learned something from the previous small, high-speed ship programs, it does not absolve the Navy of the requirement to balance the tradeoffs between speed, endurance, and payload.

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APPENDIX A: SEA STATE MATRIX

Sea State	Significant Wave Height (meters)	Significant Wave Height (feet)
0	0.0	0.0
1	0.3	1.0
2	0.9	3.0
3	1.4	4.6
4	2.1	6.9
5	3.7	12.1
6	5.5	18.0
7	12.2	40.0
8	17.7	58.1
9	> 39.0	> 128.0

Note: Data obtained from the Preliminary Design Interim Requirements Document N763F-S03-026, Littoral Combat Ship (LCS) Flight 0 Pre ACAT (Surface Warfare Directorate, 2003)

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