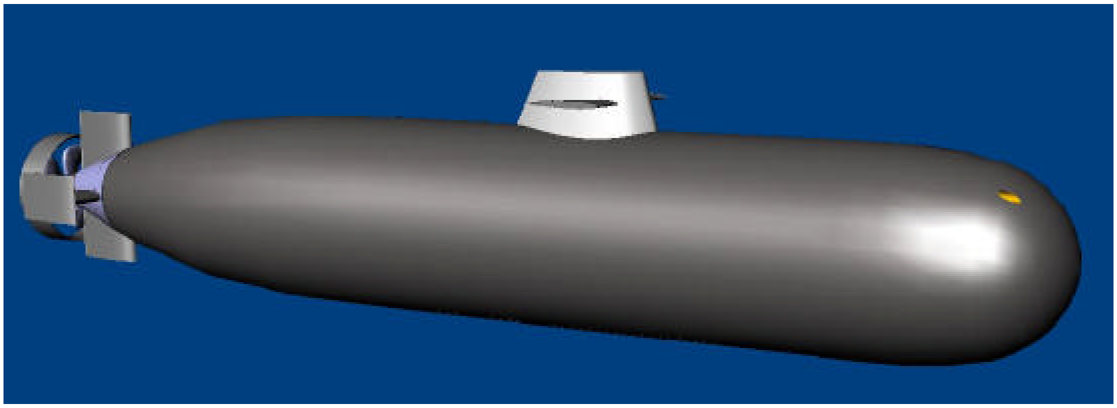
Virginia Tech
Aerospace & Ocean Engineering

Design Report

Littoral Warfare Submarine (SSLW)

VT Total Ship Systems Engineering



ATLAS
Advanced **T**actics **L**ittoral **A**lternative **S**ubmarine
Ocean Engineering Design Project
AOE 4065/4066
Fall 2004 – Spring 2005
Virginia Tech Team ATLAS

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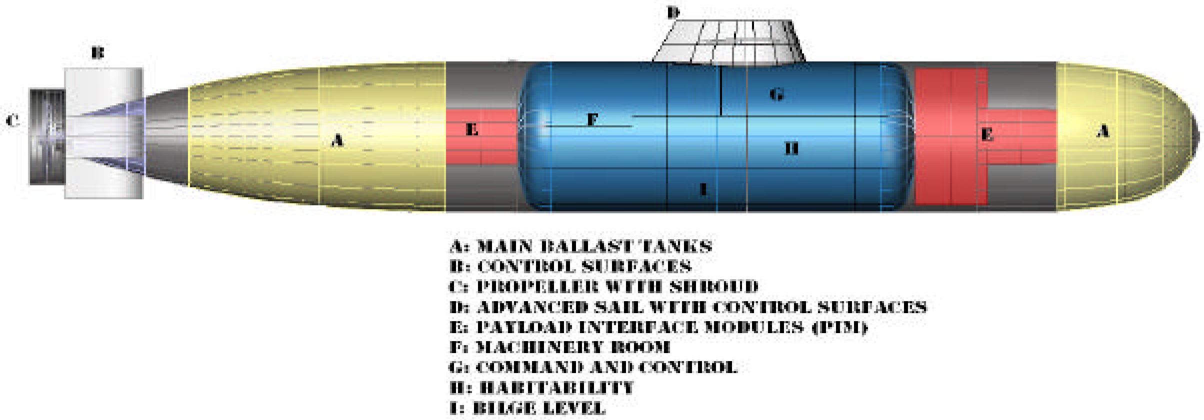
Contract Deliverables Requirements LIST (CDRL)

Design Report Requirement	Pages
Concept Selection/initial definition and sizing	43-45
Table of Principal Characteristics	45
Hull form development and Lines Drawing	47-48
General Arrangements	65-72
Arrangement sketches for typical officer/CPO/crew berthing, messing & sanitary spaces	70-72
Curves of form, hydrostatic curves, floodable length curve	48
Area/Volume summary and tank capacity plan	66,69, 93-98
Structural design and midship section drawing	48-53
Propulsion plant trade-off study	13-20
Machinery Arrangement	47, 66-67
Electrical Load Analysis/electric plant sizing	61
Major H, M, & E systems and equipment characteristics and description	62-64
Weight Estimate (lt. ship & (2) load conditions)	73-75, 91-92
Trim and intact stability analysis	74-75
Damage stability analysis	75
Speed/power analysis	53-56
Endurance Calculations	61-62
Seakeeping analysis	75
Manning Estimate	64-65
Cost analysis	75-77
Risk assessment	78-79

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 technologically advanced, covert, and small submarine capable of entering the littoral area. Mission requirements include Special Forces delivery, extraction and support, mine laying and countermeasures, defensive ASW, Search & Salvage, and AUV support. The submarine is required to have multiple and flexible mission packages.

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 ATLAS is a high risk, two-deck alternative from the non-dominated frontier. The design was chosen to provide a challenging design project. With a cost well within requirements, it is a highly effective submarine. SSLW ATLAS characteristics are listed below. ATLAS has an axisymmetric hullform. Its significant automation keeps Navy personnel out of harms way and reduces cost. Small size allows it to be a versatile design capable of entering areas previously inaccessible. Three payload interface modules allow ATLAS to be highly upgradeable and able to carry out many different missions. Meant for covert operations, it is still able to defend itself with 8 Mark 50 Torpedoes if necessary.

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, equilibrium polygon analysis, 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 assess shallow water motion in waves; assess maneuvering and control; better define and assess operations with payload packages and mother ship; reassess battery power characteristics; and better refine the structure external to the pressure hull.

Submarine Characteristic	Value
LOA	129 ft
Beam	22 ft
Depth	22 ft
Displacement	28088 ft^3
Lightship weight	603.61 lton
Full load weight	715.9 lton
Sustained Speed	26.5 knots
Endurance Speed	10 knots
Sprint Range	31 nm
Endurance Range	1004 nm
Propulsion and Power	250 kW PEM w/ Reformer, 2 Nickel Cadmium battery banks w/ 2700 kW-hr each, 1 AC Synchronous Permanent Magnet Propulsion Motor connected to an 11 ft. diameter propeller.
BHP_{ereq}	332 kW
Personnel	16
OMOE (Effectiveness)	0.724
OMOR (Risk)	0.783
Basic Cost of Construction (BCC)	$ 293.5M
Number of Payload Interface Modules	3
Combat Systems (Modular and Core)	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, side scan sonar, degaussing, 2- four man lock-out trunk
Manning and Automation Reduction Factor	0.51

Table of Contents

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. The SSLW must perform the following missions: (1) covert deployment and extraction of US Special Forces into dangerous littoral areas, (2) intelligence, reconnaissance, and surveillance, (3) mine counter measures, (4) defensive measures against threats, (5) search and salvage, and (6) support AUVs and other modular payloads.

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. AUVs will extend the SSLW mission capabilities to obtain more detailed ISR and perform limited mine hunting operations.

SSLW shall have a minimum endurance range of 500 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 15 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 including SPW personnel.

1.2 Design Philosophy, Process, and Plan

The traditional approach to ship design is largely an 'ad hoc' process. In the past, experience, design lanes, rules of thumb, preference, and imagination have guided selection of design concepts for assessment. Objectives are not always well defined at the beginning of the design process. This project optimizes the ship as a whole (once the objectives have been defined). This optimization attempts to search design space to simultaneously optimize effectiveness (based on mission), 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. The results of this process are a preliminary Operational Requirements Document (ORD1) that specifies performance and cost requirements, technology selection, and a baseline concept design.

In Concept Exploration, a multiple-objective design optimization is used to search the design space and perform trade-offs. The trade-offs are then analyzed for effectiveness in fulfilling the mission objectives, while minimizing cost and risk. A ship synthesis model is used to balance the 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 (also known as Pareto 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. This frontier represents the "optimal" designs. However, the true optimal design given the mission objectives and customer preferences for effectiveness, cost and risk, could be anywhere along the frontier.

Figure 2 is a flow chart of the Concept Exploration process. There are 4 main steps in this process, with everything else supporting these. The process begins with the Mission Need Statement (MNS). The MNS provides a clear presentation of the problem. This is needed to define the design space, and to build a quantitative measure of overall military effectiveness, necessary to rank the various design alternatives. The second step is modeling. Cost, Risk, and Effectiveness must be estimated to compare the alternatives. Technology, physics-based models, and expert opinion all play a role in assembling, balancing, determining feasibility, and assessing the various designs. After these models are created, a multi-objective optimization is performed. During the optimization, cost and risk are minimized, and effectiveness is maximized. This optimization process determines the non-dominated frontier. The final design is chosen from this frontier. After the baseline concept design is chosen from the non-dominated frontier, a final concept design is created in concept development.

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 balanced and feasible. In the process, a second layer of detail is added to the design and risk is reduced. This process is a repetitive process, and continues until a balanced baseline design is achieved.

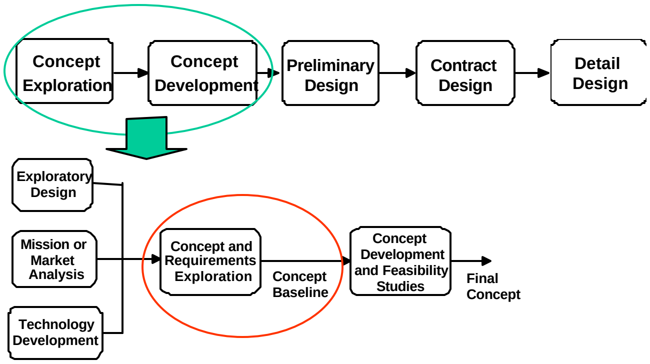


Figure 1 - Design Process

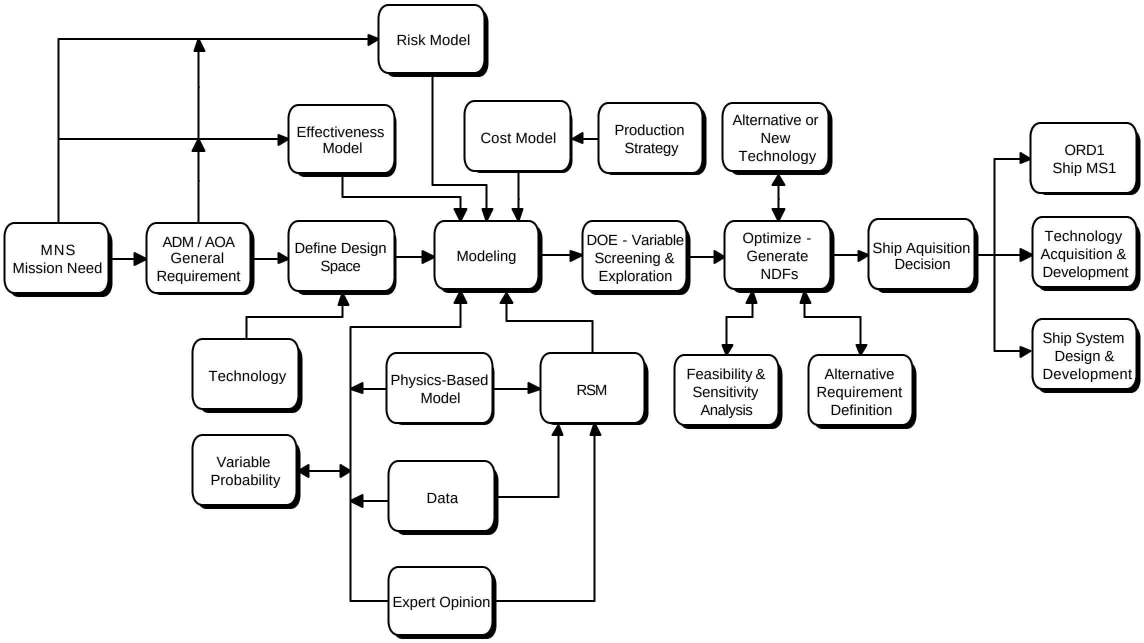


Figure 2 - Concept Exploration Process

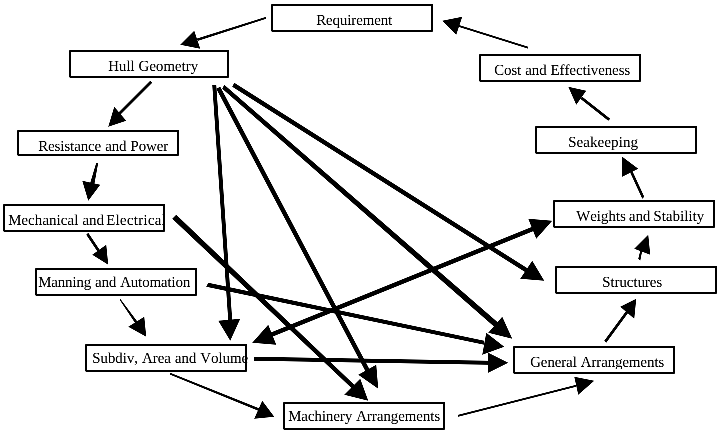


Figure 3 - Concept Development Design Spiral (Chapter 4)

1.3 Work Breakdown

SSLW Team 3 consists of five students from Virginia Tech. Each student chose specialization areas of the project according to their interests and special skills as listed in Table 1. The areas listed below were the primary focus of the corresponding individuals; however the team inevitably works together and corresponds to one another on all areas of interest listed below.

Table 1 - Work Breakdown

Name	Specialization
Darren Goff	Structures, Feasibility, Risk, Effectiveness
Donald Shrewsbury	Propulsion and Resistance, Electrical, Machinery Arrangements
Jay Borthen	Cost, Risk, Combat Systems
Jesse Geisbert	Hull form Characteristics and Properties, Subdivision, General Arrangements
Kristen Shingler	Writer, Manning and Automation, Maneuvering and Control, Equilibrium Polygon, Weights and Stability

1.4 Resources

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

Table 2 - Tools

Analysis	Software Package
Arrangement Drawings	Rhino/AutoCAD
Hullform and Hydrostatics	Rhino
Resistance/Power	MathCAD
Maneuvering and Control	GEORGE/TRAGv
Ship Synthesis Model	MathCAD/Model Center
Structure Model	MAESTRO
Cost and risk	MathCAD
Subdivision and tankage	Rhino
Area/Volume	Excel
Weights/stability	Excel

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 clarification 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

The SSLW concept of operations is based on the Mission Need Statement (MNS) and Acquisition Decision Memorandum (ADM) for a littoral warfare submarine to provide a covert platform from which to deploy Special Forces, conduct Intelligence, Surveillance, and Reconnaissance (ISR), perform Mine Counter Measures, and defensive measures against enemy ships. The submarine will operate with either a mother submarine or ship, requiring complete support until the time of launch for the mission. The submarine will be forward deployed and able to operate independently on missions lasting 14-30 days without replenishment. Autonomous systems and automation will minimize manning and maximize payload capacity for weapons, Special Forces, and ISR systems. The ship will utilize multiple, flexible autonomous mission packages that are configured for a specific mission.

SSLW will also be a first strike platform. SSLW will enter restricted waters and littoral areas undetected. The ship will carry and support SEALs to beachheads with minimal exposure to the elements and deploy them within a mile of the shore, acting as an off-shore base for the duration of the SEAL mission. While waiting for the SEALs to carry out their mission, SSLW will perform ISR operations and act as the command center for the deployed troops. The submarine will also conduct mine hunting, deactivating, and laying operations while SF troops are deployed. After extracting the Special Forces, SSLW will perform necessary Search and Rescue (SAR) or Search, Salvage, and Rescue operations to aid in fleet support and then return to the mother ship. SSLW will have self defense weapons and will rely on passive stealth to slip away from enemy restricted waters without detection.

2.2 Projected Operational Environment (POE) and Threat

The operational environment is different for the littoral submarine than for deepwater submarines. The littoral submarine must be able to navigate in shallow water and through narrow channels, detect and avoid coral reefs, avoid grounding on sandbars, and also maintain functionality in higher sea states. All of these are associated with the littoral area. The vessel must also be able to defend against threats such as torpedoes, missiles, and mines, and avoid detection by aircraft, submarines, and surface ships.

2.3 Operations and Missions

The primary SSLW missions are to transport Navy SEALs to potentially hostile areas in a covert manner, and to utilize inherent and modular systems for ISR and mine counter-measures in littoral regions. SSLW must also perform ASW and ASUW operations for self defense and against limited focused targets.

A possible 30-day mission scenario would deploy from the sea base or mother ship, transport the Navy SEALs to the target location, gather INT and perform MCM while the SEALs are performing their operation, pick-up the SEALs and return to the sea base or mother ship. A second scenario includes securing a beach area for amphibious assault and gathering INT on the surrounding area. The littoral sub would identify or clear safe passages for other ships to transit to and about littoral areas. Possible mission scenarios for the primary SSLW missions are provided in Table 3 and Table 4.

Table 3 – SPECOPS Mission

Day	Mission scenario
1-5	Leave Sea base / Mother Ship and proceed to target area
6-8	Arrive and prepare. Brief SEALs on mission as well as crew for ISR and MCM type missions
9-19	Launch SEALs at night. While carrying out their mission, conduct all ISR and MCM and use gathered intelligence to determine equipment / modules to be delivered by helicopter / ALDV. (More equipment for seals or more apparatus for ship)
20-23	SEALs return and preparation is taken to shove off and conduct necessary FSO and / or SAR operations.
24-30	Return to Sea base / Mother Ship.
	Note: Mission can be extended depending on power availability and supply replenishment.

Table 4 - SPECOPS and Evade Mission

Day	Mission scenario
1-5	Leave Sea base / Mother Ship and proceed to target area
6-8	Arrive and prepare. Brief SEALs on mission.
9-19	Launch SEALs at night. While conducting their mission, ship is spotted during MCM. Conduct countermeasures and evade attack.
20-23	SEALs return and preparation is taken to depart and conduct necessary FSO and /or SAR operations.
24-30	Return to Sea base / Mother Ship.

2.4 Required Operational Capabilities

To support the missions and mission scenarios described in Section 2.3, the capabilities listed in Table 5 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 5 - List of Critical Required Operational Capabilities (ROCs)

ROCs	Description
ASUW 1	Engage in surface attacks (defensively)
ASUW 2	Detect and track surface threats with sonar
ASUW 3	Disengage, evade and avoid surface attack
ASW 1	Engage submarine attacks (defensively)
ASW 10	Disengage, evade and avoid submarine attack by employing countermeasures and evasion techniques
SEW 2	Conduct sensor and ECM operations
SEW 3	Conduct sensor and ECCM operations
MIW 1	Conduct mine-hunting
MIW 2	Conduct mine-sweeping
MIW 3	Conduct magnetic silencing (degaussing, deperming, etc.)
MIW 4	Conduct mine laying
MIW 5	Conduct mine avoidance
MIW 6.7	Maintain magnetic signature limits
LOG 2	Transfer/receive cargo and personnel
CCC 3	Provide own unit CCC
CCC 4	Maintain data link capability
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 and control damage
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 a Piggy -Back configuration
MOB 16	Operate in day and night environments
MOB 18	Operate in full compliance of existing US and international pollution control laws and regulation
NCO 3	Provide upkeep and maintenance of own unit
FSO 5	Conduct search/salvage & rescue operations
FSO 6	Conduct SAR operations
FSO 7	Provide explosive ordnance disposal services
SPW 1	Provide lock out chamber
SPW 2	Habitability Module
SPW 3	Deliver, extract and support SEALS

3 Concept Exploration

Chapter 3 describes Concept Exploration. In Concept Exploration, trade-off studies, design space exploration and optimization are accomplished using a Multi-Objective Genetic Optimization (MOGO). Baseline designs are selected for further development.

3.1 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.

3.1.1 Hull Form Alternatives

The primary drivers for the SSLW hullform include shallow water seakeeping, stealth, structural efficiency and maneuverability. Sprint speed is a secondary objective. The idealized SSLW hullform includes a forebody, parallel midbody, and afterbody which constitute the overall SSLW length. Port and starboard half-cylinder bodies are connected by a centerline spacer. The cylinder forebody is elliptical, the midbody is cylindrical and the afterbody is conical. Figure 4 illustrates this geometry. Figure 5 shows basic geometric calculations.

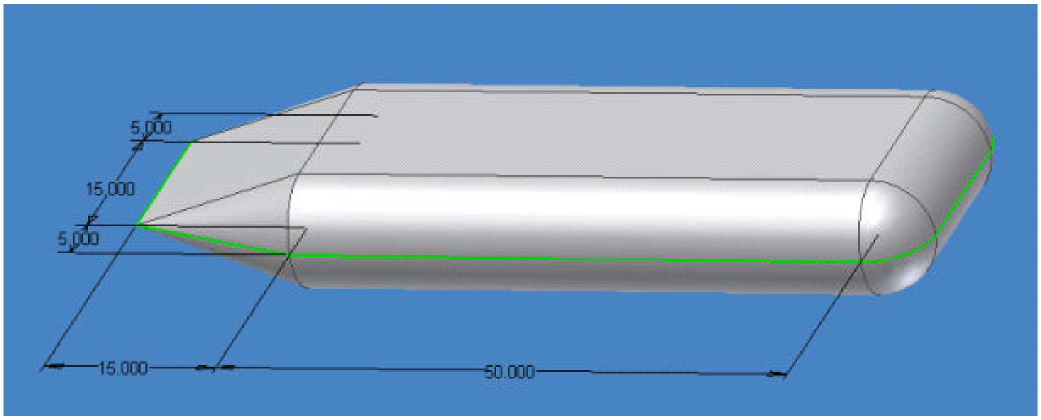
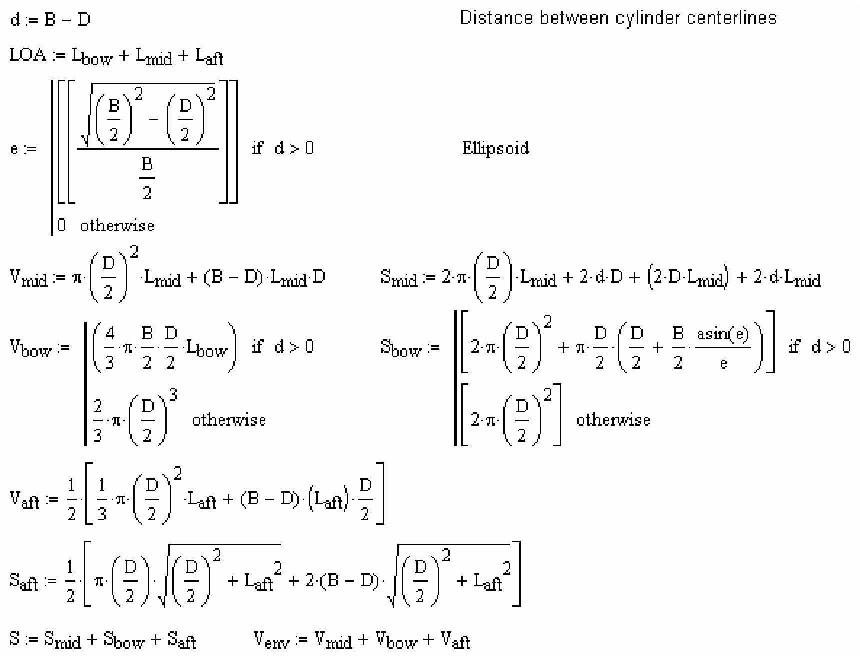


Figure 4 - Idealized Hullform used for Calculations



$$d := B - D$$ Distance between cylinder centerlines

$$LOA := L_{bow} + L_{mid} + L_{aft}$$

$$e := \begin{cases} \left[\left[\dfrac{\sqrt{\left(\frac{B}{2}\right)^2 - \left(\frac{D}{2}\right)^2}}{\frac{B}{2}}\right]\right] & \text{if } d > 0 \\ 0 & \text{otherwise} \end{cases}$$ Ellipsoid

$$V_{mid} := \pi \cdot \left(\frac{D}{2}\right)^2 \cdot L_{mid} + (B - D) \cdot L_{mid} \cdot D \qquad S_{mid} := 2 \cdot \pi \cdot \left(\frac{D}{2}\right) \cdot L_{mid} + 2 \cdot d \cdot D + (2 \cdot D \cdot L_{mid}) + 2 \cdot d \cdot L_{mid}$$

$$V_{bow} := \begin{cases} \left(\frac{4}{3} \cdot \pi \cdot \frac{B}{2} \cdot \frac{D}{2} \cdot L_{bow}\right) & \text{if } d > 0 \\ \frac{2}{3} \cdot \pi \cdot \left(\frac{D}{2}\right)^3 & \text{otherwise} \end{cases} \qquad S_{bow} := \begin{cases} \left[2 \cdot \pi \cdot \left(\frac{D}{2}\right)^2 + \pi \cdot \frac{D}{2} \cdot \left(\frac{D}{2} + \frac{B}{2} \cdot \frac{\operatorname{asin}(e)}{e}\right)\right] & \text{if } d > 0 \\ \left[2 \cdot \pi \cdot \left(\frac{D}{2}\right)^2\right] & \text{otherwise} \end{cases}$$

$$V_{aft} := \frac{1}{2} \cdot \left[\frac{1}{3} \cdot \pi \cdot \left(\frac{D}{2}\right)^2 \cdot L_{aft} + (B - D) \cdot (L_{aft}) \cdot \frac{D}{2}\right]$$

$$S_{aft} := \frac{1}{2} \cdot \left[\pi \cdot \left(\frac{D}{2}\right) \cdot \sqrt{\left(\frac{D}{2}\right)^2 + L_{aft}^2} + 2 \cdot (B - D) \cdot \sqrt{\left(\frac{D}{2}\right)^2 + L_{aft}^2}\right]$$

$$S := S_{mid} + S_{bow} + S_{aft} \qquad V_{env} := V_{mid} + V_{bow} + V_{aft}$$

Figure 5 – Idealized Hull Geometry Calculations

3.1.2 Sustainability Alternatives

SSLW minimum sustainability requirements are specified in Appendix B – 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. SSLW sustainability goals and thresholds are listed in Table 6.

Table 6 - Sustainability Goals and Thresholds

Sustainability Alternative	Threshold	Goal
Endurance Range	500 nm	1000 nm
Sprint Range	25 nm	50 nm
Sprint Speed	15 knots	25 knots
Endurance	14 days	30 days

3.1.3 Propulsion and Electrical Machinery Alternatives

The process for developing the propulsion system alternatives and preparing for optimization is as follows. First, the team develops machinery general requirements and guidelines based on the MNS, ADM, and the guidance of the project manager. Information is gathered on a broad range of technology alternatives. Viable machinery alternatives are down-selected based on the guidelines. The final alternatives are selected and developed further from manufacturer data and in ASSET. Finally, the data is assembled into the propulsion alternative data base (Table 13). The ship synthesis propulsion module is updated to be consistent with these machinery alternatives. Trade-off studies for these alternatives are performed using the multi-objective optimization (MOGO).

3.1.3.1 Machinery Requirements

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

General Requirements – SSLW missions must be carried out covertly. Integrated, all electric power will be used to minimize acoustic signature and maximize operational flexibility. The propulsion system must be a non-nuclear, air independent system. Only low to moderate risk alternatives should be considered for primary power and batteries. Batteries are considered sufficient backup for the primary power. No emergency generator is required. Hydrocarbon fuel, oxygen, and argon will be stored inboard and hydrogen will be stored outboard. SSLW systems must be Sub-Safe.

Sustained Speed and Propulsion Power – SSLW must have a minimum endurance range of 500 nm at 10 knots, a minimum sustained (sprint) speed of 15 knots, and a minimum sprint range of 25 nm. The design space will consider a range of primary power from 250 – 1000 kW. DDS 200-1 will be used as guidance for endurance calculations.

Ship Control and Machinery Plant Automation – Significant automation should be considered to reduce cost and personnel vulnerability, and maximize payload capacity. Manning shall not exceed 35 including SPECOP or specialist personnel.

Propulsion Engine and Ship Service Generator Certification – Because of the criticality of propulsion and ship service power to many aspects of the ship's mission and survivability, all machinery will be Grade A shock certified, and Navy qualified. Magnetic, acoustic and thermal signatures should be minimized.

3.1.3.2 Primary Power

The five primary power plant alternatives considered in the initial screening are fuel cells, closed cycle diesel engines, closed cycle steam turbines, Stirling cycle heat engines and small nuclear systems. The history of air independent propulsion (AIP) began with the German Walter's Cycle. It used high purity hydrogen peroxide in the combustor as the oxidizer. It was a high speed engine with low endurance. In a 1940's test it reached speeds of 28.1 knots when the rest of the world's submarines were cruising at 10 knots. This system produced very high power ranging from 2500 to 7500 hp. The first US AIP system was on the X-1 Midget Sub in 1955 which used a smaller Walter's cycle.

3.1.3.2.1 Fuel Cells

Fuel cells are classified primarily by the kind of electrolyte they use. This determines the kind of chemical reaction that takes place in the cell, the kind of catalyst required, the cell temperature range, and the fuel required. Each of these characteristics affects the application for each different cell. Fuel cell types include Polymer

Electrolyte Membrane (PEM), Phosphoric Acid, Direct Methanol, Alkaline, Molten Carbonate, Solid Oxide, and Regenerative (Reversible).

The Polymer Electrolyte Membrane Fuel Cell (PEMFC) requires hydrogen or a hydrogen rich gas for its chemical reaction. The actual fuel cell resembles a battery, but never has to be recharged. The two gases used combine to produce electricity, heat and water making PEMFCs the most suitable fuel cell for military applications. The PEMFC consists of an anode and cathode separated by an electrolyte. The electrons travel through the anode and external circuit to the cathode. The entire system is self contained with no moving parts. It is twice as efficient as a steam or internal combustion engine. Figure 6 shows the process and Table 7 lists the pros and cons of the PEMFC system.

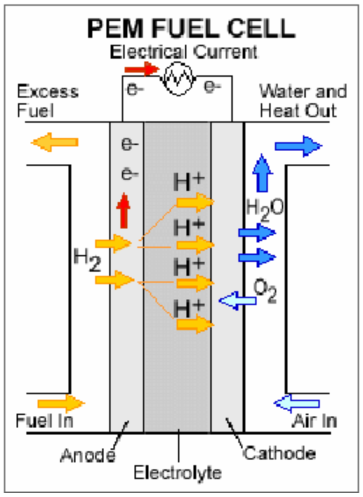


Figure 6 - PEM Fuel Cell

Table 7 - Pros and Cons for a PEM Fuel Cell

Pros	Cons
High power density	Requires a noble-metal catalyst, usually platinum (higher cost)
Low weight and low volume	
Only require hydrogen from air and water	Extremely sensitive to CO poisoning
Operate at relatively low temperatures (~80°C)	Hydrogen storage issues
Fast start-up time	

The Alkaline Fuel Cell uses non-precious metals as catalyst and operates at relatively low temperatures. However, the purification process for cleaning hydrogen and oxygen it requires is costly. Table 8 lists the pros and cons of the alkaline fuel cell.

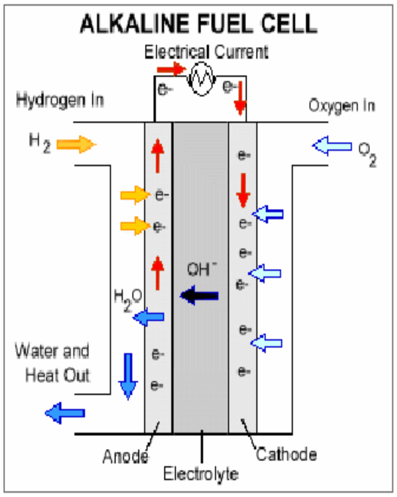


Figure 7 - Alkaline Fuel Cell

Table 8 - Pros and Cons for an Alkaline Fuel Cell

Pros	Cons
Can use non-precious metals as catalyst	Easily poisoned by carbon dioxide
Relatively low temperatures (~100°C - 250°C)	Purification process to clean hydrogen and oxygen is costly
High performance rates	Low operation time (~8000 hours)
High efficiency at about 60%	

A significant disadvantage to using these fuel cells is hydrogen storage. Hydrogen can be stored in either gaseous or liquid form. Liquid storage carries three times more energy than diesel fuel of the same weight. Super-insulated storage tanks use 2 walls to maintain the liquid at -253°C. The liquid form causes venting problems in storage since it evaporates 1-2% each day. Due to the low energy density of hydrogen, it is difficult to store enough hydrogen onboard. Higher-density liquid fuels such as methanol, ethanol, natural gas, liquefied petroleum gas, and diesel fuel can be used, but the submarine must have an onboard fuel processor to reform the fuel to hydrogen. This increases cost and maintenance requirements.

Molten Carbonate fuel cells have a relatively high efficiency but operate at extremely high temperatures that would not be as appropriate for the submarine environment.

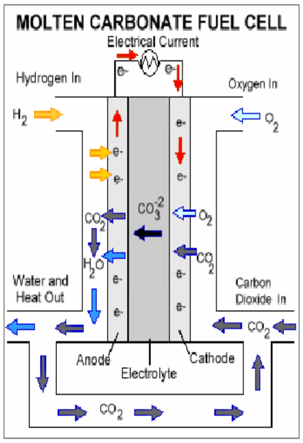


Figure 8 - Molten Carbonate Fuel Cell

Table 9 – Pros and Cons of a Molten Carbonate Fuel Cell

Pros	Cons
Can use non-precious metals as catalyst	Extremely high temperature (~650°C)
Relatively high efficiency (~85% with co-generation)	Poor durability
Do not require external reformer	Corrosive electrolyte used
Low Cost	Low cell life

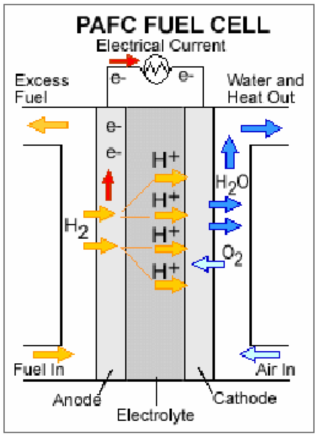


Figure 9 - Phosphoric Acid Fuel Cell

Phosphoric acid fuel cells are much less powerful than other fuel cells based on the same weight and volume. They are harder to deal with since they deal with acid.

Table 10- Pros and Cons of a Phosphoric Acid Fuel Cell

Pros	Cons
More tolerant to CO poisoning	Typically large and heavy
Efficiency of 85% when used with co-generation	Expensive, due to platinum catalyst (~$4,000-$4,500 per kW)

Solid oxide fuel cells use a hard, non-porous ceramic compound as an electrolyte and non-precious metals as a catalyst which drives the cost down. The main concern is they use extremely high operating temperatures (~1000°C).

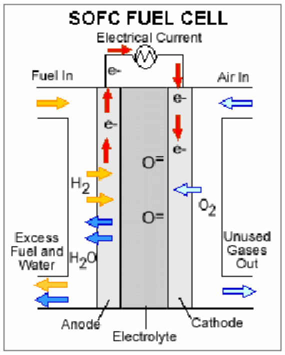


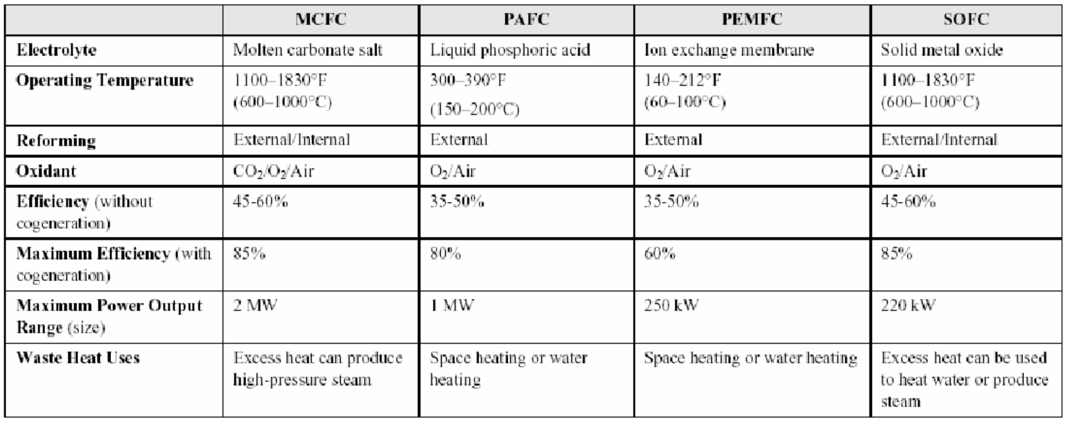
Figure 10 - Solid Oxide Fuel Cell

Table 11 - Pros and Cons of a Solid Oxide Fuel Cell

Pros	Cons
High efficiencies with co-generation (~80 – 85%)	Low start-up time
Most sulfur-resistant fuel cell type	Requires a lot of thermal shielding
No CO poisoning problems	Poor durability

A significant barrier to using these fuel cells in vehicles is hydrogen storage. Most fuel cell vehicles (FCVs) powered by pure hydrogen must store the hydrogen onboard as a compressed gas in pressurized tanks. Due to the low energy density of hydrogen, it is difficult to store enough hydrogen onboard to allow vehicles to travel the same distance as gasoline-powered vehicles before refueling, typically 300-400 miles. Higher-density liquid fuels such as methanol, ethanol, natural gas, liquefied petroleum gas, and gasoline can be used for fuel, but the vehicles must have an onboard fuel processor to reform the methanol to hydrogen. This increases costs and maintenance requirements. The reformer also releases carbon dioxide (a greenhouse gas), though less than that emitted from current gasoline-powered engines.

Figure 11 shows a comparison of four of the aforementioned fuel cells. Based on operating temperature, power output and size, PEM are the most suitable fuel cell for a littoral submarine.



	MCFC	PAFC	PEMFC	SOFC
Electrolyte	Molten carbonate salt	Liquid phosphoric acid	Ion exchange membrane	Solid metal oxide
Operating Temperature	1100–1830°F (600–1000°C)	300–390°F (150–200°C)	140–212°F (60–100°C)	1100–1830°F (600–1000°C)
Reforming	External/Internal	External	External	External/Internal
Oxidant	CO_2/O_2/Air	O_2/Air	O_2/Air	O_2/Air
Efficiency (without cogeneration)	45-60%	35-50%	35-50%	45-60%
Maximum Efficiency (with cogeneration)	85%	80%	60%	85%
Maximum Power Output Range (size)	2 MW	1 MW	250 kW	220 kW
Waste Heat Uses	Excess heat can produce high-pressure steam	Space heating or water heating	Space heating or water heating	Excess heat can be used to heat water or produce steam

Figure 11 - Fuel Cell Comparison

3.1.3.2.2 Closed Cycle Diesel Engines

Closed Cycle Diesel Engines (CCD) run on stored oxygen, inert gases (like argon), and recycled exhaust products. CCDs are just like regular diesels but use stored oxygen injected into the system instead of air. They can also be run on air at snorkeling depth. It is a proven technology and uses “off the shelf” components. The common fuel source makes it cost efficient. The only concerns are noise and exhaust management. Figure 12 shows an operational closed cycle diesel used in industry. Figure 13 shows the components in the closed cycle diesel system.

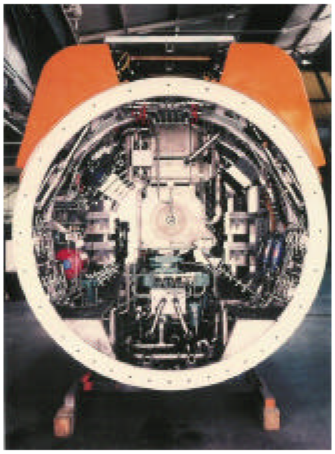


Figure 12 - CCD Operational in a RS-1 Corsair Industrial Submarine

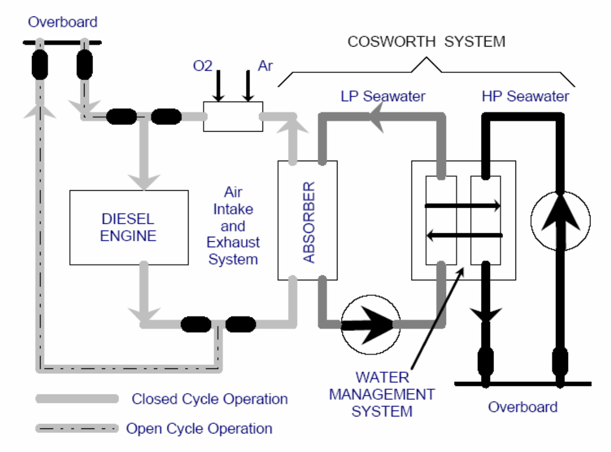


Figure 13 - Close Cycle Diesel System

3.1.3.2.3 Closed Cycle Steam Turbine

The French currently have what they call a MESMA system which is essentially a Rankine cycle. It uses the steam generated from the combustion of ethanol and oxygen to produce energy. It has an output power of 200 kW, but low efficiency and high oxygen consumption. The pros for this system are that it uses a fossil fuel source and that it is already a developed technology. The cons are that it has high temperature corrosion problems and the by-products it produces are better discharged overboard because of their high temperature. The heat created from the thermal cycle increases the thermal signature.

3.1.3.2.4 Stirling Cycle Engine

The Stirling Engine is the first AIP system to enter naval service in recent years. The Swedish Gotland-class submarine uses two adjunct systems producing 75 kW. It burns liquid oxygen and diesel fuel together to generate electricity for the propulsors and charging batteries. The system has a good plant volume and good weight compared to methanol fuel cells and closed cycle diesels. The Stirling engine contains a sealed cylinder with one part hot and the other part cold to keep the two separate. The working gas (usually helium, hydrogen or air) moves from the hot to cold side by a connected piston. The hot air heats the air inside the engine and expands to push the piston. The cold side cools the air inside and causes the piston to contract to its original position. Figure 14 and Figure 15 show two different types of Stirling Engines.

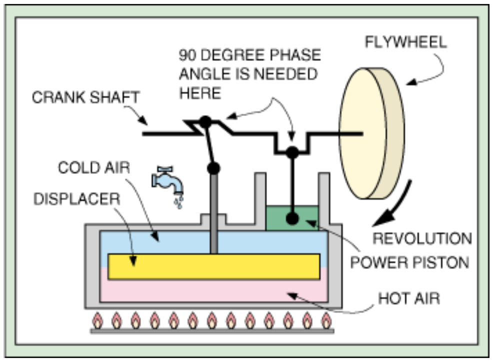


Figure 14 – Displacer Stirling Engine

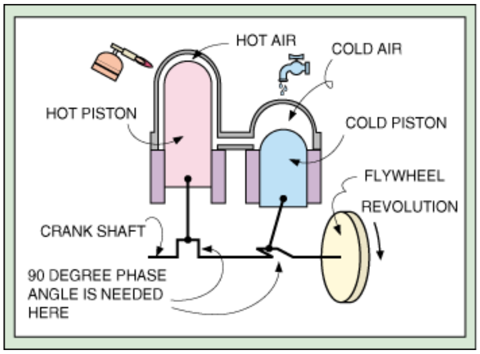


Figure 15 – Two-Piston Stirling Engine

The benefits of the Stirling cycle engine are that it is a proven technology, and it has low vibration compared to a closed cycle diesel engine. The common fuel source is also appealing, and it has high efficiency. Like the closed cycle diesel, noise reduction and exhaust management are problems. The system is complicated, but the pros outweigh the cons.

3.1.3.2.5 Thermoelectric Nuclear Reactor

Although the MNS and ADM call for a non-nuclear propulsion system, a small nuclear reactor is considered here for comparison. Space Power 100 is a small reactor that produces 100 kW of power. It is theoretically 75% efficient and has a service life of 7 years. For a similar system, sized to produce 1200 kW of power, 600 cubic feet of space is needed and it weighs over 130 ltons. It has actually only been tested to 17% efficiency. Although nuclear reactors theoretically have infinite power capacity, they are too heavy and potentially dangerous for the SSLW environment.

3.1.3.3 Batteries

Batteries are an essential propulsion component for SSLW. They store a large amount of chemical energy very compactly and are relatively lightweight with a low signature. The four main types of batteries suitable for the marine environment are lead acid, nickel-cadmium, lithium ion, and lithium ion polymer. Lead acid batteries are used most often in submarines. A single battery has 126 cells with a voltage ranging from 210 to 355 volts. Amperage capacity depends highly on discharge rate. 1 hour can generated approximately 5000 Amps (5000 amp hours), 3 hours can generate 2500 Amps per hour (7500 amp hours) and 10 hours rate at approximately 1000 amps per hour (10000 amp hours). They have a high initial expense and a high expense for disposal. Lithium ion batteries are a new technology. They have the lowest mass and volume per unit power capacity and battery heating is significantly reduced due to their energy efficiency. They have a higher life expectancy, 15-18 years, and fast charging. This is a good option, but they are unproven in submarine applications and their risk is high. Nickel-cadmium batteries have about the same life expectancy as lead acid, 5 – 10 years and 500 – 2000 cycles. Their energy density is better, 20 – 37 Wh/kg, and they are able to charge relatively fast. They have a high initial expense and a high expense for disposal.

Table 12 - Battery Data

Batteries	Weight (MT/kwhr)	Vol (m^3/kwhr)	kW/kW-hr
Lead Acid	0.0333	0.0173	0.5
Lithium Ion	0.0058	0.0027	0.56
Nickel Cadmium	0.0113	0.0032	0.87

3.1.3.4 Final Propulsion Alternatives

The selection criteria for the final propulsion alternatives are based on the MNS and ADM. Alternatives must be proven systems or feasible within the next 10 years. They must have high efficiency, low to medium risk, low weight and high power output. 6 primary systems were chosen: two closed-cycle diesels, one PEM Fuel Cell, one PEM fuel cell with reformer, an alkaline fuel cell, and a Stirling Engine. Table 13 shows the characteristics of the systems considered in the ship synthesis model and optimization.

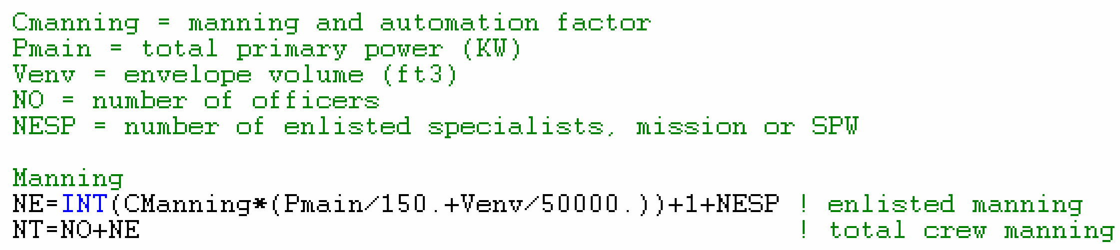
Table 13 - Propulsion Alternatives

Description	Propulsion Option (PSYS)	Main Generator Power KGg (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 per lton fuel (ft3/lton)	Oxidant volume per lton oxidant (ft3/lton)
CAT 3406E	1	410	13.7	0.213	0.84	0.03	45.15	0	36.9
CAT 3412E	2	690	23.1	0.211	0.84	0.03	45.15	0	36.9
250kW PEM	3	250	4.7	3.49	0.44	0	0	10.9	36.9
250kW PEM w/reformer	4	250	7.2	0.31	0.9	0	45.15	0	36.9
250kW Alkaline	5	250	5.3	2.9	0.37	0	0	10.9	36.9
250kW Stirling Engine	6	250	7.4	0.293	1.022	0.01	45.15	0	36.9

Description	Argon tank per lton argon (ft3/lton)	Hydrogen Tank structure weight lton/lton fuel	Oxidant tank structure weight lton/lton oxidant	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 Required Volume (m3)
CAT 3406E	29.8	0	0.375	0.1	1.535	0.995	1.231	36.49
CAT 3412E	29.8	0	0.375	0.1	1.913	1.444	1.621	61.41
250kW PEM	0	0.25	0.375	0	0	0	0	16
250 kW PEM w/ Reformer	0	0	0.375	0	0	0	0	32.5
250 kW Alkaline	0	0.25	0.375	0	0	0	0	0
250kW Stirling Engine	29.8	0	0.375	0.1	0	0	0	0

3.1.3.5 Automation and Manning Parameters

In concept exploration it is difficult to deal with automation manning reductions explicitly, so a ship manning and automation factor is used. This factor represents reductions from "standard" manning levels resulting from automation. In this project, a manning and automation factor, $C_{Manning}$, varies from 0.5 to 1.0. It is used in the regression based manning equations shown in Figure 16. A manning factor of 1.0 corresponds to a "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.



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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 16 - Manning Calculation

3.1.4 Combat System Alternatives

Critical to the survival of a littoral warfare submarine are its combat systems. These include core defensive weapons used against surface and subsurface threats and mine countermeasure systems. The systems chosen meet the requirements of the Mission Needs Statement, Acquisition Decision Memorandum and Required Operational Capabilities (ROCs), allowing the use of the most advanced technology and minimizing cost.

The ADM dictates that the inherent capabilities that the submarine must possess in the areas of ASW and ASUW self defense, C4I and ISR, and SPW. It also states that it must be able to carry Payload Interface Modules (PIMs) in standard 1280 ft^3 ISO containers (threshold = 1, goal =5).

First, identify the range of combat system alternatives and direct submarine impact (weight, space power, and cost). Next, use AHP and MAVT to estimate a Value of Performance (VOP) for each system alternative. Third, include the VOPs in total submarine synthesis model. Finally, select (trade-off) inherent combat system alternatives and PIM cargo capacity considering effectiveness, cost and risk in a multi-objective optimization.

Core or inherent (always installed) systems are discussed in this section. Modular payloads are discussed in Section 3.1.5.

3.1.4.1 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. SSLW MCM system alternatives are listed in Table 14.

Table 14 - 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

Mine avoidance sonar is a key part of the submarine's defensive systems. A versatile active/passive sonar manufactured by L-3 Communications, ELAC Nautik provides many options for the small littoral submarine system. Used primarily for mine sonar it can also detect other moving and stationary objects underwater. Its planar array can be set at 30 kHz for low frequency or 70 kHz for high frequency. Detection ranges from 850 m to 3600 m make it a formidable option. With the control and display unit weighing only 56 kg it is a good alternative for the small submersible.

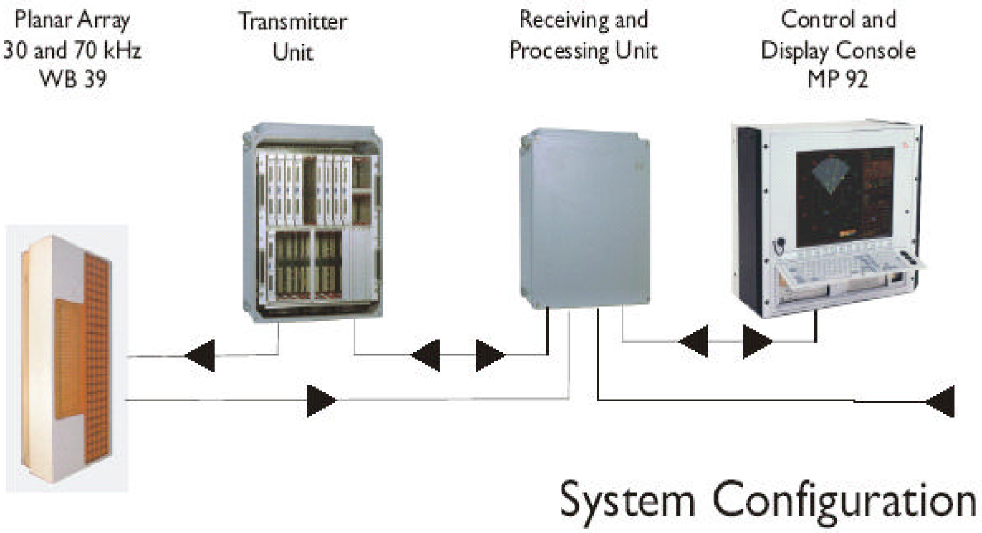


Figure 17 - SCOUT Mine avoidance and obstacle detection sonar

3.1.4.2 ASW/ASUW

Anti-Submarine Warfare (ASW) and Anti-Surface Warfare (ASUW) systems for the littoral combat submarine include primarily defensive systems to engage enemy submarines and surface ships. These include passive and active sonar for detection, targeting and avoidance, torpedoes, and countermeasures to divert enemy weapons. ASW and ASUW system alternatives are listed in Table 15.

Table 15 – ASW and 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 Torpedoes	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

The passive sonar LOPAS system made by L-3 Communications ELAC Nautik fits well in the small littoral submarine. It is a small and sophisticated system that allows for the simultaneous calculation of 96 beams. It has an operating frequency of 0.3 to 12 kHz. It stores up to 60 minutes of data automatically and can have up to 8 targets assigned to automatic tracking channels. With a power consumption of approximately 660 VA, this low cost design is fitting for the mission of the littoral craft.

Figure 18 - LOPAS System

Integrated bow arrays conform to the submarine’s hydrodynamic hullform and provide its “eyes and ears”. An example is the SSLW Elektronik DBQS 40 integrated sonar system (CSU-90 suite). It incorporates a medium-frequency, cylindrical bow array operating in the 0.3 to 12 kHz band, which integrates 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. Other options for an integrated bow array are the BQQ-6 or BQQ-5E (V) 4 passive suite bow array or the BQQ-10 suite with active/passive bow array.

Figure 19 - Integrated Bow Array

There are three main options for torpedoes in the US Armed Forces: the Mark 46, 50, and 48 torpedoes, shown in Figure 20. The Mark 46 torpedo has a 12.75 inch diameter and carries almost 100 lbs of explosives in its 520 lb shell. The Mark 48 is the largest and most powerful torpedo. It is 20 inches in diameter, almost 20ft long, and weighs 3500 lb. It has a range greater than 5 miles and carries 650 lbs of explosives. Most appropriate for a ship of the SSLW size is the Mark 50 torpedo. It also has a 12.75 inch diameter, weighs 750 pounds and carries 100 lbs of explosives. Costing approximately $2.9 M, it speeds to its target using active sonar with passive acoustical homing at 40+ knots. It is replacing the MK 46 as the fleet’s lightweight torpedo alternative and is the only practical choice for SSLW.

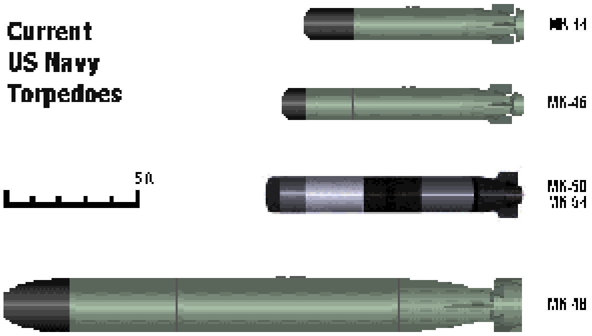


Figure 20 - US Navy Torpedoes

There are three options for launching torpedoes on SSLW. The goal system uses an internal torpedo room and two tubes with sufficient space to store, maintain, load and launch four torpedoes. Figure 21 shows a similar view.

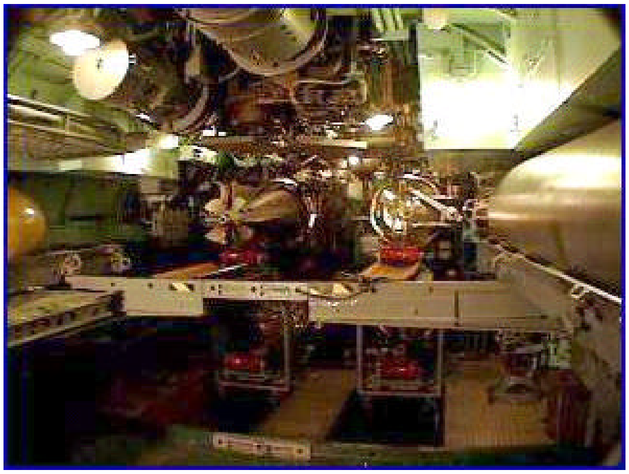


Figure 21 - Example of a Forward Torpedo Room

The second option provides a smaller internal access to two torpedo tubes to save the space and weight of racks and equipment. Torpedoes can be extracted approximately half way for inspection and maintenance. All options include some external encapsulated torpedoes, but external tubes are still unproven with higher risk. The Krupp MaK Embarkation and Loading System is an example of how reloading of internal torpedoes could be performed, Figure 22.

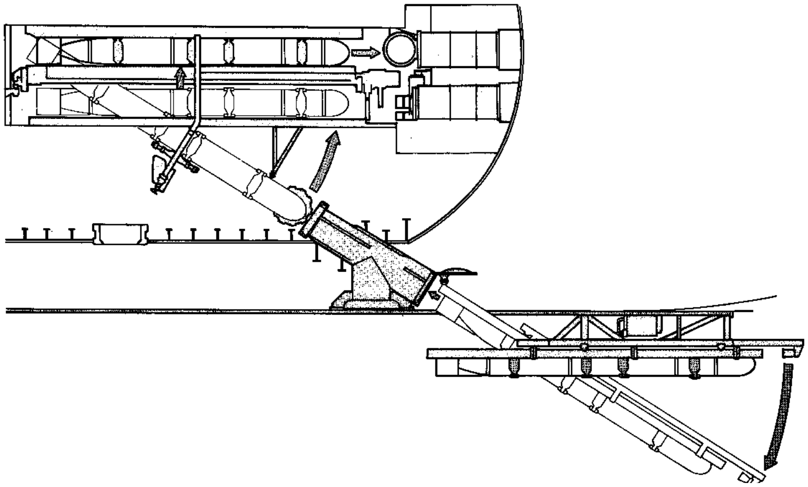


Figure 22 - Krupp MaK Embarkation and Loading System

3.1.4.3 SPW

One of the primary missions for SSLW is to deploy SEALs and act as a near-shore base. To do this, a lockout chamber is needed. Specialized equipment stowage must also be provided. SPW system alternatives are listed in Figure 16.

Table 16 – 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

Lockout cycles take roughly 20 minutes and therefore it is important that the chamber hold at least 4 team members. The lockout chamber can also act as an emergency escape for crew members in case of submarine casualty. Figure 23 shows a smaller version of a lockout chamber.

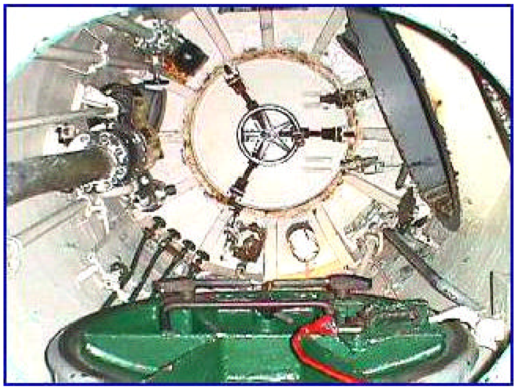


Figure 23 - Escape Trunk

A Combat Rubber Raiding Craft (CRRC) is a small, inflatable boat powered by a hand-steered outboard motor, capable of carrying up to 8 Special Force operators and their gear, Figure 24. The boat is 7.25 m long and weighs 325 lbs empty. The Zodiac RHIB (Rigid Hull Inflatable Boat) is a typical CRRC.

Figure 24 - SEALs using small inflatable boat

3.1.4.4 C4ISR

Computers, Communication, Command, Control, Intelligence, Surveillance, and Reconnaissance are critical elements in the SSLW mission. SSLW will come to periscope depth to communicate, verify location, and survey the surface, both visually and electronically. This depth will also allow the submarine snorkeling capabilities to refresh the ships air supply. C4ISR system alternatives considered for SSLW are listed in Table 17 and Table 18.

Table 17 - C4I System Alternatives

ID	C4I System Alternatives	1 (Goal)	2	3 (Threshold)
12,13	AD-16 PMP Photonics Mast w/UAVs	1	1	
14	SHRIKE ESM and Comm Mast	1	1	1
15	Multifunction Mast Antenna (MMA)	1	1	1
16	ROPE Buoy System	1		
17	UW Comms	1	1	1
18	Navigation Echo Sounders	1	1	1
19	Distress Beacon	1	1	1
20	Communications electronics and equipment	1	1	1
	C41 Value of Performance, VOP2	1.0	.405	.164

The AD-16 PMP Photonics Mast System was developed by Kollmorgen Electro-Optical. It is a non-hull penetrating system equipped with high-resolution color and black & white cameras that send images to color televisions located in the control room of the vessel. The system is also integrated with infrared laser range finder which allows for the measurement of ranges to be more precise. It has an integrated GPS receiver with a patch antenna and a sleeve antenna for the communications system.

The SHRIKE submarine ESM system is a lightweight, low cost system that rapidly detects, intercepts, analyzes, and identifies radar systems and other associated electronic threats. It is ideal for small ships and vessels because of its relatively small size and easy installation. The system is ideal for dense electromagnetic environments, such as littoral waters, because of its ability of process many different signals and maintain a high display rate. Power requirements are only 170 watts with frequency ranges from 0.7 to 2 GHz and 18 to 40 GHz. This allows for far-reaching surveillance across the horizon.

Garmin’s GPS 2010C system uses 12 satellites to compute and update the position of the submarine in real time. Accuracy is 3-5 meters and can take velocity readings at .05 meters/sec. Up to 20 courses can be saved on the operating software with 1000 waypoints for each course. Its power requirement is a maximum 24 watts and weighs less than 5 pounds.

The Remotely Operated Platform-Electronic (ROPE) System was originally designed by the Kollmorgen Corporation’s Electro-Optical Division to be towed behind a submarine to provide communications, surveillance, and positioning data. The buoy is inherently buoyant and will float to the surface when the submarine is stationary. When in motion, the buoy utilizes control surfaces to maintain a constant depth. Its sensor package includes an array of omni directional communication/navigation antennae, ESM, radar and meteorological sensors. The unit weighs between 5 and 15 lbs depending on systems aboard. ROPE provides an alternative to operating at periscope depth that can potentially reduce the submarine’s vulnerability.

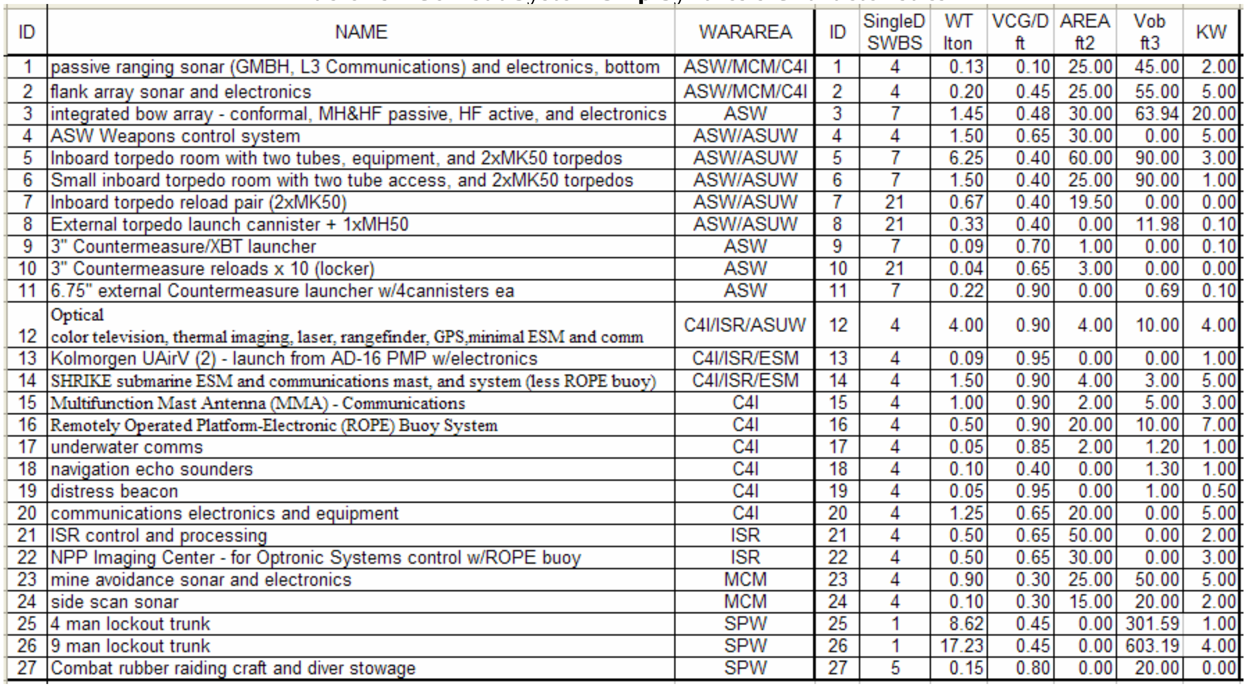
Table 18 - ISR System Alternatives

ID	ISR System Alternatives	1 (Goal)	2 (Threshold)
21	ISR Control and Processing	1	1
22	NPP Imaging Center	1	
	ISR Value of Performance, VOP3	1.0	.5

3.1.4.5 Combat Systems Payload Summary

Combat system characteristics listed in Table 19 are included in the ship synthesis model data base for trade-off in the design optimization.

Table 19 - 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

3.1.5 Payload Interface Modules

The Mission Need Statement specifies a submarine capable of supporting multiple, flexible, autonomous mission packages. Payload interface modules (PIMs) are integrated into the design to satisfy this requirement, and improve the multi-mission versatility of the submarine. These PIMs act as interfaces for International Standard Organization (ISO) containers, which measure 8ft x 8ft x 20ft. The advantage of this system is that it allows a variety of equipment, sensors, weapons, and other supplies to be secured in the ISO containers. The containers will have a universal connection to the PIM inside the submarine. Containers can be mission-specific supporting different types of missions. Specifically configured containers might be used for mine counter measures (MCM), a mine deployment system (Figure 25), a long range mine reconnaissance system, underwater autonomous vehicles (UAVs), a Surfzone Mine Crawler Bot Module, a REMUS AUV (Figure 26), anti-aircraft missiles, or the MANTA weapons system. The MANTA would not be fitted into an ISO container, but utilize the PIM interface and space (Figure 27).

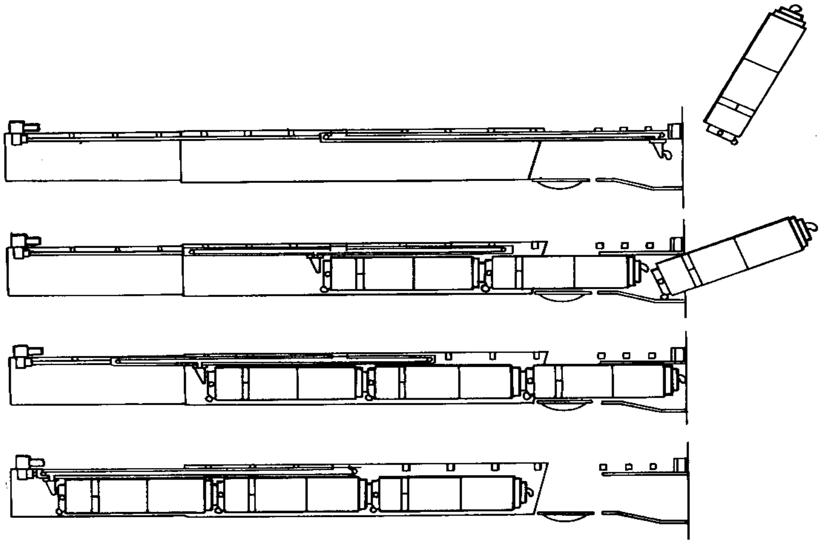


Figure 25 - Mine deployment tubes to be inserted in ISO container for integration in PIM

Figure 26 - REMUS Autonomous Underwater Vehicle

Figure 27 - MANTA weapons system pod

3.1.5.1 AUVs

Submarines can use Autonomous Underwater Vehicles (AUVs) to collect intelligence or conduct sustained undetected surveillance of critical regions around the world. These vehicles can carry sensors into areas where it may not be safe for a submarine to travel. The AUV has the option to return to the launching submarine, transmit the data to the submarine from the surface, or relay the intelligence to an orbiting satellite.

The primary function of the AUV is to carry a payload that will supplement the intelligence gathering of the submarine. The specific composition of the payload will be determined by the mission of the vehicle, but can include instrumentation to measure ocean water characteristics, map the seabed, inspect underwater installations such as pipelines, or perform some basic mine-hunting missions.

The appeal of the AUV is its ability to undertake missions over long ranges at reasonable speeds; on the order of 3 to 4 knots. Furthermore, it eliminates the need for a surface support vessel in certain high-risk missions.

One example of an AUV that is currently being considered for deployment on the SSLW is the REMUS. The REMUS is an unmanned torpedo-shaped submarine that profiles acoustic Doppler current and tests for salinity, temperature, and pH levels. It is about 7.5 inches in diameter, up to 7 feet long, and weighs 75 pounds. It is run off of lithium batteries and has a range of 50 miles operating at 3 knots.

The MANTA system is another prospect for integration into the SSLW platform for heightened offensive/defensive capabilities. The full-size MANTA pod is capable of carrying 2 full-length and 2 half-length or 6 half-length torpedoes and will be integrated into launch-and-recovery sites on the outer hull of the submarine. They have the ability to replenish their energy sources onboard and also to change out their modular packages as each specific mission dictates, giving them extraordinary flexibility. Currently, the NUWC has tested a one-third scale MANTA prototype capable of carrying multiple MK48 torpedoes, and have also demonstrated their ability to launch smaller AUVs while underway.

Figure 28 - MANTA weapons pod illustration

The CETUS and CETUS II systems are very appealing possibilities for use on the SSLW. The CETUS (Figure 29) is a flatfish-shaped envelope only six feet long and weighing just 330 pounds, including its scientific instruments. It has a low-cost propulsion system comprised of lead-acid batteries and differential thrust for control allowing it to achieve ranges up to 25 miles. It is designed for explosive-ordnance disposal applications and is smaller and more maneuverable than the REMUS UUV. The sensors on CETUS operate at shorter ranges than other systems but have a much higher resolution by comparison.

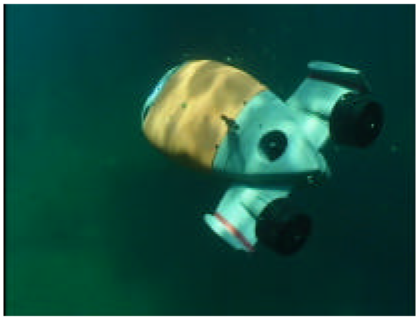


Figure 29 - CETUS I platform in action

While very similar to the CETUS I vehicle, the CETUS II (Figure 30) has some noteworthy upgrades, including the ability to hover, the lack of exposed propellers or moving control surfaces, and is the first AUV to carry the Acoustic Lens Forward-Looking Imaging Sonar. The platform employs both lead-acid and lithium ion batteries and has an endurance of up to 2.5 hours on the lead-acid batteries and up to 4.5 hours on the lithium ion batteries.

Figure 30 - CETUS II

Finally, one AUV concept that is still under development is the LOKI system. LOKI is an undersea fighter launched from a parent ship to offensively search and destroy enemy vessels. The platform is similar to the MANTA platform but on a smaller scale, including its munitions; possible mini-torpedoes. Currently, the effort is now focused on testing subscale components, such as vortex combustors and other propulsion technologies. Advanced structures, materials, and sensing technologies are also being tested for possible use on the LOKI platform.

3.1.5.2 Mines

In addition to the safe delivery and recovery of the Navy SEALs, a primary focus of the SSLW platform will be its mine detection, avoidance, and laying capabilities. For the mission of the SSLW, a mine designed for shallow water has immediate advantages since the vehicle will be operating in littoral waters. One proven design is a bottom mine, which has a large negative buoyancy that sets it down on the ocean floor and keeps it there (Figure 31).

Figure 31 - Primary Components of a Bottom Mine

There are four primary mine systems that are being considered for the SSLW platform. The MK67 SLMM was developed as a submarine deployed mine for use in areas inaccessible to other mine deployment techniques or for covert mining of hostile environments. The MK67 employs a magnetic/seismic or a magnetic/seismic/pressure target detection device. Another mine under investigation is the MK65 Quickstrike, which is a shallow water aircraft laid mine used primarily against surface craft. This particular mine is currently deployed primarily by aircraft, but the possibility of retrofitting a submarine with deployment capabilities that exists. The Quickstrike utilizes a magnetic/seismic/pressure target detection device. The last two mines being examined for possible integration into the SSLW craft are the MK56 and MK57 models. Both of these are also primarily used to destroy enemy shipping. Currently, the MK56 is configured to be deployed from an aircraft and the MK57 is a submarine laid magnetically moored mine. Both systems employ a total field magnetic exploder.

3.2 Design Space

The SSLW design is described using 20 design variables (Table 20). Design-variable values are selected by the optimizer from the range indicated and input into the ship synthesis model. The ship is then balanced, checked for feasibility, and ranked based on risk, cost and effectiveness. Hull design variables (DV1-5) are described in Section 3.1.1. The automation and manning factor, DV6, is described in Section 3.1.3.5. Stores and provisions duration, DV7, is described in Section 3.1.2. Combat System and Mission Alternatives, DV8-DV14, are described in Section 3.1.4. In Propulsion and Machinery alternatives (DV 15 and 16) are described in Section 3.1.3.

Table 20 - Design Variables

Design Variable	Name	Metric	Description	Trade-off Range
DV1	Lbow	ft	Forward section length	20-35
DV2	Lmid	feet	Parallel mid-body length	40-75
DV3	Laft	feet	Aft section length	40-70
DV4	B	feet	Beam length	20-30
DV5	D	feet	Depth of vessel	13, 21
DV6	Cmanning	factor	Manning and automation reduction factor	0.5-1.0
DV7	Ts	days	Mission length	14-30
DV8	ASW	alternative	Universal components : passive, integrated bow array sonar, weapons control, 2 3" countermeasure launcher + 1 reload 1=flank array sonar, torpedo room, 4 exterior torpedoes, 2= flank array, interior torpedo access, 6 exterior torpedoes; 3=8 exterior torpedoes; 4=	1-4
DV9	C4I	alternative	Universal components: SHRIKE, MMA, UW Comms, echo sounders, distress beacon, communication and electronic eqp. 1= photonics mast w/ UAVs, Rope buoy, 2= photonics mast w/ UAVs, 3=just universal	1-3
DV10	ISR	alternative	1=Control and process, NPP Imaging Center; 2= NPP Imaging Center	1-2
DV11	MCM	alternative	1=Forward looking sonar, side scan sonar; 2=forward looking sonar	1-2
DV12	SPW	alternative	1=squad and 4 man l/o, 2=squad and 9 man l/o, 3=platoon and 4 man l/o, 4=platoon and 9 man l/o	1-4
DV13	Depth	feet	Operating depth	250-350
DV14	Ndegaus	no/yes	Degaussing system	0,1
DV15	PSYS	alternative	1=CAT3406E CCD 410 kW, 2=CAT3412E CCD 690 kW , 3=250 kW PEM, 4=250 kW PEM w/ Reformer, 5=250 kW Alkaline, 6=250 kW Sterling	1-6
DV16	BATtyp	type	1=lithium ion, 2=nickel cadmium, 3=lead acid	1-3
DV17	Ebattery	kwhr	Battery capacity	5000-15000
DV18	Ng	number	Primary power generators	1-4
DV19	Wfuel	lton	Fuel weight	5-15
DV20	Npim	number	Payload interface modules	1-4

3.3 Ship Synthesis Model

The ship synthesis model has three objectives: to balance the design, assess its feasibility and calculate objective attributes for a given set of design variable values. Objective attributes include cost, risk, and effectiveness. The synthesis model consists of 13 modules. The outputs from one module are the inputs to subsequent modules. Ultimately, feasibility is determined; cost, effectiveness and risk are calculated, and the results are passed to the optimizer.

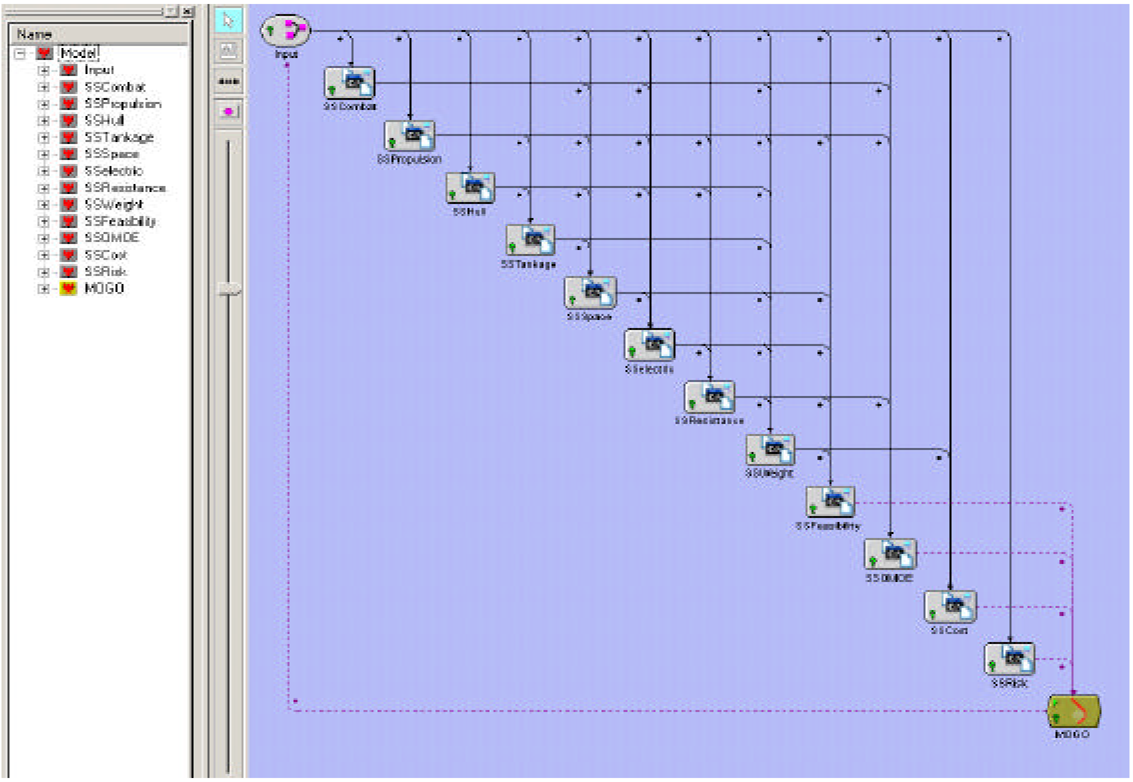


Figure 32 - Ship Synthesis Model in Model Center (MC)

The combat systems module takes the research done on weapons systems and provides the necessary weights, volumes, areas and power requirements for each system. These values are used to create the combat systems data file. Each configuration of combat systems (referred to as a combat suite) have an associated goal and threshold value of performance which are input into the FORTRAN code (Appendix H) to be used in the synthesis model. The combat system suites are design variables input into Model Center, for example, Anti Submarine Warfare (ASW), Command, Control, Communications, Computers and Intelligence (C4I), Intelligence, Surveillance and Reconnaissance (ISR), Mine Counter Measures (MCM), and Special Warfare (SPW). Characteristics data (weights and electric requirements) for combat systems are read from combat system data file. This module then outputs values such as Values of Performance (VOP), weight of payload (Wp), Vertical Center of Gravity of payload (VCGp), payload power requirements in kilowatts (KWpay), and the volume of a payload interface module (Vpim) to be used in other modules.

The propulsion system data file gives detailed data for the six power alternatives and three battery types to the propulsion system module. The module reads data based on input system type and battery type to calculate propulsion system weight, volume and power characteristics which is then provided to other modules. Table 13 shows a listing of all data for the propulsion options that was input into the ship synthesis module.

The hull module is based on the idealized hull design (Figure 4). The module calculates all volume characteristics to find pressure hull, outboard items, and every buoyant volume. The main ballast tanks are included to find the submerged displacement. Free flood volumes provide the envelop displacement. Standard margins are used for some of these calculations. For example, main ballast tanks are usually 15% of the ever-buoyant volume. This is reflected in the Fortran code. The hull module outputs the distance between the two hemisphere sections, the overall length, the surface area, and the volume.

The internal tankage and manning module calculates tankage requirements and manning. Internal tankage changes with types of propulsion system (i.e. Diesel would require liquid oxygen and diesel fuel whereas fuel cells would require liquid oxygen and hydrogen). Manning depends on how much automation is on the submarine. The amount of automation may vary between 0 and 50%. The space module determines space requirements and begins the space balance process. Outputs include all the necessary volumes and areas associated with the space on the submarine. The electric module calculates electric power requirements with margins and auxiliary machinery room total volume. Parametric equations are used to estimate power requirements.

The 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. Fuel and range calculations are based on DDS 200-1.

The weight module calculates single digit and full load weight as well as vertical centers of gravity using inputs from other modules, including propulsion and combat system weights. It uses parametric equations for other system weights. The objective of the weight module is to effectively balance the normal surface condition weight with the ever-buoyant volume while at the same time keeping the lead weight addition as low as possible. The lead weight is used as a slack variable. If the ship is too buoyant after all other weights are calculated, the lead weight is then added. If the submarine is negatively buoyant before any lead ballast is added, then the design is infeasible. This is the most important of all characteristics of the submarine because the submarine either sinks or swims depending on the weight balance.

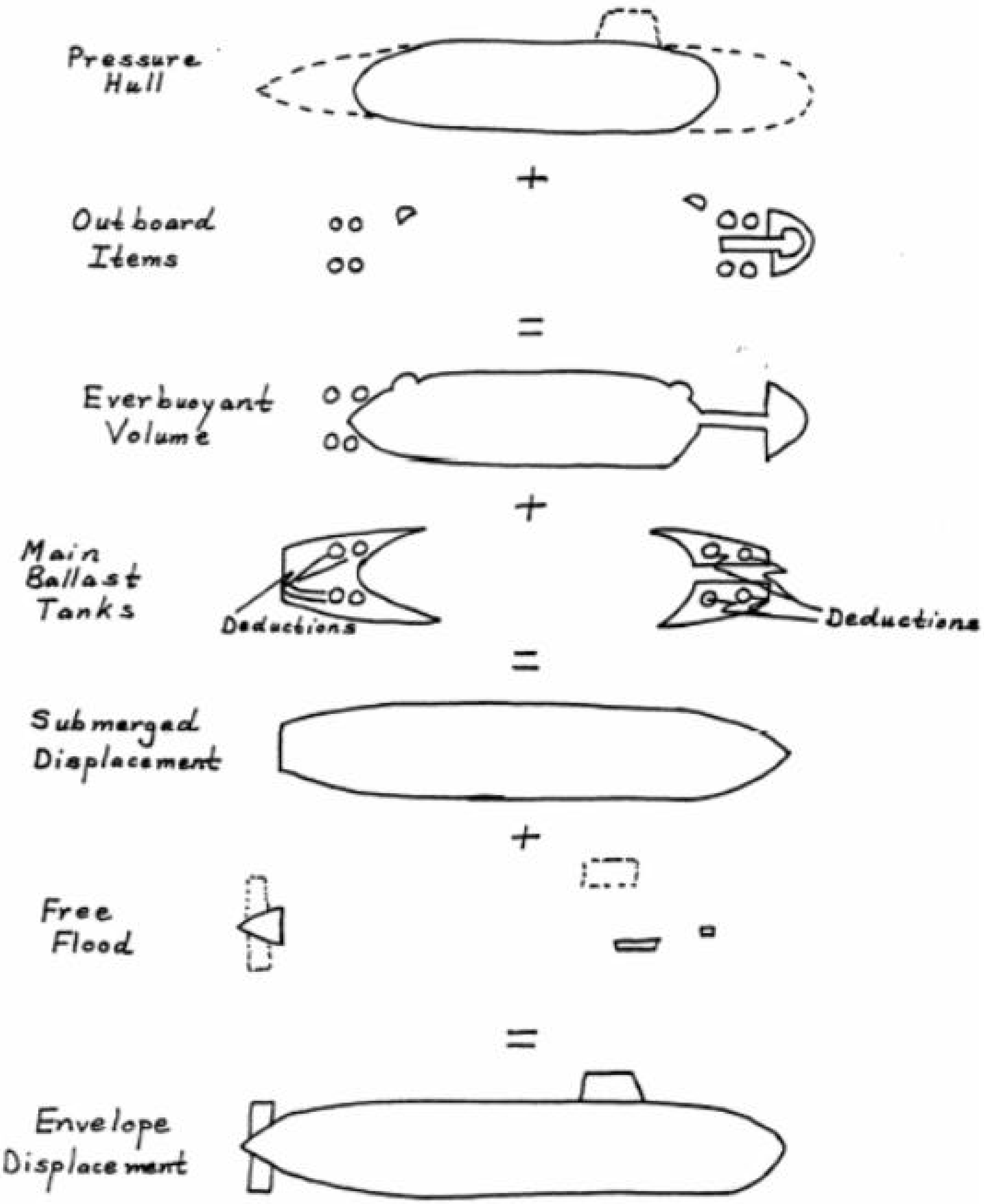


Figure 33 - Submarine Volumes [Harry Jackson Notes]

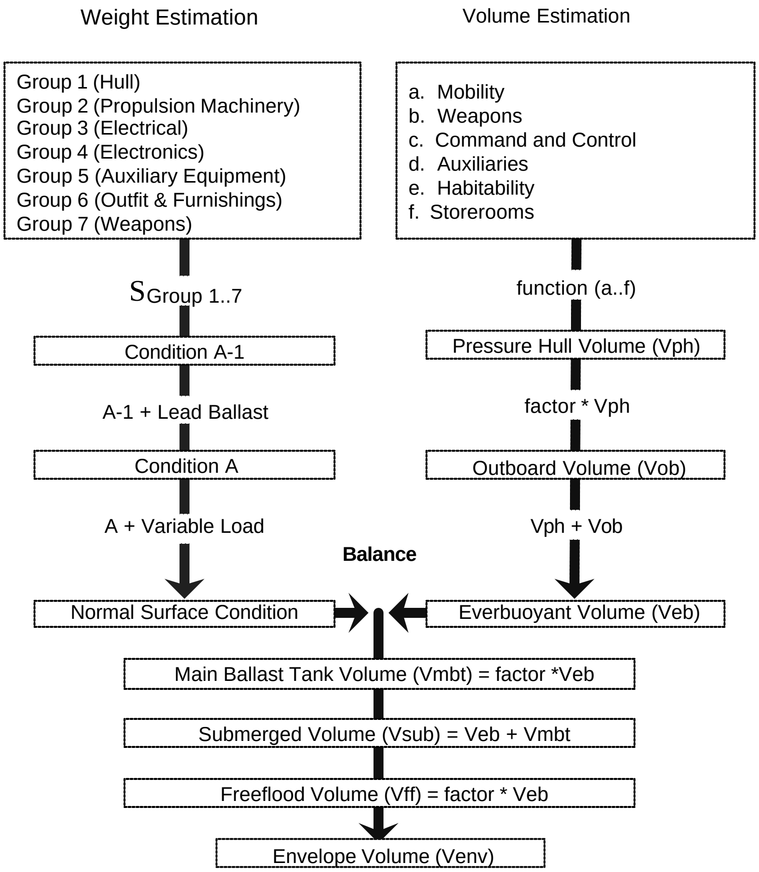


Figure 34 - Submarine Balance [Harry Jackson Notes]

The feasibility module determines the feasibility of the design based on the threshold values chosen, and the values calculated for the specific design. It takes the calculated value and subtracts the threshold value, then divides by the threshold value to get a non-dimensional measure of feasibility for each aspect. The minimum is zero, however there is a built in margin of error set at 5%.

The effectiveness module calculates the effectiveness of the submarine based on the pair-wise comparison. First, the Measures of Performance (MOPs) describe the performance metric for the required capabilities independent of missions (speed, range, etc.) for a specific ship or system. Then the Values of Performance (VOPs) are calculated. The VOPs are a figure of merit index (0-1.0) specifying the value of a specific MOP to a specific mission area for a specific mission type. The Overall Measure of Effectiveness (OMOE) describes ship effectiveness in specified missions by a single overall figure of merit index (0 – 1.0). This is a weighted average of how effective the ship will be in each mission combined with how often it will be performing that mission (see 3.4.1 for more details). The Measures of Effectiveness (MOEs) describe effectiveness for specific mission scenarios by a figure of merit index (0 – 1.0).

The cost module calculates follow ship acquisition cost. The primary inputs are from weight and propulsion modules. Several methods exist for calculating cost: Analogy method, parametric method, extrapolation method, and engineering method. The calculation method reads in various inputs and then constructs acquisition costs for each weight group. It continues to construct values for follow ships, learning rates, inflation, labor, and material. At the end of the program, code sums up the various parameters and a CBCC. The module calculates several different costs. Life Cycle Cost (LCC) is “the direct total cost to the government of acquisition and ownership of a system over its useful life. It includes the cost of development, acquisition, operations, support, and where applicable, disposal.” The Total Ownership Cost (TOC) is the LCC with more indirect components included. The Basic Construction Cost (CBCC) includes the same Direct and Indirect costs as the LCC; however, it does not take them into account over the entire lifespan of the ship. See 3.4.3 for more information.

The risk module determines an overall measure of risk based on a weighted risk assessment of each component. The risk of each component is determined by the expert, and is the product of the probability of an event happening (e.g. engine failure), and consequence of event (e.g. submarine is lost at sea). These subjective occurrences are based on our expert's opinion and are given a number to allow for a quantitative analysis (see Table 23 and Table 24). The table of all events and consequences can be seen in the risk register (Table 25). Also, see 3.4.2 for more information regarding OMOR.

3.4 Multi-Objective Genetic Optimization (MOGO)

The Multi-Objective Genetic Optimization (MOGO) uses a genetic algorithm that is able to optimize more than one objective at a time. Figure 35 shows the multi-objective genetic optimization process. For this design project it minimizes risk and cost, and maximizes effectiveness. The genetic algorithm searches the design space much more efficiently than a random search. It begins by randomly generating one set (generation) of designs. Next, it uses this generation of designs to create a new generation of designs by selecting the best designs, crossing over, and mutating others. This process is based on natural selection and evolution. After sufficient generations, the designs stop improving. The final designs represent the Pareto frontier (or non-dominated frontier). This frontier includes designs with the best performance for a given cost and risk.

The "best" points on this frontier are those that offer more effectiveness with very little additional cost, which is typically seen at a knee in the graph. Although, a limited budget may constrain the selection further, or need for extremely high effectiveness and a futuristic design may make the high end of the curve look more enticing. The entire frontier may be considered optimal. Selection depends on customer preference.

The Model Center optimizer has three types of input: objectives, constraints and design variables. Cost, risk and effectiveness are input as the objectives. They are minimized and maximized accordingly. The constraints come from the output of the feasibility module. All design variables have a range, integer or discrete, and the optimizer randomly chooses numbers within this range.

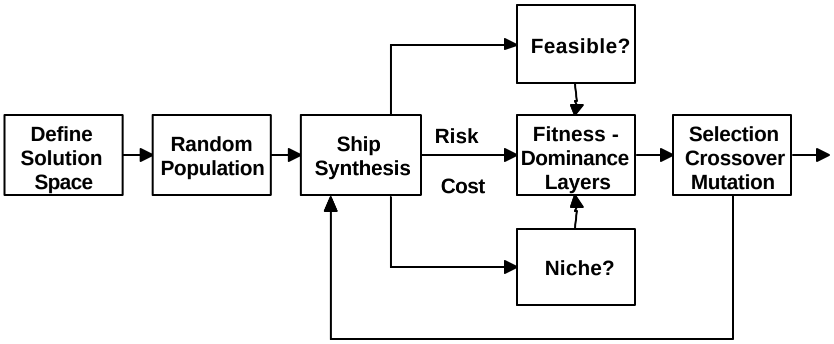


Figure 35 - Multi-Objective Genetic Optimization (MOGO)

3.4.1 Overall Measure of Effectiveness (OMOE)

The Overall Measure of Effectiveness (OMOE) describes the ship's effectiveness in all specified missions using a single overall figure of merit index (0 – 1.0). Figure 36 shows the process used to develop the OMOE and OMOR functions. It is based on the Analytical Hierarchy Process (AHP) and Multi-Attribute Value Theory (MAVT). The OMOE is a weighted average of how effective the ship will be in each mission combined with the relative importance of its missions. It is calculated using the following OMOE function:

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

Measures of Effectiveness (MOEs) describe effectiveness for specific mission scenarios by a figure of merit index (0 – 1.0). Each mission has its own MOE, these are the values used to calculate the OMOE. Measures of Performance (MOPs) describe the performance metric for the required capabilities independent of missions (speed, range, etc.) for a specific ship or system. MOPs are selected to correspond with required capabilities (ROCs, Table 5) that vary within the range of design variables, Table 20. This relationship is shown in Table 21. Resulting MOPs for SSLW are listed in Table 22. Goal and threshold values are established for each MOP.

Values of Performance (VOPs) are a figure of merit index (0-1.0) specifying the value of a specific MOP to a specific mission area for a specific mission type. A VOP value of 1.0 corresponds to the goal value of its related MOP and a VOP of 0.0 corresponds to its MOP threshold. VOPs are determined through pair-wise comparison and expert opinion. Figure 37 shows the OMOE hierarchy that was used to determine OMOE weights, w_i. Figure 38 shows the pair-wise comparison process. Figure 39 shows the resulting MOP weights.

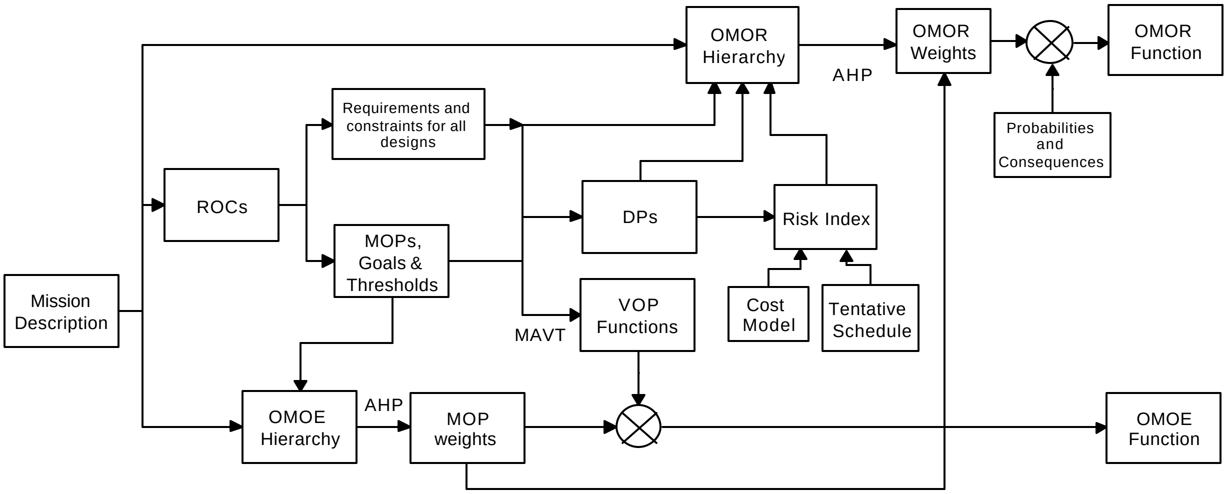


Figure 36 - OMOE and OMOR Development Process

Table 21 - ROC/MOP/DV Summary

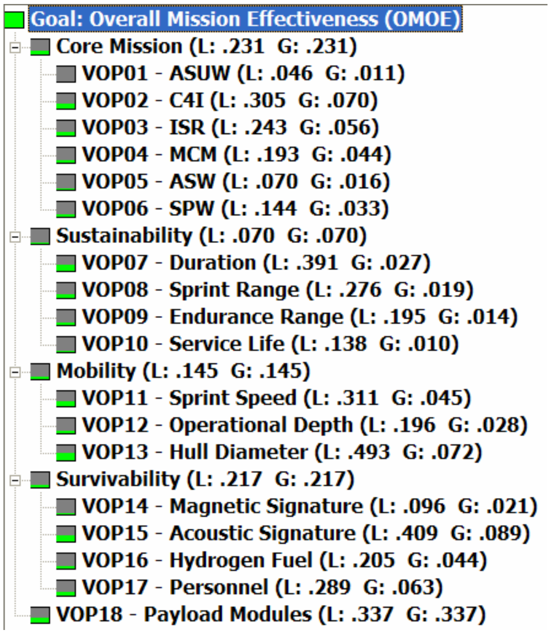
ROC	Primary MOP or Constraint	Threshold or Constraint	Goal	Related DV
ASUW 1 - Engage surface threats with anti-surface armaments	MOP1 – ASW	ASW = 4	ASW = 1	DV8 - ASW Alternative
ASUW 2 - Detect and track surface threats with sonar	MOP2 – C4I	C4I = 3	C4I = 1	DV10 - C4I Alternative
	MOP1 – ASUW	ASUW = 4	ASUW = 1	DV8 - ASUW Alternative
ASUW 3 - Disengage, evade and avoid surface attack	MOP11 – Sprint speed	15 knots	25 knots	DV1-5 - Hull form, DV2 - Displacement, DV3 - Propulsion System
ASW 1 - Engage submarines (Defensively)	MOP8 – ASW	ASW = 4	ASW = 1	DV8 - ASW Alternative
ASW 10 – Disengage, evade and avoid submarine attack by employing countermeasures and evasion techniques	MOP8 – ASW	ASW = 4	ASW = 1	DV8 - ASW Alternative
	MOP13 – Sprint Speed	15 knots	25 knots	DV 1-5 – Hull form
	MOP8 – Sprint Range	200 nm	300 nm	DV1-5 – Hull form, DV15 - Propulsion System
SEW 2 - Conduct sensor and ECM operations	Required all designs			
SEW 3 – Conduct sensor and ECCM operations	Required all designs			
MIW 1 – Conduct mine-hunting	MOP4 – MCM MOP2 – C4I	MCM = 4	MCM = 1	DV11 - MCM Alternative DV9 - C4I Alternative
MIW 2 - Conduct mine-sweeping	MOP4 - MCM	MCM = 4	MCM = 1	DV11 - MCM Alternative

ROC	Primary MOP or Constraint	Threshold or Constraint	Goal	Related DV
MIW 3 - Conduct magnetic silencing	MOP4 - MCM	MCM = 4	MCM = 1	DV11 - MCM Alternative
MIW 4 - Conduct mine laying	MOP4 - MCM	MCM = 4	MCM = 1	DV11 - MCM Alternative
MIW 5 – Conduct mine avoidance	MOP4 – MCM	MCM = 4	MCM = 1	DV11 - MCM Alternative
MIW 6.7 – Maintain magnetic signature limits	MOP14 – Magnetic Signature	No	Yes	DV14 - Degaussing System
LOG 1 - Conduct underway replenishment	Required all designs			
LOG 2 - Transfer/receive cargo and personnel	Required all designs			
CCC 3 - Provide own unit CCC	MOP2 – C4I	C4I = 3	C4I = 1	DV9 - C4I Alternative
CCC 4 - Maintain data link capability	MOP2 – C4I	C4I =3	C4I = 1	DV9 - C4I Alternative
INT 1 - Support/conduct intelligence collection	MOP3 – ISR	ISR = 2	ISR = 1	DV10 - ISR Alternative
INT 2 - Provide intelligence	MOP3 – ISR	ISR = 2	ISR = 1	DV10 - ISR Alternative
INT 3 - Conduct surveillance and reconnaissance (ISR)	MOP3 – ISR	ISR = 4	ISR = 1	DV10 - ISR Alternative
MOB 1 - Steam to design capacity in most fuel efficient manner	MOP8 – Sprint range	200 nm	300 nm	DV1-5 – Hull form, DV15 – Propulsion System
	MOP9 – Endurance range	500 nm	1500 nm	
	MOP13 – Sprint speed	15 knots	25 knots	
MOB 3 - Prevent and control damage	MOP17 – Personnel	25	10	DV6 - Manning and Automation Factor
	MOP15 – Acoustic signature	Mechanical	IPS	DV15 - Propulsion System
	MOP14 – Magnetic signature	No Degaussing	Degaussing	DV14 - 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 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			

ROC	Primary MOP or Constraint	Threshold or Constraint	Goal	Related DV
NCO 3 - Provide upkeep and maintenance of own unit	Required all designs			
FSO 5 - Conduct search/salvage & rescue operations	Required all designs			
FSO 6 - Conduct SAR operations	Required all designs			
FSO 7 - Provide explosive ordnance disposal service	Required all designs			
SPW 1 - Provide lock out chamber	Required all designs			
SPW 2 - Habitability Module	Required all designs			
SPW 3 - Be able to deliver SEALs	MOP6 - SPW	Swim	Wet Sub	DV12 – SPW Alternative

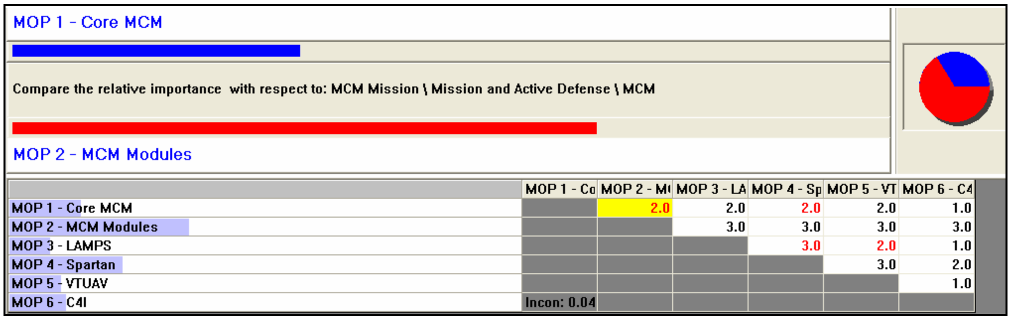
Table 22 – SSLW Measures of Performance (MOPs)

Primary MOP or Constraint	Threshold or Constraint	Goal	Related DV
MOP1 - ASUW	ASUW = 4	ASUW = 1	DV8 - ASUW Alternative
MOP2 – C4I	C4I = 3	C4I = 1	DV9 – C4I Alternative
MOP3 - ISR	ISR = 2	ISR = 1	DV10 - ISR Alternative
MOP4 – MCM	MCM = 2	MCM = 1	DV11 – MCM Alternative
MOP5 - ASW	ASW =4	ASW = 1	DV9 - ASW Alternative
MOP6 – SPW	SPW = 2	SPW = 1	DV12 – SPW Alternative
MOP7 – Duration	14 days	30 days	DV7 – Mission Length
MOP8 – Sprint Range	200nm	300 nm	DV3 - Propulsion System
MOP9 - Endurance Range	500 nm	1500 nm	DV3 - Propulsion System
MOP10 – Service Life	15 yr	20 yr	DV7 – Mission Length
MOP11 – Sprint Speed	15 kn	25 kn	DV3 - Propulsion System
MOP12 – Operational Depth	250 ft	350 ft	DV13 – Operational Depth
MOP13 – Hull Diameter	13 ft	21 ft	DV5 – Vessel Depth
MOP14 - Magnetic Signature	No Degaussing	Degaussing	DV14 - Degaussing system
	Steel	Composite	DV4 - Outer Hull Material Type
MOP15 – Acoustic Signature	Mechanical	IPS	DV3 - Propulsion System
MOP16 – Hydrogen Fuel			
MOP17 - Personnel	25	10	DV6 - Manning and Automation Factor
MOP18 – Payload Modules	Exterior	Interior	DV12 - Modular Payload



Goal: Overall Mission Effectiveness (OMOE)
- Core Mission (L: .231 G: .231)
  - VOP01 - ASUW (L: .046 G: .011)
  - VOP02 - C4I (L: .305 G: .070)
  - VOP03 - ISR (L: .243 G: .056)
  - VOP04 - MCM (L: .193 G: .044)
  - VOP05 - ASW (L: .070 G: .016)
  - VOP06 - SPW (L: .144 G: .033)
- Sustainability (L: .070 G: .070)
  - VOP07 - Duration (L: .391 G: .027)
  - VOP08 - Sprint Range (L: .276 G: .019)
  - VOP09 - Endurance Range (L: .195 G: .014)
  - VOP10 - Service Life (L: .138 G: .010)
- Mobility (L: .145 G: .145)
  - VOP11 - Sprint Speed (L: .311 G: .045)
  - VOP12 - Operational Depth (L: .196 G: .028)
  - VOP13 - Hull Diameter (L: .493 G: .072)
- Survivability (L: .217 G: .217)
  - VOP14 - Magnetic Signature (L: .096 G: .021)
  - VOP15 - Acoustic Signature (L: .409 G: .089)
  - VOP16 - Hydrogen Fuel (L: .205 G: .044)
  - VOP17 - Personnel (L: .289 G: .063)
- VOP18 - Payload Modules (L: .337 G: .337)

Figure 37 - OMOE Hierarchy



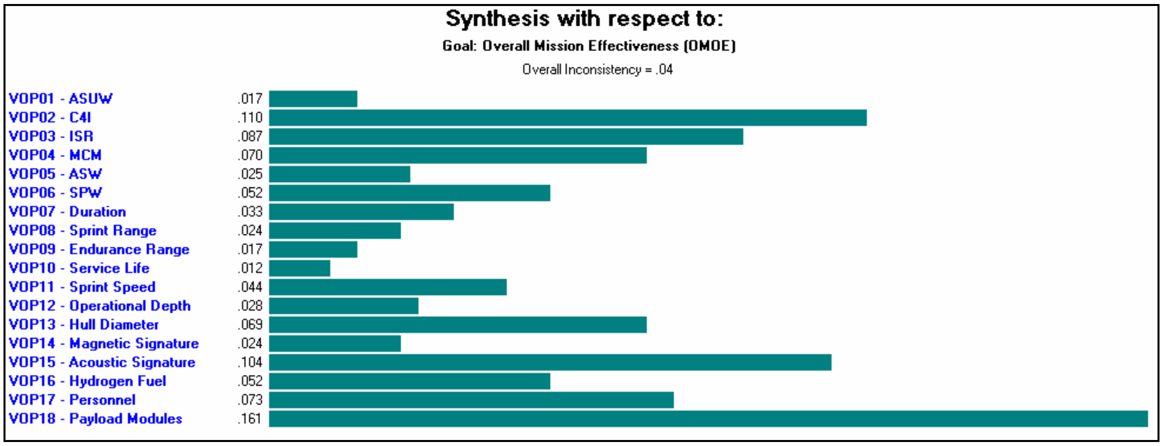
MOP 1 - Core MCM

Compare the relative importance with respect to: MCM Mission \ Mission and Active Defense \ MCM

MOP 2 - MCM Modules

	MOP 1 - Co	MOP 2 - M	MOP 3 - LA	MOP 4 - Sp	MOP 5 - VT	MOP 6 - C4
MOP 1 - Core MCM		2.0	2.0	2.0	2.0	1.0
MOP 2 - MCM Modules			3.0	3.0	3.0	3.0
MOP 3 - LAMPS				3.0	2.0	1.0
MOP 4 - Spartan					3.0	2.0
MOP 5 - VTUAV						1.0
MOP 6 - C4I	Incon: 0.04					

Figure 38 – MOP Pair-wise Comparison



Synthesis with respect to:
Goal: Overall Mission Effectiveness (OMOE)
Overall Inconsistency = .04

VOP01 - ASUW	.017
VOP02 - C4I	.110
VOP03 - ISR	.087
VOP04 - MCM	.070
VOP05 - ASW	.025
VOP06 - SPW	.052
VOP07 - Duration	.033
VOP08 - Sprint Range	.024
VOP09 - Endurance Range	.017
VOP10 - Service Life	.012
VOP11 - Sprint Speed	.044
VOP12 - Operational Depth	.028
VOP13 - Hull Diameter	.069
VOP14 - Magnetic Signature	.024
VOP15 - Acoustic Signature	.104
VOP16 - Hydrogen Fuel	.052
VOP17 - Personnel	.073
VOP18 - Payload Modules	.161

Figure 39 - Bar Chart Showing MOP Weights in OMOE

3.4.2 Overall Measure of Risk (OMOR)

The purpose of the OMOR is to calculate a quantitative overall measure of risk for a specific design based on the selection of technologies. The types of risks associated with SSLW include performance, cost, and schedule risk. Performance risk is the risk that the system will not perform as predicted. Cost risk is the risk that the cost will be significantly more than expected. Schedule risk is the risk that a technology will not be ready in time for application as planned.

The process for calculating the OMOR is to first identify the risk events associated with specific design variables and their predicted performance, schedule, and cost. The calculated risk for each event is the product of the probability of failure times the consequence of that event's failure. These are estimated using expert opinion. Table 23 shows the numerical value associated with each qualitative probability of failure. Table 24 shows the numerical value associated with each qualitative event consequence. Table 25 shows the risk register that is built after the risk for each risk event is calculated. Finally, pair-wise comparison is used to calculate the OMOR hierarchy weights and the OMOR is calculated in the risk module using the following equation:

$$OMOR = W_{perf} \sum_{i} \frac{w_i}{\sum_{i} w_i} P_i C_i + W_{\cos t} \sum_{j} w_j P_j C_j + W_{sched} \sum_{k} w_k P_k C_k$$

Table 23 - 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 24 - 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%

Table 25 - SSLW Risk Register

SWBS	System	Risk Type	Risk ID	Related	DV Description	DV Value	Risk Event Ei	Risk Description	Pi	Ci	Ri
2	Propulsion	Performance	1	DV_{16}	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
2	Propulsion	Cost	2	DV_{16}	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
2	Propulsion	Schedule	3	DV_{16}	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
2	Propulsion	Performance	4	DV_{16}	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
2	Propulsion	Cost	5	DV_{16}	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
2	Propulsion	Schedule	6	DV_{16}	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
2	Propulsion	Performance	7	DV_{16}	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

SWBS	System	Risk Type	Risk ID	Related	DV Description	DV Value	Risk Event Ei	Risk Description	Pi	Ci	Ri
2	Propulsion	Cost	8	DV$_{16}$	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
2	Propulsion	Schedule	9	DV$_{16}$	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
2	Propulsion	Performance	7	DV$_{16}$	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
2	Propulsion	Cost	8	DV$_{16}$	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
2	Propulsion	Schedule	9	DV$_{16}$	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
2	Propulsion	Performance	7	DV$_{16}$	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
2	Propulsion	Cost	8	DV$_{16}$	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
2	Propulsion	Schedule	9	DV$_{16}$	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
2	Propulsion	Performance	4	DV$_{17}$	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
2	Propulsion	Cost	5	DV$_{17}$	Battery Type (BATtyp)	1	Development, testing and qualification of Lithium Ion battery for US submarine application	Unexpected problems with development will require more money	0.8	0.3	0.24
2	Propulsion	Schedule	6	DV$_{17}$	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
2	Propulsion	Performance	4	DV$_{17}$	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
2	Propulsion	Cost	5	DV$_{17}$	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
2	Propulsion	Schedule	6	DV$_{17}$	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
7	Weapons System	Performance	7	DV$_{8}$	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
7	Weapons System	Cost	8	DV$_{8}$	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
7	Weapons System	Schedule	9	DV$_{8}$	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
4	Automation	Performance	10	DV$_{6}$	Manning and Automation Factor	0.5 - 1	Development and integration of automation	System will not meet performance requirements	0.5	0.5	0.25
4	Automation	Cost	11	DV$_{6}$	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
4	Automation	Schedule	12	DV$_{6}$	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

3.4.3 Cost

Production considerations (how to build the ship) are important to the cost models. Excess labor costs and defective part costs can be accrued if production is inefficient or not effective. Also, cost models are parametric weight based. This method uses statistics to estimate performance of the design characteristics.

Life Cycle Cost (LCC) is "the direct total cost to the government of acquisition and ownership of a system over its useful life". It is composed of primarily four parts, development cost, acquisition cost, operations and support cost, and cost of disposal. Of the four, the operations and support cost is generally the highest followed by acquisition or investment cost, development cost, and then finally the disposal cost.

Total Ownership Cost (TOC) is basically the LCC with more indirect components such as the cost of manning. In the ship synthesis model, the labor costs and the material costs are calculated separately.

The Total Lead Ship Acquisition Cost, primarily for a Naval Ship, includes the post-delivery cost plus the total end cost. The total end cost entails the government cost which consists of the program manager's growth, the payload GFE, the HM&E GFE, the outfitting cost, and other support costs and the Shipbuilder Cost this includes the Lead Ship Price, change orders, basic cost of construction, profit, margin cost, integration and engineering costs, ship assembly and support costs, and other SWBS costs. Materials that are provided by the government are also often included in the contract (GFE, GFM).

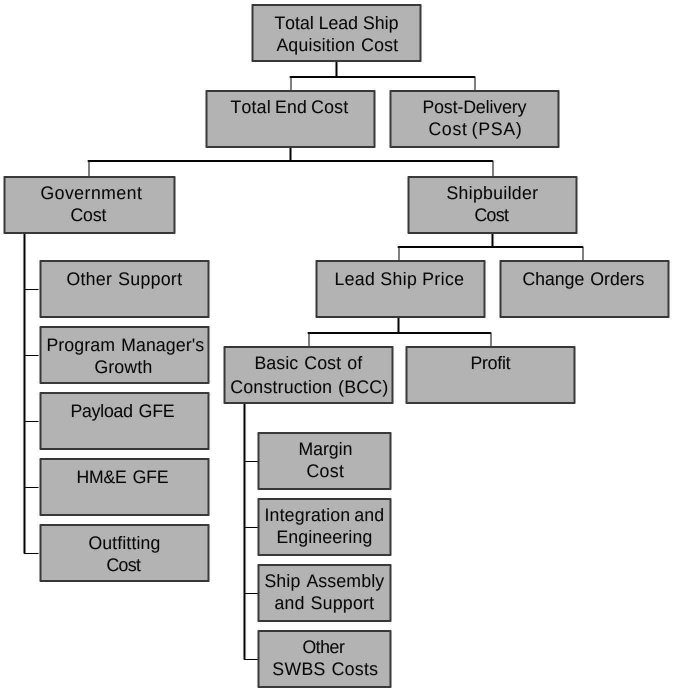


Figure 40 - Total Lead Ship Acquisition Cost

The operations and support cost includes depot maintenance costs, intermediate costs, unit level consumption costs, mission personnel costs, indirect support, and sustaining support. Unit level consumption costs, the majority of which is fuel, and mission personnel cost can typically be impacted the most in the design of the vessel. Keeping in mind that the ship's total ownership cost is more than 80% determined at the completion of the development stage, these operations and support costs need to obviously be accounted for early on in the ship's life cycle.

3.5 Optimization Results

Figure 41 shows the resulting non-dominated frontier from the optimization. Relative Risk values have been grouped together based on the relative ranges in which they fall. This was done to compress the three dimensional frontier into an easier to read two dimensional graph.

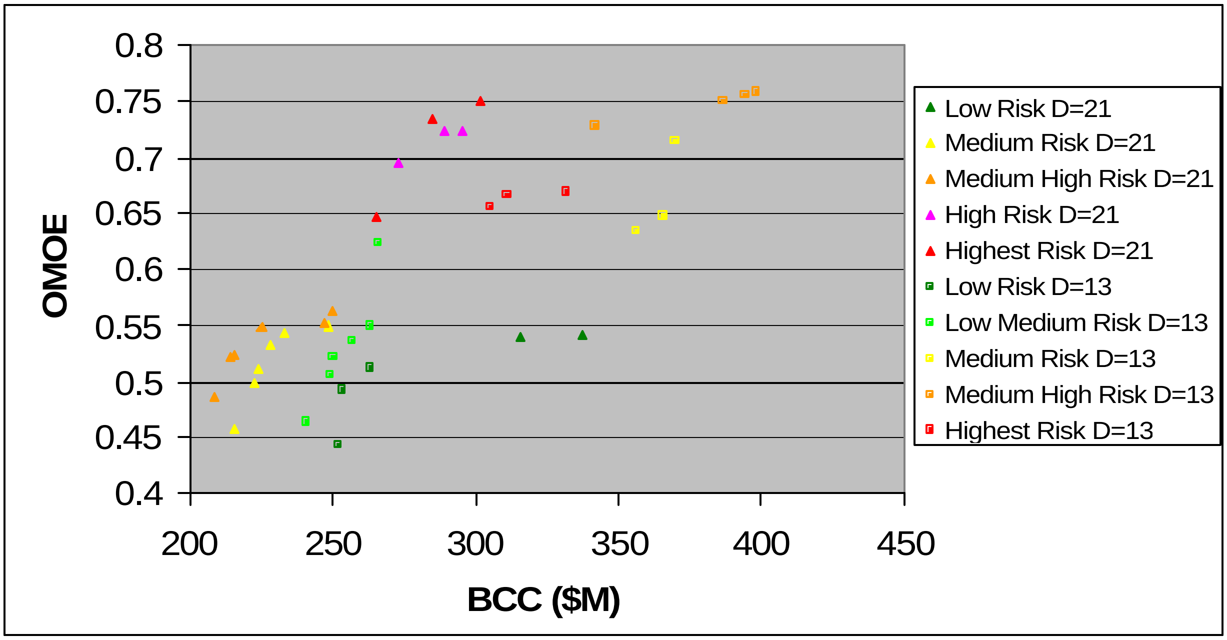
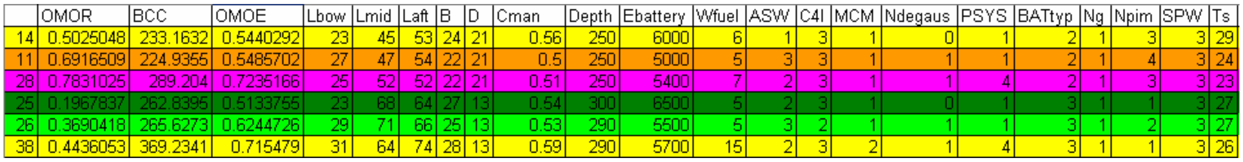


Figure 41 - Non-Dominated Frontier

All points from the Pareto front were picked off the graph. Figure 42 shows the values of the design variables for each of the given designs.



	OMOR	BCC	OMOE	Lbow	Lmid	Laft	B	D	Cman	Depth	Ebattery	Wfuel	ASW	C4I	MCM	Ndegaus	PSYS	BATtyp	Ng	Npim	SPW	Ts
14	0.5025048	233.1632	0.5440292	23	45	53	24	21	0.56	250	6000	6	1	3	1	0	1	2	1	3	3	29
11	0.6916509	224.9355	0.5485702	27	47	54	22	21	0.5	250	5000	5	3	3	1	1	1	2	1	4	3	24
28	0.7831025	289.204	0.7235166	25	52	52	22	21	0.51	250	5400	7	2	3	1	1	4	2	1	3	3	23
25	0.1967837	262.8395	0.5133755	23	68	64	27	13	0.54	300	6500	5	2	3	1	0	1	3	1	1	3	27
26	0.3690418	265.6273	0.6244726	29	71	66	25	13	0.53	290	5500	5	3	2	1	1	1	3	1	2	3	27
38	0.4436053	369.2341	0.715479	31	64	74	28	13	0.59	290	5700	15	2	3	2	1	4	3	1	1	3	26

Figure 42 - Pareto Front Design Characteristics

Design #14 is a medium risk design; it has an OMOR of 0.5025. It has a relatively low cost of $233.16 million. It has a medium effectiveness, of only 0.54402. It has a depth of 21 feet and a manning coefficient of 0.56. It has a mission duration of 29 days and 3 payload interface modules.

Design #11 is a medium-high risk design; it has an OMOR of 0.69165. It has a relatively low cost of $224.93 million. It has a medium effectiveness of 0.54857. It has a depth of 21 feet and manning coefficient of 0.5. It has a mission duration of 24 days and 4 payload interface modules.

Design #28 is a high risk design with an OMOR of 0.7831. It has a cost of $289.2 million. It has a high effectiveness of 0.72352. It has a depth of 21 feet and a manning coefficient of 0.51. It has a mission duration of 23 days and 3 payload interface modules. This is the particular design we are working with for this project due to its high effectiveness and low cost.

Design #25 is a low risk design, with an OMOR of 0.19678. It has a low cost of $262.83 million. It has a medium effectiveness of 0.51337. It has a depth of 13 feet and a relatively medium manning coefficient of 0.54. It has a mission duration of 27 days and 1 payload interface module.

Design #26 is a low-medium risk design with an OMOR of 0.36904. It has a low cost of $265.6273 million. It has a medium-high effectiveness 0.62447. It has a depth of 13 feet and a manning coefficient of 0.53. It has a mission duration of 27 days and 2 payload interface modules.

Design #38 is a medium risk design with an OMOR of 0.4436. It has a high cost of $369.23 million. It has a high effectiveness of 0.7154. It has a depth of 13 feet and a manning coefficient of 0.59. It has a mission duration of 26 days and 1 payload interface module.

3.6 ATLAS Baseline Concept Design

Design 28 is a high risk, two deck littoral submarine. The higher risk accounts for the new technologies onboard such as the fuel cell propulsion system and nickel cadmium batteries. The ship is practically cylindrical emphasizing its low drag component. A relatively low cost makes this a promising ship. The following tables summarize all important characteristics from the design optimization that will be used for concept development.

Table 26 - Design Variables Summary

Design Variable	Description	Trade-off Range	Design #28 Values
DV1	Forward section length	20-35	25
DV2	Parallel mid-body length	40-75	52
DV3	Aft section length	40-70	52
DV4	Beam length	20-30	22
DV5	Depth of vessel	13, 21	21
DV6	Manning factor	0.5-1.0	0.51
DV7	Mission length	14-30	23
DV8	Universal components : passive, integrated bow array sonar, weapons control, 2 3” countermeasure launcher + 1 reload 1=flank array sonar, torpedo room, 4 exterior torpedoes, 2= flank array, interior torpedo access, 6 exterior torpedoes; 3=8 exterior torpedoes; 4=	1-4	2
DV9	Universal components: SHRIKE, MMA, UW Comms, echo sounders, distress beacon, communication and electronic eqp. 1= photonics mast w/ UAVs, Rope buoy, 2= photonics mast w/ UAVs, 3=just universal	1-3	3
DV10	1=Control and process, NPP Imaging Center; 2= NPP Imaging Center	1-2	1
DV11	1=Forward looking sonar, side scan sonar; 2=forward looking sonar	1-2	1
DV12	1=squad and 4 man l/o, 2=squad and 9 man l/o, 3=platoon and 4 man l/o, 4=platoon and 9 man l/o	1-4	3
DV13	Operating depth	250-350	250
DV14	Degaussing system	0,1	1
DV15	1=CAT3406E CCD 410 kW, 2=CAT3412E CCD 690 kW , 3=250 kW PEM, 4=250 kW PEM w/ Reformer, 5=250 kW Alkaline, 6=250 kW Sterling	1-6	4
DV16	1=lithium ion, 2=nickel cadmium, 3=lead acid	1-3	2
DV17	Battery capacity	5000-15000	5400
DV18	Primary power generators	1-4	1
DV19	Fuel weight	5-15	7
DV20	Payload interface modules	1-4	3

Table 27 - Concept Exploration Baseline Weight Summary

Group	Weight (lton)
W100	312
Wtransmission	33
Wbasicpropulsion	7
Wreactanttanks	9
Wbattery	75
Group 200	124
Welecdist	10
Wlighting	9
Wdegaus	10
Group 300	28
Wic	4
Wshipcontrol	3
Wc&c	2
Wc&cweaps	7
Group 400	16
Group 500	46
Group 600	37
Group 700	4
Wcondition A-1	568
Lead Ballast	44
Wcondition A	612
Loads	149
Wnsc	761

Table 28 - Concept Exploration Area Summary

Area	Required
CO habitability	50
Enlisted habitability	20
Officer habitability	120
Total berthing, sanitary and messing	350
Ship control	150
Other ship functions	273.8
Total ship operations	631.8

Table 29 – Concept Exploration Electric Power Summary

Group	Description	Power (kW)
SWBS 200	Propulsion	1.1
SWBS 300	Electric Plant, Lighting	3.1
SWBS 430, 475	Miscellaneous	15.4
SWBS 521	Firemain	1.5
SWBS 540	Fuel Handling	1.5
SWBS 530, 550	Miscellaneous Auxiliary	9.1
SWBS 561	Steering	21.7
SWBS 600	Services	5.5
Degaussing	Degaussing	30.9
KW_{NP}	Non-Payload Functional Load	58.9
KW_{MFLM}	Max. Functional Load w/Margins	173.5
KW_{24AVG}	24 Hour Electrical Load, Average	98.1
	Primary Generator Required Power Rating	233.3

Table 30 - MOP/ VOP/ OMOE/ OMOR Summary

Measure	Description	Value of Performance
MOP 1	ASUW	.017
MOP 2	C4I	.110
MOP 3	ISR	.087
MOP 4	MCM	.070
MOP 5	ASW	.025
MOP 6	SPW	.052
MOP 7	Duration	.033
MOP 8	Sprint Range	.024
MOP 9	Endurance Range	.017
MOP 10	Service Life	.012
MOP 11	Sprint Speed	.044
MOP 12	Operational Depth	.028
MOP 13	Hull Diameter	.069
MOP 14	Magnetic Signature	.024
MOP 15	Acoustic Signature	.104
MOP 16	Hydrogen Fuel	.052
MOP 17	Personnel	.073
MOP 18	Payload Modules	.161
OMOE	Overall Measure of Effectiveness	0.724
OMOR	Overall Measure of Risk	0.783

Table 31 - Concept Exploration Baseline Design Principal Characteristics

Characteristic	Baseline Value
Δ (lton)	761.0
LWL (ft)	129
Beam (ft)	22
Draft (ft)	21
W1 (lton)	312.3
W2 (lton)	124.3
W3 (lton)	27.6
W4 (lton)	16.3
W5 (lton)	44.8
W6 (lton)	34.5
KG (ft)	7.6
Propulsion system	PEM with Reformer
Battery Type	Nickel Cadmium
MCM system	1
ASW system	2
ASUW system	2
SPW system	3
C4I system	3
Average deck height (ft)	7
Total Officers	5
Total Enlisted	11
Total Manning	16
Number of PIMs	3
BCC	$294 million
Life Cycle Cost	$502 million

4 Concept Development (Feasibility Study)

Concept Development of SSLW follows the design spiral, Figure 3, 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.

4.1 General Arrangement and Combat Operations Concept (Cartoon)

As a preliminary step in finalizing hull form geometry and all general arrangements, an arrangement cartoon was developed for areas supporting mission operations, propulsion, and other critical constrained functions. Figure 43 shows a Flounder diagram, the first step used to arrange the littoral submarine. This is a plot of area vs. length which creates the sectional area curve. Areas in the Flounder diagram represent volumes in the submarine. Volumes from Concept Exploration are configured inside the outer hull boundaries. Appendix F – Volumes and Areas - Requirements and Values shows the volume and area values. Using this method, a rough arrangement was developed that both checked and maintained the necessary volume balance.

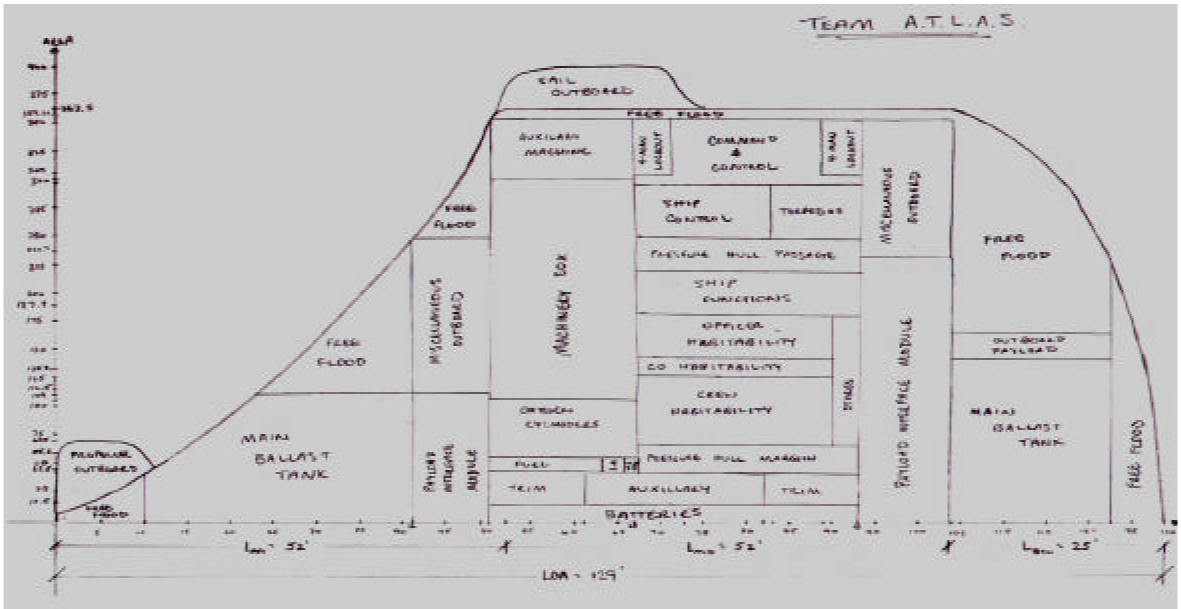


Figure 43 - Flounder Diagram

A preliminary 3-D cartoon was developed from the Flounder diagram. The general arrangement is dictated by the submarine's unique size, shape and components. The ship is divided into two decks. The upper deck is used primarily for ship functions and command and control. The lower deck is used for habitability. The machinery room aft includes both decks. Batteries and tanks will located below the lower deck. Figure 44 shows the preliminary arrangements. A small torpedo room is located forward. PIMs are located forward and aft.

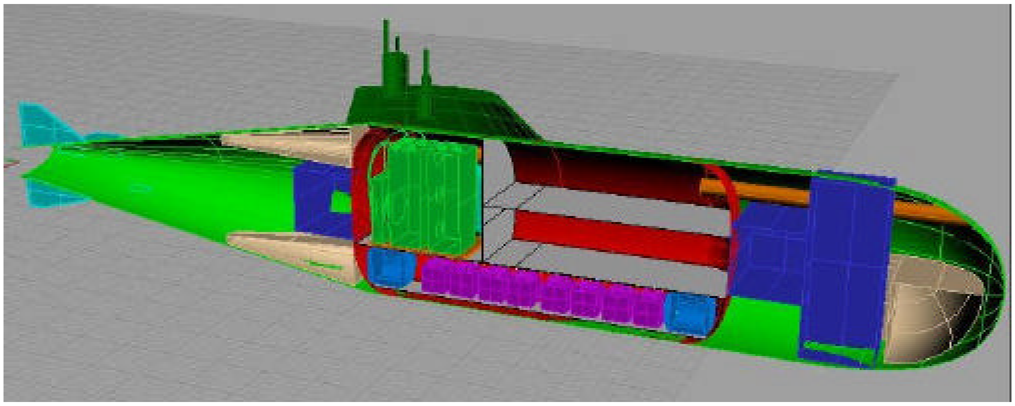


Figure 44 – 3-D Cartoon

4.1.1 Mission Operations

The mission components for the littoral platform are as follows: Passive ranging sonar (GMBH, L3 Communications); Flank array sonar and electronics; Integrated bow array - conformal, MH&HF passive, HF active, and electronics; ASW Weapons control system; Small inboard torpedo room with two tube access, and 2xMK50 torpedoes; 6 External torpedo launch canisters + 1xMH50 per canister; 3" Countermeasure/XBT launcher; 3" Countermeasure reloads x 10 (locker); 6.75" external Countermeasure launcher with 4cannisters each; Mine avoidance sonar and electronics; Side scan sonar; 9 man lock out trunk; Combat rubber raiding craft and diver stowage; SHRIKE submarine ESM and communications mast, and system (less ROPE buoy); Multifunction Mast Antenna (MMA); Underwater communications; Navigation echo sounders; Distress beacon; and communications electronics and equipment.

Mission operations range from SEAL missions, mine laying/countermeasures, and ISR, as well as self-defense. Those components playing directly into the mission of the ship are a main concern for arrangements. These include the lock-out trunk, PIMs, and torpedo tubes. The PIMs are used to house many mission packages ranging from mines to AUVs and are also used to hold SEAL equipment like the rubber raiding craft. Due to their size (8’x8’x20’), the placement is thought out carefully. Two are placed forward and one is placed aft of the pressure hull. From the cartoon analysis it was discovered that the ship would be better suited for 2 four man lockouts instead of a 9 man due to space limitations. It was decided that one of the lockouts would be best placed under the sail. This would allow it to double as access to the conning tower. The inboard torpedo room was placed on the upper deck and forward to allow the machinery plant to be aft but to still have access from Command and Control. There is more freedom in placing the 6 encapsulated torpedo tubes.

4.1.2 Machinery Room Arrangements

The machinery room arrangements were first created from the flounder diagram where the length of the machinery room was set to 17’. Also from the flounder diagram came the locations of other components related to the machinery room, including oxygen tanks, machinery, fuel tanks etc. 3-D CAD was used to verify the overall volume of the machinery room and large related components. Detailed machinery arrangements are discussed in Section 4.7.2.

4.2 Hull Form

4.2.1 Hydrodynamic Hull Form (External Envelope)

The baseline concept of the hull form is described in Section 3.1.1. Table 32 shows the optimization results with an overall length of 129 ft, beam of 22 ft and depth of 21 ft. From the cartoon arrangement analysis, it was discovered that these dimensions would not allow the PIMs to fit within the outer hull. This led to a revision of the baseline characteristics from an asymmetric hull to a symmetric hull with a diameter of 22 feet.

Table 32 - SSLW Hull Form Characteristics

	MOGO	Baseline
L_{Bow}	25	25
L_{Mid}	52	52
L_{Aft}	52	52
LOA	129	129
B	22	22
D	21	22
Δ	31985 ft^3	35427 ft^3

The transition to a symmetrical hull makes the submarine more producible, more structurally efficient and simplifies many calculations including resistance and maneuvering. Figure 45 shows the ships curves of form which are concentric circles due to its symmetry.

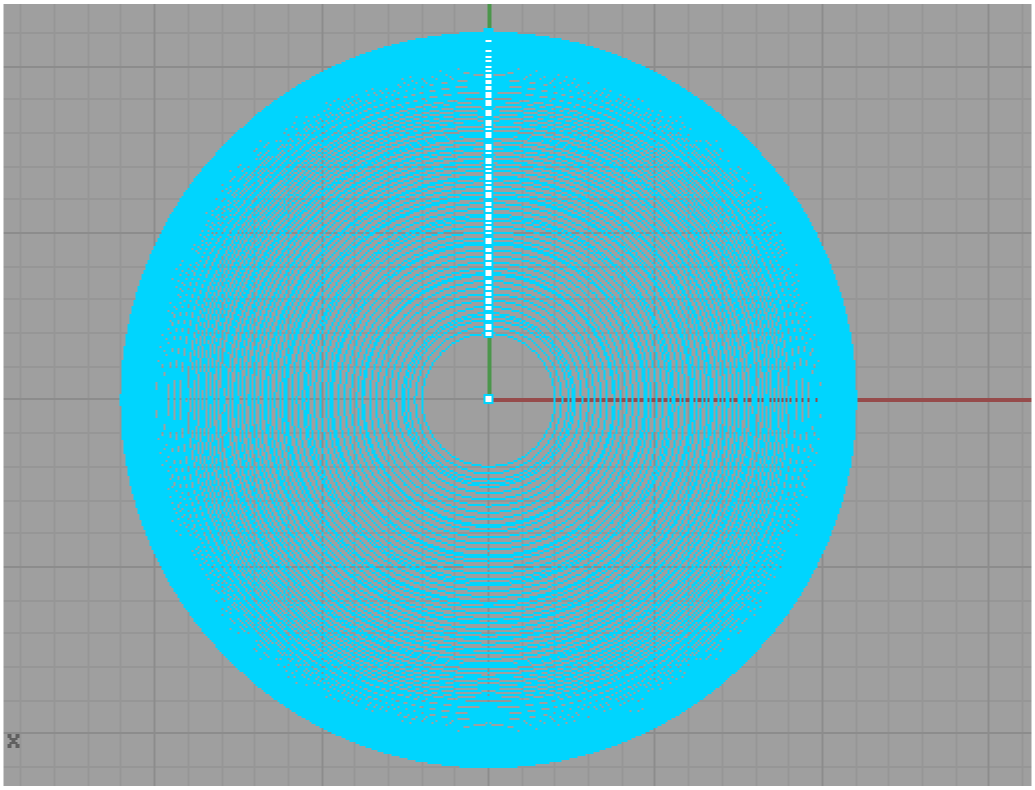


Figure 45 - Curves of Form

4.3 Structural Design and Analysis

For structural analysis purposes only the pressure hull was modeled in MAESTRO because it is the primary load bearer. The structural design begins with modeling the hull geometry in a finite element program (MAESTRO). After the geometry is modeled, the materials are chosen and the scantlings are sized. MAESTRO is run to determine adequacy, and the inadequate structures are modified with either heavier plating or larger stiffeners until the structure is adequate. Figure 46 outlines the structural design process.

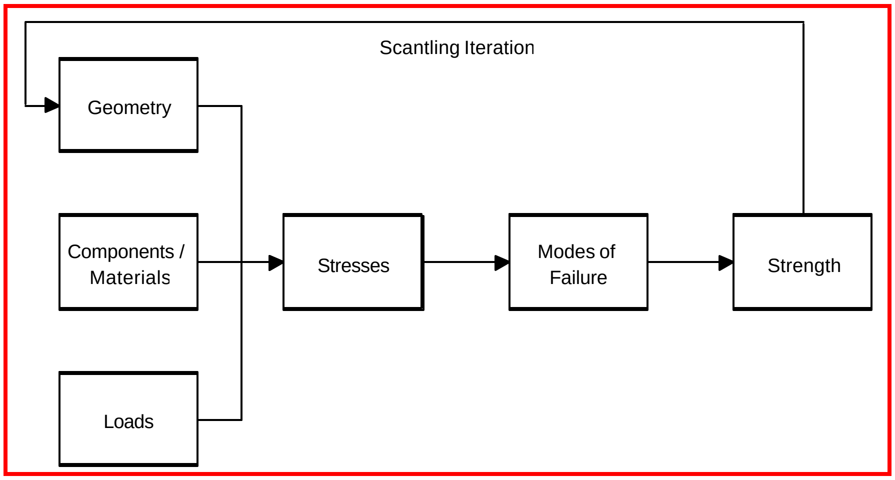


Figure 46 - Structural Design Process

4.3.1 Geometry, Components and Materials

The submarine was divided into four substructures for organizational purposes in MAESTRO. These are the fore end cap, the midsection, the aft end cap and the bulkheads. HY-80 Steel is used for the pressure hull and stiffeners since it is the common steel in use by US submarine builders. HSLA and HSS should also be considered.

The final plating is three quarter (3/4) inch thick. Table 33 and Table 34 show the scantlings. Frames are standard I-T shapes.

Table 33 - Frame Characteristics

Web Height	Web Thickness	Flange Width	Flange Thickness	Spacing
6 inches	0.25 inches	4 inches	0.25 inches	17.8

Table 34 - King Frame Characteristics

Web Height	Web Thickness	Flange Width	Flange Thickness	Number of Frames
12.25 inches	0.36 inches	4 inches	0.36 inches	1

The finite element geometry is defined in MAESTRO. For the midsection, endpoints are placed every five degrees to form a quarter of a circle; the nodes are placed every 1.5 feet (frame spacing) along the length of the 37 foot midsection. Offsets for the end caps are taken from the Rhino model and input into MAESTRO as additional nodes. There are two transverse bulkheads and one king frame. Each bulkhead is its own module which allows them to be moved in the model if necessary. Standard strakes are created for the midsection and special quad elements are defined for the end caps and bulkheads. Beam elements are used to model the king frame.

There are two bulkheads in the pressure hull, one is directly forward of the machinery room and the other is aft of the torpedo room. This corresponds to 13.5 feet and 33.3 feet along the cylindrical mid-body, respectively. A king frame was placed half way between the two bulkheads at 23.4 feet along the cylindrical mid-body. Figure 47 shows the different views of the pressure hull structure and Figure 48 shows the interior characteristics. Figure 49 shows the midship section.

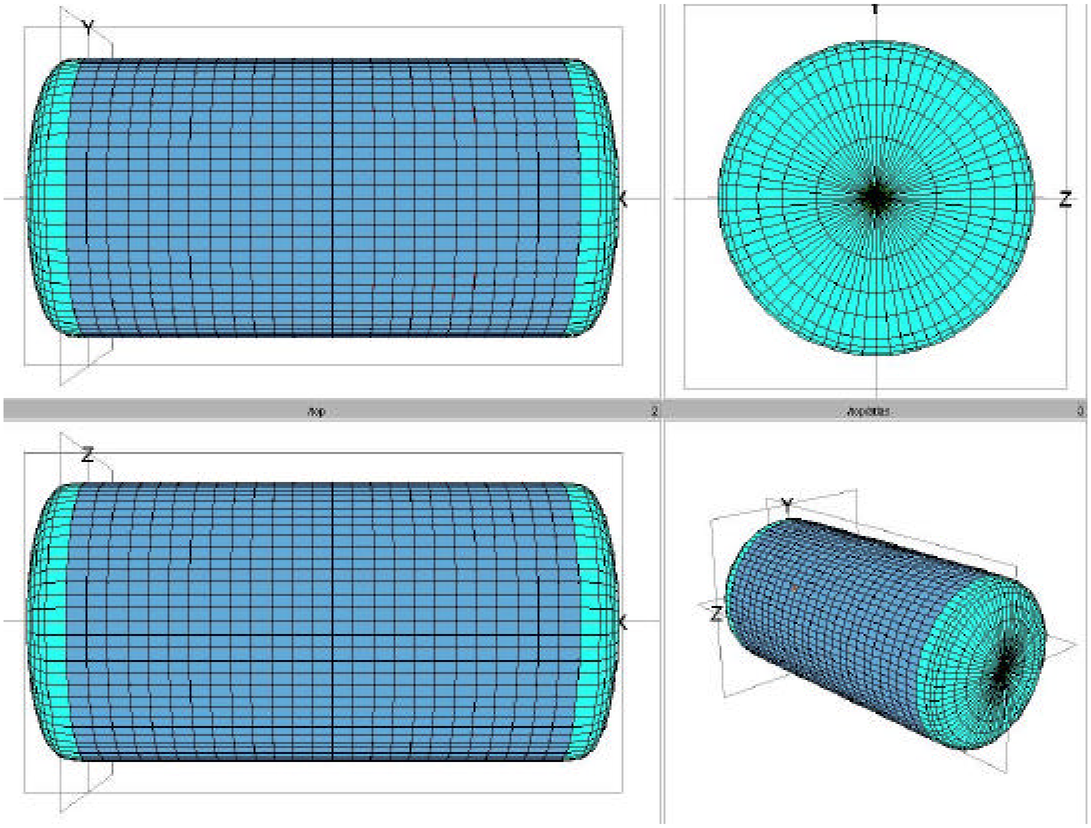


Figure 47 - Pressure Hull Model

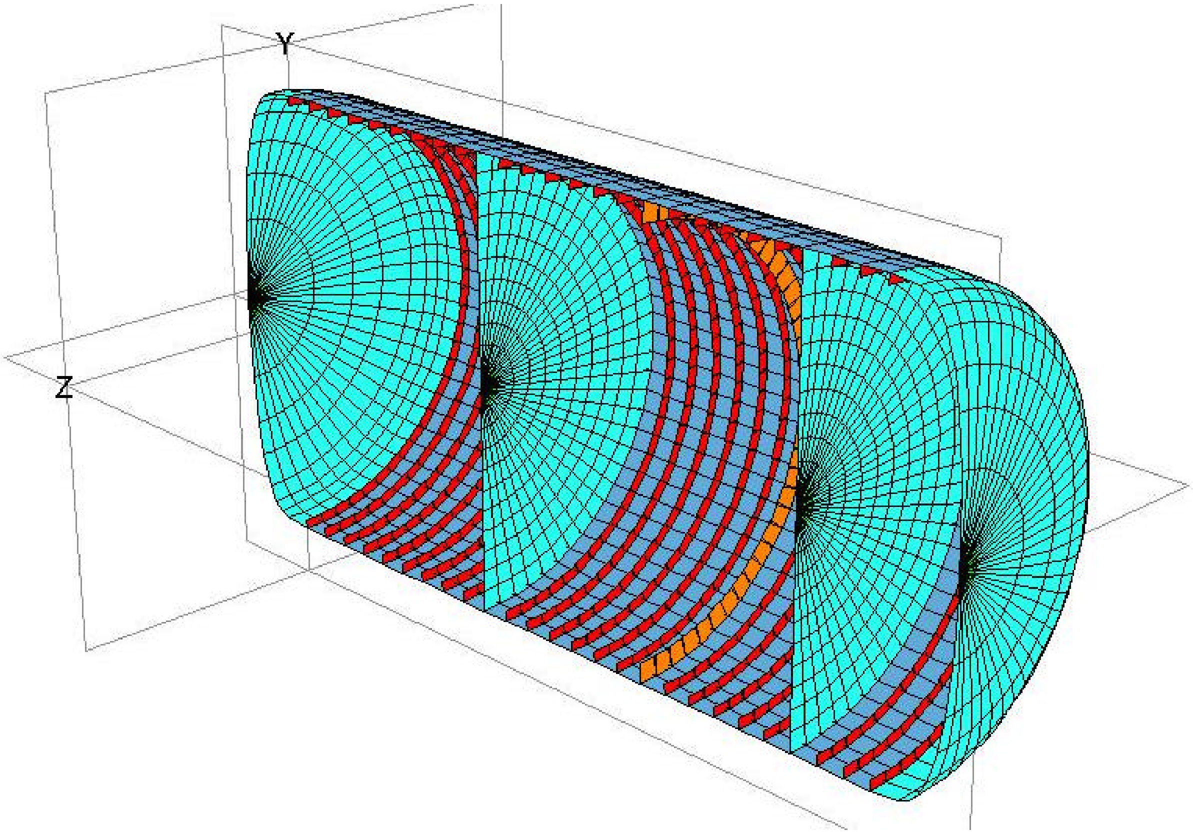


Figure 48 – Pressure Hull Structure Interior View

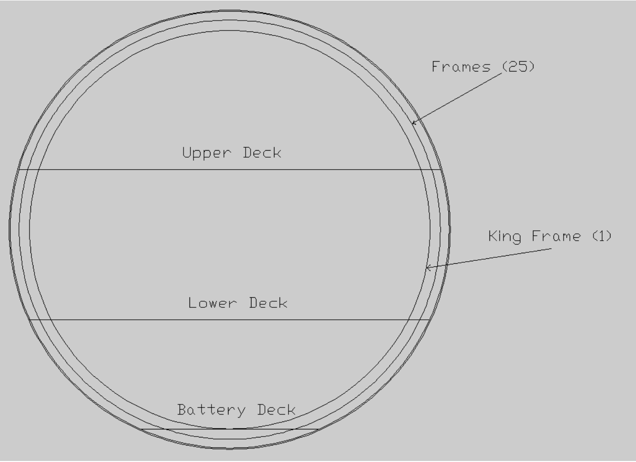


Figure 49 - Midship Section Drawing

4.3.2 Loads

For analysis, the model is restrained against heave and sway motion at the centroid of each end cap and against surge on the sides of the midsection. The only load case tested was the hydrostatic pressure at 250 foot depth. It is assumed that if the pressure hull can survive the pressure at depth then it can survive waves on the surface.

4.3.3 Adequacy

In order to reduce the overall structural weight, the scantlings are optimized first by selecting primary dimensions from a similar submersible. The frame sizing is then increased or decreased as needed. This process was carried out several times until the structure met the minimum requirements defined by the factor of safety. The factor of safety is 2 for collapse and 1.75 for serviceability.

Figure 50 shows an exaggeration of the deformation at 250 feet. The scale is in units of feet giving the midsection a deformation on the order of 1/16 inch. The end cap shows a deformation of approximately 1 inch; however, the end caps in the model are only formed to define restraints and are not accurate depictions of what deformations would actually occur to the end caps. The larger deformation in the end cap is a result of the tri-elements in the center not containing stiffeners. Figure 51 shows the end cap.

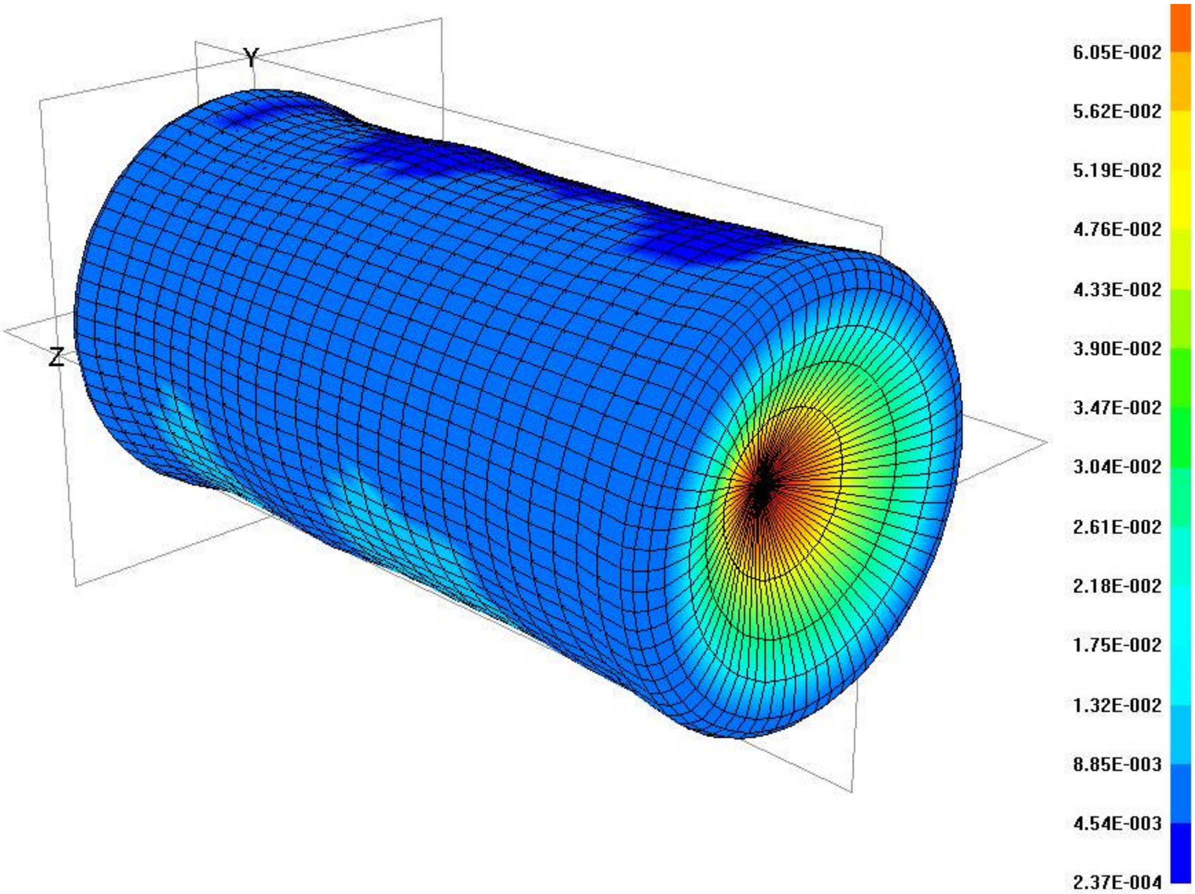


Figure 50 - Deformation at 250 ft.

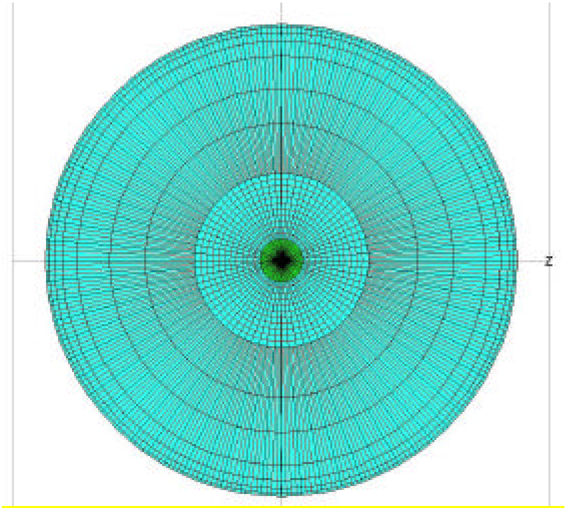


Figure 51 - End Cap

Figure 52 shows adequacy of the stiffeners under their limiting case. The worst case stiffeners have an adequacy of approximately 0.4. This translates to the stiffeners being slightly over designed and through more optimization this number could be reduced.

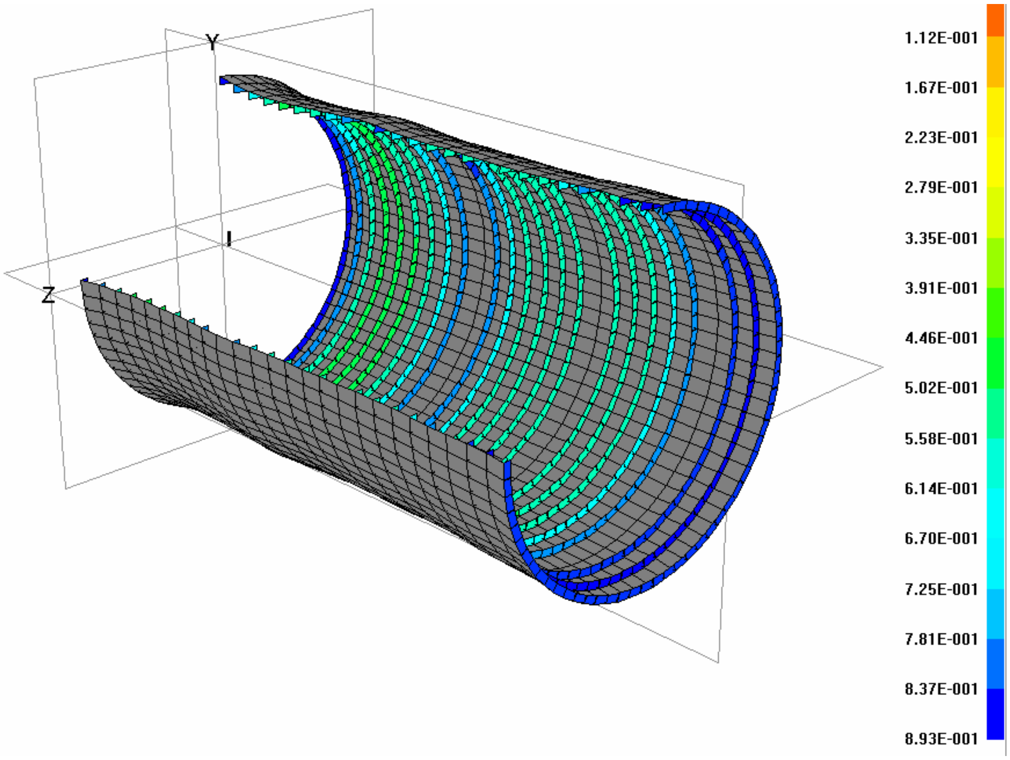


Figure 52 - Stiffener Adequacy

Figure 53 shows the adequacy of the plates under their limiting case. The worst case plates still have adequacy parameters of approximately 0.2. The bulkheads have adequacy parameters of approximately 0.8. They could be significantly reduced in size and still be adequate.

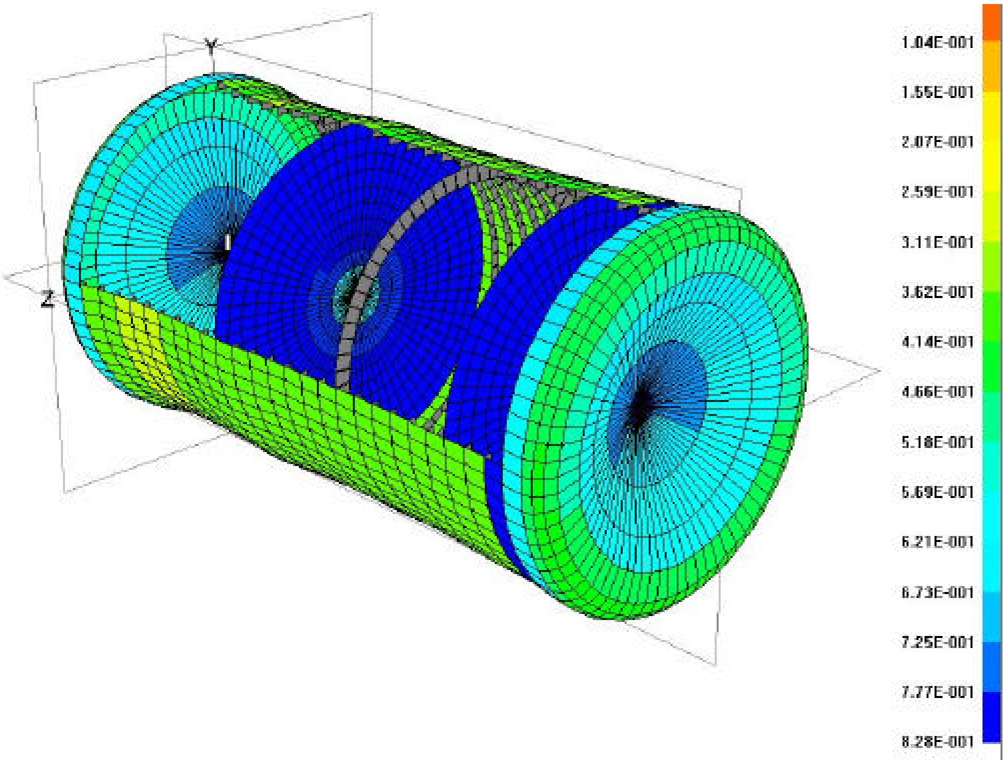


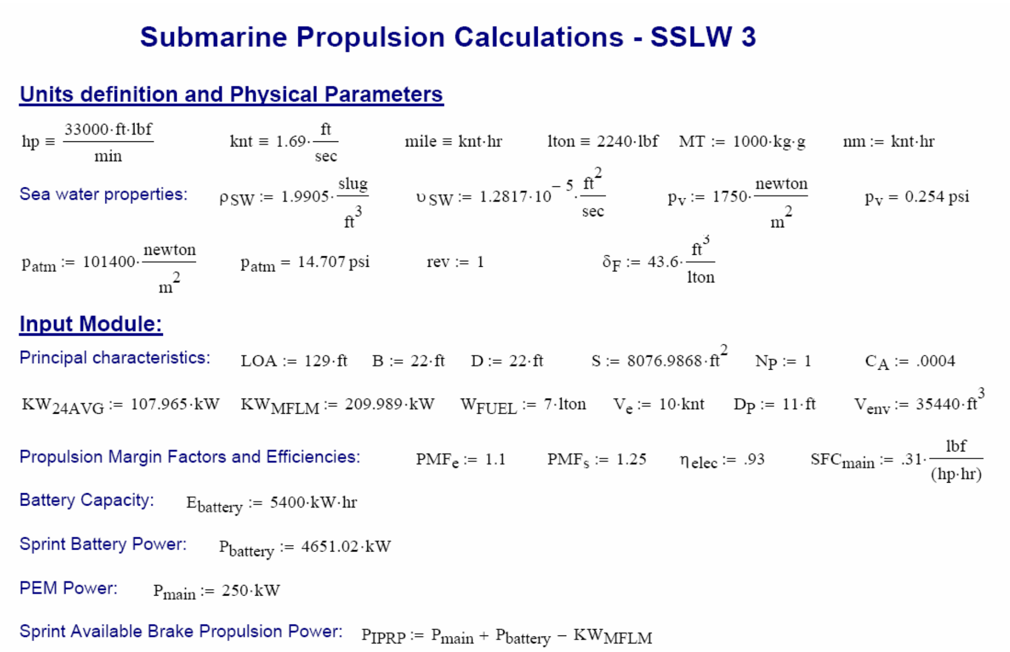
Figure 53 - Adequacy of plates under limiting case

4.4 Power and Propulsion

The SSLW propulsion system consists of one 250kW PEM fuel cell with reformer and two 2700 kW-hr parallel banks of nickel-cadmium batteries. The PEM/reformer uses diesel fuel and liquid oxygen. SSLW has an Integrated Power System (IPS) to provide electric power to a synchronous permanent magnet propulsion motor driving the propeller and ship service electric loads throughout the submarine.

4.4.1 Resistance

Resistance calculations were performed using a Gilmer and Johnson form factor and ITTC coefficient of friction to calculate viscous resistance as shown in Figure 54 and Figure 55.



Submarine Propulsion Calculations - SSLW 3

Units definition and Physical Parameters

$hp \equiv \frac{33000\cdot ft\cdot lbf}{min}$ $knt \equiv 1.69\cdot\frac{ft}{sec}$ $mile \equiv knt\cdot hr$ $lton \equiv 2240\cdot lbf$ $MT := 1000\cdot kg\cdot g$ $nm := knt\cdot hr$

Sea water properties: $\rho_{SW} := 1.9905\cdot\frac{slug}{ft^3}$ $\upsilon_{SW} := 1.2817\cdot 10^{-5}\cdot\frac{ft^2}{sec}$ $p_V := 1750\cdot\frac{newton}{m^2}$ $p_V = 0.254\,psi$

$p_{atm} := 101400\cdot\frac{newton}{m^2}$ $p_{atm} = 14.707\,psi$ $rev := 1$ $\delta_F := 43.6\cdot\frac{ft^3}{lton}$

Input Module:

Principal characteristics: $LOA := 129\cdot ft$ $B := 22\cdot ft$ $D := 22\cdot ft$ $S := 8076.9868\cdot ft^2$ $N_P := 1$ $C_A := .0004$

$KW_{24AVG} := 107.965\cdot kW$ $KW_{MFLM} := 209.989\cdot kW$ $W_{FUEL} := 7\cdot lton$ $V_e := 10\cdot knt$ $D_P := 11\cdot ft$ $V_{env} := 35440\cdot ft^3$

Propulsion Margin Factors and Efficiencies: $PMF_e := 1.1$ $PMF_s := 1.25$ $\eta_{elec} := .93$ $SFC_{main} := .31\cdot\frac{lbf}{(hp\cdot hr)}$

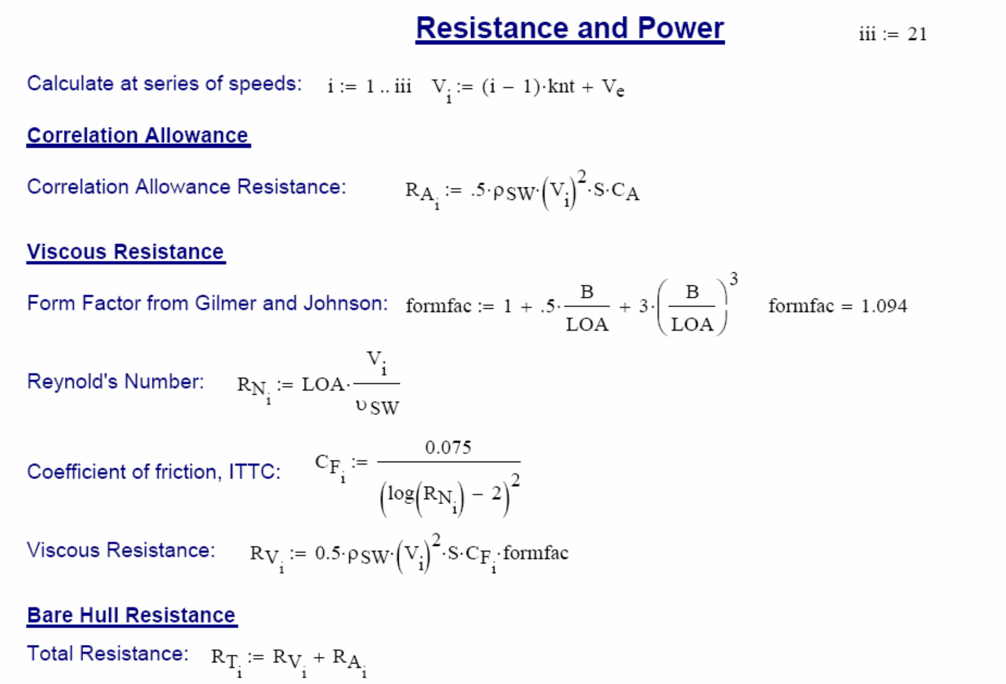
Battery Capacity: $E_{battery} := 5400\cdot kW\cdot hr$

Sprint Battery Power: $P_{battery} := 4651.02\cdot kW$

PEM Power: $P_{main} := 250\cdot kW$

Sprint Available Brake Propulsion Power: $P_{IPRP} := P_{main} + P_{battery} - KW_{MFLM}$

Figure 54 – Propulsion and Power Calculation Input



Resistance and Power $iii := 21$

Calculate at series of speeds: $i := 1\,..\,iii$ $V_i := (i-1)\cdot knt + V_e$

Correlation Allowance

Correlation Allowance Resistance: $R_{A_i} := .5\cdot\rho_{SW}\cdot\left(V_i\right)^2\cdot S\cdot C_A$

Viscous Resistance

Form Factor from Gilmer and Johnson: $formfac := 1 + .5\cdot\frac{B}{LOA} + 3\cdot\left(\frac{B}{LOA}\right)^3$ $formfac = 1.094$

Reynold's Number: $R_{N_i} := LOA\cdot\frac{V_i}{\upsilon_{SW}}$

Coefficient of friction, ITTC: $C_{F_i} := \frac{0.075}{\left(\log\left(R_{N_i}\right) - 2\right)^2}$

Viscous Resistance: $R_{V_i} := 0.5\cdot\rho_{SW}\cdot\left(V_i\right)^2\cdot S\cdot C_{F_i}\cdot formfac$

Bare Hull Resistance

Total Resistance: $R_{T_i} := R_{V_i} + R_{A_i}$

Figure 55 - Resistance Calculations

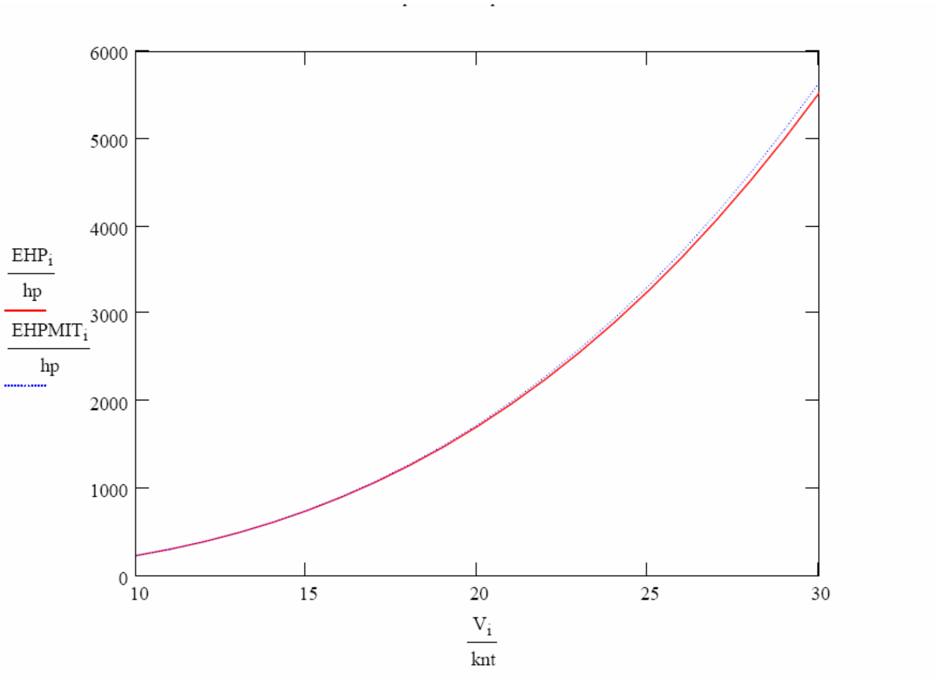
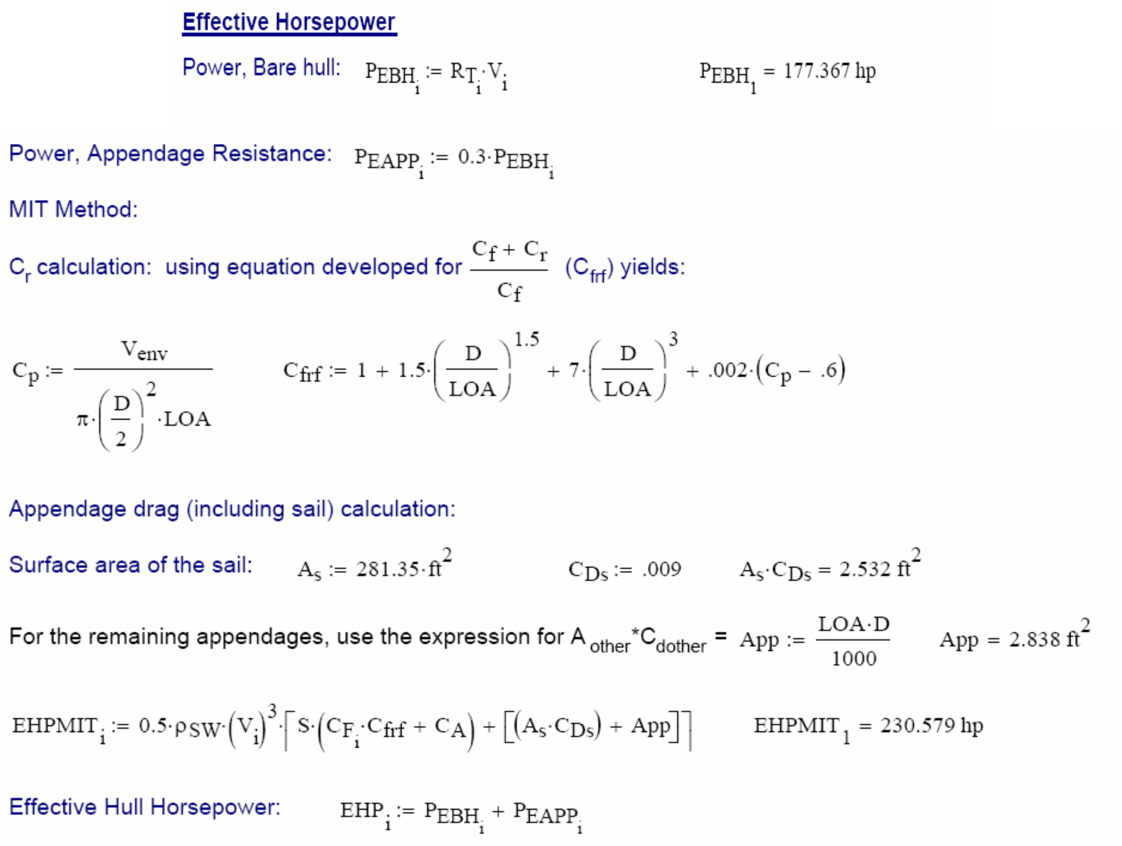


Figure 56 - Bare Hull Resistance vs. Ship Speed

Two different algorithms were developed for power calculations. One algorithm built on the resistance calculations and added a 30% margin for appendage drag. The second method was developed at the Massachusetts Institute of Technology. Figure 57 shows the two methods calculate effective horsepower and the comparisons for the two methods.



Effective Horsepower

Power, Bare hull: $P_{EBH_i} := R_{T_i} \cdot V_i$ $\qquad P_{EBH_1} = 177.367\ \mathrm{hp}$

Power, Appendage Resistance: $P_{EAPP_i} := 0.3 \cdot P_{EBH_i}$

MIT Method:

C_r calculation: using equation developed for $\dfrac{C_f + C_r}{C_f}$ (C_{frf}) yields:

$$C_p := \frac{V_{env}}{\pi \cdot \left(\frac{D}{2}\right)^2 \cdot LOA} \qquad C_{frf} := 1 + 1.5 \cdot \left(\frac{D}{LOA}\right)^{1.5} + 7 \cdot \left(\frac{D}{LOA}\right)^3 + .002 \cdot (C_p - .6)$$

Appendage drag (including sail) calculation:

Surface area of the sail: $A_s := 281.35 \cdot ft^2$ $\qquad C_{Ds} := .009$ $\qquad A_s \cdot C_{Ds} = 2.532\ ft^2$

For the remaining appendages, use the expression for $A_{other} {}^{*} C_{dother}$ = $App := \dfrac{LOA \cdot D}{1000}$ $\qquad App = 2.838\ ft^2$

$$EHPMIT_i := 0.5 \cdot \rho_{SW} \cdot (V_i)^3 \cdot \left[S \cdot (C_{F_i} \cdot C_{frf} + C_A) + [(A_s \cdot C_{Ds}) + App]\right] \qquad EHPMIT_1 = 230.579\ \mathrm{hp}$$

Effective Hull Horsepower: $EHP_i := P_{EBH_i} + P_{EAPP_i}$

Figure 57 - Power Calculations

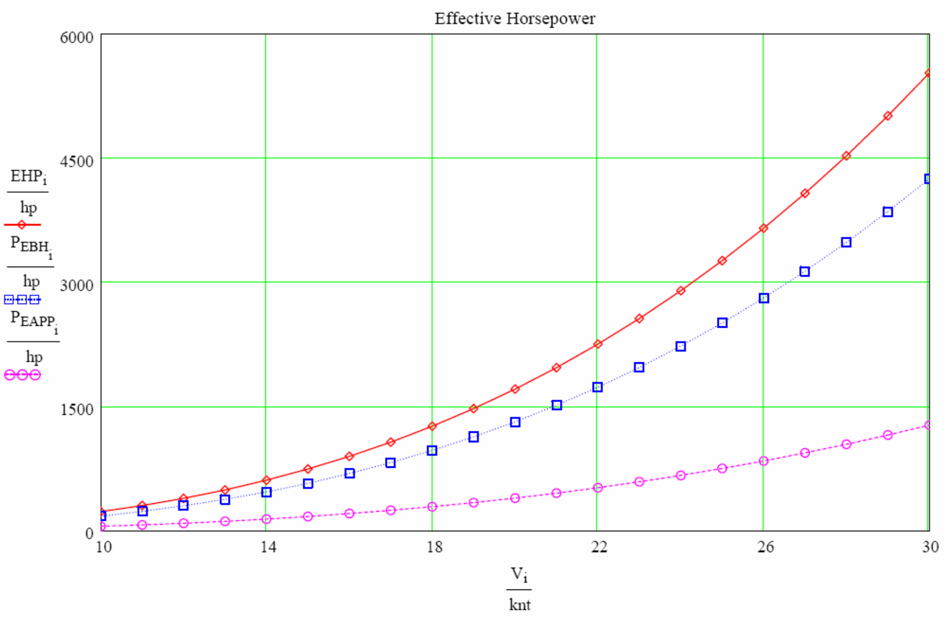
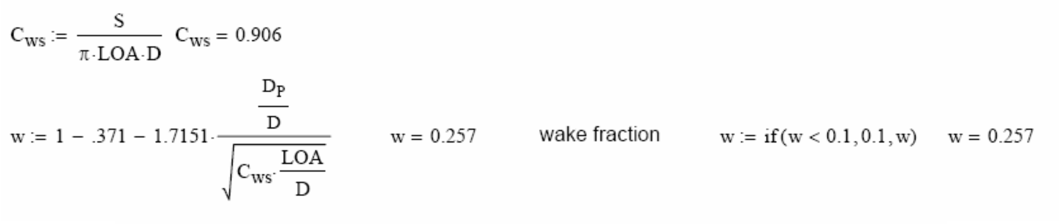


Figure 58 - Effective Horsepower vs. Ship Speed

4.4.2 Propulsion

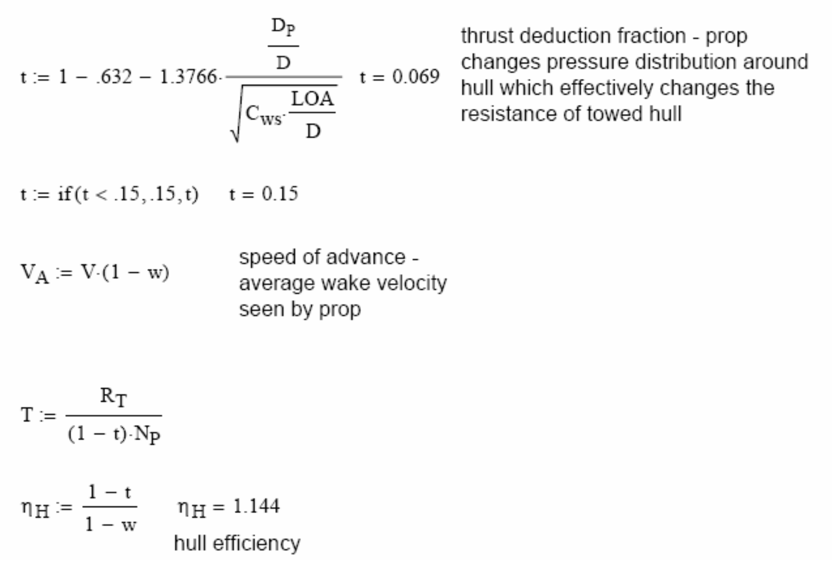
Additional calculations were performed producing a range of numbers for thrust, thrust horsepower, delivered horsepower, open water delivered horsepower, shaft horsepower, and brake horsepower. Using these values and corresponding efficiencies, a preliminary propeller analysis was run using existing 4-bladed B Series propeller data.

The MathCAD worksheet used to calculate this data is shown below.



$C_{ws} := \frac{S}{\pi \cdot LOA \cdot D}$ $C_{ws} = 0.906$

$w := 1 - .371 - 1.7151 \cdot \frac{\frac{D_P}{D}}{\sqrt{C_{ws} \cdot \frac{LOA}{D}}}$ $w = 0.257$ wake fraction $w := \text{if}(w < 0.1, 0.1, w)$ $w = 0.257$



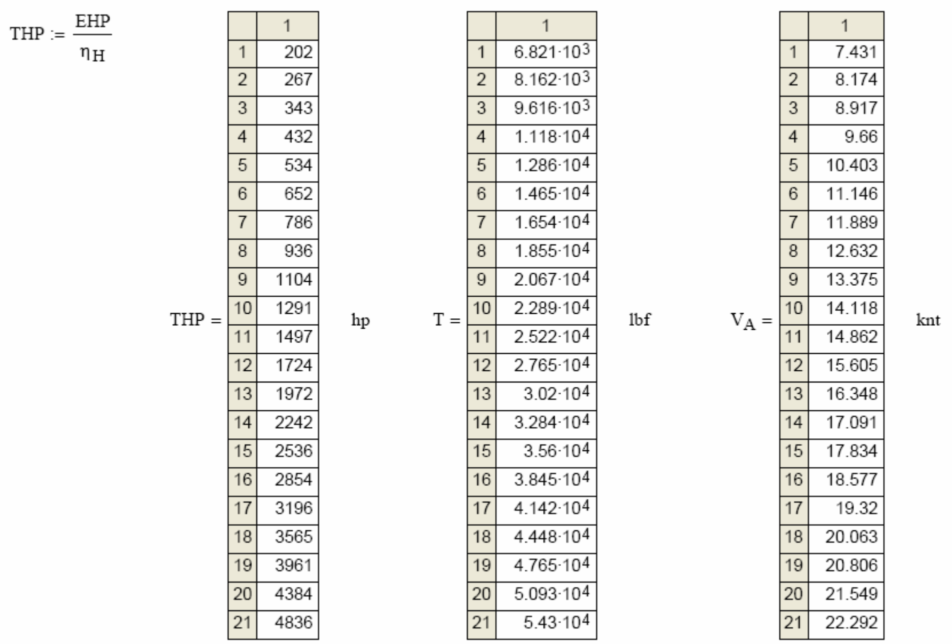
$t := 1 - .632 - 1.3766 \cdot \frac{\frac{D_P}{D}}{\sqrt{C_{ws} \cdot \frac{LOA}{D}}}$ $t = 0.069$ thrust deduction fraction - prop changes pressure distribution around hull which effectively changes the resistance of towed hull

$t := \text{if}(t < .15, .15, t)$ $t = 0.15$

$V_A := V \cdot (1 - w)$ speed of advance - average wake velocity seen by prop

$T := \frac{R_T}{(1 - t) \cdot N_P}$

$\eta_H := \frac{1 - t}{1 - w}$ $\eta_H = 1.144$ hull efficiency



$THP := \frac{EHP}{\eta_H}$

THP =

	1
1	202
2	267
3	343
4	432
5	534
6	652
7	786
8	936
9	1104
10	1291
11	1497
12	1724
13	1972
14	2242
15	2536
16	2854
17	3196
18	3565
19	3961
20	4384
21	4836

hp

T =

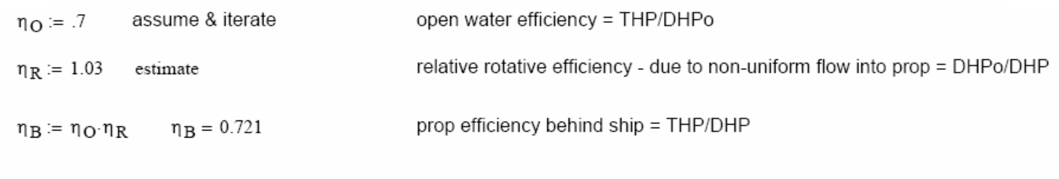
	1
1	$6.821\cdot10^3$
2	$8.162\cdot10^3$
3	$9.616\cdot10^3$
4	$1.118\cdot10^4$
5	$1.286\cdot10^4$
6	$1.465\cdot10^4$
7	$1.654\cdot10^4$
8	$1.855\cdot10^4$
9	$2.067\cdot10^4$
10	$2.289\cdot10^4$
11	$2.522\cdot10^4$
12	$2.765\cdot10^4$
13	$3.02\cdot10^4$
14	$3.284\cdot10^4$
15	$3.56\cdot10^4$
16	$3.845\cdot10^4$
17	$4.142\cdot10^4$
18	$4.448\cdot10^4$
19	$4.765\cdot10^4$
20	$5.093\cdot10^4$
21	$5.43\cdot10^4$

lbf

V_A =

	1
1	7.431
2	8.174
3	8.917
4	9.66
5	10.403
6	11.146
7	11.889
8	12.632
9	13.375
10	14.118
11	14.862
12	15.605
13	16.348
14	17.091
15	17.834
16	18.577
17	19.32
18	20.063
19	20.806
20	21.549
21	22.292

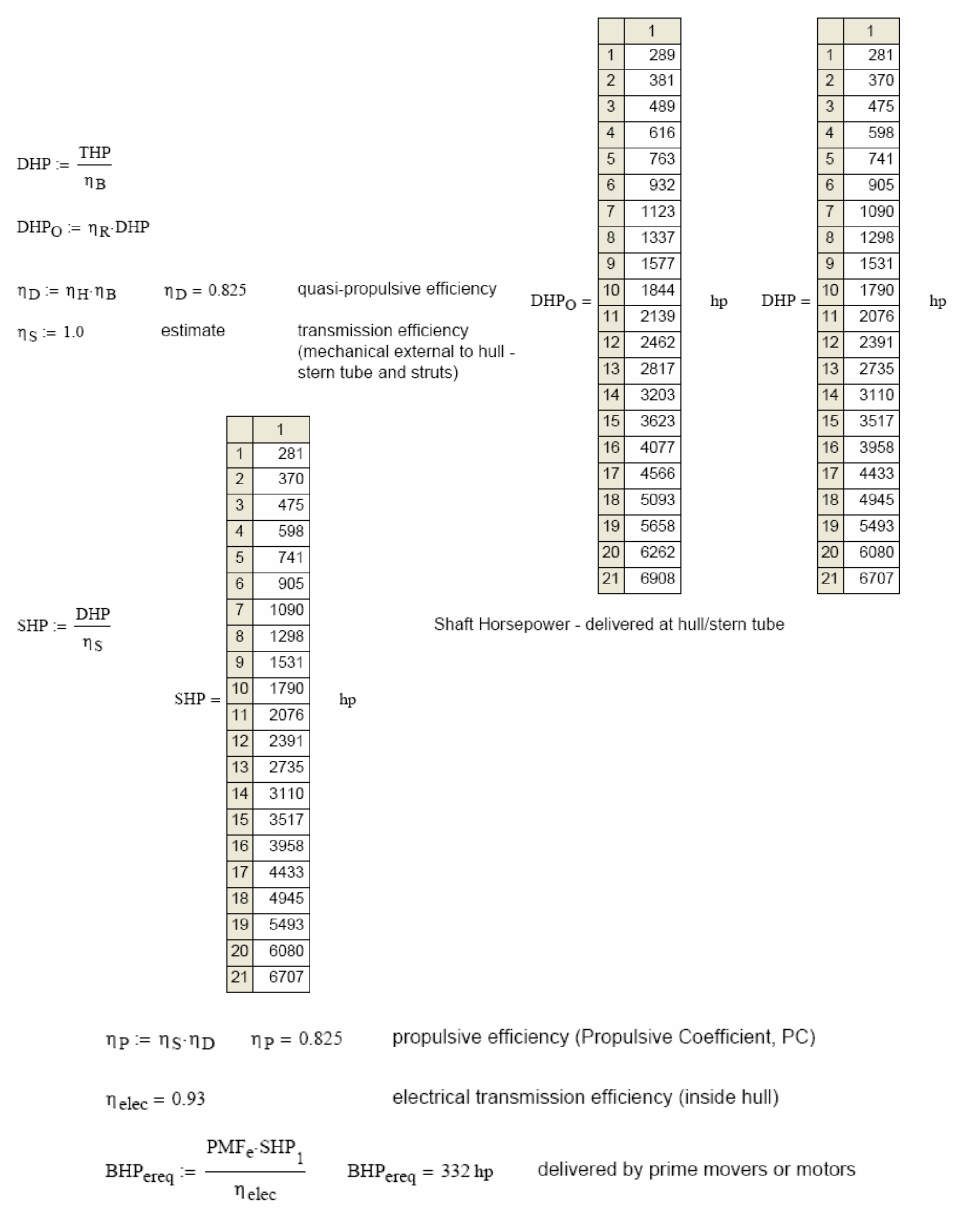
knt



$\eta_O := .7$ assume & iterate open water efficiency = THP/DHPo

$\eta_R := 1.03$ estimate relative rotative efficiency - due to non-uniform flow into prop = DHPo/DHP

$\eta_B := \eta_O \cdot \eta_R$ $\eta_B = 0.721$ prop efficiency behind ship = THP/DHP



$$DHP := \frac{THP}{\eta_B}$$

$$DHP_O := \eta_R \cdot DHP$$

$\eta_D := \eta_H \cdot \eta_B$ $\eta_D = 0.825$ quasi-propulsive efficiency

$\eta_S := 1.0$ estimate transmission efficiency (mechanical external to hull - stern tube and struts)

$DHP_O =$ (hp)

	1
1	289
2	381
3	489
4	616
5	763
6	932
7	1123
8	1337
9	1577
10	1844
11	2139
12	2462
13	2817
14	3203
15	3623
16	4077
17	4566
18	5093
19	5658
20	6262
21	6908

hp

$DHP =$

	1
1	281
2	370
3	475
4	598
5	741
6	905
7	1090
8	1298
9	1531
10	1790
11	2076
12	2391
13	2735
14	3110
15	3517
16	3958
17	4433
18	4945
19	5493
20	6080
21	6707

hp

$$SHP := \frac{DHP}{\eta_S}$$

$SHP =$

	1
1	281
2	370
3	475
4	598
5	741
6	905
7	1090
8	1298
9	1531
10	1790
11	2076
12	2391
13	2735
14	3110
15	3517
16	3958
17	4433
18	4945
19	5493
20	6080
21	6707

hp

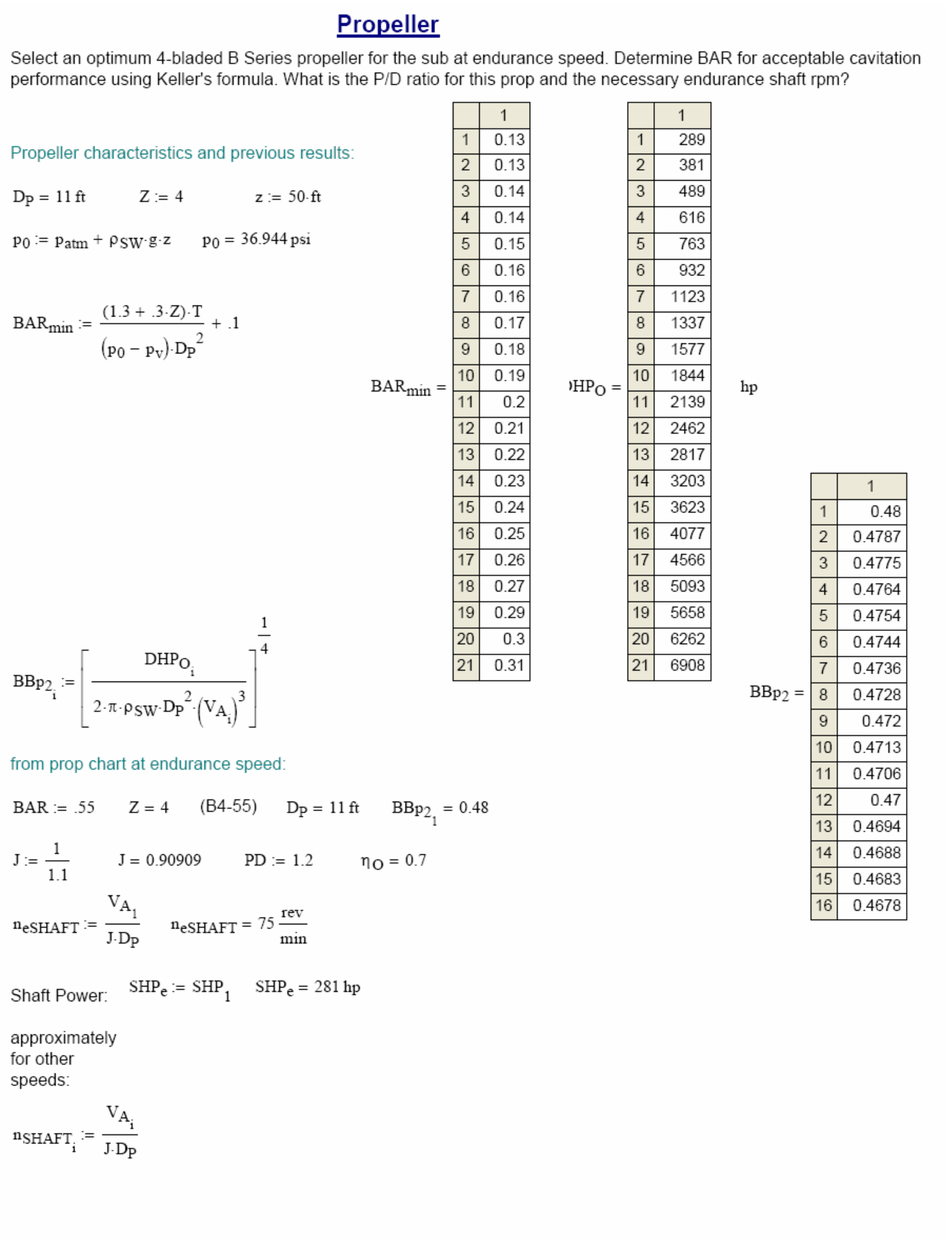
Shaft Horsepower - delivered at hull/stern tube

$\eta_P := \eta_S \cdot \eta_D$ $\eta_P = 0.825$ propulsive efficiency (Propulsive Coefficient, PC)

$\eta_{elec} = 0.93$ electrical transmission efficiency (inside hull)

$BHP_{ereq} := \frac{PMF_e \cdot SHP_1}{\eta_{elec}}$ $BHP_{ereq} = 332\,hp$ delivered by prime movers or motors

Figure 59 - Additional Power Calculations



Propeller

Select an optimum 4-bladed B Series propeller for the sub at endurance speed. Determine BAR for acceptable cavitation performance using Keller's formula. What is the P/D ratio for this prop and the necessary endurance shaft rpm?

Propeller characteristics and previous results:

$D_P = 11\,\mathrm{ft}$ $Z := 4$ $z := 50\cdot\mathrm{ft}$

$p_0 := p_{atm} + \rho_{SW}\cdot g\cdot z$ $p_0 = 36.944\,\mathrm{psi}$

$$BAR_{min} := \frac{(1.3 + .3\cdot Z)\cdot T}{\left(p_0 - p_v\right)\cdot D_P^{\,2}} + .1$$

$BAR_{min} =$

	1
1	0.13
2	0.13
3	0.14
4	0.14
5	0.15
6	0.16
7	0.16
8	0.17
9	0.18
10	0.19
11	0.2
12	0.21
13	0.22
14	0.23
15	0.24
16	0.25
17	0.26
18	0.27
19	0.29
20	0.3
21	0.31

$HP_O =$ hp

	1
1	289
2	381
3	489
4	616
5	763
6	932
7	1123
8	1337
9	1577
10	1844
11	2139
12	2462
13	2817
14	3203
15	3623
16	4077
17	4566
18	5093
19	5658
20	6262
21	6908

$$BBp2_i := \left[\frac{DHP_{O_i}}{2\cdot\pi\cdot\rho_{SW}\cdot D_P^{\,2}\cdot\left(V_{A_i}\right)^3}\right]^{\frac{1}{4}}$$

$BBp_2 =$

	1
1	0.48
2	0.4787
3	0.4775
4	0.4764
5	0.4754
6	0.4744
7	0.4736
8	0.4728
9	0.472
10	0.4713
11	0.4706
12	0.47
13	0.4694
14	0.4688
15	0.4683
16	0.4678

from prop chart at endurance speed:

$BAR := .55$ $Z = 4$ (B4-55) $D_P = 11\,\mathrm{ft}$ $BBp2_1 = 0.48$

$J := \frac{1}{1.1}$ $J = 0.90909$ $PD := 1.2$ $\eta_O = 0.7$

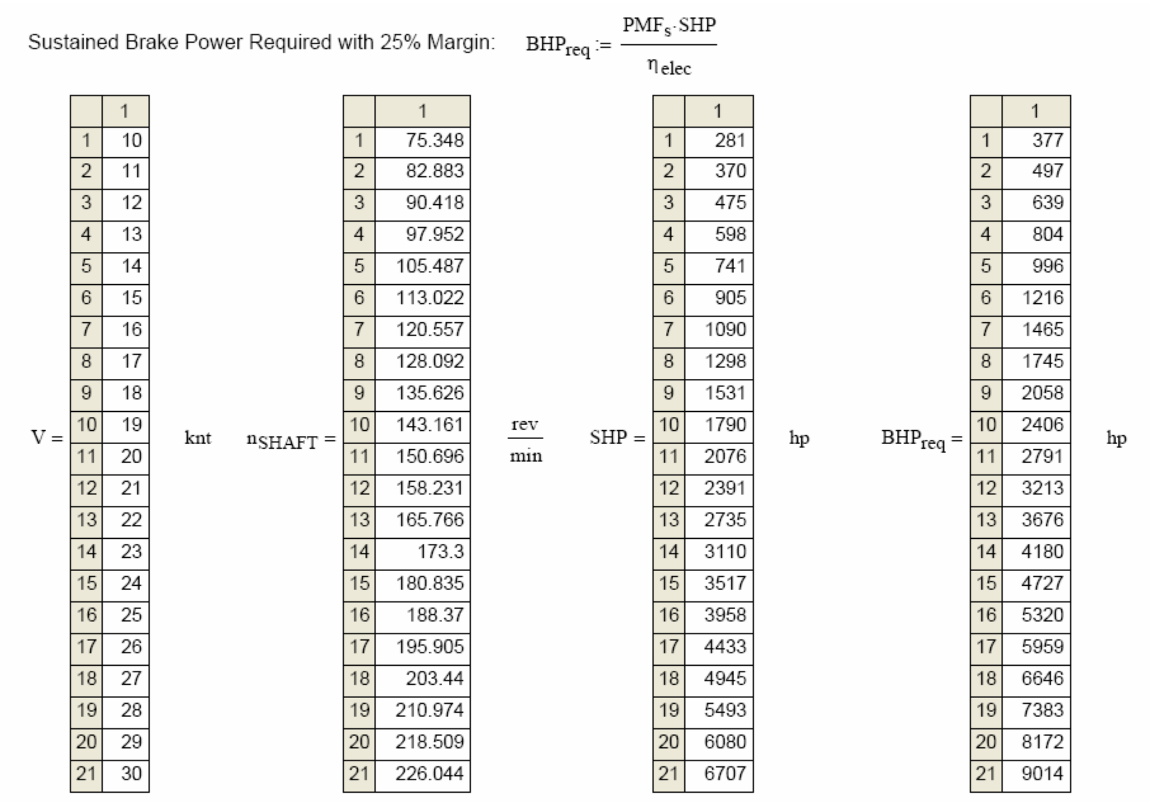
$n_{eSHAFT} := \frac{V_{A_1}}{J\cdot D_P}$ $n_{eSHAFT} = 75\,\frac{\mathrm{rev}}{\mathrm{min}}$

Shaft Power: $SHP_e := SHP_1$ $SHP_e = 281\,\mathrm{hp}$

approximately
for other
speeds:

$$n_{SHAFT_i} := \frac{V_{A_i}}{J\cdot D_P}$$

Figure 60 - Propeller Selection Calculation



Sustained Brake Power Required with 25% Margin: $BHP_{req} := \frac{PMF_s \cdot SHP}{\eta_{elec}}$

	V = (knt)	n_{SHAFT} = (rev/min)	SHP = (hp)	BHP_{req} = (hp)
1	10	75.348	281	377
2	11	82.883	370	497
3	12	90.418	475	639
4	13	97.952	598	804
5	14	105.487	741	996
6	15	113.022	905	1216
7	16	120.557	1090	1465
8	17	128.092	1298	1745
9	18	135.626	1531	2058
10	19	143.161	1790	2406
11	20	150.696	2076	2791
12	21	158.231	2391	3213
13	22	165.766	2735	3676
14	23	173.3	3110	4180
15	24	180.835	3517	4727
16	25	188.37	3958	5320
17	26	195.905	4433	5959
18	27	203.44	4945	6646
19	28	210.974	5493	7383
20	29	218.509	6080	8172
21	30	226.044	6707	9014

Figure 61 - Summary of Data (Velocity, Shaft RPM, Shaft HP and Break HP)

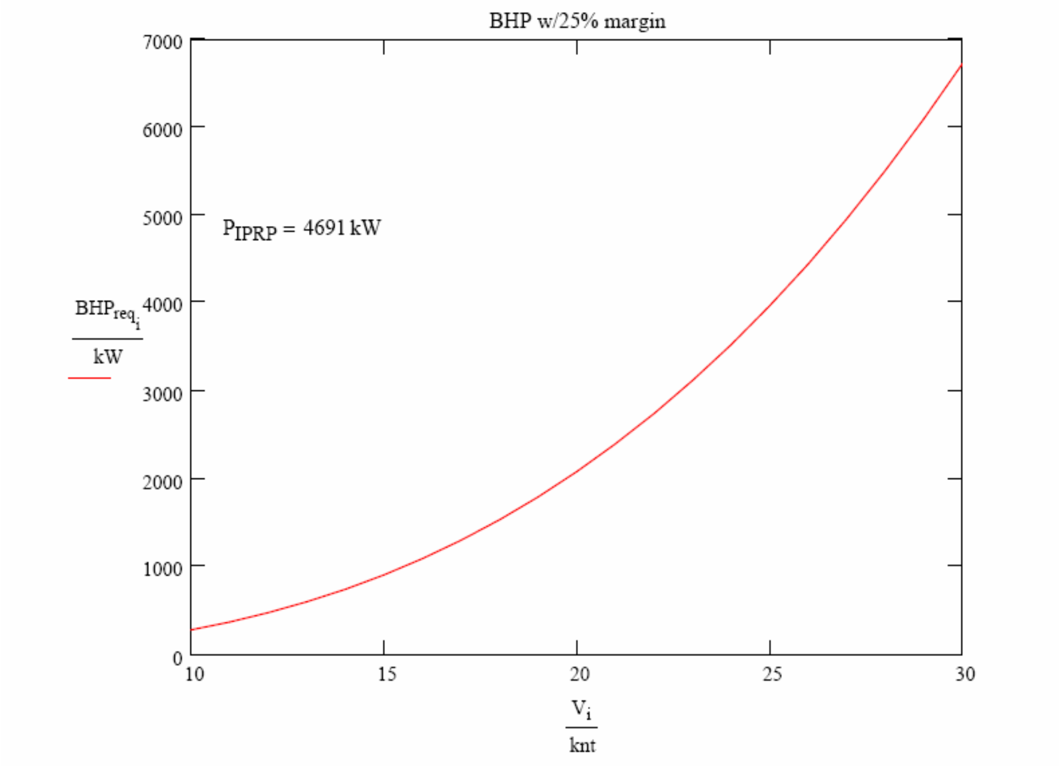


Figure 62 - Brake Horsepower with 25% Margin

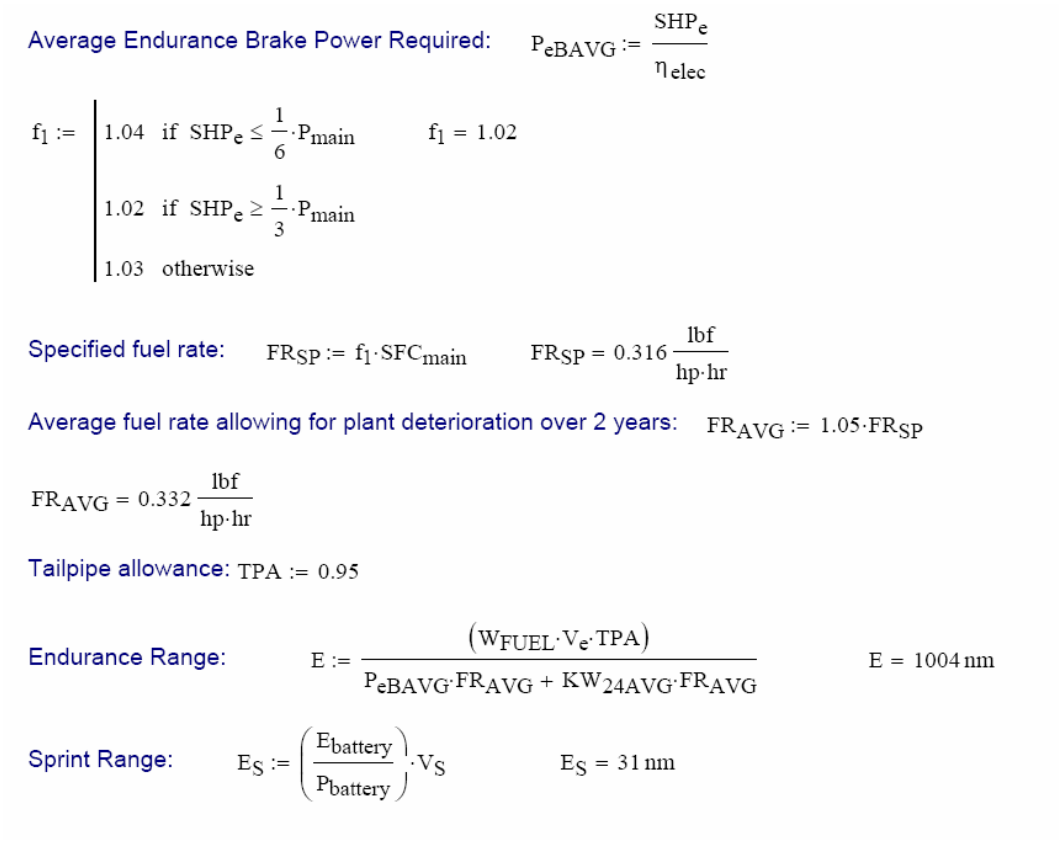
4.4.3 Electric Load Analysis (ELA)

Electric load conditions calculated in the analysis are Standard Operations (Condition I), Loiter, In Port, Anchor, and Emergency. These scenarios cover all major possible electric loading conditions that the ATLAS platform could encounter. Condition I signifies power requirements during the transit from the littoral platforms sea-base or mother ship to the mission-specific destination. The Loiter condition is the power requirements when the vessel is in the mission specific area and conducting mission operations. The In Port condition describes when the vessel is preparing to be loaded aboard its transporting vessel or docked into a land based port. The Anchor scenario describes when the ATLAS vessel is in the littoral region and either stationary at the bottom or sitting on the surface. The Emergency condition describes when the submarine is operating on minimal required electrical loads to sustain life.

SWBS	Description	Condition I (kW)	Loiter (kW)	In Port (kW)	Anchor (kW)	Emergency (kW)
200	Propulsion	1.1	1.1	0	0	0.98
300	Electric	3.1	3.1	1.5	1.5	2.2
330	Degaussing	30.9	30.9	0	0	0
430&475	Miscellaneous	15.4	15.4	1.72	2.62	2
510	HVAC	23.3	23.3	23.3	23.3	5.4
520	Seawater Systems	1.5	1.5	1.5	1.5	1.5
530&550	Misc. Auxiliary	9.1	9.1	9.1	9.1	2.8
540	Fuel Handling	1.5	1.5	0	0	0
560	Ship Controls	21.7	21.7	0	0	21.7
600	Services	5.5	5.5	5.5	5.5	2.7
	Non-Payload	58.9	58.9	58.9	58.9	58.9
	Maximum Functional Load	172	172	101.5	102.4	98.1
	MFL with Margins	210	210	122.84	123.9	118.7
	Total Load with Margins	210	210	122.84	123.9	118.7
	24 Hour Ship Service Average	98.15	98.15	51.8	51.8	58.9

4.4.4 Fuel Calculation

Figure 63 shows the fuel calculation that was performed for endurance range and sprint range in accordance with DDS 200-1.



Average Endurance Brake Power Required: $P_{eBAVG} := \frac{SHP_e}{\eta_{elec}}$

$$f_1 := \begin{cases} 1.04 & \text{if } SHP_e \le \frac{1}{6} \cdot P_{main} \\ 1.02 & \text{if } SHP_e \ge \frac{1}{3} \cdot P_{main} \\ 1.03 & \text{otherwise} \end{cases} \qquad f_1 = 1.02$$

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: $E := \frac{(W_{FUEL} \cdot V_e \cdot TPA)}{P_{eBAVG} \cdot FR_{AVG} + KW_{24AVG} \cdot FR_{AVG}}$ $\quad E = 1004\,nm$

Sprint Range: $E_S := \left(\frac{E_{battery}}{P_{battery}}\right) \cdot V_S$ $\quad E_S = 31\,nm$

Figure 63 - Fuel Calculation

The calculated sprint range for the SSLW platform is 31 nautical miles, which satisfies the ORD requirement of 25 nautical miles. Endurance range for the vessel is calculated to be 1004 nautical miles, which meets the 500 nautical mile specification of the ORD. Additionally, sprint speed was calculated to be 26.48 knots, which meets the requirements 15 knot threshold. Endurance speed was assumed to be 10 knots in the calculations.

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, and locations. The complete MEL is provided in Appendix D – Machinery Equipment List. 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 Sections 4.1.2 and 4.7.2.

4.5.1 Ship Service Power

As previously stated, the SSLW platform will house an IPS system to divide power throughout the ship and power the propulsor. The vessel is powered primarily by a DC/440V system containing multiple Power Conversion Modules (PCMs) that convert the DC power to either 120V or 440V 60Hz AC power. The battery system is split into two 2700 kW-hr banks wired in parallel.

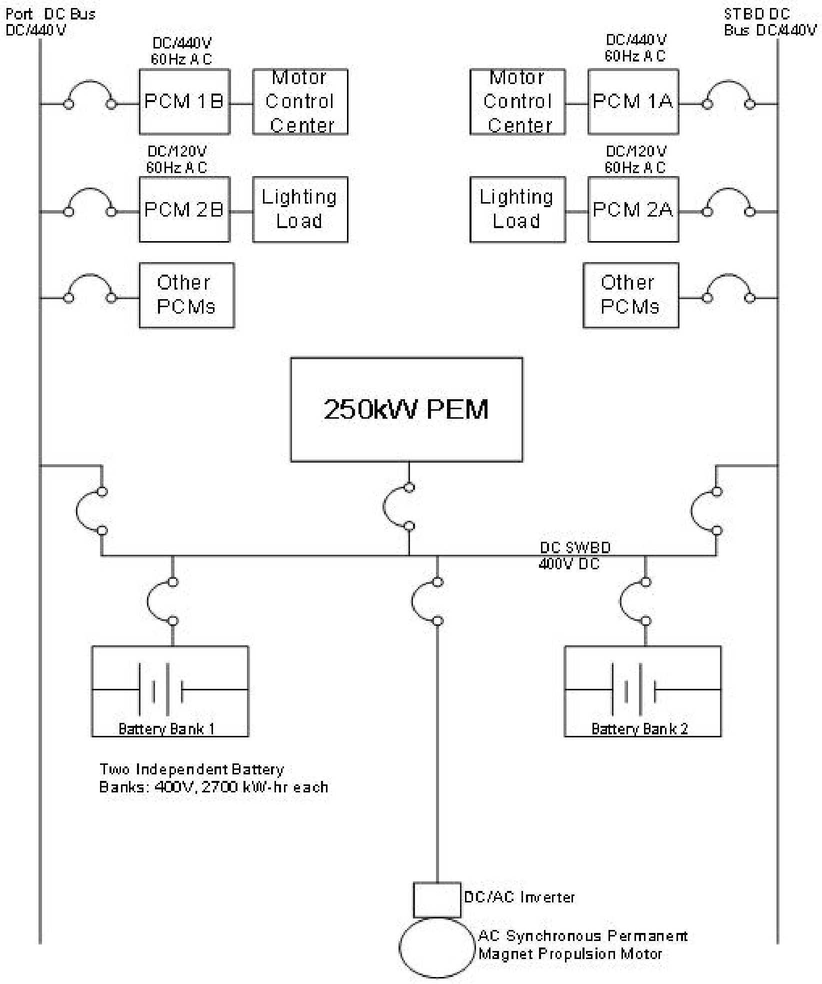


Figure 64 - Electric One-Load Diagram

4.5.2 Service and Auxiliary Systems

Unlike prior submarine designs, there is no separation between main propulsion power and submarine service electrical power, the PEM provides power for all onboard systems. The service and auxiliary systems were chosen to minimize cost and maintenance using commercial-off-the-shelf (COTS) systems. COTS systems already in use by the Navy are most desirable. Risk and cost are minimized because these systems are already tested, proven and approved by the Navy.

A Reverse Osmosis Distiller (ROD) will produce the potable water on SSLW. These systems work pushing heated seawater through a series of membranes that remove salt and other impurities. The resulting water is as pure as distilled water. The RO system that will be used is the Village Marine 2/2K unit that is able to produce up to 4000 gallons per day. For only a crew size of 12, this seems excessive, but the Special Force operations demand large amounts of fresh water to keep the dive gear and other equipment clean.

Thermal management of all electrical equipment is an important consideration in the marine environment. Cooling of systems will be done using a cooling pump capable of running water at 44° Fahrenheit like a Carrier 30HXC086 system. Another important system is the air compressor allowing pressurized air to fill the MBTs. The RIX 5R5 system 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.

The main components to the electrical system are the power converters and bus panels. These will be specifically designed to fit the needs of the submarine and meet US Navy Submarine standards. Designing the two components off of commercially available parts will allow the power converters and bus panels to be upgradeable and repaired at much lower costs. The electric systems will incorporate automation limiting the demands on the crew to maintain or supervise the equipment.

4.6 Manning

The small size and precise missions of SSLW require manning to be a considerable factor in the overall design. The crew size for the ship is 5 officers and 9 enlisted. The limited manning will result in highly trained, well-experienced sailors. The crew will need to train together before departing on the vessel. 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 ship will be highly automated with an automation factor, or reducing in manning factor, of 0.51. Automation factors were able to vary in the optimizer from 0.5 to 1.0, where 0.5 is the least manning with most automation and 1.0 is the normal amount of automation on a naval vessel.

Table 35 - Manning Accommodations

Duty	Officers	CPO	Enlisted	Total
CO	1			1
Pilot	3			3
SEAL	1			1
Torpedoman's Mate (TM)/Sonar Technician Submarine (STS)/Fire Controlman (FC)		1		1
Machinists Mate (MM)		1		1
Electricians Mate (EM)		1		1
Mess Management Specialist (MS)		1		1
SEALs/Payload Specialists			7	7
Total Crew Accommodations	5	4	7	16

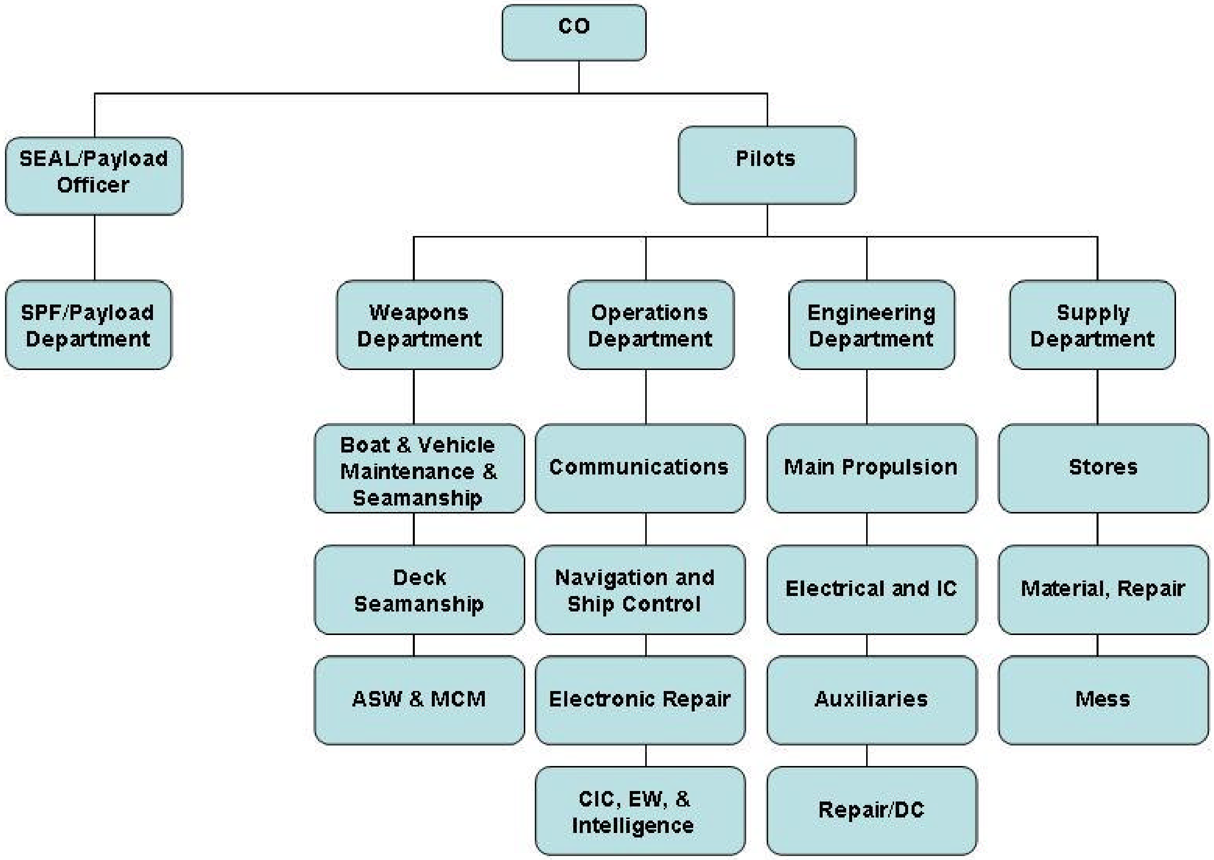


Figure 65 - Manning Organization

4.7 Space and Arrangements

Rhino and AutoCAD are used to generate and assess subdivision and arrangements. Drawings are constructed to include primary subdivision, tank arrangements, loading, inboard and outboard profiles, deck and platform plans, detailed drawings of berthing, sanitary, and messing spaces, and a 3-D model of the ship. A profile showing the internal arrangements is shown in Section 4.7.3.

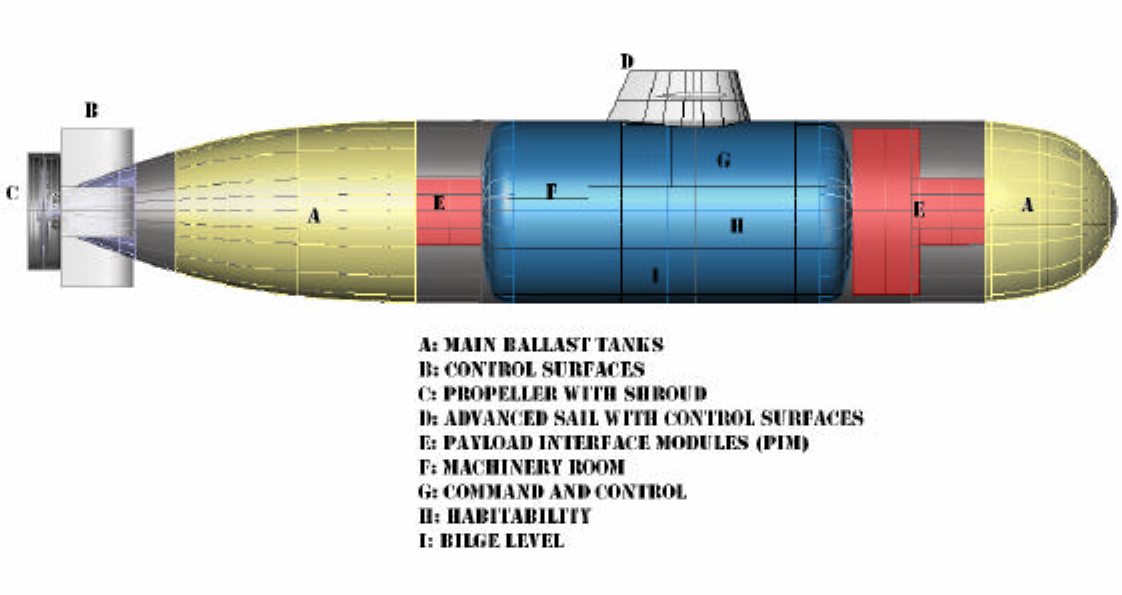


Figure 66 - Profile View Showing General Arrangements

4.7.1 Volume

Initial space requirements and availability in the ship are determined in the ship synthesis model. Arrangeable area estimates and requirements are refined in concept development arrangements and discussed in Sections 4.1 through 4.1.2 as well as outlined numerically in Appendix F – Volumes and Areas - Requirements and Values. Table 36 compares required versus actual tankage volume.

Table 36 – Required vs. Available Tankage Volume

Variable	Required (ft^3)	Final Concept Design(ft^3)
Lube Oil	42	61
Potable Water	88	88
Sewage	32	32
Clean Ballast	1008	1023
Propulsion Fuel (DFM)	316	550
Liquid Oxygen Tank	917	906

As with all submarines, space is extremely limited within the pressure hull and exterior to the pressure hull. When arranging the available space it is not a matter of where items should go, but rather if all the required systems will fit in the given volume. Being a volume based design led to this being an important consideration.

The pressure hull is 45 ft. long. The machinery room takes up 17 ft., leaving the rest of the ship to functions and habitability. The volume enclosed by the outer hull contains the main ballast tanks and the three payload interface modules that allow the ship to be adaptable.

4.7.2 Main and Auxiliary Machinery Spaces and Machinery Arrangement

The first step in arranging the machinery room is locating each component such that they would fit within the given volume while still having operating space around or near it. After the basic layout was established specific components such as pumps and burners are placed. Several views of the MMR can be seen below. Machinery Room Components are listed in Appendix D – Machinery Equipment List.

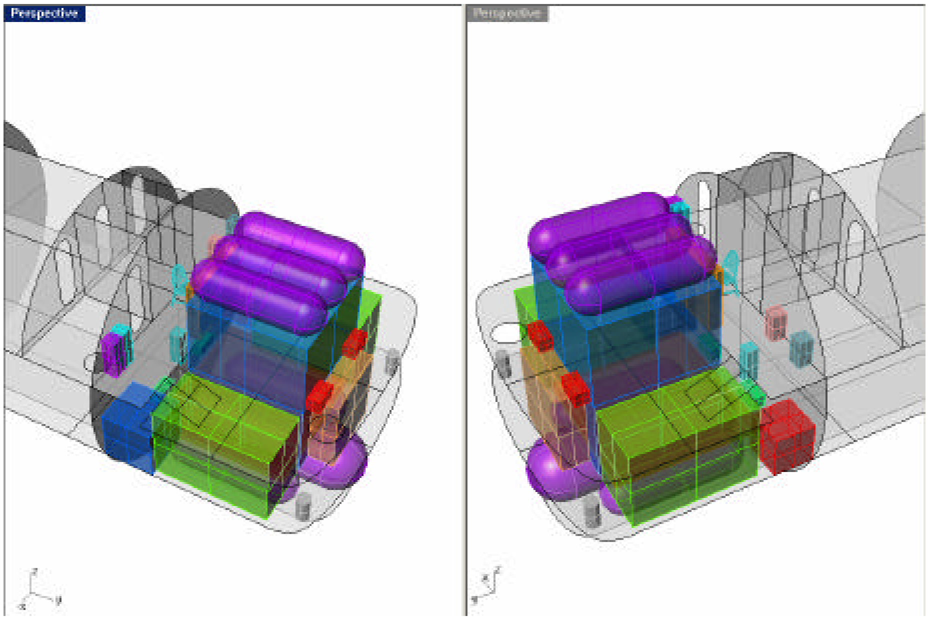


Figure 67 - Machinery Room Arrangements

4.7.3 Internal Arrangements

The submarine utilizes two decks plus a bilge level. Six space classifications are considered in the internal arrangements: weapons, machinery room, human support, mission and ship support and ballast. Area and volume estimates for these spaces were initially taken from the ship synthesis model and refined in the process of arranging the ship. Appendix E - Weights and Centers and Appendix G– SSCS Space Summary lists the area and volume summary.

The small size of the littoral submarine leaves arrangements a difficult task. The main ship functions and mission functions were consolidated into one area on the upper deck with torpedoes directly forward. The torpedo room is separated by a bulkhead. This Command and Control area will be one of the most used areas on the ship so careful planning took place in arranging it.

The machinery room was designed to be in the aft 17 ft and takes up the entire depth of the ship. Utilizing the space instead of having main decks makes the area more adaptable. The room contains the PEM with reformers as well as all counter parts needed for the ship to function. The machinery room is separated by a bulkhead from the rest of the ship. Being the largest arrangeable volume on the ship made this an important consideration for the overall arrangements. Batteries are located on the bilge level to keep the center of gravity low and to utilize the space available.

The lockout chambers will be used extensively by the SEAL units. These are located fore and aft of Command and Control. A wet room is located next to the aft lock-out chamber to protect the electrical equipment for water and allow gear to be cleaned off. The forward lock-out chamber will have the capability of cleaning off gear inside itself due to the limited space surrounding it.

The lower deck will be utilized as berthing and mess space. Mess and wardrooms will also function as recreation areas. The living arrangements are discussed in detail in Section 4.7.3.

Tankage on SSLW is primarily located on the bilge level which allows for the vertical center of gravity to be lowered inside the ship. Oxygen tanks for the PEM are located in the machinery room to allow for less piping. After initial arrangements were assigned it was discovered that an extra oxygen tank must be placed exterior of the pressure hull in order for there to be adequate oxidizer

for the system. Table 36 lists the required and actual tankage for the submarine. Trim tanks, auxiliary tanks and fuel tanks are all located on the bilge level. Table 37 lists the individual tanks throughout the ship and their volumes.

The open architecture of the machinery room and command and control allow for easy access to all work spaces. The habitability areas passageway is located along the centerline of the pressure hull and runs longitudinally. The passage way is standard width of 3 feet. There are watertight doors at all watertight bulkheads. Ladders provide access between the decks.

A complete set of detailed arrangements drawings are included throughout this chapter of the report.

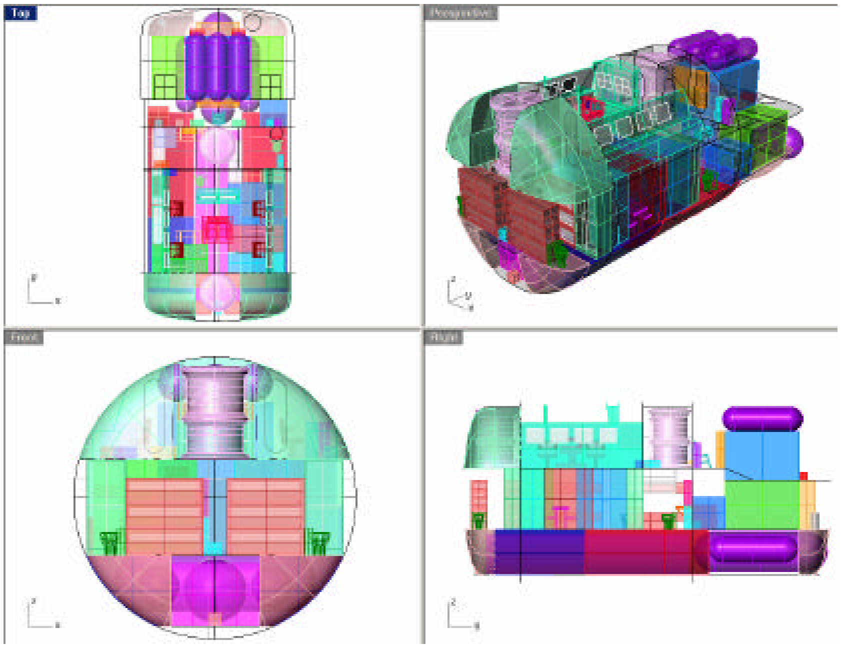


Figure 68 - Pressure Hull 3D Drawings

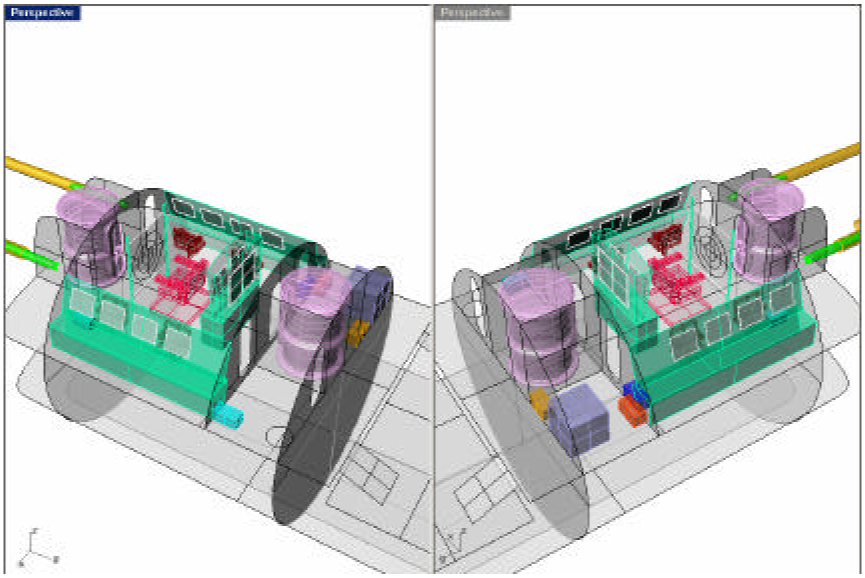


Figure 69 - Upper Deck Arrangements

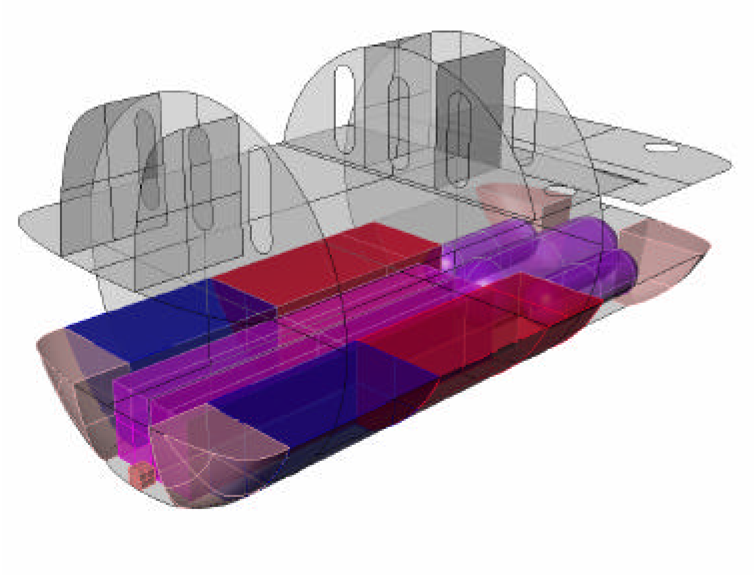


Figure 70 - Bilge Level Arrangements

Table 37 - Tank Capacity

Tank	Capacity (ft^3)
Auxiliary Tank - Port	375
Auxiliary Tank - Starboard	375
Fuel Tank - Port	275
Fuel Tank - Starboard	275
Aft Main Ballast Tank - Port	2216
Aft Main Ballast Tank - Starboard	2216
Forward Main Ballast Tank - Port	1000
Forward Main Ballast Tank - Port	1000
Center Oxygen Tank - Lower Deck	288
Center Oxygen Tank - Upper Deck	62.2
Port Oxygen Tank - Lower Deck	135
Port Oxygen Tank - Upper Deck	62.2
Starboard Oxygen Tank - Lower Deck	135
Starboard Oxygen Tank - Upper Deck	62.2
Aft Trim Tank - Port	68.5
Aft Trim Tank - Starboard	68.5
Forward Trim Tank - Port	68.5
Forward Trim Tank - Starboard	68.5

4.7.4 Living Arrangements

Living area requirements were based on the Shipboard Habitability Design Criteria Manual of the US Navy and initially estimated based on the crew size calculations in the ship synthesis model. The model estimates the area for enlisted and officer berthing, mess areas and support facilities. Living arrangements are located in close proximity to all messing spaces and support spaces to simplify movements onboard. The entire habitability area is located on the lower deck separate from working areas. Due to the short duration of the ships missions and small size of the ship, some of the normal amenities like a game room had to be combined into other spaces. The mess rooms will be used for all relaxation activities.

There are accommodations for 12 enlisted CPOs/SEALs, 4 officers, and 1 commanding officer as detailed in Table 35. The crew size determined in the ship synthesis module will use all of these short one enlisted accommodation. There are two sanitary spaces for the enlisted personnel, one sanitary space for the 4 officers and the commanding officer has his own sanitary space. The small nature of the ship only allows for these sanitary spaces near the berthing areas.

There is a separate mess room for the enlisted and the officers as is standard on all Navy ships. Both mess areas make use of an automated messing system. The enlisted personnel are bunked together in the forward section of the ship past the bulkhead on the habitability deck. The ship's pilots and SEAL or payload officer will bunk together, two per room. The commanding officer has his own berthing space. Galley and laundry rooms are also included in the habitability module. Mess rooms, officer berthing, galley and laundry are in between the two bulkheads.

A complete set of habitability arrangements drawings are detailed in this section.

Table 38 - Accommodation Space

Item	Accommodation Quantity	Per Space	Number of Spaces	Area Each (m^2)	Total Area (m^2)
CO	1	1	1	15	15
Pilots	3	2	2	10	20
Seal Officer/ Payload Officer	1				
CPO	4	12	1	15	15
SPF/Payload Specialist	7				

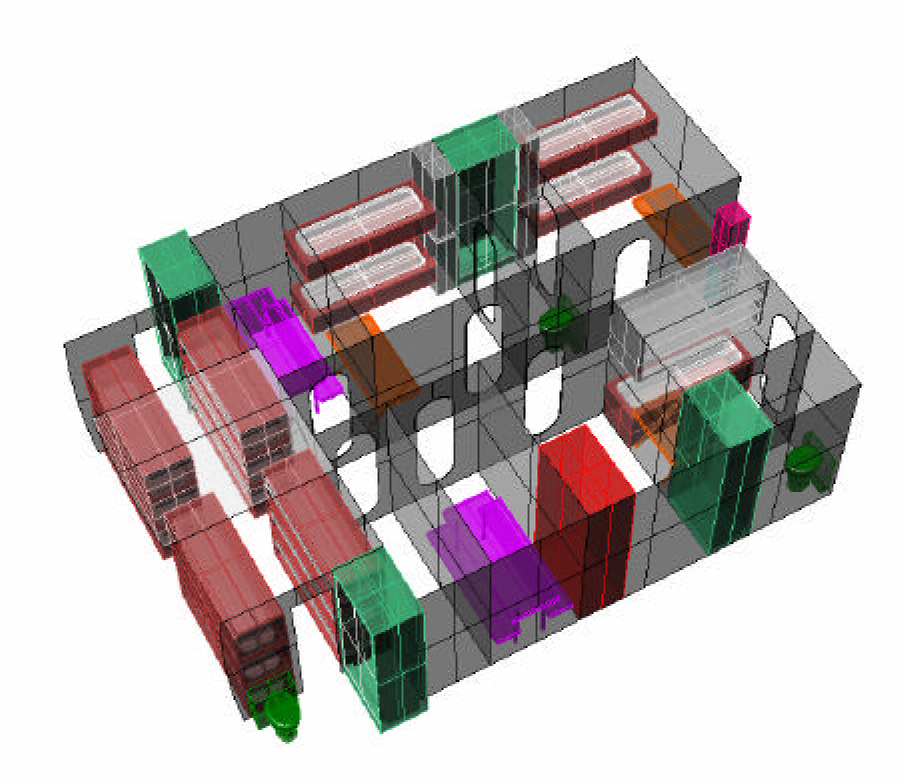


Figure 71 - Habitability Layout

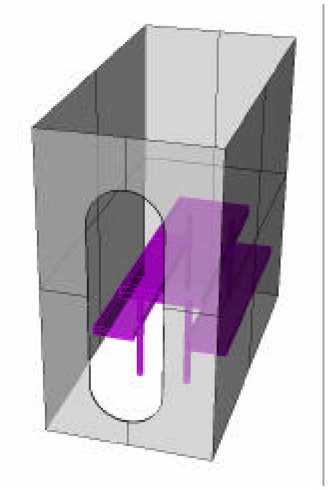


Figure 72 – Mess Arrangements

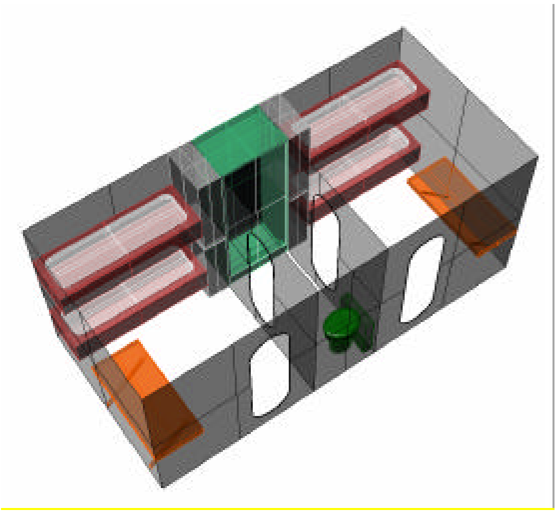


Figure 73 - Officer Berthing

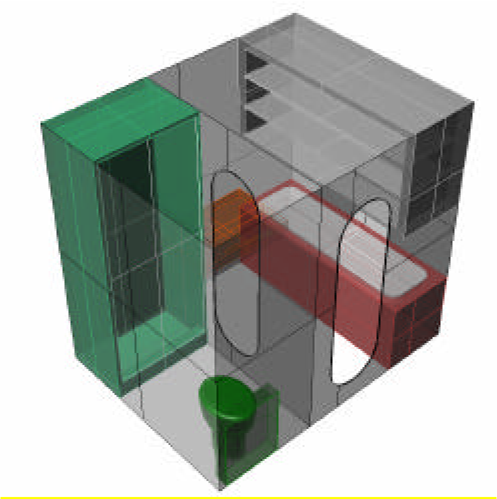


Figure 74 - Commanding Officer Berthing

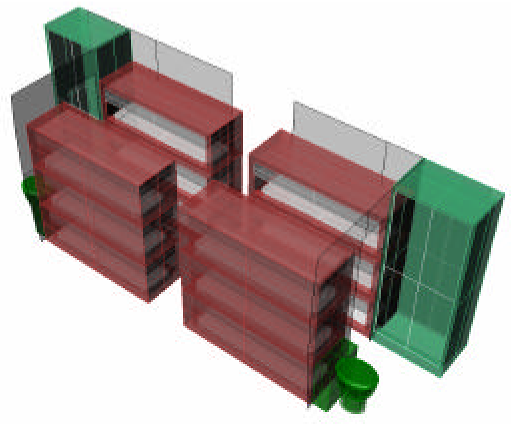


Figure 75 - Crew Berthing

4.7.5 External Arrangements

The most important criteria for external arrangements were the placement of the payload interface modules, torpedo tube, and sail design. The ship is kept covert through the use of a degaussing system. After several iterations it was discovered that the three PIMs would only fit as arranged in Figure 76. Torpedo tubes are easily placed and cut through the MBTs. The sail was designed to be large enough to contain any masts and the 3 ft. exit from the aft lockout chamber.

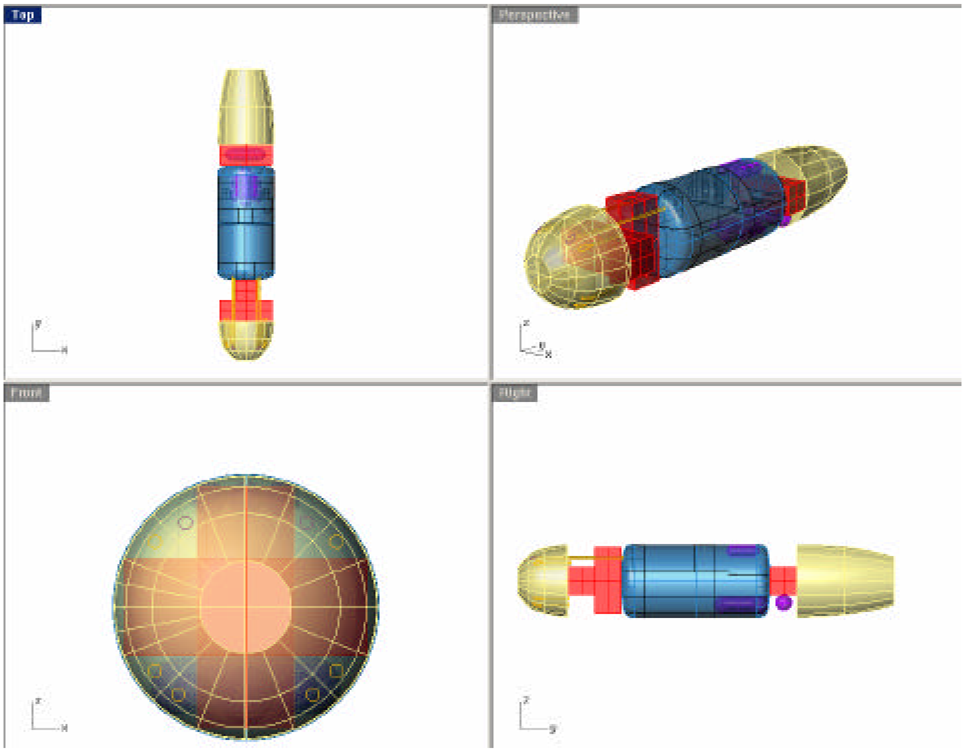


Figure 76 - External Arrangements

4.8 Weights and the Equilibrium Polygon

4.8.1 Weights

Ship weights are grouped by SWBS. Weights were obtained from the ship synthesis model and were defined from initial manufacturer research information, when possible. Weight values are estimated from the KAPPA submarine numbers when no other values are available. VCGs and LCGs for all weights are estimated from the ship and machinery arrangements. These centers are used to find moments and load conditions CG of the submarine. These centers are taken with respect to the LCB of the submerged displacement which was determined to be at the centroid of the ship, 72 ft from the aft. In order for the ship to be balanced the LCG needs to be as near to the LCB as possible. Lead margin weight was placed 5.44 ft from the front of the pressure hull and along the bottom at the center line. A summary of the lightship weights and centers of gravity by SWBS group is listed in Table 39. The weights spreadsheet is provided in Appendix E - Weights and Centers.

Table 39 - Lightship Weight Summary

SWBS Group	Weight (lton)	VCG (ft)	LCG (ft)
100	311.52	-0.05	6.77
200	124.27	-3.31	-16.61
300	28.39	1.19	-8.65
400	16.4	6	10.08
500	45.9	0.62	-20.13
600	37.04	0.1	2.97
700	3.57	5.65	20.49
Margin	35.79	-10.48	19.56
Total (LS)	602.88	-1.03	-0.12

4.8.2 Equilibrium Polygon

The equilibrium polygon is a graphical tool that is used to ensure that the submarine will be able to remain neutrally buoyant and trimmed level while submerged in any operating condition. In all operating conditions the ship must be able to compensate which is accomplished through the variable ballast tanks. The polygon is a diagram of weight vs. moment. The boundaries of the graphic are calculated from the variable tanks. Weights and moments are then calculated based on their compensation for all extreme load conditions. The ship is adequately able to compensate for each load conditions if each point lies within the polygon.

The construction of the polygon boundary starts with identifying the center and weight of each variable ballast tank. Starting with all tanks empty and plotting each point as the tanks are "filled", starting forward and ending aft and then emptying each tank, again starting forward and working aft. The cumulative weight and moment is plotted. Table 40 illustrates this process.

Table 40 - Construction of Polygon Boundaries

Item	Weight		Position From CB	Moment	
	(lb)	(lton)		(lb*ft)	(lton*ft)
Starting	**0**	**0**			**0**
Trim Forward	**8768**	**3.91**	**22.5**	**197280**	**88.07**
Aux Tanks	72000	32.14	2.497	179784	80.26
T.F + A	**80768**	**36.06**		**377064**	**168.33**
Trim Aft	8768	3.91	-17.5	-153440	-68.50
T.F + A + T.A	**89536**	**39.97**		**223624**	**99.83**
Added Totals	**89536**	**39.97**		**70184**	**31.33**
Trim Forward	8768	3.91	22.5	197280	88.07

Item	Weight (lb)	Weight (lton)	Position From CB	Moment (lb*ft)	Moment (lton*ft)
Added - T.F.	**80768**	**36.06**		**26344**	**11.76**
Aux Tanks	72000	32.14	2.497	179784	80.26
Added -T.F. - A	**8768**	**3.91**		**-153440**	**-68.50**
Trim Aft	8768	3.91	-17.5	-153440	-68.50
Added - Emptied	**0**	**0**			**0**

Utilizing the arrangements drawing, the total weights and moments for the variable load items are calculated for three of the most extreme load conditions: Normal, Heavy Number 2, and Light Number 2. Table 41 shows the calculations for each load condition. Every effort was made to keep the design balanced throughout the design process. No adjustments had to be made to the equilibrium polygon for this reason. Figure 77 shows the complete equilibrium polygon.

Table 41 - Variable Load Items for Each Condition

Group	Item	Normal Condition Weight	Distance from LCB	Moment	Light # 2 Weight	Moment	Heavy # 2 Weight	Moment
1	Crew and effects	1.72	2.50	4.29	1.72	4.29	1.72	4.29
	Sanitary tanks	0.00	21.00	0.00	0.00	0.00	0.07	1.47
	Sanitary Flush Waste	0.96	21.00	20.12	0.96	20.12	0.96	20.16
	Residual water	0.55	-24.67	-13.61		0.00	0.55	-13.57
	Nitrogen	0.23	2.50	0.58	0.23	0.58	0.23	0.57
	Oxygen candles	0.13	-11.15	-1.49	0.13	-1.49	0.13	-1.45
2	Potable Water	0.82	5.07	4.18	0.41	2.09	0.82	4.18
3	Provisions	0.46	8.00	3.68	0.00	0.00	0.46	3.68
	General Stores	0.17	8.00	1.37	0.00	0.00	0.17	1.37
	Oxygen candles	0.13	-11.15	-1.49	0.00	0.00	0.13	-1.49
4	Lubricating oil in storage and reserve tanks	1.50	-10.00	-14.96	0.75	-7.48	1.50	-14.96
5	Torpedoes	3.39	25.00	84.69	0.00	0.00	3.39	84.69
6	Passengers	1.29	2.50	3.22	0.00	0.00	1.29	3.22
	Totals and CG's	11.36	7.98	90.58	4.20	18.11	11.42	92.16
					CG	4.31	CG	8.07

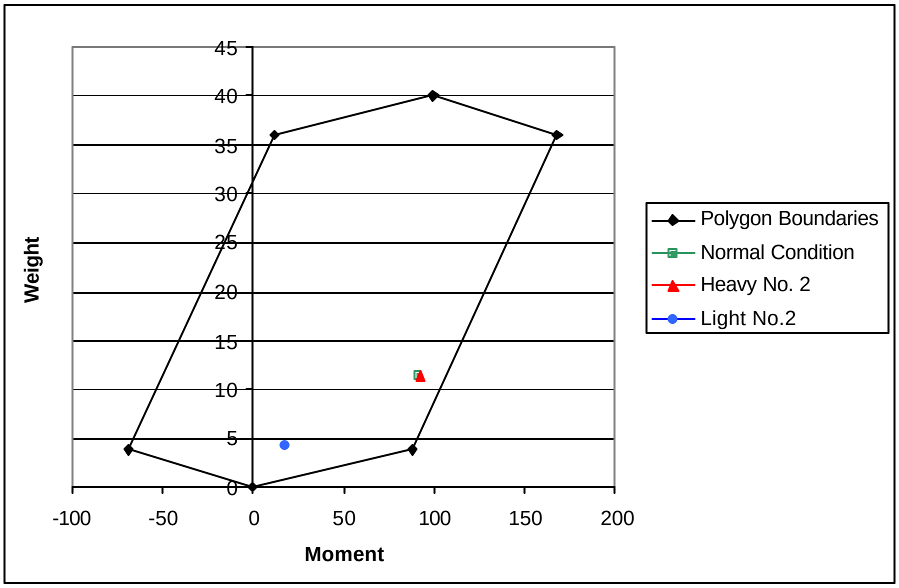


Figure 77 - Equilibrium Polygon

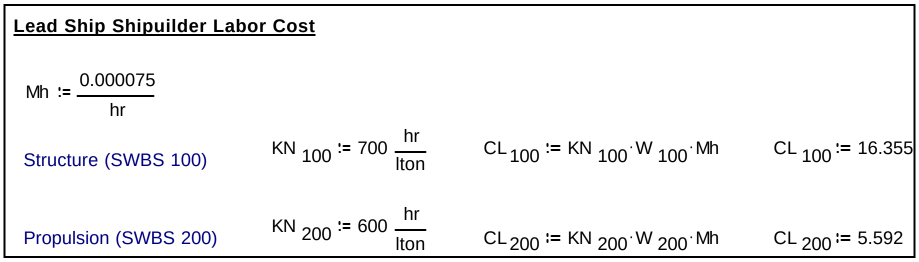
4.9 Stability and Control

Due to time constraints and lack of software readily available, only a qualitative analysis of stability and control was performed. The ability to enter and maneuver in shallow water is a main concern for the littoral submarine. This requirement calls for the control surfaces to be within the 22 ft diameter of the submarine leading the submarine to be able to fit in tighter canals. A detailed analysis of the control surfaces will be performed next time around the design spiral. Although SSLW ATLAS is a small ship, its length to depth ratio is still large enough that it can be assumed that the ship will be stable. Based on the low weight of the ship and the length to depth ratio, it is also assumed that it will be adequate to operate on the surface.

4.10 Cost and Risk Analysis

4.10.1 Cost and Producibility

Cost calculations were based primarily on group weights. Once the weights are found and tabulated into their correct SWBS groups, the cost of each group can be calculated. The labor costs were found by multiplying a specific complexity factor for each group by the weight of the group times the man-hour rate. The material costs for each group were determined by multiplying the specific complexity factor by the weight times an average inflation factor. After finding the labor costs (CL) and the material costs (CM) of each SWBS group, they were added together to get the total direct cost (DC). An example of these calculations done in MathCAD is shown below.



Lead Ship Shipuilder Labor Cost

$Mh := \frac{0.000075}{hr}$

Structure (SWBS 100) $KN_{100} := 700 \frac{hr}{lton}$ $CL_{100} := KN_{100} \cdot W_{100} \cdot Mh$ $CL_{100} := 16.355$

Propulsion (SWBS 200) $KN_{200} := 600 \frac{hr}{lton}$ $CL_{200} := KN_{200} \cdot W_{200} \cdot Mh$ $CL_{200} := 5.592$

Lead Ship Shipbuilder Material Cost

$F_i := 1.8009$ $C_{manning} := 0.51$

Structure (SWBS 100)	$KM_{100} := \frac{0.02}{lton}$	$CM_{100} := KM_{100} \cdot W_{100} \cdot F_i$	$CM_{100} := 11.22$
Propulsion (SWBS 200)	$KM_{200} := \frac{0.3}{lton}$	$CM_{200} := KM_{200} \cdot W_{200} \cdot F_i$	$CM_{200} := 67.138$

$$\boxed{DC := CL_{total} + CM_{total}}$$

The indirect costs were then calculated as a percentage of the direct costs using an overhead rate of 0.25. For a nuclear powered submarine, the overhead rate would be closer to 1.5. The cost of the ship satisfies the threshold value specified in the ORD.

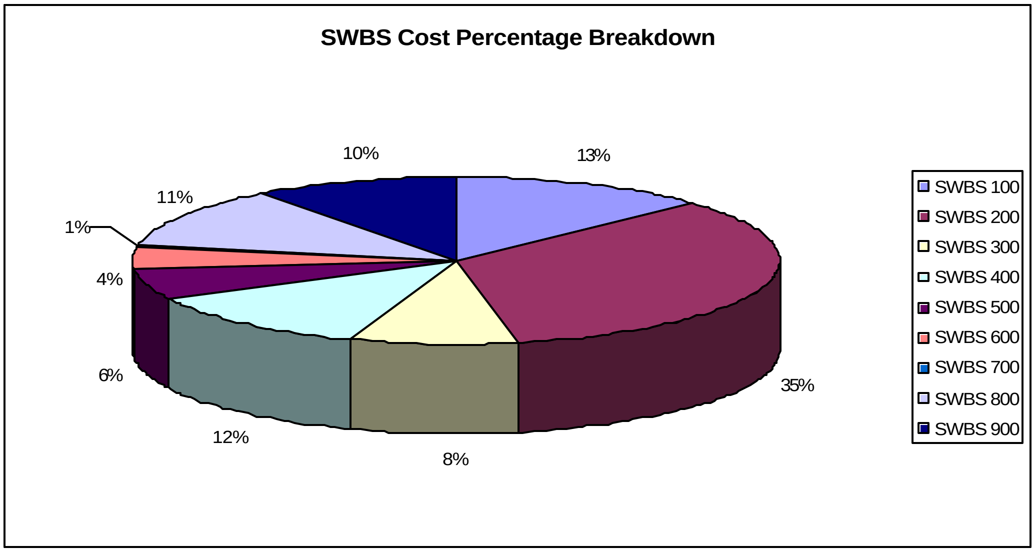


Table 42 - Cost Comparison

ENGINEERING INPUT	Concept Baseline	Final Concept Baseline
Pressure Hull Structure Material		
Steel	1	1
Aluminum	0	0
Composite	0	0
Outer Hull Material		
Steel	0	0
Aluminum	0	0
Composite	1	1
Hullform		
Monohull	1	1
Catamaran	0	0
Trimaran	0	0
Plant Type		
Gas Turbine	0	0
Diesel	0	0
Diesel Electric	0	0
PEM w/ Reformer	1	1
Plant Power		
Power Rating (in kW)	250	250
Main Propulsion Type		
Fixed Pitch Propeller	1	1
Controllable Pitch Propeller	0	0
Waterjet	0	0
Weights		
100	311.5	311.5
200	124.27	124.27
300	28.39	28.39
400	16.4	16.4
500	45.9	45.9
600	37.04	37.04
700	3.57	3.57
Margin	35.8	35.8
Lightship + Margin	602.88	602.88
Full Load + Margin Displacement	771.09	771.09
Operating and Support		
Service Life (Yrs.)	15	15
Cost Element		
Direct Cost	213.5	213.5
Indirect Cost	53.4	53.4
Basic Cost of Construction ($ Mil)	293.5	293.5
Life Cycle Cost ($ Mil)	501.5	501.5

ATLAS is a producible design. Its simplistic, symmetric hull is just a smaller version of what the Navy already has the capability to make. The variety of structural materials was kept to a minimum.

4.10.2 Risk Analysis

The high risk items are primarily the PEM with reformer's performance risk; the manning factor's performance risk; and the ASW's performance risk. The nickel-cadmium batteries, while higher risk than lead acid, does not contribute significantly to the overall measure of risk. Also, the biggest contributors are all risks associated with performance. This is because, the technology exists and the costs are pretty well known – not significantly more risk than most systems; however, these systems have not been thoroughly tested, so the performance risks are higher. PEM's with reformers have never been used as a primary power source; this increases the risk of using this system. The manning coefficient is 0.51 which is almost as much automation as was allowable. The decrease in manning and increase in automation increases the risk. Six external torpedoes raise the risk of the ASW system. Torpedo launching systems that are external to the pressure hull cannot be examined or repaired by the crew. Any system that cannot be repaired underway is going to be higher risk than one that can.

To help control the risk associated with each of these options, certain precautions will be in effect. First and foremost, production is not scheduled until 2015. This 10 year time period allows for further, testing and development all the systems that will be onboard. The efficiency and performance of the PEM will increase in that time period, safety devices for outboard torpedoes will be improved, and automation will be made much more effective, efficient, and reliable. Secondly, the crew will be very highly trained and well educated, in order to deal with the high level of automation. Also, the training level will help to minimize other risks by having professionals who know how to effectively deal with risky situations.

Table 43 - Updated OMOR

DV Description	DV Value	Risk Event Ei	Risk Description	Pi	Ci	Ri
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
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
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
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
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
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
Manning and Automation Factor	0.5 - 1	Development and integration of automation	System will not meet performance requirements	0.5	0.5	0.25

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
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
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
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
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

5 Conclusions and Future Work

5.1 Assessment

SSLW ATLAS meets and exceeds the requirements specified in the ORD as shown in Table 44.

Table 44 - Compliance with Operational Requirements

Technical Performance Measure	ORD TPM (Threshold)	Original Goal	Concept BL	Final Concept BL
Total mission payload weight (core, 3 PIM modules)	120 MT	120 MT	120 MT	120 MT
Endurance range (nm)	500	1500	1000	1004
Sprint range (nm)	25	50	25	31
Stores duration (days)	23	30	23	23
Sustained Speed Vs (knots)	25	30	25	26.5
Crew size (Including SPW or mission techs)	16	15	16	16
Diving Depth (ft)	250	250	250	250
Basic Construction Cost ($ M)	293.5	250	293.5	293.5
Maximum level of risk (OMOR)	0.783	0	0.783	0.783
Overall level of effectiveness (OMOE)	0.723	1.0	0.723	0.723

SSLW incorporates an effective combination of proven technology and new cutting edge technology. The non-traditional idea of modular mission packages utilizes the small size. The PEM and Nickel Cadmium batteries provide enough power to the submarine to be able to adequately surpass endurance range, sprint range and sprint speed threshold values. Manning is significantly reduced compared to other naval vessels through automation while maintaining a high level of personnel to carry out missions. Its high level of risk is due to the date of original conception and as time goes on, the systems will become less risky as the technology improves. The basic construction cost is much lower then specified by the ORD and the ship is very effective for the cost.

5.2 Future Work

- Consider making the pressure hull larger to more adequately fit components.
- Consider more load cases for structural analysis such as general strength, collision and damage.
- Consider the effects of the outer hull and wave interaction
- Consider a more detailed structural analysis that would include modeling the outer-hull
- Further reduce scantlings to optimize adequacy and minimize weight
- Consider use of lockout trunks to have access to PIMs from interior of ship.
- Analyze system and structural vulnerability
- Quantitatively analyze intact and damage stability
- Quantitatively analyze control surface options
- Consider a propeller with more blades to account for interference caused by the aft control surfaces.

5.3 Conclusions

The SSLW requirement is based on the SSLW Mission Needs Statement (MNS) and the Virginia Tech Acquisition Decision Memorandum (ADM). SSLW will operate in the littoral areas deploying from a mother ship and depend on stealth, maneuverability, high endurance and low manning to keep US Navy personnel out of harms way. It is required to covertly deploy and extract US Special Forces into dangerous littoral areas, perform intelligence, reconnaissance and surveillance, mine countermeasures, search and salvage, support of AUVs and other modular payloads as well as be able to defensively ward off threats.

Concept Exploration trade-off studies and design space exploration were accomplished utilizing a Multi-Objective Genetic Optimization (MOGO) after significant technology research and definition. The optimization analyzed designs based on basic construction cost; risk due to technology, schedule, performance and cost; and military effectiveness. A series of non-dominated cost-risk-effectiveness frontiers were generated from this process and used in selecting the ATLAS Baseline Concept Design. An Operational Requirements Document (ORD1) was defined based on the customer's specifications.

SSLW ATLAS is a high risk and highly effective alternative. The design was chosen to provide a challenging design project using higher risk technology while still keeping within a reasonable cost. The submarine characteristics are listed below. It is a 129 ft, 2 deck, and 22 ft diameter symmetrical hull able to house three payload interface modules, making it upgradeable and capable of many mission packages. It is a highly automated ship keeps manning down and allows for a highly trained crew.

Concept development included hull form development, structural finite element analysis, machinery system development and arrangement, general arrangements, combat system selection, equilibrium polygon analysis, cost and producibility analysis and risk analysis. The final design satisfies requirements set out in the ORD1 within cost and risk constraints with additional work required to reduce structural weight and analyze stability and control. SSLW ATLAS meets or exceeds all requirements. The hull design allows for the ship to be upgradeable using the payload interface modules. The ship systems and propeller are powered by a PEM fuel cell and nickel cadmium batteries which allow the submarine to exceed speeds of 25 knots and have an endurance range of over 1000 nm.

SSLW ATLAS is a unique, multifaceted design that will propel the Navy's littoral forces into the future.

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Appendix A – 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 200 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 – 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 500 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 15 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 SSLW – Design Alternative 28

1. Mission Need Summary

This Littoral Warfare Submarine (SSLW) requirement is based on the Virginia Tech SSLW Acquisition Decision Memorandum (ADM).

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. SSLW will support the following missions using interchangeable, networked, tailored modular mission packages and onboard (core) systems:

1. Intelligence, Surveillance, and Reconnaissance (ISR)
2. Mine Counter Measures (MCM)
3. Anti-Submarine Warfare (ASW)
4. Anti-Surface Ship Warfare (ASUW)
5. Special Warfare (SPW)

Mission packages will use "plug-in" technology, which will interface with the SSLW core support systems. These packages will be standard half-ISO containers.

SSLW will be capable of conducting search and salvage missions and more extensive mine countermeasures by utilizing AUVs. It will be a covert, upgradeable, modular and defensive ship capable of taking the U.S. Navy into the new millennium of littoral warfare.

2. Acquisition Decision Memorandum (ADM)

The SSLW ADM authorizes Concept Exploration of a material alternative for a Littoral Warfare Submarine, as proposed to the Virginia Tech Naval Acquisition Board. Additional material and non-material alternatives supporting this mission may be authorized in the future.

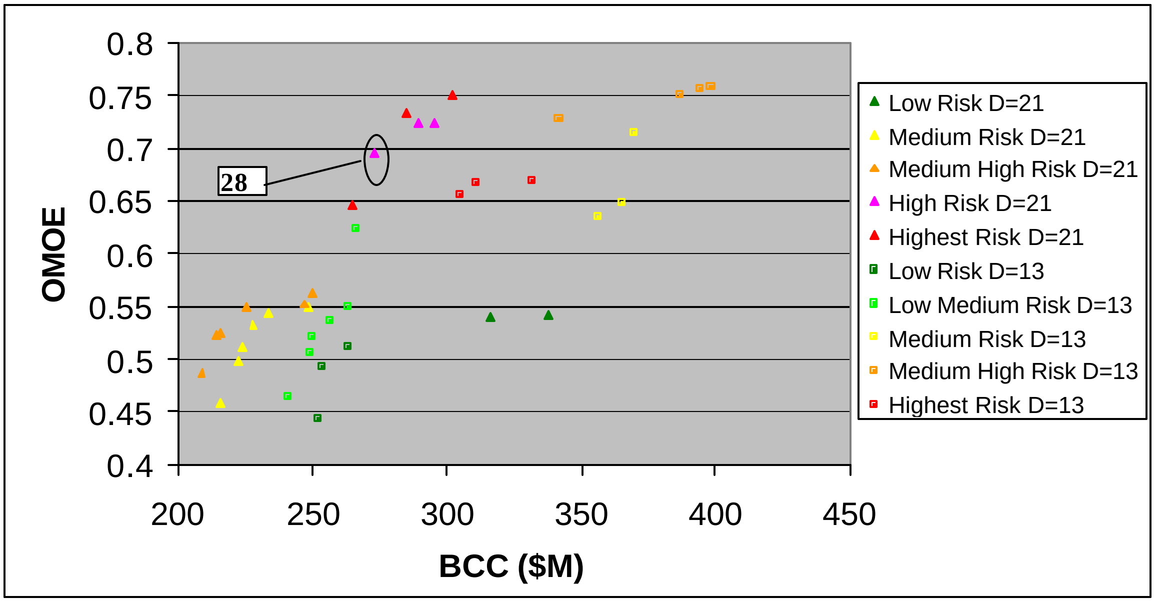

Figure 1 - SSLW Non-Dominated (ND) Frontier

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 were identified based on base cost of construction, effectiveness and risk. This ORD specifies a requirement for concept development of SSLW Alternative 28. Other alternatives are specified in separate ORDs. Alternative 28 is a two-deck, high risk, knee-in-the-curve design on the ND high-risk frontier (Figure 1).

4. Technical Performance Measures (TPMs)

TPM	Threshold
Total mission payload weight (core, 3 PIM modules)	120 MT
Endurance range (nm)	1000
Sprint range (nm)	25
Stores duration (days)	23
Sustained Speed Vs (knots)	25
Crew size (Including SPW or mission techs)	16
Diving Depth (ft)	250

5. Program Requirements

Program Requirement	Threshold
Base Construction Cost ($ M)	293.5
Maximum level of risk (OMOR)	0.783

6. Baseline Ship Characteristics (Alternative 28)

Concept development will begin with the following baseline design and design budgets:

Characteristic	Baseline	Weight Description	Baseline (lton)	Volume Description	Baseline (ft3)
L_{bow}	25.00	W100	312.3	$V_{berth\&mess}$	2730.0
L_{mid}	52.00	$W_{transmission}$	32.8	V_{stores}	354.2
L_{aft}	52.00	$W_{basicpropulsion}$	7.2	V_{ops}	4446.4
LOA	129.00	$W_{reactanttanks}$	9.3	V_{phtk}	2402.7
D	21.00	$W_{battery}$	74.9	V_{pib}	603.2
B	22.00	Group 200	124.3	$V_{battery}$	762.8
		$W_{elecdist}$	9.9	V_{mb}	2754.5
Propulsion: 250 kW PEM Fuel Cell w/Reformer, NiCad batteries		$W_{lighting}$	8.9	$V_{auxmach}$	963.6
		W_{degaus}	9.6	$V_{phpassage}$	717.6
		Group 300	28.4	V_{phmarg}	789.4
		W_{ic}	4.3	V_{ph}	16524.5
		$W_{shipcontrol}$	3.2	$V_{obhullenv}$	7453.0
		$W_{c\&c}$	2.1	$V_{obsailandprop}$	2670.0
		$W_{c\&cweaps}$	6.8	V_{eb}	26647.5
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, side scan sonar, degaussing, 9 man lock-out trunk		Group 400	16.4	V_{mbt}	5329.6
		Group 500	45.9	V_{sub}	31977.0
		Group 600	37.03	V_{ff}	2678.8
		Group 700	3.6	V_{bow}	6047.8
		$W_{condition\ A\text{-}1}$	567.8	$V_{midbody}$	19102.0
		Lead ballast	43.9	$V_{aftbody}$	6835.5
		$W_{condition\ A}$	611.7	$V_{hullenv}$	31985.8
		Loads	149.4	V_{env}	34655.8
		W_{nsc}	761.0	Δ_{eb}	761.0 lton

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:

- Hull design shall incorporate features to reduce drag and minimize structural weight.
- Propulsion plant options shall consider air independent, non-nuclear systems to satisfy 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

Appendix D – Machinery Equipment List

Machinery	Quantity	Dimensions (ft)			Location
		Length	Width	Height	
Trim and Drain Pumps	2	2	2	1	Pump Room
Reverse Osmosis Distiller	1	4	4	4	Pump Room
High Pressure Air Compressor	1	3	3	3	Pump Room
Seawater Cooling Pump	2	2	1	1	Pump Room
Main Hydraulic Pump	2	2	1	1	Pump Room
Freshwater Pump	1	1	1	1	Pump Room
Hydraulic Pressure Accumulator	2	2	Cylinder = 1 ft Dia		Pump Room
Trim Manifold	1	2	1	1	Pump Room
Induction Mast Inlet	1	Dia = 1 ft			Fan Room
Ventilation Fan	1	2	1	1	Fan Room
LP Blower	1	3	3	3	Fan Room
CO2 Scrubber	1	1	1	2	Fan Room
CO/H2 Burner	1	1	1	2	Fan Room
PEM	1	9	9	9	MMR
Regenerator	2	9	4	9	MMR
DC (400V) Main Switchboard	1	6	1	6	MMR
DC/AC Inverters/Controllers	1	2	2	1	MMR
Oxygen Tanks	7	Various			MMR + Exterior
Power Conversion Modules	2	1	1	3	MMR
Motor Control Center	1	1	1	3	MMR
Lighting Load Panel	1	1	1	3	MMR

Appendix E - Weights and Centers

The LCG is taken about the center of buoyancy at a distance 72 ft from the aft.

SWBS	COMPONENT	WT-lton	VCG-ft	Moment	LCG-ft	Moment	TCG-ft	Moment
	FULL LOAD WEIGHT + MARGIN	771.09	-0.95	-729.36	0.46	353.03	-0.01	-6.83
	LIGHTSHIP WEIGHT + MARGIN	602.88	-1.03	-618.12	-0.12	-74.27	0.00	0.00
	LIGHTSHIP WEIGHT	567.09	-0.43	-243.12	-1.37	-774.27	0.00	1.26
	MARGIN	35.79	-10.48	-375.00	19.56	700.00	-0.04	-1.26
100	**HULL STRUCTURES**	**311.52**	**-0.05**	**-16.11**	**6.77**	**2110.32**	**0.00**	**0.00**
110	SHELL + SUPPORTS	177.52	0.00	0.00	10.00	1775.22	0.00	0.00
120	PRESSURE HULL STRUCTURAL BULKHDS	80.41	0.00	0.00	2.50	200.77	0.00	0.00
140	PRESSURE HULL PLATFORMS/FLATS	6.20	-2.60	-16.11	2.50	15.47	0.00	0.00
150	CONNING TOWER	0.19	0.00	0.00	5.07	0.98	0.00	0.00
160	SPECIAL STRUCTURES	3.84	0.00	0.00	2.50	9.59	0.00	0.00
180	FOUNDATIONS	39.59	0.00	0.00	2.50	98.87	0.00	0.00
190	SPECIAL PURPOSE SYSTEMS	3.77	0.00	0.00	2.50	9.42	0.00	0.00
200	**PROPULSION PLANT**	**124.27**	**-3.31**	**-411.87**	**-16.61**	**-2063.69**	**0.00**	**0.00**
220	MAIN PROPULSOR	56.40	-7.60	-428.60	9.85	555.32	0.00	0.00
230	PROPULSION UNITS	10.31	1.50	15.46	-11.50	-118.56	0.00	0.00
240	PROPULSION POWER TRANSMISSION	36.98	0.00	0.00	-69.00	-2551.87	0.00	0.00
250	SUPPORT SYSTEMS, UPTAKES	19.75	0.00	0.00	2.50	49.31	0.00	0.00
290	SPECIAL PURPOSE SYSTEMS	0.84	1.50	1.27	2.50	2.11	0.00	0.00
300	**ELECTRIC PLANT, GENERAL**	**28.39**	**1.19**	**33.91**	**-8.65**	**-245.47**	**0.00**	**0.00**
310	ELECTRIC POWER GENERATION	22.04	1.50	33.06	-11.50	-253.43	0.00	0.00
320	ELECTRICAL DISTRIBUTION SYSTEM	4.86	0.00	0.00	2.50	12.16	0.00	0.00
330	LIGHTING SYSTEM	0.92	0.00	0.00	2.50	2.31	0.00	0.00
340	POWER GENERATION SUPPORT SYS	0.53	1.50	0.80	-11.50	-6.10	0.00	0.00
390	SPECIAL PURPOSE SYSTEMS	0.04	1.50	0.05	-11.50	-0.40	0.00	0.00
400	**COMMAND + SURVEILLANCE**	**16.40**	**6.00**	**98.40**	**10.08**	**165.35**	**0.00**	**0.00**
420	NAVIGATION SYSTEMS	1.50	6.33	9.50	10.50	15.76	0.00	0.00
430	INTERIOR COMMUNICATIONS	1.29	6.33	8.18	10.50	13.56	0.00	0.00
440	EXTERIOR COMMUNICATIONS	0.95	6.33	6.02	10.50	9.99	0.00	0.00
450	SURF SURVEILLANCE SYS (RADAR)	0.92	6.33	5.83	10.50	9.67	0.00	0.00
460	UNDERWATER SURVEILLANCE SYS	10.22	6.33	64.72	10.50	107.36	0.00	0.00
480	FIRE CONTROL SYSTEMS	0.85	0.00	0.00	2.50	2.13	0.00	0.00
490	SPECIAL PURPOSE SYSTEMS	0.65	6.33	4.14	10.50	6.87	0.00	0.00
500	**AUXILIARY SYSTEM, GENERAL**	**45.90**	**0.62**	**28.54**	**-20.13**	**-924.03**	**0.00**	**0.00**
510	CLIMATE CONTROL	4.96	0.00	0.00	2.50	12.38	0.00	0.00
520	SEA WATER SYSTEMS	0.17	0.00	0.00	2.50	0.42	0.00	0.00
530	FRESH WATER SYSTEMS	1.65	-4.00	-6.59	23.00	37.91	0.00	0.00
540	FUELS/LUBRICANTS, HANDLING+STOWAGE	0.57	1.30	0.75	10.50	6.02	0.00	0.00
550	AIR,GAS+MISC FLUID SYSTEM	16.72	0.00	0.00	2.50	41.80	0.00	0.00
560	SHIP CNTL SYS	14.07	0.00	0.00	-65.77	-925.40	0.00	0.00
580	ANCHOR, MOORING, HANDLING+STOWAGE	2.34	0.00	0.00	-65.77	-154.20	0.00	0.00
590	ENVIRONMENTAL + AUX SYSTEMS	5.43	6.33	34.39	10.50	57.05	0.00	0.00
600	**OUTFIT + FURNISHING, GENERAL**	**37.04**	**0.10**	**3.84**	**2.97**	**110.09**	**0.03**	**1.26**

610	SHIP FITTINGS	0.86	0.00	0.00	2.50	2.14	0.00	0.00
620	HULL OUTFIT	0.72	0.00	0.00	2.50	1.80	0.00	0.00
630	PERSONAL OUTFIT	15.34	0.00	0.00	2.50	38.31	0.00	0.00
640	LIVING SPACES	0.73	-0.71	-0.52	16.00	11.63	2.00	1.45
650	COMMISSARY + LAUNDRY SPACES	0.07	-0.75	-0.05	16.00	1.07	-5.50	-0.37
660	CONTROL STATION FURNISHINGS	0.71	6.33	4.47	10.50	7.41	0.00	0.00
670	LOCKERS + SPECIAL STORAGE	0.09	-0.71	-0.06	16.00	1.40	2.00	0.18
690	MARINE + HULL OUTFITTING	18.53	0.00	0.00	2.50	46.34	0.00	0.00
700	**ARMAMENT**	**3.57**	**5.65**	**20.18**	**20.49**	**73.17**	**0.00**	**0.00**
750	TORPEDOES HANDLING	3.48	5.80	20.18	21.00	73.08	0.00	0.00
760	SEALs	0.09	0.00	0.00	1.00	0.09	0.00	0.00
	Totals and CG's	567.09	-0.43	-243.12	-1.37	-774.27	0.00	1.26
	FULL LOAD CONDITION							
F00	LOADS	148.79	0.00	0.00	2.50	371.96	0.00	0.00
F10	SHIP PERSONNEL	1.72	0.00	0.00	2.50	4.29	0.00	0.00
F31	PROVISIONS+PERSONNEL STORES	0.90	-0.75	-0.68	8.00	7.21	-5.50	-4.96
F32	GENERAL STORES	0.34	-0.75	-0.25	8.00	2.72	-5.50	-1.87
F47	SEA WATER	2.15	-6.70	-14.39	2.50	5.36	0.00	0.00
F52	FRESH WATER	14.32	-6.70	-95.93	2.50	35.75	0.00	0.00
	Totals and CG's	735.30	-0.48	-354.36	-0.47	-346.97	-0.01	-5.57

Appendix F – Volumes and Areas - Requirements and Values

	Concept Exploration					Concept Development				
Requirement	Area (ft^2)	Volume (ft^3)	Volume Percent	Hull Env Volume %	P Hull Volume %	Area (ft^2)	Volume (ft^3)	Volume Percent	Hull Env Volume %	P Hull Volume %
$A_{COberth\&san}$	50	350	1.02	1.09	2.12		360	1.05	1.13	2.18
$A_{offberth\&san}$	120	840	2.46	2.63	5.08		1020	2.99	3.19	6.17
A_{offwr}							240			
A_{offhab}							1620			
A_{galley}							360			
$A_{crewmess}$							240			
$A_{crewberth}$							714			
$A_{crewsanitary}$							326			
$A_{crewhab}$	220	1540	4.51	4.81	9.32		1639.8	4.80	5.13	9.92
A_{hab}	390	2730	7.99	8.53	16.52		3260	9.54	10.19	19.73
V_{stores}		354	1.04	1.11	2.14		360	1.05	1.13	2.18
A_{p4}	148	1036	3.03	3.24	6.27		1036	3.03	3.24	6.27
A_{cont}	150	1050	3.07	3.28	6.35		1587	4.65	4.96	9.60
A_7	60	420	1.23	1.31	2.54		433	1.27	1.35	2.62
A_{sf}	277.2	1940	5.68	6.07	11.74		1940	5.68	6.07	11.74
A_{ops}	635.2	4446	13.02	13.90	26.91		4996	14.62	15.62	30.23
V_{2fuel}		316	0.93	0.99	1.91		550	1.61	1.72	3.33
V_{2ox}		917	2.68	2.87	5.55		907	2.65	2.83	5.49
V_{lo}		42	0.12	0.13	0.25		61	0.18	0.19	0.37
V_w		88	0.26	0.28	0.53		88	0.26	0.28	0.53
V_{sew}		32	0.09	0.10	0.19		32	0.09	0.10	0.19
$V_{aux\&trim}$		1008	2.95	3.15	6.10		1023	3.00	3.20	6.19
V_{tk}		2403	7.03	7.51	14.54		2660	7.79	8.32	16.10
V_{pib}		603	1.77	1.89	3.65		603	1.77	1.89	3.65
A_{phmarg}	112.772	789	2.31	2.47	4.78	112.772	789	2.31	2.47	4.77
$A_{phpassage}$	102.52	718	2.10	2.24	4.34	102.52	594	1.74	1.86	3.60
$V_{battery}$		763	2.23	2.38	4.62		767	2.24	2.40	4.64
V_{mb}		2755	8.06	8.61	16.67		2459	7.20	7.69	14.88
$V_{machroom}$							4655			

$V_{auxmach}$		964	2.82	3.01	5.83	1228	3.59	3.84	7.43
V_{ph}		16524	48.37	51.66	100.00	17716	51.86	55.39	107.21
V_{pim}		3840	11.24	12.01		3840	3840.00	12.01	
V_{pob}		429	1.26	1.34		429	429.00	1.34	
$V_{pobtotal}$		4269	12.50	13.35		4269	4269.00	13.35	
V_{prop}		600	1.76	1.88		538	601.00	1.68	
V_{sailob}		2070	6.06	6.47		488	1000.00	1.53	
V_{miscob}		3184	9.32	9.96		3184	9.32	9.95	
V_{ob}		10123	30	31.65		8479	5879	26.51	
V_{eb}		26648	78.01	83.31		26195	5931.18	81.89	
$V_{mbt\ aft}$						8535			
$V_{mbt\ forw}$						10953			
V_{mbt}		5330	15.60	16.66		12862	37.65	40.21	
V_{sub}		31977	93.61	99.97		39056	5968.83	122.10	
$V_{barehullenv}$		31986	93.63	100.00		35426	93.13	110.76	
V_{sail}		1575				2076			
V_{envtot}		34161	100			38040	5966		
V_{ff}		2184	6.39	6.83		-1016	-2.97	-3.18	
Lbow	25	6048		18.91		25	5874.50	0.08	
Lmid	52	19102		59.72		52	19766.90	0.16	
Laft	52	6836		21.37		52	9785.07	0.16	
LOA	129	31985		100.00		129	35426.47	100.00	

Appendix G – SSCS Space Summary

SSCS	GROUP	VOLUME FT3	AREA FT2
1	**MISSION SUPPORT**	1964.4	481
1.1	**COMMAND,COMMUNICATION+SURV**	1873.4	445
1.11	**EXTERIOR COMMUNICATIONS**		2
1.111	RADIO		
1.112	UNDERWATER SYSTEMS	1	2
1.113	VISUAL COM		
1.12	**SURVEILLANCE SYS**		29
1.121	SURFACE SURV (RADAR)		4
1.122	UNDERWATER SURV (SONAR)		25
1.13	**COMMAND+CONTROL**		330
1.131	COMBAT INFO CENTER		330
1.132	**CONNING STATIONS**		0
1.1321	PILOT HOUSE		
1.1322	CHART ROOM		
1.133	DATA PROCESSING		
1.14	**COUNTERMEASURES**		74
1.141	ELECTRONIC		4
1.142	TORPEDO		70
1.143	MISSILE		
1.15	INTERIOR COMMUNICATIONS		10
1.16	ENVIORNMENTAL CNTL SUP SYS		
1.2	**WEAPONS**		0
1.21	**GUNS**		0
1.211	BATTERIES		
1.214	AMMUNITION STOWAGE		
1.22	MISSILES		
1.24	TORPEDOS	90	
1.26	MINES		
1.28	WEAP MODULE STA & SERV INTER		
1.8	**SPECIAL MISSIONS**		36
2	**HUMAN SUPPORT**	2280	289
2.1	**LIVING**	2280	157
2.11	**OFFICER LIVING**	1200	120
2.111	**BERTHING**	1200	142
2.1111	**SHIP OFFICER**	1200	142
2.1111104	COMMANDING OFFICER STATEROOM	360	30
2.1111206	EXECUTIVE OFFICER STATEROOM	840	112
2.111123	DEPARTMENT HEAD STATEROOM		
2.1111302	OFFICER STATEROOM		
2.112	**SANITARY**		39

2.1121	**SHIP OFFICER**		39
2.1121101	COMMANDING OFFICER BATH		18
2.1121201	EXECUTIVE OFFICER BATH		21
2.1121203	OFFICER BATH		
2.1121303	OFFICER WR, WC & SH		
2.1124	AVIATION OFFICER		
2.12	**CPO + SPW LIVING**	1080	37
2.121	BERTHING		28
2.122	SANITARY		9
2.2	**COMMISSARY**	840	96
2.21	**FOOD SERVICE**	840	96
2.211	WARDROOM MESSRM & LOUNGE	240	24
2.212	CPO MESSROOM AND LOUNGE	240	24
2.222	**GALLEY**	360	48
2.2222	WARD ROOM GALLEY		
2.2224	CREW GALLEY		
2.223	WARDROOM PANTRY		
2.224	SCULLERY		
2.4	**GENERAL SERVICES**	180	24
2.41	SHIP STORE FACILITIES		0
2.42	LAUNDRY FACILITIES		24
2.44	BARBER SERVICE		
2.46	POSTAL SERVICE		
2.47	BRIG		
2.48	RELIGIOUS		
2.5	**PERSONNEL STORES**		10
2.51	BAGGAGE STOREROOMS		
2.52	MESSROOM STORES		
2.55	FOUL WEATHER GEAR		
2.56	LINEN STOWAGE		
2.57	FOLDING CHAIR STOREROOM		
2.7	**LIFESAVING EQUIPMENT**		2
3	**SHIP SUPPORT**		157.5
3.1	**SHIP CNTL SYS (STEERING)**		20
3.11	STEERING GEAR		20
3.12	ROLL STABILIZATION		
3.15	STEERING CONTROL		
3.3	**SHIP ADMINISTRATION**		50
3.301	GENERAL SHIP		
3.302	EXECUTIVE DEPT		
3.303	ENGINEERING DEPT		
3.304	SUPPLY DEPT		
3.305	DECK DEPT		
3.306	OPERATIONS DEPT		
3.307	WEAPONS DEPT		
3.31	SHIP PHOTO/PRINT SVCS		
3.5	**DECK AUXILIARIES**		17
3.51	ANCHOR HANDLING		10
3.52	LINE HANDLING		

3.53	TRANSFER-AT-SEA		7
3.54	SHIP BOATS STOWAGE		
3.6	**SHIP MAINTENANCE**		65
3.61	**ENGINEERING DEPT**		35
3.611	AUX (FILTER CLEANING)		0
3.612	ELECTRICAL		5
3.613	MECH (GENERAL WK SHOP)		10
3.614	PROPULSION MAINTENANCE		20
3.62	OPERATIONS DEPT (ELECT SHOP)		0
3.63	WEAPONS DEPT (ORDINANCE SHOP)		30
3.64	DECK DEPT (CARPENTER SHOP)		0
3.7	**STOWAGE**		5.5
3.71	**SUPPLY DEPT**		5.5
3.711	HAZARDOUS MATL (FLAM LIQ)		0
3.712	SPECIAL CLOTHING		5
3.713	GEN USE CONSUM+REPAIR PART		0
3.714	SHIP STORE STORES		0.5
3.715	STORES HANDLING		0
3.72	ENGINEERING DEPT		0
3.73	OPERATIONS DEPT		0
3.74	DECK DEPT (BOATSWAIN STORES)		0
3.75	WEAPONS DEPT		0
3.76	EXEC DEPT (MASTER-AT-ARMS STOR)		0
3.78	CLEANING GEAR STOWAGE		0
3.8	**ACCESS**	640	0
3.82	**INTERIOR**	640	0
3.821	NORMAL ACCESS	320	
3.822	ESCAPE ACCESS	320	
3.9	**TANKS**	1359	
3.91	**SHIP PROP SYS TNKG**	545	
3.911	**SHIP ENDUR FUEL TNKG**	545	
3.9111	ENDUR FUEL TANK (INCL SERVICE)	545	
3.914	FEEDWATER TNKG		
3.92	BALLAST TNKG	750	
3.93	FRESH WATER TNKG	64	
3.94	**POLLUTION CNTRL TNKG**	0	
3.941	SEWAGE TANKS		
3.942	OILY WASTE TANKS		
3.95	VOIDS		
3.96	COFFERDAMS		
3.97	CROSS FLOODING DUCTS		
4	**SHIP MACHINERY SYSTEM**	1.8	48
4.1	**PROPULSION SYSTEM**		
4.2	**PROPULSOR & TRANSMISSION SYST**	535	0
4.23	**PROPELLOR**	300	
4.23001	PROP SHAFT ALLEY		
4.24	AIR FAN ROOMS	235	
4.3	**AUX MACHINERY**		48
4.32	**A/C & REFRIGERATION**		0

4.321	A/C (INCL VENT)		
4.322	REFRIGERATION		
4.33	**ELECTRICAL**	1744.4	
4.331	**POWER GENERATION**	1738.4	
4.3311	PEM	972	
4.3313	BATTERIES	766.4	
4.3314	400 HERTZ		
4.332	PWR DIST & CNTRL	6	
4.334	DEGAUSSING		
4.34	**POLLUTION CONTROL SYSTEMS**		6
4.341	SEWAGE		3
4.342	TRASH		3
4.35	MECHANICAL SYSTEMS		12
4.36	VENTILATION SYSTEMS		30

Appendix H - Fortran Code

```
   program SSCombat
! Version 0.0; 11/22/04; AJB
! Calculates Payload characteristics
     real WT(150),VCG(150),AREA(150),Vob(150),KW(150),KWpay
     integer ID(150),WG(150),Pay1(17),Pay2(11),Pay3(2),Pay4(5),&
             Pay(35),ASW,C4I,SPW,Npim
     real VOP(6),MOMp100,MOMp400,MOMp500,MOMp600,MOM7,MOMF20
!
 998  open(4,file='SSCombat.in',status='old')
! Input
     read(4,*) ASW,C4I,MCM,SPW,Npim,D
!
     close(4)
!
!  Input parameters
!     ASW = ASW/ASUW alternative
!     C4I = C4ISR alternative
!     MCM = MCM alternative
!     SPW = SPW alternative
!     Npim = number of payload interface modules
!     D = hull diameter
!
! ASW/ASUW Payload
     If(ASW.eq.1) then
         Pay1=(/1,2,3,4,5,7,8,8,8,8,9,9,10,11,11,0,0/)
         VOP(1)=1.0     ! ASUW VOP
         VOP(5)=1.0     ! ASW VOP
      Else if(ASW.eq.2) then
         Pay1=(/1,2,3,4,6,8,8,8,8,8,8,9,9,10,11,11,0/)
         VOP(1)=.111
         VOP(5)=.109
      Else if(ASW.eq.3) then
         Pay1=(/1,2,3,4,8,8,8,8,8,8,8,8,9,9,10,11,11/)
         VOP(1)=.950
         VOP(5)=.900
      Else
         Pay1=(/1,3,4,8,8,8,8,9,9,10,0,0,0,0,0,0,0/)
         VOP(1)=.201
         VOP(5)=.208
     Endif
! C4ISR Payload
     If(C4I.eq.1) then
         Pay2=(/12,13,14,15,16,17,18,19,20,21,22/)
         VOP(2)=1.0     ! C4I VOP
         VOP(3)=.480    ! ISR MOP
      Else if (C4I.eq.2) then
         Pay2=(/12,13,14,15,17,18,19,20,0,0,0/)
         VOP(2)=.480
         VOP(3)=1.0
      Else
         Pay2=(/14,15,17,18,19,20,0,0,0,0,0/)
         VOP(2)=0.694
         VOP(3)=.694
     Endif
! MCM Payload
```

```
     If(MCM.eq.1) then
         Pay3=(/23,24/)
         VOP(4)=1.0     ! MCM VOP
      Else
         Pay3=(/23,0/)
         VOP(4)=0.333
     Endif
! SPW Payload
     If(SPW.eq.1) then
         Pay4=(/26,27,27,27,27/)
         NESP=14
         NO=6
         VOP(6)=1.0     ! SPW VOP
      Elseif(SPW.eq.2) then
         Pay4=(/25,27,27,27,27/)
         NESP=14
         NO=6
         VOP(6)=.823
      Elseif(SPW.eq.3) then
         Pay4=(/26,27,27,0,0/)
         NESP=7
         NO=5
         VOP(6)=1.0
      Else
         Pay4=(/25,27,27,0,0/)
         VOP(6)=.180
         NESP=7
         NO=5
     Endif
!
     Pay=(/Pay1,Pay2,Pay3,Pay4/)
!
     open(20,file='SSCombatSystems.prn',status='old')
     Read (20,*) NPAY      ! number of payload components in database
     Do 3, i=1,NPAY
 3   Read (20,*) ID(i),WG(i),WT(i),VCG(i),AREA(i),Vob(i),KW(i)
     close(20)
!
!  Initialize payload weights, power, area, moment of VCG
!
     Wp100=0            ! payload structure weight
     Wp400=0.0          ! payload command and control weight
     KWpay=0.0          ! payload electric power
     Ap4=0.0            ! payload command and control arrangeable area
required
     A7=0.0          ! payload ordnance delivery systems arrangeable area
required
     Wp500=0.0          ! payload auxiliaries weight
     W7=0.0          ! payload ordnance delivery systems weight
     WF20=0.0           ! payload expendable ordnance weight
     MOMp100=0.0        ! payload structure weight VCG moment
     MOMp400=0.0        ! payload command and control weight VCG moment
     MOMp500=0.0        ! payload auxiliaries weight VCG moment
     MOM7=0.0           ! payload ordnance delivery systems weight VCG moment
     MOMF20=0.0         ! payload expendable ordnance weight VCG moment
     Vpob=0.0           ! payload required outboard volume
     Do 100, n=1,32
      If(Pay(n).eq.0) Go to 100
```

```
      Do 10, m=1,NPAY
         If(ID(m).eq.Pay(n)) then
            If(WG(m).eq.1) then
               Wp100=Wp100+WT(m)
               MOMp100=MOMp100+WT(m)*VCG(m)
               KWpay=KWpay+KW(m)
               A7=A7+AREA(m)
               Vpob=Vpob+Vob(m)
            Endif
            If(WG(m).eq.4) then
               Wp400=Wp400+WT(m)
               MOMp400=MOMp400+WT(m)*VCG(m)
               KWpay=KWpay+KW(m)
               Ap4=Ap4+AREA(m)
               Vpob=Vpob+Vob(m)
            Endif
            If(WG(m).eq.5) then
               Wp500=Wp500+WT(m)
               MOMp500=MOMp500+WT(m)*VCG(m)
               KWpay=KWpay+KW(m)
               A7=A7+AREA(m)
               Vpob=Vpob+Vob(m)
            Endif
            If(WG(m).eq.7) then
               W7=W7+WT(m)
               MOM7=MOM7+WT(m)*VCG(m)
               KWpay=KWpay+KW(m)
               A7=A7+AREA(m)
               Vpob=Vpob+Vob(m)
            Endif
            If(WG(m).eq.20) then
               WF20=WF20+WT(m)
               MOMF20=MOMF20+WT(m)*VCG(m)
               A7=A7+AREA(m)
               KWpay=KWpay+KW(m)
               Vpob=Vpob+Vob(m)
            Endif
            Go to 100
         Endif
 10      Continue
 100  Continue
      VCGp100=MOMp100*D/Wp100          ! payload structures weight VCG
      VCGp400=MOMp400*D/Wp400          ! payload command and control weight
VCG
      VCGp500=MOMp500*D/Wp500          ! payload auxiliaries weight VCG
      VCG7=MOM7*D/W7                ! payload ordnance delivery system weight
VCG
      VCGF20=MOMF20*D/WF20          ! payload expendable ordnance weight VCG
!
      Vpim=Npim*1280.                  ! total required payload interface
module volume
      Vpob=Vpob+Vpim                ! total required payload outboard volume
      Wpim=Vpim/(1.21*35.)          ! total payload interface module weight
      Wvp=WF20+Wpim                 ! total variable payload weight
      VCGpim=.5*D
      VCGvp=(WF20*VCGF20+Wpim*VCGpim)/Wvp ! total variable payload weight VCG
      Wp=Wvp+Wp100+Wp400+Wp500+W7         ! total payload weight
      VCGp=(Wvp*VCGvp+Wp100*VCGp100+Wp400*VCGp400+Wp500*VCGp500+&
```

```
            W7*VCG7)/Wp             ! total payload weight VCG
      VOP1=VOP(1)
      VOP2=VOP(2)
      VOP3=VOP(3)
      VOP4=VOP(4)
      VOP5=VOP(5)
      VOP6=VOP(6)
!
     open(5,file='SSCombat.out',status='old')
! Output
     write(5,*) VOP1,VOP2,VOP3,VOP4,VOP5,VOP6,Wp,VCGp,Wvp,VCGvp,Wp100,&
                Wp400,Wp500,W7,WF20,Ap4,A7,KWpay,Vpim,Vpob,NESP,NO
!
     close(5)
!
      stop
     End
```

Program Cost

```
! This subroutine calculates lead and follow acquisition cost and life cycle
cost
! Version 0.0; 7/20/04; AJB
     real KN1,KN2,KN3,KN4,KN5,KN6,KN7,Mh
     real KM1,KM2,KM3,KM4,KM5,KM6,KM7,IC,LCC
     integer Ls,Yioc,Yb,BATtyp,PSYS
! Input
      open(4,file='SSCost.in',status='old')
     read(4,*)
W1,W2,W3,W4,W5,W6,W7,Ls,Ns,Yioc,Rp,Mh,Yb,R,ovhd,profit,BATtyp,PSYS,Cmanning
     close(4)
!
!  Inputs:
!  W1 = SWBS 100 stucture weight
!  W2 = SWBS 200 propulsion weight
!  W3 = SWBS 300 electrical weight
!  W4 = SWBS 400 command and control weight
!  W5 = SWBS 500 auxiliaries weight
!  W6 = SWBS 600 outfit weight
!  W7 = SWBS 700 ordnance weight
!  Yioc = initial operational capability year
!  Rp = shipbuilding rate per year after lead ship
!  Mh - average manhour rate (dollars/hr)
!  R = average inflation rate before base
!  Yb = base year (appropriation)
!  R = average inflation rate after base
!  ovhd = overhead rate
!  profit = profit margin
!
! Inflation
      Fi=1.
      DO 10 I=1,Yb-1995
 10      Fi=Fi*(1.+R/100.) ! average inflation factor from 1995
! Labor
     Mh=Mh/1000000.     ! manhour rate, $M/hr
     KN1=700.           ! structure complexity factor
     CL1=KN1*W1*Mh         ! SWBS 100 labor cost
     If(PSYS.eq.1.or.PSYS.eq.2) then
```

```
       KN2=300.           ! propulsion complexity factor
      Elseif(PSYS.eq.6) then
       KN2=400.
      Elseif(PSYS.eq.3) then
       KN2=500.
      Else
       KN2=600.
      Endif

!!!Labor Cost = complexity factor * Weight * Manhour Rate

      CL2=KN2*W2*Mh         ! SWBS 200 labor cost
      KN3=1000.          ! electrical complexity factor
      CL3=KN3*W3*Mh         ! SWBS 300 labor cost
      KN4=1500.          ! c&c complexity factor
      CL4=KN4*W4*Mh         ! SWBS 400 labor cost
      KN5=1500.          ! auxiliaries complexity factor
      CL5=KN5*W5*Mh         ! SWBS 500 labor cost
      KN6=1600.          ! outfit complexity factor
      CL6=KN6*W6*Mh         ! SWBS 600 labor cost
      KN7=1600.          ! ordnance complexity factor
      CL7=KN7*W7*Mh         ! SWBS 700 labor cost
      CL8=.5*(CL1+CL2+CL3+CL4+CL5+CL6+CL7) ! design and integration labor cost
      CL9=.25*(CL1+CL2+CL3+CL4+CL5+CL6+CL7)   ! production support labor cost
      CL=CL1+CL2+CL3+CL4+CL5+CL6+CL7+CL8+CL9  ! total labor cost
! Material
      KM1=.02            ! structures material cost factor
      CM1=KM1*W1*Fi         ! SWBS 100 material cost
      If(PSYS.eq.1.or.PSYS.eq.2) then
       KM2=.15           ! propulsion material cost factor
      Elseif(PSYS.eq.6) then
       KM2=.25
      Elseif(PSYS.eq.3) then
       KM2=.25
      Else
       KM2=.3
      Endif

!!!Material Cost = complexity factor * Weight * average inflation factor

      CM2=KM2*W2*Fi         ! SWBS 200 material cost
      KM3=.3          ! electrical material cost factor
      if(BATtyp.eq.3) KM3=.2
      CM3=KM3*W3*Fi         ! SWBS 300 material cost
      KM4=.42/Cmanning      ! C&C material cost factor
      CM4=KM4*W4*Fi         ! SWBS 400 material cost
      KM5=.1          ! auxiliaries material cost factor
      CM5=KM5*W5*Fi         ! SWBS 500 material cost
      KM6=.05            ! outfit material cost factor
      CM6=KM6*W6*Fi         ! SWBS 600 material cost
      KM7=.2          ! ordnance material cost factor
      CM7=KM7*W7*Fi         ! SWBS 700 material cost
      CM8=.05*(CM1+CM2+CM3+CM4+CM5+CM6+CM7)   ! SWBS 800 material cost
      CM9=.1*(CM1+CM2+CM3+CM4+CM5+CM6+CM7) ! SWBS 900 material cost
      CM=CM1+CM2+CM3+CM4+CM5+CM6+CM7+CM8+CM9 ! total material cost
!
      DC=CL+CM           ! total direct cost
      IC=DC*ovhd         ! total indirect cost
```

```
     CBCC=(1.+profit)*(DC+IC) ! basic cost of construction
     LCC=CBCC+20.8*10.  ! Life Cycle Cost
     if(BATtyp.eq.3) LCC=CBCC
! Output
     open(5,file='SSCost.out',status='old')
     write(5,*) CBCC,LCC
     close(5)
!
      stop
     end
```

Program SSElectric

```
! Version 0.0; 11/24/04; AJB
! This subroutine calculates electrical load and auxiliary machinery rooms
! total volume.All loads in [kW].
      real LOA,KWp,KWs,KWe,KWm,KWf,KWhn,KWa,KWserv,KWnp,KWpay
     real KWmfl,KWv,KWac,KWmflm,KWgreq,KW24,KW24avg,KWdegaus
! Input
      open(4,file='SSelectric.in',status='old')
     read(4,*)
EFMF,EDMF,E24MF,Nprop,Wp,Vph,Vmb,Vaux,Pmain,LOA,D,KWpay,NT,Ng,Ndegaus
     close(4)
!
      ! EFMF = electric functional margin factor
      ! EDMF = electric design margin factor
      ! E24MF = average electric power margin factor
      ! Wp = total payload weight
      ! Nprop = number of propellers or propulsors
      ! KWpay = payload required power
      ! Vph = pressure hull volume
      ! Vmb = machinery box volume
      ! Vaux = auxiliary space volume
      ! Pmain = total primary power
      ! LOA = hull length overall
      ! D = hull diameter
      ! NT = total crew
      ! Ng = number of primary power generators
      ! Ndegaus = degaussing (0=no,1=yes)
!
     KWp=0.004332*Pmain          ! propulsion required electric power
     KWs=0.008*LOA*D             ! steering required electric power
     KWe=0.0002*Vph              ! electric plant and lighting required
electric power
     KWm=15.4                    ! miscelaneous required electric power
     KWf=0.000097*Vph               ! firemain required electric power
     KWhn=0.0001*Vph             ! fuel handling required electric power
     KWa=0.65*NT                 ! auxiliary required electric power
     KWserv=0.395*NT             ! services required electric power
     KWdegaus=Ndegaus*Vph/500.      ! degaussing required electric power
     KWnp=KWp+KWs+KWe+KWm+KWf+KWhn+KWa+KWserv   ! non-payload required
electric power
     KWac=0.67*(0.1*NT+0.00067*(Vph-Vmb-Vaux)+0.1*KWpay+.25*KWdegaus)   ! air
conditioning required electric power
     KWv=0.103*(KWac+KWpay)         ! ventilation required electric power
     KWmfl=KWnp+KWv+KWac+KWpay+KWdegaus   ! maximum functional load
     KWmflm=EDMF*EFMF*KWmfl            ! maximum functional load with margins
     KWgreq=KWmflm/Ng/0.9           ! primary generator required power rating
     KW24=0.5*(KWmfl-KWp-KWs)+KWp+KWs     ! average required power
```

```
     KW24avg=E24MF*KW24             ! average required power with margins
! Output
     open(5,file='SSelectric.out',status='old')
     write(5,*) KWmflm,KW24avg,KWgreq
     close(5)
!
      stop
     end
```

Program Feasible

```
     real KWg,KWgreq,KWmflm
     integer PSYStype
! SI units in and out
! Version 0.0; 7/20/04; AJB
! Input
      open(4,file='SSFeasible.in',status='old')
     read(4,*) Emin,Vsmin,Esmin,GBmin,GMmin,Wleadmin,Wleadmax,Vffmin,&
               Vffmax,Wnsc,Ata,Atr,Vff,W8,Vs,KWg,KWgreq,GM,GB,E,Es
     close(4)
!
! Input variables:
!  Emin = endurance range threshold (nm)
!  Vsmin = sustained speed threshold (knt)
!  Esmin = sprint range threshold (nm)
!  GBmin = minimum GB submerged
!  GB = submerge GB
!  GMmin = minimum GM surfaced
!  GM = surfaced GM
!  Wleadmin = minimum lead weight
!  Wleadmax = maximum lead weight
!  W8 = lead weight
!  Vffmin = minimum free flood volume
!  Vffmax = maximum free flood volume
!  Vff = free flood volume
!  Wnsc = normal surface condition weight
!  Atr = total required arrangeable area
!  Ata = total available arrangeable area
!  Vs = sustained speed (knt)
!  KWg = primary generator power rating (kw), ea
!  KWgreq = required primary generator power, ea
!  E = endurance range (nm)
!  Es = sprint range (nm)
!
! Balance, Availability and Feasibility ratios
     Eta=(Ata-Atr)/Atr              ! total arrangeable area required ratio,
must be > 0
     Effmin=(Vff-Vffmin)/Vffmin     ! minimum freeflood volume required
ratio, must be > 0
     Effmax=(Vffmax-Vff)/Vffmax     ! maximum freeflood volume required
ratio, must be > 0
     Eleadmin=(W8-Wleadmin)/Wleadmin   ! minimum lead required ratio, must be
> 0
     Eleadmax=(Wleadmax-W8)/Wleadmax   ! maximum lead required ratio, must be
> 0
     Evs=(Vs-Vsmin)/Vsmin           ! sustained speed required ratio, must be
> 0
     Ekw=(KWg-KWgreq)/KWgreq        ! primary electric power required ratio,
must be > 0
```

```
     Egm=(GM-GMmin)/GMmin           ! minimum GM required ratio, must be > 0
     Egb=(GB-GBmin)/GBmin           ! minimum GB required ratio, must be > 0
     Ee=(E-Emin)/Emin               ! endurance range required ratio, must be
> 0
     Ees=(Es-Esmin)/Esmin           ! sprint range required ratio, must be >
0
! Output
     open(5,file='SSFeasible.out',status='old')
     write(5,*) Eta,Effmin,Effmax,Eleadmin,Eleadmax,Evs,Ekw,Egm,Egb,Ee,Ees
     close(5)
!
      stop
     End

      Program SSHull
! Version 0.0; 7/22/04; AJB
! Calculates hull characteristics
     real Lbow,Lmid,Laft,LOA
! Input
      open(4,file='SSHull.in',status='old')
     read(4,*) Lbow,Lmid,Laft,B,D
     close(4)
!
! Lbow = length forebody
! Lmid = length midbody
! Laft = length aftbody
! B = beam
! D = diameter or depth
     Pi=3.14159265
     del=B-D
     LOA=Lbow+Lmid+Laft                      ! length overall
     r=B/2
     r1=D/2
     if(del.gt.0.0) then
      e=sqrt(r**2-r1**2)/r                   ! eccentricity
      Vbow=1.33333*Pi*r*r1*Lbow                 ! forebody volume
      Sbow=2*Pi*r1**2+Pi*r1*(r1+r*asin(e)/e)       ! forebody surface area
     else
      Vbow=.66667*Pi*r1**3
      Sbow=2*Pi*r1**2
     endif
     Vmid=Pi*Lmid*r1**2+del*Lmid*D                 ! midbody volume
     Smid=2*Pi*r1*Lmid+2*del*D+2*D*Lmid+2*del*Lmid    ! midbody surface area
     Vaft=.5*(.333333*Pi*r1**2*Laft+del*Laft*r1)      ! aftbody volume
     Saft=.5*(Pi*r1+2*del)*sqrt(r1**2+Laft**2)        ! aftbody surface area
     S=Sbow+Smid+Saft                           ! total surface area
     Venv=Vbow+Vmid+Vaft                        ! total envelope volume
!
! Output
     open(5,file='SSHull.out',status='old')
     write(5,*) LOA,del,S,Venv
     close(5)
!
      stop
     End

      Program SSOMOE
! Version 0.0; 11/24/04; AJB
```

```
! This subroutine calculates ship OMOE for SS
     real VOP(18),WVOP(18),interp
     integer PSYS,Ts
! Input
      open(4,file='SSOMOE.in',status='old')
     read(4,*) Ts,E,Es,BATtyp,Vs,Depth,D,PSYS,NT,Npim,Ndegaus,&
               VOP1,VOP2,VOP3,VOP4,VOP5,VOP6,Emin,Esmin,Vsmin
     close(4)
!
!  Ts = stores and provisions duration
!  E = endurance range
!  Es = sprint range
!  BATtyp = battery type (1=lithiumion,2=nickelcadmiun,3=leadacid)
!  Vs = sustained or sprint speed
!  Depth = maximum operational depth
!  D = hull diameter or depth
!  PSYS = propulsion system alternative
!  NT = total crew
!  Npim = number of payload interface modules
!  Ndegaus = degaussing (0=no,1=yes)
!
     VOP(1)=VOP1  ! ASUW
     VOP(2)=VOP2  ! C4I
     VOP(3)=VOP3  ! ISR
     VOP(4)=VOP4  ! MCM
     VOP(5)=VOP5  ! ASW
     VOP(6)=VOP6  ! SPW
! Provisions
     If(Ts.lt.14) then
         VOP(7)=0.0
      Elseif(Ts.lt.17) then
         VOP(7)=interp(0.0,.1,14,17,Ts)
      Elseif(Ts.lt.20) then
         VOP(7)=interp(.1,.3,17,20,Ts)
      Elseif(Ts.lt.23) then
         VOP(7)=interp(.3,.6,20,23,Ts)
      Elseif(Ts.lt.26) then
         VOP(7)=interp(.6,.85,23,26,Ts)
      Elseif(Ts.lt.30) then
         VOP(7)=interp(.85,1.0,26,30,Ts)
      Else
         VOP(7)=1.0
     Endif
! Sprint Range
     If(Es.lt.Esmin) then
         VOP(8)=0.0
      Elseif(Es.lt.(Esmin+5.)) then
         VOP(8)=interp(0.0,.1,Esmin,(Esmin+5.),Es)
      Elseif(Es.lt.(Esmin+10.)) then
         VOP(8)=interp(.1,.3,(Esmin+5.),(Esmin+10.),Es)
      Elseif(Es.lt.(Esmin+15.)) then
         VOP(8)=interp(.3,.6,(Esmin+10.),(Esmin+15.),Es)
      Elseif(Es.lt.(Esmin+20.)) then
         VOP(8)=interp(.6,.85,(Esmin+15.),(Esmin+20.),Es)
      Elseif(Es.lt.(Esmin+25.)) then
         VOP(8)=interp(.85,1.0,(Esmin+20.),(Esmin+25.),Es)
      Else
         VOP(8)=1.0
```

```
     Endif
! Range
     If(E.lt.Emin) then
         VOP(9)=0.0
      Elseif(E.lt.(Emin+100.)) then
         VOP(9)=interp(0.0,.1,Emin,(Emin+100.),E)
      Elseif(E.lt.(Emin+200.)) then
         VOP(9)=interp(.1,.3,(Emin+100.),(Emin+200.),E)
      Elseif(E.lt.(Emin+300.)) then
         VOP(9)=interp(.3,.6,(Emin+200.),(Emin+300.),E)
      Elseif(E.lt.(Emin+400.)) then
         VOP(9)=interp(.6,.85,(Emin+300.),(Emin+400.),E)
      Elseif(E.lt.(Emin+500.)) then
         VOP(9)=interp(.85,1.0,(Emin+400.),(Emin+500.),E)
      Else
         VOP(9)=1.0
     Endif
! Battery Service Life
     If(BATtyp.eq.1) then
      VOP(10)=0.0
     Elseif (BATtyp.eq.2) then
      VOP(10)=.2
     Else
      VOP(10)=1.0
     Endif
! Sustained Speed
     If(Vs.lt.Vsmin) then
         VOP(11)=0.0
      Elseif(Vs.lt.(Vsmin+1.)) then
         VOP(11)=interp(0.0,.1,Vsmin,(Vsmin+1.),Vs)
      Elseif(Vs.lt.(Vsmin+2.)) then
         VOP(11)=interp(.1,.3,(Vsmin+1.),(Vsmin+2.),Vs)
      Elseif(Vs.lt.(Vsmin+3.)) then
         VOP(11)=interp(.3,.6,(Vsmin+2.),(Vsmin+3.),Vs)
      Elseif(Vs.lt.(Vsmin+4.)) then
         VOP(11)=interp(.6,.85,(Vsmin+3.),(Vsmin+4.),Vs)
      Elseif(Vs.lt.(Vsmin+5.)) then
         VOP(11)=interp(.85,1.0,(Vsmin+4.),(Vsmin+5.),Vs)
      Else
         VOP(11)=1.0
     Endif
! Operating Depth
     If(Depth.lt.250.) then
         VOP(12)=0.0
      Elseif(Depth.lt.300.) then
         VOP(12)=interp(0.0,.1,250.,300.,Depth)
      Elseif(Depth.lt.350.) then
         VOP(12)=interp(.1,.3,300.,350.,Depth)
      Elseif(Depth.lt.400.) then
         VOP(12)=interp(.3,.6,350.,400.,Depth)
      Elseif(Depth.lt.450.) then
         VOP(12)=interp(.6,.85,400.,450.,Depth)
      Elseif(Depth.lt.500.) then
         VOP(12)=interp(.85,1.0,450.,500.,Depth)
      Else
         VOP(12)=1.0
     Endif
! Hull Diameter
```

```
     If(D.le.13.) then
         VOP(13)=1.0
       Else
         VOP(13)=0.0
     Endif
! Magnetic Signature
     If(Ndegaus.eq.1) then
      VOP(14)=1.0
     Else
      VOP(14)=0.0
     Endif
! Acoustic Signature
     If(PSYS.eq.1.or.PSYS.eq.2) then
      VOP(15)=0.0
     Elseif(PSYS.eq.6) then
      VOP(15)=0.2
     Else
      VOP(15)=1.0
     Endif
! Hydrogen Fuel Vulnerability
     If(PSYS.eq.3.or.PSYS.eq.5) then
      VOP(16)=0.0
     Else
      VOP(16)=1.0
     Endif
! Personnel Vulnerability
     If(NT.gt.35) then
         VOP(17)=0.0
      Elseif(NT.gt.30) then
         VOP(17)=interp(0.0,.1,35,30,NT)
      Elseif(NT.gt.25) then
         VOP(17)=interp(.1,.3,30,25,NT)
      Elseif(NT.gt.20) then
         VOP(17)=interp(.3,.6,25,20,NT)
      Elseif(NT.gt.15) then
         VOP(17)=interp(.6,.85,20,15,NT)
      Elseif(NT.gt.10) then
         VOP(17)=interp(.85,1.0,15,10,NT)
      Else
         VOP(17)=1.0
     Endif
! PIM Containers
     If(Npim.le.1) then
         VOP(18)=0.2
      Elseif(Npim.eq.2) then
         VOP(18)=.8
      Elseif(Npim.eq.3) then
         VOP(18)=.9
      Else
         VOP(18)=1.0
     Endif
!

WVOP=(/.008,.02,.017,.042,.013,.056,.071,.029,.078,.078,.027,.061,.023,.023,.
211,.053,.071,.119/) ! VOP weights
     OMOE=DOT_PRODUCT(VOP,WVOP)
! Output
     open(5,file='SSOMOE.out',status='old')
```

```
     write(5,*) OMOE
     close(5)
!
      stop
     End

      Program SSPropulsion
! Version 0.0; 11/23/04; AJB
! Calculates propulsion and generator system characteristics, SI units
     real KWg,LMBreq
     integer PSYStype,PSYS
! Input
      open(4,file='SSPropulsion.in',status='old')
     read(4,*) PSYS,BATtyp,Ebattery,Wfuel,Ng,PC,eta,Nprop
     close(4)
!
!  PSYS = propulsion system alternative
!  BATtyp = battery type
!  Ebattery = battery capacity kwhr
!  Wfuel = fuel weight
!  Ng = number of primary power generators
!  PC = overall propulsive coefficient
!  eta = transmission efficiency
!  Nprop = number of propellers or propulsors
!
     open(20,file='SSPropData.prn',status='old')
     Read(20,*) NPSYS
     Do 10 n=1,NPSYS
      read(20,*) KWg,Wbm,SFCmain,SOxCmain,SArCmain,dfuelib,dfuelob,doxidant,&
                 dargon,sfuel,soxidant,sargon,LMBreq,wMBreq,HMBreq,Vmbmain
      If(n.eq.PSYS) Go to 11
 10     continue
 11     close(20)
!
! Data in propulsion data file:
!  KWg = main generator power, ea
!  wbm = basic propulsion machinery, weight per generator
!  SFCmain = main generator specific fuel consumption, kg/kwhr
!  SOxCmain = main generator specific oxidant consumption, kg/kwhr
!  SArCmain = main generator specific argon consumption, kg/kwhr
!  dfuelib = inboard fuel tank volume, per lton fuel, diesel fuel or
desulfurized diesel fuel
!  dfuelob = outboard fuel tank volume, per lton fuel, only hydrogen outboard
!  doxidant = oxidant tank volume, per lton oxidant, inboard only
!  dargon = argon tank volume, per lton argon, inboard only
!  sfuel = fuel tank structure weight, per lton fuel
!  soxidant = oxidant tank structure weight, per lton oxidant
!  sargon = argon tank structure weight, per lton argon
!  LMBreq = required machinery box length
!  wMBreq = required machinery box width
!  HMBreq = required machinery box height
!  Vmbmain = required machinery box volume
!
     Pmain=Ng*KWg                   ! total main generator power
     CorNSWC=.33                    ! battery power correction, NSWC
estimates too high
     CorVT=.8                       ! leadacid battery numbers too heavy and
large
```

```
     if(BATtyp.eq.1) then
      Wbattery=.005708*Ebattery/CorVT        ! total battery weight
      Vbattery=.09535*Ebattery/CorVT         ! total battery volume
      Pbattery=CorNSWC*1.68*Ebattery      ! total battery power
     elseif(BATtyp.eq.2) then
      Wbattery=.0111*Ebattery/CorVT
      Vbattery=.113*Ebattery/CorVT
      Pbattery=CorNSWC*2.61*Ebattery
     else
      Wbattery=.0328*Ebattery*CorVT
      Vbattery=.6109*Ebattery*CorVT
      Pbattery=CorNSWC*1.5*Ebattery
     endif
     V2prop=Nprop*200.+200.                        ! total external propulsor
volume
     Woxidant=Wfuel*SOxCmain/SFCmain                  ! total oxidant weight
     Wargon=Wfuel*SArCmain/SFCmain                    ! total argon weight
     W2reactks=sfuel*Wfuel+soxidant*Woxidant+sargon*Wargon  ! total
propulsion tank weight
     V2ib=dfuelib*Wfuel+doxidant*Woxidant+dargon*Wargon  ! total propulsion
inboard volume
     V2ob=dfuelob*Wfuel+V2prop                        ! total propulsion
outboard volume
     Vmb=Ng*Vmbmain*35.3147                        ! total amcjinery box
volume
     Wbm=Wbm*Ng                                 ! total weight basic
propulsion machinery
!

! Output
     open(5,file='SSPropulsion.out',status='old')
     write(5,*) Pmain,Pbattery,Wbm,Wbattery,Woxidant,Wargon,W2reactks,&
                Vmb,Vbattery,V2ib,V2ob,SFCmain,LMBreq,HMBreq,wMBreq,KWg
     close(5)
!
      stop
     End
```

Program Resist

```
! Version 0.0; 11/24/04, AJB
! Calculates hull resistance
     real LOA,KW24avg,V(20),Shp(20),Pireq(20)
! Input
      open(4,file='SSResistance.in',status='old')
     read(4,*)
Ve,Ca,PMF,S,KW24avg,LOA,B,D,PC,eta,Pmain,SFCmain,Pbattery,Ebattery,Wfuel,NT
     close(4)
!
!  Ve = endurance speed
!  Ca = resistance correlation allowance
!  PMF = propulsion margin factor
!  S  = bare hull surface area
!  KW24avg = average required electric power with margin
!  LOA = overall length
!  B = beam
!  D = diameter or depth
!  PC = overall propulsive coefficient
!  eta = transmission efficiency
```

```
!  Pmain = total primary electric power
!  SFCmain = primary generator specific fuel consumption
!  Pbattery = sprint battery power
!  Ebattery = battery capacity
!  Wfuel = fuel weight
!  NT = total crew
!
     ro=1.9905    ! Sea water density in [lbf*s^2/ft^4]
!
     Do 5 i=1,20     ! calculate at series of speeds, Ve to Ve+19 knots
      U=Ve+1.0*(i-1)
       V(i)=1.69*U      ! Convert knots to [ft/sec].
 5   Continue
     formfac=1.+.5*B/LOA+3.*(B/LOA)**3    ! form factor from Gilmer and
Johnson
     Piprp=Pmain+Pbattery-KW24avg         ! sprint available brake propulsion
power
     Do 10 i=1,20
! Correlation Allowance
        Ra=.5*ro*Ca*V(i)**2*S          ! Correlation allowance resistance
! Viscous resistance.
       RN=LOA*V(i)/1.2817e-5           ! Reynold's number
       CF=0.075/(log10(RN)-2)**2       ! Coefficient of friction, ITTC
       Rv=0.5*ro*S*CF*formfac*V(i)**2     ! Viscous resistance
! Bare hull total resistance.
      RT=Rv+Ra                   ! total resistance
! Effective horse power.
      PEBH=RT*V(i)*0.00135582          ! Power, Bare hull, converted to [kw].
      PEAPP=0.3*PEBH                ! power, appendage resistance
      PET=PEBH+PEAPP                ! bare hull power
      EHP=PET*PMF                   ! effective power
      Shp(i)=EHP/PC                 ! Shaft power (kW)
      Pireq(i)=1.25*Shp(i)/(eta*PMF)      ! sustained brake power required
with 25% margin
      If (Pireq(i).gt.Piprp) then         !                        = 80% MCR
        If(i.eq.1) then
         Vs=V(1)
        else
         Vs=(Piprp-Pireq(i-1))*(V(i)-V(i-1))/(Pireq(i)-Pireq(i-1))+V(i-1) !
sustained speed
        endif
        Go to 20
      Endif
 10     Continue
      Vs=V(20)
!
 20     SHPe=Shp(1)
     Vs=Vs/1.69
!
!  Endurance fuel calculation based on DDS 200-1
!
     Pebavg=SHPe/eta                         ! average endurance brake power
required
     f1=1.03
     if(1.1*SHPe.le.Pmain/6) f1=1.04
     if(1.1*SHPe.ge.Pmain/3) f1=1.02
     FRsp=f1*SFCmain*2.20462262                 ! specific fuel rate lbf/hr
     FRavg=1.05*FRsp                         ! average fuel rate
```

```
     TPA=.95                                ! tail pipe allowance
     E=Wfuel*2240.*Ve*TPA/(Pebavg*FRavg+KW24AVG*FRavg)   ! endurance range
     Es=(Ebattery/Pbattery)*Vs                     ! sprint range
!
     open(5,file='SSResistance.out',status='old')
     write(5,*) Vs,SHPe,Piprp,E,Es
     close(5)
!
      stop
     End

      program SSRisk
! Version 0.0; 7/20/04; AJB
! Calculates OMOR
     integer PSYS,BATtyp,ASW
!
 998  open(4,file='SSRisk.in',status='old')
! Input
     read(4,*) PSYS,BATtyp,ASW,Cmanning
!
     close(4)
!
!  PSYS = propulsion system option
!  BATtyp = battery type
!  ASW = ASW alternative
!  Cmanning = manning and automation factor
!
     If(PSYS.eq.1.or.PSYS.eq.2) then
         PerfRiskPower=0.06            ! primary power generator performance
risk
         CostRiskPower=0.06            ! primary power generator cost risk
         SchedRiskPower=0.06           ! primary power generator schedule
risk
      Elseif (PSYS.eq.3) then
         PerfRiskPower=.35
         CostRiskPower=.3
         SchedRiskPower=.3
      Elseif (PSYS.eq.4) then
         PerfRiskPower=.49
         CostRiskPower=.4
         SchedRiskPower=.4
      Elseif (PSYS.eq.5) then
         PerfRiskPower=.49
         CostRiskPower=.3
         SchedRiskPower=.3
      Else
         PerfRiskPower=.35
         CostRiskPower=.2
         SchedRiskPower=.2
       Endif
! Battery Type Risk
     If(BATtyp.eq.1) then
         PerfRiskBat=.56               ! battery performance risk
         CostRiskBat=.48               ! battery cost risk
         SchedRiskBat=.48           ! battery schedule risk
      Elseif(BATtyp.eq.2) then
         PerfRiskBat=.49
         CostRiskBat=.42
```

```
         SchedRiskBat=.42
      Else
         PerfRiskBat=0.
         CostRiskBat=0.
         SchedRiskBat=0.
       Endif
! ASW Torpedo System Risk
     If(ASW.eq.3.or.ASW.eq.4) then
         PerfRiskASW=.25
         CostRiskASW=.24
         SchedRiskASW=.24
      Else
         PerfRiskASW=0.
         CostRiskASW=0.
         SchedRiskASW=0.
       Endif
!
!
     PerfRiskAuto=.25*(1.0-Cmanning)/.5   ! automation performance risk
     CostRiskAuto=.24*(1.0-Cmanning)/.5   ! automation cost risk
     SchedRiskAuto=.24*(1.0-Cmanning)/.5  ! automation schedule risk
!
     PerfRisk=(PerfRiskPower+PerfRiskBat+PerfRiskASW+PerfRiskAuto)/1.55 !
total performance risk
     CostRisk=(CostRiskPower+CostRiskBat+CostRiskASW+CostRiskAuto)/1.36 !
total cost risk
     SchedRisk=(SchedRiskPower+SchedRiskBat+SchedRiskASW+SchedRiskAuto)/1.36
! total schedule risk
     OMOR=.5*PerfRisk+.3*CostRisk+.2*SchedRisk ! overall measure of risk
!
     open(5,file='SSRisk.out',status='old')
! Output
     write(5,*) OMOR
!
     close(5)
!
      stop
     End


      Program SSSpace
     real Lmid,Laft
! Version 0.0; 11/23/04; AJB
! Input
      open(4,file='SSSpace.in',status='old')
     read(4,*) Ts,HDK,NE,NO,NT,Aphmarg,Ap4,A7,Vmb,VPob,Vtk,V2ob,&
                        Vbattery,Venv,Lmid,Laft,B,D
     close(4)
!
!  Ts = stores and provisions duration
!  HDK = average deck height
!  NE = number of enlisted
!  NO = number of officers
!  NT = total crew
!  Aphmarg = pressure hull arrangeable area margin, includes unusable area
and passageways
!  Ap4 = command and control payload required area
!  A7 = ordnance delivery system payload required area
```

```
!  Vmb = machinery box volume
!  VPob = outboard payload volume
!  Vtk = total tankage volume
!  V2ob = propulsion total outboard volume
!  Vbattery = total battery volume
!  Venv = envelope volume
!  Lmid = midbody length
!  Laft = aft body length
!  B = beam
!  D = hull diameter or depth
!
     Aco=50.                  ! CO habitability area
     Ahab=20.                 ! enlisted habitability area
     Aoff=30.*(NO-1)          ! officer habitability area
     Abm=Ahab*NE+Aoff+Aco        ! total berthing, sanitary and messing area
     Vst=.1*NT*9.*Ts+1.*Ts       ! stores volume
     Acont=150.               ! ship control required arrangeable area
     Asf=250.+1.7*NT          ! other ship functions arrangeable area
     Aops=Ap4+Asf+A7+Acont       ! total ship operations arrangeable area

Vph=(Vtk+(1.+Aphmarg)*1.1*(Abm+Aops)*HDK+Vst+Vbattery+Vmb+.95*1.5*NT*HDK)/.95
! pressure hull volume
     Vaux=.05*Vph+1.5*NT*HDK     ! auxiliary space volume
     Atr=(1.+Aphmarg)*(1.1*(Abm+Aops)+(Vaux+Vmb)/HDK) ! total required
arrangeable area
     Ata=B*(Lmid+Laft/5.)*int((D-6.)/HDK)          ! total available
arrangeable area
     Vob=VPob+V2ob+.33*Vph                      ! total outboard displaced
volume
     Veb=Vph+Vob              ! everbuoyant volume
     Vmbt=.2*Veb              ! main ballast tank volume
     Vsub=Veb+Vmbt               ! submerged displaced volume
     Vff=Venv-Vsub               ! freeflood volume
     Vffmax=.1*Venv           ! maximum freeflood volume
     Vffmin=.05*Venv          ! minimum freeflood volume (unusable space)
! Output
     open(5,file='SSSpace.out',status='old')
     write(5,*) Vph,Vob,Veb,Vmbt,Vsub,Vff,Vffmin,Vffmax,Vaux,Atr,Ata
     close(5)
      stop
     end
```

Program SSTankage

```
! Version 0.0; 7/24/04; AJB
! Calculates tankage requirements
     real KW24avg
! Input from MC in SI units, kW, MT, knt, kg/kW*hr
      open(4,file='SSTankage.in',status='old')
     read(4,*) V2ib,Cmanning,Pmain,Venv,NO,NESP,Woxidant
     close(4)
!
!  V2ib = miscelaneous propulsion inboard volume
!  Cmanning = manning and automation factor
!  Pmain = total primary power
!  Venv = envelope volume
!  NO = number of officers
!  NESP = number of enlisted specialists, mission or SPW
```

```
!  Woxidant = oxidant weight
!
     dLO=39.      ! specific volume lube oil
     dW=36.    ! specific volume fresh water
     dF=43.    ! specific volume diesel fuel
     dsw=35.      ! specific volume salt water
!
!    Manning
     NE=INT(CManning*(Pmain/150.+Venv/50000.))+1+NESP ! enlisted manning
     NT=NO+NE                                ! total crew manning
!
     WF46=1.0                                ! lube oil weight
     WF52=NT*.15                             ! fresh water weight
     Vlo=1.02*1.05*WF46*dLO                     ! lube oil tank volume
     Vw=1.02*WF52*dW                         ! fresh water tank volume
     Vsew=NT*2.005                              ! sewage tank volume
     Wsew=Vsew/dsw                              ! sewage weight
     Vbal=1.02*dsw*(Woxidant+WF46+WF52)            ! variable ballast tank
volume
     Vtk=V2ib+Vlo+Vw+Vsew+Vbal                     ! total tank volume, exc
mbt
! Output
     open(5,file='SSTankage.out',status='old')
     write(5,*) Vtk,NE,NT,WF46,WF52,Wsew
     close(5)
      stop
     end


      Program SSWeight
! Version 0.0; 11/24/04; AJB
! This subroutine calculates single digit and full load weight and vcgs
      real LOA,KWg,KGmarg,KG,KB,KWmflm,KM
     integer Ts
! Input
      open(4,file='SSWeight.in',status='old')
     read(4,*)
Depth,Ndegaus,Wbattery,Wbm,WMF,Veb,Piprp,KWmflm,LOA,D,B,Vph,Wp100,&

Wp400,Wp500,W7,W2reactks,Wvp,WF46,WF52,Wfuel,Woxidant,Wsew,Wargon,&
            NT,NO,NE,Ts,HDK,VCGvp
     close(4)
!
!  Depth = operating depth
!  Ndegaus = degaussing (0=no,1=yes)
!  Wbattery = total battery weight
!  Wbm = total basic propulsion machinery weight
!  WMF = weight margin factor
!  Veb = ever buoyant volume
!  Piprp = total sprint propulsion power available
!  KWmflm = maximum functional load with margins
!  LOA = overall length
!  D = hull diameter or depth
!  B = beam
!  Vph = pressure hull volume
!  Wp100 = payload structures weight
!  Wp400 = payload command and control weight
!  Wp500 = payload auxiliaries weight
```

```
!  W7 = ordnance delivery systems weight
!  W2reactks = total propulsion tanks weight
!  Wvp = variable payload weight
!  WF46 = lube oil weight
!  WF52 = fresh water weight
!  Wfuel = fuel weight
!  Woxidant = oxidant weight
!  Wsew = sewage weight
!  Wargon = argon weight
!  NT = total crew
!  NO = number of officers
!  NE = number of enlisted
!  Ts = stores and provisions duration
!  HDK = average deck height
!  VCGvp = variable payload VCG
!
     PI=3.14159
     Wnsc=Veb/35.                   ! normal surface condition weight
! 200
     W240=0.1448*Piprp**.64            ! propulsion power transmission weight
     W2=Wbm+W240+Wbattery+W2reactks    ! total propulsion (SWBS 200) weight
! 300
     Wdist=0.00036*KWmflm*LOA          ! electrical distribution weight
     Wlight=0.000557*Vph               ! lighting system weight
     Wdegaus=.0006*Vph*Ndegaus            ! degaussing system weight
     W3=Wdist+Wlight+Wdegaus           ! total electrical (SWBS 300) weight
! 400
     Wic=5.0e-5*Vph+3.5             ! interior communication system weight
     Wco=.0002*Vph                     ! ship control weight
     Wcc=0.15*(Wp400+Wic+Wco)          ! command and control weight
     W4=Wp400+Wic+Wco+Wcc              ! total CC (SWBS 400) weight
! 500
     W593=2.0   !Environmental
     W598=6.e-5*Vph                 ! auxiliary fluids weight

Waux=(0.1*Vph**1.443+.04*Depth*Vph+20.*Vph**0.7224+377.*NT+26.15*Piprp)*1e-4
! auxiliary machinery weight
     W5=Waux+Wp500+W593+W598           ! total auxiliaries (SWBS 500) weight
! 600
     Wofh=.002*Vph                     ! hull outfit weight
     Wofp=0.8*(NT-9.5)                 ! personnel outfit weight
     W6=Wofh+Wofp                   ! total outfit (SWBS 600) weight
! 100
     Wbh=.9*(.0017*Vph*Depth/35.+.015*Wnsc)*(1.+.5*sin(B/D/2.1*PI)**2)
   ! bare hull weight
     W180=0.0735*(W2+W3+W4+W5+W6+W7)      ! foundations weight
     W1=Wbh+W180+Wp100                 ! total structures (SWBS 100) weight
!
     WF31=NT*2.45e-3*Ts             ! personnel provisions and stores weight
     WF32=0.00071*Ts*NT+0.0049*NT         ! general stores weight
     WF10=(236.*NE+250.*NO)/2240.0        ! personnel weight
     Wtrimbal=.02*Wnsc                 ! trim ballast weight
     Wresidual=.003*Wnsc               ! residual ballast weight

W9=Wvp+WF46+WF52+WF31+WF32+WF10+Wfuel+Woxidant+Wargon+Wsew+Wtrimbal+Wresidual
! variable weight
     W8=Wnsc-(W1+W2+W3+W4+W5+W6+W7+W9)    ! lead weight
     Wa1=W1+W2+W3+W4+W5+W6+W7          ! Condition A1 weight
```

```
     Wa=Wa1+W8                      ! Condition A weight
     Wleadmarg=WMF*Wnsc             ! minimum margin lead
     Wleadstab=0.0*Wnsc             ! minimum stability lead (.04)
     Wleadmin=Wleadmarg+Wleadstab         ! total minimum lead
     Wleadmax=1.5*Wleadmin             ! maximum lead
!
     NDK=floor(D/HDK)
     Bilge=D-NDK*HDK
     VCG8=((W8-Wleadmarg)+Wleadmarg*D/2)/W8  ! lead VCG - stability 1 ft
above keel, margin at D/2
     VCGF46=.55*Bilge                     ! lube oil VCG
     PF46=WF46*VCGF46                     ! lube oil weight moment
     VCGF52=VCGF46                        ! fresh water VCG
     PF52=WF52*VCGF52                     ! fresh water weight moment
     VCGF31=.3*D                       ! personnel provisions and stores VCG
     PF31=WF31*VCGF31                     ! personnel provisions and stores
VCG
     VCGF32=VCGF31                        ! general stores VCG
     PF32=WF32*VCGF32                     ! general stores weight moment
     VCGF10=.513*D                        ! personnel VCG
     PF10=WF10*VCGF10                     ! personnel weight moment
     VCGfuel=.55*Bilge                    ! fuel VCG
     Pfuel=Wfuel*VCGfuel                  ! fuel weight moment
     VCGoxidant=.424*D                    ! oxidant VCG
     Poxidant=Woxidant*VCGoxidant            ! oxidant weight moment
     VCGsew=.55*Bilge                     ! sewage VCG
     Psew=Wsew*VCGsew                     ! sewage weight moment
     Pvp=Wvp*VCGvp                        ! variable payload weight moment
     P9=PF46+PF52+PF31+PF32+PF10+Pfuel+Poxidant+Psew+Pvp ! total variable
loads weight moment
     VCG9=P9/W9                        ! variable laods VCG
     VCG1=.4*D                         ! structures VCG
     P2=(Bilge+.55*HDK)*(W2-Wbattery)+.55*Bilge*Wbattery ! propulsion VCG
moment
     VCG3=Bilge+.45*(D-Bilge)             ! electrical VCG
     VCG4=.513*D                       ! C&C VCG
     VCG5=.51*D                        ! auxiliaries VCG
     VCG6=.46*D                        ! outfit VCG
     VCG7=.7*D                         ! ordnance delivery system VCG

KG=(W1*VCG1+P2+W3*VCG3+W4*VCG4+W5*VCG5+W6*VCG6+W7*VCG7+W8*VCG8+W9*VCG9)/Wnsc
! KG
     BM=.25*LOA*B**3/(12.*Vph)               ! BM
     KB=D/2.                           ! height of center of buoyancy above
keel
     GB=KB-KG                          ! GB submerged
     KM=KB+BM                          ! KM surfaced
     GM=KM-KG                          ! GM surface
!
     open(5,file='SSWeight.out',status='old')
     write(5,*) Wleadmax,Wleadmin,GB,GM,W1,W2,W3,W4,W5,W6,W8,W9,Wnsc
     close(5)
!
      stop
     end
```