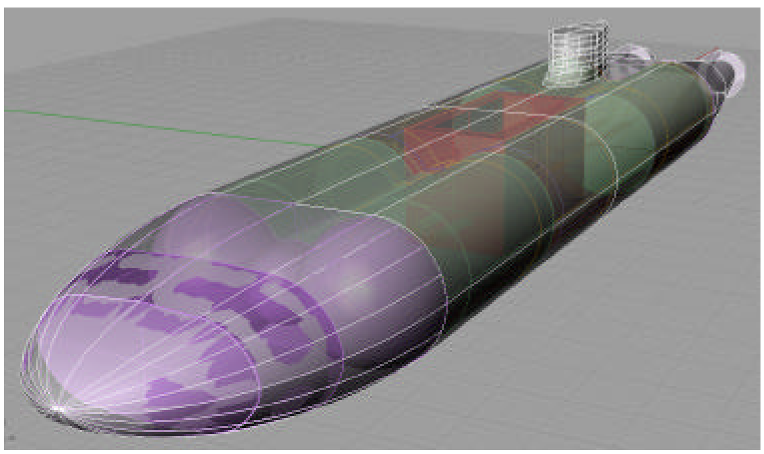
Design Report

Littoral Warfare Submarine (SSLW)

VT Total Ship Systems Engineering



Virginia Tech Ocean Engineering
AOE 4065/4066
Fall 2004 – Spring 2005
Team SCRAP

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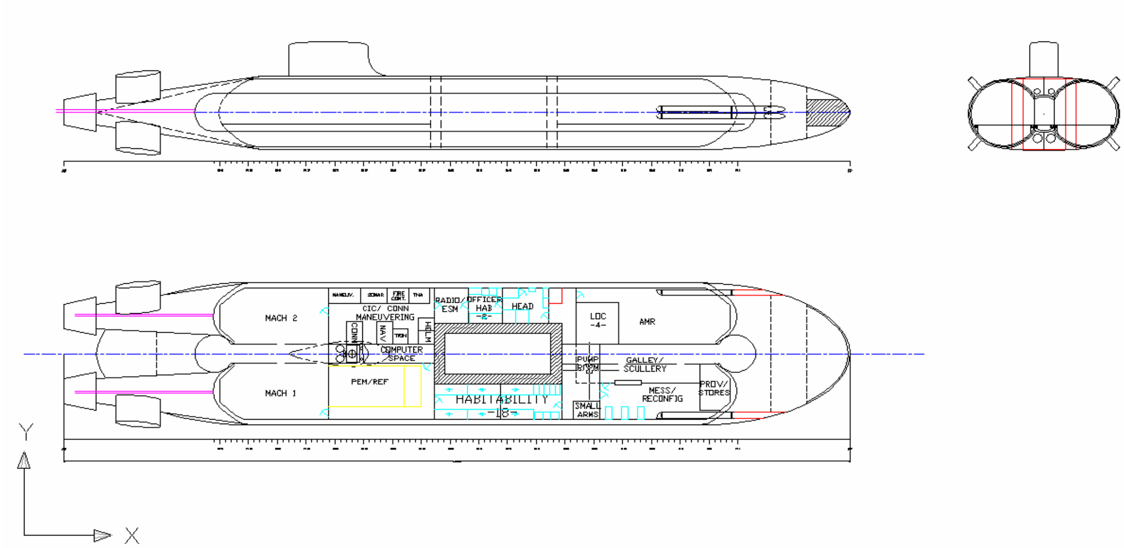
Executive Summary



This report describes the Concept Exploration and Development of a Littoral Warfare Submarine (SSLW) for the United States Navy. This concept design was completed in a two-semester ship design course at Virginia Tech.

The SSLW requirement is based on the need for a small, maneuverable vehicle to support special warfare operations. A shallow water submarine allows the possibility of covert insertion and extraction of these forces, as well as reconnaissance to support their operations and other theater operations. An Acquisition Decision Memorandum was produced specifying small size, high maneuverability, a non-nuclear air-independent propulsion system, and the need to operate from a mother ship or sea-base concept.

Concept Exploration trade-off studies and design space exploration are accomplished using a Multi-Objective Genetic Optimization (MOGO) after significant technology research and definition. Objective attributes for this optimization are cost, risk (technology, cost, schedule and performance) and military effectiveness. The product of this optimization is a series of cost-risk-effectiveness frontiers which are used to select alternative designs and define Operational Requirements (ORD1) based on the customer's preference for cost, risk and effectiveness.

SSLW Design 38, presented here, achieves a high level of effectiveness while maintaining a medium level of risk by using a cutting-edge propulsion system with extremely reliable and low-risk lead-acid batteries. The fuel cell propulsion system along with a reformer allows for extremely quiet operation completely independent of an external air source. The catamaran design gives a large deck area and features a small molded depth well-suited for littoral waters. The boat's covert features allow it to slip in and out of enemy waters undetected, yet it retains the ability to strike enemy naval targets if the need arises.

Concept Development included hull form development, structural finite element analysis, propulsion and power system development and arrangement, general arrangements, machinery arrangements, combat system definition and arrangement, cost and producibility analysis and risk analysis. The final concept design satisfies critical operational requirements in the ORD within cost and risk constraints with additional work required to ensure a good balance between weight and volume, evaluate static and dynamic stability and seakeeping, and finalize overall structural design.

Ship Characteristic	Value
LOA	147 ft
Beam	28 ft
Depth	13 ft
Submerged Displacement	1430 lton
Sustained Speed	20 knots
Endurance Speed	6 knots
Sprint Range	40 nm
Endurance Range	2590 nm
Diving Depth	290 ft
Propulsion and Power	250kW PEM Fuel Cell w/ reformer, lead-acid batteries, 2 AC motors, and IPS system
BHP	250 kW
Personnel	9 enlisted, 3 officer, 8 special forces/mission technician
OMOE (Effectiveness)	0.716
OMOR (Risk)	0.444
Ship Acquisition Cost	$369M
Combat Systems (Modular and Core)	4x inboard torpedo tubes, 6x external encapsulated torpedoes, 4x countermeasure launchers, passive, active, and mine avoidance sonar, four man lockout trunk, 2x Zodiac RHIB, accommodations for 1 special warfare unit, degaussing system, and 1 8x8x20ft. Payload Interface Module (PIM)

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1 Introduction, Design Process and Plan

1.1 Introduction

This report describes the concept exploration and development of a Littoral Warfare Submarine (SSLW) for the United States Navy. The SSLW requirement is based on the SSLW Mission Need Statement (MNS), and Virginia Tech SSLW Acquisition Decision Memorandum (ADM), Appendix A and Appendix B. This concept design was completed in a two-semester ship design course at Virginia Tech. SSLW must perform the following missions:

- Covert insertion, extraction, and support of U.S. Special Forces
- Covert intelligence gathering (electronic, human, and visual)
- Covert, precision mine countermeasures and mine warfare
- Support autonomous and remotely operated land, air, and sea vehicles (multiple, flexible mission packages)

The SSLW design is driven by several key constraints:

- Extended endurance
- Low cost
- Low manning
- Highly producible, minimum time for concept-to-delivery
- Platforms must operate within current logistics support capabilities
- Non-nuclear or innovative small nuclear

SSLW will be able to operate independently for extended time periods while performing multiple mission tasks. It will be capable of deploying U.S. Special Forces deep within coastal waters and performing ISR and Mine/Anti-Mine operations. It must depend on passive stealth to slip away through enemy restricted waters without detection.

SSLW will operate from a mother ship, and deploy into restrictive littoral regions. It will utilize passive stealth qualities, relatively small size, and high maneuverability to routinely operate closer to enemy shores than previous US submarines. This will allow SSLW to deploy Special Forces closer to shore, limit their exposure to cold water, provide an offshore base and avoid possible detection. The SSLW will also perform harbor penetration missions to gain detailed ISR and perform MCM. UUVs will extend the SSLW mission capabilities to obtain more detailed ISR and perform limited mine hunting operations.

SSLW will have a minimum endurance range of 1000 nm at 10 knots, a minimum sustained (sprint) speed of 15 knots, a minimum sprint range of 25 nm, a minimum operating depth of 250 feet, and a service life of 30 years. It shall be completely air-independent. It is expected that 10 ships of this type will be built with IOC in 2015. Average follow-ship acquisition cost shall not exceed $500M. Manning shall not exceed 35 personnel.

1.2 Design Philosophy, Process, and Plan

The traditional approach to ship design is largely an 'ad hoc' process. Experience, design lanes, rules of thumb, preference, and imagination guide selection of design concepts for assessment. Often, objective attributes are not adequately synthesized or presented to support efficient and effective decisions. This project uses a total system approach for the design process, including a structured search of the design space based on the multi-objective consideration of effectiveness, cost and risk.

The scope of this project includes the first two phases in the ship design process, Concept Exploration and Concept Development, as illustrated in Figure 1. Also in Figure 1, note how the Concept Exploration and Development stages follow the US Navy acquisition process. The concept exploration process is shown in Figure 2. The process begins with the identification of a mission need and general requirements. Other steps in the process include developing models for ship synthesis, risk, effectiveness, and cost to quantitatively balance and compare different designs. This comparison is carried out using variable screening and optimization. An acquisition decision selects preferred alternatives from these designs. The products of this process are a preliminary Operational Requirements Document (ORD1) that specifies performance and cost requirements, a baseline concept design, and a selection of preferred technologies.

In Concept Exploration (Figure 2), a multiple-objective design optimization is used to search the design space and perform trade-offs. SSLW Concept Exploration considers various combinations of hull form, propulsion systems, combat systems and automation within the design space using mission effectiveness, risk and acquisition cost as objective attributes. A ship synthesis model is used to balance these parameters in total ship designs, to assess feasibility and to calculate cost, risk and effectiveness. The final design combinations are ranked by cost, risk and effectiveness, and presented as a series of non-dominated frontiers. A non-dominated frontier (NDF) represents ship designs in the design space that have the highest effectiveness for a given cost and risk. Concepts for further study and development are chosen from this frontier.

Figure 3 shows the more traditional design spiral process followed in Concept Development for this project. A complete circuit around the design spiral at this stage is frequently called a Feasibility Study. It investigates each step in the traditional design spiral at a level of detail necessary to demonstrate that assumptions and results obtained in concept exploration are not only balanced, but feasible. In the process, a second layer of detail is added to the design and risk is reduced. Notice that each step is not independently performed, but rather involves a large amount of collaboration among the other steps in order to evaluate effects of the design steps on other design aspects.

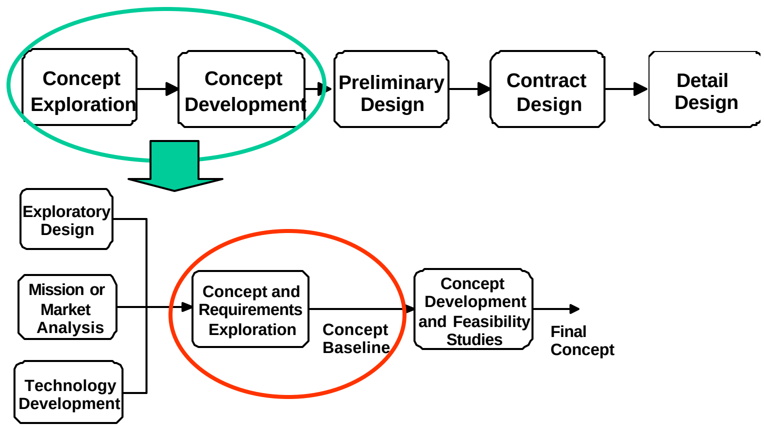

Figure 1 – Ship Design Process

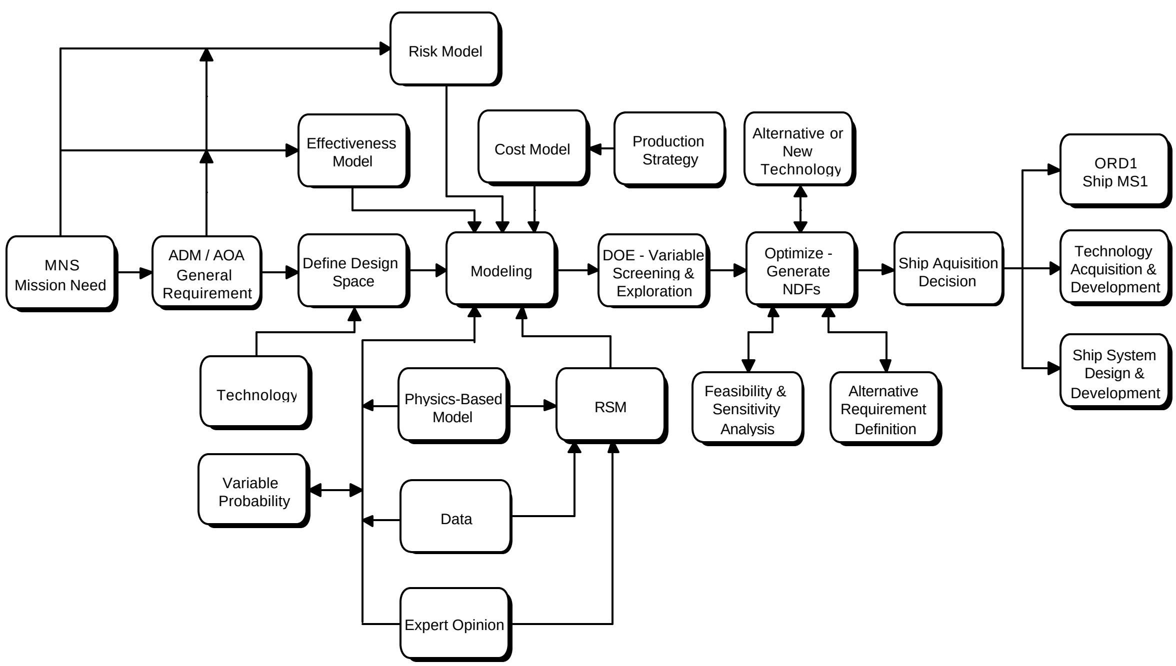

Figure 2 – Concept Exploration Process

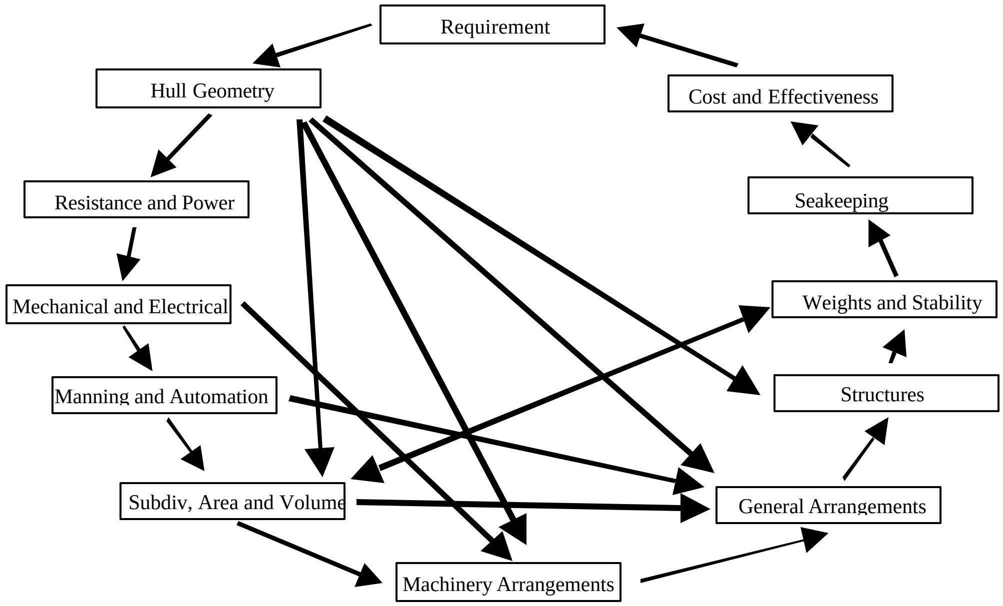

Figure 3

1.3 Work Breakdown

SSLW Team SCRAP consists of six students from Virginia Tech. Each student is assigned areas of work according to his or her interests and special skills as listed in Table 1. Most team members worked on many areas of the design, and very few design aspects were achieved by one student alone.

Table 1 - Work Breakdown

Name	Specialization
Justin Chin	Machinery Arrangements, Electrical System
Davy Hansch	Structures, Weights
Nate Lambeth	Writer, Stability, Maneuvering and Control, Seakeeping, OMOE/OMOR
Chris Michie	Resistance and Propulsion, Powering
Dave Owens	Hullform, General Arrangements, Balance
Solomon Whalen	Modeling, General Arrangements, Machinery Arrangements

1.4 Resources

Computational and modeling tools used in this project are listed in Table 2.

Table 2 - Tools

Analysis	Software Package
Arrangement Drawings	AutoCAD/Rhino
Hull form Development	AutoCAD/Rhino
Hydrostatics	Rhino
Resistance/Power	MathCAD
Ship Motions	GEORGE
Ship Synthesis Model	MathCad/Model Center
Structure Model	MAESTRO

2 Mission Definition

The SSLW requirement is based on the SSLW Mission Need Statement (MNS), and Virginia Tech SSLW Acquisition Decision Memorandum (ADM), Appendix A and Appendix B with elaboration and darification obtained by discussion and correspondence with the customer, and reference to pertinent documents and web sites referenced in the following sections.

2.1 Concept of Operations

SSLW will operate from either a mother submarine or surface ship, requiring complete support until the time of launch for the mission. The platform will be forward deployed and able to operate independently for extended periods of time using multiple, flexible mission packages, autonomous systems and minimal crew. It will be capable of operating as a first strike platform, entering restricted waters and littoral areas undetected, carrying U.S. Special Forces with minimal exposure and deploying them deep within coastal waters. SSLW can serve as an off-shore base for the duration of the mission, performing ISR operations and gathering information in the interim. It must depend on passive stealth to slip away through enemy restricted waters without detection.

2.2 Projected Operational Environment (POE) and Threat

SSLW will operate in shallow coastal waters and must face all accompanying threats. A hostile littoral environment would present threats ranging from enemy diesel-electric submarines to surface ships or air assets with sonar, sonar buoys, and torpedoes to mines. The sub must be stealthy and flexible enough to identify and evade any threat that presents itself.

2.3 Specific Operations and Missions

SSLW mission components will include airborne littoral data collection, submerged littoral ISRT data collection, collecting intelligence on vessel movements, delivery and support of Special Forces, forward destruction/disruption of enemy subs and small boats, and mine reconnaissance, clearing, and laying. The platform must be flexible in order to perform any number of mission components or variations on them.

2.4 Mission Scenarios

Mission scenarios for the primary SSLW missions are provided in Table 3.

Table 3 - Sample Mission

Day	Mission scenario
1-3	Transit with host ship to forward deployment area
4-5	Configure mission packages, embark Special Forces
6	Transit to combat deployment area, deploy Special Forces
7-17	Conduct ISR and MCM operations, provide logistic and intelligence support to other units
18	Embark Special Forces, transit to re-supply area
19-21	Reconfigure mission packages, re-supply, disembark Special Forces
22	Transit to mission area
23-33	Conduct mine-laying and ECCM operations, provide intelligence support to other units
34	Transit to re-supply area
35-36	Reconfigure mission packages, embark mission specialist(s)
37-45	Conduct search and rescue and salvage operations
46-47	Rendezvous with salvage ship, deliver recovered payload
48	Transit to re-supply area

2.5 Required Operational Capabilities

In order to support the missions and mission scenarios described in Section 2.4, the capabilities listed in **Error! Reference source not found.** are required. Each of these can be related to functional capabilities required in the ship design, and, if within the scope of the Concept Exploration design space, the ship's ability to perform these functional capabilities is measured by explicit Measures of Performance (MOPs).

Table 4 - Required Operational Capabilities

ROC	Description
ASW 1	Engage submarines (defensively)
ASW 1.3	Engage submarines at close range
ASW 7.6	Engage submarines with torpedoes
ASW 7.8	Engage submarines with missiles
ASW 10	Disengage, evade, and avoid submarine attack by employing countermeasures and evasion techniques
ASU 1	Engage surface threats with missiles or torpedoes
ASU 4.2	Detect and track a surface target with SONAR
ASU 6	Disengage, evade, and avoid surface attack
MIW 1	Conduct mine hunting
MIW 2	Conduct mine sweeping
MIW 3	Conduct magnetic silencing (degaussing, deperming, etc.)
MIW 4	Conduct mine laying
MIW 6.7	Maintain magnetic signature limits
CCC 3	Provide own unit CCC
CCC 4	Maintain data link capability
SEW 2	Conduct sensor and ECM operations
SEW 3	Conduct sensor and ECCM operations
FSO 5	Conduct search/salvage & rescue operations
FSO 6	Conduct SAR operations
FSO 7	Provide explosive ordnance disposal services
INT 1	Support/conduct intelligence collection
INT 2	Provide intelligence
INT 3	Conduct surveillance and reconnaissance
MOB 1	Steam to design capacity in most fuel efficient manner
MOB 3	Prevent damage (not control)
MOB 7	Perform seamanship and navigation tasks
MOB 10	Replenish at sea
MOB 12	Maintain health and well being of crew
MOB 14	Operate in towed or piggy-backed configuration
NCO 3	Provide upkeep and maintenance of own unit
LOG 1	Conduct underway replenishment (not vertical)
LOG 2	Transfer/receive cargo and personnel

3 Concept Exploration

Chapter 3 describes SSLW Concept Exploration. Trade-off studies, design space exploration and optimization are accomplished using a Multi-Objective Genetic Optimization (MOGO).

3.1 Standards and Specifications

Submarine standards and specifications are almost exclusively proprietary or classified information, and as such are not available to the team.

3.2 Trade-Off Studies, Technologies, Concepts and Design Variables

Available technologies and concepts necessary to provide required functional capabilities are identified and defined in terms of performance, cost, risk and ship impact (weight, area, volume, power). Trade-off studies are performed using technology and concept design parameters to select trade-off options in a multi-objective genetic optimization (MOGO) for the total ship design. Technology and concept trade spaces and parameters are described in the following sections.

3.2.1 Hull Form Alternatives

Selection of the Littoral Warfare submarine's hull form must consider its unique operating environment. To effectively carry out its missions with covertness and stealth in shallow water, the hull form must be different from previous designs. The unique littoral environment necessitates a small, maneuverable submarine that can operate proficiently in less then 100 feet of water. The SSLW hull form must satisfy the following general requirements:

- Decreased draft
- Shallow water seakeeping
- Stealth
- Maneuverability
- Structural Efficiency
- Efficient use of inboard volume

An idealized, simplified hull form, shown in **Error! Reference source not found.**, was used in concept exploration. The diameter of the forebody hemisphere, length of parallel midbody, length of afterbody, overall beam and overall depth are varied in the designs. This allows the optimization program to reduce the beam until a traditional cylindrical hull exists, while providing the option to consider an alternative hull form that has a more desirable beam to depth ratio for a littoral hull. Single and multiple decks are also considered in the design; however a large emphasis is placed on maintaining a small depth.

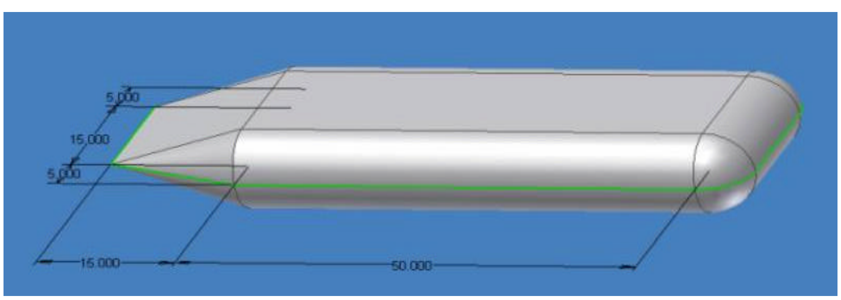

Figure 4 - Idealized Hullform

The structural concept for the SSLW pressure hull is a catamaran configuration with two separate pressure hulls connected by a third cylindrical section to create the small draft to beam ratio that is desired for the littorals. **Error! Reference source not found.** illustrates the cross section of this hull concept. The advantages / disadvantages of this catamaran hull are listed in **Error! Reference source not found.**. The most noteworthy quality of this design is that structural efficiency is maintained by allowing hoop stress to carry the primary pressure load. This reduces sheer stress and allows an elliptical external hull or envelope to be created without the added cost of additional steel.

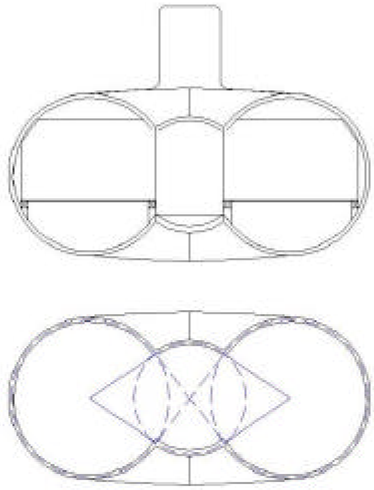

Figure 5 - Cross Section of Catamaran Hull Design

Table 5 - Hullform Advantages and Disadvantages

	Surface Stability	Dynamic Stability	Maneuvering	Good Large-Object Spaces	Efficient use of steel structure	Structural Integrity	Resistance at Sustained Speed	Cost
Elliptical Pressure Hull	-	+	+	-	+	+ +	+	-
Catamaran – Style Pressure Hull	+ +	- -	-	+ +	+ +	+	-	-

3.2.2 Sustainability Alternatives

SSLW minimum sustainability requirements are specified in Appendix B – SSLW Acquisition Decision Memorandum (ADM). Goals and thresholds were developed considering the mission, the location of the objective, and the distance between the objective and the sea base and /or support vessel. A great deal of consideration is also given to the threats in the littorals, and the risk involved. SSLW sustainability goals and thresholds are listed in Table 6.

Table 6 - Sustainability Goals and Thresholds

Sustainability Alternative	Threshold	Goal
Endurance Range	500 nm	1500 nm
Sprint Range	25 nm	50 nm
Sprint Speed	15 knots	25 knots
Endurance	14 days	30 days

The goal and threshold for endurance range allows the SSLW to travel to and from the estimated sea base / support vessel location while varying the amount of traveling required to complete its mission. It is estimated that the sea base / support vessel may be 200 nm offshore. The goal and threshold of the sprint range allows the SSLW to either evade a single threat, or retreat to the safety of the sea base or support vessel. The sprint speed is determined considering the threats in the littorals, and the endurance was determined considering the requirements of the mission scenarios.

3.2.3 Propulsion and Electrical Machinery Alternatives

3.2.3.1 Machinery Requirements

Based on the ADM and Program Manager guidance, pertinent propulsion plant design requirements are summarized as follows:

General Requirements – SSLW must perform its prescribed missions with the utmost concern for covertness, requiring a propulsion system that provides maximum operational flexibility and minimum acoustic, magnetic, thermal and wake signatures. An Integrated Propulsion System (IPS) was selected considering these constraints. IPS provides power for both the main propulsion motors and ship service electrical loads from the primary power source (engines or fuel cells) and batteries in a single integrated system. The use of electric propulsion is very important to reduce acoustic signature because it eliminates the mechanical linkage between engine and propulsor.

The second important requirement is that the main propulsion be air-independent. This means that in standard operating mode, the submarine does not require the intake of air and expulsion of exhaust to produce power. Current US Navy submarines use a Pressurized Water Nuclear Reactor (PWR) that is large, relatively 'noisy', and requires significant manning and maintenance. The SSLW ADM specifies that SSLW propulsion be non-nuclear.

Additionally, all submarine systems should be US Navy Grade 'A' shock certified, as well as SubSafe-compliant.

Sustained Speed and Propulsion Power – SSLW will have an endurance speed of 10 knots and a sustained or sprint speed of at least 15 knots. It is estimated that, including ship service power, SSLW will require 250-2000 kW for primary power and 5000-15000 kwhr battery capacity.

Range and Endurance – SSLW is required to have a range of at least 500 miles. Since the Littoral Warfare submarine needs a support vessel, this larger submarine or ship will transport the SSLW into the theater of operations. At this point the SSLW will deploy independently at a range out to 200 miles from the target coastline. This will allow the support vessel to stay out of the restrictive littoral region and harms way. The SSLW is also expected to have an on-station endurance of at least 14 days.

Ship Control and Machinery Plant Automation – A major concern for the Littoral Warfare submarine is minimizing the crew size. The propulsion plant is one of the areas where the application of automation and other new technologies can significantly reduce the number of crew. The current PWR plants on nuclear submarines require 20-30 sailors on duty at any time to maintain the propulsion plant. By having propulsion and auxiliary machinery systems that have lower maintenance and employ automation, the number of crew can be reduced.

3.2.3.2 Machinery Plant Alternatives

Primary propulsion power alternatives evaluated for the Littoral Warfare submarine are fuel cells, fuel cells with reformer, closed-cycle diesel engines, and a Stirling engine. Battery types include lead acid, lithium ion and nickel cadmium.

3.2.3.2.1 PEM Fuel Cells

A fuel cell produces power by harnessing the extra electrons of a chemical reaction and converting them to electricity. There are many types of fuel cells commercially available; each having different physical and operating characteristics.

Many fuel cell alternatives were explored including Molten Carbonate, Phosphoric Acid, Alkaline, and others, but the fuel cell type chosen for the SSLW was a Proton Exchange Membrane Fuel Cell (PEMFC). A PEMFC produces electricity by introducing hydrogen molecules to a catalyst. This catalyst breaks the protons free from the molecule which pass through the membrane. The remaining hydrogen ions are diverted around the membrane where the electricity is harnessed. The ions are reintroduced to the protons and oxygen molecules to produce pure water. This process occurs in a cell, which is less then ½ inch thick. These cells can be stacked and their total power output and efficiency is increased. Figure 6 illustrates this process.

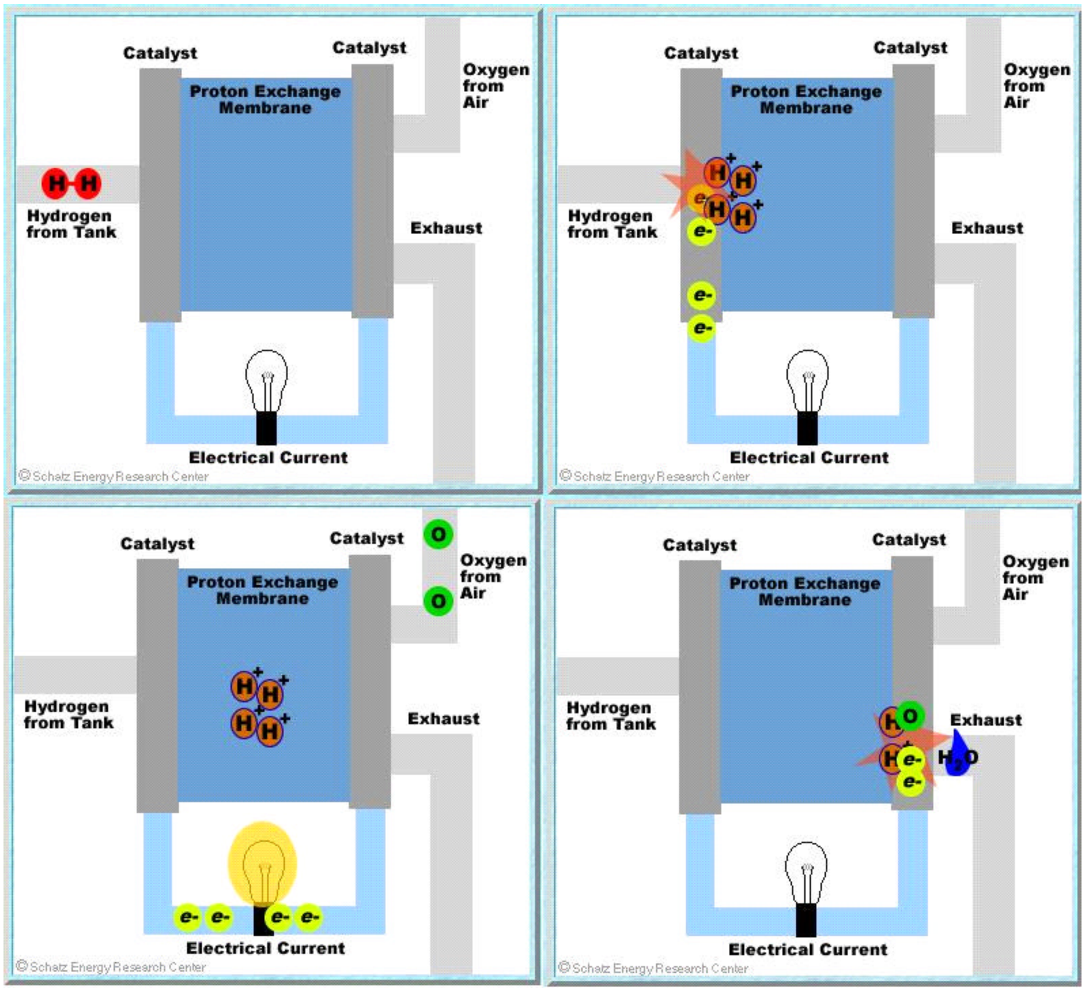

Figure 6 - Basic functionality for PEM Fuel Cell

The PEMFC system can use a wide variety of fuels, including diesel fuel, methanol, and any other hydrogen rich fuel. The fuel is processed in a reformer which extracts the hydrogen and sends it into the fuel cell stacks. Current PEMFC technology allows efficiencies in the 60%-70% range, which is twice that of a standard diesel generator. The PEMFC can also use pure hydrogen, eliminating the need for a reformer and increasing overall system efficiency. Hydrogen can be stored as a gas under pressure in large tanks external to the hull.

Advantages of the PEMFC are that it's a fairly mature technology, it has extremely low signatures, and its only exhaust is pure water. The fuel cell technology is new, but being widely explored and used in the commercial industry. The German Navy has developed the 212 class submarine, which relies on PEM fuel cells as its primary power source. PEM fuel cells have no moving parts other than small pumps and are extremely quiet compared to diesel motors or steam turbines. The operating temperature of the PEMFC is roughly 140°-160°F, much less than the 800°-1200°F exhaust temperatures from combustion-based power sources. Exhaust from the PEMFC is pure water, which can be reused aboard the SSLW.

Disadvantages of the PEMFC are the survivability of the cells themselves and the storage of high pressure hydrogen and oxygen. The catalysts in the fuel cells are very delicate and any impurities in the hydrogen fuel will poison the cell, causing failure. Additionally, having large tanks of both hydrogen and cryogenic oxygen aboard has its associated risks. Though the tanks could be kept outside of the pressure hull, a casualty to the tanks or surrounding structure could result in a catastrophic explosion.

The Proton Exchange Membrane fuel cell has the potential to be a valuable, transformational technology aboard the Littoral Warfare submarine. As a propulsion system alternative, its high efficiency and low signatures are extremely attractive. The PEMFC system can also potentially act as both the main propulsion system and the emergency generator. By adding a reformer system and carrying a supply of diesel fuel, the PEMFC will be able to run on the surface and re-fill the hydrogen and oxygen tanks.

3.2.3.2.2 Closed Cycle Diesel

A Closed Cycle Diesel system (Figure 7) is a conventional Diesel engine that is modified to operate independent of the outside environment. The closed cycle diesel uses argon and oxygen combined with the exhaust products to create an artificial atmosphere for the combustion process. Exhaust gas is scrubbed, cooled and separated. Then the argon is recycled and the rest of the gasses are discharged. Oxygen is usually stored as liquid oxygen (LOX) in a cryogenic state.

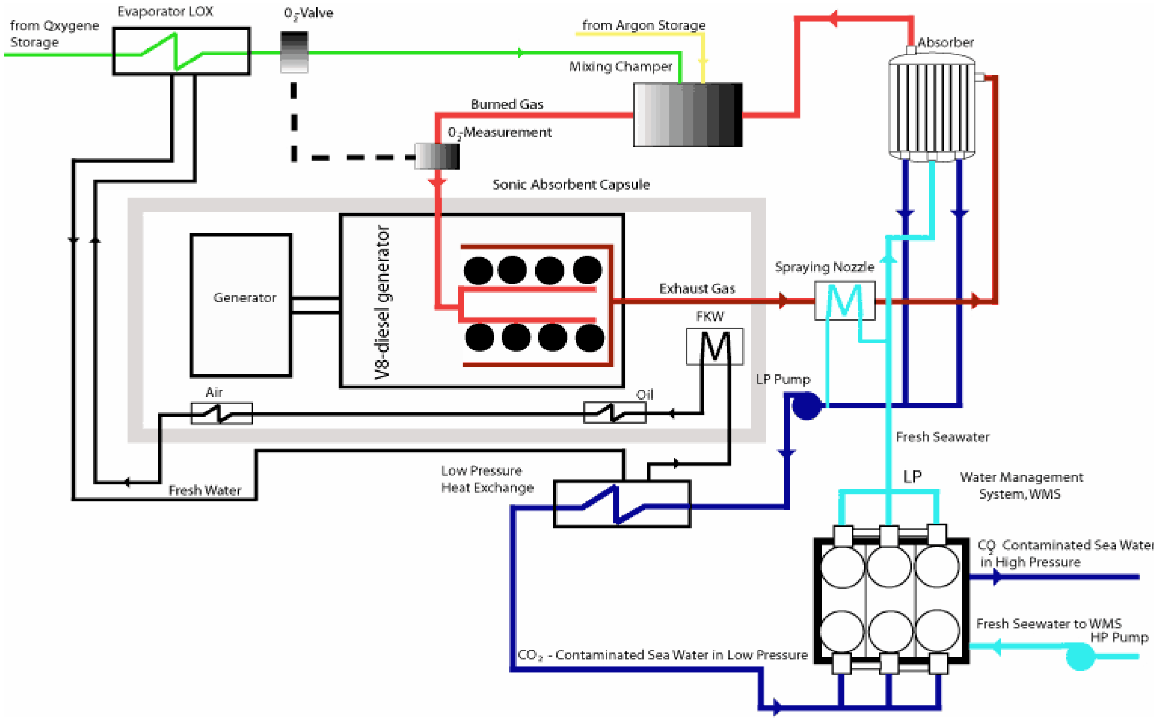

Figure 7 - Closed Cycle Diesel Schematic

Closed Cycle Diesel systems are a proven technology, being used on many types of submarines in many foreign navies. They are relatively simple to operate and maintain, and have a low acquisition cost as compared to some of the other propulsion options. The CCD offers an acceptable power density, but still requires a considerable amount of volume in the hull to accommodate all of the required systems. The CCD also requires the submarine to carry cryogenic oxygen, and requires a complex muffler system to exhaust the gasses produced by the engine.

3.2.3.2.3 Stirling Engine

A Stirling Engine (Figure 8 and Figure 9) is a modification to a standard Diesel that uses an external heat source to heat a gas which forces pistons to move generating mechanical energy. The Swedish Navy uses the Stirling engine extensively in its submarine force. Stirling engines are flexible, silent and practically vibration free, making them an attractive option for use in submarines. For submarines they use liquid oxygen and diesel fuel. The LOX must be stored in cryogenic tanks.

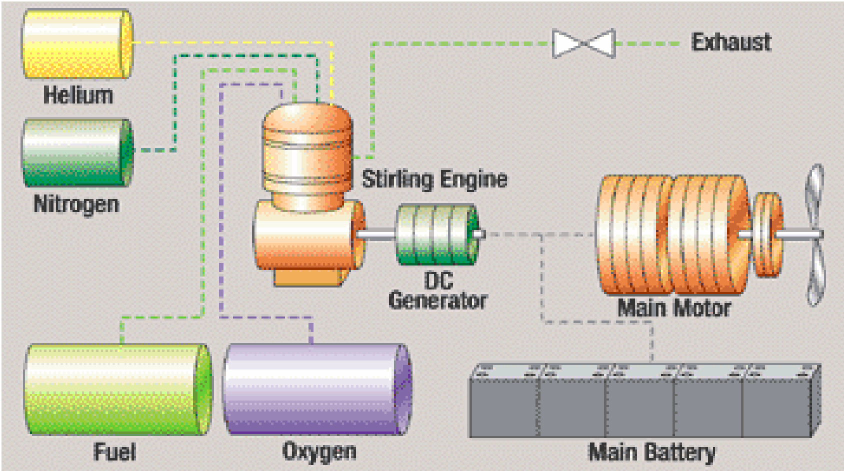

Figure 8 - Stirling Engine Schematic

The Stirling engine uses a high volume of fuel and liquid oxygen. All exhaust gasses must be sent overboard, requiring a complex and expensive muffler system.

Figure 9 - Stirling Engine and Installation

Table 7 - Propulsion Alternatives Data

Description	Propulsion Option (PSYS)	Main Generator Power KWg (kW)	Basic Propulsion Machinery Weight (lton)	SFC(kg/kwhr)	Specific Oxidant Consumption (kg/kwhr)	Specific Argon Consumption (kg/kwhr)	Inboard fuel tank volume per lton fuel (ft3/lton) including structure	Outboard fuel tank volume per lton fuel (ft3/lton)	Oxidant tank volume per lton oxidant (ft3/lton)	Argon tank volume per lton argon (ft3/lton)
CAT 3406E	1	410	13.7	0.213	0.84	0.03	45.15	0	36.9	29.8
CAT 3412E	2	690	23.1	0.211	0.84	0.03	45.15	0	36.9	29.8
250kW PEM	3	250	4.7	3.49	0.44	0	0	10.9	36.9	0
250kW PEM w/reformer	4	250	7.2	0.31	0.9	0	45.15	0	36.9	0
250kW Alkaline	5	250	5.3	2.9	0.37	0	0	10.9	36.9	0
250kW Stirling Engine	6	250	7.4	0.293	1.022	0.01	45.15	0	36.9	29.8

Table 8 - Propulsion Alternatives Data

Description	Hydrogen tank structure weight lton/lton fuel	Oxidant tank structure weight lton/lton ox	Argon tank structure weight lton/lton argon	Minimum Machinery Room Length Required (m)	Minimum Machinery Room Width Required (m)	Minimum Machinery Room Height Required (m)	Propulsion Machinery Box Required Volume (m3)
CAT 3406E	0	0.375	0.1	1.535	0.995	1.231	87.576
CAT 3412E	0	0.375	0.1	1.913	1.444	1.621	147.384
250kW PEM	0.25	0.375	0	0	0	0	38.4
250kW PEM w/reformer	0	0.375	0	0	0	0	0
250kW Alkaline	0.25	0.375	0	0	0	0	42
250kW Stirling Engine	0	0.375	0.1	0	0	0	49.8

3.2.3.3 Propulsor Alternatives

A traditional seven-bladed submarine fixed-blade propeller is the lowest cost and lowest risk alternative to propel SSLW. The fixed-blade propeller has been used successfully for decades by most submarines. It is a proven technology that has been developed through the years as a quieter and more efficient method of propulsion. As the fixed-blade propeller is made quieter, however, it tends to lose some of its efficiency. Some of the earlier American SSNs were faster than today's classes, but less consideration was given to their acoustic signature. Today's submarines are quieter by several orders of magnitude, and with the technological advances of the last 40 years, are re-gaining the lost efficiency. The traditional fixed-blade propeller is open to damage and fouling by external sources, and has a tendency to cavitate at higher RPMs.

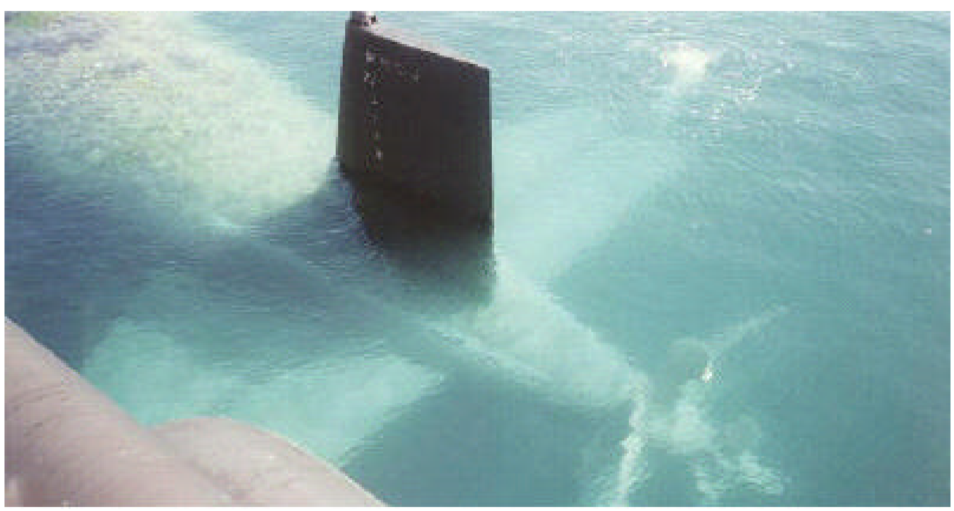

Figure 10 - Traditional Fixed-blade propeller

A second alternative is two shaft driven propellers with full shrouds. A shrouded propulsor is identical to a standard shafted propeller system, but with a cylindrical ring of metal attached at the tips of the propeller blades around the full circumference. This type of propeller has been used on prior submarines and provides improvement over exposed propeller designs in both efficiency and acoustic signature. As an exposed propeller blade travels through the water, cavitation occurs behind the leading edge, especially around the tips. This cavitation makes noise and can quickly give away a submarine's position. Also, large swirls of water called vortices come from the propeller tips, causing inefficiencies that can be prevented.

A shrouded propeller system combats both of these problems. By ducting the water flow through the shroud, the tip vortices can be harnessed to provide thrust. Cavitation is also greatly reduced with the shroud because the duct maintains higher pressure around the blade tips and prevents cavitation bubbles from forming. Overall, the shroud is a beneficial modification to a standard propulsion system that greatly enhances the covert mission capability of the SSLW.

Submerged navigation in littoral regions, particularly enemy ports, will require maneuverability beyond that normally required of a submarine. To augment the Littoral Warfare submarine's main propulsors in the confined waters of the coastal region, tunnel thrusters, a commerical off the shelf (COTS) technology, will aid in maneuvering. Tunnel thrusters are a small propeller mounted in a tube, powered by a hydraulic motor in the hub. These thrusters would provide operate in the transverse and vertical directions, allowing for safer submarine operation in environmentally constricting areas and at slower speeds, when control surfaces may not be effective. To meet the need for dynamic positioning ability, SSLW will be equipped with multiple tunnel thrusters mounted in the corners of SSLW's outer hull. Hydraulically powered thrusters are commercially available in a range of sizes from 40 to 2500 lbs thrust each.

Ducted Pump Jet Propulsion is being developed by Penn State University. The DPJP concept uses a set of ducts that intake seawater, accelerate it through a reducing cross-section of ducts into a pump that quietly moves the water out the rear of the boat. The use of multiple ducts and cross-sections allow SSLW to be a highly mobile and maneuverable platform because it is able to direct thrust in almost any direction. The pumps can be "tuned" to reduce the amount of vibration and signature that is attenuated into the surrounding environment. Since there are no blades or screws, there is less chance of cavitation, or erosion of the propulsor. This makes DPJP a very quiet and attractive alternative. The DPJP system is not as efficient as some traditional screws, but the versatility and maneuverability is excellent. Since DPJP is an entirely internal system, there is little chance of fouling in the pumps.

3.2.4 Automation and Manning Parameters

In concept exploration it is difficult to deal with automation-based manning reductions explicitly, so a ship manning reduction factor is used. This factor represents reductions from "standard" manning levels resulting from automation. The manning factor, $C_{MANNING}$, varies from 0.5 to 1.0. It is used in the regression based manning equations shown in Figure 11. A manning factor of 1.0 corresponds to a US Navy "standard" fully-manned ship. A ship manning factor of 0.5 results in a 50% reduction in manning and implies a large increase in automation. The manning factor is also applied using simple expressions based on expert opinion for automation cost, automation risk, damage control performance and repair capability performance. A more detailed manning analysis is performed in concept development.

```
Cmanning = manning and automation factor
Pmain = total primary power (KW)
Venv = envelope volume (ft3)
NO = number of officers
NESP = number of enlisted specialists, mission or SPW

Manning
NE=INT(CManning*(Pmain/150.+Venv/50000.))+1+NESP ! enlisted manning
NT=NO+NE                                         ! total crew manning
```

Figure 11 – Manning Calculation

3.2.5 Combat System Alternatives

Critical to the Littoral Warfare submarine's operations are its combat systems. These systems include the defensive / offensive weapons and equipment needed to perform its various missions. The Acquisition Decision Memorandum (ADM) provides direction when choosing combat systems to complete the submarine's missions. This includes defining inherent core capabilities for ASW and ASUW self defense, C4ISR, and SPW. The submarine is also tasked to carry Payload Interface Modules (PIMs) in standard 1280 ft^3 ISO containers.

The process of choosing these combat systems begins by identifying the range of combat system alternatives and direct submarine impact, such as weight, volume, power, and cost. The process continues by using AHP and MAVT to estimate Value of Performance (VOP) for system alternatives, and then including these calculations in total submarine synthesis model. Finally, selections of inherent combat system alternatives and the PIM cargo capacity are made considering effectiveness, cost and risk in a multi-objective genetic optimization.

3.2.5.1 ASW/ASUW

Anti-Submarine Warfare (ASW) and Anti-Surface Warfare (ASUW) combat systems are designed to protect the SSLW from enemy submarines and surface ships. Its primary mission is to find and evade enemies deploying countermeasures as needed and fire torpedoes defensively. ASW / ASUW system alternatives are listed in Table 9

Table 9 - ASW/ASUW System Alternatives

ID	ASW/ASUW System Alternatives	1 (Goal)	2	3	4 (Threshold)
1	Passive ranging sonar	1	1	1	1
2	Flank array sonar	1	1	1	
3	Integrated bow array sonar	1	1	1	1
4	ASW weapons control	1	1	1	1
5,7	Inboard torpedo Room w/ 2 torpedoes in tubes and 2 reloads	1			
6	Inboard Torpedo Access w/2 torpedoes in tubes		1		
8	External Encapsulated Torpedos	4	6	8	4
9	3” Countermeasure Launcher	2	2	2	2
10	3” Countermeasure Reloads	1	1	1	1
11	6.75” Countermeasure Tube (external)	2	2	2	
	ASUW Value of Performance, VOP1	1.0	.704	.196	.175
	ASW Value of Performance, VOP5	1.0	.572	.179	.088
	Primary power	Fuel cell			Engine
	Acoustic Signature Value of Performance, VOP15	1.0			0.0

Specific sub-system descriptions are as follows:

- The integrated bow array incorporates a medium-frequency, conformable bow array operating in the 0.3 to 12 kHz band, a flank array (FAS-3), a Passive Ranging Sonar (PRS), an intercept sonar, a low-frequency, passive towed array sonar (TAS-3), and the active HF MOA 3070 obstacle avoidance sonar in order to locate enemies, targets, and obstacles.
- The weapons control system is necessary to arm, fire, guide, and track weapons, including torpedoes. It utilizes the sonar systems and the C4ISR systems to perform its tasks.
- The Mk-50 (Figure 12) is an advanced lightweight torpedo for use defensively against the fast, deep-diving, sophisticated submarines. It can be fired from an internal torpedo room, from external capsules, or externally, with access to the torpedoes from inside the hull.

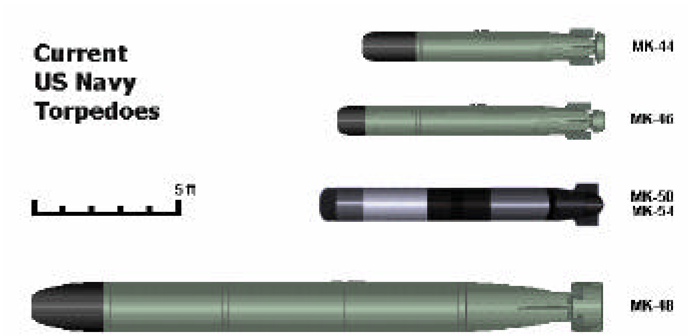

Figure 12 - MK-50 torpedo size comparison

The 3” and 6.75” countermeasures are designed to confuse enemy torpedoes. If fired upon, the SSLW can attempt to evade the incoming torpedo with countermeasures and evasion tactics.

3.2.5.2 C4ISR

Command, Control, Communications, Computers and Intelligence (C4I), and Intelligence Surveillance, and Reconnaissance (ISR) includes a variety of reconnaissance components to gather and process information regarding enemy activity. These are the eyes and ears of SSLW.

- The AD-16 PMP Photonics Mast, SHRIKE ESM/Comm Mast, and MMA all function to allow SSLW to monitor and communicate with ships and other assets or enemies on the surface. They are electronic and do not require a mast penetrating the hull into the Command space. This allows greatly flexibility in arranging the boat.
- The Kollmorgen UAV is a small, disposable unmanned air vehicle that can be piloted remotely or operate autonomously. It folds into a cylinder only a few inches in diameter, and can be launched from a tube located on the submarine's mast, allowing the crew to survey surface targets remotely over a large radius.

Table 10 - C4ISR System Alternatives

ID	C4ISR System Alternatives	1(Goal)		2(Threshold)
12	AD-16 PMP Photonics Mast	1	1	0
13	Kollmorgen UAV Mast -Launch capability	Required by all designs		
14	SHRIKE ESM and Comm Mast	Required by all designs		
15	Multifunction Mast Antenna (MMA)	Required by all designs		
16	ROPE Buoy System	1		
17	UW Comms	Required by all designs		
18	Navigation Echo Sounders	Required by all designs		
19	Distress Beacon	Required by all designs		
20	Communications electronics and equipment	Required by all designs		
21	ISR Control and Processing	Required by all designs		
22	NPP Imaging Center	1	0	0
	C4I Value of Performance, VOP2	1.0	0.405	0.164
	ISR Value of Performance, VOP3	1.0	0.75	0.5

3.2.5.3 MCM

Mine Countermeasures (MCM) includes any activity to prevent or reduce the danger from enemy mines. Passive countermeasures operate by reducing a ship's acoustic and magnetic signatures, while active countermeasures include mine avoidance, mine hunting, minesweeping, detection and classification, and mine neutralization. MCM system alternatives are listed in Table 11.

Table 11 - MCM System Alternatives

ID	MCM System Alternatives	1 (Goal)	2 (Threshold)
23	Mine Avoidance Forward Looking Sonar	1	1
24	Side Scan Sonar	1	
	MCM Value of Performance, VOP4	1.0	.33
	Degaussing	yes	no
	Magnetic Signature Value of Performance, VOP14	1.0	0.0

Specific sub-system descriptions are as follows:

- The mine avoidance forward looking sonar (Figure 13), and side scan sonar are two systems that can be utilized together to locate and avoid mines.
- A degaussing system is a complex electrical system which allows a ship to cancel its magnetic signature. Steel hulls can develop a magnetic signature over time, and degaussing is usually employed during overhaul or refit periods to make the ship stealthier. Carrying this system onboard allows SSLW to maintain its magnetic signature independently.

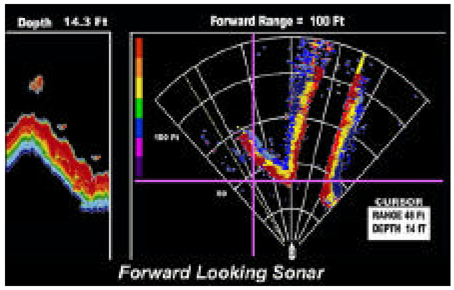

Figure 13 - Forward Looking Sonar display

3.2.5.4 SPW

Special Operations Warfare (SPW) includes the delivery and support of Special Forces operations. The SSLW will have a distinct mission that will provide a platform for a platoon of Special Forces personnel. SPW system alternatives are listed in Table 12.

Table 12 – SPW System Alternatives

ID	SPW System Alternatives	1 (Goal)	2	3	4 (Threshold)
25	4-man lockout trunk		1		1
26	9-man lockout trunk	1		1	
	SEAL squad (officer + 7 enlisted)	2	2	1	1
27	Zodiac RHIB and diver stowage	4	4	2	2
	SPW Value of Performance, VOP6	1.0	.8	.3	0.0

Specific sub-system descriptions are as follows:

- A lockout chamber (Figure 14) is a space that can be sealed off and flooded with water to allow the deployment of divers while the submarine is submerged. A Special Forces squad consists of 8 people, so the 4-man lockout trunk would permit egress of an entire squad in two cycles.
- The Special Force operations will also use a Combat Rubber Raiding Craft (CRRC). The CRRC is a small rigid hull inflatable boat (RHIB) powered by a hand-steered outboard motor, capable of carrying up to 8 Special Forces personnel and their gear.

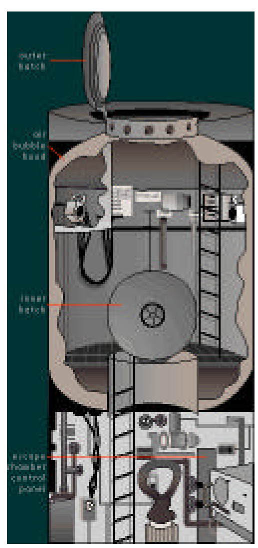

Figure 14 - Lockout chamber arrangement

3.2.5.5 Mission Payload Modules

This design allows for the insertion of one 8x8x20ft Payload Interface Module. These modules allow the boat's inherent capabilities to be enhanced depending on mission needs. Possible payloads include autonomous or remotely operated underwater vehicles, strike weapons, torpedoes, special warfare equipment stowage, or other modules.

Particular payloads of interest are those that enhance SSLW's core missions. For MCM-related missions, a PIM could be carried that could be used to deploy and operate a myriad of anti-mine unmanned underwater vehicles such as REMUS, NMRS (Figure 15), or LMRS. PIMs could also be designed to allow special forces teams to store more equipment or weaponry, to enhance electronic surveillance and countermeasures capabilities, or perform ranged strike against land or sea targets.

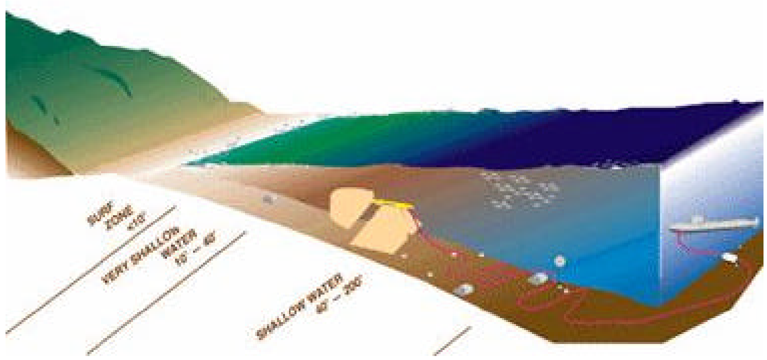

Figure 15 - Near-Term Mine Reconnaissance System (NMRS)

3.2.5.6 Combat Systems Payload Summary

In order to trade-off combat system alternatives with other alternatives in the total ship design, combat system characteristics listed in **Error! Reference source not found.** are included in the ship synthesis model data base.

Table 13 - Combat System Ship Synthesis Characteristics

ID	NAME	WARAREA	ID	SingleD SWBS	WT lton	VCG/D ft	AREA ft2	Vob ft3	KW
1	passive ranging sonar (GMBH, L3 Communications) and electronics, bottom	ASW/MCM/C4I	1	4	0.13	0.10	25.00	45.00	2.00
2	flank array sonar and electronics	ASW/MCM/C4I	2	4	0.20	0.45	25.00	55.00	5.00
3	integrated bow array - conformal, MH&HF passive, HF active, and electronics	ASW	3	7	1.45	0.48	30.00	63.94	20.00
4	ASW Weapons control system	ASW/ASUW	4	4	1.50	0.65	30.00	0.00	5.00
5	Inboard torpedo room with two tubes, equipment, and 2xMK50 torpedos	ASW/ASUW	5	7	6.25	0.40	60.00	90.00	3.00
6	Small inboard torpedo room with two tube access, and 2xMK50 torpedos	ASW/ASUW	6	7	1.50	0.40	25.00	90.00	1.00
7	Inboard torpedo reload pair (2xMK50)	ASW/ASUW	7	21	0.67	0.40	19.50	0.00	0.00
8	External torpedo launch cannister + 1xMH50	ASW/ASUW	8	21	0.33	0.40	0.00	11.98	0.10
9	3" Countermeasure/XBT launcher	ASW	9	7	0.09	0.70	1.00	0.00	0.10
10	3" Countermeasure reloads x 10 (locker)	ASW	10	21	0.04	0.65	3.00	0.00	0.00
11	6.75" external Countermeasure launcher w/4cannisters ea	ASW	11	7	0.22	0.90	0.00	0.69	0.10
12	Optical color television, thermal imaging, laser, rangefinder, GPS,minimal ESM and comm	C4I/ISR/ASUW	12	4	4.00	0.90	4.00	10.00	4.00
13	Kolmorgen UAirV (2) - launch from AD-16 PMP w/electronics	C4I/ISR/ESM	13	4	0.09	0.95	0.00	0.00	1.00
14	SHRIKE submarine ESM and communications mast, and system (less ROPE buoy)	C4I/ISR/ESM	14	4	1.50	0.90	4.00	3.00	5.00
15	Multifunction Mast Antenna (MMA) - Communications	C4I	15	4	1.00	0.90	2.00	5.00	3.00
16	Remotely Operated Platform-Electronic (ROPE) Buoy System	C4I	16	4	0.50	0.90	20.00	10.00	7.00
17	underwater comms	C4I	17	4	0.05	0.85	2.00	1.20	1.00
18	navigation echo sounders	C4I	18	4	0.10	0.40	0.00	1.30	1.00
19	distress beacon	C4I	19	4	0.05	0.95	0.00	1.00	0.50
20	communications electronics and equipment	C4I	20	4	1.25	0.65	20.00	0.00	5.00
21	ISR control and processing	ISR	21	4	0.50	0.65	50.00	0.00	2.00
22	NPP Imaging Center - for Optronic Systems control w/ROPE buoy	ISR	22	4	0.50	0.65	30.00	0.00	3.00
23	mine avoidance sonar and electronics	MCM	23	4	0.90	0.30	25.00	50.00	5.00
24	side scan sonar	MCM	24	4	0.10	0.30	15.00	20.00	2.00
25	4 man lockout trunk	SPW	25	1	8.62	0.45	0.00	301.59	1.00
26	9 man lockout trunk	SPW	26	1	17.23	0.45	0.00	603.19	4.00
27	Combat rubber raiding craft and diver stowage	SPW	27	5	0.15	0.80	0.00	20.00	0.00

3.3 Design Space

A numerical value for each design variable within the specified range is selected by the optimizer and is transferred into ship synthesis model. The SSLW design has 20 design variables (**Error! Reference source not found.**). Hull design variables (DV1-5) are described in Section 3.2.1. The automation and manning factor, DV6, is described in Section 3.2.4. Stores and provisions duration, DV7, is described in Section 3.2.2. Combat System and Mission Alternatives, DV8-DV14, are described in Section 3.2.5. Propulsion and Machinery alternatives (DV 15 and 16) are described in Section 3.2.3.2.

Table 14 - Design Variables

Design Variable	Name	Metric	Description	Trade-off Range
DV1	Lbow	ft	Length of bow section	25-40
DV2	Lmid	feet	Length of parallel midbody	30-45
DV3	Laft	feet	Length of aft section	40-70
DV4	B	feet	Beam	30-45
DV5	D	feet	Molded depth	17-25
DV6	Cmanning	factor	Manning reduction factor	0.5-1.0
DV7	Ts	days	Time on station	14-24
DV8	ASW	alternative	Anti Surface/Submarine Warfare package	1-4
DV9	C4ISR	alternative	C4ISR package	1-3
DV10	MCM	alternative	MCM package	1-2
DV11	SPW	alternative	Special Warfare package	1-4
DV12	Depth	feet	Rated Depth	250-350
DV13	Ndegaus	no/yes	Degaussing system	0,1
DV14	PSYS	alternative	Propulsion system	1-6 (PEM, reformer, diesel)
DV15	BATtyp	type	Battery Type	1-3 (lithium ion, nickel cadmium, lead acid)
DV16	Ebattery	kwhr	Battery capacity	5000-15000
DV17	Ng	number	Number of generators	1-4
DV18	Wfuel	lton	Fuel weight	5.0-15.0
DV19	Npim	number	Number of PIM interfaces	1-4

3.4 Ship Synthesis Model

In Concept Exploration, a ship synthesis model is used to balance and assess designs selected by the optimizer. Ship synthesis model modules are integrated in Model Center (Figure 16). The Multi-Objective Genetic Optimization (MOGO) is also executed in Model Center. Measures of Performance (MOPs) are computed based on the design parameters and the predicted performance in a balanced design. Values of Performance (VOPs), an Overall Measure of Effectiveness (OMOE), Overall Measure of Risk (OMOR) and life cycle cost are computed by the ship synthesis model. To reject unacceptable designs, design feasibility margins are calculated, ensuring that a design that is produced that does not have the proper balance of characteristics (such as between weight and volume, speed and power, electrical load and power, etc.) is rejected as unfeasible. A small submarine synthesis model was developed specifically for this project.

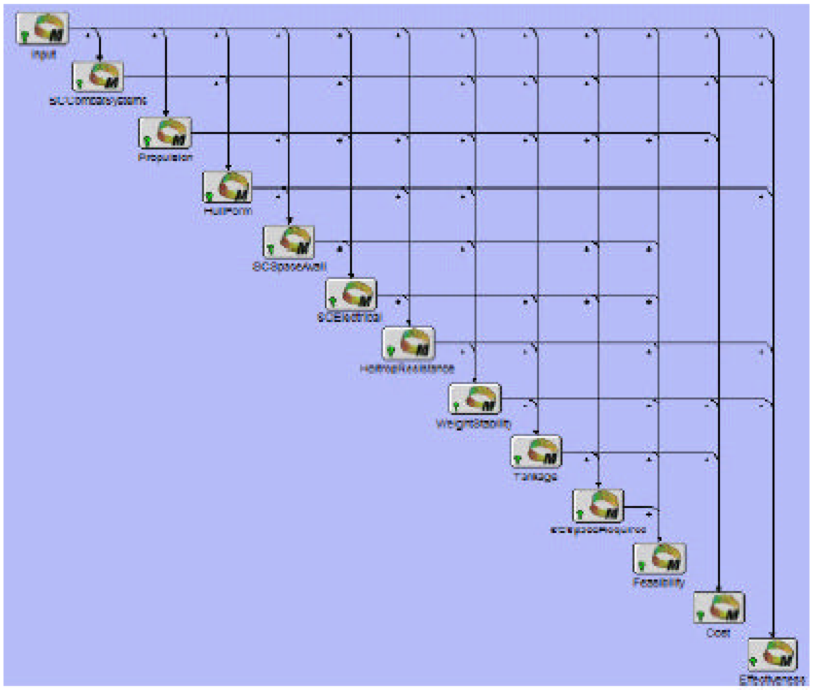

Figure 16 - Ship Synthesis Model in Model Center (MC)

3.4.1 Input Module

The design requirements are inputs to the first module of the submarine synthesis model. In the Concept Exploration phase of the design process, the input requirements are changed frequently to meet the optimized condition of the model design.

3.4.2 Combat System Module

In the Combat System (CS) Module, input values are collected from the Combat System Data Base as specified by the combat system design variables. Selected CS components are assembled. Then, SWBS weight groups are updated with payload requirements. Warfighting VOPs based on selected alternatives are assigned. Inputs for the Combat System Module are ASW alternative, C4I alternative, ISR alternative, MCM alternative, SPW alternative, Number of PIM modules, and Molded depth. The calculated outputs are payload weights, VCGs, areas, power requirements, and warfighting VOPs.

3.4.3 Propulsion Module

The Propulsion Module reads propulsion system data based on input system type and battery type. It calculates propulsion system weight, volume and power characteristics and provides data to other modules in the ship synthesis model. Here are some input variables for the module: Propulsion system type, Battery type, Total battery capacity, Total fuel weight, Number of primary power generators, Overall propulsive coefficient, Transmission efficiency, Number of propulsors. With these variables, Propulsion Module computes the following output values: Total main generator power, Total battery power, Total weight basic propulsion machinery, Total battery weight, Total oxidant weight, Total argon weight, Total propulsion tank weight, Total machinery box volume, Total battery volume, Total propulsion and inboard volume, Generator specific fuel consumption, Required machinery box length, height, and width, Main generator power.

3.4.4 Hull Form Module

Hull form principal characteristics are calculated in Hull Form Module. It uses input dimensions to calculate principal dimensions, volumes, and surface area. Inputs for this module are bow section length, midsection length, aft length, beam, and molded depth. Examples of outputs are length overall (LOA), total surface area, envelope volume.

3.4.5 Electric Module

Electric Module calculates the required powers for specific onboard services such as steering, propulsion, fuel handling, and etc, based on parametric equations. Total services, sum, and additional margins are found through this process. The maximum functional electric load with margins is also calculated.

General inputs for Electric Module are functional margin factor, design margin factor, average power margin factor, total payload weight, number of propulsors, payload required power, pressure hull volume, machinery box volume, auxiliary space volume, total primary power, length overall, hull diameter, total crew, number of primary power generators, and degaussing. With these input variables, the following output values are calculated: maximum functional load with margins, average required power with margins, and primary generator required power rating.

3.4.6 Resistance Module

Resistance Module calculates hull resistance assuming primarily viscous resistance and using the ITTC frictional resistance equation with form factor. The form factor is calculated as a function of Beam/Length ratio. Outputs from the module include endurance shaft horsepower, sustained speed, endurance range and sprint range. Fuel and range calculations are based on DDS 200-1. In this module, a number of Input variables exist: Endurance speed, Resistance correlation allowance, Propulsion margin factor, Bare hull surface area, Average required electric power with margin, Overall length, Beam, Molded depth, Overall propulsive coefficient, Transmission efficiency, Total primary electric power, Primary generator specific fuel consumption, Sprint battery power, Battery capacity, Fuel weight, Total crew. From the input variables, following output values are obtained: Sustained speed, Effective shaft power, Sprint available brake propulsion power, Endurance range, Sprint range.

3.4.7 Weight and Stability Module

The weight and stability module calculates maximum and minimum ship weights, total weight, fuel weight, GM/GB, SWBS group weights, and normal surface condition weights. The module uses known weights and parametric equations to calculate the SWBS Group weights. There are a number of input variable for the module including operating depth, degaussing, total battery weight, total basic propulsion machinery weight, weight margin factor, everbuoyant volume, total sprint propulsion power available, maximum functional load with margins, overall length, molded depth, beam, pressure hull volume, payload structures weight, payload command and control weight, payload auxiliaries weight, ordnance delivery systems weight, total propulsion tanks weight, variable payload weight, lube oil weight, fresh water weight, fuel weight, oxidant weight, sewage weight, argon weight, total crew, number of officers, number of Enlisted, stores and provisions duration, average deck height, variable payload VCG.

3.4.8 Tankage Module

Tankage volumes and weights based on propulsion and manning inputs are computed in the tankage module. It uses input variables including miscellaneous propulsion inboard volume, manning and automation factor, total primary power, envelope volume, number of officers, number of enlisted specialists, mission, SPW, and oxidant weight. It uses parametric equations and computes the following output values: total tank volume excl. MBT, enlisted manning, total crew manning, lube oil weight, fresh water weight, and sewage weight.

3.4.9 Space Required Module

This module determines space requirements and initiates the space balance process. A parametric equation calculates volumes and areas using hull dimensions, manning, and other area inputs. Input variables for the module are: stores and provisions duration, average deck height, number of enlisted, number of officers, total crew, pressure hull arrangeable area margin, command and control payload required area, ordnance delivery system required area, machinery box volume, outboard payload volume, total tankage volume, propulsion total outboard volume, total battery volume, envelope volume, midbody length, aft body length, beam, molded depth. From these input variables the module calculates following output values: pressure hull volume, outboard volume, everbuoyant volume, MBT volume, submerged volume, free flood volume, free flood volume min and max, auxiliary volume, total required arrangeable area, total available arrangeable area

3.4.10 Feasibility Module

The feasibility module assesses the overall design feasibility of SSLW. Available characteristics and required characteristics are compared in terms of total arrangeable ship area, sustained speed, electrical plant power, endurance range, spring range. To do so, first all relevant model characteristics are inputted into the module and checking process against minimum and required constraints are performed. It also produces error measures that can be used to eliminate infeasible designs (E<0).

Input variables for the feasibility module are minimum endurance range, min sprint speed, min sprint range, min GB, min GM, min and max lead, min and max free flood volume, normal surface condition weight, total arrangeable area, total required arrangeable area, free flood volume, lead weight, sprint speed, primary generator power rating, required power, GM, GB, endurance range, and sprint range. With these input variables, following output values are calculated: arrangeable area error, minimum and maximum free flood error, minimum and maximum lead error, sprint speed error, KW error, GM error, GB error, endurance and sprint range error.

3.5 Multi-Objective Optimization

The Multi-Objective Genetic Optimizer (MOGO) is used to identify a non-dominated frontier of SSLW designs. These designs represent the maximum effectiveness for a given risk and cost. Because of the size of the SSLW design space, it is not feasible to assess every possible design for feasibility, effectiveness, risk and cost. A more efficient method is required. This is the reason for the genetic optimization process which is shown in Figure 17. The MOGO initially selects a random population of designs, then takes the best designs from this population and "breeds" them by combining their attributes to get the next population or generation. After several generations, the MOGO identifies a non-dominated frontier that is very similar to the non-dominated frontier that would be found if every possible design was evaluated, with significantly less calculation.

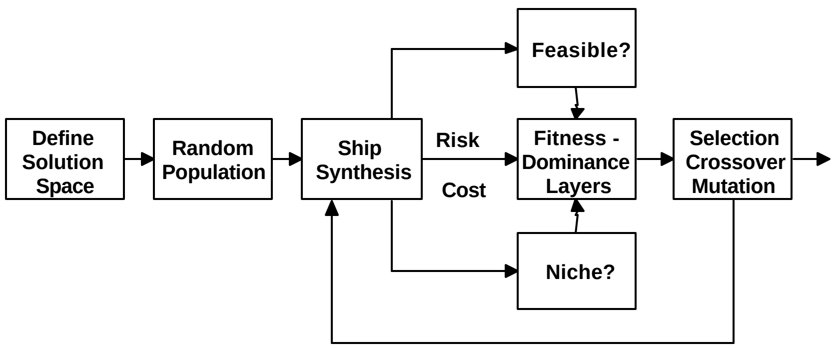

Figure 17 - Multi-Objective Genetic Optimization (MOGO)

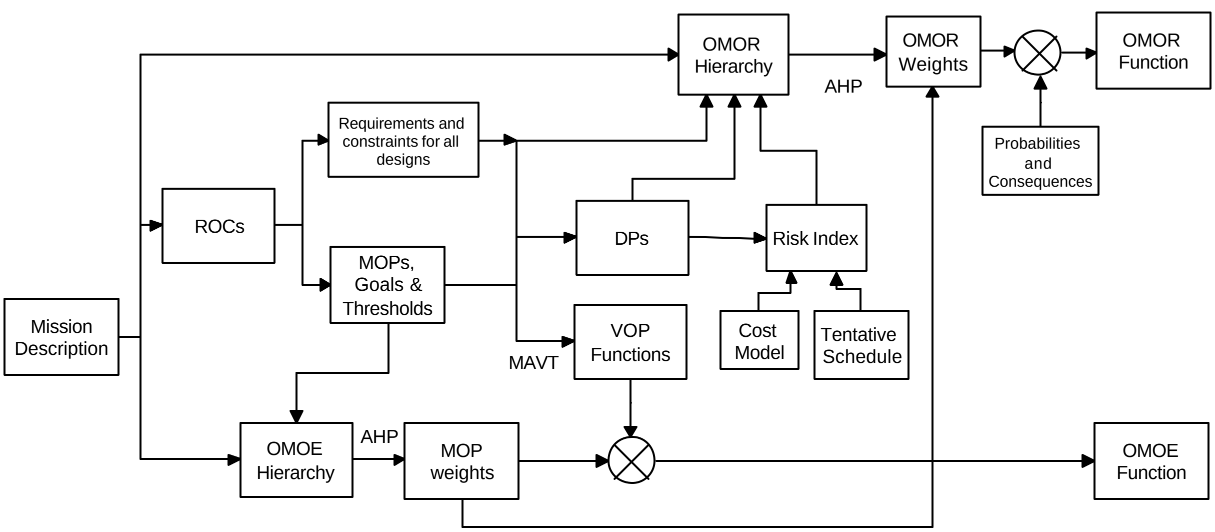

Figure 18 - OMOE and OMOR Development Process

3.5.1 Overall Measure of Effectiveness (OMOE)

The Overall Measure of Effectiveness (OMOE) is a method of quantifying the effectiveness of each design that the optimizer considers. The measure of effectiveness is an index between zero and one describing ship effectiveness in specified missions using Equation 1. To quantify mission effectiveness, each ROC that varies for different designs is assessed using a Measure of Performance (MOP). The MOPs are specific ship or system performance metrics for required capabilities independent of the mission. For example ROC MOB 1 is to steam to design capacity in most fuel efficient manner, this can be broken down into Sprint Speed, Sprint Range and Endurance Range. It is important to note that the same MOP can be a factor in satisfying several ROCs, for example, MOP 8 ASW contributes to ROCs ASW 1, 1.3 and 10. Each MOP has a threshold or minimum value and a goal value.

Table 15 - ROC/MOP/DV Summary

ROC	Primary MOP or Constraint	Threshold	Goal	Related DV
ASUW 1 - Engage surface threats with anti-surface armaments	MOP7 – SUW	ASUW = 4	ASUW = 1	DV11 – ASUW
	MOP5 – UAV	MCM = 4	MCM = 1	DV16 – UAV
ASUW 2 - Detect and track surface threats with sonar	MOP6 – C4ISR	C4ISR = 2	C4ISR = 1	DV14 – C4ISR
	MOP7 – SUW	ASUW = 4	ASUW = 1	DV11 – ASUW
ASUW 3 - Disengage, evade and avoid surface atack	MOP13 – Sprint speed	15 knots	25 knots	DV1 - Hull form, DV2 - Displacement, DV3 - Propulsion System
ASUW 6 - Disengage, evade and avoid surface attack	MOP13 – Sprint speed	15 knots	25 knots	DV1 – Hull form
				DV2 – Displacement
				DV7 – Propulsion System alternative
ASW 1 - Engage submarines	MOP8 – ASW	ASW = 4	ASW = 1	DV13 – ASW
ASW 1.3 – Engage submarines at close range (torpedo)	MOP8 – ASW	ASW = 4	ASW = 1	DV13 – ASW
ASW 10 – Disengage, evade and avoid submarine attack by employing countermeasures and evasion techniques	MOP8 – ASW	ASW = 4	ASW = 1	DV13 – ASW
	MOP13 – Sprint Speed	15 knots	25 knots	DV1 – Hull form
	MOP10 – Sprint Range	200 nm	300 nm	DV2 -Displacement
				DV7 – Propulsion System alternative
CCC 3 - Provide own unit CCC	MOP6 – C4ISR	C4ISR = 4	C4ISR = 1	DV14 – C4ISR
CCC 4 - Maintain data link capability	MOP6 – C4ISR	C4ISR = 4	C4ISR = 1	DV14 – C4ISR
FSO 5 - Conduct search/salvage & rescue operations	MOP6 – C4ISR, MOP5 -UAV	C4ISR = 4	C4ISR = 1	DV14 – C4ISR, DV16 - UAV, DV21 -SEALS
FSO 7 – Provide explosive ordnance disposal services	MOP2 – MCM Modules	MCM = 4	MCM = 1	DV10 – MCM
INT 1 - Support/conduct intelligence collection	MOP5 – UAV	MCM = 4	MCM = 1	DV16 – UAV
INT 2 - Provide intelligence	MOP6 – C4ISR	C4ISR = 4	C4ISR = 1	
INT 3 - Conduct surveillance and reconnaissance (ISR)	MOP5 – UAV	UAV = 0	UAV = 1	DV16 – UAV
	MOP6 – C4ISR	C4ISR = 4	C4ISR = 1	DV14 – C4ISR
LOG 1 - Conduct underway replenishment	Required all designs			
LOG 2 - Transfer/receive cargo and personnel	Required all designs			
MIW 1 – Conduct mine-hunting	MOP1 – MCM	MCM = 4	MCM = 1	DV10 – MCM
	MOP2 – MCM Modules			
	MOP5 – UAV			DV16 – UAV
	MOP6 – C4ISR			DV14 – C4ISR
MIW 2 - Conduct mine-sweeping	MOP 1 - MCM, MOP 2 - MCM Module	MCM = 4	MCM = 1	
MIW 3 - Conduct magnetic silencing	MOP 1 - MCM, MOP 2 - MCM Module	MCM = 4	MCM = 1	
MIW 4 - Conduct mine laying	MOP 1 - MCM, MOP 2 - MCM Module	MCM = 4	MCM = 1	
MIW 5 – Conduct mine avoidance	MOP1 – MCM	MCM = 4	MCM = 1	DV10 – MCM
MIW 6.7 – Maintain magnetic signature limits	MOP 23 – Magnetic Signature	Steel	Composite Hull	DV4 – Hull Material type
		No	Yes	DV 8 – Degaussing System
MOB 1 - Steam to design capacity in most fuel efficient manner	MOP10 – Sprint range	50 nm	250 nm	DV1 – Hull form, DV2 - Displacement, DV 7 – Propulsion System alternative
	MOP11 – Endurance range	500 nm	1500 nm	
	MOP13 – Sprint speed	15 knots	25 knots	
MOB 3 - Prevent and control damage	MOP16 – Structural vulnerability	Steel Hull	Composite Hull	DV4 – Hull material type
	MOP17 – Personnel vulnerability	25	10	DV9 – Manning and automation factor
	MOP21 – Acoustic signature	Mechanical	IPS	DV7 – Propulsion System alternative
	MOP22 – IR Signature	Stirling Cycle w/ battery backup	Closed Cycle Diesel (For now) w/ battery backup	DV7 – Propulsion System alternative
	MOP23 – Magnetic signature	Steel Hull	Composite Hull	
		No Degaussing	Degaussing	DV8 – Degaussing system
MOB 7 - Perform seamanship, airmanship and navigation tasks (navigate, anchor, mooring, scuttle, life boat/raft capacity, tow/be-towed)	Required all designs			
MOB 10 - Replenish at sea	Required all designs			
MOB 12 - Maintain health and well being of crew	Required all designs			
MOB 13 - Operate and sustain self as a	MOP11 – Endurance range	500 nm	1500 nm	DV1 – Hull form

forward deployed unit for an extended period of time during peace and war without shore-based support				DV2 – Displacement DV7 – Propulsion System alternative
	MOP12 – Provisions	14 days	24 days	DV18 – Provisions Duration
MOB 14 - Operate in a Piggy-Back configuration	Required all designs			
MOB 16 - Operate in day and night environments	Required all designs			
MOB 18 - Operate in full compliance of existing US and international pollution control laws and regulations	Required all designs			
NCO 3 - Provide upkeep and maintenance of own unit	Required all designs			
SEW 2 - Conduct sensor and ECM operations	Required all designs			
SEW 3 – Conduct sensor and ECCM operations	Required all designs			
SPW 1 - Provide lock out chamber	Required all designs			
SPW 2 - Habitability Module	Required all designs			
SPW 3 – Deploy Special Forces troops	Required all designs			

Values of performance (VOP) are figures of merit indexes specifying the value of a specific MOP to a specific mission area for a specific type of mission. These VOPs are values between zero and one with one corresponding to the goal value and zero corresponding to the threshold value. Values of performance for values between the goal and threshold values are calculated from functions that are created from expert opinions. The MOPs used to determine the OMOE for each design are shown in Table 16. Each MOP is weighted via pairwise comparison to give a relative importance to the overall effectiveness of the design. Each MOP is based on the balanced ship produced from the design variables. The related design variables used in the optimizer are also shown in Table 16.

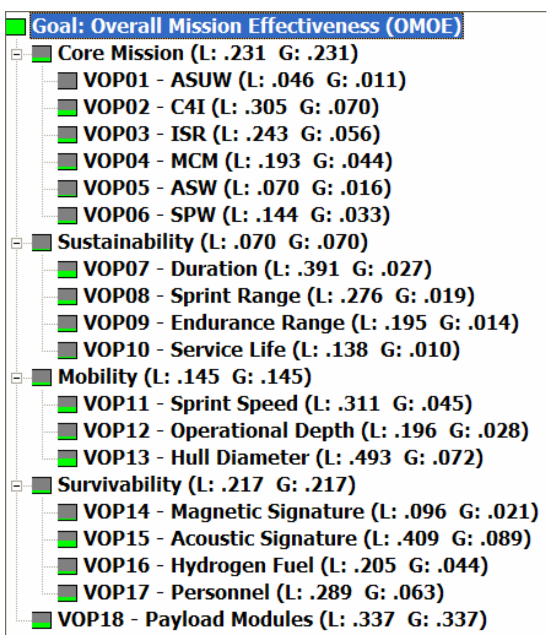

Figure 19 - OMOE Hierarchy

Table 16 - MOP Table

Primary MOP or Constraint	Threshold or Constraint	Goal	Related DV
MOP 01 - MCM	MCM = 4	MCM = 1	DV10 - MCM
MOP 06 - C4ISR	C4ISR = 2	C4ISR = 1	DV14 - C4ISR
MOP 08 - ASW	ASW = 4	ASW = 4	DV13 - ASW
MOP 10 - Sprint Range	200 nm	300 nm	DV2 - Displacement
MOP 11 - Endurance Range	500 nm	1500 nm	DV1 -Hull Form
MOP 12 - Provisions	14 days	24 days	DV2 - Displacement
MOP 13 - Sprint Speed	15 knots	25 knots	DV3- Propulsion DV18 - Provisions Duration DV1 -Hull Form
MOP 16 - Structural Vulnerability	Steel	Composite Hull	DV2 - Displacement
			DV3- Propulsion

MOP 17 - Personnel Vulnerability	25	10	DV4 - Hull Material Type
			DV9 - Manning and Automation Factor
MOP 18 - Special Ops	Swim	Wet sub	DV1 -Hull Form
MOP 19 - Hull form	Exterior	Interior	DV1 -Hull Form
MOP 2 - MCM Modules	MCM = 4	MCM = 1	DV10 - MCM
MOP 21 - Acoustic signature	Mechanical	IPS	DV7 - Propulsion System alternatives
MOP 22 - IR Signature	Stirling Cycle w/ battery backup	Closed Cell Diesel w/ battery backup	DV3- Propulsion
MOP 23 - Magnetic Signature	Steel	Composite Hull	DV4 - Hull Material Type
	No	Yes	DV8 - Degaussing System

Equation 1

$$OMOE = g[VOP_i(MOP_i)] = \sum_i w_i VOP_i(MOP_i)$$

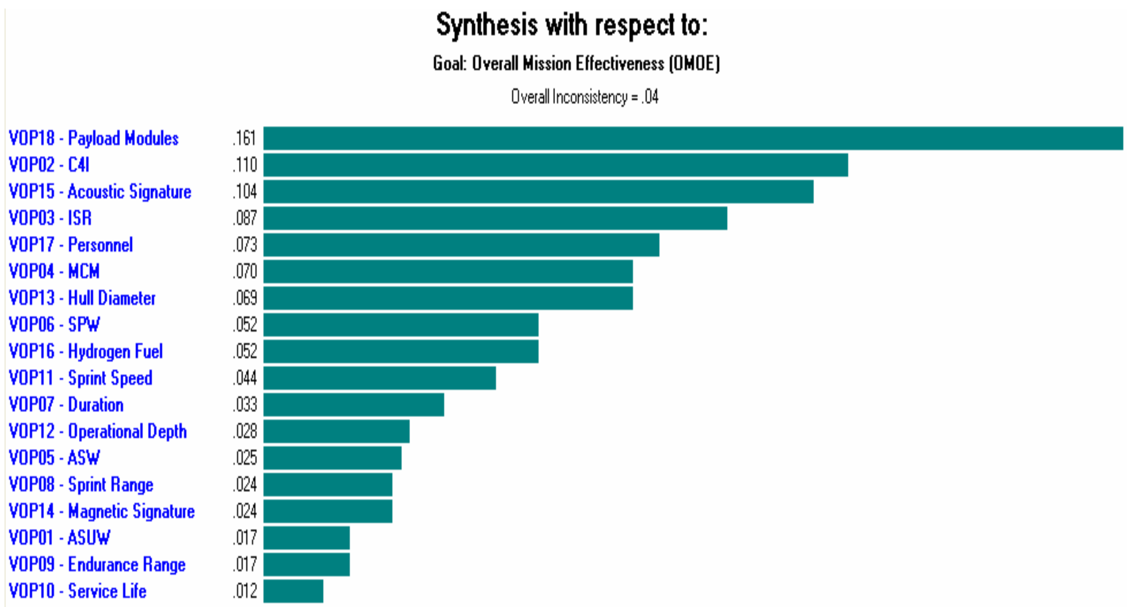

Figure 20 – VOP Weights per OMOE Synthesis

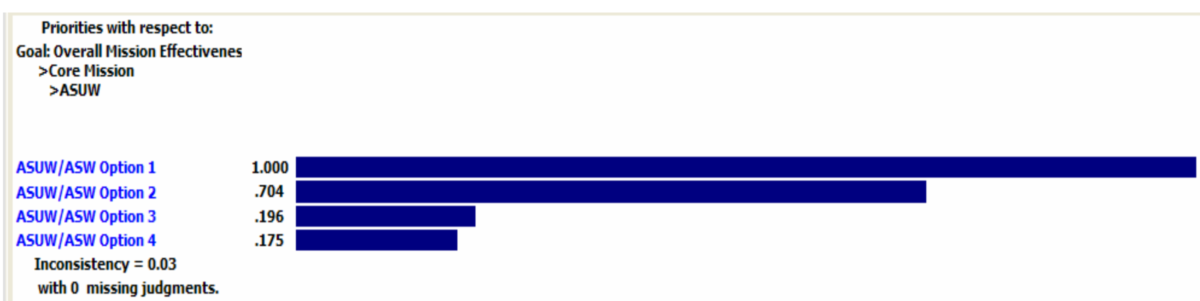

Figure 21 - Value of Performance Function for ASW Alternative

3.5.2 Overall Measure of Risk (OMOR)

Risk is the likelihood that a problem could arise in the design or construction of the submarine. This problem could be such that it affects the cost, production schedule or performance of the vessel. The failure of a vendor to achieve a desired level of performance for a ship system or cost overruns associated with the development and implementation of a system are examples of possible problems. In order to judge the overall risk of a design, a metric similar to the OMOE is necessary. This Overall Measure of Risk (OMOR) is a value (0-1.0) that allows for the comparison of the level of risk of two designs. The OMOR is created by identifying risk events and then estimating the probability of occurrence for each risk event (P_i) and the consequence of occurence (C_i). The probability and consequence of a risk event can be estimated using the Navy Standards shown in tables 18 and 19. The risk of each event is then P_i * C_i. These risk events and their probability and consequence are then compiled into a risk register such as Table 17. Each risk event in turn affects the overall risk to cost, performance or schedule. The risk of the cost, performance or schedule being affected is then further weighted to achieve the OMOR.

$$OMOR = W_{perf} \sum_i \frac{w_i}{\sum_i w_i} P_i C_i + W_{cost} \sum_j w_j P_j C_j + W_{sched} \sum_k w_k P_k C_k$$

Table 17 - SSLW Risk Register

System	Risk Type	Risk ID	Related DV	DV Description	DV Value	Risk Event Ei	Risk Description	Pi	Ci	Ri
Propulsion	Performance	1	DV16	Primary Power Alternative (PSYS)	1,2	Development, testing and qualification of closed cycle diesel system for US submarine application	System will not meet performance and safety requirements	0.2	0.6	0.12
Propulsion	Cost	2	DV16	Primary Power Alternative (PSYS)	1,2	Development, testing and qualification of closed cycle diesel system for US submarine application	Unexpected problems with development will require more money	0.3	0.3	0.09
Propulsion	Schedule	3	DV16	Primary Power Alternative (PSYS)	1,2	Development, testing and qualification of closed cycle diesel system for US submarine application	Unexpected problems with development will require more time	0.3	0.3	0.09
Propulsion	Performance	4	DV16	Primary Power Alternative (PSYS)	3	Development, testing and qualification of PEM Fuel Cell for US submarine application	System will not meet performance and safety requirements	0.4	0.5	0.2
Propulsion	Cost	5	DV16	Primary Power Alternative (PSYS)	3	Development, testing and qualification of PEM Fuel Cell for US submarine application	Unexpected problems with development will require more money	0.5	0.3	0.15
Propulsion	Schedule	6	DV16	Primary Power Alternative (PSYS)	3	Development, testing and qualification of PEM Fuel Cell for US submarine application	Unexpected problems with development will require more time	0.5	0.3	0.15
Propulsion	Performance	7	DV16	Primary Power Alternative (PSYS)	4	Development, testing and qualification of PEM Fuel Cell with reformer for US submarine application	System will not meet performance and safety requirements	0.7	0.5	0.35
Propulsion	Cost	8	DV16	Primary Power Alternative (PSYS)	4	Development, testing and qualification of PEM Fuel Cell with reformer for US submarine application	Unexpected problems with development will require more money	0.8	0.3	0.24
Propulsion	Schedule	9	DV16	Primary Power Alternative (PSYS)	4	Development, testing and qualification of PEM Fuel Cell with reformer for US submarine application	Unexpected problems with development will require more time	0.8	0.3	0.24
Propulsion	Performance	7	DV16	Primary Power Alternative (PSYS)	5	Development, testing and qualification of Alkaline Fuel Cell for US submarine application	System will not meet performance and safety requirements	0.6	0.5	0.3
Propulsion	Cost	8	DV16	Primary Power Alternative (PSYS)	5	Development, testing and qualification of Alkaline Fuel Cell for US submarine application	Unexpected problems with development will require more money	0.7	0.3	0.21
Propulsion	Schedule	9	DV16	Primary Power Alternative (PSYS)	5	Development, testing and qualification of Alkaline Fuel Cell for US submarine application	Unexpected problems with development will require more time	0.7	0.3	0.21
Propulsion	Performance	7	DV16	Primary Power Alternative (PSYS)	6	Development, testing and qualification of Stirling Engine for US submarine application	System will not meet performance and safety requirements	0.3	0.5	0.15
Propulsion	Cost	8	DV16	Primary Power Alternative (PSYS)	6	Development, testing and qualification of Stirling Engine for US submarine application	Unexpected problems with development will require more money	0.4	0.3	0.12
Propulsion	Schedule	9	DV16	Primary Power Alternative (PSYS)	6	Development, testing and qualification of Stirling Engine for US submarine application	Unexpected problems with development will require more time	0.4	0.3	0.12

Propulsion	Performance	4	DV17	Battery Type (BATtyp)	1	Development, testing and qualification of Lithium Ion battery for US submarine application	System will not meet performance requirements	0.7	0.4	0.28
Propulsion	Cost	5	DV17	Battery Type (BATtyp)	1	Development, testing and qualification of Lithium Ion battery for US submarine application	Unexpected pr oblems with development will require more money	0.8	0.3	0.24
Propulsion	Schedule	6	DV17	Battery Type (BATtyp)	1	Development, testing and qualification of Lithium Ion battery for US submarine application	Unexpected problems with development will require more time	0.8	0.3	0.24
Propulsion	Performance	4	DV17	Battery Type (BATtyp)	2	Development, testing and qualification of Nickel Cadmium battery for US submarine application	System will not meet performance requirements	0.3	0.4	0.12
Propulsion	Cost	5	DV17	Battery Type (BATtyp)	2	Development, testing and qualification of Nickel Cadmium battery for US submarine application	Unexpected problems with development will require more money	0.4	0.3	0.12
Propulsion	Schedule	6	DV17	Battery Type (BATtyp)	2	Development, testing and qualification of Nickel Cadmium battery for US submarine application	Unexpected problems with development will require more time	0.4	0.3	0.12
Weapons System	Performance	7	DV8	ASW System alternative	3,4	Development, testing and qualification external torpedo launch for US submarine application	System will not meet performance requirements	0.5	0.5	0.25
Weapons System	Cost	8	DV8	ASW System alternative	3,4	Development, testing and qualification external torpedo launch for US submarine application	Unexpected problems with development will require more money	0.6	0.4	0.24
Weapons System	Schedule	9	DV8	ASW System alternative	3,4	Development, testing and qualification external torpedo launch for US submarine application	Unexpected problems with development will require more time	0.6	0.4	0.24
Automation	Performance	10	DV6	Manning and Automation Factor	0.5 - 1	Development and integration of automation	System will not meet performance requirements	0.5	0.5	0.25
Automation	Cost	11	DV6	Manning and Automation Factor	0.5 - 1	Development and integration of automation	Unexpected problems with development will require more money	0.6	0.4	0.24
Automation	Schedule	12	DV6	Manning and Automation Factor	0.5 - 1	Development and integration of automation	Unexpected problems with development will require more time	0.6	0.4	0.24

Table 18 - Event Probability Estimate

Probability	What is the Likelihood the Risk Event Will Occur?
0.1	Remote
0.3	Unlikely
0.5	Likely
0.7	Highly likely
0.9	Near Certain

Table 19 - Event Consequence Estimate

Consequence Level	Given the Risk is Realized, What Is the Magnitude of the Impact?		
	Performance	Schedule	Cost
0.1	Minimal or no impact	Minimal or no impact	Minimal or no impact
0.3	Acceptable with some reduction in margin	Additional resources required; able to meet need dates	<5%
0.5	Acceptable with significant reduction in margin	Minor slip in key milestones; not able to meet need date	5-7%

0.7	Acceptable; no remaining margin	Major slip in key milestone or critical path impacted	7-10%
0.9	Unacceptable	Can't achieve key team or major program milestone	>10%

3.5.3 Cost

Lead ship acquisition cost plus life cycle battery replacement cost is used as the cost objective attribute. It is calculated for SSLW as shown in Figure 22. Weights for each of the SWBS groups are used to calculate material cost and labor cost. The total direct cost of the ship is the sum of the cost of labor and the cost of material. To find the indirect cost, an overhead margin is applied. Overhead costs account for all extraneous expenditures beyond the actual labor and material costs. Profit equal to 10% of the total direct and overhead costs is added to calculate the Basic Cost of Construction (BCC). A life cycle cost component for battery replacement is added to BBC.

Direct Costs:

1. Labor Cost: $C_L = \Sigma C_{Li}$
2. Material Cost: $C_M = \Sigma C_{Mi}$
3. Direct Cost: $DC = C_L + C_M$

Indirect Cost:

Enter Overhead Rate: ovhd = 1.2

IC = DC*ovhd

Basic Cost of Construction:

Enter Profit Rate: profit = 0.1

CBCC = (1 + profit)*(DC + IC)

Life Cycle Cost

LCC = CBCC + 20.8*(3 – BatteryType)*10

Figure 22 - SSLW Cost Model

3.6 Optimization Results

The MOGO produced a non-dominated frontier as seen in Figure 23. Design 38 is indicated by a red circle. This design has higher cost than most others in the NDF, but also features a high level of effectiveness compared to its overall measure of risk. The design was chosen by looking for "knees" in the curves of the D=13ft. designs. Its effectiveness is matched or beaten by many of the significantly cheaper D=21ft designs, but they all incur almost double the risk for relatively small effectiveness gains.

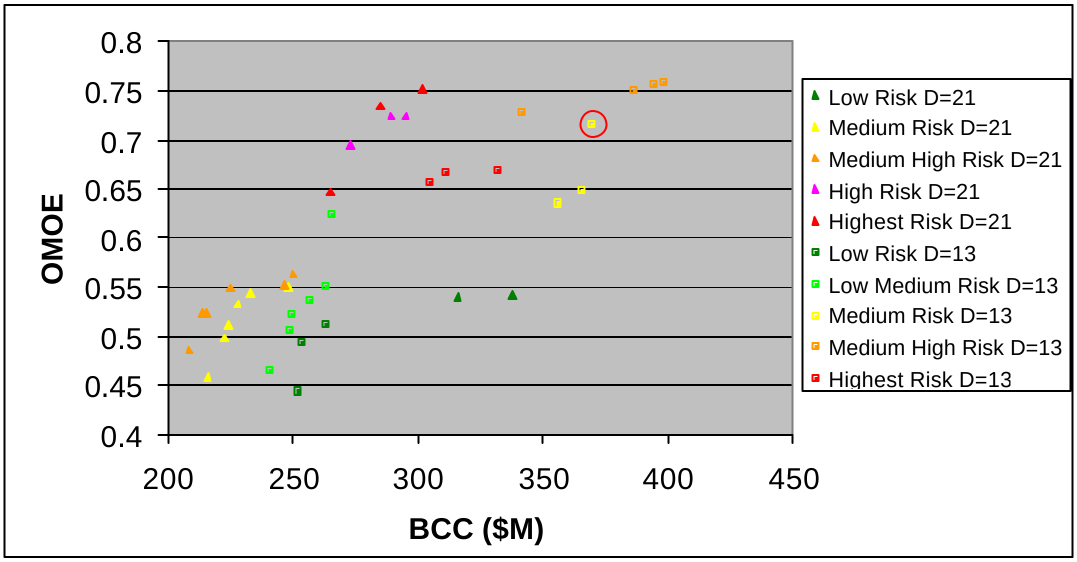

Figure 23 - Non-Dominated Frontier

3.7 Design 38 Baseline Concept Design

Pertinent baseline design characteristics can be seen in the following tables. Baseline design 38 was dubbed "Submersible Covert Reconnaissance – Alternative Platform" or SCRAP by team 4.

Table 20 - Design Variable Summary

Design Variable	Description	Trade-off Range	Your Design Values
DV1	Length of bow section (ft)	25-40	31
DV2	Length of parallel midbody (ft)	30-45	64
DV3	Length of aft section (ft)	40-70	74
DV4	Beam (ft)	30-45	28
DV5	Molded depth (ft)	17-25	13
DV6	Manning reduction factor	0.5-1.0	0.59
DV7	Time on stat ion (days)	14-24	26
DV8	Anti Surface/Submarine Warfare package (option)	1-4	2
DV9	C4ISR package (option)	1-3	3
DV10	MCM package (option)	1-2	2
DV11	Special Warfare package (option)	1-4	3
DV12	Rated Depth (ft)	250-350	290
DV13	Degaussing system (0=no, 1=yes)	0,1	1
DV14	Propulsion system (option)	1-6 (PEM, reformer, diesel)	4 (PEM w/ reformer)
DV15	Battery Type (option)	1-3 (lithium ion, nickel cadmium, lead acid)	3 (lead acid)
DV16	Battery capacity (kWhr)	5000-15000	5700
DV17	Number of generators (number)	1-4	1
DV18	Fuel weight (lton)	5.0-15.0	15
DV19	Number of PIM interfaces (number)	1-4	1

Table 21 - Concept Exploration Weights and Vertical Center of Gravity Summary

Group	Weight (lton)	VCG (ft)
SWBS 100	309	5.2
SWBS 200	201	4.9
SWBS 300	36.6	9.2
SWBS 400	17.5	6.7
SWBS 500	53.5	6.6
SWBS 600	43.6	5.98
SWBS 700	3.57	9.1
SWBS 800	51.9	5.5

Condition A1	665	
Condition A	717	
Normal Surface Condition	843	5.16

Table 22 - Concept Exploration Area Summary

Area	Required	Available
Total-Arrangeable	1783	2206

Table 23 - Concept Exploration Electric Power Summary

Group	Description	Power
SWBS 200	Propulsion	1.08
SWBS 300	Electric Plant, Lighting	4.00
SWBS 430, 475	Miscellaneous	15.4
SWBS 521	Firemain	1.94
SWBS 540	Fuel Handling	2.00
SWBS 530, 550	Miscellaneous Auxiliary	9.09
SWBS 561	Steering	17.6
SWBS 600	Services	5.53
Deguassing	Degaussing	40.0
KW_{NP}	Non-Payload Functional Load	56.6
KW_{MFLM}	Max. Functional Load w/Margins	220.
KW_{24}	24 Hour Electrical Load	100.

Table 24 - Concept Exploration Baseline Design Principal Characteristics

Characteristic	Baseline Value
Hull form	Catamaran, single -deck
WNSC (lton)	843
LOA (ft)	169
Beam (ft)	28
Molded Depth (ft)	13
Length to Beam Ratio	6.04
W1 (lton)	309
W2 (lton)	201
W3 (lton)	36.6
W4 (lton)	17.5
W5 (lton)	53.5
W6 (lton)	43.6
W7 (lton)	3.57
Wp (lton)	51.9
Condition A (lton)	717
KG (ft)	5.16
GB (ft)	1.03
Propulsion system	PEM Fuel Cell w/ Reformer
Propulsor	Dual shrouded propulsors w/ DPJP/ducted thrusters
ASW system	2 (VOP=0.111)
MCM system	2 (VOP=0.333)
C4ISR system	3 (VOP=0.694)
SPW system	3 (VOP=1)
Total Officers	3
Total Enlisted	9
Total Manning	12 (plus eight special forces

Characteristic	Baseline Value
	personnel)
Number of PIMs	1
Ship Acquisition Cost	$196M
Life Cycle Cost	$369M

4 Concept Development (Feasibility Study)

Concept Development of SCRAP follows the design spiral, seen in Figure 24, in sequence after Concept Exploration. In Concept Development the general concepts for the hull, systems and arrangements are developed. These general concepts are refined into specific systems and subsystems that meet the ORD requirements. Design risk is reduced by this analysis and parametrics used in Concept Exploration are validated.

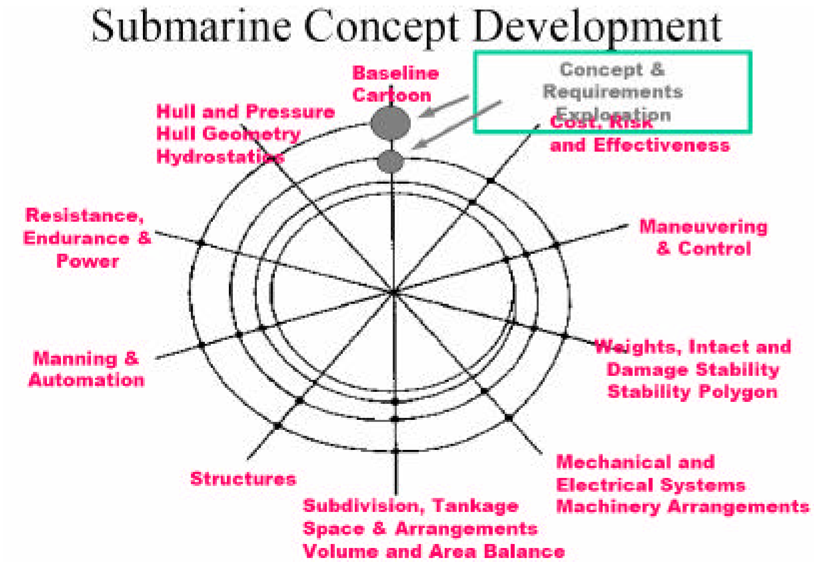

Figure 24 - Submarine design spiral

4.1 General Arrangement and Combat Operations Concept (Cartoon)

The general arrangement concept for the Littoral Warfare submarine was not derived from the traditional US Navy submarine arrangements. These general arrangement designs are dictated by a submarine's unique size, shape, and using the space as effectively as possible. The shape chosen for the SCRAP submarine concept is far different from anything the US Navy has explored in the past. SCRAP will be separated into two compartments, divided by a transverse bulkhead. The aft compartment, the Engine Room (ER), is dedicated to the main propulsion and all that it encompasses; including the fuel cells, bus panels, potable water system, and the majority of the auxiliary machinery. The bow compartment, called the Operational Compartment (OC), holds all the men and material necessary to complete the mission. This includes mission systems, electronic equipment, berthing, messing, and the control room. Another key component in the submarine 'cartoon' design is the Payload Interface Module, located in the center of the hull. This location was chosen because it provided the least effect on the boat's list and trim during loading and unloading of payloads. The variable ballast tanks (VL) are located forward and aft at the ends of the hull, as well as a Payload Compensation Tank (PLC) that surrounds the Payload Interface Module. This tank is designed as a hard tank to take in seawater to the trim and drain system, and to compensate the weight of expended payloads. While the Main Ballast Tanks allow SCRAP to surface and submerge, the variable ballast is designed to prevent trim and list situations. These tanks are usually located at opposite ends of the submarine to offer the greatest moment to counteract other forces. The basic cartoon, in profile view, is shown in Figure 25.

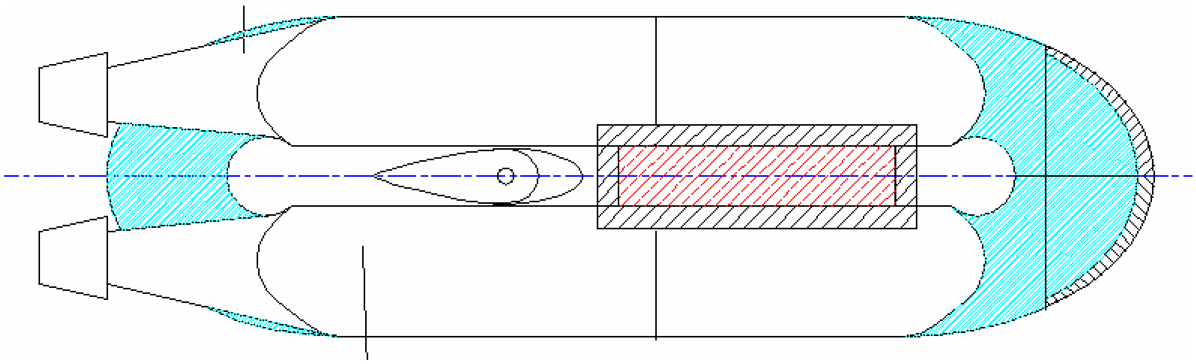

Figure 25 - Cartoon for SCRAP

The desired layout of the Engine Room is different from anything the US Navy has previously deployed. The US Navy has never deployed a PEM or Reformer; therefore the arrangements of the machinery spaces will differ greatly from their nuclear counterparts. Overall the volume of the ER is significantly smaller than that of its nuclear brethren. On current submarines, the Operational Compartment is dictated by the placement of the periscopes, forcing the control room to be located at this point. With the transformational technologies aboard SCRAP, the layout can be more functional.

4.1.1 Mission Operations

SCRAP will also have very unique mission systems because of its particular missions. To support the Special Forces operations, the submarine will have an extremely large diver lockout chamber and a specially configured sail packed with their gear. The Intelligence, Surveillance, and Reconnaissance (IRS) missions will require sophisticated electronics in the Control Room to work in conjunction with the different masts and Mission Augmentation Buoy. The third designated mission is the UUV operations, which will require the support electronics and storage facilities. The final mission system would be the offensive/defensive weapons; ten Mark-50 torpedoes and their fire control electronics, with 4 in internal tubes, and 6 housed externally.

To support the Special Forces missions, SCRAP will have some systems and modifications that other submarines in the fleet do not have. For getting the Special Force operators out of the submarine as fast possible, a 4 diver lockout chamber will be incorporated into the hull. This chamber would have internal and external pressure hatches much larger then standard Navy hatches to allow the operators to enter and exit the chamber with ease. The chamber itself will be located on the centerline of the port hull and slightly forward of the center of gravity, being placed there to keep the submarine as stable as possible. The sail was also specifically designed to hold two Combat Rubber Raiding Craft for the Special Force operators. This small boat will allow the operators a covert surface insertion capability. The CRRC will be stored in the sail's aft section, which will open claw-shell style and have the ability to be operated either submerged or on the surface.

The ISR mission systems will focus on the submarine's 'eyes and ears'; the communication masts and periscopes. Just as with the machinery and electrical systems, COTS technologies will be employed as much as possible to keep cost down and have upgradeability. The Kollmorgen Electro-Optical company produces a fully digital periscope system for the US Navy's Virginia Class submarines. This system has a variety of different cameras for all lighting and environmental conditions, including high definition black and white, color, infrared, and thermal imaging. In the control room of the SSLW there will be 180° wrap-around monitor for the Officer of the Deck to watch instead of putting his eye into the lens of a periscope and have only a pinhole sized view of the surface. SCRAP will have two redundant masts mounted directly within the sail. These masts are non-penetrating, so the control room may be divorced from the sail's location. These masts hold the digital cameras, the Electronic Surveillance Measures (ESM) receiver, the communications antennas, and the GPS receiver. The ESM system will be able to recognize the electronic signals radiating from the enemy's coastline and classify them, allowing the crew to tell the fleet of the enemy's radar and communication capabilities. Communications is vital to the Littoral Warfare submarine in staying connected with the rest of the fleet and with the overall command. The antenna will be capable across a wide range of frequencies as well as the ability to link to satellites. Navigation will be based off of a Garmin commercially available GPS system where the small receiver will be mounted in either mast.

The UUV mission systems demand other considerations in the overall design. These UUVs will be deployed out of the submarine through the Payload interface module, or the Kollmorgen Electro-Optical mast. To operate the UUVs, an electronics system will be built into the Control Room with all the rest of the ship control systems. Extra berths in the crew quarters will allow for any personnel who are specific to the UUV operations to come onboard.

Though SCRAP has very specific missions, it is required to have some sort of offensive/defensive weapons. To fulfill this requirement the submarine will carry specially modified Mark-50 torpedoes. The Mk-50 was originally a surface or air launched lightweight torpedo, mounted in launch tubes or hung from a weapon hard-point on a plane or helicopter. But for use onboard SCRAP, six torpedoes will each be stored in a pressure resistant canister mounted within the hull. The fire control system will be located in the Control Room and will be integrated with all the other electronics onboard the submarine so that any of the work stations will be able to fire the torpedoes. The four conventional tubes will be operated in the same manner as their larger counterparts in an attack submarine. Conformal Bow arrays, Passive ranging sonar, and flank arrays comprise the sonar suite, allowing defensive ASW operations. Mine avoidance sonar is also utilized, as the littoral environment is often a heavily mined area. SCRAP has been designed with the ability to utilize NMRS, LMRS, or other anti-mine unmanned vehicles within PIM or externally encapsulated in the hull.

4.1.2 Machinery Room Arrangements

There are two machinery rooms, MMR#1 and MMR#2, located aft of amidships. The rooms are parallel to each other and each contains a propulsion motor and DC/AC inverter. In addition to these, the main machinery rooms contain two power conversion modules, motor control center and a lighting load panel.

The auxiliary machinery room houses some of the pumps used by the submarine. This includes the trim and drain pumps, seawater cooling pumps, freshwater pumps, main hydraulic pump, hydraulic pressure accumulator and the high pressure air compressor. The reverse osmosis distiller is also located in this room.

The PEM room contains the PEM fuel cells, regenerator, and the DC (400V) main switchboard.

Machinery arrangements are discussed in more detail in section 4.7.3.

4.2 Hull Form

The hull form chosen for SCRAP is a flattened oval shape rather then the cylindrical hull normally associated with submarines. Mission requirements demand that the submarine be able to operate in waters less then 100 feet deep, which requires a small molded depth. To accomplish this while also allowing enough arrangeable deck area, a single deck, flattened oval hull form is chosen. An ordinary oval shape was considered, but concerns with excess structural weight and the need for large stanchions called for a more innovative design. A catamaran hull was chosen because it allowed for a large useable deck area in a small hull depth, and provided good structural efficiency for a non-cylindrical design.

The catamaran design is made of three hulls connected together. The two larger outer hulls are 13 feet in diameter, and the smaller inner hull is 7.5 feet in diameter. The hulls join together where the tangent lines from the outer hull would pass through the center point of the center hull, minimizing shear stress, as seen in Figure 26.

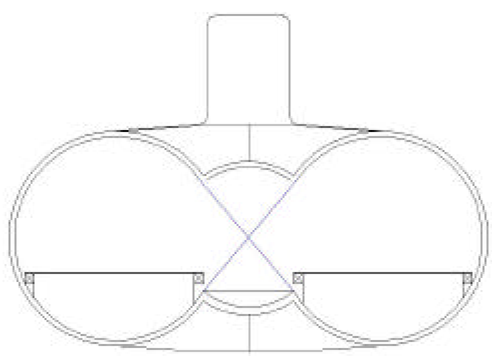

Figure 26 - Hullform Cross Section

The entire pressure load is carried by the hoop stress, just like in a cylindrical hull. The hull itself would be 13 feet tall, 29 feet wide, and 142 feet long; with a sail increasing the height another 5 feet. At the bow, the submarine would have a relatively sharp nose, then 98 feet of parallel midbody, then slope down to a wide flat stern. Research shows that the length of the sloping stern should be approximately 2 times the diameter. In this case, the height was used as the ‘diameter’ and the length of the stern section was determined to be 24 feet.

4.3 Structural Design and Analysis

The structural design process for SCRAP is illustrated in Figure 27. The structural design and analysis was performed in a program called MAESTRO, a coarse-mesh finite element solver and modeler with the ability to assess individual failure modes. After creating the model, stresses are analyzed and then adequacy is assessed for each failure mode. After analyzing the adequacy of each element, the scantlings are adjusted and the hull can be re-evaluated.

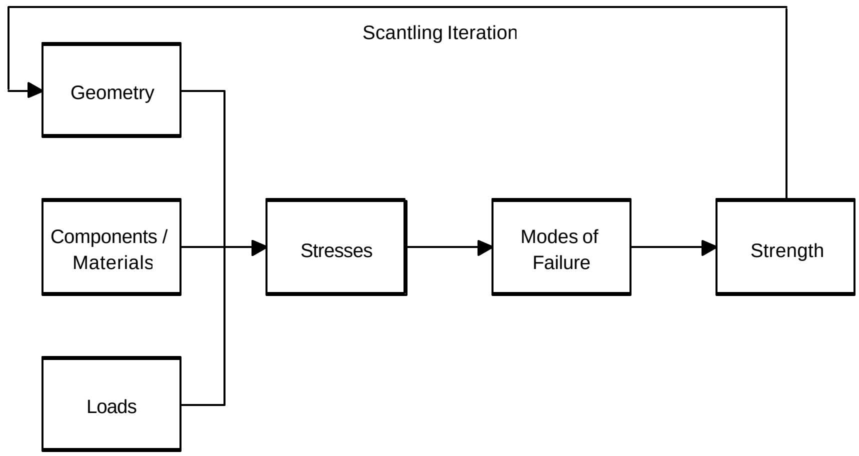

Figure 27 - Structural Design Process

4.3.1 Geometry, Components and Materials

The primary hulls are partial cylinders. The tangency line from the intersection of each primary hull with the center hull runs through the geometric center of the center hull. This tangency allows the X frames to transfer the hoop stress from one primary hull to the other which eliminates shear stress. The pressure hull is completely constructed of HY-80 steel. The pressure hull plate is 1 inch thick with ring frames spaced every 13 inches in the forward and aft sections and every 12 inches in the PIM section of the hull. King frames are located one frame in from the forward and aft endcap and at the forward and aft ends of the PIM. There are no internal structural bulkheads in the pressure hull. It was predicted that MAESTRO may not handle the hemispherical endcaps in the design, so the endcaps were modeled as flat bulkheads.

Table 25 - Scantlings for SCRAP

Stiffener	Web Height (in)	Web Thickness (in)	Flange Width (in)	Flange Thickness (in)
King Frames	12.0	2.0	8.0	2.0
Ring Frames	5.15	0.27	5.03	0.43
X-Frames	9.6	9.6		
Longitudinals	14.06	0.418	10.04	0.718

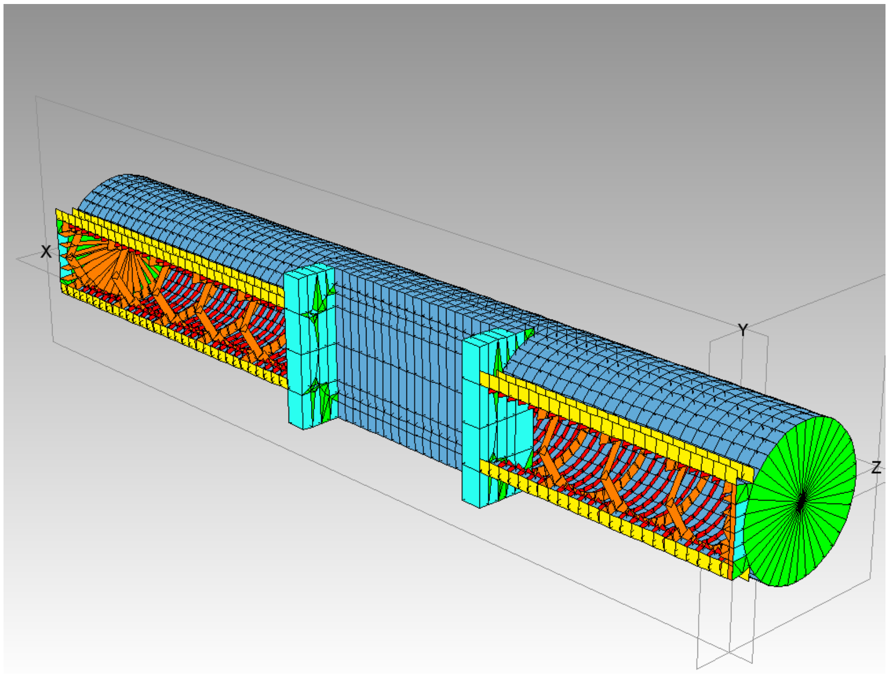

Figure 28 – Pressure Hull Structural Model

4.3.2 Loads

The primary load case for a pressure hull is the pressure and primary structure self weight load at test depth. It is assumed that this is the worst case loading scenario for the submarine. The non-pressure hull was not designed at this stage so hogging and sagging conditions where not considered.

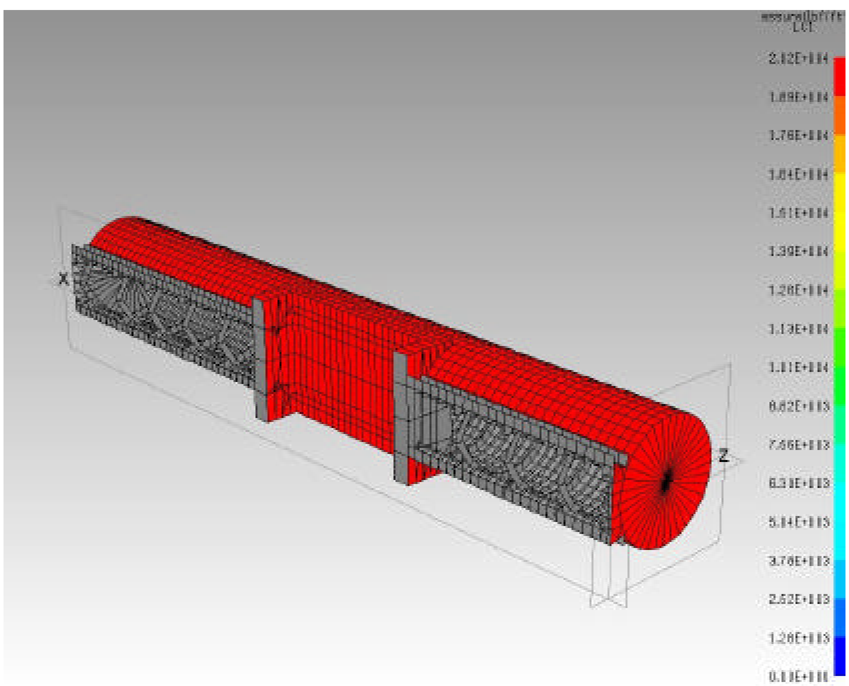

Figure 29 - Load on pressure hull from depth

4.3.3 Adequacy

MAESTRO calculates the stresses caused by each load case and compares them to the limit state values for the various failure modes. Dividing stress by the failure stress for each failure mode yields the strength ratio, r, for that mode. MAESTRO then calculates an adequacy parameter to normalize the results. This parameter is defined as (1-r)/(1+r). This parameter always varies from negative one to positive one. Values close to negative one indicate that an element is extremely inadequate while values close to positive one are extremely over designed. The ideal adequacy value is zero which indicates that the element meets the required strength with a given factor of safety. At this level of design the goal is to make the adequacy as close to zero as possible while keeping it positive. In a more detailed analysis the objective would be to drive the adequacy parameters to zero everywhere. For this submarine the buckling and stiffener failure factors of safety were 2.5 while the membrane yield factor of safety was 1.5. Figure 30 shows the minimum values for plate and beam failure modes for all load cases.

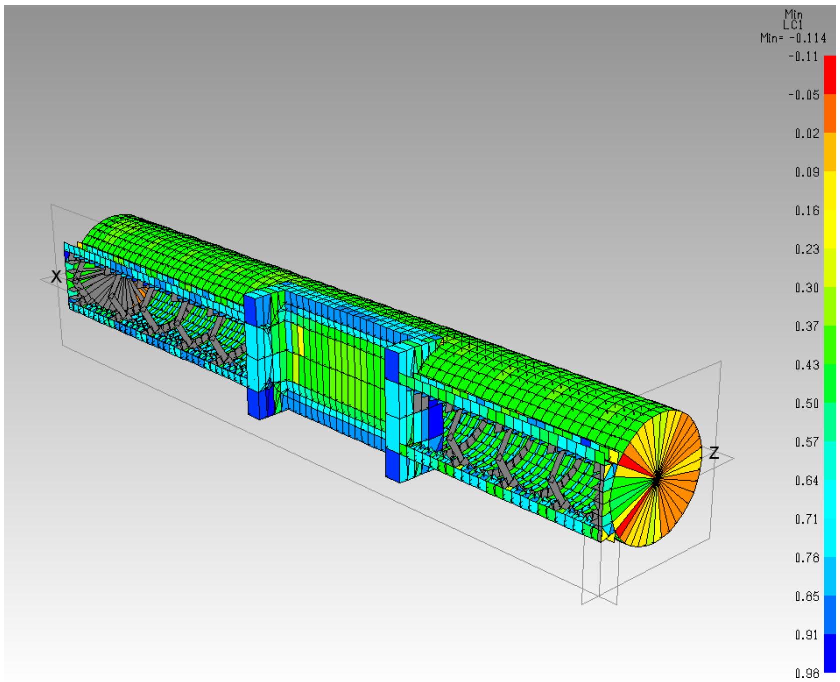

Figure 30 - Plate and beam adequacy

4.4 Power and Propulsion

SCRAP uses an Integrated Power System (IPS) for primary propulsion as well as for ship service power. Power is created by a single 250kW Proton Exchange Membrane (PEM) fuel cell with reformer. Two direct drive permanent magnet motors that are sized for the power requirements power the twin screws.

4.4.1 Resistance

Resistance, speed and power calculations are performed using analytical calculations. Frictional resistance calculations used the ITTC Line, and residuary resistance data was obtained from several empirical analyses performed on a very similar hull design. A standard correlation allowance of 0.0004 was chosen, and a total resistance was calculated. As seen in Appendix G, this resistance calculation was then compared to two independent axisymmetric analytical algorithms, one developed at Virginia Tech, and another developed at MIT. The method developed at Virginia Tech based its algorithm off of a form factor from Gilmer and Johnson in order to find the residual resistance. The MIT method used its own form factor for the calculation. As can be seen from the speed versus power curve in Figure 31, the analytical calculations are all within 5% of each other at the designed sprint speed, and the difference in results are due to the Virginia Tech and MIT method being designed for axisymmetric hull designs. An additional 10% margin is added to the resistance calculation for the endurance speed/fuel calculation and a 25% margin is added for the sustained speed calculation.

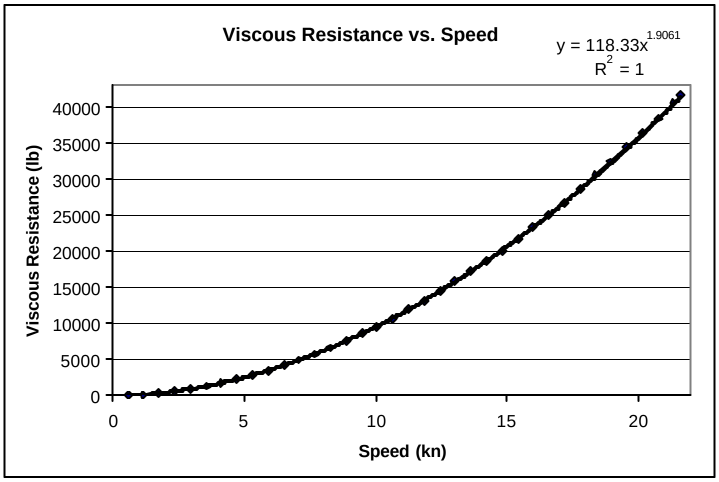

Figure 31 - Plot of resistance vs. speed

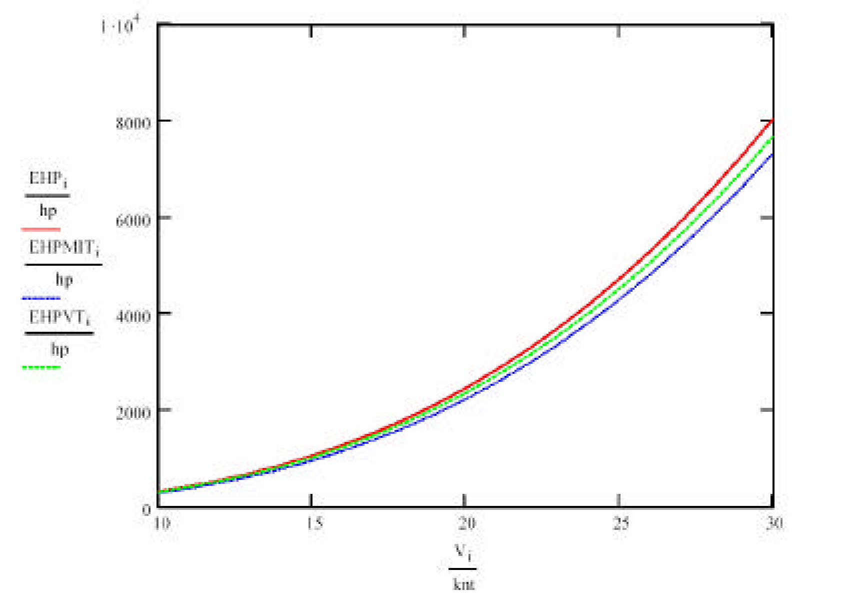

Figure 32 - Plot of EHP vs. speed

4.4.2 Propulsion

The pair of propellers was designed from the B4-55 propeller chart from Principles of Naval Architecture, Volume II. Each propeller is 6.5 ft in diameter, and is powered by a direct drive permanent magnet motor. After the specific four bladed propeller charts were chosen, open-water efficiency was estimated and then iterated in order to find the best propeller characteristics for the design. The calculations and characteristics of the propeller design can be seen in Appendix G. Figure 33 shows shaft propulsion power vs. engine speed, including the 25% sustained speed margin. A more complete propulsion system description and arrangements are provided in Section 4.5 and 4.7.3.

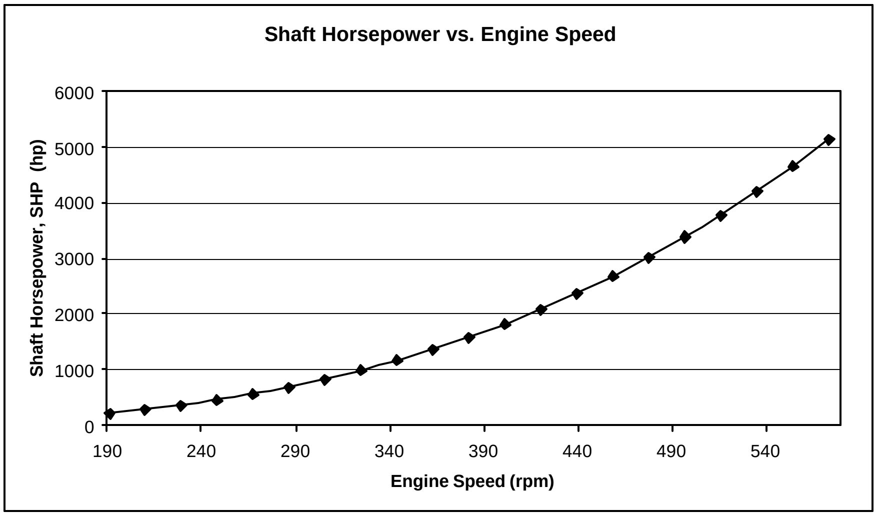

Figure 33 - Plot of SHP vs. shaft speed

4.4.3 Electric Load Analysis (ELA)

Electric power requirements for SWBS groups 100 through 600 equipment and machinery are listed in the electric load analysis summary, Table 26. Load factors are used to estimate the electric power requirement for each component in each of five operating conditions, including endurance, sprint, loiter, mother ship supported, and emergency. The PEM is loaded to its maximum capacity in most conditions. Further iterations of the design could recommend a larger PEM in order to provide more available power.

Table 26 - Electric load analysis summary

SWBS	Description		Endurance (kW)	Sprint (kW)	Loiter (kW)	Mothership supported (kW)	Emergency (kW)
100	Deck		0.0	0.0	0.0	0.0	0.0
200	Propulsion		1.1	1.1	1.1	0.0	1.1
300	Electric		4.0	4.0	4.0	4.0	4.0
400	C&S		58.5	18.5	58.5	18.5	18.5
500	Auxiliary Systems		42.1	42.1	42.1	9.1	42.1
600	Services		32.3	32.3	32.3	32.3	32.3
	Max Functional Load		182.0	142.0	182.0	63.9	98.0
	MFL w/ Margins		220.2	171.8	220.2	77.3	118.5
	24 Hour Average		110.3	88.3	110.3	44.8	64.1
Number	**Generator**	**Rating (kW)**					
1	PEM fuel cell	250	1	1	1	1	1
1	5700kWhr Batteries	2821	0	1	0	0	0
	Power Available (kW)		250.0	3071.0	250.0	250.0	250.0

4.4.4 Fuel Calculation

A fuel calculation is performed for endurance range and sprint range in accordance with DDS 200-1. The fuel calculations are shown in Figure 34, and also in Appendix G. Results indicate an endurance range of 2590 nm and a sprint range of 40 nm satisfying endurance range thresholds specified in the ORD.

Specified fuel rate: $FR_{SP} := f_1 \cdot SFC_{main}$ $\quad FR_{SP} = 0.316 \frac{lbf}{hp \cdot hr}$

Average fuel rate allowing for plant deterioration over 2 years: $FR_{AVG} := 1.05 \cdot FR_{SP}$

$FR_{AVG} = 0.332 \frac{lbf}{hp \cdot hr}$

Tailpipe allowance: $TPA := 0.95$

Endurance Range: $$E := \frac{(W_{FUEL} \cdot V_e \cdot TPA)}{P_{eBAVG} \cdot FR_{AVG} + KW_{24AVG} \cdot FR_{AVG}} \qquad E = 2587\,nm$$

Sprint Range: $$E_S := \left(\frac{E_{battery}}{P_{battery}}\right) \cdot V_S \qquad E_S = 39\,nm$$

Figure 34 - Range and fuel calculation

4.5 Mechanical and Electrical Systems

Mechanical and electrical systems are selected based on mission requirements, standard naval requirements for combat ships, and expert opinion. The Machinery Equipment List (MEL) of major mechanical and electrical systems includes quantities, dimensions, weights, and locations. The complete MEL is provided in Appendix D. The major components of the mechanical and electrical systems and the methods used to size them are described in the following two subsections. The arrangement of these systems is detailed in Section 4.7.3.

4.5.1 Integrated Power System (IPS)

Due to the Navy's commitment to all-electric ships, an integrated power system was selected during the concept development process. By doing this it is possible to utilize direct current to supply a common bus which feeds both propulsion and ship service loads.

Figure 35 shows the one line diagram for the ship's propulsion and service power. The PEM provides 440V, 60 Hz to the ship's primary switchboard. This power may be routed to the ship service loads through Power Conversion Modules and the port and starboard zonal buses, or to the propulsion buses and power converters which control the speed of the ship by varying the AC frequency to the AC propulsion motors. This power can also be diverted to the ship's two independent battery banks. The ship's battery capacity is rated at 5700 kW and can be used to directly power the ship and propulsors.

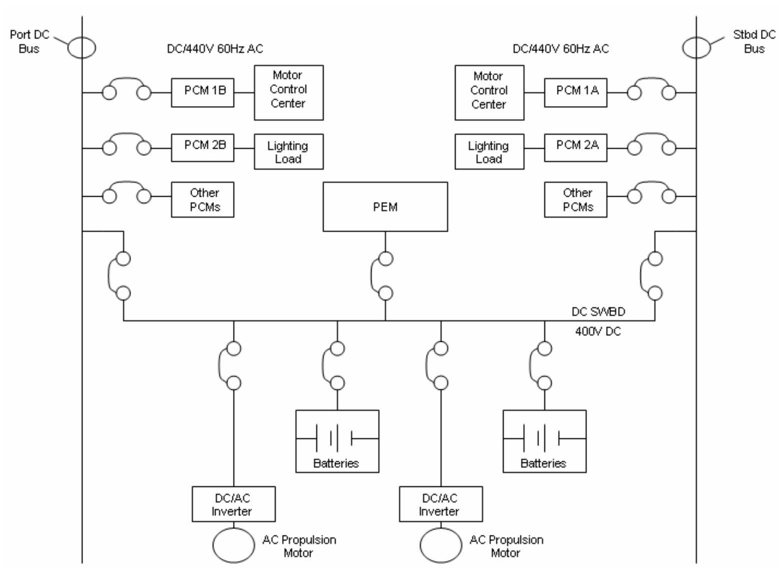

Figure 35 - One Line Electrical Diagram

4.5.2 Service and Auxiliary Systems

Tanks for lube oil, fuel oil and waste oil are sized based on requirements for the Ship Synthesis model. Equipment capacity and size are based on similar ships.

Potable water for the submarine will be produced using a Reverse Osmosis Distiller. These systems work by heating seawater and pushing it through a series of membranes that both remove the salt from the water as well as remove any other impurities. The resulting water's purity is equal to that of distilled water. To maximize efficiency, the PEM Fuel Cells could heat the seawater before it enters the unit.

Environmental control is provided by the submarine fan room located beneath the mast. This includes an induction inlet which can be used to ventilate hull exhaust. This system also includes a CO_2 scrubber and CO_2/H_2 burner.

The submarine also employs a high pressure air compressor for filling and emptying the main ballast tanks. This is used in conjunction with the main, trim and drain pumps to distribute ballast throughout the submarine as well as in the distiller system to pump in seawater.

4.5.3 Ship Service Electrical Distribution

The submarine's integrated power system (IPS) is used to power the propulsion system, provide ship service power, as well as charge the batteries. Power from the PEM is sent to the main switchboard where it can then be distributed to any of the three areas previously described. Ship service power is first sent to the zonal buses where it is then distributed to the Power Conversion Modules (PCM) where it can be converted from DC to AC or AC to DC as needed. These PCMs provide circuit protection and automatic reconfiguration for their particular area.

4.6 Manning

The unique missions and size of SCRAP require that manning be a considerable factor in the overall design. Taking into account all the constraints and requirements placed on the boat, the crew size for the Littoral Warfare submarine is set at 2 officers, 2 chiefs, and 8 enlisted personnel. The limited manning forces the crew to all be highly trained and experienced sailors. There would be no enlisted under the rank of Petty Officer 2nd Class and the officers would minimally be Lieutenants with at least one sea-tour. The crew would be basically split up, with half dedicated to manning the ER and ensuring that all the mechanical systems were maintained and the other half manning the OC and running the submarine. The 8 SEALs are not permanently embarked, therefore are not considered crew. There is one SEAL officer, and seven enlisted men who make up the one embarked SEAL platoon.

Table 27 - Manning summary

Crew Member	QTY	Rank	Duty
CO	1	O-4	All Command Duties
XO	1	O-3	OOD, Engineering Officer, Weapons Officer, Dive, and Navigation Officer
Chiefs	2	E-(6-7)	Chief of the Boat, Dive Chief, Fire Control Chief, Engineering Chief
Operational Crew	4	E-(4-5)	Sonarmen, Radiomen, Diver, Boatswains Mate, Electrical Technician, Cook, Yeomen
Engineering Crew	4	E-(4-5)	Machinists Mate, Electricians Mate, Electrical Technician, Diver

4.7 Space and Arrangements

Submarine space and arrangement plans are made in AutoCAD and Rhino. AutoCAD is used for 2-D drawings of the submarine subdivision and arrangement as well as plan views of the inboard and outboard space and arrangement. Rhino is used for constructing and arranging 3-D views of the submarine hull, main ballast tanks, pressure hull, PIM module, main deck arrangements, tank subdivisions, weapon & combat systems module, habitability module, and machinery spaces. To balance the submarine, tank volumes and other associated volumes are calculated in Rhino. As with all submarines, space is extremely limited for the SCRAP design. At the Concept Development stage, when laying out the Machinery Space, Operation and Living Compartment the focus is not on specifically where items should go and how space should be used, but rather if all of the required systems will fit inside the pressure hull. The hull arrangements are divided into three main sections: Sub-deck, Machinery Space, and Living Compartment.

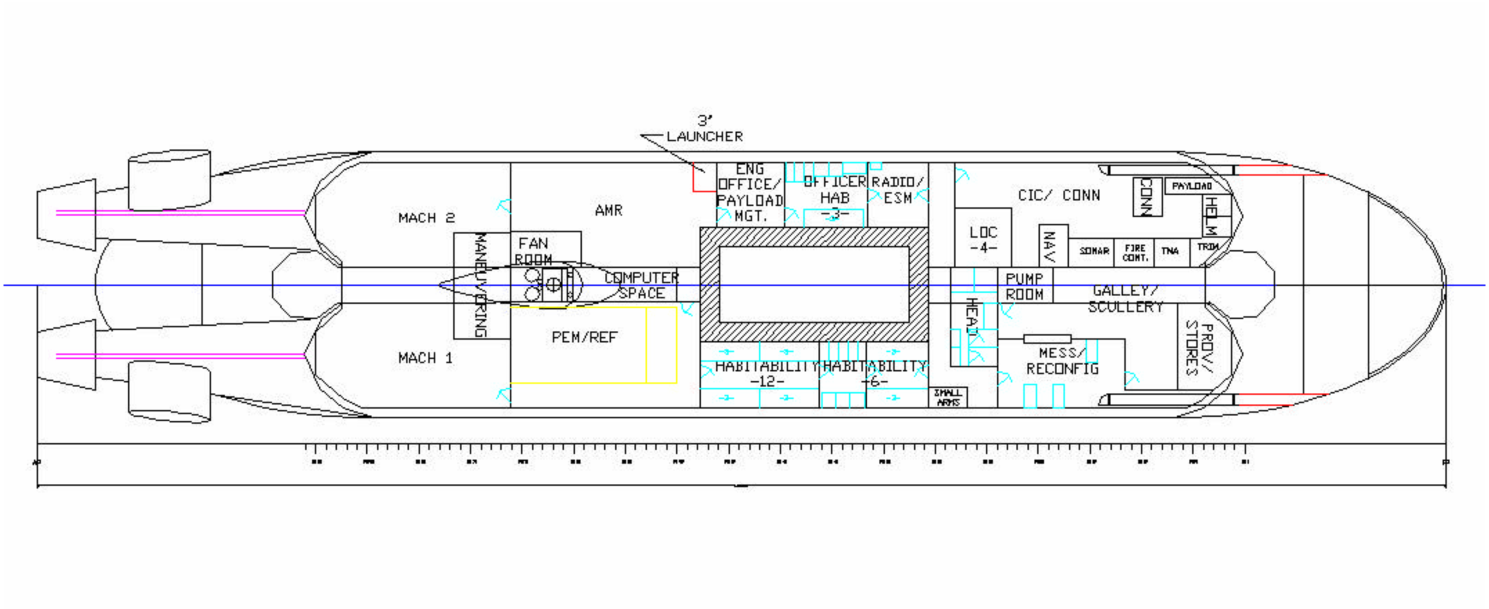

Figure 36 - Plan view with arrangements

4.7.1 Volume

Baseline space requirements and availability in the ship are determined by the ship synthesis model. Volume parameters output by the model are as follows: PIM, propulsion fuel, potable water, sewage, lube oil, battery, auxiliary tank, and main ballast tank. The submarine is modeled in Rhino, and final volumes are taken from the model. SCRAP has a single deck that is divided into enlisted living quarters, officer living quarters, command, mess, commissary, auxiliary machinery, motor and machinery spaces.

4.7.2 Internal Arrangements

SCRAP's pressure hull diameter is 13 feet, providing enough space for only a single deck configuration. The main deck height is set 4.1 feet above the baseline, giving an overhead height of 8.9 feet. This deck height is to ensure enough overhead space for the hull structure, piping, ventilation ducting, and wire-ways. Below the main deck, there is a crawl space for tanks, batteries, auxiliary rooms. The arrangement of this space is shown in Figure 37. Under the main deck, Variable Ballast Tanks (VBT) are located in the each corner, total six tanks. VBT tanks provide the trim and list corrections as the loads change within the hull. The VBT affect will be maximized by placing them as far from the longitudinal and transverse centers of gravity. Auxiliary thank 1 and 2 is followed by the three forward trim tanks respectively. These tanks can be used for extra fuel, lube oil, waste oil, and other liquid storage. After Auxiliary tank 1 and 2, water and sewage tanks are located. These are directly under the galley and head. Conventional lead acid batteries are used in SCRAP, which are heavier than other compartment sections. Therefore the batteries are located in the center bottom of the submarine to keep the vertical gravity low. They are placed along the longitudinal sides of the PIM module. Diesel fuel tanks are followed by battery storage space in the stern direction. Auxiliary tank 3 is placed after the diesel fuel tanks. This tank can be used for oxygen storage or extra fuel storage.

Table 28 - SCRAP tankage volumes

Tank	Capacity (ft3)
Vwrt	81
V trim fwd	225
V trim aft	271
VAux1	660
VAux2	660
VAux3	1187

V2fuel	1251
Vlo	45.9037587
Vwater	221
V air flask	262
V2ox	961.5
Vsew	56.577647

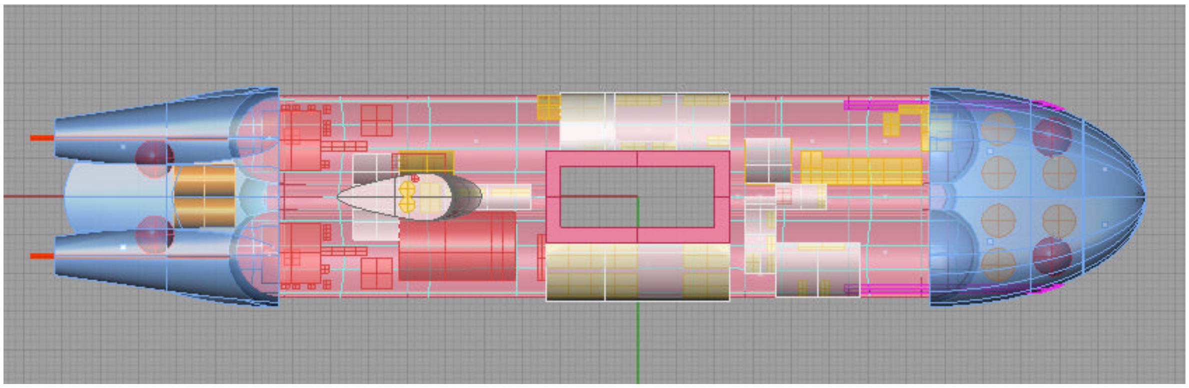

Figure 37 - Under-deck arrangement

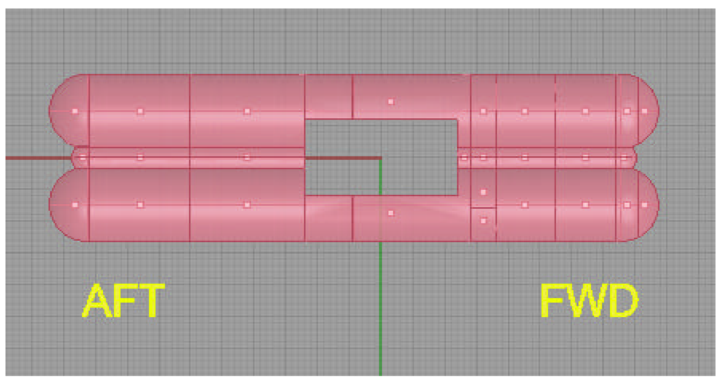

Figure 38 - SCRAP tankage subdivisions

4.7.3 Machinery Room Arrangements

The machinery space is designed to suit the PEM propulsion system and its associated subsystems. This configuration has been implemented by foreign navies on other non-nuclear boats. Since SCRAP uses dual shrouded propellers, identical sets of machinery items and arrangements exist for port and starboard propulsors. Tentative machinery items are as follows: trim and drain pump, reverse osmosis distiller, high pressure air compressor, seawater cooling pump, main hydraulic pumps, freshwater pump, hydraulic pressure accumulator, trim manifold, induction mast inlet, induction and ventilation fans, LP blower, CO2 scrubber, CO/H2 burner, PEM, DC main switchboard, propulsion DC/AC inverters/controllers, and oxygen tanks.

SCRAP implements traditional AC electric motors to drive its propulsors. The primary source of power is the 250kW PEM fuel cell. In this arrangement, there is control equipment consisting of switches, resistance units, and protective devices designed to permit flexibility of control.

The high pressure air compressor, main hydraulic pumps, freshwater pumps, and hydraulic pressure accumulator are located in the auxiliary machinery room space. The air compressor provides the pressurized air for filling and emptying the MBTs as well as other ship systems. This compressor will be a RIX 5R5 system. The 5R5 is an oil free, water-cooled compressor that can handle up to four different gasses and can reach a maximum pressure of 5000 psig. The system uses a screw style compressor stage that virtually eliminates all vibration, therefore decreasing the submarine's overall acoustic signature.

A reverse osmosis distiller (ROD) is used to produce potable water for the submarine. An ROS system works by heating seawater and pushing it through a series of membranes that remove salt as well as any other impurities from the water. The resulting water's purity is the same as of distilled water. In addition to crew health and comfort needs, large amounts of fresh water are needed by Special Forces operators to keep their dive gear and other equipment clean.

The fan room is located vertically under the sail to ensure prompt ventilation in case of an inboard fire breakout. Induction mast inlet, induction and ventilation fans, LP blower, CO2 scrubber, and the CO/H2 burner are located in the fan room.

4.7.4 Living Arrangements

The unique missions and size of SCRAP requires that manning be a considerable factor in the overall design. Taking into account all the constraints and requirements placed on the boat, the crew size for the submarine is set at 3 officers and 1 SEAL officer, 9 enlisted personnel and 7 SEAL enlisted.

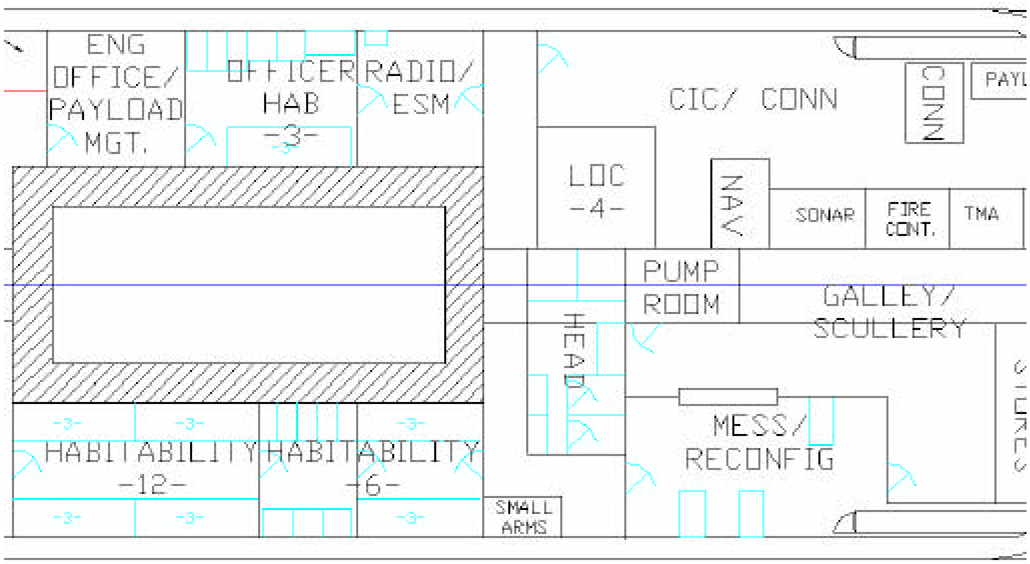

Figure 39 - SCRAP living arrangements

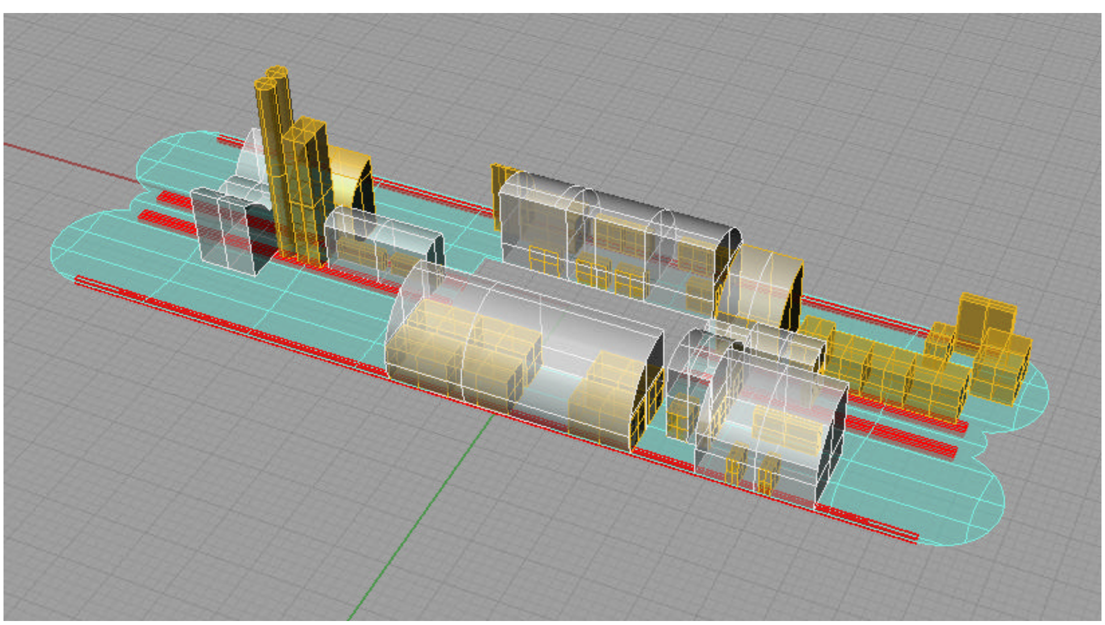

Figure 40 - SCRAP living and operation arrangements

Table 29 - Accomodation space summary

Item	Accommodation Quality	Per Space	Number of Spaces	Area Each	Total Area
Officer	4	4	1	58.51	58.51
Enlisted	16	16	1	158.05	158.05
Officer &Enlisted Sanitary	20	20	1	262.54	262.54
Total			3		479.1

4.7.5 External Arrangements

At this point in the design, the only external arrangements for SCRAP are the PIM module and torpedo tubes. The PIM module is located in the center of the pressure hull, but is independent from the pressure hull and can only be accessed from the outside. PIM hatches will be placed on the top and bottom surface of the hull area exterior to the PIM module space. This allows flexible mission packages and special forces stowage. In the bow section of the submarine, there are total four torpedo tubes penetrating the hull by way of an inboard torpedo access room each holding one torpedo. Inboard stackup length is not available to support internal reloading of these tubes.

Also of note is SCRAP's use of an "x-stern" control plane configuration. This configuration allows better control on the surface than a cruciform stern, and better maneuverability at speed.

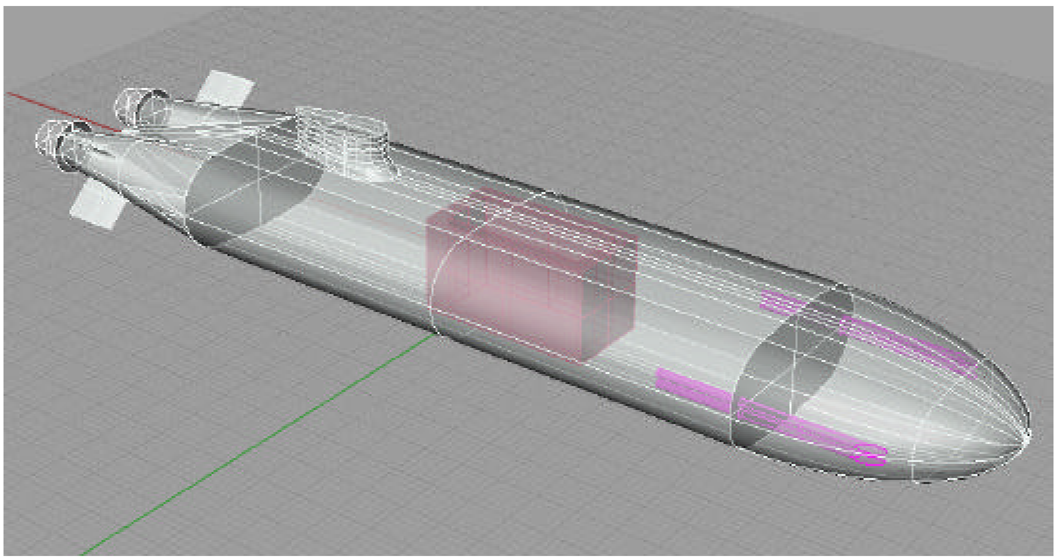

Figure 41 - SCRAP external arrangements

4.8 Weights and Loading

4.8.1 Weights

Ship weights are grouped by SWBS. Where possible, weights were taken from manufacturer information. The pressure hull weight came from the MAESTRO model. Several weights were parametrically modeled from the KAPPA 3 digit weight report. Weight values were taken from the baseline ship synthesis model when there was no other method of estimating them available. Centers are estimated from the general arrangements. A summary of lightship weights and centers of gravity by SWBS group is listed in Table 30.

Table 30 - Lightship Weight Summary

SWBS Group	Weight (lton)	VCG (ft-Abv BL)	LCG (ft-Aft FP)
100	564.25	72.10	6.14
200	635.91	102.22	5.40
300	28.55	83.04	7.32
400	29.58	56.39	4.40

SWBS Group	Weight (lton)	VCG (ft-Abv BL)	LCG (ft-Aft FP)
500	90.26	81.64	7.25
600	58.07	43.31	4.15
700	16.47	29.40	6.55
800	7.82	69.07	7.31
Lightship	1430.92	84.30	5.80

4.8.2 Loading Conditions

Five operating conditions were considered for SCRAP: a normal condition, a light condition, a heavy condition, a heavy forward condition and a heavy aft condition. These are the standard conditions that need to be considered for investigating submarine submerged stability. A stability polygon which shows the ability of the submarine's trim and auxiliary tanks to return the vessel to neutral weight and trim while submerged was plotted. The operating conditions were plotted on the stability polygon to make sure that the vessel is indeed stable at all load conditions. A summary of the load conditions is provided in Table 31. The stability polygon is shown in Figure 42.

Table 31 - Load condition summary

	Req'd Wt (lton)	Req'd Longitudinal Moment
Normal Condition	-969	-5503
Light	-960	-5523
Heavy	-976	-5479

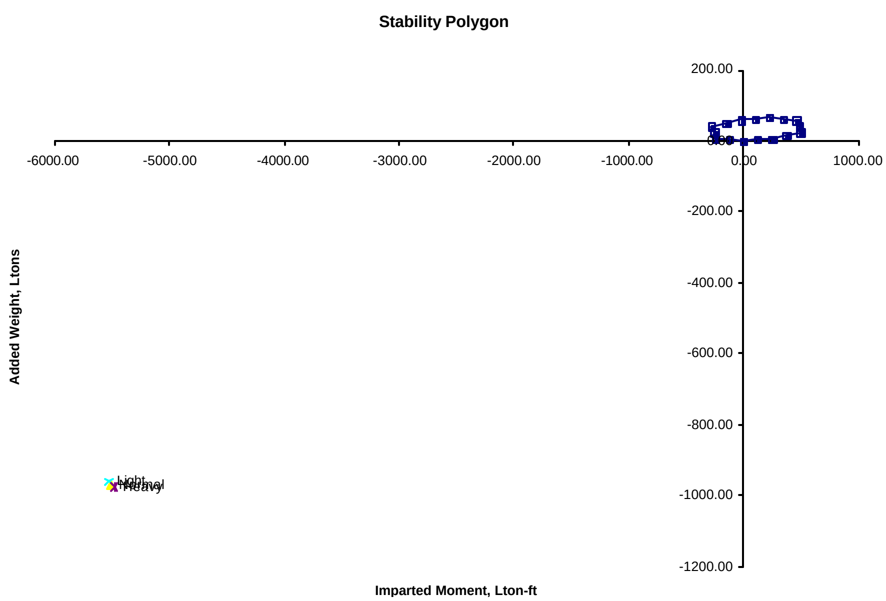

Figure 42 - Stability polygon

4.9 Hydrostatics and Stability

4.9.1 Intact Stability

SCRAP benefits from the inherent stability of the catamaran hullform. On the surface, it has a GM of nearly five feet, and submerged it has a BG of one foot. Both of these values are quite large for a small submarine, and SCRAP may even be too stable, leading to an unpleasant environment for the sailors on board. Submarine designs often suffer from stability problems, and SCRAP is likely no different.

4.9.2 Damaged Stability

SCRAP is at a considerable disadvantage in the area of damaged stability. The low envelope volume and lack of structure to create watertight subdivisions indicate that the design would face catastrophic stability problems if flooded. Additionally, with the lack of the wealth of backup systems seen on nuclear submarines, a casualty to vital pieces of equipment would likely force the abandonment of the ship. As this design is not designed for strike or combat missions, the need for small size and a covert nature outweigh the desire for resilience to damage.

4.10 Seakeeping, Maneuvering, and Control

Submarine seakeeping consists mainly of developing an operating envelope for surfaced operation. If seas develop an unsafe or undesirable operating condition for SCRAP, the crew will dive the boat to a safe depth. Given SCRAP's significant surfaced stability, behavior in light to moderate seas should be acceptable. At depth, the boat will still be subject to wave action from the surface, especially in littoral waters. As on the surface, SCRAP's large GB will provide excellent stability in turbid water.

SCRAP would incur extra research spending, as the maneuvering and dynamic characteristics of catamaran are not well known. Due to the use of the "x-stern" control surface configuration, some sort of computer control system would need to be employed to translate operator inputs to appropriate fin deflections as well as to damp any dynamic instability due to the unorthodox hullform.

4.11 Cost and Risk Analysis

During the initial optimization, the ship synthesis model was programmed to estimate cost and the risk associated with the design parameters that is considers. From this information, a baseline cost and risk assessment was developed, and updated as the design matured though the first iteration of the design spiral.

4.11.1 Cost and Producibility

The cost of SSLW is estimated as a lifecycle cost, based on the diagram shown in Figure 43.

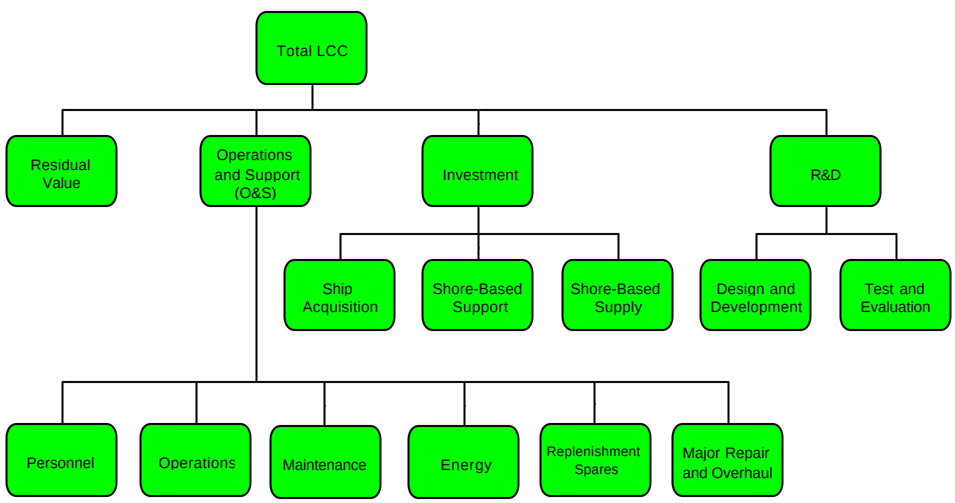

Figure 43 - Lifecycle cost breakdown for SSLW

The investment in research and development of the catamaran concept hull will be significantly more than a conventional cylindrical hull of the same displacement due to the design's relative youth. Extensive testing will be necessary to ensure the safety and performance of the design. Ship acquisition costs simply for vessel construction will be approximately $195.6M. The shore and fleet based support structure for rearming and refueling, as well as underway replenishment of a new class of submarine will also warrant further study as the design matures. These studies will include investigating the merits of Sea Basing or deployment from a mother ship, such as an LHD-class ship with a well deck or moon pool. Operational support costs will be much the same as a conventional submarine design with a crew of 20. The NR-1 research submarine was studied to form a baseline operations and support model for the SSLW, as it is a small special needs submarine. The overall lifecycle cost of the SSLW is estimated to be $369M.

4.11.2 Risk Analysis

As with any new ship design, a certain amount of risk is included with the development of new systems and technologies. These risks were assessed by assigning a value to the likelihood of the risk event to occur, and the level of impact that the risk event would have on the boat. This data was fed into the optimization program, which developed an Overall Measure of Risk, or OMOR. The SSLW concept chosen as the baseline for this design was given an OMOR of .4436, which is classified as “medium”. This higher level of risk is attributed mainly to the use of a PEM and Reformer as the primary means of powering the boat, the use of externally encapsulated torpedoes, and the innovative catamaran hullform design. However, the boat’s risk is mitigated through the use of extremely reliable and field-tested lead acid batteries.

5 Conclusions and Future Work

5.1 Assessment

Much work was undertaken to produce a design from the baseline characteristics specified by the optimizer. Work carried out in Concept Development has shown that the optimizer produced some optimistic baseline numbers and some conservative. With the added surface area of a catamaran hullform, SCRAP cannot reach its intended sprint speed of 21.6 knots. This additionally affects the sprint range. The endurance range calculated in the propulsion section of this document proved to be much higher than expect, and is almost enough for a transit of the Atlantic Ocean. Structural adequacy will most likely allow for a diving depth beyond 300 feet.

Overall, the final concept baseline shows a close agreement with the specifications of the ORD as well as the original concept baseline, as seen in Table 32.

Table 32 - Compliance with Operational Requirements

Technical Performance Measure	ORD TPM (Threshold)	Original Goal	Concept BL	Final Concept BL
Number of PIMs	1	1	1	1
Endurance range (nm)	1113	500	2590	2590
Sprint range (nm)	43.6	50	40	40
Stores duration (days)	26	30	29	29
Diving depth (ft)	290	300	290	300+
Sustained speed Vs (knt)	21.6	25	21.6	20
Crew size (excluding SPW or mission techs)	13	10	13	13
SPW/Mission techs	8	8	8	8

5.2 Future Work

There is still much work to be accomplished on the SCRAP concept baseline.

- Perform analyses or research to discover SCRAP’s dynamic stability and maneuverability as well as seakeeping characteristics. Are there any issues maneuvering at speed? Can they be corrected through computer control or design alteration?
- Conduct further research into submarine propulsors. The 4-bladed B-series propulsor used here is an acceptable first guess, but using high-skew props with 7 blades or more may be more efficient, allowing higher sprint speeds and longer endurance ranges.
- Revise weight and volume estimates. SCRAP in its current form suffers from a lack of buoyancy. Can additional tankage or other volumes balance the design? Achieve a more accurate weight estimate.
- Review arrangements and tankages. Is the design maximizing useable space? Can it be more functional? Are there issues with arrangements, especially in regards to fuel cell/reformer and machinery arrangements? Can the fuel cell be scaled to produce more power (300kW+)?
- Long term: Investigate mother-ship/Sea Base arrangements available to SCRAP. Can it utilize an LHD-type ship with a well deck/moon pool? What other options (near term and long term) are available for SCRAP’s transit-to-station?

5.3 Conclusions

As previously listed, there are still many concerns with the SCRAP design in its current state. However, the research involved in addressing these concerns is beginning at many universities and US Navy labs. Fuel cell power is currently deployed by foreign navies, and many other systems are available as off-the-shelf commercial solutions.

The need for a submarine design with SCRAP's capabilities cannot be ignored. Featuring a propulsion plant with fewer moving parts than a nuclear reactor and the size to operate in the enemy's rivers and harbors, SCRAP would serve to revolutionize the United States warfighting system by providing quick and quiet transit for special forces teams, reconnaissance packages, AUVs, and even limited-range strike weaponry. Modern concerns over piloting nuclear vessels close to shore in hostile waters would be immaterial, as would qualms with placing hundreds of lives in harms way.

SCRAP provides a more capable operator delivery platform than current technologies such as DSRV or ASDS, and does so at a fraction of the cost of the new *Virginia*-class submarines. This boat is quiet, relatively quick, and has the provisions for extended independent operation. SCRAP can deploy multiple modular flexible mission packages that are easily and quickly loaded and can be configured to extend SCRAP's mission capabilities or solve entirely new problems. With only a few knowledge barriers to hurdle, SCRAP is highly effective with minimal risk, and is the ideal solution to the new model of covert warfare.

Submersible **C**overt **R**econnaissance **– A**lternative **P**latform: Changing the way freedom is delivered.

References

1. Brown, A.J., “Ship Design Notes”, Virginia Tech AOE Department, 2004.

2. Comstock, John P., ed. Principles of Naval Architecture, New Jersey: Society of Naval Architects and Marine Engineers (SNAME), 1967.

3. Gilmer, Thomas C. and Johnson, Bruce. Introduction to Naval Architecture. Naval Institute Press, Annapolis, MD, 1982

4. Harrington, Roy L, ed. Marine Engineering. New Jersey: Society of Naval Architects and Marine Engineers (SNAME), 1992.

5. *U.S. NavyFact File*. 2004. U.S. Navy Home Page. http://www.chinfo.navy.mil/navpalib/factfile/ffiletop.html

Appendix A – SSLW Mission Need Statement (MNS)

MISSION NEED STATEMENT

FOR

Littoral Warfare Submarine – SSLW

1. DEFENSE PLANNING GUIDANCE ELEMENT.

With the collapse of the Cold War, the Department of the Navy developed a new policy, called "From the Sea". This document outlines a significant change in priorities from a "Blue Water Navy fighting a traditional Super Power". The rapidly changing global political climate prompted the Department of the Navy to publish a revised policy, "Forward from the Sea", in December 1994. This policy set forth a directive for the Navy and Marine Corps team to have faster and more conflict specific responses. Most recently, the Quadrennial Defense Review Report and the Department of the Navy's new whitepaper, "Naval Transformational Roadmap," provide additional unclassified guidance and clarification on current DOD and USN defense policies and priorities.

The Quadrennial Defense Review Report identifies six critical US military operational goals. These are: protecting critical bases of operations; assuring information systems; protecting and sustaining US forces while defeating denial threats; denying enemy sanctuary by persistent surveillance, tracking and rapid engagement; enhancing space systems; and leveraging information technology.

The Naval "Transformational Roadmap" provides the US Navy's plan to support these goals including nine necessary warfighting capabilities in the areas of Sea Strike – strategic agility, maneuverability, ISR, time-sensitive strikes; Sea Shield – project defense around allies, exploit control of seas, littoral sea control, counter threats; and Sea Base – accelerated deployment & employment time, enhanced seaborne positioning of joint assets.

This Mission Need Statement specifically addresses six of these warfighting capabilities. They are: ISR, time-sensitive strike, accelerated deployment and employment time, information operations, littoral sea control, and mine countermeasures. While addressing these capabilities, there is also a need to reduce cost and minimize personnel in harms way.

2. MISSION AND THREAT ANALYSIS.

a. Threat.

(1) Adversaries may range from Super Powers to numerous regional powers, and as such the US requires increased flexibility to counter a variety of threat scenarios that may rapidly develop. There are two distinct classes of threats to US national security interests:

(a) Threats from nations with a major military capability, or the demonstrated interest in acquiring such a capability, i.e. China, India, Russia, and North Korea. Specific weapons systems that could be encountered include coastal patrol craft, airborne sub detecting hardware, scuba divers, and other submarines.

(b) Threats from smaller nations who support, promote, and perpetrate activities which cause regional instabilities detrimental to international security and/or have the potential for development of nuclear weapons, .i.e. Iraq and Iran. Specific weapon systems include diesel/electric submarines, land-based air assets, and small littoral attack vessels.

(2) Since many potentially unstable nations are located on or near geographically constrained bodies of water, the tactical picture will be on a smaller scale relative to open ocean warfare. Threats in such an environment include: (1) technologically advanced weapons - land-based attack aircraft, fast coastal patrol gunboats armed with guns and torpedoes, and diesel-electric submarines; and (2) unsophisticated and inexpensive passive weapons – mines and anti-submarine nets. Many encounters may occur in shallow water, which increases the difficulty of detecting and successfully prosecuting targets using standard sonar equipment. Platforms chosen to support and replace current assets must have the capability to dominate all aspects of the littoral environment.

b. Required Mission Capabilities.

Enhance our ability to provide the following capabilities specified in the Defense Planning Guidance:

(1) Extract vital enemy information through covert ISR operations from near-shore locations.

(2) Insert, extract, and support U.S. Special Forces by covert means to shore targets as close as possible.

(3) Conduct precise and timely ASUW/ASW strikes with a stealthy approach and evasion.

(4) Conduct mine countermeasures

(5) Capable of multiple and flexible missions

Given the following significant constraints:

(1) Minimize personnel in harms way.
(2) Reduce cost.

c. Need.

Current assets supporting these capabilities include:

(1) SSN and SSBN submarines with DDS shelters deploying SEALS with the SDV
(2) U.S. Special Forces high speed insertion craft or air dropped
(3) Space-based reconnaissance
(4) Surface Vessels

These assets are costly and/or put significant numbers of personnel in harms way. Their cost does not allow for sufficient worldwide coverage of all potential regions of conflict and sufficient penetration of the littoral zone to carry out the prescribed missions. None of the current assets have the facilities necessary to support continuous ISR operations and Special Forces readiness for time-sensitive missions. The Special Forces have extremely difficult missions that require a level of preparation and pinpoint insertion that none of the assets offer.

There is a mission need for a SSLW support and delivery system or platform to provide the mission capabilities specified in paragraph (b.) above. This transformational system must be developed with highly focused mission goals to attain the stealth ability required for littoral operations.

3. NON-MATERIAL ALTERNATIVES.

a. Change the US role in the world by reducing international involvement.
b. Increase reliance on non-military assets and options to enhance the US performance of the missions identified above while requiring a smaller inventory of naval forces.
c. Increased use of SSNs and SSGNs fitting with DDS and capable of deploying Special Forces.
d. Increasing production of the ASDS, which is coming online FY2003.
e. Increased use of current Special Forces insertion methods via air drop or high speed surface vessels.

4. POTENTIAL MATERIAL ALTERNATIVES.

a. Modify the current ASDS or DSRV design to increase mission time and overall mission effectiveness.
b. Modify existing SSN submarines for shallow water operation.
c. Create a new class of technologically advanced, mid-sized littoral warfare submarine with the ability for covert warfare.

5. CONSTRAINTS

a. The platform must be non-nuclear powered, too keep down cost and manning.
b. The submarine must have an on-station, independent endurance of at least 30 days.
c. The submarine must have a crush depth no less then 300 feet.
d. The platform must be highly producible, minimal time from design to production.
e. The submarine must be fast and covert.
f. The submarine must be capable of upgrades, flexible and multiple missions.

Appendix B – SSLW Acquisition Decision Memorandum (ADM)

1 September 2004

From: Virginia Tech Naval Acquisition Executive
To: SSLW(X) Design Team

Subject: ACQUISITION DECISION MEMORANDUM FOR A LITTORAL WARFARE SUBMARINE (SSLW(X))

Ref: (a) SSLW(X) Mission Need Statement

1. This memorandum authorizes concept exploration for a Littoral Warfare Submarine, as proposed to the Virginia Tech Naval Acquisition Board in Reference (a).

2. Concept exploration is authorized for SSLW(X) consistent with the mission requirements and constraints specified in Reference (a). SSLW(X) will operate from a mother ship, and deploy into restrictive littoral regions. It will utilize passive stealth qualities, relatively small size, and high maneuverability to routinely operate closer to enemy shores than previous US submarines. This will allow SSLW(X) to deploy Special Forces closer to shore, limit their exposure to cold water, provide an offshore base and avoid possible detection. The SSLW(X) will also perform harbor penetration missions to gain detailed ISR and perform MCM needed for battles of the future. UUVs will extend the SSLW(X) mission capabilities to obtain more detailed ISR and perform limited mine hunting operations.

3. Exit Criteria. SSLW(X) shall have a minimum endurance range of 1500 nm at 10 knots, a minimum sustained (sprint) speed of 15 knots, a minimum sprint range of 25 nm, a minimum operating depth of 250 feet, and a service life of 30 years. It shall be completely air-independent. It is expected that 10 ships of this type will be built with IOC in 2015. Average follow-ship acquisition cost shall not exceed $500M. Manning shall not exceed 35 personnel.

A.J. Brown
VT Acquisition Executive

Appendix C– Operational Requirements Document

Operational Requirements Document (ORD)

Littoral Warfare Submarine (SSLW)

Virginia Tech Team 4 –Design Alternative 38

1. Mission Need Summary

This Littoral Warfare Submarine (SSLW) requirement is based on the Virginia Tech SSLW Acquisition Decision Memorandum (ADM) and SSLW Mission Need Statement (MNS).

SSLW will operate from a mother ship or Sea Base to conduct littoral operations. A small crew size will put less people in harms way, and low cost will facilitate efficient forward deployment in numbers. SSLW will support the following missions using interchangeable, networked, tailored modular mission packages and onboard (core) systems:

- Covert insertion, extraction, and support of U.S. Special Forces
- Covert intelligence gathering (electronic, human, and visual)
- Covert, precision mine countermeasures and mine warfare
- Support autonomous and remotely operated land, air, and sea vehicles (multiple, flexible mission packages)

2. Acquisition Decision Memorandum (ADM)

The SSLW ADM authorizes Concept Exploration of a new design for a Littoral Warfare Submarine (SSLW), as proposed to the Virginia Tech Naval Acquisition Board.

3. Results of Concept Exploration

Concept exploration was performed using a multi-objective genetic optimization (MOGO). A broad range of non-dominated SSLW alternatives within the scope of the ADM was identified based on basic construction cost, effectiveness and risk. This ORD specifies a requirement for concept development of SSLW alternative 38. Other alternatives are specified in separate ORDs. Design Alternative 38 is a high-end, medium-risk, single-deck alternative shown in Figure 1.

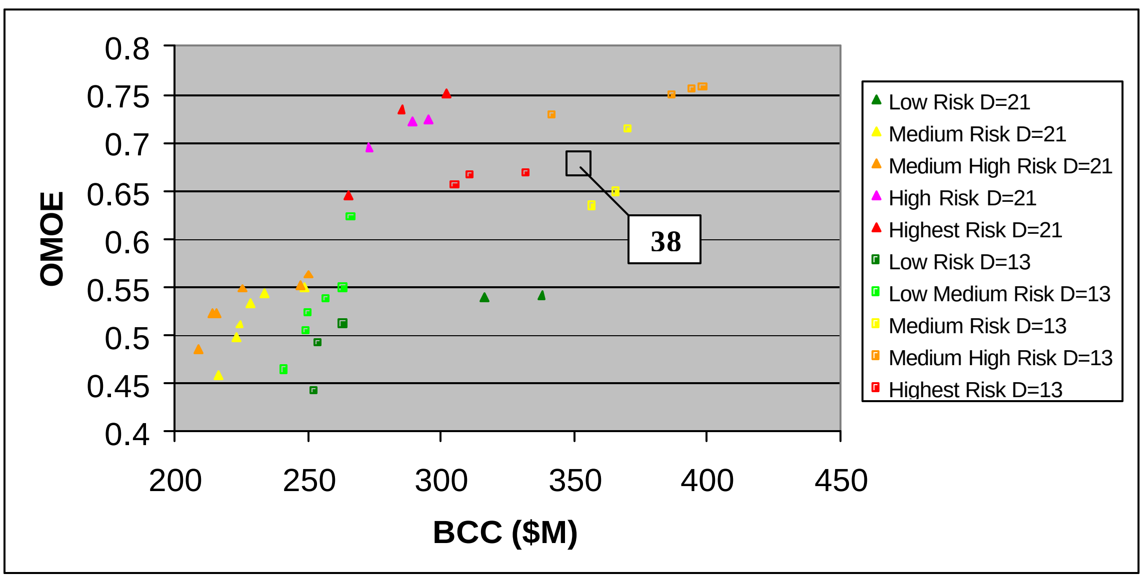

Figure 1 - SSLW Non-Dominated (ND) Frontier

4. Technical Performance Measures (TPMs)

TPM	Threshold
Number of PIMs	1
Endurance range (nm)	1113
Sprint range (nm)	43.6
Stores duration (days)	26
Diving Depth (ft)	290
Sustained Speed Vs (knt)	21.6
Crew size (excluding SPW or mission techs)	13
SPW or Mission Techs	8

5. Program Requirements

Program Requirement	Threshold
Basic Cost of Construction ($M)	375

6. Baseline Ship Characteristics (HI2 Alternative)

Concept development will begin with the following baseline design:

Hullform	Catamaran with partial connecting hull
Hull Material	Steel
Δ (lton) (Wnsc)	1282
LOA (ft)	169
Beam (ft)	28
Depth (ft)	13
W1 (lton)	309.4
W2 (lton)	200.9
W3 (lton)	36.56
W4 (lton)	17.5
W5 (lton)	53.5
W6 (lton)	43.6
W7 (lton)	3.6
$W_{condition\ A-1}$ (lton)	665.1
Lead Ballast (lton)	51.9
$W_{condition\ A}$	716.9
BG (ft)	1.1
Propulsion system	250kW PEM Fuel Cell w/ Reformer IPS
Core Combat Systems	Passive ranging sonar, flank array sonar, integrated bow array sonar, 2 inboard torpedo tubes, 6 external torpedoes, countermeasure launchers, UAV mast launch, Shrike mast, MMA, mine avoidance sonar, degaussing, 9 man lock-out trunk
Number of Payload Modules	1

7. Other Design Requirements, Constraints and Margins

KG margin (m)	1.0
Propulsion power margin (endurance)	10 %
Propulsion power margin (sustained speed)	25% (0.8 MCR)
Electrical margins	5%
Weight margin (design and service)	10%

8. Special Design Considerations and Standards

Concept development shall consider and evaluate the following specific areas and features:

- Ship impact of equipping SSLW with a degaussing system.

- Propulsion plant options shall consider the need for reduced acoustic and infrared signatures while addressing required speed and endurance.
- Reduced manning and maintenance factors shall be considered to minimize total ownership cost

The following standards shall be used as design “guidance”:

- SUBSAFE
- Endurance Fuel: DDS 200-1
- Electric Load Analysis: DDS 310-1

Use the following cost and life cycle assumptions:

- Ship service life = L_S = 15 years
- Base year = 2010
- IOC = 2015
- Total ship acquisition = N_S = 15 ships
- Production rate = R_P = 2 per year

Appendix D – Machinery Equipment List

Item	Equipment Name	Quantity	Dimensions (LxWxH)
1	Trim and Drain Pumps	2	2x1x1 ft
2	Reverse Osmosis Distiller	2	4x4x4 ft
3	High Pressure Air Compressor	1	3x3x3 ft
4	Seawater Cooling Pump	2	2x1x1 ft
5	Main Hydraulic Pump	2	2x1x1 ft
6	Freshwater Pump	2	1x1x1 ft
7	Hydraulic Pressure Accumulator	2	Cylinder: D = 1 ft, L = 2 ft
8	Trim Manifold	2	2x1x1 ft
9	Induction Mast Inlet	1	Cylinder: D = 1ft
10	Induction and Ventilation Fan	2	2x1x1 ft
11	Low Pressure Blower	1	3x3x3 ft
12	CO2 Scrubber	2	1x1x2 ft
13	CO2/H2 Burner	2	1x1x2 ft
14	PEM	1	9x4x9 ft
15	DC Main Switchboard	1	6x1x6 ft
16	Propulsion Motor	2	7.75x7.75x6.67 ft
17	Propulsion DC/AC Inverter	2	2x2x1 ft
18	Power Conversion Module	4	1x1x3 ft
19	Motor Control Center	2	1x1x3 ft
20	Lighting Load Panel	2	1x1x3 ft

Appendix E - Weights and Centers

The weight spreadsheet is maintained in a large set of Microsoft Excel worksheets. They can be found posted on the Team 4 Blackboard group page.

Appendix F – SSCS Space Summary

Space and volume numbers are incomplete currently. This will be updated.

Appendix G - MathCAD Propulsion Model

The propulsion calculations can be found in Team 4's group page on Blackboard as "PropCalc.pdf".