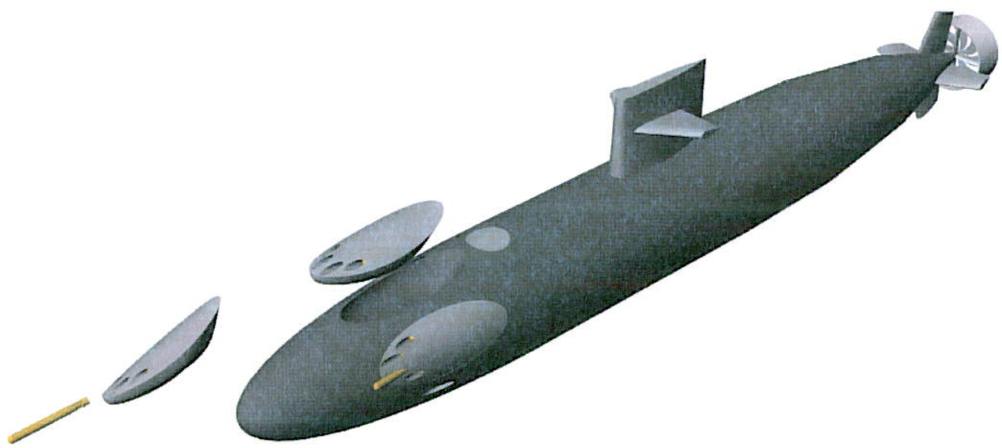
Virginia Tech
Aerospace & Ocean Engineering

Design Report

Large Ocean Interface Submarine

SSLOI

VT Total Ship Systems Engineering



SSLOI
Ocean Engineering Design Project
AOE 4065/4066
Fall 2006 – Spring 2007
Virginia Tech Team 6

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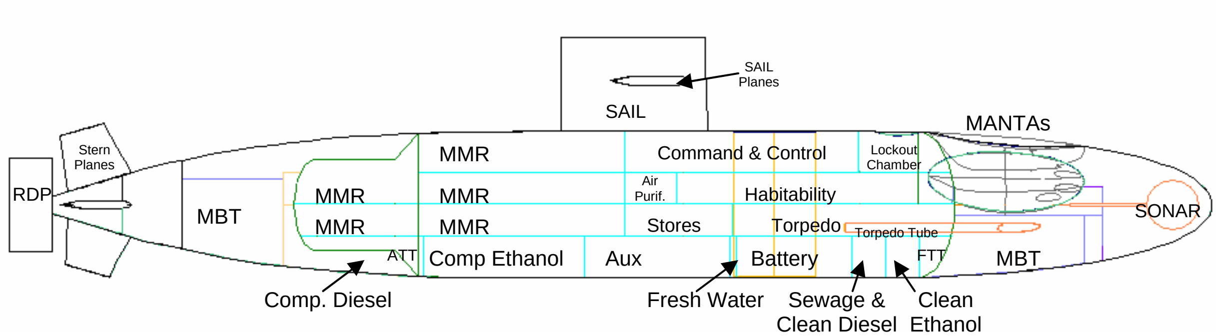
Executive Summary



This report describes the Concept Exploration and Development of a non-nuclear, Large Open Interface Submarine (SSLOI) for the United States Navy. This concept design was completed in a two-semester ship design course at Virginia Tech.

The SSLOI requirement is based on the need for persistent surveillance and reconnaissance in shallow-water regions without jeopardizing valuable nuclear assets. The shift in emphasis from global Super Power conflict to numerous regional conflicts requires increased flexibility to counter a variety of threat scenarios which may rapidly develop. Primary mission requirements for the SSLOI therefore include the time-sensitive, covert launch of mission configured UUV(s), MANTA(s) in this project, mine countermeasures, ISR, and transport of special operations Navy SEAL teams to support the Joint Force battle force from the sea.

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

SSLOI is a high effectiveness, moderate risk, and moderate cost alternative selected from the non-dominated frontier. This design was chosen to provide a challenging, barrier-pushing project in which modern, innovative technologies such as PEM fuel cells for air-independent propulsion, Rim-Driven Propulsor (RDP), and MANTA(s) were utilized. SSLOI has two torpedo tubes with 8 reloads and 3 MANTAs, each capable of carrying 4 torpedoes. SSLOI has many other attractive qualities including high maneuverability, an axis-symmetric hullform for producibility, and a sonar system capable of both active and passive sonar for ASW missions. The basic characteristics of SSLOI are listed in the table below. The final concept design satisfies key performance requirements in the CDD within cost and risk constraints.

Ship Characteristic	Value
LOA	257.6 ft
Beam	32 ft
Diameter	32 ft
Submerged Displacement	4160 lton
Submerged Displaced Volume	145500 ft^3
Sprint Speed	21 knt
Snorkel Range - 12 knt	5718 nm
AIP Endurance - 5 knt	28 days
Sprint Endurance	1.1 hours
Propulsion and Power	Open Cycle Diesel/AIP, 2xCAT 3512 V12 + 2x500kW PEM; 6000kW-hr lead acid batteries, 1x19.6ft RDP
Weapon Systems	Reconfigurable torpedo room, 2x21" tubes, 8 reloads; 3 MANTA UUVs
Sensors	EDO Model 1122 Passive Bow Array, EDO Model 1121 Flank Array, high frequency sail and chin-array (mine and obstacle avoidance), Photonics Mast, Type 8 Mod 3, Type 18 Mod 3; BSY-2/CCSM
P_{req} for Sprint Speed	3930 kW
P_{req} for Snorkel	800 kW
Battery Capacity	6000 kW-hr
Diving Depth	1000 ft
Total Officers	8
Total Enlisted	44
Total Manning	52
Basic Cost of Construction	$919M

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1 Introduction, Design Process and Plan

1.1 Introduction

This report describes the concept exploration and development of a Large Ocean Interface Submarine (SSLOI) for the United States Navy. The SSLOI requirement is based on the SSLOI Initial Capabilities Document (ICD) and the Virginia Tech SSLOI Acquisition Decision Memorandum (ADM). The design was completed in a two semester ship design course in the Aerospace and Ocean Engineering Department at Virginia Tech.

The overarching capability gap addressed by the SSLOI ICD is: To provide a conventional launch and recovery submarine of adequate size and flexibility with a large payload aperture. This capability will allow the submarine to be configured for specific missions including mine countermeasures, ISR and special operations, supporting vehicles of larger size than can be accommodated by 21 inch torpedo tubes. This capability must be provided while maintaining core inherent capabilities of stealth, anti-submarine warfare, anti-surface warfare and mobility.

SSLOI must support the following Joint Force functional areas:

- Assure access for the Joint Force from the Sea
- Provide self defense, project defense around friends and joint forces
- Provide persistent Intelligence, Surveillance, and Reconnaissance (ISR)

The US military has identified six critical operational goals in the Quadrennial Defense Review. The SSLOI must support four of these goals.

- Protect critical bases of operations
- Protect and sustain US forces while defeating denial threats
- Deny enemy sanctuary by persistence surveillance
- Track and rapid engagement

The "Naval Transformational Roadmap" and "Sea Power 21" provide the US Navy's plan to support these goals in the areas of Sea Strike, Sea Shield, and Sea Base. These concepts are explained further in Section 2.1. The design of the SSLOI must be cost effective with a lead-ship Basic Cost of Construction (BCC) less than $1B. It is expected that 5 ships of this type will be built with IOC in 2015. SSLOI must minimize personnel vulnerability in combat through automation, innovative concepts for minimum crew size, and signature reduction.

1.2 Design Philosophy, Process, and Plan

Traditionally the submarine design process is based on experience and rules of thumb. The process followed at Virginia Tech utilizes a Multi-Objective Genetic Optimization (MOGO). The MOGO uses a genetic algorithm to search the design space for optimal, feasible designs by considering three objective attributes: risk, effectiveness, and cost. Each submarine is designed to maximize effectiveness and minimize cost and risk. This method allows a total systems approach to be integrated into the design process. This design project includes concept and requirements exploration in the fall semester and concept development and in the spring semester; this is illustrated in Figure 1.

The process used for concept and requirements exploration is presented in Figure 2. This leads to a baseline design from which a preliminary Capability Development Document (CDD) is developed. The CCD specifies key performance requirements, design constraints, concepts to be explored and serves as the primary requirements document for concept development. Based on the ICD and ADM, a Concept of Operations (CONOPs), Projected Operational Environment (POE), mission scenarios, and Required Operational Capabilities (ROCs) are defined for the SSLOI missions. The ROCs may require new technologies in the areas of hull form, power and propulsion, combat systems and automation. With the design space defined by the available technologies, metrics for risk, cost, and effectiveness were developed to be compared in a non-dominated frontier. A synthesis model is created and used to perform the MOGO. The optimization results are used to create a non-dominated frontier and a baseline design is chosen.

The design spiral is used in concept development as presented in Figure 3. After each completion of the spiral the quality of the design is improved by reducing the overall risk of the design within cost constraints and satisfying key performance requirements. Balance and feasibility are demonstrated.

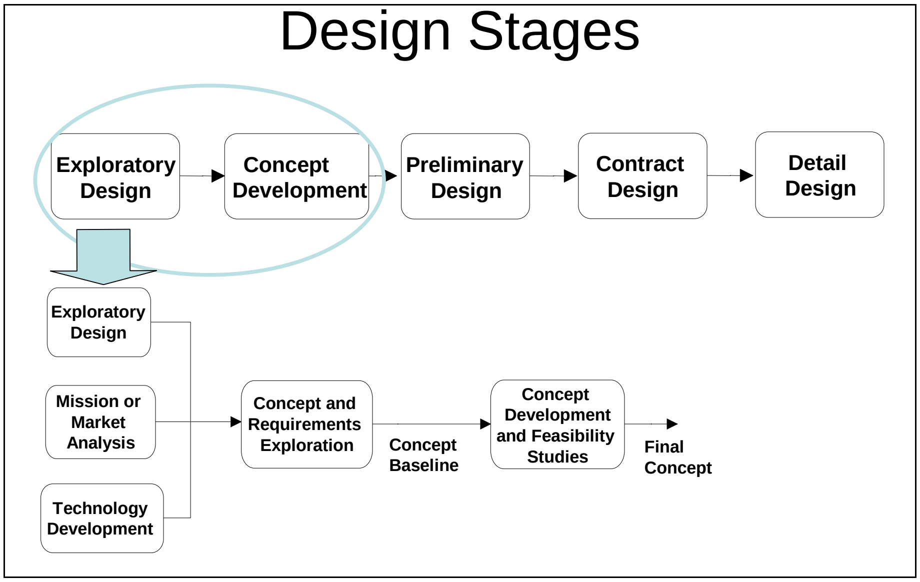


Figure 1: Design Process

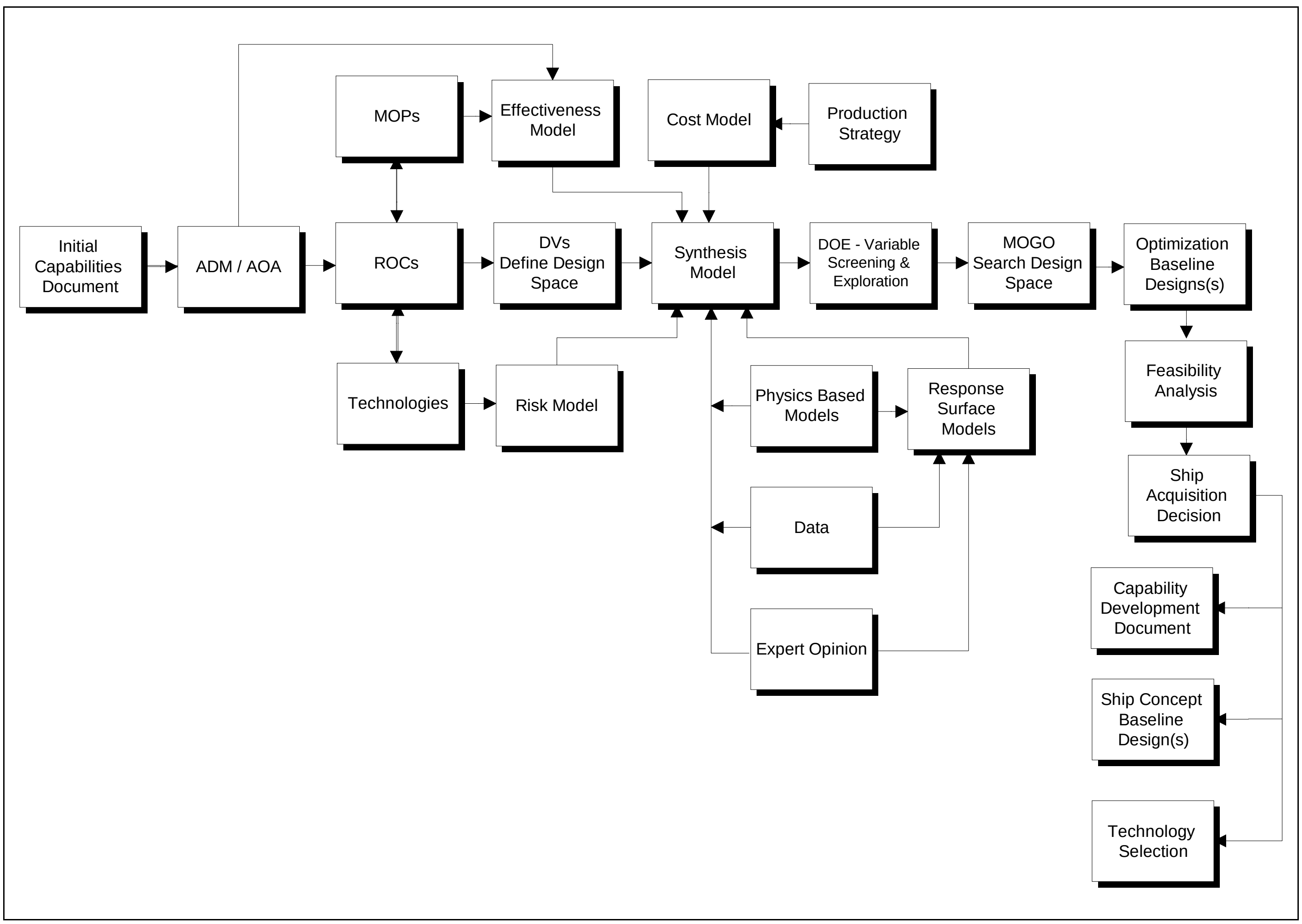


Figure 2: Concept and Requirements Exploration

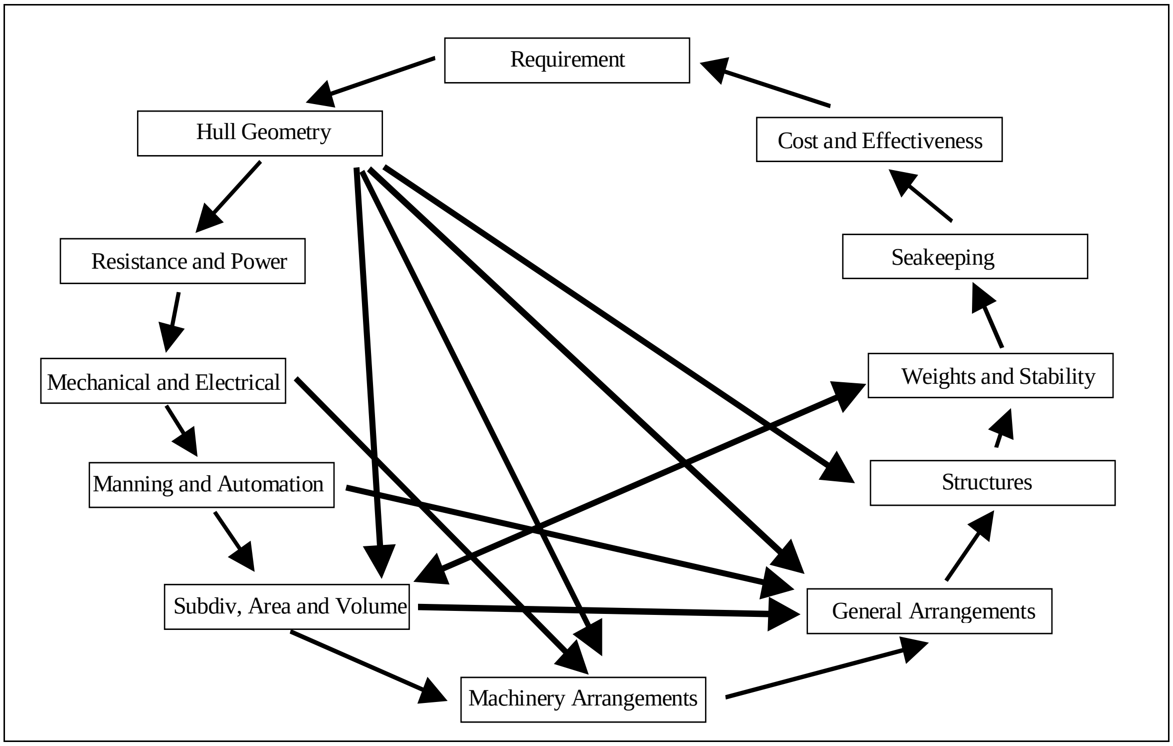


Figure 3: VT Concept Development Design Spiral.

1.3 Work Breakdown

SSLOI Team 6 consists of six students from Virginia Tech. Each student is assigned areas of work according to his or her interests and special skills as listed in Table 1.

Table 1 - Work Breakdown

Name	Specialization
Andrea Maines	Hullform Arrangements
Matthew Martz	Propulsion / Maneuvering
J. Spencer Ovren	Structures
Michael Palmer	Balance and Weights
Amy Sloan	Structures & Cost/Producibility
W. Rob Story	Arrangements/Modeling

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
Hull form Development	Rhino
Hydrostatics and Balance	Rhino/Rhino Marine, Excel
Resistance/Power	MathCad / MATLAB
Dynamics and Control	VT Sub Stab
Ship Synthesis Model	MathCad/Model Center/Fortran
Structure Model	MAESTRO

The analysis also uses rough estimates and calculations to check the reasonableness of the software results.

2 Mission Definition

The SSLOI requirement is based on the SSLOI Initial Capabilities Document (ICD) and Virginia Tech SSLOI Acquisition Decision Memorandum (ADM), Appendices A and 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. Table 3 lists ICD capability gaps, goals and thresholds.

Table 3: Capability Gap Thresholds and Goals

Priority	Capability Description	Threshold Systems or metric	Goal systems or metric
1	Large ocean interface aperture, stowage volume and interfaces for advanced unmanned/remotely controlled tactical and C_4/I reconnaissance vehicles	25ftx12ft aperture, volume (Lxwxh)=25ftx12ft x8ft, 150kW	30ftx15ft aperture, volume Lxwxh)=30ftx15ft x10ft, 200kW
2	ISR	688I	Virginia
3	Mobility	Depth=500ft, Sprint speed=15knt, snorkel range=5000nm@12knt, AIP @5knt=20days	Depth=1000ft, Sprint speed=22knt, snorkel range=6000nm@12knt, AIP @5knt=30days
4	ASW, ASUW	SUBTICS (Thales): Passive Cylindrical bow array, PVDF planar flank arrays, sail and chinarrays, torpedoes: 6x21inch tubes, 24 reloads	BQQ-10 Bow Dome Passive/Active, LWWAA, BSY-2, sail and chin arrays, 12 external encapsulated torpedoes

2.1 Concept of Operations (CONOPS)

The range of military operations for SSLOI includes: force application from the sea; force application, protection and awareness at sea; and protection of homeland and critical bases from the sea. The timeframe considered is 2010-2050. This extended timeframe demands flexibility in upgrade and capability over time. The 2001 Quadrennial Defense Review identifies seven critical US military operational goals. These are: 1) protecting critical bases of operations; 2) assuring information systems; 3) protecting and sustaining US forces while defeating denial threats; 4) denying enemy sanctuary by persistent surveillance, 5) tracking and rapid engagement; 6) enhancing space systems; and 7) leveraging information technology.

SSLOI will be among the first military forces on-scene having "staying and convincing" power to promote peace and prevent crisis escalation. The force must have the ability to provide a "like-kind, increasing lethality" response to influence decisions of regional political powers. It must also have the ability to remain invulnerable to enemy attack. SSLOI must complement and support this force.

Power Projection requires the execution and support of flexible strike missions and support of naval amphibious operations. This includes protection to friendly forces from enemy attack, unit self defense against littoral threats, area defense, and mine countermeasures. SSLOI must be able to support, maintain and conduct operations with the most technologically advanced unmanned/remotely controlled tactical and C^4/I reconnaissance vehicles. SSLOI must possess sufficient mobility and endurance to perform all missions on extremely short notice, at locations far removed from home port. To accomplish this, SSLOI must be pre-deployed, virtually on station in sufficient numbers around the world.

2.2 Projected Operational Environment (POE) and Threat

The shift in emphasis from global Super Power conflict to numerous regional conflicts requires increased flexibility to counter a variety of threat scenarios which may rapidly develop. The United States experiences threats to national security interests from three main categories: threats from nations with either a significant military capability, or the demonstrated interest in acquiring such a capability, and threats from smaller nations who support, promote, and perpetrate activities which cause regional instabilities detrimental to international security. Specific weapons systems that could be encountered include: significant land-based air assets with the capability to hunt and sink submarines; surface ships with full ASW capabilities; AIP, diesel and possibly nuclear submarines; mines (surface, moored and bottom).

Since many potentially unstable nations are located on or near geographically constrained bodies of water, the tactical picture will be on smaller scales relative to open ocean warfare. Many encounters may occur in shallow water, which increases the difficulty of detecting and successfully prosecuting targets. SSLOI must be capable of operating in the following environments: dense contact and threats with complicated targeting, noisy and reverberation-limited areas, crowded shipping areas, open ocean (sea states 0 through 9) and littoral regions, and all-weather scenarios.

2.3 SSLOI Operations and Missions

SSLOI missions include the following:

- Intelligence, Surveillance, and Reconnaissance
- Mine countermeasures
- Transport of special operations SEAL teams
- Time-sensitive, covert launch of mission configured MANTA(s)

2.4 Mission Scenarios

Mission scenarios for the primary SSLOI missions are provided in Table 4, Table 5, and Table 6.

Table 4: Special Warfare (SPW) Mission

Day	Task
1-15	Depart from CONUS on snorkel to area of hostilities
15-16	Proceed independently to within 10 nm of enemy mainland
16	Launch Special Ops Team and MANTA (with equipment) from MANTA Bay
20	Recover Special Ops Team and MANTA (with equipment)
21	Refuel MANTA
16-29	Avoid enemy ASW detection
16-29	Avoid / neutralize enemy submarine attack
21-29	Continue Launch and Recovery of Special Ops Team and Manta (with equipment)
30	Return to sea base for rearming and refueling

Table 5: Intelligence, Surveillance, and Reconnaissance (ISR)

Day	Task
1-15	Depart from CONUS on snorkel to area of hostilities
15-16	Proceed independently to within 10 nm of enemy mainland
16-29	Conduct mine counter warfare. Launch MCM-equipped MANTA(s) that will detect and neutralize mine threat
16-29	Avoid / neutralize enemy submarine attack
16-29	Avoid enemy ASW detection
30	Return to sea base for rearming and refueling

Table 6: Mine Countermeasures (MCM)

Day	Task
1-15	Depart from CONUS on snorkel to area of hostilities
15-16	Proceed independently to within 10 nm of enemy mainland
16-18	Launch ISR-equipped MANTA(s) to gather intelligence.
16-29	Avoid / neutralize enemy submarine attack
16-29	Avoid enemy ASW detection
18-19	Recover / Refuel MANTA(s)
19-30	Continue launching of ISR-equipped MANTA(s) to gather intelligence. Refuel MANTA(s) when necessary.
30	Return to sea base for rearming and refueling

2.5 Required Operational Capabilities (ROCs)

In order to support the missions and mission scenarios described in Section 2.4, the capabilities listed in Table 7 are required. Each of these can be related to functional capabilities required in the submarine design, and, if within the scope of the Concept Exploration design space, the SSLOI's ability to perform these functional capabilities is measured by explicit Measures of Performance (MOPs). SSLOI will have focused mission capabilities of UUV, C4I/ISR, ASW, ASUW, and MCM.

Table 7: Required Operational Capabilites (ROCs)

ROCs		ROCs	
ASUW 1	Engage surface threats with anti-surface armaments	INT 15	evacuation operation (NEO)
ASUW 1.1	Engage surface ships at long range	LOG 1	Conduct underway replenishment
ASUW 1.2	Engage surface ships at medium range	LOG 2	Transfer/receive cargo and personnel
ASUW 2	Engage surface ships in cooperation with other forces	MCM 3	Conduct mine neutralization/destruction
ASUW 4	Detect and track a surface target	MCM 3.1	neutralization/destruction
ASUW 6	Disengage, evade and avoid surface attack	MCM 4	Conduct mine avoidance
ASW 1	Engage submarines	MCM 6	Conduct magnetic silencing (degaussing, deperming)
ASW 1.2	Engage submarines at medium range	MCM 6.7	Maintain magnetic signature limits
ASW 1.3	Engage submarines at close range	MCM 7	Launch AUV mine detectors (MANTA)
ASW 2	Engage submarines in cooperation with other forces	MOB 1	Steam to design capacity in most fuel efficient manner
ASW 7	Attack submarines with antisubmarine armament	MOB 3	Prevent and control damage
ASW 7.6	Engage submarines with torpedoes	MOB 5	Maneuver in formation
ASW 8	Disengage, evade, avoid and deceive submarines	MOB 7*	anchor, mooring, scuttle, life boat/raft capacity, tow/be-towed)
C4I 2*	mission assignments	MOB 10	Replenish at sea
C4I 3	Provide own unit Command and Control	MOB 12	Maintain health and well being of crew
C4I 4	Maintain data link capability	MOB 13	an extended period of time during peace and war without shore-
C4I 6	Provide communications for own unit	MOB 16	Operate in day and night environments
C4I 9	Relay communications	MOB 17	Operate in heavy weather
C4I 21	Perform cooperative engagement	MOB 18	pollution control laws and regulations
FSO 3	Provide support services to other units	MOB 19	Operate submerged
FSO 5*	Conduct search/salvage rescue operations	MOB 19.1	Ability to charge batteries with snorkel
FSO 6	Conduct SAR operations	MOB 20	Operate littoral
FSO 7	Provide explosive ordnance disposal services	MOB 21	Operate covertly
FSO 8	Conduct port control functions	NCO 3	Provide upkeep and maintenance of own unit
FSO 9	Provide routine health care	NCO 19	Conduct maritime law enforcement operations
FSO 10	Provide first aid assistance	SEW 2	Conduct sensor and ECM operations
FSO 12	casualties/patients	SEW 3	Conduct sensor and ECCM operations
FSO 14	receipt of casualties and patients	SEW 5	Conduct coordinated SEW operations with other units
FSO 16	Provide routine and emergency dental care	UUV 1	ISR (Intelligence Survey and Reconnaissance)
INT 1	Support/conduct intelligence collection	UUV 2	Undersea Search and Survey
INT 2	Provide intelligence	UUV 3	MCM - Mine Counter Measures
INT 3	Conduct surveillance and reconnaissance	UUV 4	Communication Navigational Aids
INT 8	Process surveillance and reconnaissance information	UUV 5	ASW (Track and Trial)
INT 9	information		

3 Concept Exploration

Chapter 3 describes Concept Exploration. Trade-off studies, design space exploration and optimization are accomplished using a Multi-Objective Genetic Optimization (MOGO). The key to the success of this process is the preparation of alternatives, good data, necessary modifications to the ship synthesis model, and the development of rational and correct objective attributes.

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 submarine 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 submarine design. Technology and concept trade spaces and parameters are described in the following sections.

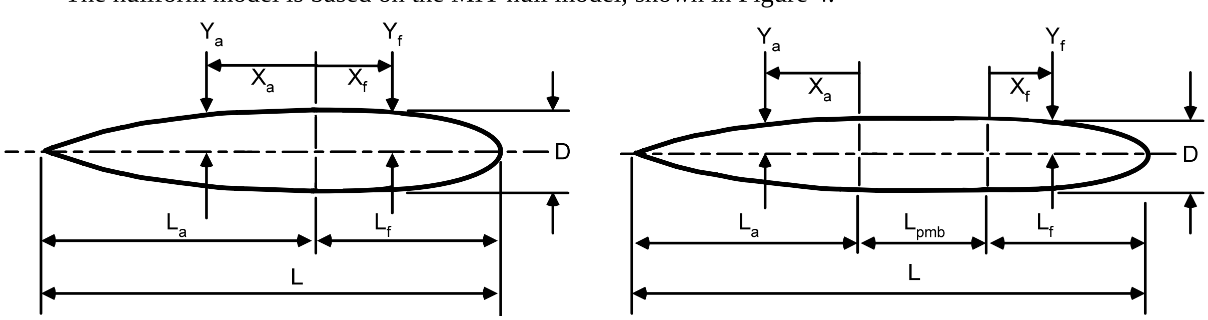
3.1.1 Hull-Form Alternatives

The technology selection process considered performance metrics, hull-form options, and modeling alternatives. Design lanes were used to specify hull-form design parameter ranges and initial hull-form point designs. Applicable alternatives were selected for consideration in Concept Exploration design space.

- High speed resistance (sprint/sustained speed)
- Low speed resistance (AIP/endurance)
- Snorkel Resistance
- Stability and maneuverability
- Teardrop shape
- Cost and producibility: axisymmetric shape lowers costs
- Volume for large object spaces (machinery spaces, mission spaces, MANTAs)
- Stack-up length including extra length for mission bay space
- Number of decks: 2 or 3 decks depending on internal arrangements
- Hull depth/axisymmetric diameter
- Structural efficiency (pressure hull)

Two major hullform alternatives were considered: an axisymmeteric teardrop hullform with parallel midbody and an elliptical non-symmetric hullform. The advantages of the axisymmetric hull are its producibility, low resistance, and structural efficiency; the elliptical submarine increased cost with larger arrangeable area and payload using a catamaran-style double-hull. The axisymmetric teardrop was chosen to be the better option given its superior producibility, efficiency, and lower technology risk.

The hullform model is based on the MIT hull model, shown in Figure 4.



$$L = L_a + L_f$$
$$\frac{L_a + L_f}{D} = 6$$
$$L_a = 0.6L = 3.6D$$
$$L_f = 0.4L = 2.4D$$

$$Y_f = b\left[1 - \left(\frac{X_f}{L_f}\right)^{n_f}\right]^{1/n_f}$$
$$Y_a = b\left[1 - \left(\frac{X_a}{L_a}\right)^{n_a}\right]$$

$$L = L_a + L_{pmb} + L_f$$
$$L_a = 3.6D$$
$$L_f = 2.4D$$

Figure 4: MIT hull model with teardrop shape; without parallel midbody (left), with parallel midbody (right)

The original designs for the cross-section of SSLOI are shown in Figure 5. The initial diameter was determined by incorporating a double hull with 7.0-8.0 foot platforms in configurations of 2 or 3 platform hulls. The largest possible cross-section is depicted on the left and the smallest possible diameter is depicted on the right. These two designs were set as parameters for the optimization. The other parameters for the hullform optimization are the length to diameter ratio of 8-12, the forward fullness exponent (n_{fopt}) of 2.0-2.5, and the aft fullness exponent (n_{aopt}) of 2.5-3.0. **This arrangement was modified in our later variants as will be discussed in Section 3.7.3 and 3.8.**

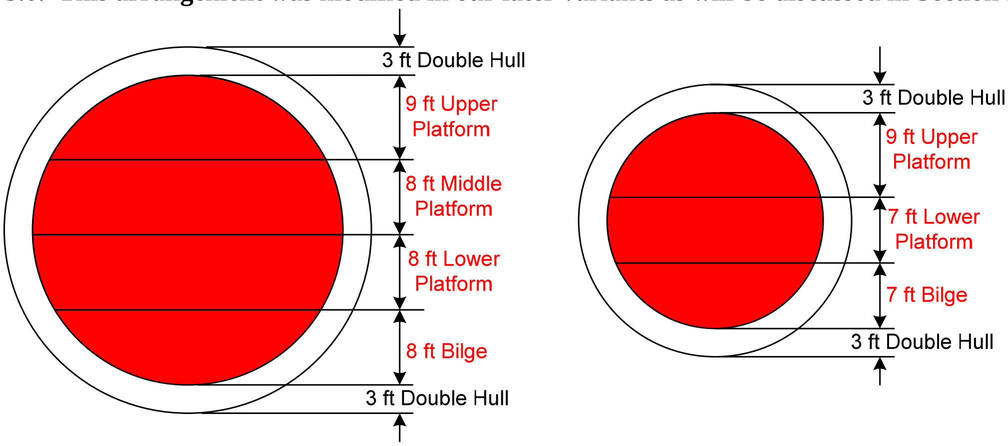


Figure 5: Initial Cross-Sectional Designs for 2-Deck and 3-Deck Designs

To create a preliminary hullform characteristics estimate, the median of the parameters for the 2-platform and 3-platform submarines are defined in the first four rows of Table 8. From these parameters and the MIT hullform equations, initial volume, weight, and powering characteristics were estimated for 2-platform and 3-platform submarines as shown in the last four rows of Table 8. The two submarine designs are also depicted in Figure 6 with diameters, forward length, parallel midbody length, aft length, and length overall.

Table 8: Initial Values for 2-Platform and 3-Platform Designs

		2-Platform	3-Platform
Defined Values	Diameter	30.5	37.5
	L/D	10	10
	n_{fopt}	2.25	2.25
	n_{aopt}	2.75	2.75
Calculated Values	Volume	177000ft^3	329000ft^3
	Weight	5058 LT	9401 LT
	Resistance	9.95LT	14.72LT
	BHP	1546kW	2287kW

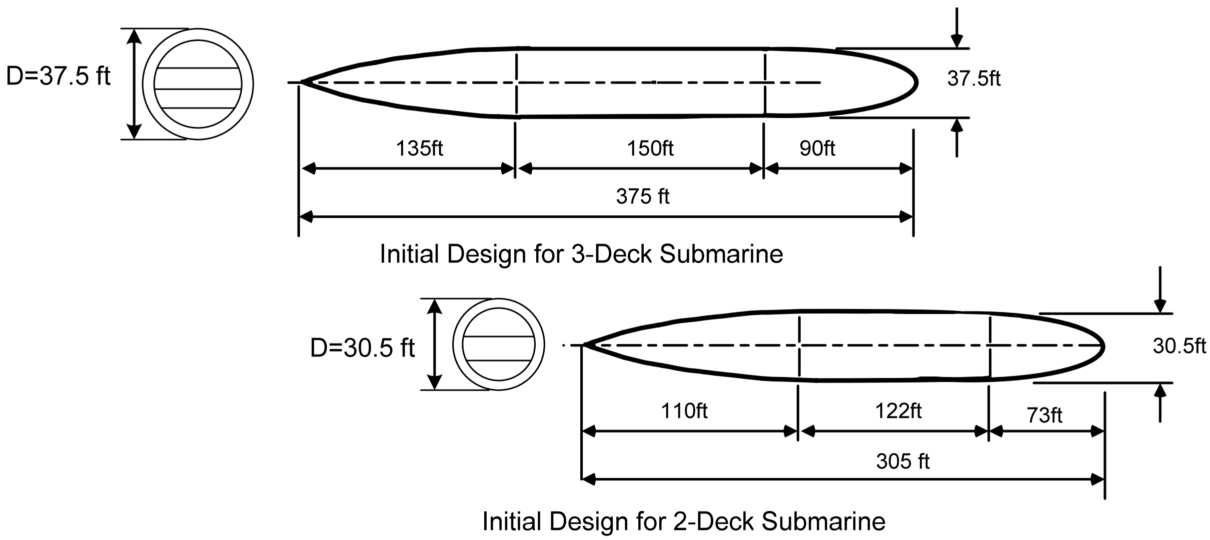


Figure 6: Initial Hullform Layouts for 2-Platform and 3-Platform Designs

3.1.2 Propulsion and Electrical Machinery Alternatives

3.1.2.1 Machinery Requirements

Based on the ICD, preliminary sizing (Section 3.1.1), and expert guidance, propulsion plant design requirements are as follows:

General Requirements:

Propulsion must be non-nuclear and SSLOI must be capable of traveling from base to area of conflict under its own power on snorkel. Once in area of conflict, SSLOI must be capable of stealthy littoral maneuvering. To achieve these goals, SSLOI must operate in two modes: AIP with sprint and snorkel.

Sustained Speed and Propulsion Power:

The sprint speed threshold is 15 knots with a goal of 22 knots. The snorkel range threshold at 12 knots is 3000 nm with a goal of 5000 nm (later increased to 5000-6500 nm based on design review). When functioning in AIP, the SSLOI must be capable of running at 5 knots for 20-30 days.

Submarine Control and Machinery Plant Automation:

To reduce cost, minimum cost-effective manning must be used, considering a high level of automation. Commercial off the Shelf (COTS) hardware will be considered where feasible. COTS will reduce cost, allow for greater producibility, and easier upgrades.

Propulsion Engine and Submarine Service Generator Certification:

Because of the nature of combat, SSLOI must carry Navy-qualified, Grade A shock-certified machinery. To reduce signatures a shrouded propeller and an Integrated Power System (IPS) should be considered.

3.1.2.2 Machinery Plant Alternatives

The development process for submarine propulsion alternatives began by developing general machinery requirements and selection guidelines (Section 3.1.2.1). Propulsion system trade-off alternatives were selected to be consistent with the General Machinery Requirements and Guidelines and the preliminary power estimates (Table 8). The final propulsion system alternatives selected for trade-off in SSLOI are listed in Table 9.

Table 9: Propulsion Systems Design Variable Alternatives

DV #	DV Name	Description	Design Space
7	PSYS	Propulsion system alternative	Option 1) CCD, 2xCAT 3512 V12 diesel engines
			Option 2) CCD, 2xCAT 3516 V16 diesel engines
			Option 3) CCD, 2xCAT 3608 IL8 diesel engines
			Option 4) OCD/AIP, 2xCAT 3512 V12 + 2x250KW PEM Fuel Cells
			Option 5) OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM Fuel Cells
			Option 6) OCD/AIP, 2xCAT 3516 V16 + 2x250KW PEM Fuel Cells
			Option 7) OCD/AIP, 2xCAT 3516 V16 + 2x500KW PEM Fuel Cells
			Option 8) OCD/AIP, 2x CAT 3608 IL8 + 2x250KW PEM Fuel Cells
			Option 9) OCD/AIP, 2x CAT 3608 IL8 + 2x500KW PEM Fuel Cells
			Option 10) OCD/AIP, 2xCAT 3512 V12 + 2x250KW PEM+reformers
			Option 11) OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM+reformers
			Option 12) OCD/AIP, 2xCAT 3516 V16 + 2x250KW PEM+reformers
			Option 13) OCD/AIP, 2xCAT 3516 V16 + 2x500KW PEM+reformers
			Option 14) OCD/AIP, 2x CAT 3608 IL8 + 2x250KW PEM+reformers
			Option 15) OCD/AIP, 2x CAT 3608 IL8 + 2x500KW PEM+reformers
8	PROPtype	Propulsor Type	Option 1) RDP, Rim Driven Prop
			Option 2) Shrouded
9	BATtype	Battery system type alternative	Option 1) Nickel Cadmium
			Option 2) Lead Acid
			Option 3) Zebra
10	Ebat	Battery Capacity	2500-7000 kwhr

Various technologies were considered in initial propulsion concept development. Sterling engines, Rankine cycle systems, hydrogen storage, reformers and oxygen storage, closed cycle diesels, fuel cells, batteries, and propulsors were all assessed to determine their advantages and disadvantages.

Sterling engines burn diesel fuel and are water cooled. They have been proven in the Swedish Gotland class submarines and have proved to have low vibration, quiet operation, and low infrared signature. The drawbacks of this system are that the machinery is complicated and heavy. Figure 7 and Figure 8 diagram a typical Sterling engine and the external systems connected to the engine.

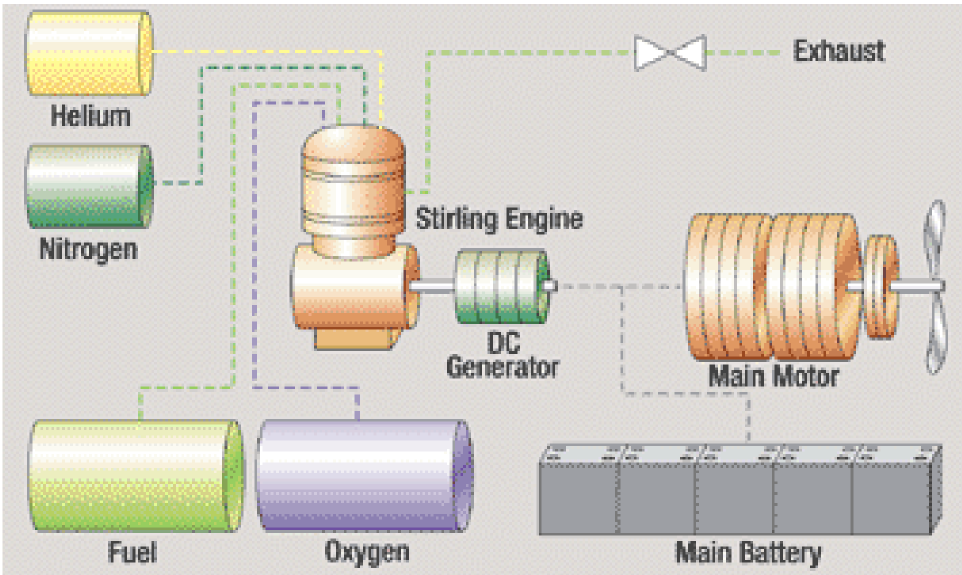


Figure 7: Propulsion system schematic using Sterling engine

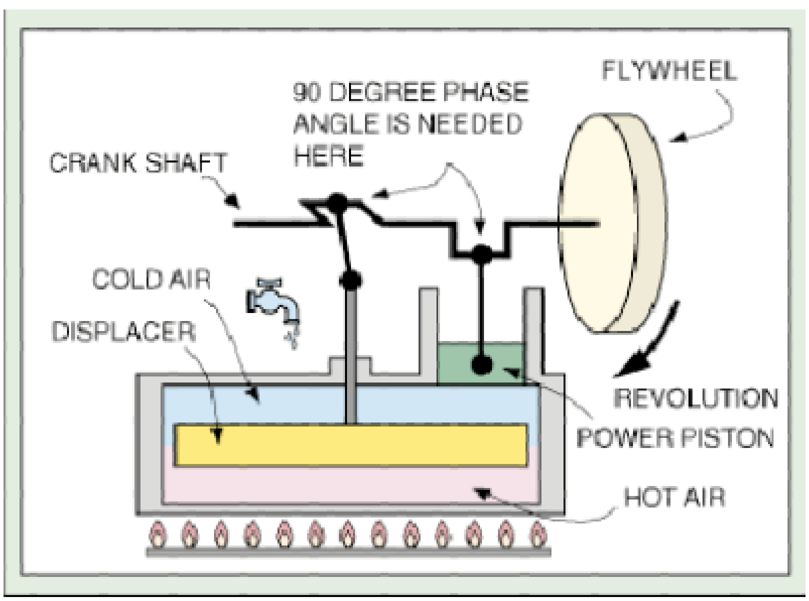


Figure 8: Schematic of Sterling engine

The MESMA (Module d’Energie Sous-Marine Autonome) is a Rankine cycle system, which is a closed cycle steam process. It is an anaerobic system where steam is created by combusting ethanol and oxygen. This technology has rather low efficiency, generates considerable heat, and consumes high levels of oxygen.

Closed cycle diesel systems allow for snorkel and AIP operation (air is used while snorkeling). Closed cycle oxygen is added from a cryogenic liquid oxygen system. The engine exhausts to an absorber which extracts carbon dioxide and contaminants, and replenishes argon back into the system. The CO2 absorber uses the Cosworth system. As shown in Figure 9, the system absorbs carbon dioxide into the seawater, which prevents the sub from leaving a carbon dioxide trail.

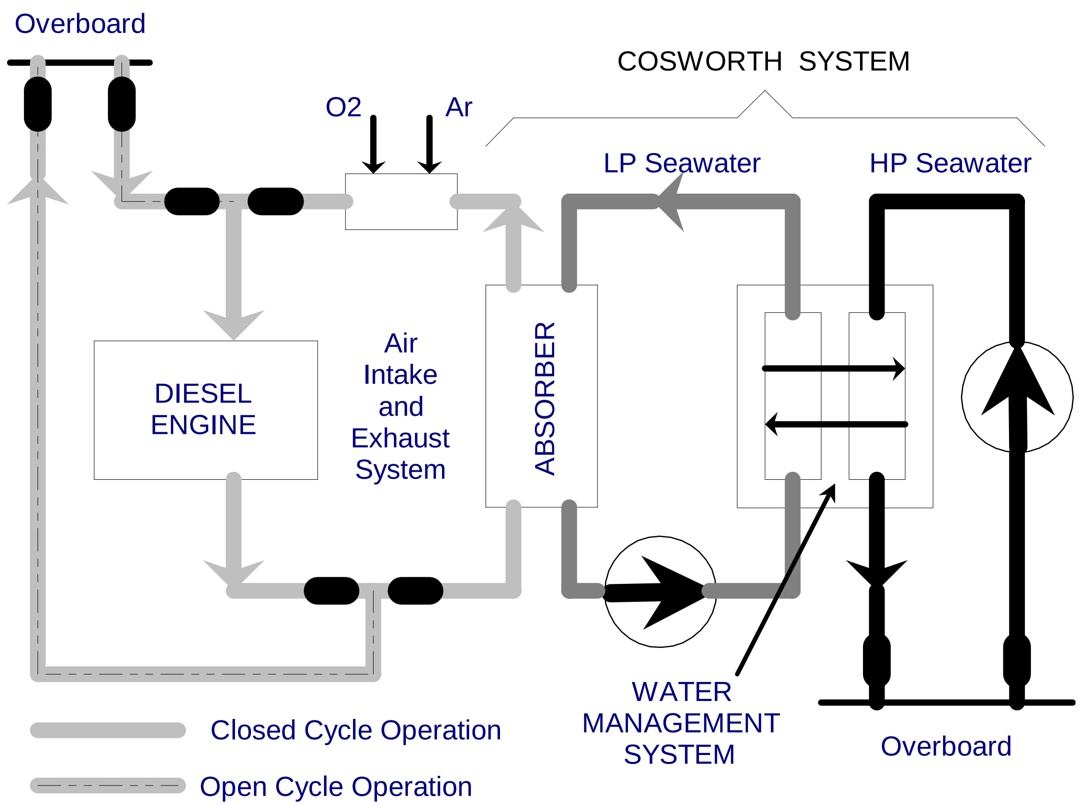


Figure 9: Schematic of Closed Cycle Diesel System

Closed cycle diesel engines offer advantages in risk, safety, cost, and power density. These engines have been in service for many years and therefore have low risk associated with their use and maintenance. Compared to other systems that run on hydrogen, these engines run on diesel fuel which is more stable and safer to store and transport than hydrogen. They have a good power density and are less expensive than other systems. They also have the capability to drive a DC or an AC generator, with the AC being more efficient than the DC. The disadvantages of these engines are that they are noisy and require a large machinery space.

Three types of Caterpillar diesel engines were considered for the propulsion options using a diesel engine, the Caterpillar 3512, Caterpillar 3516, and the Caterpillar 3608. Information on the Caterpillar diesel engines was collected from the company's information brochures and is shown in Table 10

Table 10: Caterpillar Diesel Engine Information

	Caterpillar 3512	Caterpillar 3516	Caterpillar 3608
Configuration	Vee 12 Cylinder	Vee 16 Cylinder	In-line 8 Cylinder
Cycle	4 - Stroke - Cycle	4 - Stroke - Cycle	4 - Stroke - Cycle
LxWxH (mm)	2715 mm x 1703 mm x 2053 mm	3690 mm x 1703 mm x 2053 mm	5561 mm x 1722 mm x 104 mm
LxWxH (in)	107 in x 67.1 in x 80.8 in	145.3 in x 67.1 in x 80.8 in	219 in x 68 in x 87.8 in
Weight - dry	6531 - 6537 kg (14,398 - 14,411 lb)	8028 kg (17,699 lb)	8112 kg (17,885 lb)
Maximum Continuous Rating	1500 bhp @ 1800 rpm	2000 bhp @ 1800 rpm	3634 bhp @ 1000 rpm

After consideration of these technologies, diesel engines were determined to be the best option for SSLOI. 15 options of open cycle diesels (OCDs) combined with fuel cells (Section 3.1.2.2.1) and closed cycle diesels (CCDs) were chosen for trade-off as design variable options as listed in Table 9. These options and their characteristics are described in Table 12 and Table 13.

Table 11: Acronyms for Propulsion System Spreadsheets

Acronym	Description
Kwsnork	Kilo-watt power snorkel (kw)
Kwaip	Kilo-watt power AIP (kw)
VH2C	Volume Hydrogen Consumption (1/kw*hr)
VH2S	Volume Hydrogen Stowage (1/kw*hr)
VO2C	Volume Oxygen Consumption (1/kw*hr)
VO2S	Volume Oxygen Stowage (1/kw*hr)
VArC	Volume Argon Consumption (1/kw*hr)
VarS	Volume Argon Stowage (1/kw*hr)
VBMaip	Volume Machinery Box AIP (1/kw)
VBMdg	Volume Machinery Box Diesel (1/kw*hr)
MH2C	Mass Hydrogen Consumption
MH2S	Mass Hydrogen Stowage
MO2C	Mass Oxygen Consumption
MO2S	Mass Oxygen Stowage
MArC	Mass Argon Consuption
MarS	Mass Argon Stowage
MBMaip	Machinery Box Mass AIP (kg/kw)
MBMdg	Machinery Box Mass Diesel (kg/kw)
SFC	Specific Fuel Consuption

Table 12: Propulsion System Spreadsheet

Description	Propulsion Option (PSYS)	AIP Type (AIPtype) (1=CCD, 2=fuel cell)	Kwsnork (kw)	Kwaip (kw)	VH2C (l/kwhr)	VH2S (l/kwhr)	VO2C (l/kwhr)	VO2S (l/kwhr)	VArC (l/kwhr)	VArS (l/kwhr)	VBMaip (l/kw)
2xCAT 3512 V12	1	1	1752	1752	0.000	0.000	0.735	0.130	0.021	0.037	89.000
2xCAT 3516 V16	2	1	2536	2536	0.000	0.000	0.735	0.130	0.021	0.037	89.000
2xCAT3608 1L8	3	1	5056	5056	0.000	0.000	0.735	0.130	0.021	0.037	89.000
2xCAT 3512 V12 w/ 2 AIP 250KW PEM	4	2	1752	500	0.634	0.250	0.390	0.058	0.000	0.000	64.000
2xCAT 3512 V12 w/ 2 AIP 500KW PEM	5	2	1752	1000	0.634	0.250	0.390	0.058	0.000	0.000	64.000
2xCAT 3516 V16 w/ 2 AIP 250KW PEM	6	2	2536	500	0.634	0.250	0.390	0.058	0.000	0.000	64.000
2xCAT 3516 V16 w/ 2 AIP 500KW PEM	7	2	2536	1000	0.634	0.250	0.390	0.058	0.000	0.000	64.000
2xCAT3608 1L8 w/ 2 AIP 250KW PEM	8	2	5056	500	0.634	0.250	0.390	0.058	0.000	0.000	64.000
2xCAT3608 1L8 w/ 2 AIP 500KW PEM	9	2	5056	1000	0.634	0.250	0.390	0.058	0.000	0.000	64.000
2xCAT 3512 V12 w/ 2 AIP 250KW PEM w/reformer	10	2	1752	500	0.519	0.222	0.539	0.081	0.000	0.000	115.000
2xCAT 3512 V12 w/ 2 AIP 500KW PEM w/reformer	11	2	1752	1000	0.519	0.222	0.539	0.081	0.000	0.000	115.000
2xCAT 3516 V16 w/ 2 AIP 250KW PEM	12	2	2536	500	0.519	0.222	0.539	0.081	0.000	0.000	115.000
2xCAT 3516 V16 w/ 2 AIP 500KW PEM	13	2	2536	1000	0.519	0.222	0.539	0.081	0.000	0.000	115.000
2xCAT3608 1L8 w/ 2 AIP 250KW PEM	14	2	5056	500	0.519	0.222	0.539	0.081	0.000	0.000	115.000
2xCAT3608 1L8 w/ 2 AIP 500KW PEM	15	2	5056	1000	0.519	0.222	0.539	0.081	0.000	0.000	115.000

Table 13: Continuation of Propulsion System Spreadsheet

Description	VBMdg (l/kw)	MH2C (kg/kwhr)	MH2S (kg/kwhr)	MO2C (kg/kwhr)	MO2S (kg/kwhr)	MArC (kg/kwhr)	MArS (kg/kwhr)	MBMaip (kg/kw)	MBMdg (kg/kw)	SFC (kg/kwhr)	Transmission efficiency eta
2xCAT 3512 V12	30.3	0	0	0.84	0.317	0.030	0.002	34	0	0.216	0.93
2xCAT 3516 V16	26.0	0	0	0.84	0.317	0.030	0.002	34	0	0.216	0.93
2xCAT3608 1L8	17.6	0	0	0.84	0.317	0.030	0.002	34	0	0.189	0.93
2xCAT 3512 V12 w/ 2 AIP 250KW PEM	30.3	3.490	0.874	0.44	0.165	0.000	0.000	19	30.99	0.216	0.96
2xCAT 3512 V12 w/ 2 AIP 500KW PEM	30.3	3.490	0.874	0.44	0.165	0.000	0.000	19	30.99	0.216	0.96
2xCAT 3516 V16 w/ 2 AIP 250KW PEM	26.0	3.490	0.874	0.44	0.165	0.000	0.000	19	22.98	0.216	0.96
2xCAT 3516 V16 w/ 2 AIP 500KW PEM	26.0	3.490	0.874	0.44	0.165	0.000	0.000	19	22.98	0.216	0.96
2xCAT3608 1L8 w/ 2 AIP 250KW PEM	17.6	3.490	0.874	0.44	0.165	0.000	0.000	19	17.78	0.189	0.96
2xCAT3608 1L8 w/ 2 AIP 500KW PEM	17.6	3.490	0.874	0.44	0.165	0.000	0.000	19	17.78	0.189	0.96
2xCAT 3512 V12 w/ 2 AIP 250KW PEM w/reformer	30.3	0.410	0.074	0.648	0.225	0.000	0.000	29	30.99	0.216	0.96
2xCAT 3512 V12 w/ 2 AIP 500KW PEM w/reformer	30.3	0.410	0.074	0.648	0.225	0.000	0.000	29	30.99	0.216	0.96
2xCAT 3516 V16 w/ 2 AIP 250KW PEM	26.0	0.410	0.074	0.648	0.225	0.000	0.000	29	22.98	0.216	0.96
2xCAT 3516 V16 w/ 2 AIP 500KW PEM	26.0	0.410	0.074	0.648	0.225	0.000	0.000	29	22.98	0.216	0.96
2xCAT3608 1L8 w/ 2 AIP 250KW PEM	17.6	0.410	0.074	0.648	0.225	0.000	0.000	29	17.78	0.189	0.96
2xCAT3608 1L8 w/ 2 AIP 500KW PEM	17.6	0.410	0.074	0.648	0.225	0.000	0.000	29	17.78	0.189	0.96

3.1.2.2.1 AIP Fuel Cells

For the air-independent propulsion system of the SSLOI, fuel cells were researched as an option. Fuel cells are classified primarily by electrolyte. The four major types are: Molten Carbonate (MCFC), Phosphoric Acid (PAFC), Polymer Electrolyte Membrane (PEMFC), and Solid Oxide (SOFC). The operating characteristics of these fuel cells are provided in Table 14.

Table 14: Fuel Cell data

	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)	2MW	1MW	250kW	220kW
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

Molten Carbonate (MCFC) fuel cells have a high efficiency (~85% with co-generation) and do not require an external reformer. They are also less expensive because the catalyst in the system can be a non-precious metal. However, MCFC fuel cells have shown to have a low cell life and poor durability, and the electrolyte used is corrosive. These fuel cells must also run at an extremely high temperature (~650°C), which can cause significant problems in submarine application.

Phosphoric Acid (PAFC) fuel cells also have a high efficiency (85%) when used with cogeneration, but they have many disadvantages. They are typically large and heavy and less powerful than other fuel cells given same weight and volume. PAFCs are expensive due to the necessity of a platinum catalyst and are considered a high risk technology because they are yet unproven.

Polymer Electrolyte Membrane (PEMFC) fuel cells are a proven, solid cell technology; they have less risk and are less corrosive than other types of fuel cells. They run quietly at a low temperature and produce only pure water with little heat rejection. Still, PEMFCs require pure reactants, one of which – hydrogen – is difficult to store or requires an external reformer to produce. Solid cells also can be poisoned by impurities which reduces output.

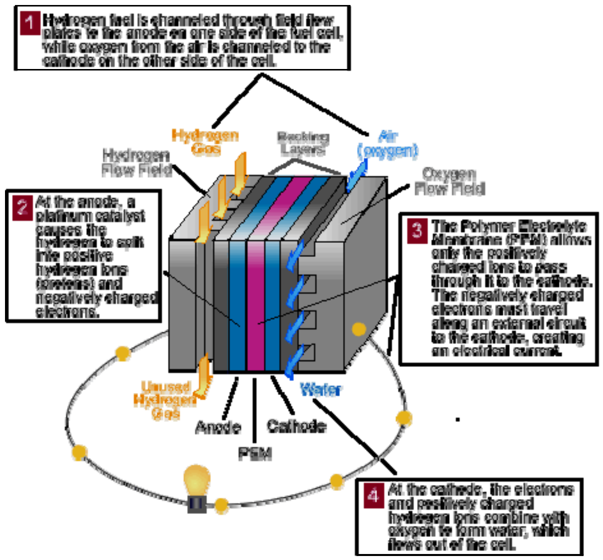


Figure 10: PEM Fuel Cell Schematic

Solid Oxide (SOFC) fuel cells use a hard, non-porous, ceramic compound as an electrolyte, which is very sulfur-resistant. The system is highly efficient with cogeneration (80-85%) and inexpensive because non-precious metals can be used for the catalyst. A disadvantage of the SOFCs is that they must run at very high temperatures (~1000°C), which requires a great deal of thermal shielding. They also have a slow start up time and can be vulnerable to shock damage. PEM fuel cells with reformers were selected for use in SSLOI as listed in Table 9.

3.1.2.2.2 Hydrogen and Oxygen Storage

A necessary requirement for many of these propulsion systems is hydrogen. There are four methods of storing or producing the hydrogen: as a gas, a liquid, a hydride, or as ethanol that can later be reformed to obtain the need hydrogen. Hydrogen stored as a gas has a low energy density, is heavy, and often limited to special operations. Hydrogen stored as a liquid has a higher energy density than diesel but has many storage requirements including being maintained at -253 degrees C. Iron titanium hydride can be stored in low-pressure tanks either inside or outside the pressure hull. This hydride is very stable and is a mature technology compared to other interstitial liquid storage methods. This is a very heavy and the hydride powder only provides 1-2% liquid hydrogen by weight.

The fourth method of extracting the hydrogen from ethanol is an established technology that allows for a safer and more convenient method of carrying hydrogen. The fuel processor reforms an ethanol and water vapor mix to produce a gaseous reformate. This is then fed to the membrane which allows only pure hydrogen to pass through, leaving a liquid. The hydrogen is passed to the anode of the fuel cell and the remaining liquid is fed to the burner of the reformer as fuel.

Oxygen must also be stored for the AIP systems. Oxygen storage is most efficient when it is in the form of a cryogenic liquid (LOX). Storing oxygen as a gas is not an efficient weight/volume relationship for submarine use. Large volumes and high pressures are required for gas storage. LOX is a well established technology that is safe and effective. The LOX can be stored inside or outside the pressure hull; however, when stored inside maintenance and pipe runs become easier.

3.1.2.2.3 Batteries

Batteries provide the primary source power for submerged sprint speed and back-up power. When no AIP propulsion exists, batteries must also provide power for endurance speed submerged. In each of these states batteries must supply power for propulsion and ship services loads including payload, command and control, and habitability. Batteries are charged by a generator run by a prime mover or by an AIP system. The stowage of batteries can be complex and may require watertight, redundant compartments which are rubber-lined and ventilated. Table 15 and Table 16 describe important battery characteristics. Lead acid, Nickel/Cadmium and Zebra batteries were selected for trade-off in SSLOI as listed in Table 9.

Table 15: Battery type comparison data

Classification	Lead-Acid	Alkaline	Alkaline	High Temp	Molton Salt
Battery Type	Lead Acid	Nickel/Cadmium	Silver/Zinc	LAIS	ZEBRA
Maturity	Mature	Mature	Mature	In Development	Very Immature
Energy Density (Wh/kg)	20-35	20-37	90	160-225	90
Power Density (kW/kg)	0.02-0.175	0.1-0.6	0.2-0.4	0.19-0.36	0.15
Cycle Life (# of cycles)	200-2000	500-2000	100-2000	1000	1000-3000
Service Life (years)	3-10	5-10	3	Unknown	5-10
Battery Effluent	H2 Gas	None	None	None	None
Ease of Operation	Good, frequent monitoring required	Very Good	Poor, strict operating requirements	Projected to be maintenance free	Projected to be maintenance free

Table 16: Battery Type Advantages and Disadvantages

	Pros	Cons
Lead Acid	Mature / proven technology Long cell life Recent improvements	Least energy dense Evolves hydrogen when charging Requires frequent monitoring
Nickel-Cadmium	Higher energy density than lead acid Longer cell life than lead acid Rapid charging Reduced maintence	Unproven at sea Abrupt cut-off when fully charged Memory effects Expensive relative to lead acid
Silver-Zinc	High energy density compared to both lead acid and Ni/Cd Rapid charging Reduced maintence	Prone to internal short circuits High heat generation
Lithium-Aluminum/Iron Sulfide	High energy density compared to both lead acid and Ni/Cd Rapid charging Reduced maintence High energy efficiency	Not mature technology High operating temperatures Battery must be heated before operating
ZEBRA	50% lighter weight than lead acid No emission gasses Rapid discharge for max sprint speed Tolerant of short circuits	High operating temperatures Battery must be heated before operating Thermal management needed Only produced by one factory in the world

3.1.2.3 Propulsors

Propulsors may be one stern-mounted propulsor or multiple propulsors mounted in a variety of locations and allowing for vectored thrust. Many different propulsor-types are in production and each has advantages and disadvantages:

- Open-shaft propellers typically have 6 or 7 blades and either a flow-accelerating or flow-decelerating shroud. The shroud provides improvement in efficiency and acoustic signature over unshrouded propeller designs. It also reduces tip cavitation and losses, but the shroud increases cost.
- Rim-driven propellers (RDP) are similar to a jet engine arrangement with an integral motor, propeller rotor, and a rim/shroud stator. The motor is placed aft where the propeller would be and takes the form of a thin ring mounted within a shroud. The stator carries the permanent magnet rotor in water-lubricated bearings and the rotor is fitted with propeller blades that point inwards. Flow imitates a jet engine, but without the use of combustion.
- Ducted pump jet propulsion (DPJP) intakes seawater and accelerates it through ducts of reducing cross-section. From the ducts the water moves out the rear of the boat. DPJPs are able to direct thrust in almost any direction, and pumps can be tuned to reduce vibration and signatures. However, this system tends to be less efficient than an open propeller.
- Tunnel thrusters are commercial off the shelf technology, which is mature and less expensive than other options. Thrust comes from a small propeller that is mounted in a tube powered by a hydraulic motor in the hub. These can operate in transverse and vertical directions and are commercially available from 40 to 2500 lbs of thrust. Because they are not likely to be made specifically for the boat there can be problems with signatures, but acoustic signatures can be reduced through careful placement.

Shrouded and rim-driven propellers were selected for trade-off in SSLOI as listed in Table 9.

3.1.3 Automation and Manning

Over the past half century, automation on submarines has increased. With these technological advances comes the debate about what should be run by computers and what still requires manpower. A reduction in manpower can significantly reduce the operating cost of a vessel as it has been estimated that up to 60% of life cycle cost is required for manning. Automation also frequently means a faster response time and less careless errors. Those who man a highly automated submarine will become more computer literate which can improve future career endeavors. For safety reasons, less crew onboard means less men and women that will be put in harms way.

Still, having a vessel crewed by too few can be dangerous in emergency situations where computer systems may not be able to make decisions in the absence of power. Though some new firefighting technology has been developed, many critics do not trust these systems to protect a submarine and want to continue to place firefighting in the hands of crew members.

With conflicting options on the necessity of manpower, a manning factor, C_{man}, was created to show reduction from "standard" manning levels due to the introduction of automation. In this study, C_{man} varies from 0.5 to 1.0 and its impact is determined through expert opinion for automation cost, automation risk, damage control performance, and repair capability performance. C_{man} of .5 indicates a 50% reduction in manning due to a considerable increase in automation. Once determined, the manning factor is used in a regression based equation as shown:

Calculation for total manning

KW_{snork} = Total snorkel power
C_{man} = Manning and automation factor
V_{env} = Envelope volume
NO = Number of officers
NE = Enlisted manning
NT = Total crew manning

$$NE = C_{man}\left(\frac{KW_{snork}}{150} + \frac{V_{env}}{5000}\right) \quad (1)$$

$$NT = NE + NO$$

When the vessel is volume limited a small crew is advantageous, so a lower C_{man} is preferred. For weight limited vessels a larger crew can be accommodated and therefore less automation is necessary.

3.1.4 Combat System Alternatives

3.1.4.1 Sonar and Combat Control Systems

The SONARSYS design variable options are listed in Table 17 below. SONARSYS consists of sonar and combat systems options. These systems and components were selected fromJane's Underwater Warfare Systems 2005-2006 based on their applicability to the SSLOI mission, cost and risk thresholds.

Table 17: SONARSYS system alternative components

Design Variable	Options	Components
Sonar/Combat System Alternatives	Option 1) BQQ-10 Bow Dome Passive/Active, LWWAA, BQS-24 high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-23; BSY-2/CCSM	1,2,3,10,14,16,19,20,24, 60,61,62,63,64
	Option 2) EDO Model 1122 MF Passive bow array, MFA, PRS, EDO Model 1121 flank array, Scout HF Chin Array, EDO Model 1123 towed array, BSY-2/CCSM	4,5,6,12,15,17,21,24,60, 61,62,63,64
	Option 3) ATLAS Elektronik DBQS 40 MF cylindrical bow array, MFA, PRS, TAS-3 low-frequency towed array, FAS-3 flank array sonar, and MOA 3070 high frequency mine detection sonar; ISUS-90 CCS	7,8,9,13,15,17,22,25, 60,61,62,63,64
	Option 4) Cylindrical MFP bow array, MFA array, PRS, long range flank array; Scour mine detection sonar, SUBICS 900 CCS	4,5,6,12,17,26, 60,61,62,63,64

Table 18 lists the SONARSYS components with their related weight, vertical center, area, outboard volume, and power consumption rates.

Table 18: Components List for SONARSYS system

ID	NAME	WARAREA	ID	SingleD SWBS	WT lton	VCD ft-CL	AREA ft2	Vob ft3	KW
1	BQQ-5E bow sonar dome passive/active structure and access	SONARSYS	1	1	85.70	0.00	0.00	2200.00	0.00
2	BQQ-10 sonar electronics and software	SONARSYS	2	4	67.40	0.00	300.00	0.00	75.00
3	BQQ-5 bow sonar dome hull damping	SONARSYS	3	6	20.10	0.00	0.00	0.00	0.00
4	EDO Model 1122 bow sonar dome passive/active structure and access	SONARSYS	4	1	65.00	0.00	0.00	1800.00	0.00
5	EDO Model 1122 sonar electronics and software	SONARSYS	5	4	57.00	0.00	200.00	0.00	65.00
6	EDO Model 1122 bow sonar dome hull damping	SONARSYS	6	6	15.00	0.00	0.00	0.00	0.00
7	DBQS-40 bow sonar dome passive/active w/PRS and IA, structure and access	SONARSYS	7	1	55.00	0.00	0.00	1500.00	0.00
8	DBQS-40 sonar electronics andsoftware	SONARSYS	8	4	50.00	0.00	150.00	0.00	55.00
9	DBQS-40 bow sonar dome hull camping	SONARSYS	9	6	10.00	0.00	0.00	0.00	0.00
10	LWWAA	SONARSYS	10	4	45.00	-4.00	150.00	250.00	30.00
11	BQG-5 WAA	SONARSYS	11	4	65.00	-4.00	150.00	275.00	18.00
12	EDO Model 1121 Flank Array (FAS)	SONARSYS	12	4	45.00	-4.00	150.00	350.00	30.00
13	Atlas Electronik FAS-3 Flank Array	SONARSYS	13	4	45.00	-4.00	150.00	350.00	30.00
14	high frequency sail array, BQS-24 HF	SONARSYS	14	4	3.20	14.00	16.67	30.60	22.00
15	high frequency sail array, HF MOA-3070	SONARSYS	15	4	3.00	14.00	12.00	20.00	15.00
16	chin array	SONARSYS	16	4	5.00	-12.00	20.00	38.00	32.00
17	Scout HF array	SONARSYS	17	4	4.00	-12.00	18.00	32.00	30.00
18	SUBTICS Sonar and Combat Control System Suite	SONARSYS	18	4	100.00	-3.00	17.64	2153.00	119.00
19	TB-16 thick towed array and winch	SONARSYS	19	4	32.00	7.00	16.67	87.30	20.00
20	TB-29 thin towed array and winch	SONARSYS	20	4	19.00	7.00	16.67	51.00	4.00
21	EDO Model 1123 towed array andwinch	SONARSYS	21	4	15.00	7.00	15.00	40.00	3.00
22	Atlas Electronik TAS-3	SONARSYS	22	4	14.00	7.00	14.00	35.00	2.50
23	BSY-1 CCS Mk 2 Block 1C	SONARSYS	23	4	5.00	0.00	450.00	0.00	60.00
24	BSY-2/CCSM	SONARSYS	24	4	4.00	0.00	400.00	0.00	39.00
25	ISUS 90	SONARSYS	25	4	3.00	0.00	350.00	0.00	35.00
26	SUBICS 900	SONARSYS	26	4	2.80	0.00	340.00	0.00	34.00
61	underwater comms	SONARSYS	61	4	0.05	11.00	2.00	1.20	1.00
62	navigation echo sounders	SONARSYS	62	4	0.10	0.00	0.00	1.30	1.00
63	communications electronics and equipment	SONARSYS	63	4	1.25	0.00	20.00	0.00	5.00
64	ISR control and processing	SONARSYS	64	4	0.50	0.00	50.00	0.00	2.00

SONARSYS Option 1 includes an AN/BQQ-10 bow mounted spherical sonar array with passive and active capabilities. Figure 11 shows a US Navy sonar dome outside of the hull. The AN/BQQ-10 is an upgraded BQQ-5 series using commercial off the shelf software. The software upgrade allows for an increase in acoustic performance, improved combat control capabilities and the replacement of obsolete equipment. The AN/BQQ-10 bow mounted array is a good option because it is integrated in the CCSM or BSY control systems. It also works in conjunction with towed array systems and flank arrays. Also included in Option 1 are TB-16 and TB-29 towed arrays. Both towed arrays are dispensed from the stern planes. The TB-29 thin line towed array is one of the most advanced towed arrays in the world and can work in conjunction with the CCSM or BSY control system.

Option 1 is the only option that includes both a Light Weight Wide Aperture Array (LWWAA) and the BQS-24 high frequency sail and chin array. The BQS-24 system is used for mine, ice, and obstacle avoidance. The LWWAA is a set of large array panels mounted on either side of the submarine. The use of large, lightweight sonar panels on either side of the submarine greatly increases the input into the submarine's combat systems suite. LWWAAs use fiber-optic and laser technologies to convert acoustic energy into information that can be quickly utilized by the combat systems of the submarine.

Figure 11: US Navy Submarine Sonar Dome

SONARSYS Option 2 utilizes an EDO Model 1122 MF Passive bow array instead of the AN/BQQ-10 Active/Passive array. The EDO Model 1122 is a hull cylindrical sonar array that uses a passive one-meter diameter, forward, hull-mounted transducer. It also includes Passive Ranging Sonar, an EDO Model 1123 towed array, and Scout high frequency mine detection and obstacle avoidance sonar. The EDO Model 1123 uses a dual-nested hydrophone configuration in the array. The Scout HF sonar is forward looking multi-purpose sonar which offers navigation, detection, collision, obstacle and mine avoidance advantages. The system is designed primarily to detect mines, but will also be used to detect other moving or stationary underwater objects. It can be used as navigation sonar during a submarines surfacing maneuver, or as a navigational aid in narrow or dangerous waters. Figure 12 shows the coverage of the Scout sonar.

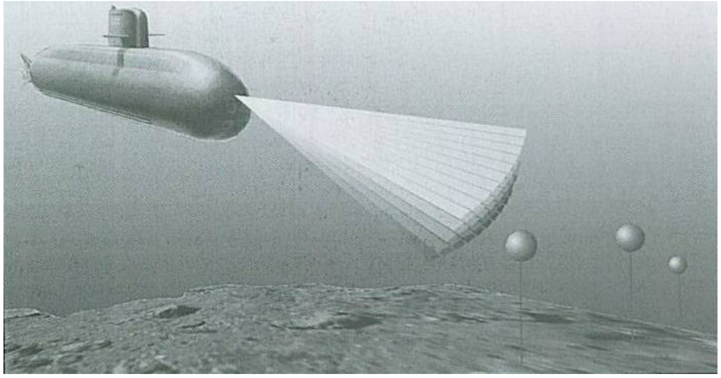


Figure 12: Coverage of the Scout Sonar

Both SONARSYS Options 1 and 2 include the BSY-2/CCSM combat systems suites. These systems control sonar, combat control, electronics and major subsystems. The BSY-2 system has been developed to counter the submarine threat of the 21st century, and as such is an upgrade of the BSY-1 system which offers integration of future mission and upgraded capacity. The upgraded capacity enables the submarine to detect targets in a much shorter time than is currently possible, allows operators to perform multiple tasks, handles multiple targets simultaneously, and greatly reduces the time between threat detection and threat neutralization. CCSM utilizes commercial off the shelf software to upgrade the BSY-2 system. It is a full combat suite integration solution which will encompass sonar, combat control, and architecture major subsystems, plus the integration of all additional combat suite electronics. Combat suite electronics include ESM, radar, external and internal communications, submarine defensive warfare systems, navigation, total ship monitoring, periscope/imaging, navigation sensor system interface, tactical support devices and special purpose subsystems.

SONARSYS Option 3 uses an ATLAS Elektronik DBQS 40 integrated sonar system with ISUS-90 CCS. The DBQS 40 is an integrated bow array that incorporates a medium-frequency, cylindrical bow array operating in the 0.3 to 12 kHz band. It integrates a FAS-3 flank array, a Passive Ranging Sonar (PRS), intercept sonar a low frequency, passive towed array sonar (TAS-3). It also integrates active high frequency MOA 3070 mine detection sonar.

The final SONARSYS Option uses a cylindrical medium frequency passive bow array, an MFA array, PRS and a long range flank array. Option 4 also incorporates the Scout mine detection sonar. Option 4 uses the SUBICS 900 Combat Control System. The SUBmarine Integrated Combat System (SUBICS) is a totally integrated combat system that meets multi-mission requirements for modern diesel-electric submarines. Tactical functions of the SUBICS 900 CCS include tactical evaluation and planning; integrated surveillance and threat prosecution; and combat navigation. The system is capable of performing threat identification and enables tactical evaluation and planning. It also evaluates possible responses, gathers data and processes this to provide contact information on the tactical display. It performs torpedo/missile control functions and has displays that include information on the geographical situation with navigation function including alerts to approaching hazards. The combat suite integrates acoustic, electromagnetic, and electro-optic sensors and can track 68 targets simultaneously. Figure 13 shows a block schematic of the SUBICS 900 system.

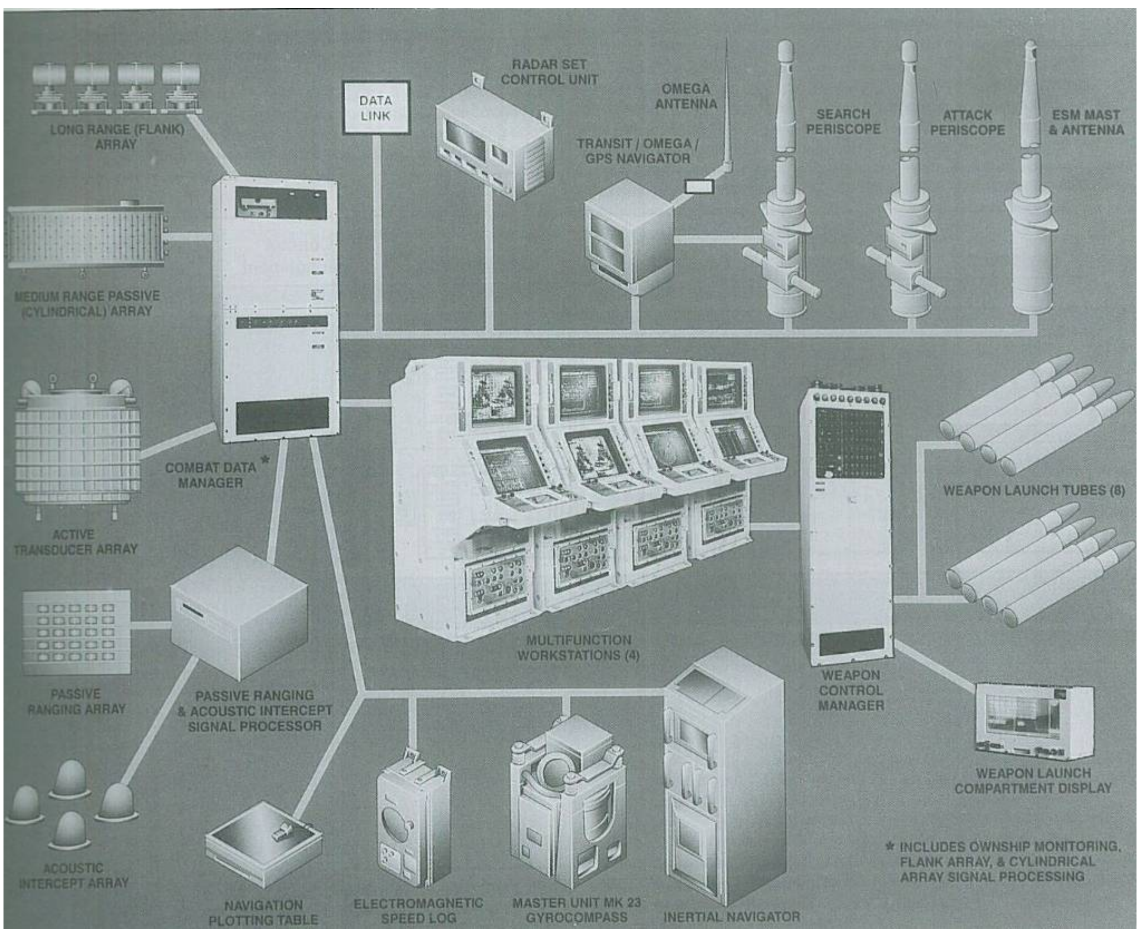


Figure 13: Block Schematic of SUBICS 900 System

3.1.4.2 Sail

The SAIL design variable options are listed in Table 19 below. The sail contains the radar, visual, and communication equipment of the submarine. Each option includes two of either a photonics mast or traditional mast and radar equipment. Each option also includes the necessary snorkel equipment, an Unmanned Aerial Vehicle, and a Seal Locker.

Table 19: SAIL system alternative components

Design Variable	Options	Components
Sail (Radar, Masts and Periscopes, and communication)	Option 1) BPS-16 Radar; 2xAN/BRA-34 Multiband; AN/BVS-1 Photonics mast; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA	41,44,43,50,51,45, 46, 47,48,49,55
	Option 2) BPS-16 Radar; 2xAN/BRA-34 Multiband; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA, AN/BRD-7/BLD-1	41,44,50,51,45,46, 47,48,49,55
	Option 3) BPS-16 radar; 2xAN/BRA-34; SERO 14 Search Periscope, SERO 15 Attack Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; Shrike	41,44,50,51,45,46, 47,48,53

Table 20 lists the SAIL components with their related weight, vertical center, area, outboard volume, and power consumption rates.

Table 20: Components list for SAIL system

ID	NAME	WARAREA	ID	SingleD SWBS	WT lton	VCD ft+CL	AREA ft2	Vob ft3	KW
41	BPS 16 radar	SAIL	41	4	2.90	14.00	16.67	24.00	2.00
42	2 x AN/BPS 16 radar	SAIL	42	4	2.90	14.00	16.67	24.00	2.00
43	AN/BVS 1 photonics mast	SAIL	43	4	8.80	12.00	8.00	22.00	10.00
44	2 x AN/BRA-34 multiband	SAIL	44	4	4.20	12.00	4.20	11.00	6.60
45	snorkel	SAIL	45	2	26.00	10.00	2.36	11.80	0.10
46	IEM	SAIL	46	4	1.10	12.00	2.10	5.50	3.30
47	Sea Sentry	SAIL	47	4	0.50	12.00	0.00	6.00	0.00
48	Seal Locker	SAIL	48	7	0.50	12.00	0.00	6.00	6.00
49	OE 315 HSBCA	SAIL	49	4	0.50	14.00	0.00	10.00	7.00
50	Type 8 Mod 3 periscope	SAIL	50	4	4.40	12.00	4.00	11.00	5.00
51	Type 18 Mod 3 periscope	SAIL	51	4	4.40	12.00	4.00	11.00	5.00
60	distress beacon	SAIL	60	4	0.05	12.00	0.00	1.00	0.50

SAIL Option 1 includes an AN/BVS-1 Photonics mast, a Type 8 Mod 3 periscope, a Type 18 Mod 3 periscope, and an OE-315 HSBCA. The BVS-1 Photonics mast is non-hull penetrating and provides surveillance, intelligence gathering, and electronic warfare operations capabilities. This mast affords the capability to readily upgrade existing sensors and to incorporate new state-of-the-aft multi-spectral devices to ensure dominance of the submarine battle force. Contained in the mast is a suite of electro-optical sensors including two high definition TV systems, a mid-wave staring IR sensor, an eye-safe laser range-finder, ESM, microwave DF and other RF sensors.

SAIL Option 2 also has a Type 8 Mod 3 periscope, a Type 18 Mod 3 periscope, and an OE-315 HSBCA. The Type 8 Mod 3 is a high-performance electro-optical periscope with day and night capabilities. It is proven, low risk, and can be integrated with CSYS. The Type 18 Mod 3 periscope is an improved version of the Type 8, but with improvements in video. It is installed on Los Angeles and Seawolf class submarines. The OE-315 HSBCA is a rope buoy system. It is a towed buoy that operates on the surface and relays visual images to the submerged, towing submarine at cruise depth via a real-time fiber-optic data link.

SAIL Option 2 equips the submarine with an AN/BRD-7 and an AN/BLD-1 system. The AN/BRD-7 is a high-performance submarine communications DF system which uses an omni antenna mounted on a periscope. The AN/BLD-1 system is a precision radar direction finding system (installed as an adjunct to the BRD-7 system). The system delivers precise threat bearing information, which is integrated with other sensor data for tactical surveillance.

SAIL Option 3 uses a SERO 14 Search Periscope and a SERO 15 Attack Periscope. Both are German periscopes that comprise a modular system. The SERO 14 features a two-axis line-of-sight stabilization for visual and IR channels and remote control capabilities from a combat system console. The SERO 14 also has integration facilities on top for a wide variety of antennas. The SERO 15 features an eye-safe laser range-finder on top of the periscope and the capability of attaching a variety of cameras at the auxiliary eyepiece. The SERO 15 is an attack periscope and is installed into a hoisting device with streamlined fairing. Figure 14 show both the SERO 14 and SERO 15 periscopes.

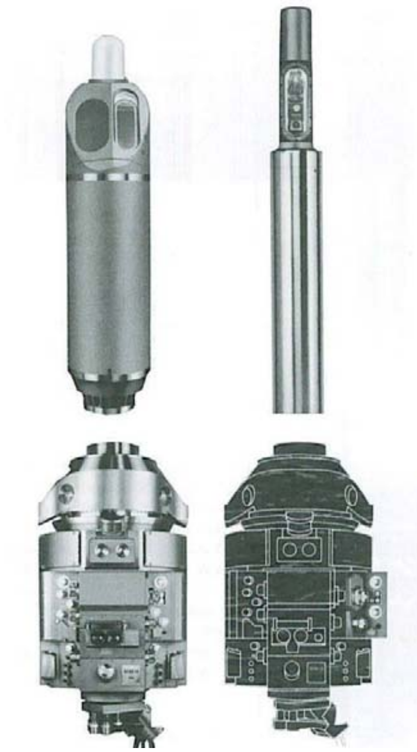


Figure 14: SERO 14 (left) and SERO 15 (right) periscopes

All options include the BPS-16 Radar, two AN/BRA-34 multi-band masts, snorkel, Integrated Electronics Mast (IEM), Sea Sentry, and a Seal Locker. The BPS-16 Radar is the latest upgrade to the BPS 15 radar. It has a 50 km range and is used for navigation, surface surveillance, and x-band. The BPS-16 features a new 50 kW frequency-agile transmitter in I-band and the latest in signal processing techniques to enhance operational performance. It is currently equipped on Seawolf, Los Angeles, and the third and fourth Virginia class submarines. The AN/BRA-34 multi-band mast is used for navigation, communications, IFF, two-way HF and UHF, and receive-only VLF/LF and GPS. Figure 15 shows the communications capabilities required in the 4 different modes of operation: stealth, covert, low risk, and overt.

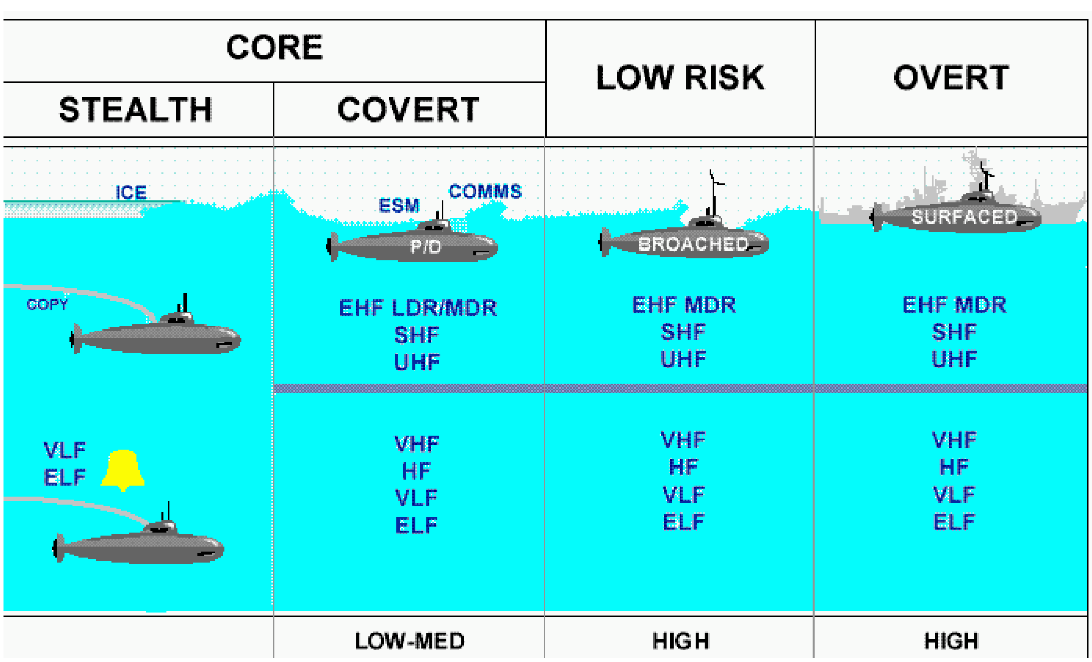


Figure 15: Communications capabilities required by mode of operation

The Sea Sentry included in all design options allows the submarine to deploy an expendable Unmanned Aerial Vehicle (UAV). The UAV allows the submarine to retrieve tactical data and target beyond the periscope's line of sight. It uses existing submarine communications assets for uplink/downlink allowing it to provide real-time, detailed tactical information. Figure 16 shows the Sea Sentry in flight.

Figure 16: Sea Sentry in flight

In typical sail arrangements, the radar is located in the forward section and the snorkel is far aft. Masts and communications equipment are placed between these components. Towed arrays are attached to the trailing edge of the sail. There is generally space left available for the addition of equipment over the life of the submarine. Figure 17 shows arrangements for four sail configurations – the 688, 688I, Virginia Class, and SSN 21.

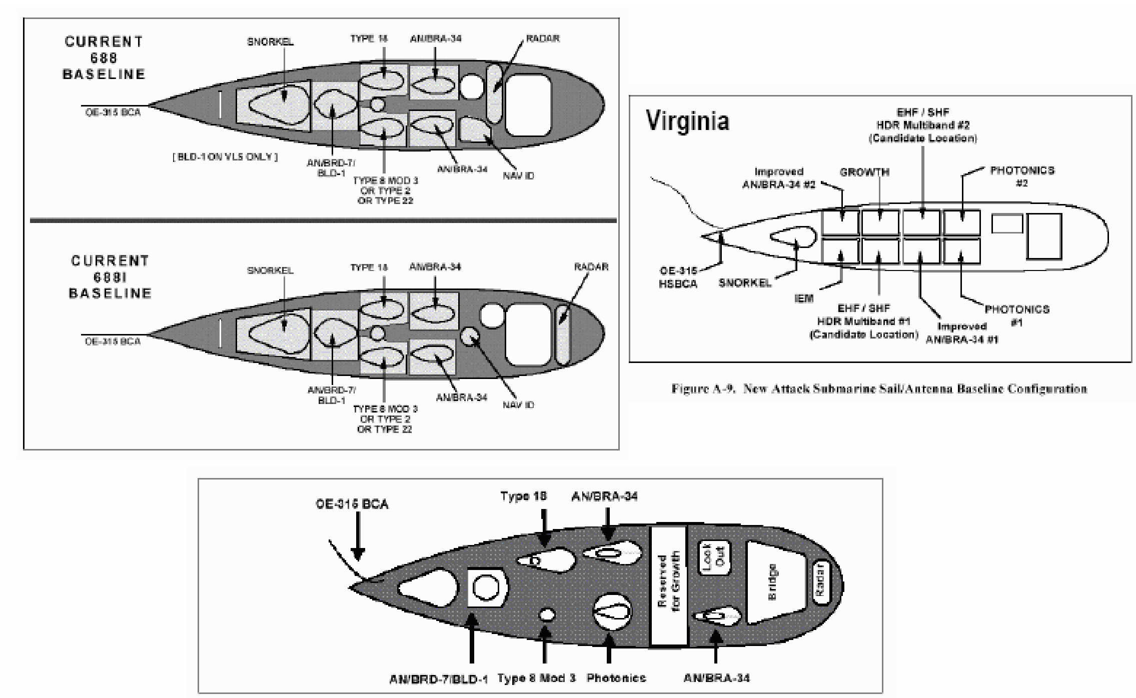


Figure 17: Sail Configuration Alternatives

Hulls 5 and 6 of the Virginia Class submarine will be receiving a new advanced composite sail. The advanced composite sail will offer approximately 4 times the volume of a typical sail and improve the hydrodynamics. Figure 18 shows an artists conception of an advanced sail for the Virginia Class.

Figure 18: Artists conception of advanced sail for Virginia Class

3.1.4.3 ESM

The ESM design variable options are listed in Table 21. Both alternatives include the WLY-1 acoustic interception and countermeasure system; one or two 3" Countermeasure Launcher with reloads, and two 6.75" Countermeasure tubes.

Table 21: ESM system alternative components

Design Variable	Options	Components
ESM Alternatives	Option 1) WLY-1 acoustic interception and countermeasures system; AN/WLQ-4, AN/BLQ-10 Electronic Support Measures (ESM) system; 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube	53,56,54,57,57,58,59,59
	Option 2) AN/WLY-1, 3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube	53,56,57,58,59

Table 22 lists the ESM components with their weight, vertical center, area, outboard volume, and power consumption rates.

Table 22: Component lists for ESM system

ID	NAME	WARAREA	ID	SingleD SWBS	WT lton	VCD ft+CL	AREA ft2	Vob ft3	KW
52	SHRIKE ESM	ESM	52	4	1.50	10.00	4.00	3.00	5.00
53	WLY-1 acoustics interception and countermeasures system	ESM	53	4	1.75	10.00	9.00	3.00	5.00
54	AN/BLQ-10 (ESM)	ESM	54	4	1.20	12.00	4.00	4.00	4.50
55	AN/BRD-7/BLD-1	ESM	55	4	1.10	12.00	4.00	4.00	4.00
56	WLQ-4 Submarine Detection and Analysis System	ESM	56	4	1.50	10.00	8.00	3.00	4.50
57	3" Countermeasure/XBT launcher	ESM	57	7	0.09	6.00	1.00	0.00	0.10
58	3" Countermeasure reloads x 10 (locker)	ESM	58	20	0.04	6.00	3.00	0.00	0.00
59	6.75" external Countermeasure launcher w/4cannisters ea	ESM	59	7	0.66	6.00	0.00	0.00	0.10

The AN/WLY-1 acoustic intercept and countermeasures command and control unit is an advanced submarine countermeasures controller unit. It has an expandable capability for countermeasures device inventory management, processing tactical solutions, target data management, and launch sequencing of all externally configured launchers. The WLY-1 performs threat platform sonar and torpedo recognition for early detection/classification/tracking. It is installed on the Seawolf and Virginia class SSNs.

Standard 3" and 6.75" diameter countermeasure tubes (widely used in the submarine fleet) are designed to launch countermeasure systems which jam the homing heads on incoming torpedoes.

ESM Option 1 also has the AN/WLQ-4 Signals Intelligence (SIGINT) detection and analysis system, and AN/BLQ-10 Electronic Support Measures (ESM) system. The AN/WLQ-4 (also known as Sea Nymph) is an automated, modular signal collection system which allows for the identification of the nature and sources of unknown radar emitter and communication signals. The AN/BLQ-10 ESM system (formerly the Advanced Submarine Tactical ESM System, ASTECS) is a fully integrated radar and communications ESM that combines threat warning and intelligence gathering. It provides detection, identification, and direction-finding for radar and communication signals emanating from ships, aircraft, submarines, and other emitters.

3.1.4.4 Torpedo/UUV

The TORP design variable options are listed in Table 23. All options have at least one MANTA. Options 1-3 have two 21" torpedo tubes with 8 reloads, while Options 4 and 5 rely on the MANTAs for torpedo offense/defense.

Table 23: TORP system alternative components

Design Variable	Options	Components
Unmanned Underwater Vehicle System	Option 1) 3 Mantas with 2 torpedo tubes and 8 reloads	32,32,32,26,28,30,31
	Option 2) 2 Mantas with 2 torpedo tubes and 8 reloads	32,32,26,28,30,31
	Option 3) 1 Manta with 2 torpedo tubes and 8 reloads	32,26,28,30,31
	Option 4) 3 Mantas	32,32,32
	Option 5) 2 Mantas	32,32

Table 24 lists the TORP components with their weight, vertical center, area, outboard volume, and power consumption rates.

Table 24: Component lists for TORP system

ID	NAME	WARAREA	ID	SingleD SWBS	WT lton	VCD ft+CL	AREA ft2	Vob ft3	KW
27	2 x 21" MK-69 torpedo tubes and doors	TORP	27	7	19.00	-4.00	0.00	88.00	3.60
28	6 x Mk 48(Adcap) Torpedoes	TORP	28	20	9.90	-4.00	0.00	0.00	0.00
29	8 x Mk48(Adcap) Torpedoes	TORP	29	20	13.20	-4.00	0.00	0.00	0.00
30	6 x Torpedo Racks	TORP	30	7	29.00	-4.00	232.00	0.00	0.00
31	8 x Torpedo Racks	TORP	31	7	32.00	-4.00	276.00	0.00	0.00
32	2 x Torpedo Machinery	TORP	32	5	4.50	-4.00	144.00	0.00	1.80
34	6 external encapsulated torpedoes (Mk 48Adcap)	TORP	34	20	12.00	-10.00	0.00	420.00	1.00
33	1 x MANTA UUV	TORP/UUV	33	20	109.00	8.00	0.00	3804.00	50.00

Torpedo Payload Options include the Mk 48 ADCAP for ASW operations, Tomahawk missile for strike (STK) missions, Harpoon for ASUW missions, the Mk 60 Mine Launcher and various UUVs for other ASW tasks.

Unmanned Underwater Vehicles (UUVs) reduce personnel risk. Some UUVs are expendable and do not need to be recovered to obtain data from them. The US Navy's 2004 UUV Master Plan stresses the importance of development and fielding advanced technologies, such as UUVs, to significantly contribute to the Navy's control of the maritime battlespace. Figure 19 shows a slide from the UUV Master Plan. Using Sea Power 21 for guidance, the UUV Master Plan specifies nine Sub-Pillar capabilities that are identified and prioritized. These include:

1. Intelligence, Surveillance, and Reconnaisance
2. Mine Countermeasures
3. Anti-Submarine Warfare
4. Inspection/Identification
5. Oceanography
6. Communication / Navigation Network Node
7. Payload Delivery
8. Information Operations
9. Time Critical Strike

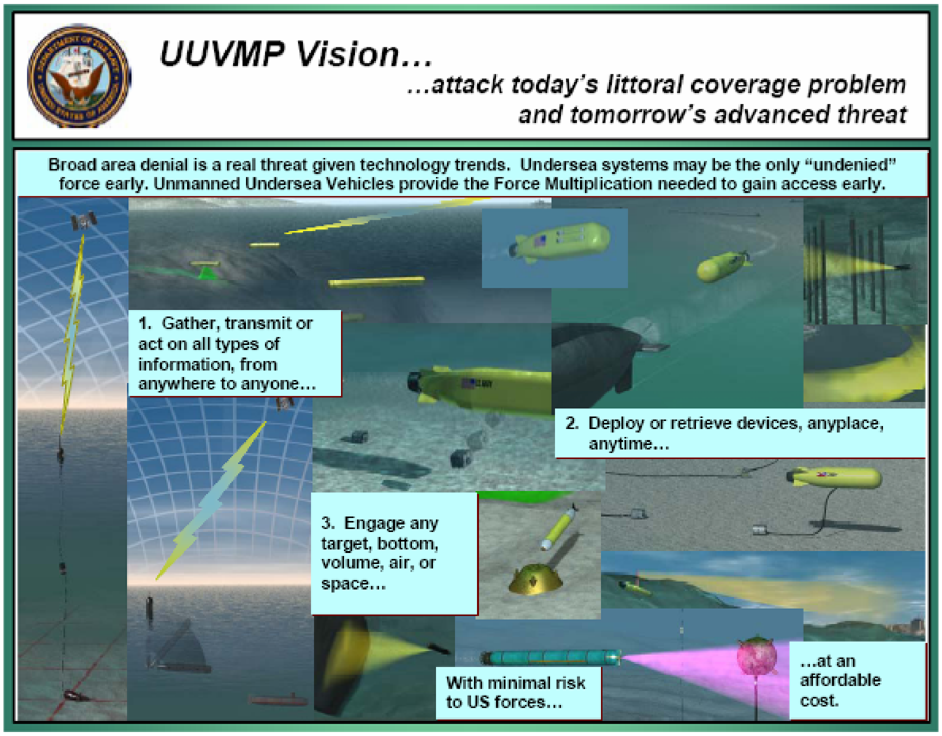


Figure 19: Slide from UUV Master Plan

The MANTA is a concept for an autonomous, re-usable, reconfigurable UUV having a multi-mission capability. It is designed to mount conformally within depressions in a submarine's hydrodynamic hull. MANTA would be deployed from standoff distances and transit clandestinely to forward shallow water areas. MANTA could operate independently using its own sensors, weapons, and countermeasures; or be controlled by other manned platforms (including from the parent vessel). While attached to the submarine, MANTAs would have the capability of firing their own weapons to augment the submarine's defensive or offensive armament. The MANTA considered for our design has the capability of carrying two full length torpedoes and 2 half-length torpedoes, or 6 half-length torpedoes. The MANTA design is modular such that the vehicle can be easily reconfigured to carry various payloads (wet or dry) allowing it to perform a wide variety of missions while keeping the parent vessel out of harms way. Various sizes of MANTA have been studied, with lengths ranging from approximately 15 meters to more than 25 meters and typically weighing 50 ton. A 90 ton 'Super MANTA' would have a range of 1000 nm. Figure 20 shows a possible MANTA arrangement on a submarine's hull, and Figure 21is an artist's rendition of MANTA.

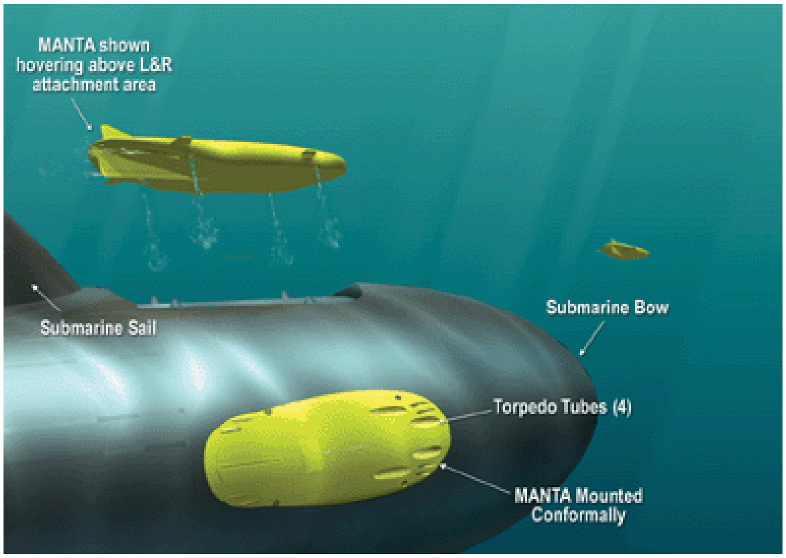


Figure 20: MANTA Arrangement on submarine

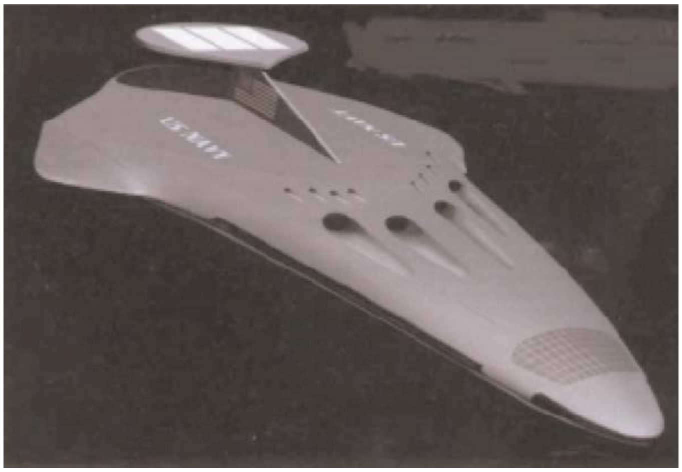


Figure 21: Artist's rendition of a MANTA

3.1.4.5 VLS

The VLS design variable options are listed in Table 25. The three alternatives include options for 6 VLS cells, 4 VLS cells, or no VLS capability.

Table 25: VLS system alternative components

Design Variable	Options	Components
Vertical Launching System Alternatives	Option 1) 6 Cell VLS	34,35,36
	Option 2) 4 Cell VLS	37,38,39
	Option 3) none	0

Table 26 lists the VLS components with their weight, vertical center, area, outboard volume, and power consumption rates.

Table 26: Component lists for VLS system

ID	NAME	WARAREA	ID	SingleD SWBS	WT lton	VCD ft+CL	AREA ft2	Vob ft3	KW
35	6 cell VLS	VLS	35	7	121.60	-10.00	0.00	420.00	15.00
36	6 TLAM	VLS	36	20	11.85	-10.00	0.00	0.00	0.00
37	VLS machinery 6 cells	VLS	37	5	56.00	0.00	30.00	60.00	5.40
38	4 cell VLS	VLS	38	7	80.26	-10.00	0.00	277.00	10.00
39	4 TLAM	VLS	39	20	7.80	-10.00	0.00	0.00	0.00
40	VLS machinery 4 cells	VLS	40	5	37.00	0.00	30.00	40.00	5.40

A Vertical Launching System (VLS) is a type of missile-firing system used aboard submarines. Derived from the launch systems developed for ballistic missiles aboard SSBNs, a VLS provides a method for launching cruise missiles such as the Tomahawk, surface-to-air missiles (SAMs), and the Standard missile. The system enables attack submarines to carry more weapons in addition to their torpedo tubes. More significantly, VLS allows both submarines and surface combatants to have more weapons ready for firing at a given time than with other launching systems.

3.1.4.6 Combat Systems Payload Summary

In order to trade-off combat system alternatives with other alternatives in the total ship design, combat system characteristics listed in Table 27 (Section 3.2) are included in the submarine synthesis model data base.

3.2 Design Space

The nineteen Design Variables (DVs) in Table 27 make up the design space from which the final submarine design is chosen. These DVs are input into the synthesis model which is then used in the MOGO. The MOGO assigns a value to each variable and uses the synthesis results to search for non-dominated designs.

Table 27: SSLOI Design Variables (DVs)

DV #	DV Name	Description	Design Space
1	D	Diameter	29-32 ft
2	LtoD	Length to Depth Ratio	8-12
3	BtoD	Beam to Depth Ratio	1
4	n_a	Fullness factor aft	2.5-3.0
5	n_f	Fullness factor forward	2-2.5
6	Depth	Diving Depth	500-1000ft
7	PSYS	Propulsion system alternative	Option 1) CCD, 2xCAT 3512 V12Engines
			Option 2) CCD, 2xCAT 3516 V16 Engines
			Option 3) CCD, 2xCAT 3608 IL8
			Option 4) OCD/AIP, 2xCAT 3512 V12 + 2x250KW PEM
			Option 5) OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM
			Option 6) CCD/AIP, 2xCAT 3516 V16 + 2x250KW PEM
			Option 7) CCD/AIP, 2xCAT 3516 V16 + 2x500KW PEM
			Option 8) CCD/AIP, 2x CAT 3608 IL8 + 2x250KW PEM
			Option 9) CCD/AIP, 2x CAT 3608 IL8 + 2x500KW PEM
			Option 10) CCD/AIP, 2xCAT 3512 V12 + 2x250KW PEM+reformer
			Option 11) CCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM+reformer
			Option 12) CCD/AIP, 2xCAT 3516 V16 + 2x250KW PEM+reformer
			Option 13) CCD/AIP, 2xCAT 3516 V16 + 2x500KW PEM+reformer
			Option 14) CCD/AIP, 2x CAT 3608 IL8 + 2x250KW PEM+reformer
			Option 15) CCD/AIP, 2x CAT 3608 IL8 + 2x500KW PEM+reformer
8	PROPtype	Propulsion Prop Type	Option 1) RDP, Rim Driven Prop Option 2) Shrouded
9	BATtype	Battery system type alternative	Option 1) Nickel Cadmium Option 2) Lead Acid Option 3) Zebra
10	Ebat	Battery Capacity	2500-5000 kwhr
11	Wfsnork	Weight Fuel Snorkel	50-150lton
12	Wfaip	Weight Fuel AIP	10-50lton
13	Ndegaus	Degaussing	0=none; 1=degaussing
14	Cman	Manpower Reduction	0.5-1.0
15	UUV/TORP	Unmanned Underwater Vehicle System	Option 1) 3 Mantas with 2 torpedo tubes and 8 reloads
			Option 2) 2 Mantas with 2 torpedo tubes and 8 reloads
			Option 3) 1 Manta with 2 torpedo tubes and 8 reloads
			Option 4) 3 Mantas
			Option 5) 2 Mantas
16	VLS	Vertical Launching System Alternatives	Option 1) 6 Cell VLS
			Option 2) 4 Cell VLS
			Option 3) none
17	SSYS	Sonar/Combat System Alternatives	Option 1) BQQ-10 Bow Dome Passive/Active, LWWAA, BQS-24 high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-23; BSY-2/CCSM
			Option 2) EDO Model 1122 MF Passive bow array, MFA, PRS, EDO Model 1121 flank array, Scout HF Chin Array, EDO Model 1123 towed array, BSY-2/CCSM
			Option 3) ATLAS Elektronik DBQS 40 MF cylindrical bow array, MFA, PRS, TAS-3 low-frequency towed array, FAS-3 flank array sonar, and MOA 3070 high frequency mine detection sonar; ISUS-90 CCS
			Option 4) Cylindrical MFP bow array, MFA array, PRS, long range flank array; Scour mine detection sonar, SUBICS 900 CCS
19	SAIL	Sail (Radar, Masts and Periscopes, and communication)	Option 1) BPS-16 Radar; 2xAN/BRA-34 Multiband; AN/BVS-1 Photonics mast; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA
			Option 2) BPS-16 Radar; 2xAN/BRA-34 Multiband; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA, AN/BRD-7/BLD-1
			Option 3) BPS-16 radar; 2xAN/BRA-34; SERO 14 Search Periscope, SERO 15 Attack Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; Shrike
20	ESM	ESM Alternatives	Option 1) WLY-1 acoustic interception and countermeasures system; AN/WLQ-4, AN/BLQ-10 Electronic Support Measures (ESM) system; 2x3” Countermeasure Launcher w/ Reloads, 2x6.75” Countermeasure Tube
			Option 2) AN/WLY-1, 3” Countermeasure Launcher w/ Reloads, 2x6.75” Countermeasure Tube

3.3 Submarine Synthesis Model

The submarine synthesis model builds and balances a design based on specified inputs and estimates its feasibility, effectiveness, cost, and risk. The individual modules are arranged and linked in Model Center, the analysis window of which is shown in Figure 22. There are modules for each major component of the sub (i.e. combat, propulsion, hull, etc.), which are described below. Model Center connects the output of one module to the associated input of another module, integrating all modules into an overall submarine synthesis model. The modules are written in FORTRAN or MathCAD, and are connected to Model Center through the use of file wrappers. Balance is achieved by calculating the slack variable (lead) so that the weight of the sub matches the buoyancy. Weights are summed over the 7 SWBS groups to calculate condition A-1 weight; this is balanced with the everbuoyant volume from the pressure hull and outboard volume to determine the lead weight.

The submarine synthesis model is used during optimization. The optimizer automatically selects input variable values to evaluate many designs, and explore the entire design space.

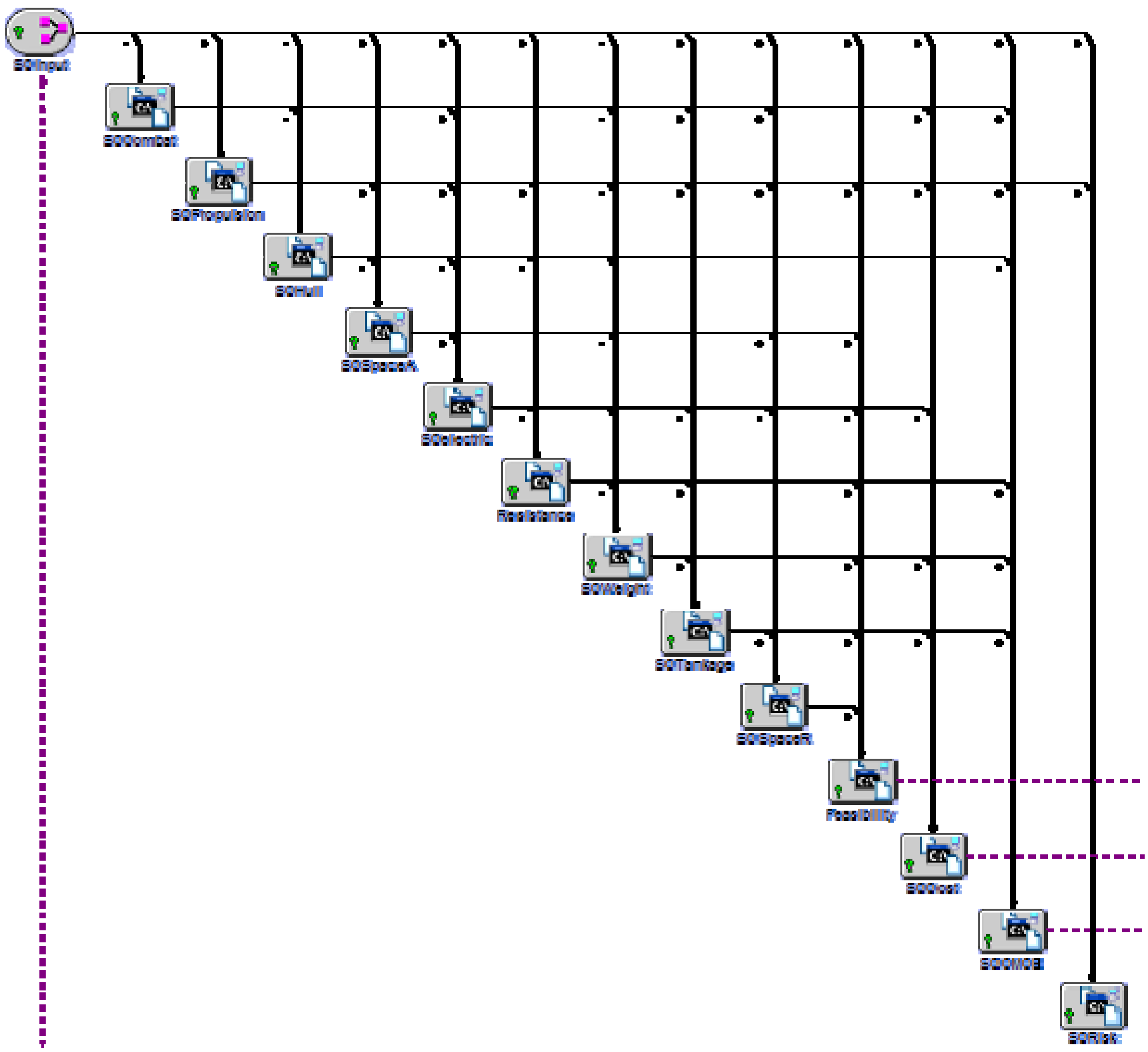


Figure 22: Submarine Synthesis analysis window in Model Center

The following modules are used in the submarine synthesis model:

- Input Module**:** This first module serves one main purpose: to collect the values of the input variables before providing them to specific modules. The MOGO module output connects as an input to this module, allowing the optimizer to adjust input variables for different designs.

- Combat Systems Module: The combat systems module has five specific functions: to calculate the total weight and VCG of all combat system components, as well as their electrical, area, and outboard volume requirements. The total weight, electrical, area and outboard volume requirements are calculated using a simple summation. The total VCG is calculated using a moment about the baseline of the submarine.
- Propulsion Module: The propulsion module determines battery specifications (weight, volume, and power), prop specifications, fuel weights and volumes and total machinery space. All parametric data is read from an Excel spreadsheet. The module outputs total battery power, battery weight, battery volume, basic machinery weight, weight of fuels (methanol, argon, oxygen, diesel), weight of methanol storage, and volume of propulsion machinery.
- Hull Module: Unlike the other modules, a MathCAD algorithm is used for this module. The hull follows the optimum "tear drop" shape shown in Figure 4, with a parallel mid-body. The optimum tear drop shape is based on an MIT model; it consists of an ellipsoidal fore-body and parabolic aft-body. Using this teardrop shape with the input shape parameters (n_a, n_f), diameter, and length/diameter, the total envelope volume is computed by summing up the three sections (fore-body, parallel mid-body, aft body). MathCAD also calculates the total surface area.
- Tankage Module: Using the input parameters for manning, power, envelope volume, fuel weight, and type of propulsion plant, this module predicts the volumes and weights of the required internal tanks. The specific volumes of the fuels are used to find the total volumes of each fuel. Diesel fuel is split into two tanks, one outboard (compensated tank) and one inboard (clean tank). Fresh water and sewage volumes are calculated based on the manning, which is based on the size and power of the sub and the manning factor. This module outputs total inboard tank volume, outboard compensated diesel tankage, manning, fuel weight, sewage and fresh water weights.
- Space Module: Using the input values for provisions duration, manning, deck height, volumes of individual components and tanks, and envelope volume, the space module computes the required pressure hull volume. There are two main types of volume to consider: volume occupied by physical components (tanks, machinery, etc.) and volume that is required for submarine operation and crew (berthing, messing, passage way, etc). Berthing and habitability volumes are computed based on the crew size and simple parametric equations. Arrangeable area is computed taking into account margins for fitting rectangular spaces into cylinders. Summing up these values and adding margins gives the total required arrangeable area. The available arrangeable area is then computed based on a parametric equation and the two areas are compared in the feasibility module. The total outboard displacement volume is calculated, from which the main ballast, submerged and free-flood volumes are all calculated.
- Electric Module: This module computes electrical power requirements for the submarine. The input parameters (size, payload power, volume, weights, and margins) are used to compute these requirements. First, non-payload power consumption is calculated by summing individual components (steering, lighting, miscellaneous, firemain, fuel handling, auxiliary, services and degaussing). This value is then combined with payload, air conditioning, and ventilation to obtain the maximum functional load. Margins are then included and the module outputs the functional load and 24 hour average usage.
- Resistance Module: The function of this module is to perform the calculation of sustained speed, sprint speed and duration, AIP endurance duration, snorkel range and mission duration. The total resistance of the sub is estimated based on its size using parametric equations. A correlation allowance is added to the viscous resistance to calculate the total resistance. Wave-making resistance is added for the snorkel-depth calculation. Resistance is calculated for both snorkel and fully-submerged AIP scenarios. The bare hull power is then calculated and shaft power is determined. From this the values of endurance range, duration, AIP endurance and snorkel range are computed, with margins.
- Weight Module: The main objective of this module is to determine the lead weight needed to balance the sub. This is done using the weight breakdown shown in Figure 23. The first step is to do a volume/displacement weight balance to obtain the normal surface condition weight (NSC). Summing all SWBS groups gives the lightship or A-1 weight. Adding variable (loads) weight (SWBS 7) gives the condition A weight of the sub. The difference between the NSC weight and the Condition A weight is the required lead. Necessary lead margins are computed to ensure that there is sufficient lead for all conditions and stability using submerged GB and surface GM. These are obtained by calculating the overall VCG and dividing by NSC to obtain KG. With the KG value, surface BM and thus GM are calculated and the submerged GB is determined.

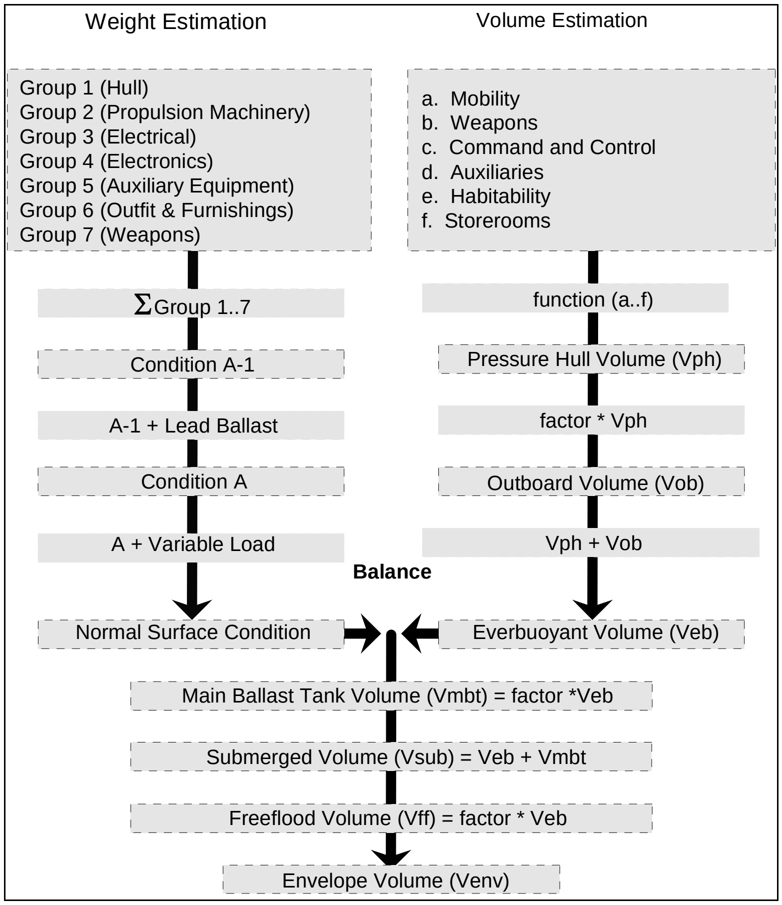


Figure 23: Weight and Volume Balance

- Feasibility Module: This module compares available values to required values using a feasibility ratio, (avail-req)/req. Characteristics such as free flood volume, endurance range and duration, GM, GB, lead, and arrangeable area are all examined to determine feasibility. In order for a specific design to be feasible all feasibility ratios must be greater then zero. The module returns values of the various comparisons, demonstrating which aspects of the design are feasible and which are not.
- OMOE Module: This module calculates the overall measure of effectiveness for a specific design based on its VOP values and their associated weights obtained during pairwise comparison. First the module determines a VOP for each MOP and stores all VOP values in a vector. A vector is stored containing the weights of each individual VOP, the dot product of these two vectors is computed, and this calculation provides the overall measure of effectiveness.
- Cost Module: The primary function and output of this module is basic cost of construction. To calculate this cost, material and labor cost are estimated separately. The cost of labor for each SWIBS group is based on a man-hour rate, the value of which is summed for all SWIBS groups, giving the overall labor cost. The material cost is found in a similar manner by computing each SWBS material cost separately and summing. Together the labor and material cost make up the direct cost. Adding margins, inflation rates and overhead, the basic cost of construction is computed.
- Risk Module: The risk module works in a similar manner to the OMOE module, calculating an OMOR (overall measure of risk). The calculation considers three types of technology risk: performance, cost and schedule. Summing these three values of risk for applicable risk events and multiplying each type of risk by its associated weight factor results in the OMOR. The technology risk events considered for SSLOI include the use of PEMs, reformer, RDP, NiCd battery, Zebra battery, MANTA, SONARSYS, and automation.
- MOGO Module: The multi-objective genetic optimizer module is used to estimate the non-dominated frontier of optimum designs. The goal of this optimizer is to maximize OMOE for a given level of risk and cost.

3.4 Objective Attributes

3.4.1 Overall Measure of Effectiveness (OMOE)

To understand overall measure of effectiveness, certain terms must be defined:

- Overall measure of effectiveness (OMOE) - a single figure of merit index (0-1.0) describing submarine effectiveness in specified missions.
- Mission or Mission Type Measures of Effectiveness (MOEs) – Figure of merit index (0-1.0) for specific mission scenarios or mission types.
- Measures of Performance (MOPs) – Specific submarine or system performance metric in required capabilities; independent of mission.
- Value of Performance (VOP) – 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 considerations for an OMOE include: defense policy and goals, threat, environment, missions, mission scenarios, and force structures. Ideally, these could be simulated in a master war-gaming module in a series of probabilistic scenarios. Regression analysis would be applied to results and a mathematical relationship between input measures of performance (MOPs) and output effectiveness would be developed. The accuracy of this method depends on modeling detailed interactions of complex human and physical interactions and because the cases are probabilistic a full set of data must be made for each set of discrete input variables. Practically, no system like this exists at this time.

The alternative to this system is to use expert opinion to integrate these diverse inputs and assess the value or utility of submarine MOPs for a given scenario. A variety of methods are used to combine these expert opinions into statistical data; the approach used for this submarine combined the Analytical Hierarchy Process (AHP) and the Additive Multi-Attribute Value Theory (MAVT).

Most decisions in the design process involve multiple criteria with complex relationships, and the human mind has limited capacity to consider everything at once. The Analytical Hierarchy Process is a decision theory developed by Thomas Saaty that works to correct the human limitations. AHP organizes the criteria in a natural hierarchy and quantifies a few things at a time using pair-wise comparison. The system works with quantitative and qualitative characteristics to synthesize results and provide feedback on consistency and sensitivity.

The AHP in this situation is used to build an OMOE function. MOPs critical to the submarine mission are identified with goal and threshold values for each. The MOPs are organized into an OMOE hierarchy, Figure 24, and weights are found for each MOP using pair-wise comparison and AHP, **Figure 25**. The weights for each MOP are used in the OMOE function as presented as Equation (2). Appendix D provides all pairwise comparison results.

$$OMOE = g[VOP_i(MOP_i) = \Sigma w_i VOP_i(MOP_i) \qquad (2)$$

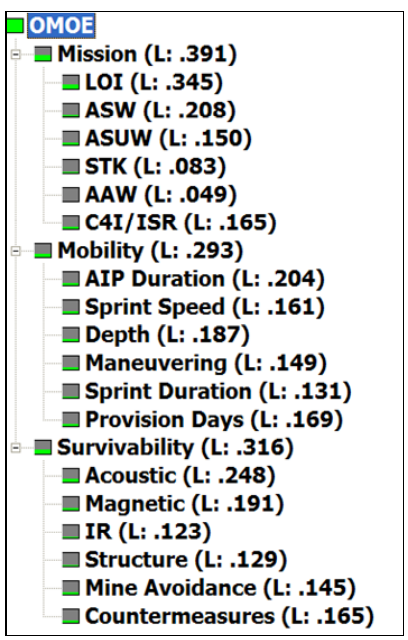


Figure 24: MOP Hierarchy

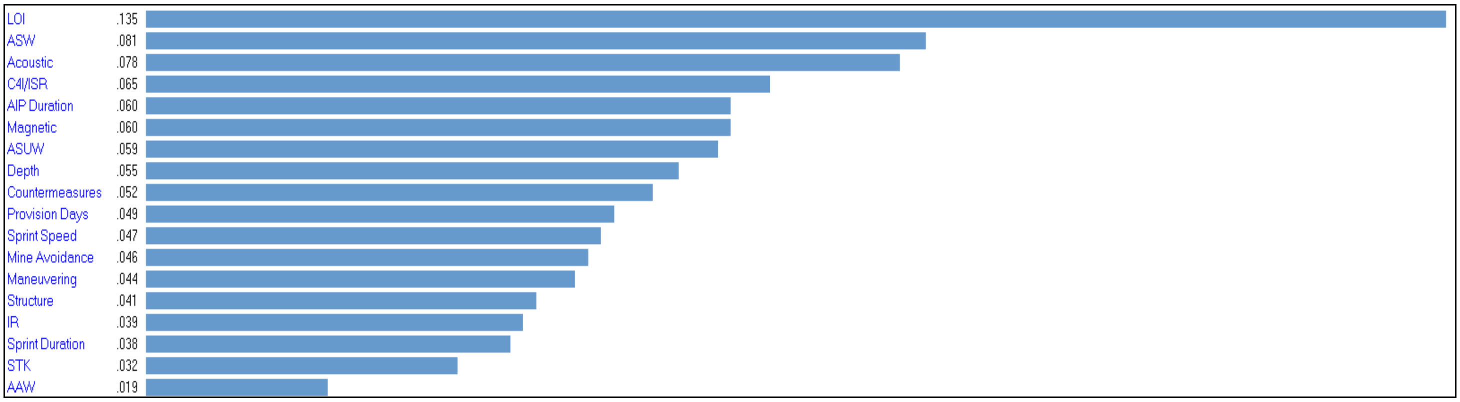


Figure 25: Pairwise Comparison Results – MOP Weights

3.4.2 Overall Measure of Risk (OMOR)

The purpose of the overall measure of risk (OMOR) is to provide a quantitative measure of technology risk for a specific design based on the selection of technologies. These technologies are specified by the design variables in Table 27. The calculation of the value of risk for any given variable, *i*, is the probability of failure, $P_{i,}$ multiplied by the consequence of said failure C_i, given in Equation (3).

$$R_i = P_i C_i \tag{3}$$

Three types of risk are considered: performance, cost, and schedule. Risk events are associated with specific design variables. P_i and C_i are estimated using Table 28 and Table 29. In order to be considered in the risk factors the event must have major impact on performance, cost, or schedule.

Table 28: Event probability estimate

Probablitiy	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 29: Event consequences estimate

Consequence Level	Given the risk is realized, what is the Magnitude of the impact? Preformance	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 dates	<5%
0.5	Acceptible 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%

Each event is then documented with its given value of risk and associated design variable or variables. Values for weight (W_{pref}, W_{cost}, *and C*) were given to the three types of risk according to a pair-wise comparison by expert option on the subject. The value for OMOR was determined by W_i, P_i, and C_i according to Equation (4).

$$OMOR = W_{pref} \frac{\Sigma P_i C_i}{\sum_i (P_i C_i)_{\max}} + W_{\cos t} \frac{\Sigma P_j C_j}{\sum_j (P_{\backslash j} C_j)_{\max}} + W_{sched} \frac{\Sigma P_k C_k}{\sum_k (P_k C_k)_{\max}} \tag{4}$$

The weight factor for performance risk (W_{pref}) is 0.5, the weight factor for cost risk (W_{cost}) is 0.3, and the weight factor for scheduling risk (W_{cost}) is 0.2. The final risk register is presented in Table 30.

Table 30: Risk Register

SWBS	Risk Type	Related DV #	DV Options	DV Description	Risk Event Ei	Event #	Pi	Ci	Ri
2	Performance	DV7	5-9	PSYS	PEM does not meet performance TLRs	1	0.5	0.7	0.35
2	Schedule	DV7	5-9	PSYS	PEM schedule delays impact program	2	0.4	0.8	0.32
2	Cost	DV7	5-9	PSYS	PEM development and acquisition cost overruns	3	0.5	0.3	0.15
2	Performance	DV7	10-15	PSYS	Reformer does not meet performance TLRs	4	0.5	0.9	0.45
2	Schedule	DV7	10-15	PSYS	Reformer schedule delays impact program	5	0.5	0.5	0.25
2	Cost	DV7	10-15	PSYS	Reformer development and acquisition cost overruns	6	0.3	0.3	0.09
2	Performance	DV8	1	Prop Type	RDP does not meet performance TLRs	7	0.4	0.8	0.32
2	Schedule	DV8	1	Prop Type	RDP schedule delays impact program	8	0.4	0.5	0.2
2	Cost	DV8	1	Prop Type	RDP development and acquisition cost overruns	9	0.6	0.3	0.18
3	Performance	DV8	1	Battery Type	NiCd Batteries do not meet performance TLRs	10	0.3	0.7	0.21
3	Schedule	DV8	1	Battery Type	NiCd Batteries' schedule delays impact program	11	0.3	0.2	0.06
3	Cost	DV8	1	Battery Type	NiCd Battery development and acquisition cost overruns	12	0.3	0.2	0.06
3	Performance	DV8	3	Battery Type	Zebra batteries do not meet performance TLRs	13	0.4	0.7	0.28
3	Schedule	DV8	3	Battery Type	Zebra batteries schedule delays impact program	14	0.4	0.2	0.08
3	Cost	DV8	3	Battery Type	Zebra battery may be very expensive compared to alternatives	15	0.4	0.2	0.08
4	Performance	DV13	0.5	Cman	Increased automation and reduced manning may not work	16	0.6	0.6	0.36
4	Schedule	DV13	0.5	Cman	Increased automation and reduced manning may cause delays	17	0.5	0.3	0.15
4	Cost	DV13	0.5	Cman	Increased automation and reduced manning may have cost overuns	18	0.5	0.5	0.25
20	Performance	DV15	1-5	UUV/TORP	Mantas do not meet performance TLRs	19	0.5	0.8	0.4
20	Schedule	DV15	1-5	UUV/TORP	Mantas schedule delays impact program	20	0.7	0.5	0.35
20	Cost	DV15	1-5	UUV/TORP	Mantas price is relatively unknown and could be prohibitively expensive	21	0.6	0.4	0.24
7	Performance	DV16	1,2	VLS	VLS does not meet performance TLRs	22	0.3	0.3	0.09

3.4.3 Cost

Figure 26 is the cost module diagram which shows the process used to calculate the Basic Cost of Construction (BCC) for the SSLOI. The first step of the process is to input the cost module variables. These are defined in Table 31.

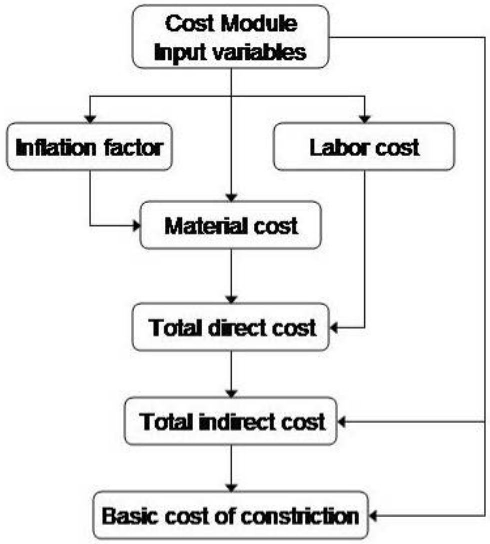


Figure 26: Cost module diagram

Table 31: Cost module input variables

Input Variable	Description
W1	SWBS 100 structure weight
W2	SWBS 200 propulsion weight
W3	SWBS 300 electrical weight
W4	SWBS 400 comand and control weight
W5	SWBS 500 auxiliaries weight
W6	SWBS 600 outfit weight
W7	SWBS 700 ordnance weight
Yoic	Initial operational capibility year
Rp	Shipbuilding rate per year after lead ship
Mh	Average man - hour rate (dollar/hr)
R	Average inflation rate
Yb	Base year (appropriation)
ovhd	Overhead rate
profit	Profit margin
PROPtype	Propulsion propeller type
BATtype	Battery type
PSYS	Propulsion system
Cman	Manning and automation factor

As shown in Figure 26, the process to produce the BCC of the submarine involves an inflation factor, labor cost, material cost, total direct cost, and indirect cost. The total cost for each component is calculated as follows:

- The inflation factor is determined using the average inflation rate and number of years between the initial estimate and the base year. This factor is then multiplied by the estimate of years of production.
- The labor cost is determined by the ship work breakdown structure (weights), complexity factors, and man-hour rate. The SWBS 100-700 labor cost is determined by multiplying the man-hour rate by the SWBS weight and the complexity factor. Labor cost for production support is determined by using the sum of SWBS labor costs times a complexity factor, and the labor cost for design and integration is determined by using the sum of the SWBS labor costs times a complexity factor.
- The material cost is determined using the SWBS weights, material cost factors, inflation factor, battery type, propulsion propeller type, and manning and automation factor.
- The total direct cost is the sum of the total labor costs and the total material cost.
- The indirect cost is found by multiplying the total direct cost by the overhead rate.
- The BCC is determined by multiplying the sum of the direct and indirect costs by one plus the profit margin (10%).

3.5 Multi-Objective Genetic Optimization

A Multi-Objective Genetic Optimization (MOGO) is used to search the design space to develop a set of optimal feasible designs for the SSLOI(X). The MOGO uses a genetic algorithm to improve a population of potential optimum designs. The process begins by randomly choosing 64 designs from the design space. Each design is then run though the synthesis model to determine the feasibility, effectiveness, risk and cost. Once all 64 designs have been evaluated they are compared to each other to determine their relative dominance and assigned a probability of selection value. Dominance is defined as the design with the best effectiveness, for a given cost and risk. At this point a new population is chosen based on the dominance and probability values. To ensure that the new population has a rich combination of genetic material two processes are performed on the population: crossover and mutation. Crossover is the merging of two designs with half of the variable values being swapped between the two designs. This ensures that different combinations of good gene pools are found. Mutation is the changing of only one design variable value in a design. This ensures that the populations will use the total design space. Once the new population is finalized the process begins again by evaluating all the designs with the synthesis model. The MOGO process is illustrated in Figure 27. The algorithm runs through hundreds of generations and provides multiple baseline designs in a non-dominated frontier.

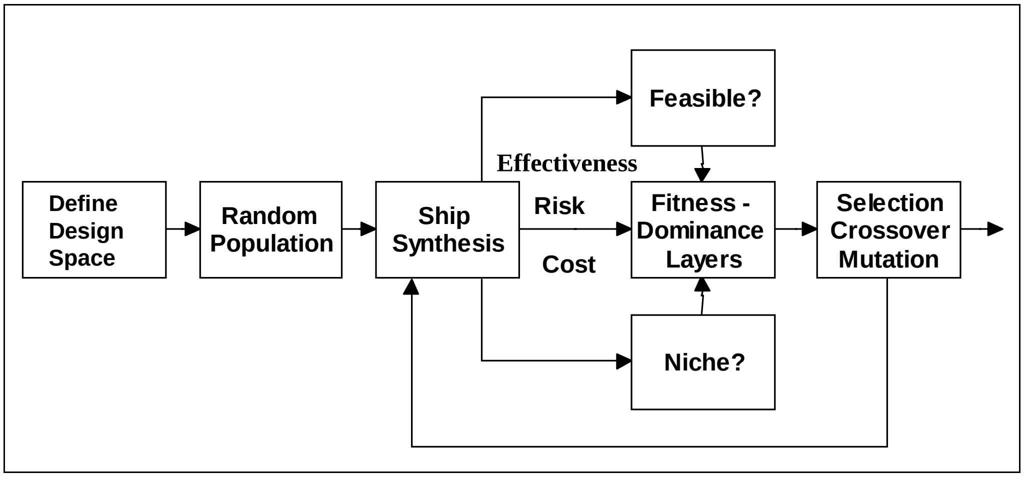


Figure 27: Multi-Objective Genetic Optimization Process.

3.6 Optimization Results

Figure 28 shows the initial non-dominated frontier developed by the MOGO. The designs circled in white represent “knees” in the graph. Knees are designs that have a large increase in overall effectiveness for only a small increase in cost or risk. Design 90, highlighted with a pink X was chosen as the first baseline design. It is a design with moderate risk, high effectiveness, and moderate cost. Design 90 has a cost of $661 million and an overall measure of effectiveness (OMOE) of 0.726. The selected design incorporates new and innovative technologies such as an air-independent system that is fueled by methanol reformers. This technology is not currently used by the US Navy but has been proven to be reliable in foreign, non-nuclear submarines.

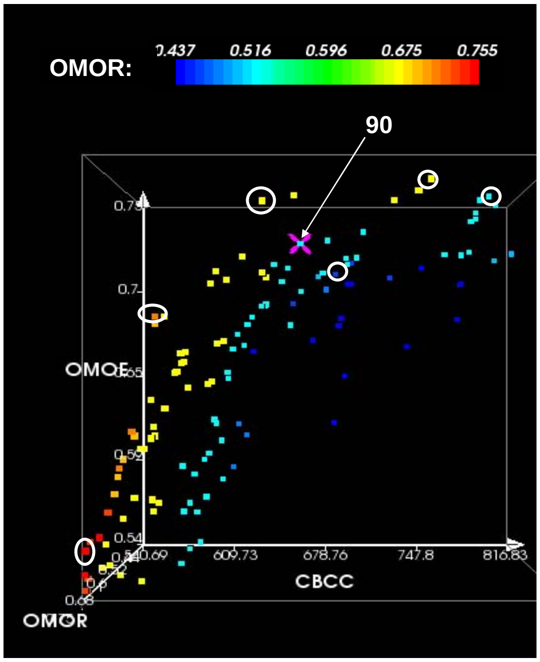


Figure 28: Non-dominated Frontier

Once Design 90 was selected, further optimization was conducted on the design by varying only continuous variables. The re-optimization was conducted to increase the OMOE as a single objective. The cost and risk were treated as upper constraints. This ensured that the cost or risk would not increase from Design 90. The optimization held the discreet variables, such as TORP, SAIL, ESM, etc., constant while varying the continuous variables such as Diameter, Length to Diameter ratio, Depth, etc. This final optimization raised the OMOE to 0.73.

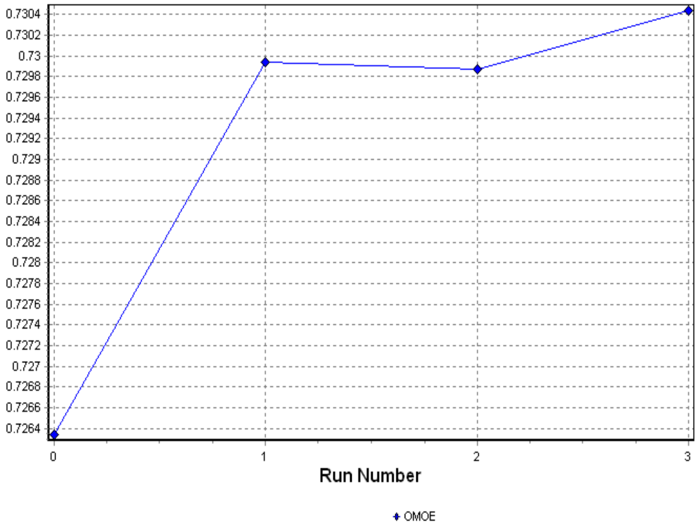


Figure 29: Additional Optimization Results

3.7 Baseline Concept Design and Design Review

Design 90 has a diving depth of 851 feet, and propulsion system Option 11: Open Cycle Diesel/AIP 2xCat 3512 V12 + 2x500kW PEM fuel cells + reformer. This particular system uses a diesel for snorkel transit and AIP for submerged power. AIP propulsion power is generated using PEM fuel cells, with methanol reformers. This is a higher risk option; however, foreign navies have used these reformers successfully. Propulsion is provided through a rim-driven propeller. Lead-acid batteries were chosen; these are the most proven, and therefore low risk, US batteries. The torpedo capabilities of the sub are supplied by the MANTAs and 2 torpedo tubes on the ship. The 3 MANTAs can fire when docked with the capability of holding 2 full size and 2 half-length or 6 half-length torpedoes. Within the sub there are 8 reloads. Option 2 of the SONARSYS was selected by the optimizer. This

EDO system (discussed in section 3.1 page 21) has no proven US capability, but again, foreign navies have used it successfully. The goal options of SAIL and ESM where chosen by the optimizer.

3.7.1 Baseline Concept Design Arrangements

Given the characteristics for the baseline design from the optimizer, a preliminary arrangement was made for the hydrodynamic hull, pressure hull, and displacing volumes to better assess its feasibility. The synthesis model estimated the volume needed for major items within the submarine including the main machinery room, auxiliary machinery room, ballast tanks, fuel, habitability, and other spaces inboard and outboard of the pressure hull. Figure 30 is the outboard profile view for the baseline design with the major components labeled. Figure 31 is a 3-D profile perspective of the hull and a 2-D diagram of the major compartments.

The basic arrangement has 3 main ballast tanks, 2 forward and 1 aft. Forward of the pressure hull are the loading areas for the MANTAs, a sonar sphere and access tube, and 2 torpedo tubes in addition to the main ballast tanks. The aft portion of the hull has room for the propulsor and main ballast tank, and the compensated fuel tank wraps around the pressure hull. The turtleback serves to run the snorkel inlet and exhaust from the main machinery room to the sail.

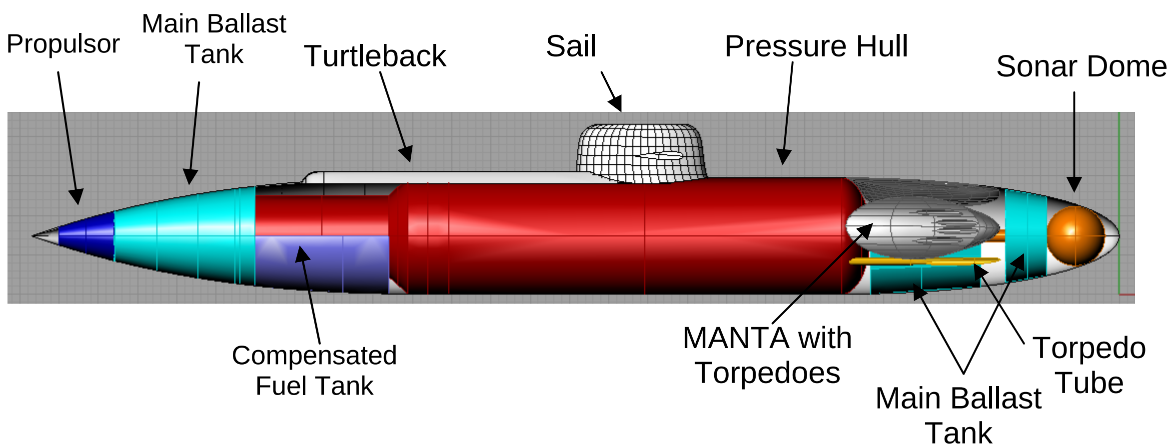


Figure 30: Baseline Design Outboard Profile View

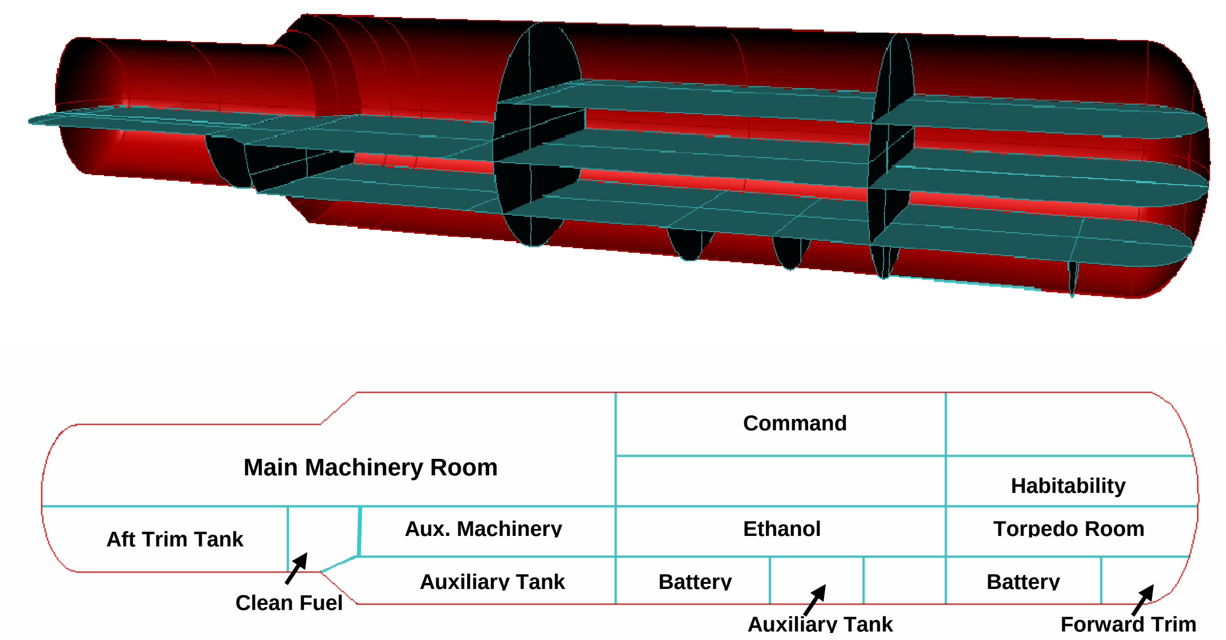


Figure 31: Baseline Design Pressure Hull Arrangement

3.7.2 Equilibrium Polygon

The equilibrium polygon is a tool used to ensure that the submerged submarine is balanced and feasible and it can be trimmed in all conditions. The overall weight and moment of the ship are calculated for each loading condition and these values are compared with the available trim ballast. If there is a loading submerged condition that the ballast can not compensate, either the ballast needs to be adjusted or the loads need to be adjusted.

Before the equilibrium polygon was created, the preliminary arrangement of the submarine was completed. From this preliminary arrangement the longitudinal center of buoyancy (LCB) of the ship is obtained. The LCB of the displacing volumes is calculated and from these the overall ship LCB is computed. The next step is to calculate the longitudinal center of gravity (LCG) of the submarine. Again the sum of each individual component is used to find the ship LCG. This LCG is used to establish a "normal" load condition. Each of the other load conditions are compared to this one.

Variations in weight and moment from this normal load condition were calculated and plotted. Table 54 in Section 4.7.5 outlines each of these loading conditions. Following the calculations of these load conditions, the weight and moment effects of sequentially filling variable ballast tanks were calculated and plotted as a polygon. The polygon must be able to compensate for all load condition variables, i.e. the polygon must contain all load points.

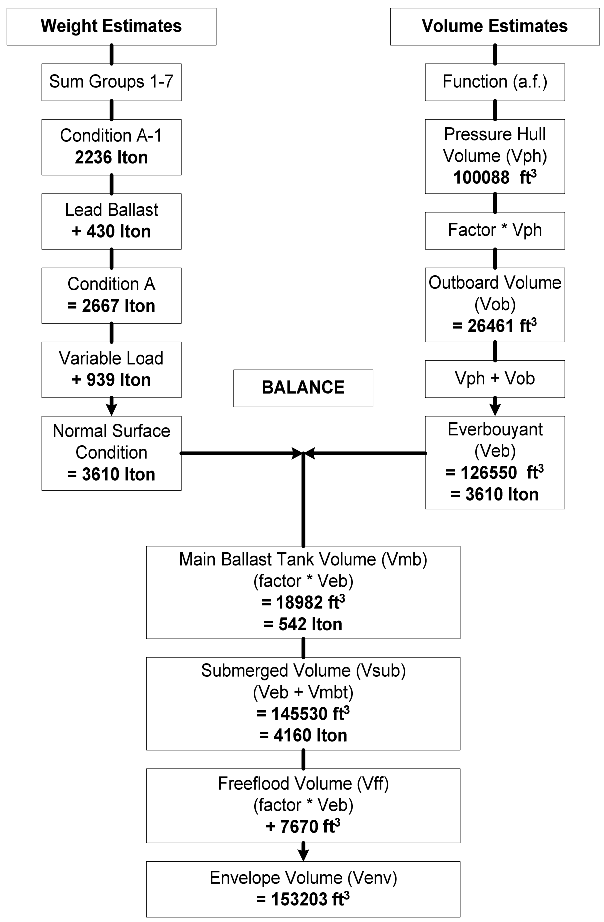


Figure 32: Initial Weight and Volume Balance

Table 32: Initial Volume

Volume			
	Volume (ft3)	Vol % of sub disp	Disp (LT)
Pressure Hull	100088	0.69	2860
Outboard Volume	26461	0.18	756
Everbouyant Volume	126550	0.87	3610
Main Ballast	18982	0.13	542
Submerged Displacement Volume	145530	1.00	4160
Freeflood Volume	7670	0.05	219
Envelope Volume	153203	1.05	4377

Table 33: Initial Weights

Weights		% of NSC
Group 1	1084	0.30
Group 2	564	0.16
Group 3	79	0.02
Group 4	195	0.05
Group 5	188	0.05
Group 6	74	0.02
Group 7	53	0.01
Condition A-1	2236	0.62
Lead Ballast	430	0.12
Condition A	2667	0.74
Variable Loads	939	0.26
Normal Surface Condition	3610	

When all points lie within the polygon, the submarine is balanced and feasible with sufficient ballast to compensate all operating conditions. The initial weight and volume balance is shown in Figure 32, the weight and volume flowchart. Table 32 and Table 33 are the summary of the weights and volumes for the baseline design. The initial equilibrium polygon was created (Figure 33) based on Table 32, Table 33, and Figure 32.

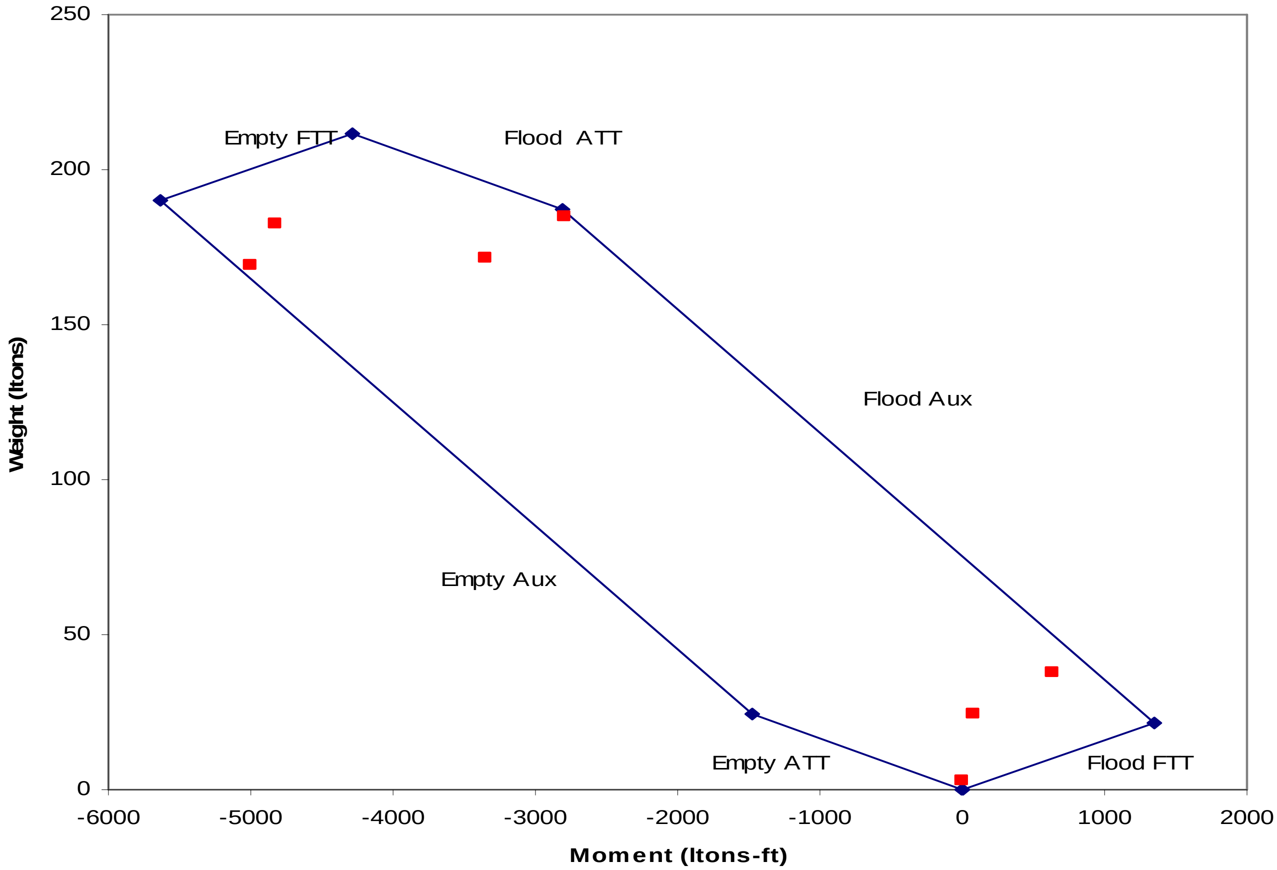


Figure 33: Initial Equilibrium Polygon

3.7.3 Baseline Design Review

On 30 January 2007 the initial submarine described in Figure 30 - Figure 1Figure 33 was presented to five submarine experts. During the design review a variety of comments and suggestions was made about necessary improvements. The following are a list of the major comments:

- The diameter of the boat is too small to be practical or producible.
- The hold and battery space of 6.5ft is too small and should be a minimum of 8.5-9ft.
- The boat contains too much variable ballast.

- Watertight bulkheads are not necessary or practical for this type of boat.
- The frames will interfere with spacing more than accounted for in the baseline model.
- The power requirements for the US combat system should be higher.
- The sprint speed might be higher than necessary or manageable.
- The cost of the combat systems is not properly calculated, and it will cost more than estimated.
- The weight and displacement of the MANTAs should be accounted for even if they are neutrally buoyant.
- The lead weight should be differentiated into trim lead, stability lead, and marginal lead.

Following the review, the synthesis modules were modified based on the comments. The major changes are as follows:

- Increased SWBS 400 and 700 labor complexity factors and material cost factors (included in this is automation and manning)
- Increased combat systems power requirements.
- For sprint speed: battery space requirements increased and sprint speed value of performance reduced.
- Variable ballast requirements adjusted.
- MANTAs: weight and displacement accounted for separately.
- Lead margins broken up separately in weight report.
- Arrangements:
  - Space module now considers specific arrangement alternatives given diameter.
  - Space module also allows for more frame depth interference.
  - More arrangement required upfront to adapt synthesis model for particular design before running optimization.
  - Hold / Battery space now required to be 9ft.

The optimizer was then rerun under the new constraints and Iteration 1 of Design 90 had the greatest value of overall measure of effectiveness (OMOE).

3.8 Baseline Iteration 1

Table 34: Iteration 1 Design Variable Values Summary

#	DV Name	Description	Design Space	Iteration 1 Values
1	D	Diameter	29-32 ft	32 ft
2	LtoD	Length to Depth Ratio	8-12	8.05
3	BtoD	Beam to Depth Ratio	1	1
4	n_a	Fullness factor aft	2.5-3.0	2.75
5	n_f	Fullness factor forward	2-2.5	2.15
6	Depth	Diving Depth	500-1000ft	1000
7	PSYS	Propulsion system alternative	Option 1) CCD, 2xCAT 3512 V12Engines Option 2) CCD, 2xCAT 3516 V16 Engines Option 3) CCD, 2xCAT 3608 IL8 Option 4) OCD/AIP, 2xCAT 3512 V12 + 2x250KW PEM Option 5) OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM Option 6) OCD/AIP, 2xCAT 3516 V16 + 2x250KW PEM Option 7) OCD/AIP, 2xCAT 3516 V16 + 2x500KW PEM Option 8) OCD/AIP, 2x CAT 3608 IL8 + 2x250KW PEM Option 9) OCD/AIP, 2x CAT 3608 IL8 + 2x500KW PEM Option 10) OCD/AIP, 2xCAT 3512 V12 + 2x250KW PEM+reformer Option 11) OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM+reformer Option 12) OCD/AIP, 2xCAT 3516 V16 + 2x250KW PEM+reformer Option 13) OCD/AIP, 2xCAT 3516 V16 + 2x500KW PEM+reformer Option 14) OCD/AIP, 2x CAT 3608 IL8 + 2x250KW PEM+reformer Option 15) OCD/AIP, 2x CAT 3608 IL8 + 2x500KW PEM+reformer	Option 11) OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM+reformer

Table 35: Design Variable Values (Cont)

DV	DV Name	Description	Design Space	Iteration 1 Values
8	PROPtype	Propulsion Prop Type	Option 1) RDP, Rim Driven Prop Option 2) Shrouded	Option 1) RDP, Rim Driven Prop
9	BATtype	Battery system type alternative	Option 1) Nickel Cadmium Option 2) Lead Acid Option 3) Zebra	Option 2) Lead Acid
10	Ebat	Battery Capacity	2500-6500 kwhr	6000 kwhr
11	Wfsnork	Weight Fuel Snorkel	50-150lton	149 lton
12	Wfaip	Weight Fuel AIP	50-150lton	130 lton
13	Ndegaus	Degaussing	0=none; 1=degaussing	1 = degaussing
14	Cman	Manpower Reduction	0.5-1.0	0.87
15	UUV/TORP	Unmanned Underwater Vehicle System	Option 1) 3 Mantas with 2 torpedo tubes and 8 reloads Option 2) 2 Mantas with 2 torpedo tubes and 8 reloads Option 3) 1 Manta with 2 torpedo tubes and 8 reloads Option 4) 3 Mantas Option 5) 2 Mantas	Option 1) 3 Mantas with 2 torpedo tubes and 8 reloads
16	VLS	Vertical Launching System Alternatives	Option 1) 6 Cell VLS Option 2) 4 Cell VLS Option 3) none	Option 3) none
17	SSYS	Sonar/Combat System Alternatives	Option 1) BQQ-10 Bow Dome Passive/Active, LWWAA, BQS-24 high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-23; BSY-2/CCSM Option 2) EDO Model 1122 MF Passive bow array, MFA, PRS, EDO Model 1121 flank array, Scout HF Chin Array, EDO Model 1123 towed array, BSY-2/CCSM Option 3) ATLAS Elektronik DBQS 40 MF cylindrical bow array, MFA, PRS, TAS-3 low-frequency towed array, FAS-3 flank array sonar, and MOA 3070 high frequency mine detection sonar; ISUS-90 CCS Option 4) Cylindrical MFP bow array, MFA array, PRS, long range flank array; Scour mine detection sonar, SUBICS 900 CCS	Option 2) EDO Model 1122 MF Passive bow array, MFA, PRS, EDO Model 1121 flank array, Scout HF Chin Array, EDO Model 1123 towed array, BSY-2/CCSM
19	SAIL	Sail (Radar, Masts and Periscopes, and communication)	Option 1) BPS-16 Radar; 2xAN/BRA-34 Multiband; AN/BVS-1 Photonics mast; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA Option 2) BPS-16 Radar; 2xAN/BRA-34 Multiband; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA, AN/BRD-7/BLD-1 Option 3) BPS-16 radar; 2xAN/BRA-34; SERO 14 Search Periscope, SERO 15 Attack Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; Shrike	Option 1) BPS-16 Radar; 2xAN/BRA-34 Multiband; AN/BVS-1 Photonics mast; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA
20	ESM	ESM Alternatives	Option 1) WLY-1 acoustic interception and countermeasures system; AN/WLQ-4, AN/BLQ-10 Electronic Support Measures (ESM) system; 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube Option 2) AN/WLY-1, 3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube	Option 1) WLY-1 acoustic interception and countermeasures system; AN/WLQ-4, AN/BLQ-10 Electronic Support Measures (ESM) system; 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube

Table 36: Concept Exploration Weights and Vertical Center of Gravity Summary

Groups	Weight (lton)	VCG (ft)
SWBS 100	971.8	14.75
SWBS 200	512.1	14.75
SWBS 300	78.0	19.85
SWBS 400	219.5	19.85
SWBS 500	163.5	19.85
SWBS 600	61.8	19.85
SWBS 700	51.1	19.85
Condition A-1	2057.8	19.85
Lead Ballast	481.4	5.60
Condition A	2539.2	17.15
Variable Laods	857.1	14.22
Normal Surface Condition	3396.3	16.41

Table 37: MOP / VOP / OMOE / OMOR Summary

Measure	MOP	Value of Performance	Actual
1	LOI	**1**	UUV/TORP = 1
2	ASW	**0.566**	SSYS =2, UUV/TORP = 1
3	ASuW	**0.684**	SSYS = 2, UUV/TORP =1
4	STK	**0.373**	VLS =3
5	AAW	**0.567**	VLS =3
6	C4I/ISR	**0.91**	SAIL =1
7	AIP Duration	**0.969**	EAIP=28.35 days
8	Sprint Speed	**0.91**	Vs=21knt
9	Diving Depth	**1**	1000ft
10	Maneuvering	**0**	Mnk=1
11	Sprint Duration	**1**	Es=1 hours
12	Provision Days	1	Ts=60 days
13	Acoustic Signature	**1**	PROPtype=1, PSYS = 11
14	Magnetic Signature	**0.822**	Ndegaus=1
15	IR Signature	**0.143**	PSYS=11
16	Structure	**1**	1000ft
17	Mine Avoidance	**0.801**	SSYS =2
18	Countermeasures	1	ESM=1
OMOE		Overall Measure of Effectiveness	0.731
OMOR		Overall Measure of Risk	0.521

Table 38: Principle Characteristics for Baseline Design and Iteration 1 Design

Characteristic	Baseline Value	Iteration 1 Value
Normal Surface Condition Weight (lton)	3610	3396
Submerged Displacement (lton)	4160	3906
L (ft)	277	258
Depth Diameter (ft)	29.5	32
Beam (ft)	29.5	32
KG (ft)	13.75	13.75
GM (ft) (normal surface condition)	1.51	1.96
GB (normal surface condition)	1	1.37
Lead weight (lton)	430	445
GM/B (surface condition)	0.051	0.061
Propulsion and power system and AIP type	OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM+reformer	OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM+reformer
Propulsor	Rim Driven Pod	Rim Driven Pod
Total Power Required for Sprint Speed (kW)	6843	6053
Total Power Required for Snorkel (kW)	1752	1752
Sprint Speed (knots)	22	21.2
Snorkel Range @ 12 knots (nm)	4129	4360
AIP Endurance (hours)	600	680
Battery Capacity (kwhr)	7295	6000
Diving Depth (ft)	851	1000
TORP system	3 Mantas with 2 torpedo tubes and 8 reloads	3 Mantas with 2 torpedo tubes and 8 reloads
VLS system	None	None
Sonar and CS system	EDO Model 1122 MF Passive bow array, MFA, PRS, EDO Model 1121 flank array, Scout HF Chin Array, EDO Model 1123 towed array, BSY-2/CCSM	EDO Model 1122 MF Passive bow array, MFA, PRS, EDO Model 1121 flank array, Scout HF Chin Array, EDO Model 1123 towed array, BSY-2/CCSM
SAIL	BPS-16 Radar; 2xAN/BRA-34 Multiband; AN/BVS-1 Photonics mast; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA	BPS-16 Radar; 2xAN/BRA-34 Multiband; AN/BVS-1 Photonics mast; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA
ESM	WLY-1 acoustic interception and countermeasures system; AN/WLQ-4, AN/BLQ-10 Electronic Support Measures (ESM) system; 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube	WLY-1 acoustic interception and countermeasures system; AN/WLQ-4, AN/BLQ-10 Electronic Support Measures (ESM) system; 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube
Total Officers	8	8
Enlisted	32	44
Total Manning	40	52
Basic Cost of Construction ($M)	645.7	918

4 Concept Development (Feasibility Study)

Concept Development of SSLOI follows 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 CDD requirements. Design risk is reduced by this analysis and he parametric equations used in Concept Exploration are validated. After the reoptimization (Section 3.8), Iteration 1 was modified until the Final Concept Design met all feasibility criteria. Concept Development starts with the Iteration 1 design.

4.1 Hull Form

4.1.1 Final Hull Form Design

The process to design the hull form is described in Section 3.1.1. The MIT hullform model has a teardrop shape and a parallel midbody. The ship is axisymmetric to improve producibility and dynamic stability. To produce the hull form the baseline characteristics were taken from the multi-objective genetic optimization (MOGO), the offsets were calculated using the MIT model equations, and then the offsets were revolved in Rhino to create a hullform. After expert critiques of this hullform, adjustments were made to the hull form in response to this feedback and other balance corrections. The expert critiques suggested that a ship diameter should be no less than 31 feet, so as shown in Figure 34, each of the level heights were determined for the selected arrangement and a 32 diameter was specified.

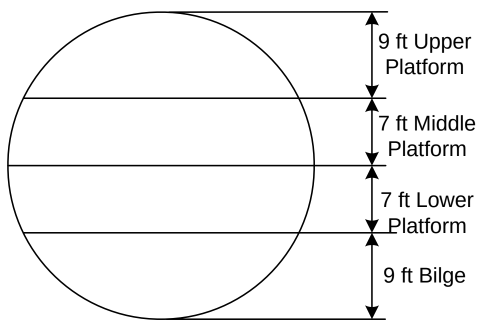


Figure 34: Cross-section of Final Hull Form

Using the 32 foot diameter, the design was re-optimized in Iteration 1 and the hull form characteristics were redefined. Table 39 is a summary of the basic characteristics used to create the final hull form. Figure 35 shows the final hull form with the divisions of the forebody, parallel midbody, and aftbody determined from the hand calculations shown in Figure 36, Figure 37, and Figure 38.

Table 39: Final Concept Hullform Characteristics

DV	Value
LOA	257.6’
D	32’
L to D	8.05
n_f	2.15
n_a	2.75

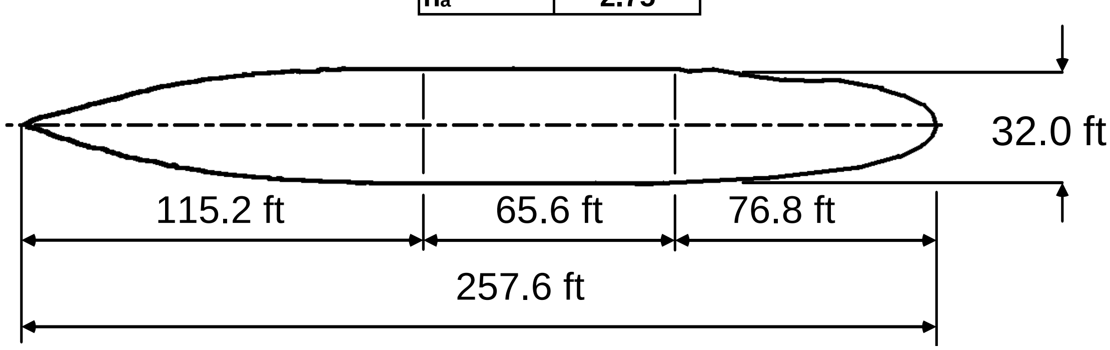


Figure 35: Final Concept Hullform

Input Values:

DVs: $D := 32 \cdot ft$ $LOD := 8.05$ $BtoD := 1.0$ $n_f := 2.15$ $n_a := 2.75$

$LOA := D \cdot LOD$ $LOA = 257.6\,ft$ $B := BtoD \cdot D$ $B = 32\,ft$ $del := B - D$ $del = 0\,ft$ $lton := 2240 \cdot lbf$ $\delta_{SW} := 35 \cdot \frac{ft^3}{lton}$

Select teardrop forebody and run L/D: $LOD_{td} := 6.0$ (6.0 opt) $L_{td} := LOD_{td} \cdot D$ $L_{td} = 192\,ft$

Select L including PMB: $L_{pmb} := LOA - LOD_{td} \cdot D$ $L_{pmb} = 65.6\,ft$

Entrance (fig 5-3): $n_f = 2.15$ (2.25 opt) $L_f := 2.4 \cdot D$ $L_f = 76.8\,ft$ (resistance optimum)

Run (fig 5-2): $n_a = 2.75$ (2.75 opt) $L_a := 3.6 \cdot D$ $L_a = 115.2\,ft$

Figure 36: Hullform Calculations

CALCULATIONS:

1. Entrance (forebody) and PMB: $x1 := 0 \cdot ft, .1 \cdot ft .. L_f + L_{pmb}$

$$yf1(x1) := \left[1 - \left(\frac{L_f - x1}{L_f}\right)^{n_f}\right]^{\frac{1}{n_f}} \cdot \frac{D}{2} \qquad offf(x1) := if\left(x1 < L_f, yf1(x1), \frac{D}{2}\right)$$

2. Run: $x1 := 0 \cdot ft, .1 \cdot ft .. LOA$

$$ya(x1) := \left[1 - \left[\frac{x1 - (L_f + L_{pmb})}{L_a}\right]^{n_a}\right] \cdot \frac{D}{2} \qquad offt(x1) := if\left(x1 \le L_f + L_{pmb}, offf(x1), ya(x1)\right)$$

3. Total Ship:

$$V_{tot} := \int_{0 \cdot ft}^{LOA} offt(x1)^2 \cdot \pi\, dx1 + (B - D) \cdot \int_{0 \cdot ft}^{LOA} offt(x1)\, dx1 \qquad V_{tot} = 153203\,ft^3 \qquad \Delta_{env} := \frac{V_{tot}}{\delta_{SW}} \qquad \Delta_{env} = 4377\,lton$$

$$V_{tot} := \int_{0 \cdot ft}^{LOA} offt(x1)^2 \cdot \pi\, dx1 \qquad V_{tot} = 153203\,ft^3 \qquad C_p := \frac{V_{tot}}{\frac{\pi D^2 LOA}{4}} \qquad C_p = 0.739$$

$$SS := \int_{0 \cdot ft}^{LOA} offt(x1) \cdot 2 \cdot \pi\, dx1 + 2 \cdot del \cdot \int_{0 \cdot ft}^{LOA} \sqrt{1 + \left(\frac{d}{dx1} offt(x1)\right)^2}\, dx1 \qquad SS = 21314\,ft^2$$

Figure 37: Final Calculations (cont.)

$L_f = 76.8\,ft$ $L_f + L_{pmb} = 142.4\,ft$ $\frac{D}{2} = 16\,ft$ $LOA = 257.6\,ft$ $offt(LOA) = 5.329 \times 10^{-15}\,ft$

$x1 := 0 \cdot ft, \frac{L_f}{10} .. L_f$ $x2 := (L_f + L_{pmb}), \left(L_f + L_{pmb} + \frac{L_a}{10}\right) .. LOA$

x1 = (ft)	offt(x1) = (ft)	x2 = (ft)	offt(x2) = (ft)
0	0	142.4	16
7.68	7.616	153.92	15.972
15.36	10.215	165.44	15.809
23.04	11.967	176.96	15.416
30.72	13.249	188.48	14.712
38.4	14.209	200	13.622
46.08	14.92	211.52	12.073
53.76	15.429	223.04	10
61.44	15.764	234.56	7.338
69.12	15.947	246.08	4.025
76.8	16	257.6	$-3.908 \cdot 10^{-14}$

Figure 38: Hullform Calculations (cont.)

The full calculations are shown in Appendix G - Hullform Model. From these calculations, the offsets were revolved in Rhino to create the 3-D hullform shown in Figure 39.

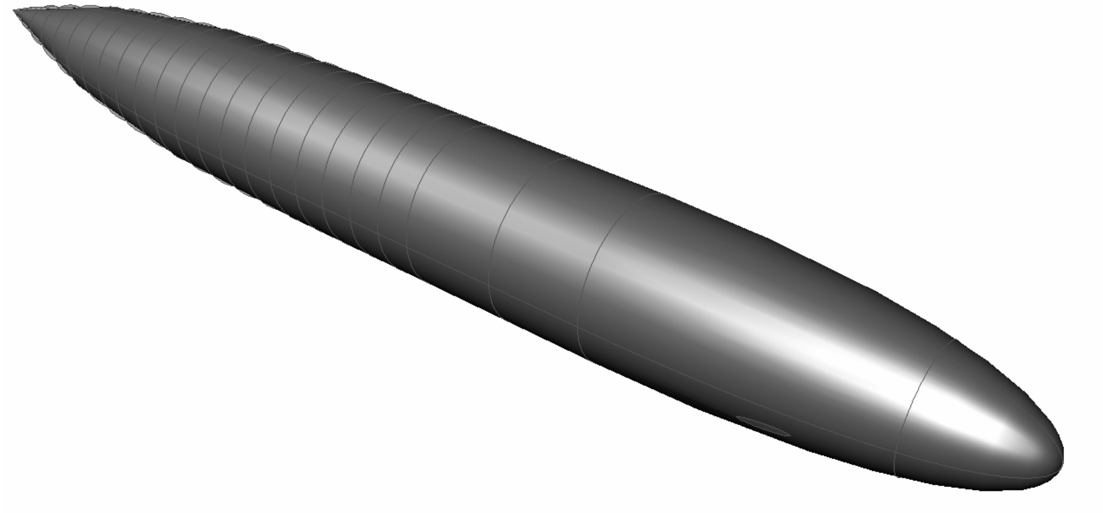


Figure 39: Final Hull Form in Rhino

The hull form was then used to calculate the envelope volume and surface area of the hydro hull. The calculated values are the hand calculations from Figure 36, Figure 37, and Figure 38; the Rhino values are less than 1% different from the hand calculations as shown in Table 40.

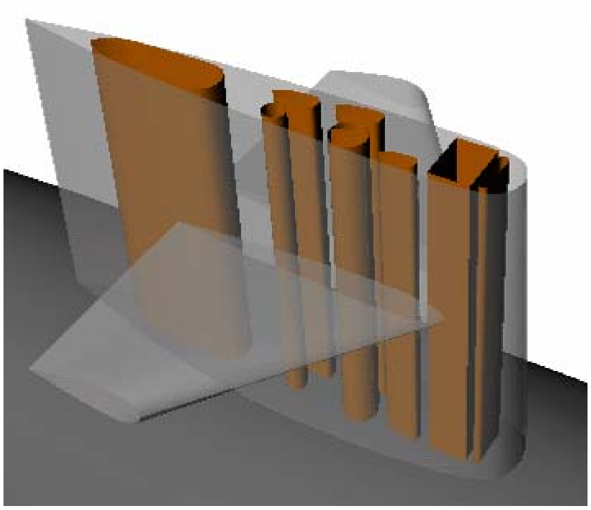
Table 40: Surface Area and Volume for Final Hull form

	Volume	Surface Area
Calculated Values	153203 ft^3	21310 ft^2
Rhino Values	153188 ft^3	21506 ft^2

4.1.2 Sail

Figure 40 shows the sail with internal components labeled. The cross-section is a NACA 0020 airfoil, with the leading edge 111 ft aft of the bow of the submarine. The reason for the large distance between the leading edge of the sail and the bow of the submarine is to allow direct access from the machinery room to the snorkel without the use of a turtleback. The chord of the sail is 31 feet while the height is 21 feet. Section 4.9.2 presents further details about the sizing of the sail and the other control surfaces.

The sail contains one photonics mast (AN/BVS-1), one Type 8 Mod 3 Periscope, one Type 18 Mod 3 Periscope, two AN/BRA-34 Multiband Radars, one AN/BPS-16 Radar, and the OE 315 HSBCA. These items were determined from Concept Exploration as described in Chapter 3.



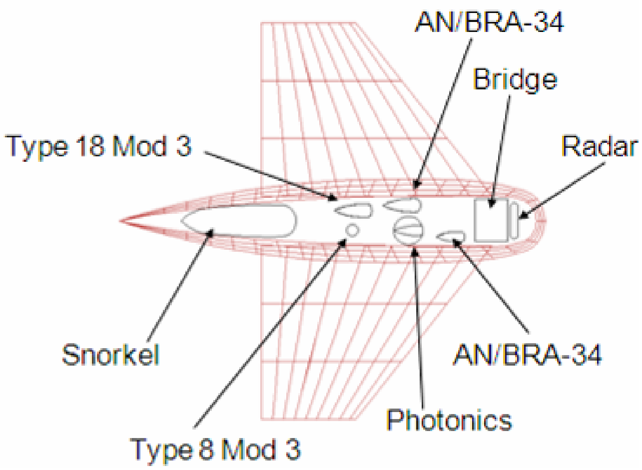


Figure 40: Sail Arrangement

4.2 Structural Design and Analysis

The iterative process of defining the structure geometry, determining structural adequacy, and adjusting scantlings is outlined in Figure 1. Only the pressure hull structure is developed in this project.

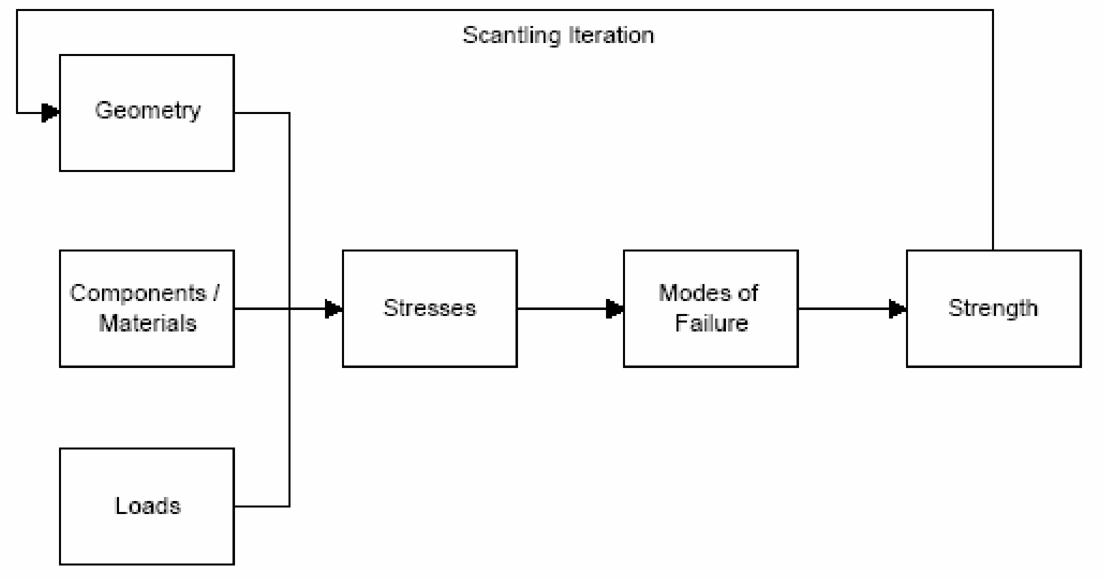


Figure 41 – Iterative Structural Design Process

The global pressure-hull geometry is based on the shape developed in the arrangement cartoon and on rules of thumb provided in Captain Harry Jackson's notes. Initial scantlings were estimated, optimized and assessed using Captain Jackson's calculation procedure implemented in a Model Center weight optimization. Once initial scantlings were obtained, they were modeled in MAESTRO. Repeated attempts to obtain results in MAESTRO were not successful due to MAESTRO modeling problems with a cylindrical geometry. As of this writing, Proteus is working on the problem. This report presents the Jackson calculation results for SSLOI.

4.2.1 Geometry, Components, and Materials

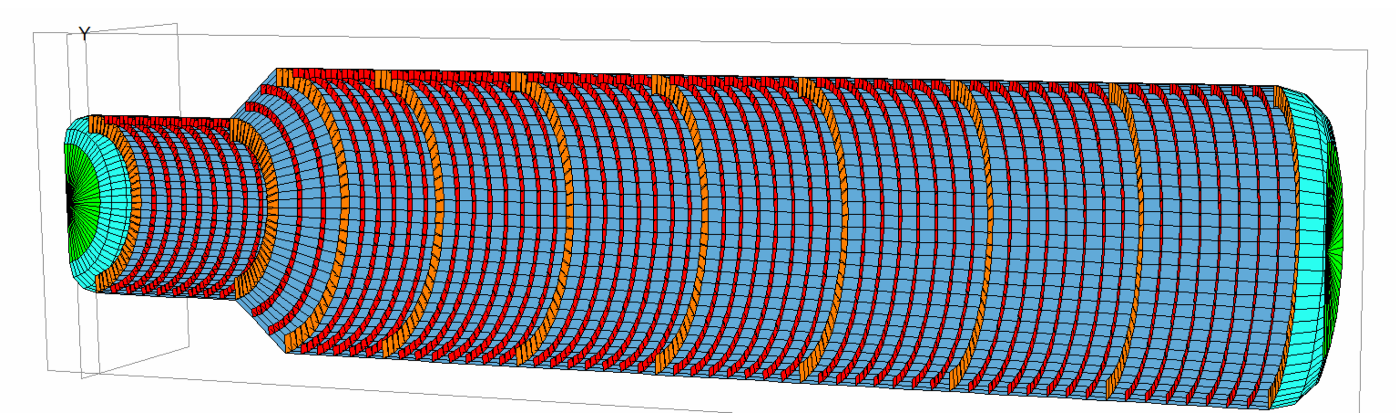


Figure 42 – Pressure Hull Geometry

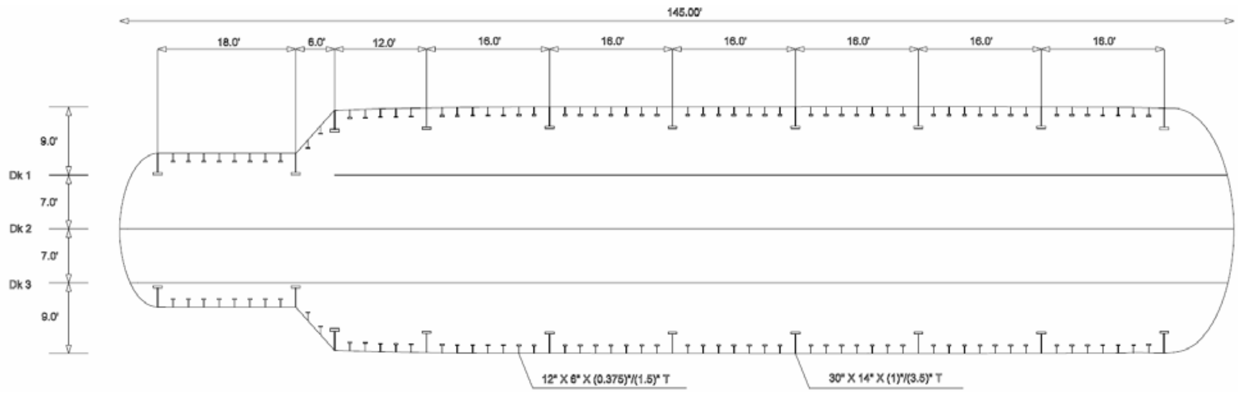


Figure 43: SSLOI Pressure Hull Primary Structure

Figure 42 and Figure 43 show the general pressure-hull arrangement for SSLOI. In the single-hull portion of the submarine which has no space between the pressure hull and the hydrodynamic hull, internal frames are used to support the structure. Aft of the frustum where the pressure hull tapers down to a smaller diameter than the external hull, external frames are used. The external frames allow more arrangeable area in the main machinery room, the aft-most section of the pressure hull.

A general structural rule for bulkhead and king frame placement suggests a bulkhead or king frame spacing of one to two hull diameters. Calculations using the Jackson method in this project showed the lowest buoyancy ratios with king frame spacing closer to one half the diameter. This is reflected in the SSLOI design with a king frame spacing of 12 to 18 feet. Since structural bulkheads limit arrangements and add weight, king frames were used in lieu of bulkheads in this design. Constraints provided by the arrangements fixed the approximate king frame locations. An aft smaller diameter section, 20 feet in diameter and 18 feet in length, with external frames contains part of the machinery room. Forward of this section is the frustum which is 6 feet long which also has external frames. Due to stress concentrations at geometric discontinuities, i.e. where the pressure hull forms an angle, king frames were used at each end of the frustum for additional support. Forward of this aft section the submarine pressure hull is flush with the hydrodynamic hull, so internal frames are used the rest of the way forward. A rule of thumb for frame spacing suggests one tenth to one fifth of the hull diameter between the frames. The frame spacing for this design was chosen as an even 2 feet throughout the pressure hull, slightly less than one tenth the hull diameter, to ensure ample support while facilitating the placement of king frames.

HY-100 steel, a high strength alloy which has a yield strength of 100,000 psi, was used for the pressure hull shell plating and all framing. The framing geometry uses standard T-shapes.

The primary load acting on the pressure hull is the hydrostatic pressure at maximum depth. A depth of 1000 feet is required for SSLOI based on concept exploration results. This is equivalent to 461 psi.

4.2.2 Stresses and Modes of Failure (Limit States)

Capt Jackson's calculation method was coded in MathCad, and a structural optimization was run for plating thickness and frame scantlings minimizing the buoyancy factor, the ratio of structural weight to buoyancy. These calculations use the hydrostatic pressure at maximum depth to consider the following limit states or failure modes: shell yielding (SY), lobar buckling (LB), general instability (GI), frame yielding (fy), and frame instability (FI). Dividing stress by the failure stress for each failure mode yields a strength ratio, r, for that mode. An adequacy parameter form is used to normalize the results. This parameter is defined as (1-r)/(1+r). This parameter always varies from negative one to positive one. Values close to negative one indicate that an element is extremely inadequate while values close to positive one are extremely over-designed. The ideal adequacy value is zero which indicates that the element meets the required strength with a given factor of safety. At this level of design the goal is to make the adequacy as close to zero as possible while keeping it positive.

The factors of safety used for these limit states were as follows: SY (1.5), fy (1.5), FI (1.8), LB (2.25), GI (3.75). It should be noted that the shell of the pressure hull is designed to fail by yielding, not buckling thus the large factors of safety for general instability and lobar buckling.

Figure 44 shows the input for a single module, Bay 1 (forward king frame through third king frame), which is representative of the other modules. The pressure hull is divided into 5 modules or bays, each represented separately in the optimization as shown in Figure 45. The optimization is performed over a continuous range for frame and plating scantlings. Figure 46 is the calculation for shell yielding, Figure 47 for lobar buckling, Figure 48 for general instability, Figure 49 for frame yielding and Figure 50 for frame buckling. The final adequacy parameter values are all be greater than zero as shown in Figure 51.

Bay1 - ADEQUACY OF SUBMARINE DESIGN PARAMETERS - Internal Frames

Ref: "Hull Material Trade Off Study", D Fox, Jan 94; PNA 1967; rev 21 Jan 97 MIT; 3/15/2007 VT

Global Variable Inputs:

Operating depth: $D_t \equiv 1000 \cdot ft$ $\rho \equiv 1030 \cdot \frac{kg}{m^3}$

Material:(HY100) $\sigma_y \equiv 100000 \cdot \frac{lbf}{in^2}$ $\rho_{st} \equiv 7.8 \cdot 10^3 \cdot \frac{kg}{m^3}$ $E \equiv 30 \cdot 10^6 \cdot \frac{lbf}{in^2}$ $\nu \equiv 0.3$

Geometry:

shell diam	$D \equiv 32 \cdot ft$	$R \equiv \frac{D}{2}$	flange tickness	$t_f \equiv 1.5 \cdot in$
frame spacing	$L_f \equiv 2 \cdot ft$		flange width	$w_f \equiv 6 \cdot in$
bulkhead spacing	$L_s \equiv 16 \cdot ft$		web thickness	$t_w \equiv .375 \cdot in$
			web height	$h_w \equiv 12 \cdot in$
			shell thickness	$t_p \equiv 1.5 \cdot in$

Define input parameters:

eccentricity $e := \frac{0.40}{100} \cdot \frac{D}{2}$ $e = 0.768\,in$

Note: variables have been changed to global variables for iteration purposes. Inputs are at the end of this spreadsheet.

Compute areas: $R_f := R - \frac{t_p}{2}$

flange,web $A_f := t_f \cdot w_f$ $A_w := t_w \cdot h_w$ $A := A_f + A_w$ $A = 13.5\,in^2$

Compute structural efficiency (buoyancy ratio):

$P_o := (\rho \cdot g \cdot D_t) + 14.7 \cdot psi$

$$BF := \frac{2 \cdot \rho_{st} \cdot \left[\left(R - \frac{t_p}{2}\right) \cdot L_f \cdot t_p + \left(R - t_p - \frac{h_w}{2}\right) \cdot t_w \cdot h_w + \left(R - t_p - h_w - \frac{t_f}{2}\right) \cdot w_f \cdot t_f\right]}{\rho \cdot R^2 \cdot L_f}$$

$BF = 0.159$ $BF = 15.946\%$

Figure 44 – Bay 1 Structural Adequacy Calculation – Input

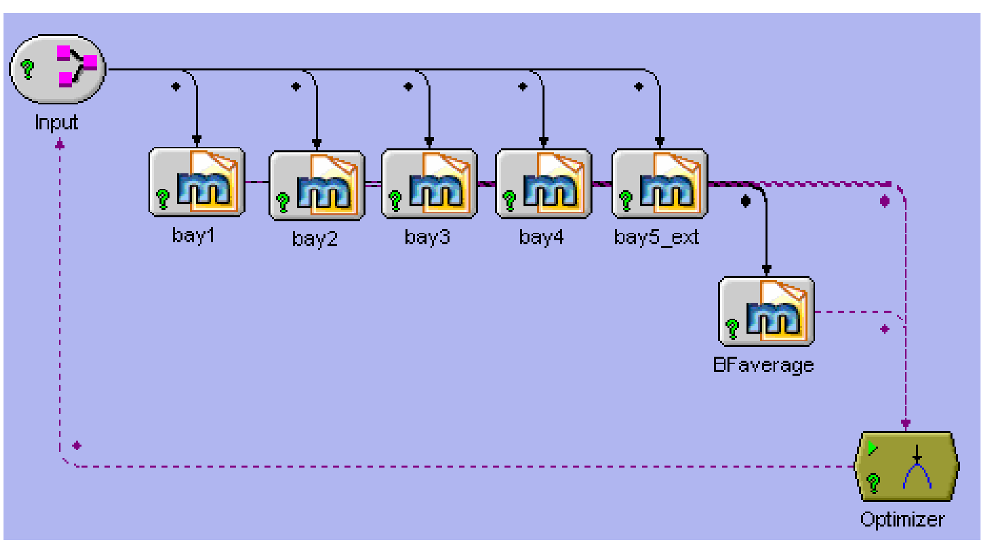


Figure 45: Model Center Optimization Model using Jackson Method

PART 1 SHELL YIELDING Safety factor is (1.5 normal): $SF_{sy} := 1.5$

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{sy}$ $P = 669.8\,\text{psi}$ $D_t = 1000\,\text{ft}$ $P_o = 461.233\,\text{psi}$

Area ratio $B := \dfrac{t_w \cdot t_p}{A + t_w \cdot t_p}$ $B = 0.04$

Slenderness parameter: $\theta := L_f \left[\dfrac{3 \cdot (1 - \nu^2)}{(R \cdot t_p)^2} \right]^{\frac{1}{4}}$

Deflection coefficient: $N := \dfrac{\cosh(\theta) - \cos(\theta)}{\sinh(\theta) + \sin(\theta)}$ $\theta = 1.818$

Frame flexability parameter: $\beta := \dfrac{2 \cdot N}{A + t_w \cdot t_p} \cdot \left[\dfrac{1}{3 \cdot (1 - \nu^2)} \right]^{0.25} \cdot \sqrt{R \cdot t_p}^{\,3}$ $\beta = 2.417$

Frame deflection parameter: $\Gamma := \dfrac{\left(1 - \frac{\nu}{2}\right) - B}{1 + \beta}$ $\Gamma = 0.237$

Bending effect (mem): $H_M := -2 \cdot \dfrac{\sinh\left(\frac{\theta}{2}\right) \cdot \cos\left(\frac{\theta}{2}\right) + \cosh\left(\frac{\theta}{2}\right) \cdot \sin\left(\frac{\theta}{2}\right)}{\sinh(\theta) + \sin(\theta)}$ $H_M = -0.895$

Bending effect (bend): $H_E := -2 \cdot \left(\dfrac{3}{1 - \nu^2} \right)^{0.5} \cdot \dfrac{\sinh\left(\frac{\theta}{2}\right) \cdot \cos\left(\frac{\theta}{2}\right) - \cosh\left(\frac{\theta}{2}\right) \cdot \sin\left(\frac{\theta}{2}\right)}{\sinh(\theta) + \sin(\theta)}$ $H_E = 0.457$

Midbay shell stress is calculated:

Bending efffect near frame: $K := \dfrac{\sinh(\theta) - \sin(\theta)}{\sinh(\theta) + \sin(\theta)}$

$\sigma_{\phi\phi so} := \dfrac{-P \cdot R}{t_p} \cdot \left[1 + \Gamma \cdot (H_M + \nu \cdot H_E) \right]$ outer $\sigma_{xxso} := \dfrac{-P \cdot R}{t_p} \cdot (0.5 + \Gamma \cdot H_E)$

$\sigma_{\phi\phi si} := \dfrac{-P \cdot R}{t_p} \cdot \left[1 + \Gamma \cdot (H_M - \nu \cdot H_E) \right]$ inner $\sigma_{xxsi} := \dfrac{-P \cdot R}{t_p} \cdot (0.5 - \Gamma \cdot H_E)$

hoop axial

Shell stress at frames is:

$\sigma_{\phi\phi fo} := \dfrac{-P \cdot R}{t_p} \cdot \left[1 - \Gamma \cdot \left[1 + \nu \cdot \left(\dfrac{3}{1 - \nu^2} \right)^{0.5} \cdot K \right] \right]$ outer $\sigma_{xxfo} := \dfrac{-P \cdot R}{t_p} \cdot \left[0.5 - \Gamma \cdot \left(\dfrac{3}{1 - \nu^2} \right)^{0.5} \cdot K \right]$

$\sigma_{\phi\phi fi} := \dfrac{-P \cdot R}{t_p} \cdot \left[1 - \Gamma \cdot \left[1 - \nu \cdot \left(\dfrac{3}{1 - \nu^2} \right)^{0.5} \cdot K \right] \right]$ inner $\sigma_{xxfi} := \dfrac{-P \cdot R}{t_p} \cdot \left[0.5 + \Gamma \cdot \left(\dfrac{3}{1 - \nu^2} \right)^{0.5} \cdot K \right]$ $j := 1..8$

$$\sigma_{sy} := \begin{pmatrix} \sigma_{\phi\phi so} \\ \sigma_{\phi\phi si} \\ \sigma_{xxso} \\ \sigma_{xxsi} \\ \sigma_{\phi\phi fo} \\ \sigma_{\phi\phi fi} \\ \sigma_{xxfo} \\ \sigma_{xxfi} \end{pmatrix} \qquad \sigma_{sy} = \begin{pmatrix} -70319.754 \\ -64751.254 \\ -52148.033 \\ -33586.367 \\ -59752.115 \\ -71070.868 \\ -24002.61 \\ -61731.789 \end{pmatrix} \text{psi}$$

$\sigma_1 := \sigma_{sy_0}$ $\sigma_2 := \sigma_{sy_2}$ $\sigma_{SYM} := \left(\sigma_1^{\,2} - \sigma_1 \cdot \sigma_2 + \sigma_2^{\,2} \right)^{\frac{1}{2}}$

$\sigma_3 := \sigma_{sy_5}$ $\sigma_4 := \sigma_{sy_7}$ $\sigma_{SYF} := \left(\sigma_3^{\,2} - \sigma_3 \cdot \sigma_4 + \sigma_4^{\,2} \right)^{\frac{1}{2}}$

$\sigma_{SYM} = 63223.795\,\text{psi}$ $\sigma_{SYF} = 66892.079\,\text{psi}$ $\sigma_{SY} := \max\left(\begin{pmatrix} \sigma_{SYM} \\ \sigma_{SYF} \end{pmatrix} \right)$ $\sigma_{SY} = 66892.079\,\text{psi}$

Now according to Von Mises (max distortion theory) applied at mid bay(outer) and frame(inner):

$r_{SY} := \dfrac{\sigma_{SY}}{\sigma_y}$ $r_{SY} = 0.669$ $\gamma_{SY} := \dfrac{1 - r_{SY}}{1 + r_{SY}}$ $\gamma_{SY} = 0.198$

Figure 46: Bay 1 Structural Adequacy Calculation – Shell Yielding

PART 2 LOBAR BUCKLING Safety factor is (2.25 normal) : $SF_{lb} := 2.25$

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{lb}$ $P = 1004.7\,psi$

Collapse pressure:

$$P_{cLB} := \frac{2.42 \cdot E \cdot \left(\frac{t_p}{D}\right)^{2.5}}{\left(\frac{L_f}{D} - 0.45 \cdot \sqrt{\frac{t_p}{D}}\right) \cdot \left(1 - \nu^2\right)^{0.75}} \qquad P_{cLB} = 2161.787\,psi \qquad r_{LB} := \frac{P}{P_{cLB}} \qquad r_{LB} = 0.465$$

$$\gamma_{LB} := \frac{1 - r_{LB}}{1 + r_{LB}} \qquad \gamma_{LB} = 0.365$$

Figure 47: Bay 1 Structural Adequacy Calculation – Lobar Buckling

PART 3 GENERAL INSTABILITY Safety factor is: $SF_{gi} := 3.75$

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{gi}$ $P = 1674.5\,psi$

Compute effective frame spacing: $\gamma := \frac{P}{2 \cdot E} \cdot \left(\frac{R}{t_p}\right)^2 \cdot \sqrt{3 \cdot \left(1 - \nu^2\right)}$ $\gamma = 0.756$

Compute clear length: $L_c := L_f - t_w$ $L_c = 23.625\,in$

$n_1 := 0.5 \cdot \sqrt{1 - \gamma}$ $n_1 = 0.247$ $n_2 := 0.5 \cdot \sqrt{1 + \gamma}$ $n_2 = 0.662$

$$F_1 := \frac{4}{\theta} \cdot \left| \frac{\cosh(n_1 \cdot \theta)^2 - \cos(n_2 \cdot \theta)^2}{\frac{\cosh(n_1 \cdot \theta) \cdot \sinh(n_1 \cdot \theta)}{n_1} + \frac{\cos(n_2 \cdot \theta) \cdot \sin(n_2 \cdot \theta)}{n_2}} \right| \qquad F_1 = 0.928$$

must be less than 1.00

Effective plate length: $L_{eff} := L_c \cdot F_1 + t_w$ $L_{eff} = 22.307\,in$

Theoretical critical lobe number values are: $i := 0..2$ $t_w = 0.375\,in$ Effective plate area: $A_{eff} := L_{eff} \cdot t_p$

Circumferential: $n := \begin{pmatrix} 2 \\ 3 \\ 4 \end{pmatrix}$

Frame-plate neutral axis (ref web centre+ toward flange): $y_{na} := \frac{\left(\frac{h_w + t_f}{2}\right) \cdot A_f - \left(\frac{h_w + t_p}{2}\right) \cdot A_{eff}}{A_{eff} + A_w + A_f}$ $y_{na} = -3.516\,in$

Longitudinal: $mm := \pi \cdot \frac{R}{L_s}$ $mm = 3.142$

Moments of inertia for plate,flange,web: $I_p := \frac{L_{eff} \cdot t_p^{\,3}}{12}$ $I_w := \frac{t_w \cdot h_w^{\,3}}{12}$ $I_f := \frac{w_f \cdot t_f^{\,3}}{12}$

$$I_{pcor} := I_p + A_{eff} \cdot \left[\left(\frac{t_p + h_w}{2}\right) + y_{na}\right]^2 \qquad I_{wcor} := I_w + A_w \left(y_{na}\right)^2 \qquad I_{fcor} := I_f + A_f \left(\frac{t_f + h_w}{2} - y_{na}\right)^2$$

$I_{pcor} = 356.25\,in^4$ $I_{wcor} = 109.627\,in^4$ $I_{fcor} = 950.188\,in^4$

Total: $I_{eff} := I_{pcor} + I_{wcor} + I_{fcor}$ $I_{eff} = 1.416 \times 10^3\,in^4$

The critical pressure is:

$$P_{cGI_i} := \frac{E \cdot t_p}{R} \cdot \frac{mm^4}{\left[\left(n_i\right)^2 - 1 + \frac{mm^2}{2}\right] \cdot \left[\left(n_i\right)^2 + mm^2\right]^2} + \frac{\left[\left(n_i\right)^2 - 1\right] \cdot E \cdot I_{eff}}{12 \cdot R^3 \cdot L_f}$$

$$P_{cGI} = \begin{pmatrix} 15019.591 \\ 5123.798 \\ 2023.881 \end{pmatrix} psi \qquad P_{cGI} := \min(P_{cGI}) \qquad P_{cGI} = 2023.881\,psi \qquad \lambda := \left[\frac{\frac{L_f}{D}}{\left(\frac{t_p}{D}\right)^{\frac{3}{2}}} \cdot \frac{\sigma_y}{E}\right]^{\frac{1}{2}} \qquad \lambda = 0.924$$

$$r_{GI} := \frac{P}{P_{cGI}} \qquad r_{GI} = 0.827 \qquad \gamma_{GI} := \frac{1 - r_{GI}}{1 + r_{GI}} \qquad \gamma_{GI} = 0.094$$

Figure 48: Bay 1 Structural Adequacy Calculation – General Instability

PART 4 FRAME YIELDING Safety factor is: $SF_{fy} := 1.5$

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{fy}$ $P = 669.8\,psi$

Compute direct stress: $\beta_f := \frac{t_w}{L_f}$ Radius to frame NA: $R_{fna} := \frac{D}{2} - t_p - \frac{h_w}{2} - y_{na}$

$$\alpha_p := \frac{A}{L_f \cdot t_p} \cdot \frac{\frac{D - t_p}{2}}{R_{fna}} \qquad \Gamma_p := \frac{P}{2 \cdot E} \cdot \left(\frac{\frac{D-t_p}{2}}{t_p}\right)^2 \cdot \left[3 \cdot \left(1 - \nu^2\right)\right]^{\frac{1}{2}}$$

$$n_1 := \frac{1}{2} \cdot \left(1 - \Gamma_p\right)^{\frac{1}{2}} \qquad n_2 := \frac{1}{2} \cdot \left(1 + \Gamma_p\right)^{\frac{1}{2}}$$

$$F_1 := \frac{4}{\theta} \cdot \frac{\cosh\left(n_1 \cdot \theta\right)^2 - \cos\left(n_2 \cdot \theta\right)^2}{\frac{\cosh\left(n_1 \cdot \theta\right) \cdot \sinh\left(n_1 \cdot \theta\right)}{n_1} + \frac{\cos\left(n_2 \cdot \theta\right) \cdot \sin\left(n_2 \cdot \theta\right)}{n_2}}$$

Stress adjuster: $SA := 1 - \frac{\alpha_p}{\alpha_p + \beta_f + \left(1 - \beta_f\right) \cdot F_1}$ $SA = 0.711$

$$\sigma_{direct} := \frac{\left(1 - \frac{\nu}{2}\right) \cdot P \cdot \left(\frac{D}{2} - \frac{t_p}{2}\right)^2}{t_p \cdot \left(\frac{D}{2} - t_p - h_w - t_f\right)} \cdot SA \qquad \sigma_{direct} = 55789.629\,psi$$

Compute bending stress due to eccentricity:

Shell-frame length: $c := \frac{t_p}{2} + h_w + t_f$ $n := 2$

Bending stress: $\sigma_{bend} := \frac{E \cdot c \cdot e \cdot \left\lfloor (n)^2 - 1 \right\rfloor}{R^2} \cdot \frac{P}{P_{cGI} - P}$ $\sigma_{bend} = 13216.51\,psi$

Total stress: $\sigma_{fr} := \sigma_{direct} + \sigma_{bend}$ $\sigma_{fr} = 69006.138\,psi$

$$r_{fy} := \frac{\sigma_{fr}}{\sigma_y} \qquad r_{fy} = 0.69 \qquad \gamma_{fy} := \frac{1 - r_{fy}}{1 + r_{fy}} \qquad \gamma_{fy} = 0.183$$

Figure 49: Bay 1 Structural Adequacy Calculation – Frame Yielding

PART 5 FRAME INSTABILITY   Safety factor is: $SF_{fi} := 1.8$

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{fi}$ $P = 803.76\,psi$

Area of plate: $A_p := t_p \cdot L_f$ $A_p = 0.023\,m^2$

Frame-plate neutral axis
(ref web centre+ toward flange):
$$y_{na2} := \frac{\left(\frac{t_f}{2} + \frac{h_w}{2}\right) \cdot A_f - \left(\frac{t_p}{2} + \frac{h_w}{2}\right) \cdot A_p}{A_p + A_w + A_f} \qquad y_{na2} = -3.682\,in$$

Moments of inertia for plate,flange,web (compute Ip using actual plate length: $I_p := \frac{L_f \cdot t_p^3}{12}$ $I_p = 6.75\,in^4$

Correct the individual moments from the na:

$$I_{pcor} := I_p + A_p \cdot \left(\frac{t_p}{2} + \frac{h_w}{2} + y_{na2}\right)^2 \qquad I_{wcor} := I_w + A_w \cdot y_{na2}^2 \qquad I_{fcor} := I_f + A_f \left(\frac{h_w}{2} + \frac{t_f}{2} - y_{na2}\right)^2$$

Then total plate, frame moment of inertia is: $I := I_{pcor} + I_{wcor} + I_{fcor}$

Diameter to NA is: $D_{na} := D - 2 \cdot t_p - h_w - 2 \cdot y_{na2}$ $D_{na} = 31.364\,ft$

Compute pressure limit: $P_{cFI} := \frac{25 \cdot E \cdot I}{D_{na}^3 \cdot L_f}$ $P_{cFI} = 845.111\,psi$ $P = 803.76\,psi$

$$r_{FI} := \frac{P}{P_{cFI}} \qquad r_{FI} = 0.951 \qquad \gamma_{FI} := \frac{1 - r_{FI}}{1 + r_{FI}} \qquad \gamma_{FI} = 0.025$$

Figure 50: Bay 1 Structural Adequacy Calculation – Frame Instability

Results: $\gamma_{SY} = 0.198$ $\gamma_{LB} = 0.365$ $\gamma_{GI} = 0.094$ $\gamma_{fy} = 0.183$ $\gamma_{FI} = 0.025$ $BF = 0.159$

Figure 51: Bay 1 Structural Adequacy Calculation - Results

4.3 Power and Propulsion

The SSLOI propulsion system consists of two CAT 3512 V12 diesel engines for use during snorkel, two 500KW PEM fuel cells used during submerged operations, two ethanol reformers, and lead-acid batteries. The PEM fuel cells use hydrogen from the ethanol reformers, and pure oxygen, stored in liquid form inside the pressure hull. SSLOI has an Integrated Power System (IPS) to distribute power throughout the ship and power the Rim Driven Propulsor (RDP).

The process for determining the power and propulsion requirements began with a series of calculations of resistance, SHP, sprint speed, AIP endurance, sprint endurance, and snorkel endurance. The calculated values must satisfy the CDD requirements and should closely correlate to the values produced by the MOGO. After endurance calculations were determined to be consistent with the MOGO, a propeller optimization was run. The prop was initially optimized based on AIP, but adjusted to ensure no cavitation at other speed conditions. Prop characteristics were plugged back into the propulsion model and the endurances were checked with the CDD. Corrections were made if the calculated endurances did not meet the CDD.

4.3.1 Resistance and Effective Horsepower

Submerged bare hull resistance calculations were performed using a modified Gilmer and Johnson method and checked with the MIT Harry Jackson method. Figure 52 shows the VT method. The initial values used in this method correlate closely with those from the MOGO. The viscous resistance is found using a modified Gilmer and Johnson form factor and an ITTC coefficient of friction which uses a 30% correction factor for sails and appendages. The total bare hull resistance is the sum of viscous resistance, correlation allowance and wavemaking resistance when near the surface. Using this resistance, the Effective Horsepower (EHP) was determined over a range of speeds. The results were compared with those from the MIT method (shown in Figure 53) for validation. The MIT method includes the sail directly and other appendages using a percentage. Figure 54 shows the bare hull resistance curves. Figure 55 shows a comparison of the VT and MIT methods for calculating EHP. There is good agreement between the methods. Figure 56 shows the SSLOI EHP curve.

Resistance and Power $ii := 21$

Calculate at series of speeds: $i := 1..ii$ $V_i := (i-1)\cdot knt + V_0$

Correlation Allowance

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

Viscous Resistance

Form Factor adapted from Gilmer and Johnson: $formfac := 1 + .5\cdot\frac{B}{LOA} + 3\cdot\left(\frac{B}{LOA}\right)^{\left(7-n_f-\frac{n_a}{2}\right)}$ $formfac = 1.064$

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

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

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

Bare Hull Resistance

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

Effective Horsepower

Power, Bare hull: $P_{EBH_i} := R_{T_i}\cdot V_i$

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

Figure 52: Resistance Calculations

MIT Method (for comparison and validation to VT method):

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

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

Appendage drag (including sail) calculation:

Surface area of the sail: $A_s := 400\cdot ft^2$ $C_{Ds} := .009$ $A_s\cdot C_{Ds} = 3.6\,ft^2$

For the remaining appendages, use the expression for $A_{other}*C_{dother}$ = $App := \frac{LOA\cdot D}{1000}$ $App = 8.243\,ft^2$

$$EHPMIT_i := 0.5\cdot\rho_{SW}\cdot(V_i)^3\cdot\left[S\cdot\left(C_{F_i}\cdot C_{hf} + C_A\right) + \left[\left(A_s\cdot C_{Ds}\right) + App\right]\right] \qquad EHPMIT_1 = 70.781\,hp$$

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

Figure 53: MIT Method Resistance Calculations

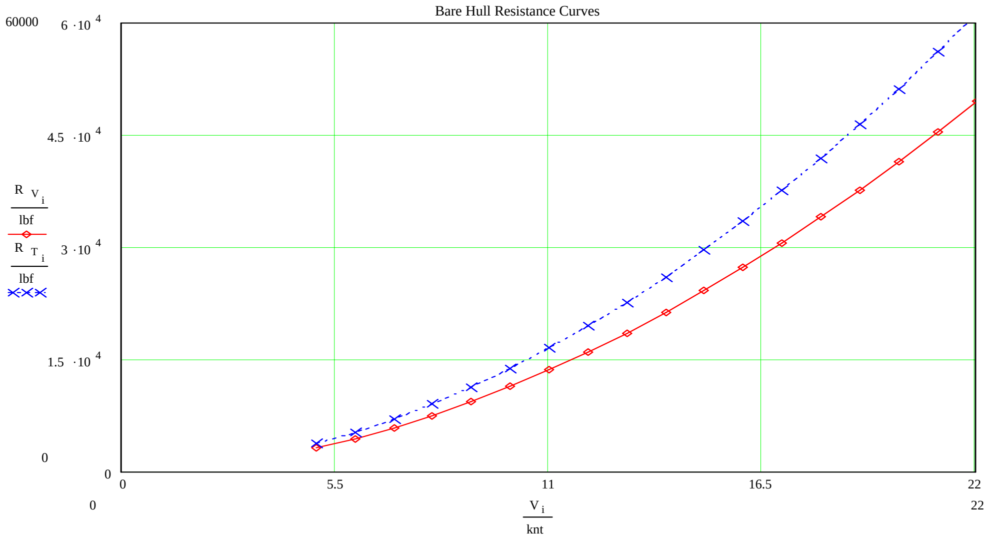


Figure 54: Submerged Bare Hull Resistance vs. Speed

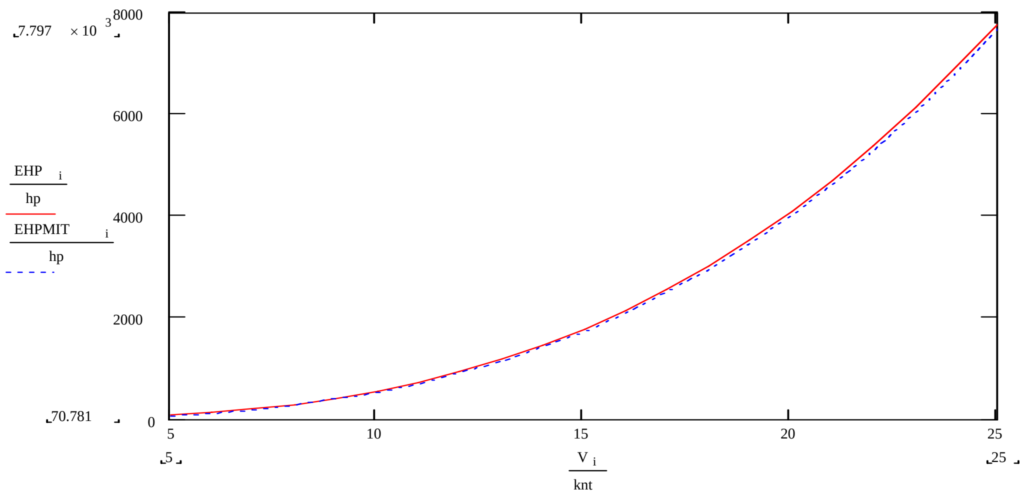


Figure 55: Comparison of VT and MIT methods

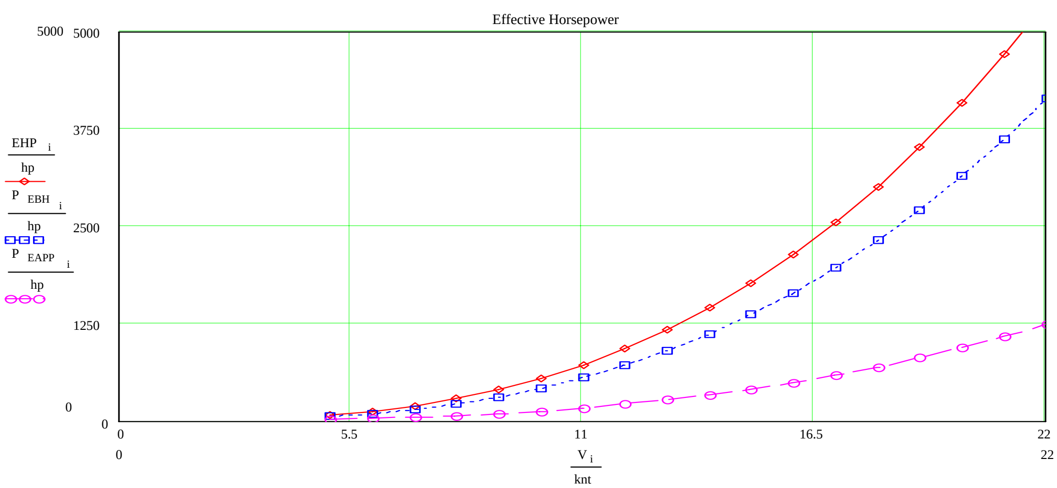


Figure 56: Submerged EHP vs. Speed

4.3.2 Propulsion

Additional calculations provided values for the wake fraction, thrust deduction factor and thrust. Figure 57 shows the calculations for these values. These values were necessary for optimization of the propeller.

$$C_{ws} := \frac{S}{\pi \cdot LOA \cdot D} \qquad C_{ws} = 0.823$$

$$w := 1 - .371 - 1.7151 \cdot \frac{\frac{D_P}{D}}{\sqrt{C_{ws} \cdot \frac{LOA}{D}}} \qquad w = 0.205$$

wake fraction

$$w := \mathrm{if}(w < 0.1, 0.1, w) \qquad w = 0.205$$

$$t := 1 - .632 - 1.3766 \cdot \frac{\frac{D_P}{D}}{\sqrt{C_{ws} \cdot \frac{LOA}{D}}} \qquad t = 0.028$$

thrust deduction fraction - prop changes pressure distribution around hull which effectively changes the resistance of towed hull

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

$$V_A := V \cdot (1 - w)$$

speed of advance - average wake velocity seen by prop

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

$$\eta_H := \frac{1 - t}{1 - w} \qquad \eta_H = 1.07$$

hull efficiency

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

Figure 57: Calculation of Wake Fraction, Thrust Deduction Factor and Thrust

Optimization of the propeller is performed using the Michigan POP (Propeller Optimization Program). The program is based on the Wageningen B Series propeller curves. The propeller is optimized for AIP endurance and is then evaluated for snorkel and AIP sprint. If the propeller cavitates or is not feasible, it must be re-optimized. Table 41 shows the input values for the propeller analysis.

Table 41: Input Values for Propeller Optimization

Description	Value
Thrust AIP endurance @ 5 knt	19.47 kN
Thrust AIP Sprint @ 22 knt	293.5 kN
Thrust Snorkel (submerged) @ 12 knt	101.6 kN
Propeller Diameter (Dp) (optimized)	5.97 m
Wake fraction (based on Prop Dia)	0.221
Depth of shaft centerline (submerged)	100 m
Depth of shaft center line (surfaced)	18 m
Number of blades	7
Burrill Percent of Back Cavitation	5%
Weight fuel AIP	130 lton
Weight fuel Diesel	170 lton

Initial estimates were made for Expanded Area Ratio (EAR), Pitch to Diameter Ratio and propeller diameter (D_P). Using the Wageningen B Series, POP optimizes all these values. The wake fraction is updated using the optimized D_P. The optimization is redone with the new wake fraction. This iteration process is performed until D_p does not change. During the optimization process, 7-bladed propellers were found to be the most efficient.

The optimization results were used to evaluate the snorkel and sprint conditions to ensure the efficiencies satisfied the CDD and that the propeller does not cavitate. The POP program uses Burrill's Simple Cavitation Diagram, shown in Figure 58; this is a plot of the mean thrust loading against the local cavitation number. To keep the signatures as small as possible, a strict 5% Burrill back cavitation criteria is used. If the propeller violates the cavitation criteria, the POP program gives a warning and changes must be made. The most effective change is a decrease of the P/D ratio.

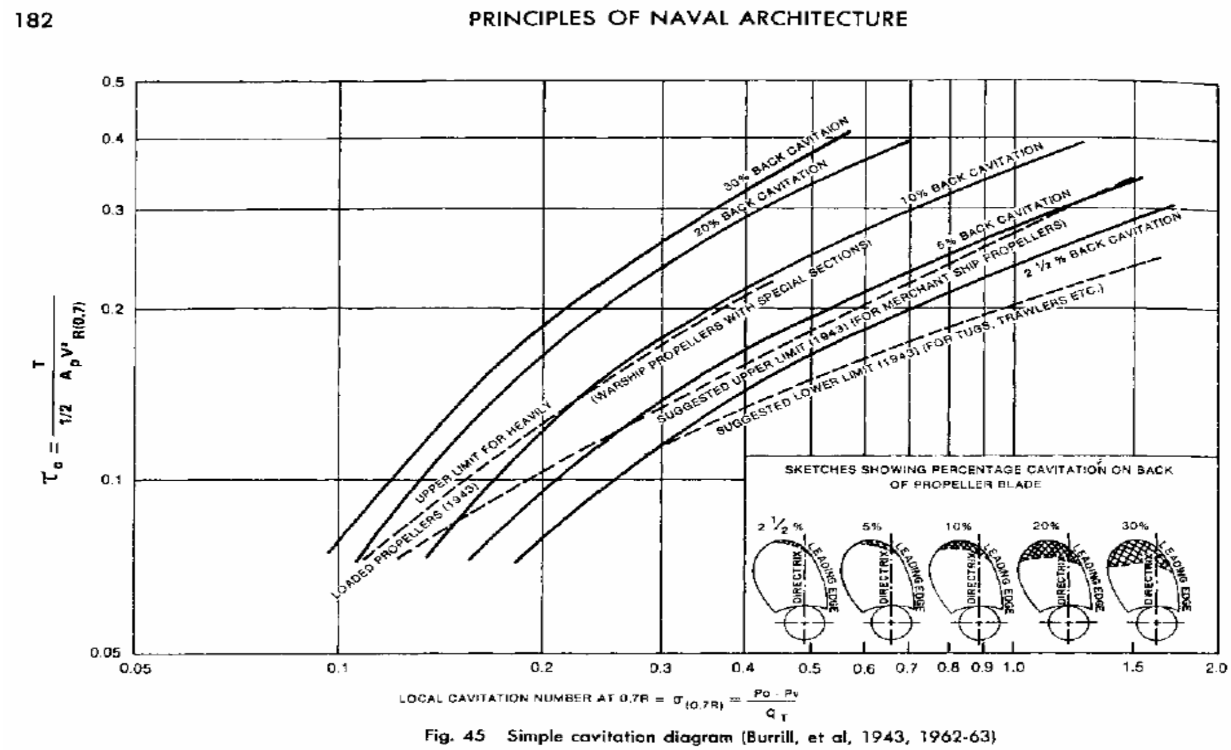


Figure 58: Burrill's Simple Cavitation Diagram (*Principles of Naval Architecture*)

The iteration process is repeated until all CDD efficiencies are satisfied and the propeller does not cavitate during snorkel and sprint. The CDD for AIP Endurance of 28 days was not met in the initial calculation. To correct for this, 3 ltons of ethanol were added to the design. Figure 59 and Figure 60 show the propeller curves for AIP endurance and AIP sprint respectively. Figure 61 shows the propeller curves for snorkel endurance.

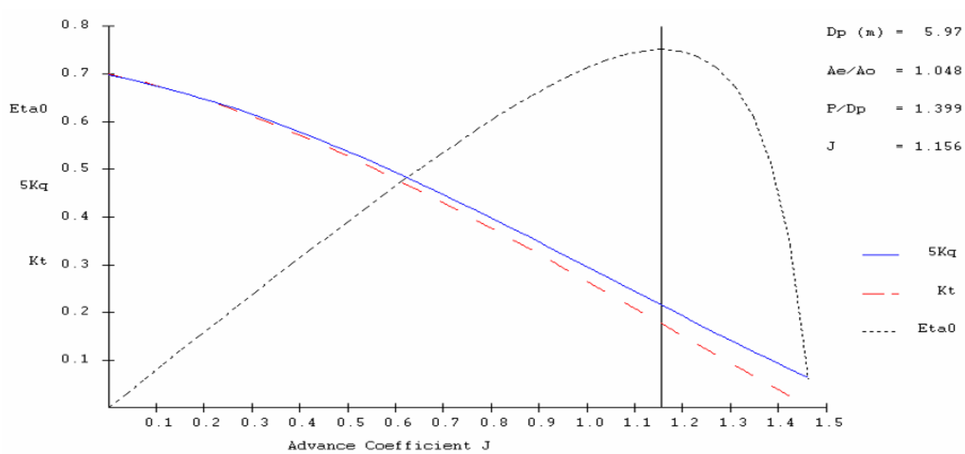


Figure 59: Propeller Curves for AIP Endurance (5 knt)

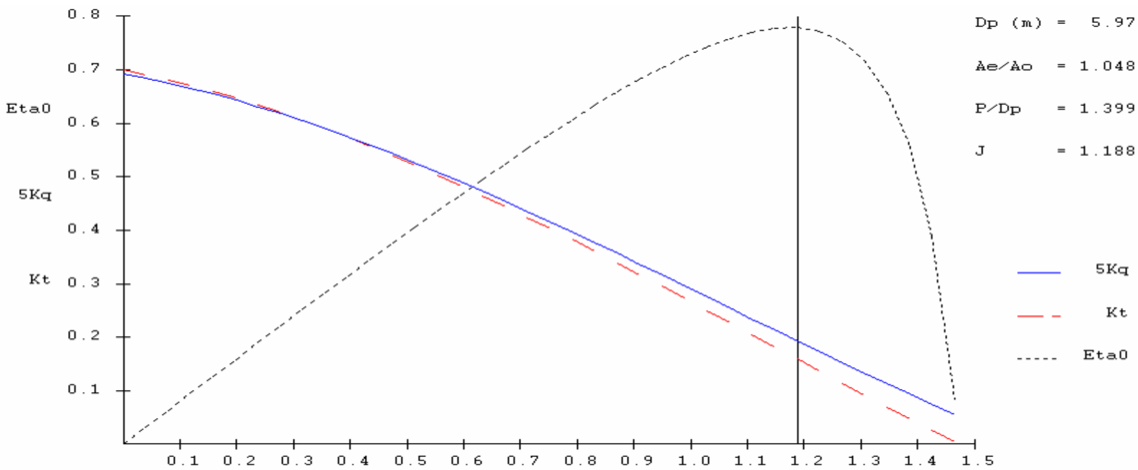


Figure 60: Propeller Curves for AIP Sprint (21 knt)

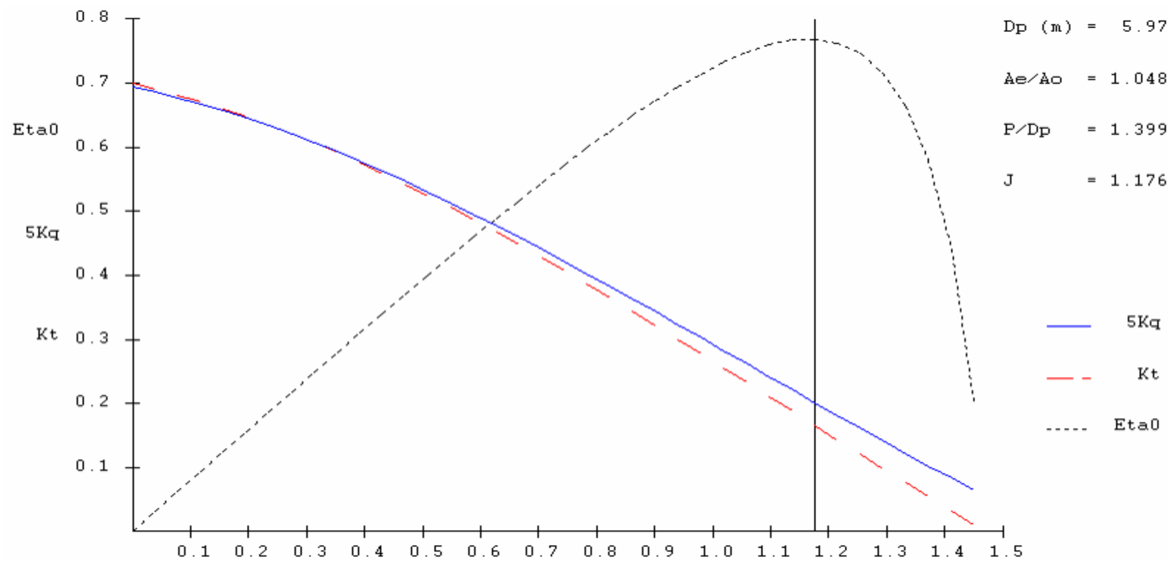


Figure 61: Propeller Curves for Snorkel Endurance (12 knt)

The propeller characteristics after optimization are summarized in Table 42. The propeller is 7-bladed with a diameter of 5.97 m.

Table 42: Summary of Optimized Propeller Characteristics

Description	Optimization Result
P/D	1.4
Pitch (P)	8.32 m
EAR	1.048
# Blades	7
D_P	5.97 m
Wake Fraction	0.221

4.3.3 Fuel Calculations (Speed and Range)

The optimized propeller characteristics and performance values are used in the propulsion model to determine the speed and endurance for each condition, and ensure these values meet the CDD requirements. Table 43 summarizes the input values.

Table 43: Summary of Input Values for Speed and Endurance Calculations

Condition	V (knt)	SFC (lbf/ ((hp*hr))	Weight Fuel (lton)	Battery Capacity (kW*hr)	PMF	Eta Electric	KW24Avg (kW)
AIP Endurance	5	0.674	133 (ethanol)	6000	1.1	0.93	342.2
AIP Sprint	21	n/a (battery)	n/a (battery)	6000	1.25	0.93	342.2
Snorkel	12	0.355	220 (diesel)	6000	1.1	0.93	342.2

The Shaft Horsepower (SHP) and Brake Horsepower (BHP) are calculated for each condition to determine the endurance. Figure 62 shows the AIP endurance and sprint calculations. It was only necessary to determine a submerged SHP for these conditions.

Calculate AIP Endurance:

$$P_{aipavg} := \frac{KW_{24AVG}}{\eta_{elec}} + BHP_{aipreq} \qquad P_{aipavg} = 448.17\,kW \qquad E_{faip} := Wfaip \cdot \frac{1.}{SFC_{aip}} \qquad E_{faip} = 3.296 \times 10^{5}\,kW \cdot hr$$

$$E_{aip} := \frac{E_{faip}}{(f_1 \cdot 1.05 \cdot P_{aipavg})} \qquad E_{aip} = 28.061\,days$$

Yellow Values must be within CDD

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

$$V_{17} = 21\,knt \qquad SHP_{sprint} = 3930\,kW \qquad BHP_{req} = 5283\,kW \qquad P_{IPRP} = 4254\,kW$$

Calculate AIP Sprint: $E_{sprint} := \frac{E_{battery}}{BHP_{req}}$ $\qquad E_{sprint} = 1.136\,hr$

$$E_S := (E_{sprint}) \cdot V_{18} \qquad E_S = 25\,nm$$

Figure 62: AIP Endurance and Sprint Calculations

The total SHP for the snorkel condition is the sum of the submerged SHP and the wave-induced SHP. To obtain an accurate wave induced coefficient of drag, a sixth degree polynomial is fit to a drag curve provided by Captain Jackson's propulsion notes. The calculation of the snorkel endurance is given in Figure 63.

Calculate submerged SHPsnrk:

$$DHP_{snrk} := \frac{THP_8}{\eta_{Bsnrk}} \qquad SHP_{snrkv} := \frac{DHP_{snrk}}{\eta_S}$$ (viscous component of snorkel resistance only)

Calculate Wave Induced drag SHPw:

Froude # for Cdw Coef Calc:

$$Fn := \frac{V_{esnork}}{(g \cdot LOA)^{.5}} \qquad Fn = 0.223$$

$$C_{DW} := 3561.3 \cdot Fn^6 - 8812.6 \cdot Fn^5 + 8148.4 \cdot Fn^4 - 3454.3 \cdot Fn^3 + 654.09 \cdot Fn^2 - 40.235 \cdot Fn + .2726$$

$$C_{DW} = 1.249$$

$$C_W := \frac{C_{DW}}{4 \left[\left(\frac{LOA}{D} \right) - 1.3606 \right] \left(\frac{LOA}{D} \right)^2} \qquad C_W = 7.206 \times 10^{-4}$$

Wave Induced:

$$SHP_W := C_W \cdot S \cdot \rho_{SW} \cdot V_{esnork}^{3} \qquad SHP_W = 345.759\,kW$$

$$SHP_{snrk} := SHP_{snrkv} + SHP_W \qquad SHP_{snrk} = 1061\,kW$$

Calculate Endurance Snorkel Range:

$$FR_{SPsnk} := f_1 \cdot SFC_{snk} \qquad FR_{SPsnk} = 0.495\,\frac{lbf}{kW \cdot hr}$$

$$FR_{AVGsnk} := 1.05 \cdot FR_{SPsnk} \qquad FR_{AVGsnk} = 0.52\,\frac{lbf}{kW \cdot hr}$$

$$P_{snkAVG} := \frac{SHP_{snrk} + KW_{24AVG}}{\eta_{elec}} \qquad P_{snkAVG} = 2157\,hp$$

$$E_{snork} := \frac{(W_{fsnk} \cdot V_{esnork} \cdot TPA)}{P_{snkAVG} \cdot FR_{AVGsnk}} \qquad E_{snork} = 6718\,nm$$

Figure 63: Calculations for Snorkel

Table 44 shows a summary of the speed and endurance calculated values. The range for each condition meets the CDD requirements.

Table 44: Summary of Speed and Endurance Calculated Values

Condition	Thrust (kN)	Overall SHP (kW)	Eta Prop Efficiency THP/DHP	Eta PC (Propulsion Coefficient)	Range	CDD Requirement
AIP Endurance	19.47	64.17	0.791	0.863	28 days	28 days
AIP Sprint	293.5	3930	0.818	0.863	1.136 hr/ 24 nm	59 min
Snorkel	101.6	804.1	0.791	0.863	6718 nm	4300 nm

4.3.4 Propulsor

The propulsor type in the SSLOI design is a Rim Driven Podded Propulsor (RDP). If feasible, a single RDP is more efficient and producible. A single RDP would also have a reduced signature. However, a double RDP configuration would have greater survivability from redundancy and may have advantages in maneuvering.

The maximum brake horsepower required for SSLOI electric loads is 3.9 MW at sprint speed. The information from Table 45 shows the feasibility of a single propulsor. [Blarcom, Hanhinen, and Mewis, SNAME, 2003]

Table 45: RDP Capabilities

	ABB Azipod	EB's CRDP	SSLOI Requirement
Nominal Power Rating	~20 MW	18.5 MW	3.9 MW
Continuous Torque Rating	~1340 kN-m (est)	1918 kN-m	1000 (est)
Length	11.40 m	3.90 m	3 m (est)
Hub Diameter	2.85 m	1.46 m	1.5 m
Propeller Diameter	5.80 m	4.90 m (prop) 5.85 m (duct)	5.97 m

Figure 64 shows the envelope hull with the single RDP. The propeller diameter is 19.6 ft and the shroud length is 9 ft.

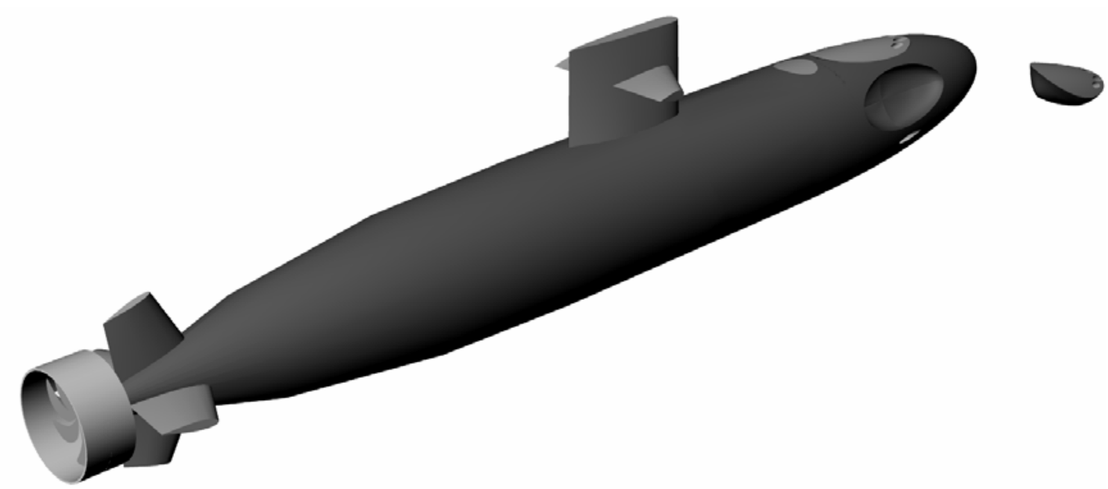


Figure 64: SSLOI Hull with RDP

4.3.5 Electric Load Analysis (ELA)

Table 46 is a summary of the Electric Load Analysis (ELA) for SSLOI. AIP, snorkel and sprint were the electric load conditions analyzed. A partial Machinery Equipment List is shown in Table 47 with the full list in Appendix E. This list was used to determine power required by each piece of equipment and total power required. Load factors were applied for the specified conditions. Available power is shown in Table 46 and is greater than power required.

4.4 Mechanical and Electrical Systems

The main components of the mechanical and electrical systems are shown in the MEL, Table 47. Appendix D is a complete MEL. This section describes the location, quantity, size, weight, and power requirements for each component. Whenever possible commercial off the shelf (COTS) systems are used to reduce the cost and make repairs less costly. Primary systems for the SSLOI include hydraulics, compressed air, salt water, ventilation and air, and electrical power distribution. The arrangements of these systems are found in Section 4.6.2.

The Integrated Power System (IPS) is used to provide the submarine with ship service power, and propulsion power. Figure 65 shows the one-line diagram of the IPS system. When surfaced or snorkeling, power is generated by the two 3512 CAT diesel engines and AC generators, each having a power conversion module (PCM a-b) in line with the generator. DC power is connected to the main switchboard (SWB), where it is then distributed throughout the ship as needed. When the submarine is submerged the main power comes from the PEM fuel cells which are directly connect to the SWB. During sprint operation, the main batteries, which are also connected to the SWB provide another 6000 kW of power to the propulsor for one hour. There are four other PCMs which are used for ship service power. PCM 2 series provides 120V, 60 Hz AC power for the lighting panel while PCM 1 series provides 440 V DC power for the control centers.

Table 46: Electric Load Analysis

SWBS	Description	Connected (kW)	AIP (kW)	Snorkel (kW)	Sprint (kW)
100	Deck	84.0	0.0	0.0	0.0
200	Propulsion	15.1	508.0	1326.1	5467.0
220	Battery	1.0	1.0	1.0	1.0
235	Electric Propulsion Drive	0.0	492.0	1310.0	5451.0
250&260	Support	14.1	15.0	15.1	15.0
300	Electric	23.0	23.0	23.0	23.0
310	Power Generation	10.0	10.0	10.0	10.0
330	Switch Board	4.0	4.0	4.0	4.0
400	Combat Systems	215.5	214.0	214.5	211.0
500	Combat Systems	1.8	1.8	1.8	1.8
500	Aux Machinery	25.0	25.0	10.0	25.0
510	HVAC	61.0	61.0	10.0	61.0
520	Seawater Systems	11.0	11.0	1.0	11.0
530	Fresh Water Sys	18.0	18.0	16.0	18.0
550	Air and Gas	45.0	45.0	33.0	45.0
560	Ship Control	15.0	15.0	15.0	15.0
593	Environmental	12.0	12.0	12.0	12.0
500	Overall	188.8	188.8	98.8	188.8
700	Payload	3.8	3.8	3.8	3.8
	Max Functional Load		937.6	1666.2	5893.6
	MFL w/ Margins		984.5	1749.5	6188.3
	24 Hour Average		346.0	346.0	346.0
Number	**Generator**	**Rating (kW)**	**AIP**	**Snorkel**	**Sprint**
1	Diesel Generators	1752.0	0	1	0
2	PEM	500.0	2	0	2
1	Battery	6000.0	0	0	1
	Power Available (kW)		1000.0	1752.0	7000.0

Table 47: Machinery Equipment List

ITEM	QTY	DESCRIPTION	LOCATION	SWBS
		Propulsion and Electrical:		
1	2	Proton Exchange Membrane Fuel Cell	MMR	235
2	2	CAT 3512 V12 Diesel Generator (AC)	MMR	230
3	1	Main Machinery Control Console	MMR	310
4	2	Main Batteries - Bank	Bat Compt	320
5	1	DC (400V) Main SWB	MMR	300
6	1	Emergency SWB	AUX	320
7	2	Oxygen Tanks, spherical	MMR	520
8	2	Power Conversion Modules (ACtoDC)	MMR	300
9	1	Motor Control Center	MMR	300
10	2	Lighting Load Panel	MMR	300
11	1	Control Station	MMR	300
12	1	Degaussing	Various	310
		Fuel Transfer and Storage:		
13		Reformer	MMR	250/260
14	2	FO Purifier	MMR	250/260
15	2	FO Transfer Pump	MMR	250/260
		Lube Oil Transfer and Storage		
16	2	LO Purifier	MMR	250/260
17	2	LO Transfer Pump	MMR	250/260
18	2	Oily Waste Transfer Pump #1	MMR	250/260
19	2	Oily Water Separator	MMR	
		Steering and Control		
20	1	Steering Hydraulics	aft	560
21	1	Aft Plane Hydraulics	aft	560
22	1	Sail Plane Hydraulics	Sail	560
		Air Systems:		
23	2	Air Compressor	MMR	550
24	2	Air Dehydrator	MMR	550
25	12	Air Cyliners	MBT	550
26	2	Air Reducer Manifold	MMR	550
		Hydraulic Systems:		
27	2	Main Hydraulic Pump	MMR	550
28	2	Hydraulic Pressure Accumulator	MMR	530/550
29	1	Hydraulic vent and Suppy Tank	MMR	550
		Fresh Water Systems:		
30	2	Potable Water Pump	MMR	530
31	2	Hot Water Circ Pump	MMR	530
32	2	Reverse Osmosis Distiller	MMR	530
33	2	Distiller Feed Pump	MMR	531
		Salt Water Systems:		
34	2	Trim manifold	MMR	520
35	2	Trim pump	MMR	520
36	2	Drain and Bilge Pump	MMR	528
37	2	Salt Water Circulating Pump	MMR	250/260
		Ventilation and Air purification:		
38	2	Main Induction Blower	Sail	510
39	2	Main Exhaust Fan	MMR	513
40	2	Ventilation Fan	Air Pur Rm	510
41	2	CO2 Scrubber	Air Pur Rm	510
42	2	CO/H2 Burner	Air Pur Rm	510
		AC and Refrigeration		
43	2	AC Unit	MMR	514
44	2	Chilled Water Pump	MMR	514
45	2	Refrigeration Units	MMR	516
46	1	Chill/Freeze Box	Galley	516
		Environmental Systems		
47	1	Trash Disposal Unit (TDU)	Galley	593
48	2	Sewage Vacuum Sys	Air Pur Rm	593
49	2	Waste Water Discharge Pump	Air Pur Rm	593

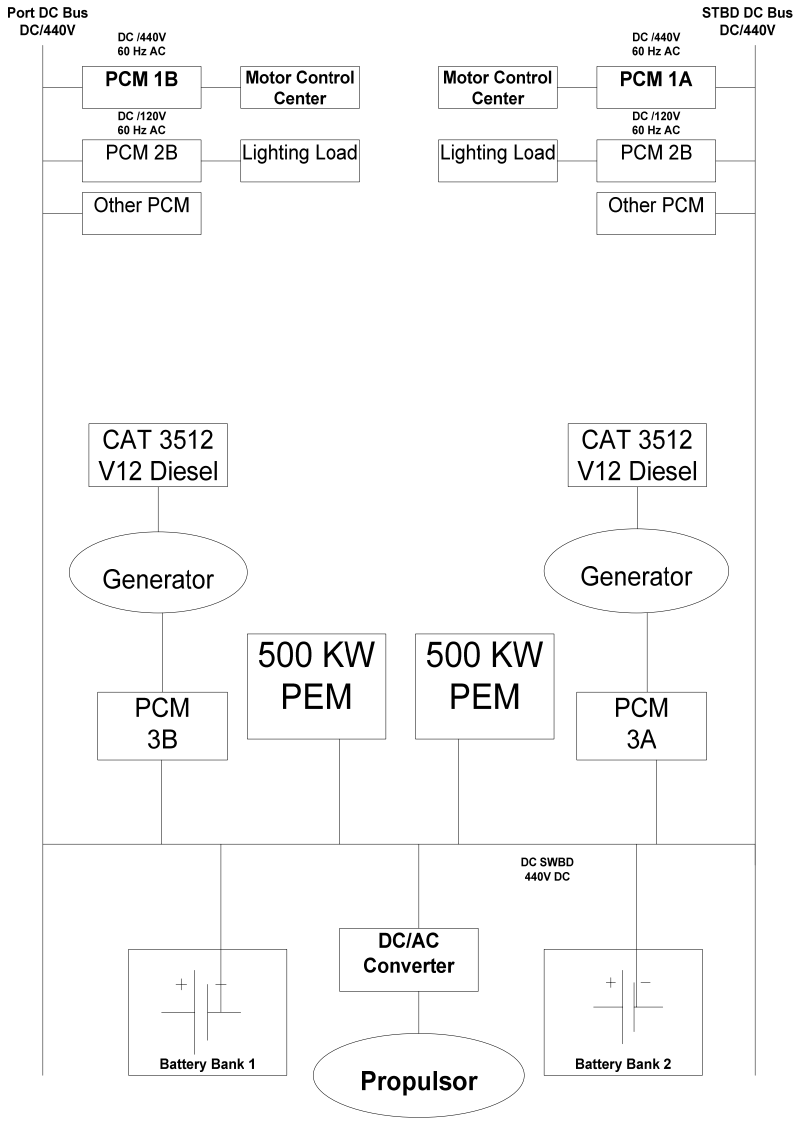


Figure 65: Electric One-Line Diagram

4.5 Manning

The original manning estimate was generated in Concept Exploration. This process is described in Section 3.1.3. The automation on the SSLOI reduces the number of officers to 8 and reduces the required crew to 44. The division breakdown is shown in Figure 66. The manning on this submarine is broken down into 5 Departments:

- Executive/Administrative Department
- Operations Department
- Weapons Department
- Engineering Department
- Supply Department

Table 48 shows how the officers, CPOs, and crew are divided among the departments. Though each member will specialize in their departmental tasks, the crew will also be required to be knowledgeable in firefighting and damage control in the event of an emergency. The automation in the ship allows for reduced maintenance crew for the machinery. There are sensors to detect any malfunctions in the machinery and automated auxiliary systems which control the climate within the ship without human direction.

4.6 Space and Arrangements

Rhino is used to generate and assess subdivision and arrangements. A profile showing SSLOI internal arrangements is shown in Figure 67.

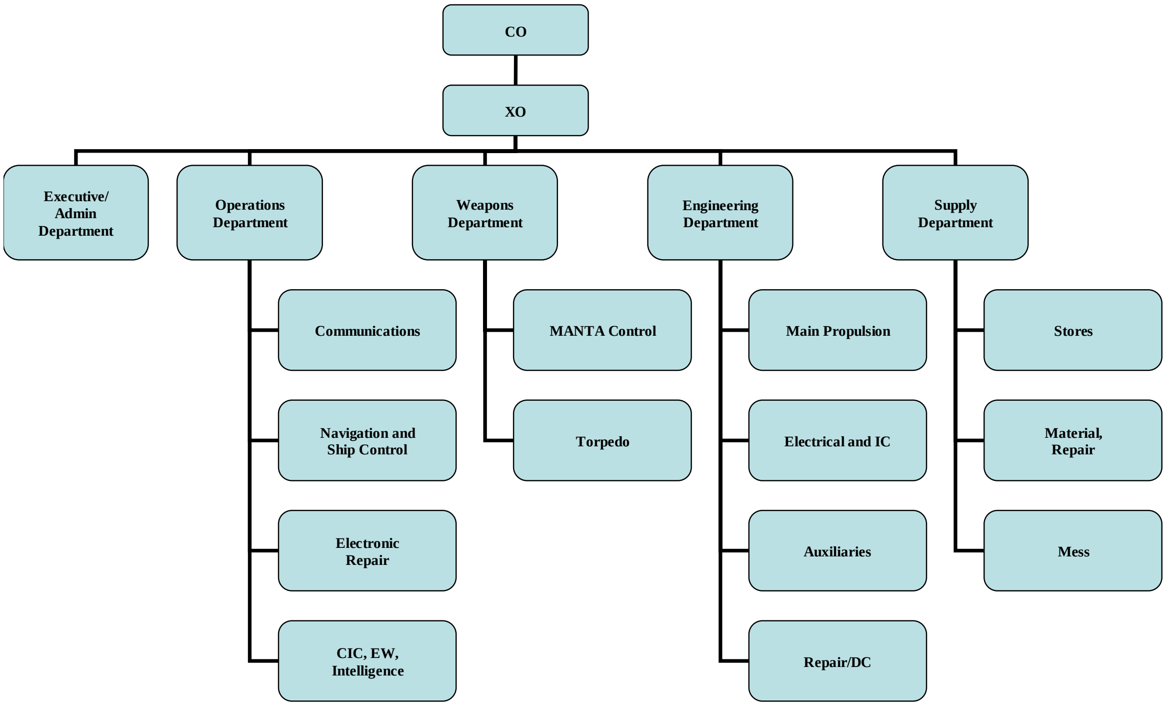


Figure 66: SSLOI Manning Organization

Table 48: SSLOI Manning Estimate

Departments	Division	Officers	CPO	Enlisted	Total Department	Rationale
Executive/Admin	CO/XO	2			2	Required
	Department Heads	4			4	minimum
	Executive/Admin		1	1	2	CPO to run office, one yeomen, one personnelman
Operations	Communications	1	1	3	5	3 enlisted watch standers (3x1), CPO, officer required
	Nav./Ship Control		1	3	4	CPO navigator, 3 enlisted watch standers (3x1)
	Electronic Repair		1	2	3	Minimum for maintenance and expertise
	CIC, EW, Intell.		1	3	4	Minimum for maintenance and expertise
Weapons	MANTA Control	1	1	1	3	Minimum for maintenance and expertise
	Torpedo		1	2	3	Minimum for maintenance and expertise
Eng. Department	Main Propulsion		1	3	4	Minimum for maintenance and expertise
	Electrical and IC		1	2	3	Minimum for maintenance and expertise
	Auxiliaries		1	2	3	Minimum for maintenance and expertise
	Repair/DC		1	2	3	Minimum for maintenance and expertise
Supply Dept.	Stores			2	2	Minimum for workload and expertise
	Material, Repair		1	2	3	Minimum for workload and expertise
	Mess		1	3	4	Minimum for workload and expertise
	Total	8	13	31	52	

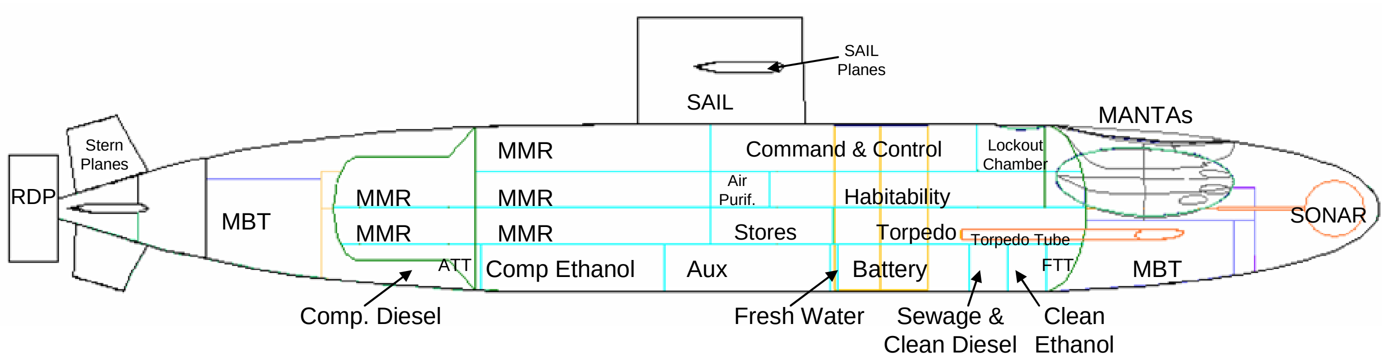


Figure 67: Profile View Showing Arrangements

4.6.1 Volume

Initial space requirements and availability in SSLOI are determined in the ship synthesis model. Arrangeable area estimates and requirements are refined in concept development arrangements and discussed in Sections 4.6.2 through 4.6.4. Table 49 compares required versus actual tankage volume.

Table 49: Required vs. Available Liquid Tankage Volume

Variable	Required (ft3)	Final Concept (ft3)
Trim Tanks	7649.2	8076.3
Inboard Clean Diesel	1166.5	1422.3
Compensated Fuel Tanks	5424.2	7606.2
Lube Oil	41.8	42.3
Fresh Water	286.4	289.4
Sewage	104.3	104.5
Ethanol	8359.0	7954.1
Main Ballast Tanks	18982.5	18288.8
Liquid Oxygen	6990.6	6976.7

Initial longitudinal arrangement of the required systems is developed using the cartoon and flounder diagram. The weight and volume balance and equilibrium polygon are used to further refine the arrangement and check the feasibility of the arrangement under all loading conditions.

The auxiliary tanks, main machinery room, trim tanks, clean fuel tank, batteries, ethanol, liquid oxygen tanks, CCC, habitability, stores, and torpedo room are located inside the pressure hull. The remaining space enclosed by the outer hull contains the main ballast tanks, compensating fuel tank, torpedo tubes, modular MANTA bay, and the sonar dome.

4.6.2 Main Machinery Spaces and Machinery Arrangement

The location of the main machinery room is shown in Figure 68. It is located separated from command and control and habitability to provide protection in the event of an emergency in the machinery room.

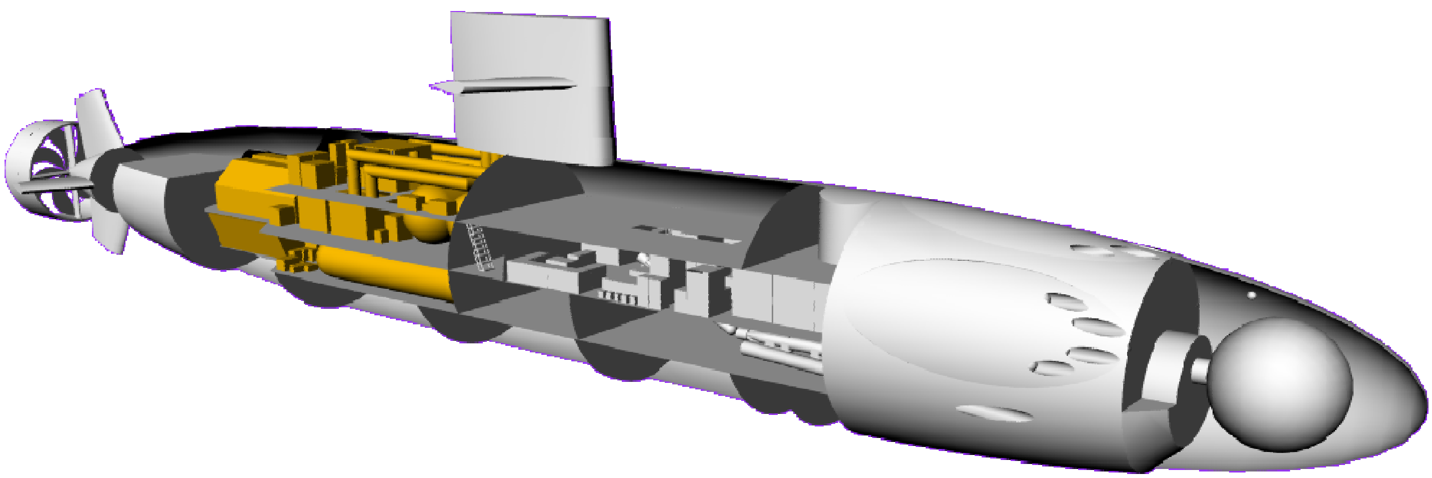


Figure 68: Main Machinery Room Location

The volume for the main machinery room was calculated in the synthesis model and then adjusted for arrangements and balance. Figure 69 shows the main layout of the machinery room with three decks and access between them. The electric one-line diagram in Figure 65 was used to locate the diesel engines, generators, PEM fuel cells, and reformers. The main oxygen tanks are spherical to reduce surface area and boil-off of oxygen. The inlet and exhaust are then run from the engines and generators up through the sail.

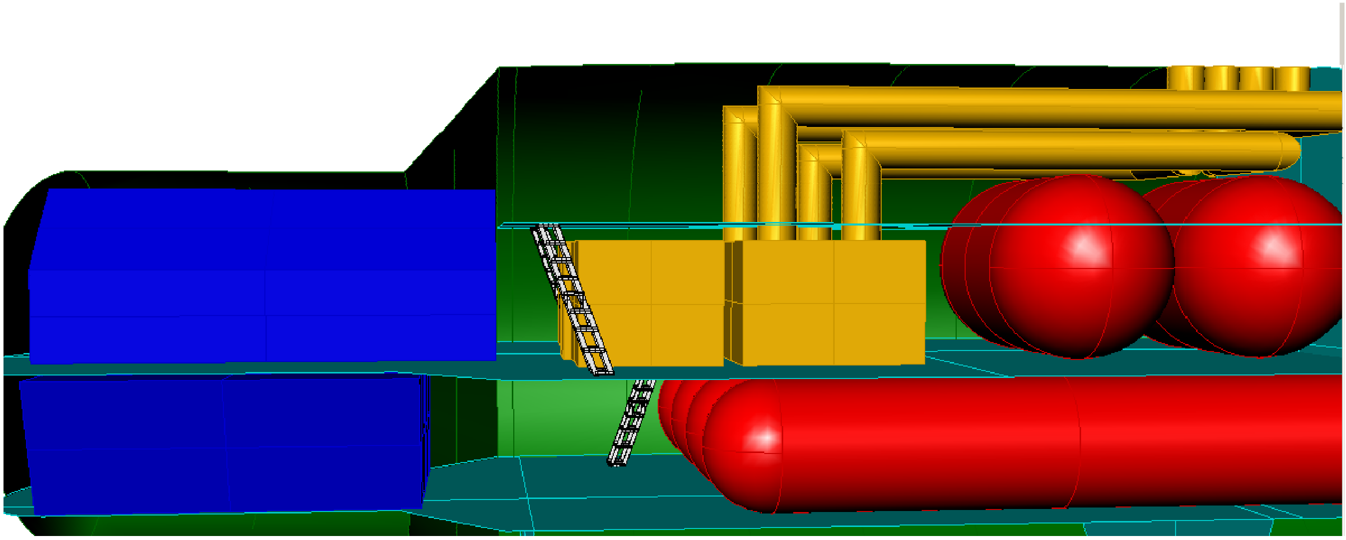
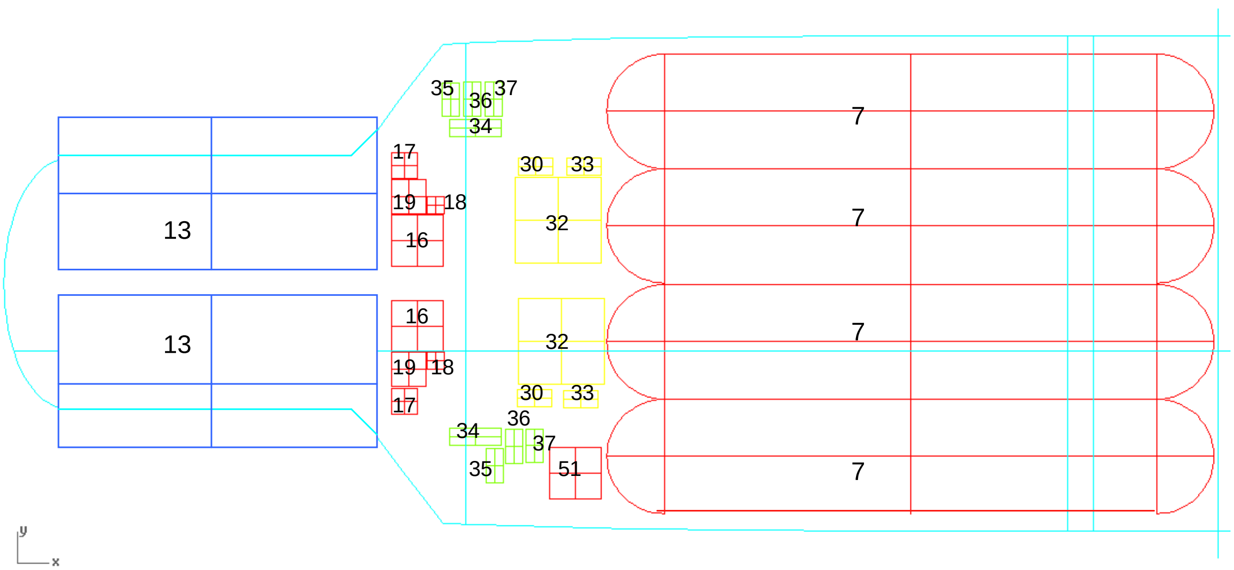


Figure 69: Main Machinery Room

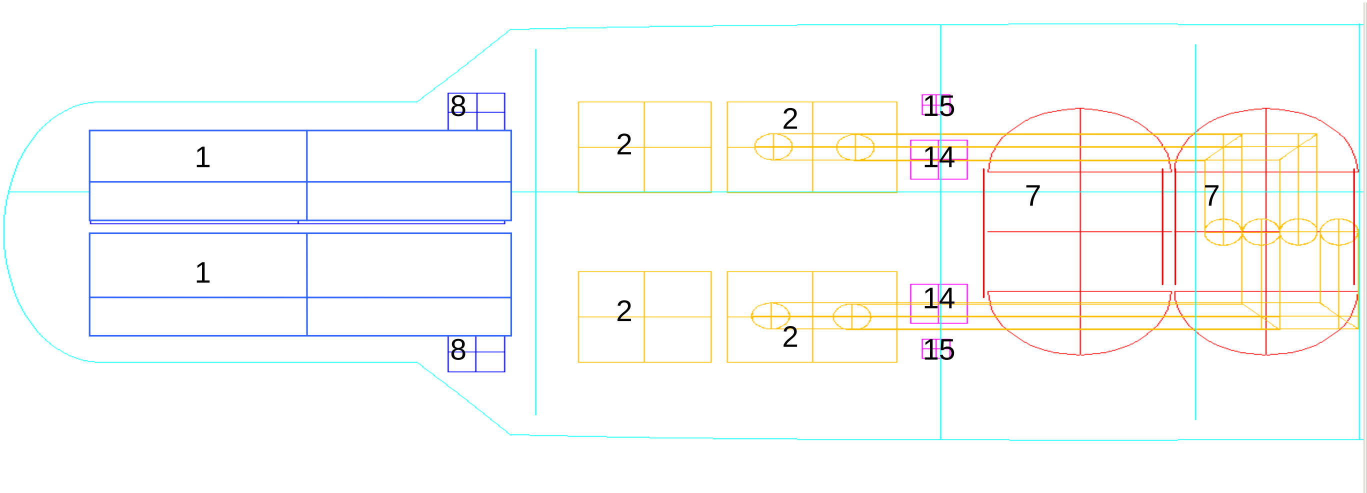
After the main machinery was located, the MEL (Table 47) was used to place the small equipment. Figure 70 shows the layout of the lower level of the main machinery room. Many of the pumps for the liquid tankage as well as necessary purifiers were placed between reformers and oxygen tanks on this level. There is repetition in almost every system to ensure that no failed system will cause the submarine to fail.



7 – Oxygen Tanks
13 – Reformer
16 – LO Purifier
17 – LO Transfer Pump
18 – Oily Waste Transfer Pump
19 – Oily Water Separator
30 – Potable Water Pump
32 – Reverse Osmosis Distiller
33 – Distiller Feed Pump
34 – Trim Manifold
35 – Trim Pump
36 – Drain and Bilge Pump
37 – Salt Water Circulating Pump
51 – Lube oil Tank

Figure 70: Lower Level Machinery Room Layout

As shown in Figure 71, the second level of the machinery room houses the diesel engines, generators, fuel cells, and more oxygen tanks. There are also power converters to provide power from the generators to the main DC bus, and fuel oil purifiers for the engines.

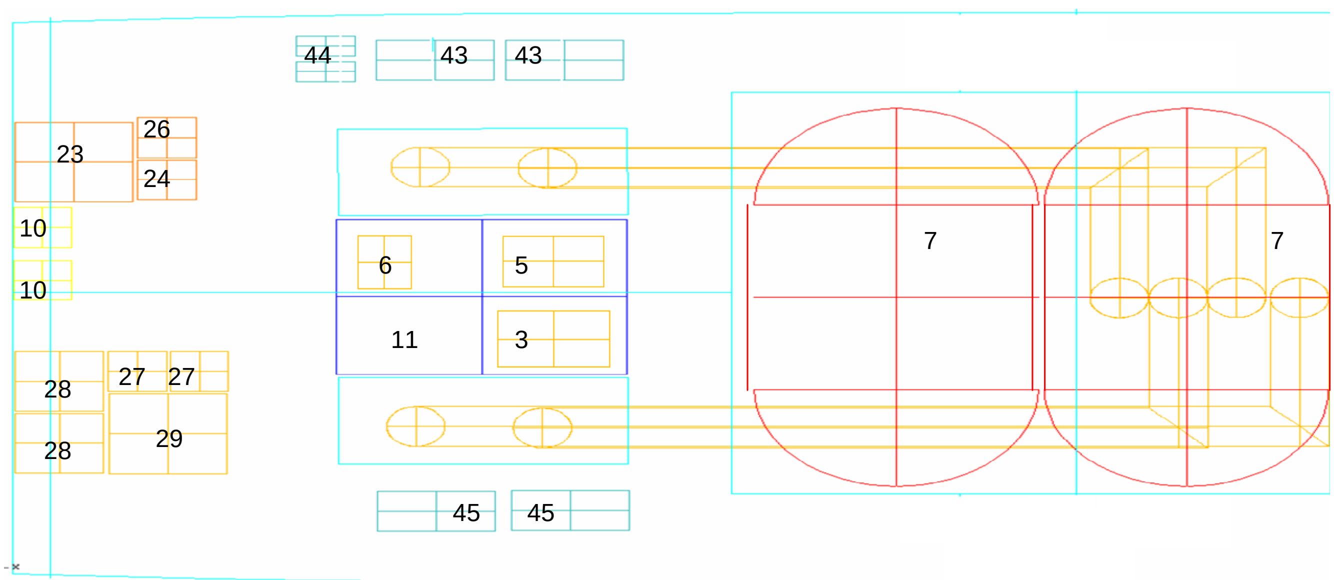


1 - Proton Exchange Membrane
2 - Diesel Generator Set
7 - Oxygen Tank

8 - Power Conversion Module
14 - FO Purifier
15 - FO Transfer Pump & Manifold

Figure 71: Middle Level Machinery Room Layout

The upper level of the machinery room (as shown in Figure 72) has space for the oxygen tanks, inlet, and exhaust to extrude through the floor. Between the inlet and exhaust ducts is the engineering operation station with the DC main salt water ballast, emergency salt water ballast, and main machinery control console. This level also houses space for air conditioning units, refrigeration units, and lighting panels.



7 – Oxygen Tanks
3 – Main Machinery Control Console
5 – DC Main SWB
6 – Emergency SWB
10 – Lightening Panels
11 – EOS

23 – Air Compressor
24 – Air Dehydrator
26 – Air Reducer Manifold
27 – Main Hydraulic Pump
28 – Hydraulic Pressure Actuator
29 – Hydraulic Vent and Supply Tank

43 – AC Units
44 – Chilled Water Pumps
45 – Refrigeration Units

Figure 72: Upper Level Machinery Room Layout

Figure 73 shows a perspective view of all levels of the main machinery room. The legend shows the color coding of each of the major machinery elements.

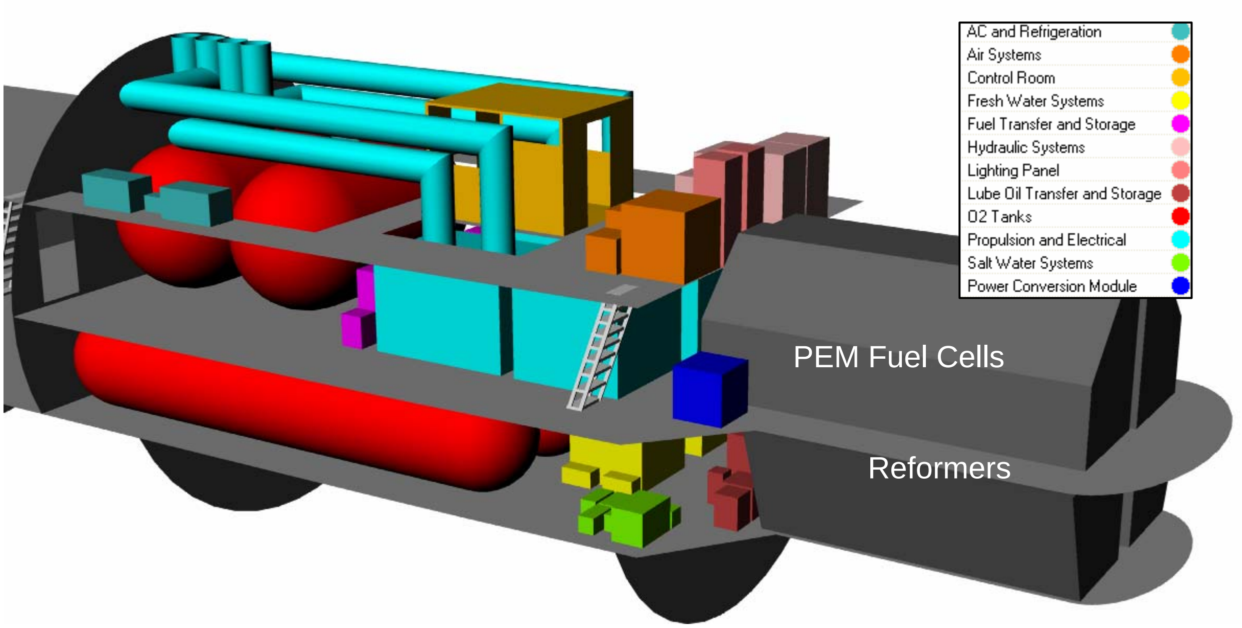


Figure 73: Main Machinery Room Perspective View

4.6.3 Internal Arrangements

The pressure hull is divided into three decks and a bilge or hold. The volume is divided to accommodate combat systems, habitability, stores, mission, machinery, and ballast. The required areas and volumes for these spaces was determined by regression equations in the optimization and then assessed by expert opinion and similar arrangements. Additional volume requirements were determined from the weight and volume balance and the equilibrium polygon. Figure 74 is a profile view of the internal arrangements for the SSLOI.

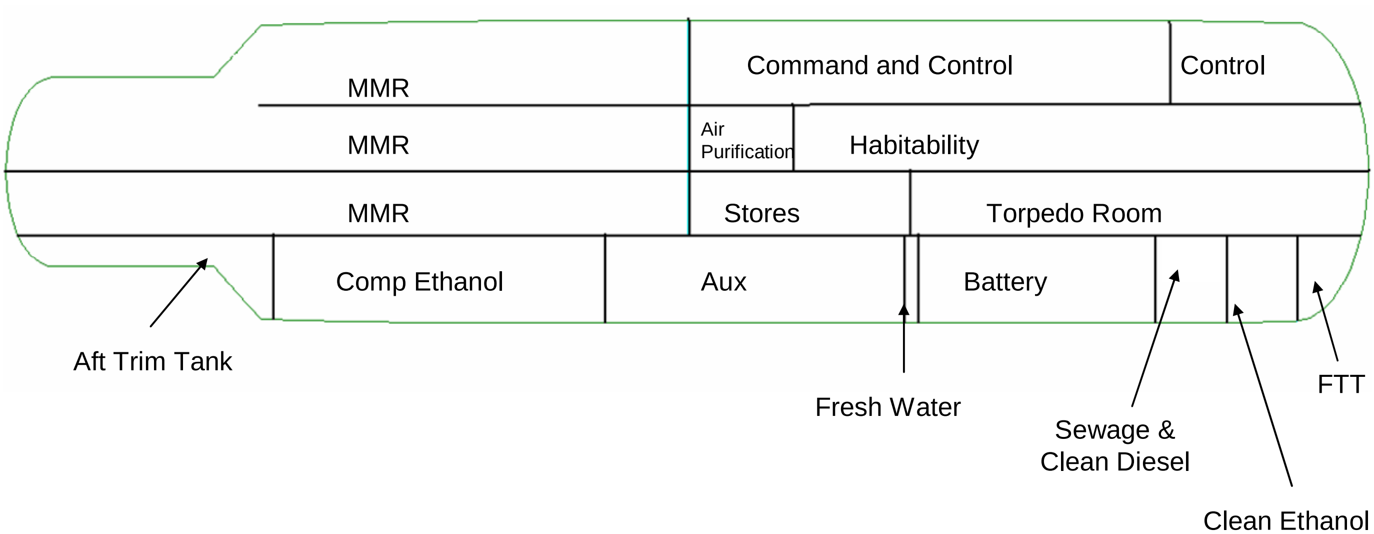


Figure 74: Profile View of Pressure Hull Internal Arrangements

4.6.4 Living Arrangements/Habitability

The volume required for habitability was estimated in the synthesis model and validated by arrangement. The location of habitability was chosen to be easily accessible to command and control and forward of the main machinery room for fire protection and sound absorption.

Table 50: Habitability Space and Volume

Item	Accomodation Quantity	Volume (ft^3)	Total Area (ft^2)	Area (ft^2) per Person
Quarters				
CO	1	344.8	49.3	49.3
XO	1	264.6	37.8	37.8
Other Officers	6	1455.7	208.0	34.7
Enlisted	44	5074.3	724.9	16.5
Heads				
CO/XO Head	2	158.6	22.7	11.3
Officers Head	6	195.4	27.9	4.7
Enlisted Head	44	1101.4	157.3	3.6
Other Habitability Space				
CO/XO Ward Room	6	293.6	41.9	7.0
Officers Mess	8	410.5	58.6	7.3
Enlisted Mess	20	1262.3	180.3	9.0
Galley	5	882.1	126.0	25.2

Figure 75 shows the layout of the staterooms, galleys, and mess spaces. There are two 3.5 foot passageways off of a 4 foot passageway bisecting the center of the ship. Table 50 gives the breakdown of the volume and area for each officer and crew member. The galley and enlisted mess are on the starboard side of the hallway, and the ward room is on the opposite side for easy access to the galley, but still allowing for sound insulation from it. Also along the first passageway are the commanding officer's stateroom and the executive officer's stateroom. Each of these staterooms has a desk and a bunk, with the executive officers room being slightly smaller due to frames extruding into the space from the sides of the ship. The CO and XO share a head at the end of the passageway with one shower, one head, and one sink. The second hallway has three staterooms for the 6 other officers in the ship. They are double bunked staterooms with fold down desks for each officer. The officers' head has one toilet, one sink, and one shower shared by all 6 officers.

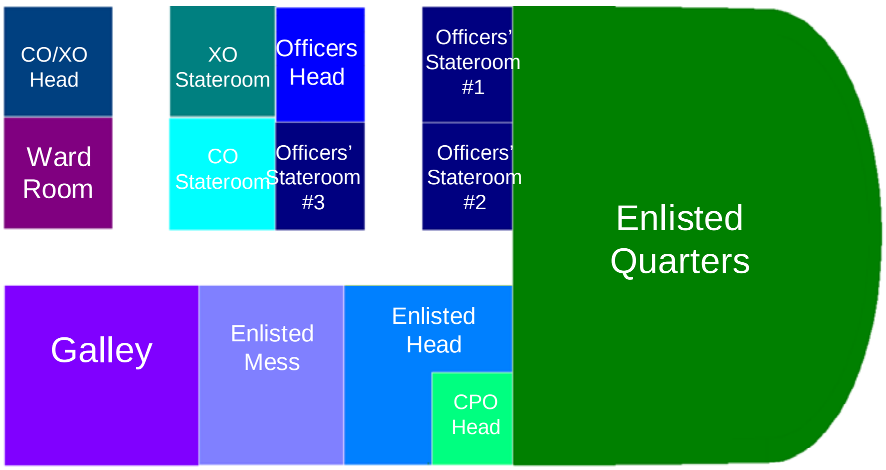


Figure 75: Layout of Habitability Rooms

Figure 76 shows the basic layout of the berthing and heads. There is enough bunking space for 54 crew members, even though only 44 crew members were mandated in our optimization. The reduced crew is a reflection of the increased automation as shown in Section 3.1.3 and Section 4.5. The enlisted bunks are 3 tier and comply with the *Shipboard Habitability Design Criteria Manual* published in 1995 that, "In submarines, thirty percent of berth tiers in berthing spaces shall fit a 76 inch mattress and all other berths shall accommodate at least a 72-1/2 inch mattress." The crew head has 2 showers, 2 sinks, 2 urinals, and 2 toilets. The CPOs are given their own head with a toilet, sink, and shower.

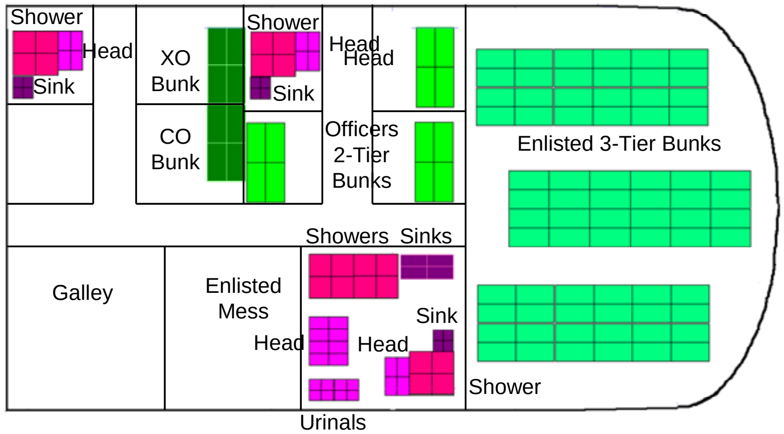


Figure 76: Berthing Arrangements

4.6.5 Final Concept External Arrangements

The final external arrangements are shown in Figure 77 and Figure 78. Outboard displacing volume is described in Section 4.7.1, and tankage is described in Section 4.7.2.

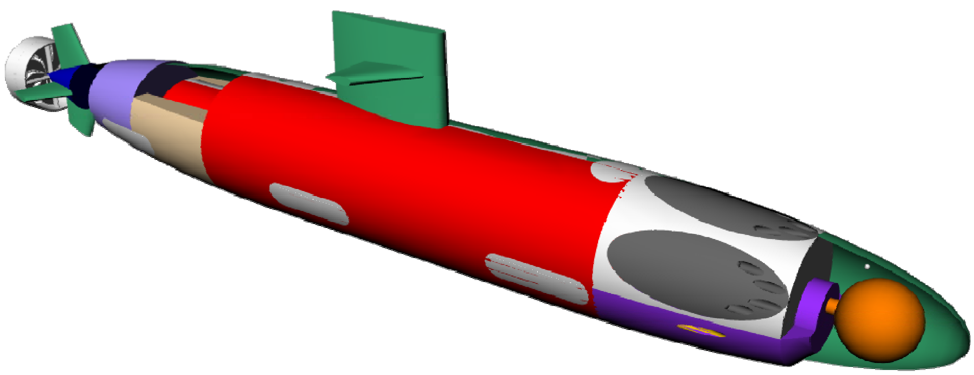


Figure 77: Final External Arrangements Perspective

The locations of the MANTAs and the main machinery room have the greatest impact on the final external arrangements. The sail is far enough aft to allow the exhaust to go directly into the sail without a turtleback, but is still close enough forward to be above command and control. Sail planes were required because there was no space forward due to the torpedo tubes and the MANTAs. Figure 78 shows the locations of external tankage, flank array sensors, propulsor, torpedo loading, seal lockout chamber and sonar sphere.

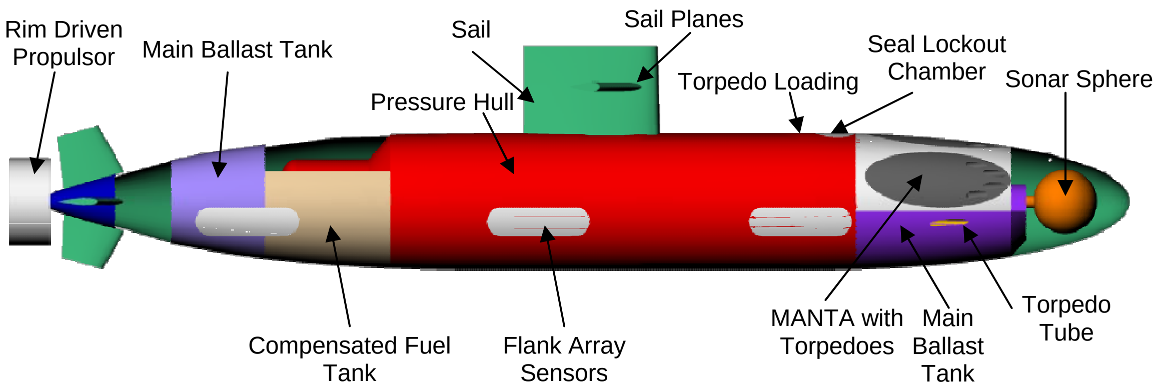


Figure 78: Final External Arrangements

4.7 Final Concept Design Balance and Trim

4.7.1 Displacing Volumes

Figure 79 below shows hull displacement volumes. Together these volumes provide the buoyancy for the ship and ultimately determine the location of the LCB. The everbouyant displacement volume of the submarine must balance with the normal surface condition weight.

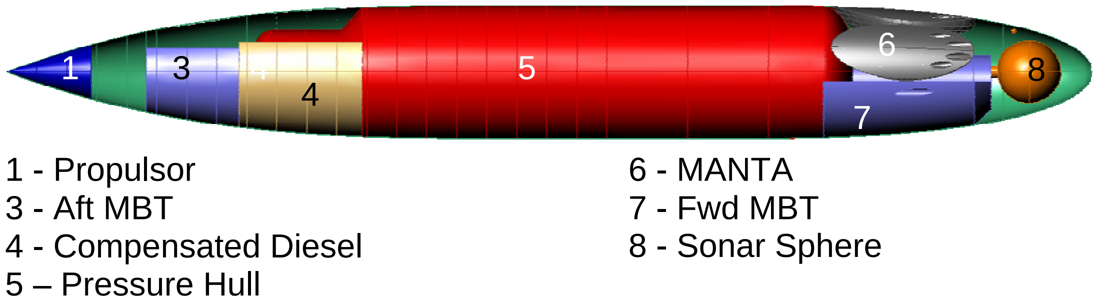


Figure 79: SSLOI Hull Displacement Volumes

The overall LCB was obtained by taking moments of each individual volume about the forward most point of the envelope hull. The VCB was calculated in the same manner, taking moments about the baseline. Table 51 below shows these values.

Table 51: LCB and VCB for Major Ship Components

Description	Volume (ft^3)	Buoyancy (lton)	LCB (ft)	VCB (ft)
Pressure Hull	100089	2860	-122	15
Sonar	1800	51	-15	16
MBT (fwd)	9491	271	-43	10
MBT (aft)	7491	214	-212	16
Comp Diesel Fuel	7601	217	-189	12
Propulsor	900	26	-242	16
MANTA	4950	141	-45	23
Misc 1	3003	86	-201	23
Misc 2	3003	86	-240	16
total (Vsub)	138328	3952	-126	15

4.7.2 Internal and External Tanks

Figure 80 and Figure 81 show the internal and external tankage arrangements. Table 52 is a summary of the tankage LCG and VCG values.

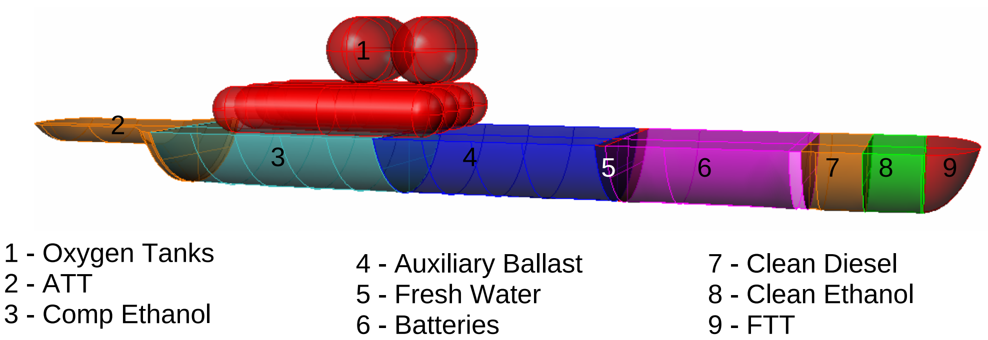


Figure 80: Internal Tankage

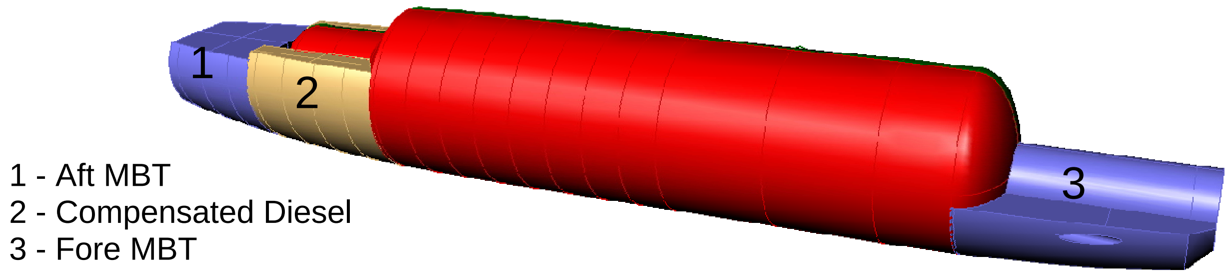


Figure 81: External Tankage

Table 52: Tankage LCG and VCG

Tank	Weight	LCG - ft (fwd FP)	VCG-ft (above centerline)
Oxygen	205.46	-143.00	-1.50
ATT	34.29	-182.60	-9.00
Fresh Water	7.80	-91.20	-9.39
Aux Tank	171.43	-121.00	-9.30
Batteries	234.00	-91.00	-9.39
Clean Diesel	25.33	-74.80	-9.39
Clean Ethanol	30.65	-67.40	-9.39
Comp Ethanol	102.35	-154.00	-9.39
FTT	751.80	-61.30	-10.00

Oxygen is the largest variable weight, so it was placed as close to the LCB as possible. This reduces the moment generated by the loss in oxygen. The fresh water tank was placed between the auxiliary ballast tank and the battery tank so that it did not boarder a fuel tank, preventing and contamination. The main aux tank provides the largest compensating weight so it was placed as close the LCB as possible, again reducing the trim moment. The clean diesel and ethanol were placed forward to balance the aft trim moment created by the expenditure of oxygen. The clean and compensated ethanol tanks were sized so that no change in weight was created by use of ethanol.

Table 53: SWBS Weights Table

SWBS Group	Weight (lton)	VCG (ft) (above center-line)	LCG(ft) (fwd LCB)
100	1084.42	0.23	-3.92
200	563.53	-4.52	-13.00
300	79.42	3.06	-38.79
400	194.78	1.74	85.47
500	188.23	-0.04	-16.60
600	74.04	1.23	11.28
700	52.50	-3.56	49.74
8 (lead)	505.00	-9.55	33.67
F10	5.53	6.00	-2.47
F20	208.24	4.28	36.86
F30	10.11	-3.00	16.03
F40	479.62	-9.39	-57.96
F50	21.63	-12.79	17.75
900	725.13	-5.36	-26.25
Condition A-1	2236.91	-0.81	1.03
Condition A	2741.91	-2.42	7.04
NSC	3467.03	-3.04	0.08

4.7.3 Final Weights

Weights are broken down by SWBS groups. An Excel spread sheet was used keep track of weights. Each component has a specified weight, longitudinal center of gravity, and vertical center of gravity in the spread sheet.

These locations were obtained from the arrangement drawings. Taking weighted moments, the overall LCG and VCG of each SWBS group is calculated. The variable loads in Group 9 were broken down into 5 subcategories: personal, mission expendables, stores, fuel and lubricants, and liquids and gasses. Group 9 weights were used in the loads chart and the equilibrium polygon was used to ensure all these variable weights could be accounted for. Table 53 shows the break-down of these weights and centers of gravity. The overall ship LCG is 10 ft fwd of the LCB. Group 8 is lead; this value was adjusted so that the NSC weight balances with the submerged buoyancy of the submarine. Two types of lead were considered; margin and trim/stability. Trim/Stability lead is used to trim the normal surface condition and also to increase the vertical stability of the submarine; this lead is placed just above the keel, with its longitudinal position determined by the trim. Margin lead is used for design and life cycle margins. This lead is used to account for the additions and upgrades of new systems on the submarine (and the lead's subsequent removal). It ensures the future additions in weight can be compensated. Margin lead is assumed to be placed at the VCG and LCG of the submarine and its weight is five percent of the normal surface condition weight. Figure 82 shows the balance of the submarine using the known weights and volumes.

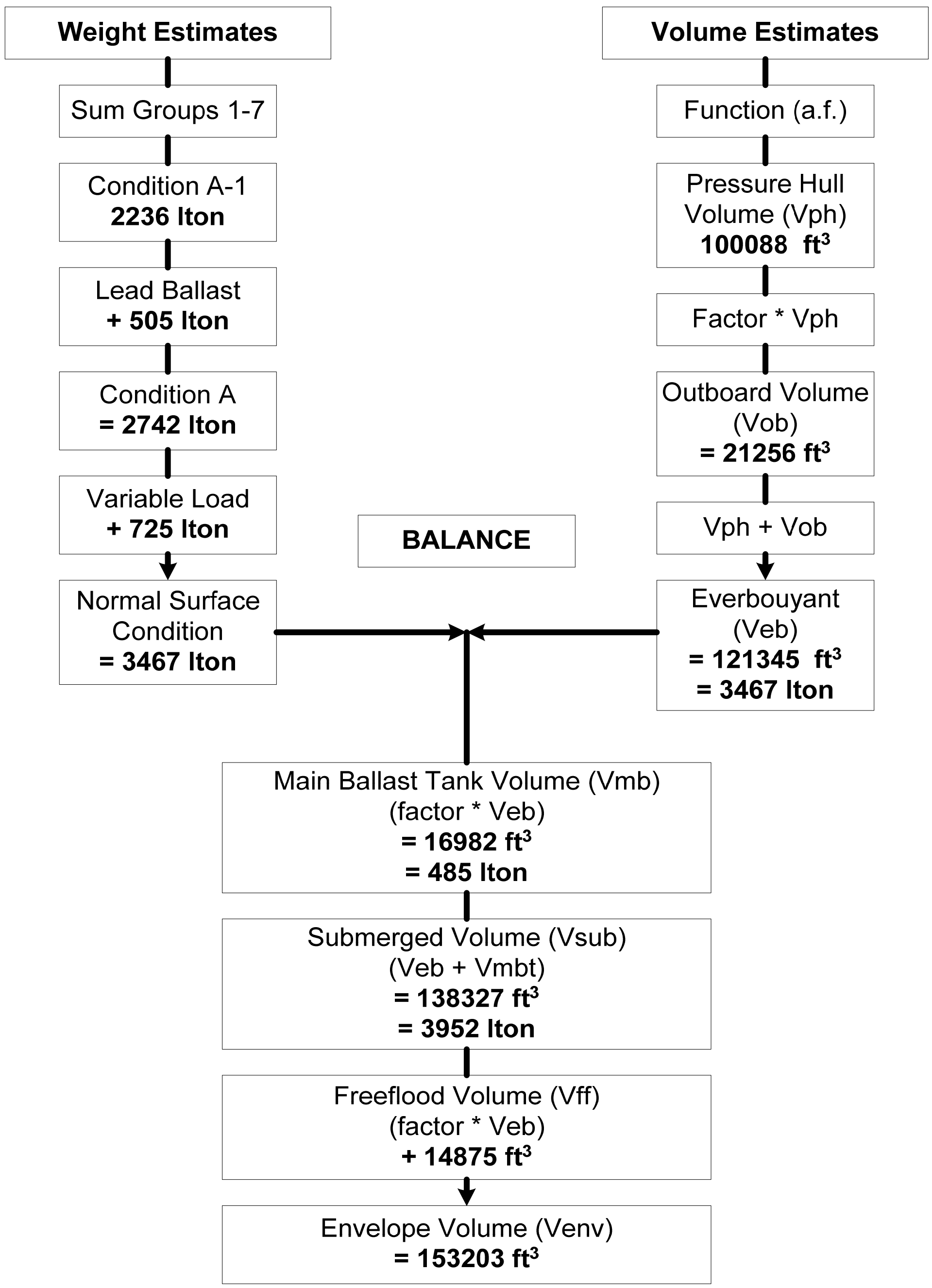


Figure 82: Final Weight/Buoyancy Flowchart

4.7.4 Equilibrium Polygon

The equilibrium polygon, as described in Section 3.7, is a tool used to access the feasibility and longitudinal balance of the submarine. It is a plot of change in weight vs. moment generated by each loading condition from normal condition. For the submarine to be feasible, all the loading conditions must fall within this auxiliary ballast polygon. **Error! Reference source not found.** is the final polygon for the SSLOI. Each red dot is loading condition and the blue line is the boundary created by the auxiliary ballast.

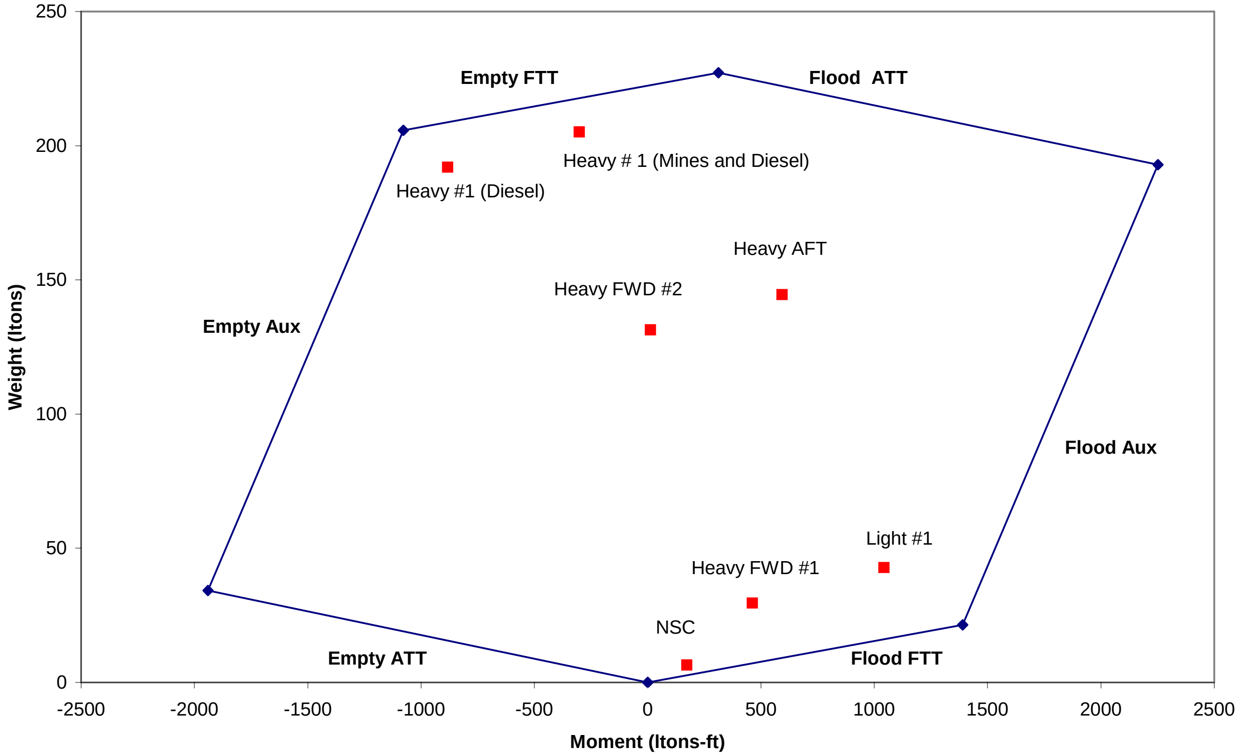


Figure 83: SSLOI Equilibrium Polygon

4.7.5 Load Conditions

Loads are examined for the submarine by changing the SWBS 900 (variable) weights. There are seven different loading conditions considered for SSLOI representing the extreme operating conditions. Table 54 describes each of these seven loading conditions:

- Normal Condition: All expendables full, in average (64lb/ft3) water
- Light #1: Beginning of short voyage or training mission
  - Full fuel, no torpedoes, heavy density water
- Heavy #1: End of patrol
  - No fuel, all torpedoes, in light density water
- Heavy #1 (mines): Same as Heavy #1 except mines instead of torpedoes
- Heavy fwd #1: Early in Patrol
  - Half torpedo's, NFO tanks full, heavy density water
- Heavy fwd#2 : Late in Patrol
  - Half fuel, full torpedoes, heavy density water
- Heavy aft: Late in Patrol
  - Half fuel, no torpedoes, heavy density water

Table 54: Loading Conditions

Group	Item	Ship Synthesis			Normal Condition N	Light #1 (diesel)	Heavy #1 (diesel)	Heavy #1 (diesel) (mines)	Heavy Fwd #1 (diesel)	Heavy Fwd #2 (diesel)	Heavy Aft (diesel)
	Water Density (lbf/ft3)	64			64	64.3	63.6	63.6	64.3	64.3	64.3
		Equation	Value	LCG (fwdLCB)	% Full	% Full	% Full	% Full	% Full	% Full	% Full
Condition A		Wa	2741.91	7.04							
Disp sub (adjusted for density, lton)		Disp'	3952.21	0.00							
Main Ballast Tanks (adjusted for density, lton)		Wmbt'	460.95	8.48							
Weight to Submerge (lton) adjusted for density		Ws'	1210.30	-15.96							
1,2,3	Fixed Loads: crew and effects, ballistic missiles, sanitary, lube oil sumps, candles	WF10+ Wsew+ 0.1*WF46	8.61	-2.86	100.00	100.00	100.00	100.00	100.00	100.00	100.00
1		WF10	5.53	-2.47	100.00	100.00	100.00	100.00	100.00	100.00	100.00
2		Wsew	2.98	-2.47	100.00	100.00	100.00	100.00	100.00	100.00	100.00
3		0.1*WF46	0.10	-35.97	100.00	100.00	100.00	100.00	100.00	100.00	100.00
4	Gases: oxgen and ethanol	Wo2	205.46	-16.97	100.00	100.00	0.00	0.00	100.00	50.00	50.00
		We2 Clean	30.65	58.63	100.00	100.00	0.00	0.00	100.00	50.00	50.00
		We2 Comp	102.35	-27.97	100.00	100.00	0.00	0.00	100.00	50.00	50.00
5	Torpedoes, missiles, mines and Ammunition	Wvp	13.24	43.89	100.00	0.00	Torp and Missile	Mine and Missile	aft expanded	aft expanded	Fore expanded
	Torpedo	Wtorp	13.20	44.03	100.00	0.00	100	0	100	100	0
	Missile	Wmis	0.00	17.53	100.00	0.00	100	100	100	100	0
	Mines	Wcounter	0.04	-2.47	100.00	0.00	0	100	50	50	50
	MANTA	Wmanta	141.00	-44.70	100.00	100.00	100	100	100	100	100
6	Potable and fresh water	WF52	7.80	34.83	100.00	50.00	100.00	100.00	50.00	50.00	50.00
7	Provisions and general stores	WF31+ WF32	10.11	71.11	100.00	75.00	50.00	50.00	75.00	50.00	50.00
		WF31	7.64	70.48							
		WF32	2.47	73.06							
8	Lube oil in storage tanks	0.9*WF46	0.90	-35.97	100.00	75.00	50.00	50.00	75.00	50.00	50.00
9	Compensating fuel tanks (no fuel ballast tanks)	Wfcomp	217.17	-62.97	100 fuel	100 fuel	100 SW	100 SW	100 fuel	50 fuel	50fuel
10	Fuel in clean fuel tanks	Wfclean	25.33	51.23	100.00	100.00	0.00	0.00	100.00	50.00	50.00
11	Cargo										
12	Passengers										
13	Residual SW	Wresidual	10.85	11.03	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Total	VLI	WF00	725.13	-152.28							

Each of these loading conditions has an associated change in weight and moment which must be accounted for. Table 55 summarizes this change in weight and moment. Equation (**5)** was used to solve for the weight of variable ballast required to submerge:

$$VB = W_S' - MBT' - WLI \tag{5}$$

where VB is volume of variable ballast, Ws' is weight to submerge, MBT' is weight in main ballast tanks and WLI is variable load weight. To solve for the moment required Equation (**6)** was used.

$$(VB)(LCG_{VB}) = (W_S')(LCG_{W_S}) - (MBT')(LCG_{MBT}) - (WLI)(LCG_{WLI}) \tag{6}$$

where VB is the volume of variable ballast, LCG_{VB} is the longitudinal center of gravity of the variable ballast, W_S is the weight to submerge, MBT' is the main ballast tank volume, LCG_{MBT} is the center of gravity of the main ballast, WLI is the weight of the variable load and LCG_{WLI} is the center of gravity of the variable load.

Table 55: Changes in Weight and Moment of each Loading Condition

Loading Condtion	Change in Weight (lton)	Change in Moment (ft - lton)
Normal Condtion N	6.5	173.2
Light #1 (diesel)	42.8	1043.4
Heavy #1 (diesel)	192.0	-882.7
Heavy #1 (diesel and mines)	205.1	-301.5
Heavy Fwd #1 (Diesel)	29.6	462.3
Heavy Fwd #2 (Diesel)	131.3	12.3
Heavy Aft (Diesel)	144.5	593.5

4.7.6 Final Polygon Boundaries

Table 56 defines the polygon boundaries. The aux and trim tanks are filled one at a time and then emptied one at a time. Each time a tank is filled or emptied, it forms another boundary line on the polygon shown in Figure 83. The fwd and aft trim tanks were placed as far forward and aft as possible to give them the largest moment arm, so they could generate the largest moment with the minimum weight.

Table 56: Polygon Boundaries

Tanks	Volume (ft^3)	Weight (ltons)	Moment (ltons-ft)
Empty	0	0	0
FTT	751.8	21.5	1416.6
FFT+Aux 1	6751.8	192.9	2488.3
FTT+Aux 1+ATT	7951.8	227.2	590.6
Aux + ATT	7200.0	205.7	-826.1
ATT	1200.0	34.3	-1897.7
Empty	0	0	0

4.7.7 Surface Condition

The normal surface condition was calculated by balancing the normal surface condition weight (empty MBT tanks) with the displacement at a balance surfaced draft. Table 57 describes the surfaced condition. Since the shapes of all the tanks are very complex, Rhino Marine was used to calculate the displacements and surface characteristics. Rhino Marine was also used to plot the curves in Figure 84, Figure 85, Figure 86, and Figure 87. The reserve buoyancy of the sub was calculated as the MBT volume divided by the NSC volume. The target reserve buoyancy was 15%, with the final design having 14% reserve buoyancy.

Table 57: Surface Characteristics

Description	Surface Condtion
Displacment	3467 lton
LWL	200 ft
T	26.8 ft
B	32 ft
Trim	5 deg fwd
GMT	16 ft
GML	102 ft
Reserve Bouyancy	14%

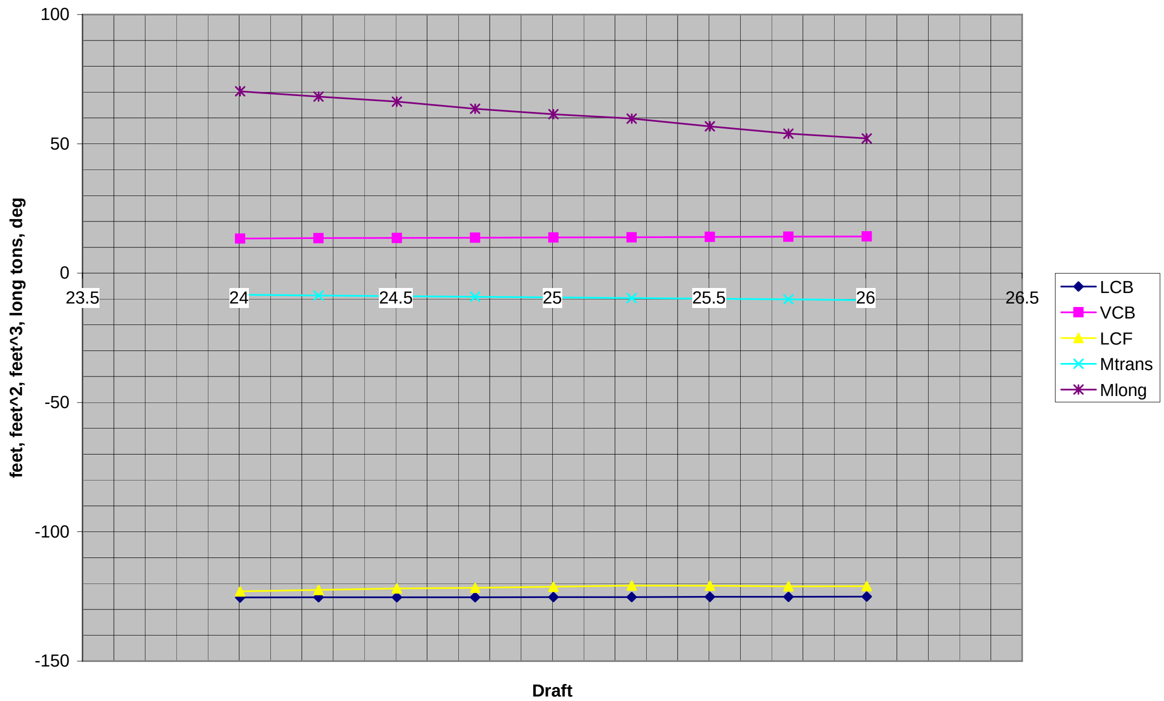


Figure 84: Curves of Form - Centers

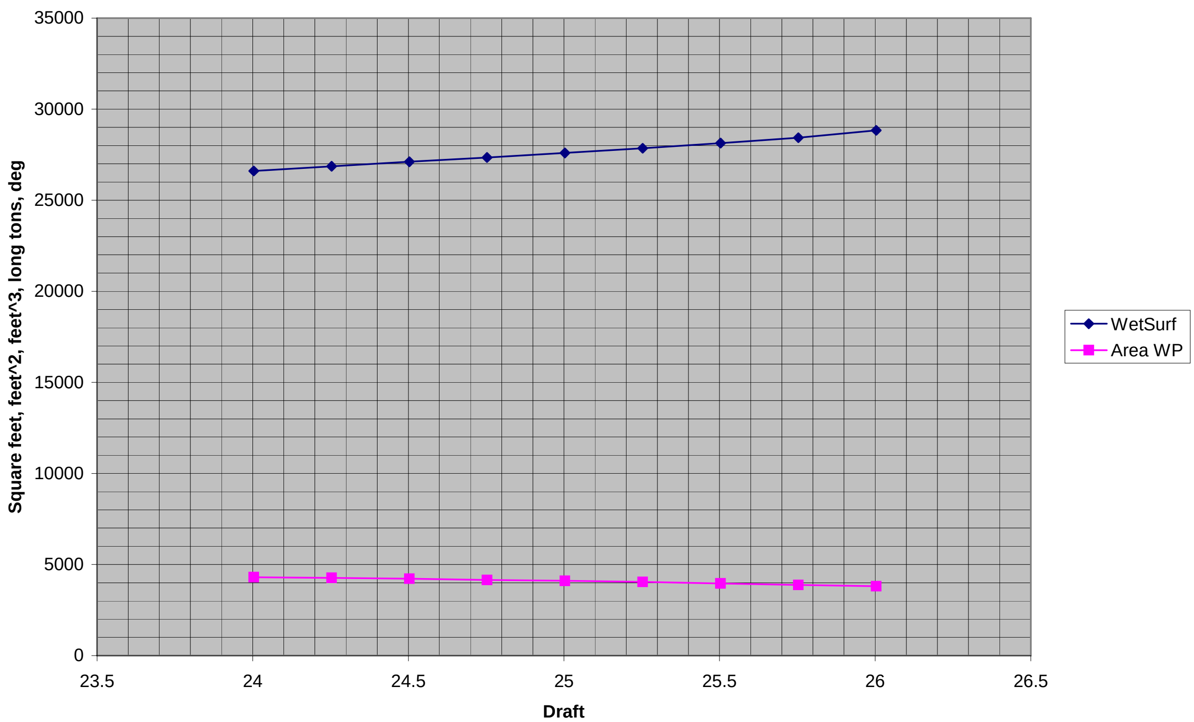


Figure 85: Curves of Form - Wetted Surface Area and Water Plane Area

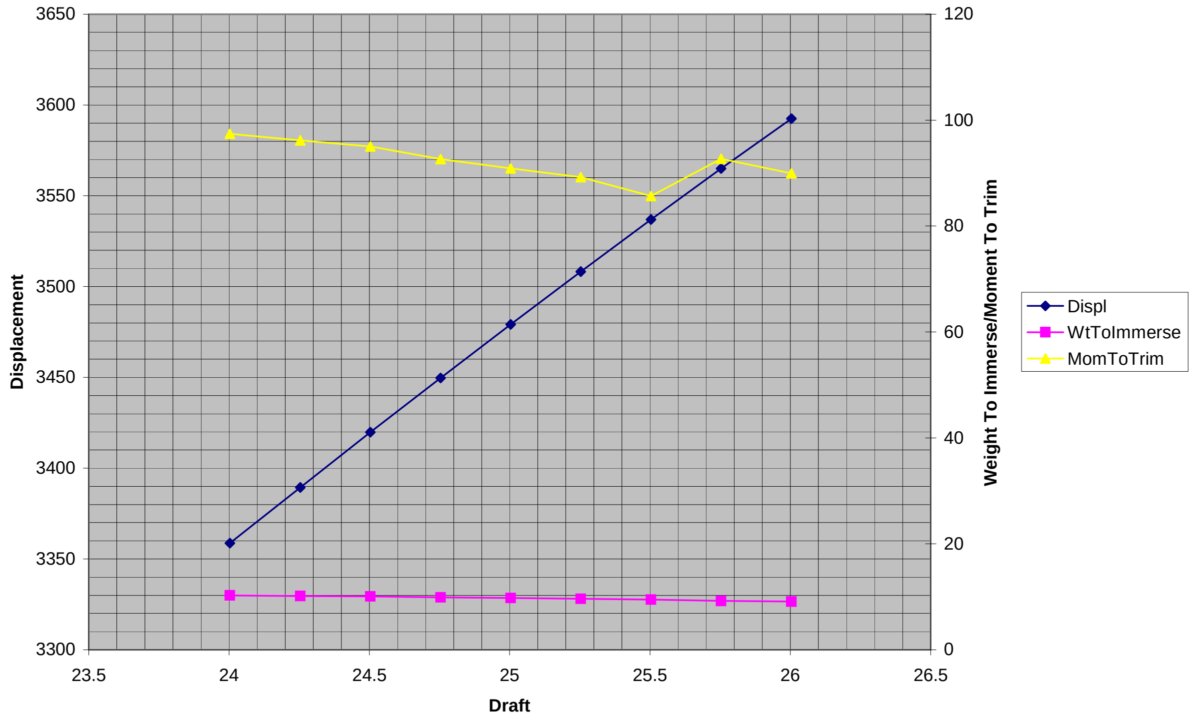


Figure 86: Curves of Form - Displacement

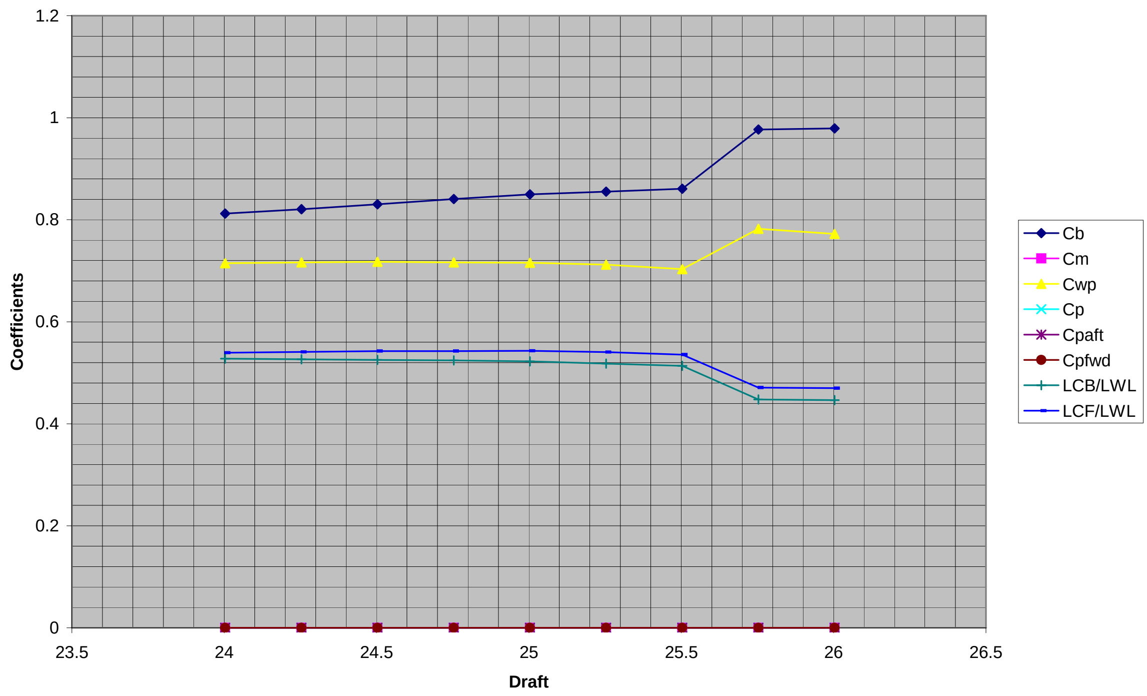


Figure 87: Curves of Form - Coefficients

4.8 Dynamic Stability and Maneuverability

Design of the SSLOI hullform and control surfaces requires balancing dynamic stability and maneuverability. A submarine's stability is its ability to return to equilibrium without using the controls after some disturbance; its maneuverability is its ability to perform specific maneuvers using the controls. Highly stable submarines require greater control deflections to carry out these maneuvers. The SSLOI should have control surfaces that provide stability in the horizontal and vertical planes but this stability should be low enough that control deflections are effective for maneuvering. Stability becomes more critical at higher speeds. Considerations of stability, speed, and controllability determine the safe operating envelope. Concerns with vertical stability and control are particularly important to prevent the submarine from going too deep or broaching.

Submarine stability is defined in the horizontal and vertical planes. Horizontal stability is the ability to maintain a set course with little variation in heading; stable submarines will not need continuous changes in rudder deflections to maintain a straight-line path. Stability in the vertical plane is its ability to maintain a constant depth without continuous deflection of the hydroplanes. The submarine's dynamic stability is critical in deep submergence when little can be done to vary the hydrodynamic forces acting on the vehicle. This stability is expressed in terms of the hydrodynamic stability coefficients in the horizontal and vertical planes, G_H and G_V respectively. These coefficients are a function of the submarine's control surfaces and hullform. Stability is ensured by positive coefficients. However, higher coefficients indicate less maneuverability. The desired range for G_H is 0.15 – 0.3; the desired range for G_V is 0.5 – 0.7. Higher stability is more critical in the vertical plane; it is undesirable for a ship to tend to surface or dive deeper without a controls deflection.

Submarines have forward and aft control surfaces. The forward surfaces are either sail or bow planes. They are used primarily for diving and are most useful at low speeds. They provide a way to independently control pitch angle and depth; the submarine can therefore remain level while changing depth. At higher speeds, pitch and heave are coupled and must be controlled by the aft planes. The aft planes consist of horizontal stabilizers and vertical rudders. The stabilizers provide stability in the vertical plane; the rudders give stability in the horizontal plane. The surface area of the stabilizers must be large to ensure stability; flaps, or elevators, are generally added to provide maneuvering ability. The size of the rudders must also be significant for stability. However, the whole surface is allowed to move to produce fast maneuvers in the horizontal plane. The span of the lower rudder is constrained by docking constraints. This asymmetry is also beneficial in counteracting the roll moment created by the sail. Traditional aft plane configurations are cruciform. However, alternative designs have been explored to provide planes that have more submerged area in the surface condition. The most common alternative is the x-stern. The disadvantage of the x-stern is the symmetry of the forces generated in the horizontal and vertical planes. It is therefore difficult to independently adjust the stability and maneuvering characteristics with an x-stern.

4.8.1 Motion and Control Surface Calculations

Figure 88 shows the process used to determine the configuration, size, and location of the SSLOI control surfaces. Lisa Minnick of Virginia Tech developed a control surface database by measuring the control surfaces of twelve submarines. This information was used to create a regression model that is a function of the submarine's diameter and length to diameter ratio. The regression model estimated the size and location of the surfaces. A Response Surface Model (RSM) was developed using NSWC Carderock stability code which calculates G_H and G_V to determine the feasibility of the calculated control surfaces. The SSLOI is stable with sail planes and a cruciform stern described in Section 4.8.2.

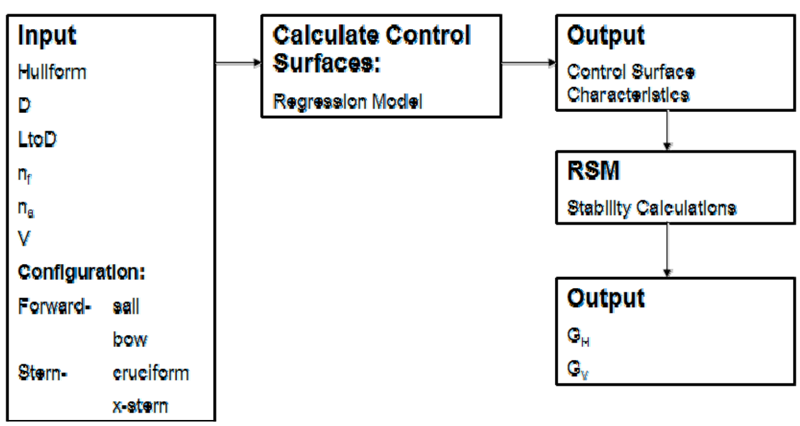


Figure 88: Control Surface Calculations and RSM Flowchart

4.8.2 SSLOI Control Surfaces

The size, location, and configuration of the submarine's sail and control surfaces were provided by the control surface calculations and RSM. SSLOI has sail planes and a cruciform stern. Table 58 lists a summary of the sail and control surface characteristics given by the RSM. All surfaces have a NACA 0020 symmetrical airfoil cross-section. The X values in Table 58 represent the distance from the nose of the submarine to the leading edge of the control surface planes. The span (b) for the sail and sail planes is the exposed span; for the horizontal and vertical stern planes (h and v respectively) b is referenced from the centerline of the submarine. The vertical stern planes, rudders, are not symmetric; the lower plane will have a shorter span due to port restrictions. The chord (c) is the distance from the leading edge to the trailing edge of the control surface cross section; it is given at the root (c_r) and the tip (c_t). These control surfaces provide SSLOI with a G_H of 0.045 and a G_V of 0.158. These stability indices are outside of the preferred range, but are stable and allow for a great deal of maneuverability. Figure 89 shows the SSLOI model with sail planes and a cruciform stern.

Table 58: SSLOI Sail and Control Surface Characteristics

Description	Value (ft)
X_{sail}	110.6
b_{sail}	21.0
c_{rsail}	32.0
c_{tsail}	31.2
$X_{sailplane}$	113.9
$b_{sailplane}$	13.1
$c_{rsailplane}$	17.2
$c_{tsailplane}$	7.0
X_h	235.5
b_h	15.0
c_{rh}	14.5
c_{th}	9.8
X_{vtop}	235.5
b_{vtop}	15.0
c_{rvtop}	14.5
c_{tvtop}	9.8
$X_{vbottom}$	235.5
$b_{vbottom}$	13.0
$c_{rvbottom}$	14.5
$c_{tvbottom}$	9.8

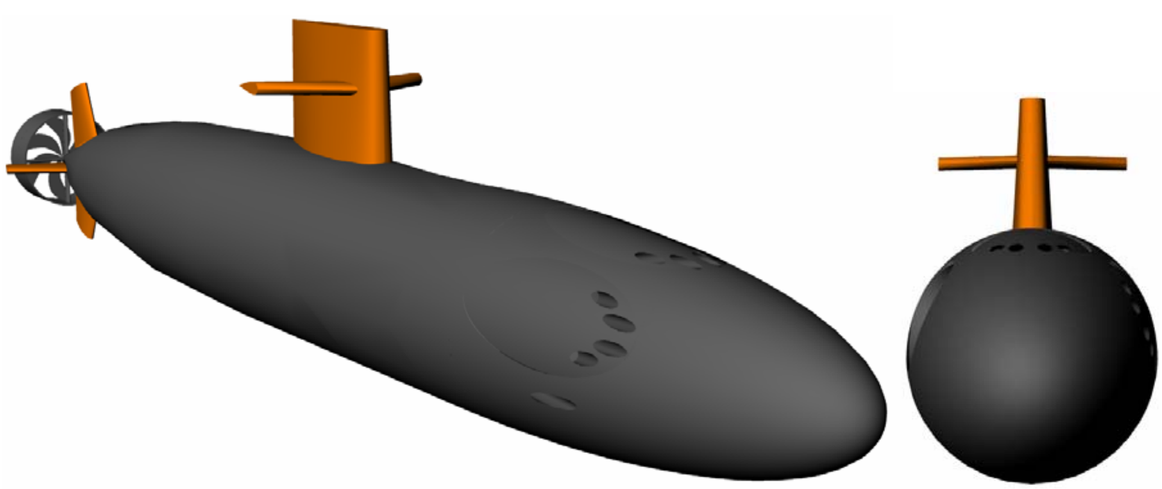


Figure 89: SSLOI with Sail and Control Surfaces

4.9 Cost and Risk Analysis

4.9.1 Cost and Producibility

The SSLOI pressure hull structure is constructed of HY-100 steel. This steel was first used on the US Seawolf submarines to achieve a greater operating depth than could have been reached using the traditional HY-80 steel. The hull's beam to depth ratio of one allows for minimal production costs that arise from unsymmetrical hull forms. The design of the SSLOI incorporates a modular bay located in front of the pressure hull. The module is currently configured to support the MANTA UUVs, however this could be replaced with modules that could support other large UUVs or be tailored for specific mission needs.

The cost calculation is primarily based on the SWBS group weights. A labor cost and material cost is calculated for each group. The labor cost is determined by multiplying the SWBS weight, the man-hour rate, and the complexity factor together. The material cost is determined by multiplying the material cost factor by the SWBS group weight and the inflation rate. Once each SWBS group has a material cost and labor cost, the direct cost (DC) and indirect cost (IC) can be determined. The DC is the sum of all labor and material costs. The IC is determined by multiplying the DC by the overhead rate of 25%. Examples of these calculations are provided in Figure 90.

C. Lead Ship Shipbuilder Labor Cost:

Update Man Hour Rate (fully burdened): $Mh := \frac{75 \cdot dol}{hr}$

Structure $K_{N1} := \frac{400 \cdot hr}{lton}$ $C_{L_1} := K_{N1} \cdot W_1 \cdot Mh$ $C_{L_1} = 32.5\,Mdol$

+ Propulsion $K_{N2} := \frac{800 \cdot hr}{lton}$ $C_{L_2} := K_{N2} \cdot W_2 \cdot Mh$ $C_{L_2} = 33.8\,Mdol$

D. Lead Ship Shipbuilder Material Cost:

Structure $K_{M1} := \frac{18 \cdot Kdol}{lton}$ $C_{M_1} := F_I \cdot K_{M1} \cdot W_1$ $C_{M_1} = 26.3\,Mdol$

+ Propulsion $K_{M2} := \frac{150 \cdot Kdol}{lton}$ $C_{M_2} := F_I \cdot K_{M2} \cdot W_2$ $C_{M_2} = 113.9\,Mdol$

F. Direct Costs:

1. Labor Cost: $C_L := \sum_{i=1}^{9} C_{L_i}$ $C_L = 258.9\,Mdol$

2. Material Cost: $C_M := \sum_{i=1}^{9} C_{M_i}$ $C_M = 409.6\,Mdol$

3. Direct Cost: $DC := C_L + C_M$ $DC = 668.5\,Mdol$

G. Overhead: **Enter Overhead Rate:** $ovhd := .25$

$IC := DC \cdot ovhd$ $IC = 167.1\,Mdol$

Figure 90: Cost Calculation Example

The basic cost of construction of the SSLOI is $919 million. This satisfies the goal of a lead ship BCC of less than $1 billion. Figure 91 illustrates the total cost breakdown including all SWBS groups. The SSLOI is a cost efficient and producible supplement to today's United States Navy.

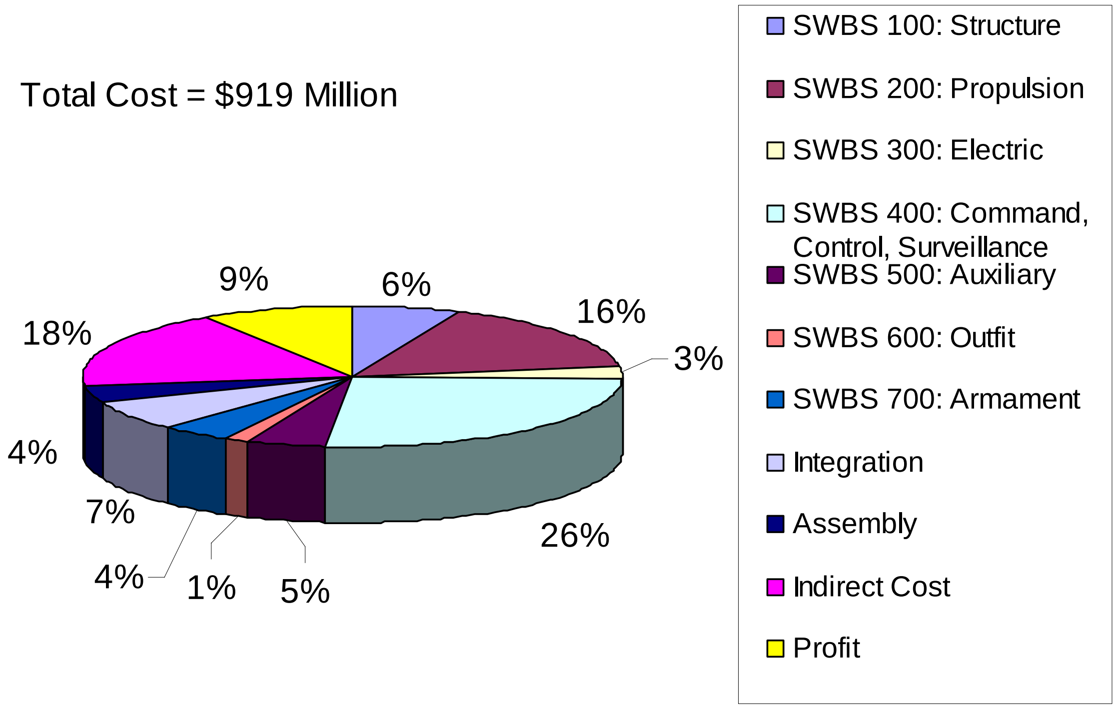


Figure 91: Direct Cost Breakdown

4.9.2 Risk

The selected baseline design for the SSLOI is a moderate risk design with an OMOR of 0.44. The systems that are associated with the highest risk are the rim-driven propeller, the use of the reformers for hydrogen, the PEM fuel cells, and the integrations of the Manta UUVs. The risk associated with many of these systems comes from the United States lack of experience with these new technologies. The use of these systems will require extensive testing and qualifying. The development of the reformer system has been investigated by the Office of Naval Research and has shown great promise and marked it as a key enabling technology in future electric ship construction. The PEM fuel cells are successfully being used on the German U212/214 submarines.

The risk that is associated with these systems is being managed by setting the production for 2015. This eight year time period allows for further testing and development of all systems to be used onboard. The eight year window will also allow for the crew of this non-nuclear ship to be highly trained and well educated with the new systems aboard the submarine.

5 Conclusions and Future Work

5.1 Assessment

The analysis and calculations carried out in Concept Development have demonstrated that the baseline design was a good start for the SSLOI. With the guidance and advice from experts, adjustments were made to the baseline design and synthesis model to improve future designs. In the combat systems module, the cost estimate calculations were increased and the estimated power requirements were increased. The weight and displacement of the MANTAs were accounted for despite their natural buoyancy. Overall, the changes made to the baseline design resulted in an improved final design. The Key Performance Parameters (KPPs) for both the baseline and final designs are compared to the threshold and goal values for each KPP Parameters in Table 59.

Table 59 - Compliance with Key Performance Parameters

Technical Performance Measure	Threshold	Goal	Concept Exploration BL/ ORD TPM	Final Concept Development BL
Mission payload	Passive/Active ranging sonar, 2 Manta UUVs, countermeasure launcher, 688 Class Sail masts	Advanced Passive/Active ranging sonar, 2 torpedo tubes, 3 Manta UUVs, Virginia Class Sail masts, countermeasure launcher, degaussing, 4 man lock-out trunk, 6 VLS cells	Advanced Passive/Active ranging sonar, 2 torpedo tubes, 3 Manta UUVs, countermeasure launchers, Virginia Class Sail masts, degaussing, 4 man lock-out trunk	Advanced Passive/Active ranging sonar, 2 torpedo tubes, 3 Manta UUVs, countermeasure launchers, Virginia Class Sail masts, degaussing, 4 man lock-out trunk
Propulsion	CCD, 2xCAT 3512 V12, Lead Acid batteries	OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM +reformer, Zebra batteries	OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM +reformer, Lead Acid batteries	OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM +reformer, Lead Acid batteries
Snorkel Endurance (nm)	5000 (revised)	6000	4129	5718
Sprint Endurance (hr)	1	2	0.95	1.14
AIP Endurance (days)	20	30	25	28.3
Snorkel Speed (knots)	12	12	12	12
Sprint Speed Vs (knots)	15	22	22	21
AIP Speed (knots)	5	5	5	5
Crew size	55	29	40	52
Diving Depth (ft)	500	1000	851	1000

5.2 Summary of Changes Made in Concept Development

As the weight and volume of the systems was finalized the initial arrangements of the pressure hull went through many changes. Based on improved weight and volume estimations, the size of the auxiliary trim tanks was reduced. The ethanol fuel storage was move down into the bilge and converted to a compensated tank using a bladder system to keep the water separate from the ethanol fuel. The split in the battery storage room was removed and the overall height of the bilge was increased. These changes allowed the ship to balance and enclose all load conditions in the equilibrium polygon, ensuring stability in even the most extreme load conditions.

5.3 Future Work

The following will be implemented in the SSLOI the next time around the design spiral:

- Further investigation and testing of the sail shape, size and location to optimize the efficiency of the sailplanes and minimize the drag.

- Further investigation and testing of the seakeeping and maneuvering capabilities.

5.4 Conclusions

The SSLOI provides a non-nuclear platform to aid the United States Navy in the increasingly common shallow-water regional missions that require great flexibility to counter a variety of threat scenarios. The SSLOI allows for this flexibility by supporting the unmanned vehicle, MANTA, that has the ability to be configured for a variety of missions. The SSLOI supports three MANTAs that have the ability to fire their two full size torpedoes and six half size torpedoes while docked. In addition to the MANTA's torpedoes the SSLOI has two inboard torpedo tubes. The SSLOI is a cost effective submarine that uses the alternative propulsion option, fuel cells. The use of fuel cells allows cost saving by reducing the amount of fuel to operate and the reduced level of moving machinery allows for quieter operation. Although this technology is new to the United States Navy, fuel cells are a maturing technology in foreign submarines. With only a few knowledge barriers to conquer, SSLOI is highly producible and effective with minimal risk, and is the ideal solution to the new model of a cost effective littoral warfare.

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Appendix A – Initial Capabilities Document (ICD)

UNCLASSIFIED

INITIAL CAPABILITIES DOCUMENT

FOR A

LARGE OCEAN INTERFACE SUBMARINE (SSLOI)

1. JOINT FUNCTIONAL AREA(S).

- Force Application
- Force Protection
- Battlespace Awareness

The range of military application for the functions in this ICD includes: force application, protection and awareness from the sea. Timeframe considered: 2010-2050. Extended timeframe demands flexibility in upgrade and capability over time.

2. REQUIRED CAPABILITY(S).

- Assure access for the Joint Force from the sea.
- Provide self defense, project defense around friends and joint forces
- Provide persistent surveillance and reconnaissance.

3. CONCEPT OF OPERATIONS SUMMARY

The Quadrennial Defense Review identifies six critical US military operational goals. These are: 1) protecting critical bases of operations; 2) assuring information systems; 3) protecting and sustaining US forces while defeating denial threats; 4) denying enemy sanctuary by persistent surveillance, 5) tracking and rapid engagement; 6) enhancing space systems; and 7) leveraging information technology.

The "Naval Transformational Roadmap" and "Sea Power 21" provide 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.

Power Projection, or Sea Strike, requires the execution and support of flexible strike missions and support of naval amphibious operations. This includes protection to friendly forces from enemy attack and mine countermeasures. Naval forces must possess sufficient mobility to perform all missions on extremely short notice.

This mobility requires preparation, often by stealth, to insure that necessary information and intelligence has been obtained, and that sea lanes from the sea are open when they are required from the full range of enemy threats including mines. This must be accomplished placing minimum personal and assets in harms way.

4. CAPABILITY GAP(S)

The overarching capability gap addressed by this ICD is:

- Provide and support functional areas specified above with the most technologically advanced unmanned/remotely controlled tactical and C^4/I reconnaissance vehicles with stealth, but without placing high-value nuclear submarines and their large crews in harms way. Provide a conventional launch and recovery submarine platform of adequate size and flexibility with a large payload aperture. This capability will allow the submarine to be configured for specific missions including mine countermeasures, ISR and special operations, supporting vehicles of larger size than can be accommodated by 21 inch torpedo tubes. Provide this capability while maintaining core inherent capabilities of stealth, anti-submarine warfare, anti-surface warfare and mobility.

Specific required capabilities (in non-nuclear submarine platform) include:

Priority	Capability Description	Threshold Systems or metric	Goal Systems or metric
1	Large ocean interface aperture, stowage volume and interfaces for advanced unmanned/remotely controlled tactical and C^4/I reconnaissance vehicles	25ftx12ft aperture, volume (Lxwxh)=25ftx12ft x8ft, 150kW	30ftx15ft aperture, volume (Lxwxh)=30ftx15ft x10ft, 200kW
2	Stealth	Virginia	Seawolf
3	ISR	688I	Virginia
4	Mobility	Depth=500ft, Sprint speed=15knt, snorkel range=3000nm@12knt, AIP @5knt=20days	Depth=1000ft, Sprint speed=22knt, snorkel range=4000nm@12knt, AIP @5knt=30days
5	ASW, ASUW	SUBTICS (Thales): Passive Cylindrical bow array, PVDF planar flank arrays, sail and chin-arrays, torpedoes: 6x21inch tubes, 24 reloads	BQQ-10 Bow Dome Passive/Active, LWWAA, BSY-2, sail and chin-arrays, 12 external encapsulated torpedoes

5. TREAT AND OPERATIONAL ENVIRONMENT

The shift in emphasis from global Super Power conflict to numerous regional conflicts requires increased flexibility to counter a variety of threat scenarios which may rapidly develop. Two distinct classes of threats to U.S. national security interests exist:

- Threats from nations with either a significant military capability, or the demonstrated interest in acquiring such a capability. Specific weapons systems that could be encountered include: significant land-based air assets with the capability to hunt and sink submarines; surface ships with full ASW capabilities; AIP, diesel and possibly nuclear submarines; mines (surface, moored and bottom).
- Threats from smaller nations who support, promote, and perpetrate activities which cause regional instabilities detrimental to international security. Specific weapon systems

include diesel/electric submarines, surface ships and craft with ASW capability, and mines (surface, moored and bottom).

Since many potentially unstable nations are located on or near geographically constrained bodies of water, the tactical picture will be on smaller scales relative to open ocean warfare. Many encounters may occur in shallow water which increases the difficulty of detecting and successfully prosecuting targets.

The platform or system must be capable of operating in the following environments:

- Dense contact and threat with complicated targeting
- Noisy and reverberation-limited
- Crowded shipping
- Open ocean (sea states 0 through 9) and littoral
- All-Weather

6. FUNCTIONAL SOLUTION ANALYSIS SUMMARY.

a. *Ideas for Non-Materiel Approaches (DOTMLPF Analysis).*

- Change the U.S. role in the world by reducing U.S. international involvement.
- Increase reliance on foreign political and military activity to meet the interests of the U.S.
- Increase reliance on non-military assets and options to enhance the U.S. performance of the missions identified above while requiring a smaller inventory of naval forces.

b. *Ideas fo Materiel Approaches.*

- Limit UUV size to be compatible with 21 inch torpedo tubes and support from existing SSN assets
- Limit UUV size to be compatible with 21 inch torpedo tubes and support from new non-nuclear submarine design
- Modify existing submarine assets to support large aperture UUVs
- Design and build a new non-nuclear AIP submarine able to support large aperture UUVs

7. FINAL RECOMMENDATIONS.

The overarching capability specified in this document is to provide a large UUV aperture in a submerged submarine without placing high-value nuclear submarines and their large crews in harms way. Although a nuclear submarine could be used and is planned (SSN Jimmy Carter) the non-nuclear capability requirement is still valid. Only a new non-nuclear AIP submarine able to support large aperture UUVs supports this requirement.

It is essential that the acquisition cost of the new submarine be kept to an absolute minimum, no more than 25% of the cost of a new Virginia Class SSN. The submarine must be highly producible, minimizing the time from concept to delivery to the fleet, and maximizing system commonality with existing SSNs. The submarine must operate within current logistics support capabilities. Inter-service and Allied C^4/I (inter-operability) must be considered. The new submarine must have absolute minimum manning.

Appendix B - Acquisition Decision Memorandum (ADM)

Virginia Tech

Aerospace and Ocean Engineering

VIRGINIA POLYTECHNIC INSTITUTE
AND STATE UNIVERSITY

215 Randolph Hall
Mail Stop 0203, Blacksburg, Virginia 24061
Phone # 540-231-6611 Fax: 540-231-9632

August 16, 2006

From: Virginia Tech Naval Acquisition Executive
To: SSLOI Design Teams

Subject: ACQUISITION DECISION MEMORANDUM FOR a Large Ocean Interface Submarine

Ref: (a) Virginia Tech SSLOI Initial Capabilities Document

1. This memorandum authorizes concept exploration of a single material alternative proposed in Reference (a) to the Virginia Tech Naval Acquisition Board on 16 August 2005. Additional material and non-material alternatives supporting these capabilities may be authorized in the future.

2. Concept exploration is authorized for a new non-nuclear AIP submarine able to support large aperture UUVs. Design capabilities must be consistent with the capabilities and constraints specified in Reference (a). The design must minimize personnel vulnerability in combat through automation, innovative concepts for minimum crew size, and signature reduction. Average follow-ship acquisition cost shall not exceed $500M ($FY2010) with a lead ship acquisition cost less than $1B. It is expected that 5 ships of this type will be built with IOC in 2015.

3. The AOA shall be conducted in accordance with the Virginia Tech Concept Exploration process.

A.J. Brown
VT Acquisition Executive

Appendix C – Capability Development Document (CDD)

UNCLASSIFIED

CAPABILITY DEVELOPMENT DOCUMENT

FOR

Large Ocean Interface Submarine (SSLOI) Variant # 90
VT Team 6

1 Capability Discussion

The Initial Capabilities Document (ICD) associated with this CDD was issued by the Virginia Tech Acquisition Authority on 31 August 2006. The overarching capability gaps addressed by this ICD are: Provide and support functional areas with the most technologically advanced unmanned/remotely controlled tactical and C4/I reconnaissance vehicles with stealth, but without placing high-value nuclear submarines and their large crews in harms way. Provide a conventional launch and recovery submarine platform of adequate size and flexibility with a large payload aperture. This capability will allow the submarine to be configured for specific missions including mine countermeasures, ISR and special operations, supporting vehicles of larger size than can be accommodated by 21 inch torpedo tubes. Provide this capability while maintaining core inherent capabilities of stealth, anti-submarine warfare, anti-surface warfare and mobility. Specific Capability Gaps with goals and thresholds are summarized in Table 1.

Priority	Capability Description	Threshold Systems or metric	Goal Systems or metric
1	Large ocean interface aperture, stowage volume and interfaces for advanced unmanned/remotely controlled tactical and C^4/I reconnaissance vehicles	1 x MANTA UUV	3 x MANTA UUV
2	ISR	688I	Virginia
3	Mobility / power	Depth=500ft, Sprint speed=15knt, snorkel range=5000nm@12knt, diesel propulsion and AIP @5knt=20days	Depth=1000ft, Sprint speed=22knt, snorkel range=6500nm@12knt, diesel propulsion and AIP @5knt=30days
4	ASW, ASUW	Passive Cylindrical bow array, PVDF planar flank arrays, sail and chin-arrays, torpedoes: 2x21inch tubes, 8 reloads	BQQ-10 Bow Dome Passive/Active, LWWAA, BSY-2, sail and chin-arrays, torpedoes: 4x21inch tubes, 16 reloads

2 Acquisition Decision Memorandum

An Acquisition Decision Memorandum was issued on September 7, 2006 by the Virginia Tech Acquisition Authority. It directed Concept Exploration and Analysis of Alternatives (AoA) for a new non-nuclear AIP submarine able to support large aperture UUVs. Required capabilities are stealth, ISR, mobility, ASW, ASUW, and accommodation of advanced unmanned/remotely controlled UUVs with a large ocean interface aperture. The design must minimize personnel vulnerability in combat through automation, innovative concepts for minimum crew size, and signature reduction.

Concept Exploration was conducted from 12 September 2006 through 5 December 2006. A Concept Design and Requirements Review was conducted on 30 January 2007. This CDD presents the baseline requirements resulting from this review.

Available technologies and concepts necessary to provide required functional capabilities were identified and defined in terms of performance, cost, risk and ship impact (weight, area, volume, power). Trade-off studies were performed using technology and concept design parameters to select trade-off options in a multi-objective genetic optimization (MOGO) for the total ship design. The result of this MOGO was a non-dominated frontier, Figure 1. This frontier includes designs with a wide range of risk and cost, each having the highest effectiveness for a given risk and cost. Preferred designs are often "knee in the curve" designs at the top of a large increase in effectiveness for a given cost and risk, or designs at high and low extremes. The **design selected for Virginia Tech Team 6, and specified in this CDD, is the moderate-risk, moderate-cost design shown with an X in Figure 1**. Selection of a point on the non-dominated frontier specifies requirements, technologies and the baseline design.

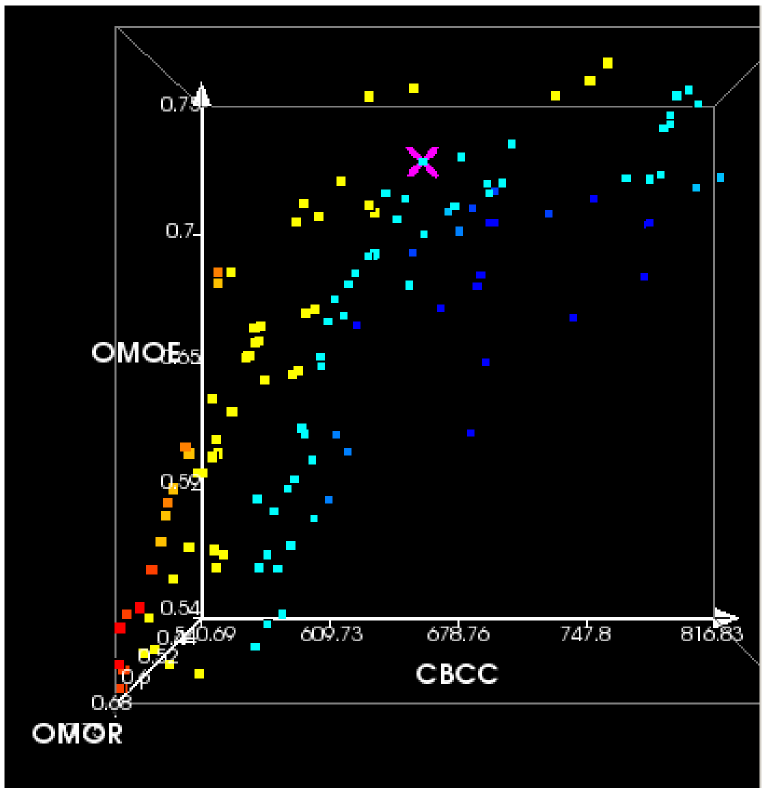


Figure 1 – SSLOI Non-Dominated Frontier

3 Concept of Operations Summary

The range of military operations for the functions in this ICD includes: force application from the sea; force application, protection and awareness at sea; and protection of homeland and critical bases from the sea. Timeframe considered: 2010-2050. This extended timeframe demands flexibility in upgrade and capability over time. The 2001 Quadrennial Defense Review identifies seven critical US military operational goals. These are: 1) protecting critical bases of operations; 2) assuring information systems; 3) protecting and sustaining US forces while defeating denial threats; 4) denying enemy sanctuary by persistent surveillance, 5) tracking and rapid engagement; 6) enhancing space systems; and 7) leveraging information technology.

These goals and capabilities must be achieved with sufficient numbers of ships for worldwide and persistent coverage of all potential areas of conflict, vulnerability or interest.

Forward-deployed naval forces will be the first military forces on-scene having "staying and convincing" power to promote peace and prevent crisis escalation. The force must have the ability to provide a "like-kind, increasing lethality" response to influence decisions of regional political powers. It must also have the ability to remain invulnerable to enemy attack. New ships must complement and support this force.

Power Projection requires the execution and support of flexible strike missions and support of naval amphibious operations. This includes protection to friendly forces from enemy attack, unit self defense against littoral threats, area defense, mine countermeasures and support of theater ballistic missile defense. Submarines must be able to support, maintain and conduct operations with the most technologically advanced unmanned/remotely controlled tactical and C^4/I reconnaissance vehicles. Naval forces must possess sufficient mobility and endurance to perform all missions on extremely short notice, at locations far removed from home port. To accomplish this, they must be pre-deployed, virtually on station in sufficient numbers around the world.

Missions specified for SSLOI include:

- Intelligence, Surveillance, and Reconnaissance (ISR)
- Mine Countermeasures (MCM)
- Special Warfare (SPW) Mission

4 Threat Summary

The shift in emphasis from global Super Power conflict to numerous regional conflicts requires increased flexibility to counter a variety of asymmetric threat scenarios which may rapidly develop. Two distinct classes of threats to U.S. national security interests exist:

- Threats from nations with either a significant military capability, or the demonstrated interest in acquiring such a capability. Specific weapons systems that could be encountered include: significant land-based air assets with the capability to hunt and sink submarines; surface ships with full ASW capabilities; AIP, diesel and possibly nuclear submarines; mines (surface, moored and bottom).
- 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. Specific weapon systems include diesel/electric submarines, surface ships and craft with ASW capability, and mines (surface, moored and bottom).

Since many potentially unstable nations are located on or near geographically constrained (littoral) bodies of water, the tactical picture will be on smaller scales relative to open ocean warfare. Threats in such an environment include: (1) technologically advanced weapons - cruise missiles like the Silkworm and Exocet, land-launched attack aircraft, fast gunboats armed with guns and smaller missiles, and diesel-electric submarines; and (2) unsophisticated and inexpensive passive weapons – mines (surface, moored and bottom), chemical and biological weapons. Many encounters may occur in shallow water which increases the difficulty of detecting and successfully prosecuting targets. Platforms chosen to support and replace current assets must have the capability to dominate all aspects of the littoral environment.

The platform or system must be capable of operating in the following environments:

- Dense contact and threat with complicated targeting
- Noisy and reverberation-limited
- Crowded shipping
- Open ocean (sea states 0 through 9) and littoral
- All-Weather

5 System Capabilities and Characteristics Required for Current Development Increment

Key Performance Parameter (KPP)	Development Threshold or Requirement
Mission Payload	Multiple MANTAs/UUVs with torpedo capabilities contained in large ocean interface; 8 torpedo reloads and 2 torpedo tubes in submarine
Propulsion	Diesel w/AIP, 2xCAT 3512 V12, 2x500KW PEM fuel cell with ethanol reformer and rim-driven propeller
Mobility	Depth = 1000 feet Maximum Crew Size = 55 Sprint Speed = 21.2 knots Sprint Duration = 59 minutes Snorkel Range @ 12knt = 5000nm AIP @ 5knt = 28 days

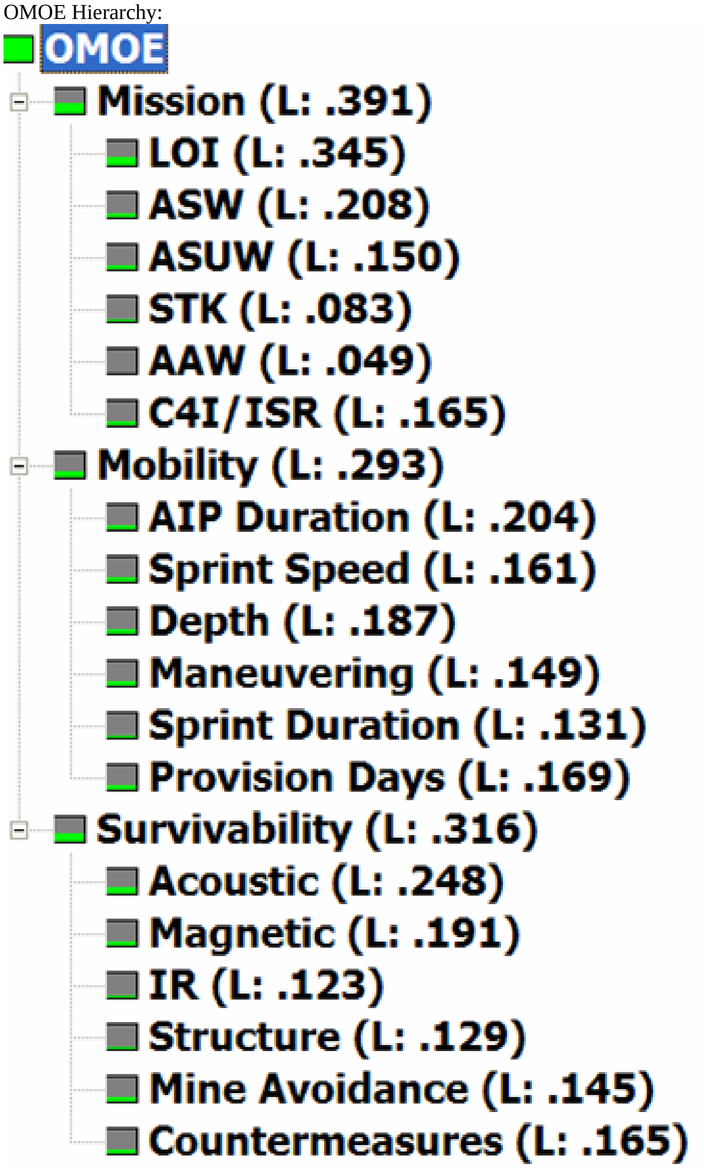
Combat Systems	EDO Model 1122 MF Passive bow array, MFA, PRS, EDO Model 1121 flank array, Scout HF Chin Array, EDO Model 1123 towed array, BSY-2/CCSM
SAIL	BPS-16 Radar; 2xAN/BRA-34 Multi-band; AN/BVS-1 Photonics mast; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA
ESM	WLY-1 acoustic interception and countermeasures system; AN/WLQ-4, AN/BLQ-10 Electronic Support Measures (ESM) system; 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube

6 Program Requirements

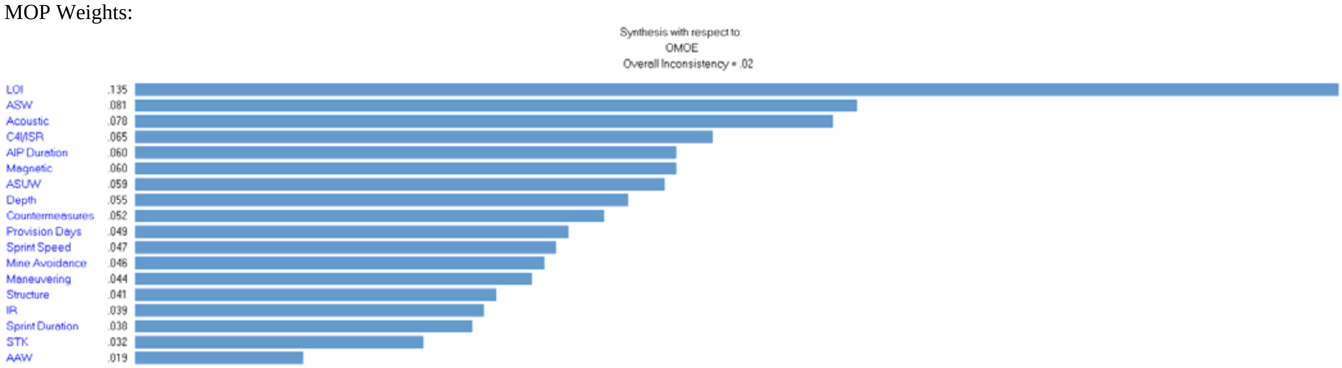
The basic cost of construction will not exceed $920M. It is expected that the year in commission for the first submarine is 2015. The maximum overall level of risk (OMOR) is 0.45 (moderate level of risk).

Appendix D – Measures of Performance (MOP) and Values of Performance (VOP) – Pairwise Comparison Results

OMOE Hierarchy:



MOP Weights:



Mission:

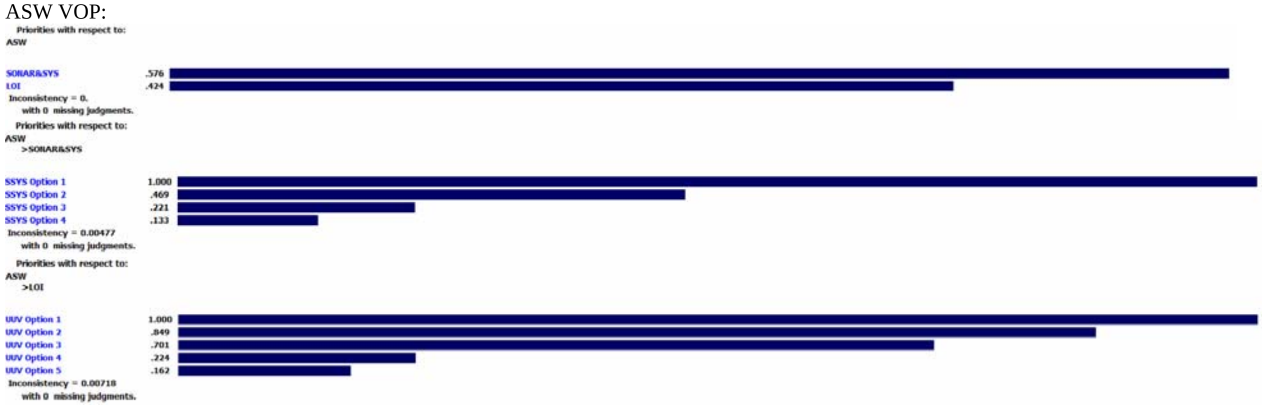
LOI VOP:

STK VOP:

AAW VOP:

C4I/ISR VOP:

ASW VOP:



ASUW VOP:

Mobility:

AIP Duration VOP:

Sprint Speed VOP:

Depth VOP:

Sprint Duration VOP:

Provision days VOP:

Survivability:

Acoustic Signature VOP:

Magnetic Signature VOP:

Countermeasures VOP:

IR Signature VOP:

Mine Avoidance VOP:

Structure Vulnerability VOP:

Appendix E – Machinery Equipment List

ITEM	QTY	DESCRIPTION	LOCATION	SWBS	UNIT WEIGHT	POWER REQ (kW)	DIMENSIONS (ft) LxWxH
		Propulsion and Electrical:					
1	2	Proton Exchange Membrane	MMR	235	8.5		8x8x7
2	2	CAT 3512 V12 Diesel Generator (AC)	MMR	230	54		diesel 9x7x6 generator 7x7x6
3	1	Main Machinery Control Console	MMR	310	2	5	3x6x3
4	2	Main Batteries - Bank	Bat Compt	320	2	6	35x5x5
5	1	DC (400V) Main SWB	MMR	300	5	2	3x6x6
6	1	Emergency SWB	AUX	320	1	2	3x3x6
7	2	Oxygen Tanks, spherical	MMR	520	107	1	cylinders
8	2	Power Conversion Modules (ACtoDC)	MMR	300	7.5	5	3x3x3
9	1	Motor Control Center	MMR	300	1	6	2x2x6
10	2	Lighting Load Panel	MMR	300	2	3	2x2x6
11	1	Control Station	MMR	300	2	1	10x7.5x7.5
12	1	Degaussing	Various	310	8.4	8.4	panel 1x1x2
		Fuel Transfer and Storage:					
13		Reformer	MMR	250/260	30	1	18.4x7x6
14	2	FO Purifier	MMR	250/260	0.5	1	3x3x4
15	2	FO Transfer Pump	MMR	250/260	0.5	2	1.5x1.5x2
		Lube Oil Transfer and Storage					
16	2	LO Purifier	MMR	250/260	0.5	1	3x3x4
17	2	LO Transfer Pump	MMR	250/260	0.5	2	1.5x1.5x2
18	2	Oily Waste Transfer Pump #1	MMR	250/260	0.3	2	1x1x2
19	2	Oily Water Separator	MMR		0.3	1	2x2x2
		Steering and Control					
20	1	Steering Hydraulics	aft	560	2	5	2x2x2
21	1	Aft Plane Hydraulics	aft	560	2	5	2x2x2
22	1	Sail Plane Hydraulics	Sail	560	2	5	2x2x2
		Air Systems:					
23	2	Air Compressor	MMR	550	0.5	10	4x4x4
24	2	Air Dehydrator	MMR	550	0.5	2	2x2x3
25	12	Air Cyliners	MBT	550	0.5	1	1x1x5
26	2	Air Reducer Manifold	MMR	550	0.3	1	2x2x2
		Hydraulic Systems:					
27	2	Main Hydraulic Pump	MMR	550	12	20	2x2x3
28	2	Hydraulic Pressure Accumulator	MMR	530/550	5	3	3x3x5
29	1	Hydraulic vent and Suppy Tank	MMR	550	5	4	4x4x4
		Fresh Water Systems:					
30	2	Potable Water Pump	MMR	530	0.7	5	2x1x1
31	2	Hot Water Circ Pump	MMR	530	0.3	2	2x1x1
32	2	Reverse Osmosis Distiller	MMR	530	0.5	1	5x5x4
33	2	Distiller Feed Pump					
		Salt Water Systems:					
34	2	Trim manifold	MMR	520	2	5	3x1x1
35	2	Trim pump	MMR	520	2	5	2x1x1
36	2	Drain and Bilge Pump	MMR		16	10	2x1x1
37	2	Salt Water Circulating Pump	MMR	250/260	1	2	2x1x1
		Ventilation and Air purification:					
38	2	Main Induction Blower	Sail		8	5	2x2x2
39	2	Main Exhaust Fan	MMR		8	5	2x2x2
40	2	Ventilation Fan	Air Pur Rm	510	8	5	2x2x2
41	2	CO2 Scrubber	Air Pur Rm	510	2.5	8	2x2x5
42	2	CO/H2 Burner	Air Pur Rm	510	2.5	8	2x2x3
		AC and Refrigeration					
43	2	AC Unit	MMR		4.9	40	4x2x2
44	2	Chilled Water Pump	MMR		1	2	2x1x1
45	2	Refrigeration Units	MMR		2	4	4x2x2
46	1	Chill/Freeze Box	Galley		2	5	6x4x6
		Environmental Systems					
47	1	Trash Disposal Unit (TDU)	Galley	593	0.5	2	2x2x2
48	2	Sewage Vacuum Sys	Air Pur Rm	593	1	5	3x2x2
49	2	Waste Water Discharge Pump	Air Pur Rm	593	1	5	2x1x1

Appendix F - Weights and Centers by SWBS Number

ITEM	QTY	DESCRIPTION	LOCATION	SWBS	UNIT WEIGHT	POWER REQUIRED (kW)	DIMENSIONS (ft) LxWxH
		Propulsion and Electrical:					
1	2	Proton Exchange Membrane	MMR	235	8.5		8x8x7
2	2	CAT 3512 V12 Diesel Generator (AC)	MMR	230	54		diesel 9x7x6 generator 7x7x6
3	1	Main Machinery Control Console	MMR	310	2	5	3x6x3
4	2	Main Batteries - Bank	Bat Compt	320	2	6	35x5x5
5	1	DC (400V) Main SWB	MMR	300	5	2	3x6x6
6	1	Emergency SWB	AUX	320	1	2	3x3x6
7	2	Oxygen Tanks, spherical	MMR	520	107	1	cylinders
8	2	Power Conversion Modules (ACtoDC)	MMR	300	7.5	5	3x3x3
9	1	Motor Control Center	MMR	300	1	6	2x2x6
10	2	Lighting Load Panel	MMR	300	2	3	2x2x6
11	1	Control Station	MMR	300	2	1	10x7.5x7.5
12	1	Degaussing	Various	310	8.4	8.4	panel 1x1x2
		Fuel Transfer and Storage:					
13		Reformer	MMR	250/260	30	1	18.4x7x6
14	2	FO Purifier	MMR	250/260	0.5	1	3x3x4
15	2	FO Transfer Pump	MMR	250/260	0.5	2	1.5x1.5x2
		Lube Oil Transfer and Storage					
16	2	LO Purifier	MMR	250/260	0.5	1	3x3x4
17	2	LO Transfer Pump	MMR	250/260	0.5	2	1.5x1.5x2
18	2	Oily Waste Transfer Pump #1	MMR	250/260	0.3	2	1x1x2
19	2	Oily Water Separator	MMR		0.3	1	2x2x2
		Steering and Control					
20	1	Steering Hydraulics	aft	560	2	5	2x2x2
21	1	Aft Plane Hydraulics	aft	560	2	5	2x2x2
22	1	Sail Plane Hydraulics	Sail	560	2	5	2x2x2
		Air Systems:					
23	2	Air Compressor	MMR	550	0.5	10	4x4x4
24	2	Air Dehydrator	MMR	550	0.5	2	2x2x3
25	12	Air Cyliners	MBT	550	0.5	1	1x1x5
26	2	Air Reducer Manifold	MMR	550	0.3	1	2x2x2
		Hydraulic Systems:					
27	2	Main Hydraulic Pump	MMR	550	12	20	2x2x3
28	2	Hydraulic Pressure Accumulator	MMR	530/550	5	3	3x3x5
29	1	Hydraulic vent and Suppy Tank	MMR	550	5	4	4x4x4
		Fresh Water Systems:					
30	2	Potable Water Pump	MMR	530	0.7	5	2x1x1
31	2	Hot Water Circ Pump	MMR	530	0.3	2	2x1x1

32	2	Reverse Osmosis Distiller	MMR	530	0.5	1	5x5x4
33	2	Distiller Feed Pump					
		Salt Water Systems:					
34	2	Trim manifold	MMR	520	2	5	3x1x1
35	2	Trim pump	MMR	520	2	5	2x1x1
36	2	Drain and Bilge Pump	MMR		16	10	2x1x1
37	2	Salt Water Circulating Pump	MMR	250/260	1	2	2x1x1
		Ventilation and Air purification:					
38	2	Main Induction Blower	Sail		8	5	2x2x2
39	2	Main Exhaust Fan	MMR		8	5	2x2x2
40	2	Ventilation Fan	Air Pur Rm	510	8	5	2x2x2
41	2	CO2 Scrubber	Air Pur Rm	510	2.5	8	2x2x5
42	2	CO/H2 Burner	Air Pur Rm	510	2.5	8	2x2x3
		AC and Refrigeration					
43	2	AC Unit	MMR		4.9	40	4x2x2
44	2	Chilled Water Pump	MMR		1	2	2x1x1
45	2	Refrigeration Units	MMR		2	4	4x2x2
46	1	Chill/Freeze Box	Galley		2	5	6x4x6
		Environmental Systems					
47	1	Trash Disposal Unit (TDU)	Galley	593	0.5	2	2x2x2
48	2	Sewage Vacuum Sys	Air Pur Rm	593	1	5	3x2x2
49	2	Waste Water Discharge Pump	Air Pur Rm	593	1	5	2x1x1

Appendix G - Hullform Model

DVs: $D := 32 \cdot ft$ $LOD := 8.05$ $BtoD := 1.0$ $n_f := 2.15$ $n_a := 2.75$

$LOA := D \cdot LOD$ $LOA = 257.6\,ft$ $B := BtoD \cdot D$ $B = 32\,ft$ $del := B - D$ $del = 0\,ft$ $lton := 2240 \cdot lbf$ $\delta_{SW} := 35 \cdot \frac{ft^3}{lton}$

Select teardrop forebody and run L/D: $LOD_{td} := 6.0$ (6.0 opt) $L_{td} := LOD_{td} \cdot D$ $L_{td} = 192\,ft$

Select L including PMB: $L_{pmb} := LOA - LOD_{td} \cdot D$ $L_{pmb} = 65.6\,ft$

Entrance (fig 5-3): $n_f = 2.15$ (2.25 opt) $L_f := 2.4 \cdot D$ $L_f = 76.8\,ft$

(resistance optimum)

Run (fig 5-2): $n_a = 2.75$ (2.75 opt) $L_a := 3.6 \cdot D$ $L_a = 115.2\,ft$

CALCULATIONS:

1. Entrance (forebody) and PMB: $x1 := 0 \cdot ft, .1 \cdot ft .. L_f + L_{pmb}$

$$yf1(x1) := \left[1 - \left(\frac{L_f - x1}{L_f}\right)^{n_f}\right]^{\frac{1}{n_f}} \cdot \frac{D}{2} \qquad offf(x1) := if\left(x1 < L_f, yf1(x1), \frac{D}{2}\right)$$

2. Run: $x1 := 0 \cdot ft, .1 \cdot ft .. LOA$

$$ya(x1) := \left[1 - \left[\frac{x1 - (L_f + L_{pmb})}{L_a}\right]^{n_a}\right] \cdot \frac{D}{2} \qquad offt(x1) := if\left(x1 \le L_f + L_{pmb}, offf(x1), ya(x1)\right)$$

3. Total Ship:

$$V_{tot} := \int_{0 \cdot ft}^{LOA} offt(x1)^2 \cdot \pi\, dx1 + (B - D) \cdot \int_{0 \cdot ft}^{LOA} offt(x1)\, dx1 \qquad V_{tot} = 153203\,ft^3 \qquad \Delta_{env} := \frac{V_{tot}}{\delta_{SW}} \qquad \Delta_{env} = 4377\,lton$$

$$V_{tot} := \int_{0 \cdot ft}^{LOA} offt(x1)^2 \cdot \pi\, dx1 \qquad V_{tot} = 153203\,ft^3 \qquad C_p := \frac{V_{tot}}{\frac{\pi D^2 LOA}{4}} \qquad C_p = 0.739$$

$$SS := \int_{0 \cdot ft}^{LOA} offt(x1) \cdot 2 \cdot \pi\, dx1 + 2 \cdot del \cdot \int_{0 \cdot ft}^{LOA} \sqrt{1 + \left(\frac{d}{dx1} offt(x1)\right)^2}\, dx1 \qquad SS = 21314\,ft^2$$

$$A(x) := BtoD \pi (offt(x))^2 \qquad p(x) := 2 \cdot \pi \cdot \sqrt{.5 \cdot offt(x)^2 \cdot (1 + BtoD^2)}$$ (assumes elliptical cross section)

$$V_{env} := \int_{0 \cdot ft}^{LOA} A(x)\, dx \qquad V_{env} = 153203\,ft^3$$

$$S := \int_{0 \cdot ft}^{LOA} p(x)\, dx \qquad S = 2.131 \times 10^4\,ft^2$$

$$V_f := \int_{0 \cdot ft}^{L_f} offt(x1)^2 \cdot \pi\, dx1 + (B - D) \cdot \int_{0 \cdot ft}^{L_f} offt(x1)\, dx1 \qquad V_f = 4.295 \times 10^4\,ft^3 \qquad C_{pf} := \frac{V_f}{\frac{\pi D^2 L_f}{4}} \qquad C_{pf} = 0.695$$

$$V_{pmb} := \int_{L_f}^{L_f + L_{pmb}} offt(x1)^2 \cdot \pi\, dx1 + (B - D) \cdot \int_{L_f}^{L_f + L_{pmb}} offt(x1)\, dx1 \qquad V_{pmb} = 5.276 \times 10^4\,ft^3 \qquad C_{ppmb} := \frac{V_{pmb}}{\frac{\pi D^2 L_{pmb}}{4}} \qquad C_{ppmb} = 1$$

$$V_a := \int_{L_f + L_{pmb}}^{LOA} offt(x1)^2 \cdot \pi\, dx1 + (B - D) \cdot \int_{L_f + L_{pmb}}^{LOA} offt(x1)\, dx1 \qquad V_a = 5.749 \times 10^4\,ft^3 \qquad C_{pa} := \frac{V_a}{\frac{\pi D^2 L_a}{4}} \qquad C_{pa} = 0.621$$

$$V_{tot} := V_f + V_{pmb} + V_a \qquad V_{tot} = 1.532 \times 10^5\,ft^3$$

$$formfac := 1 + .5\cdot\frac{B}{LOA} + 3\cdot\left(\frac{B}{LOA}\right)^{7-n_f-\frac{n_a}{2}}$$ $n_f = 2.15$ $n_a = 2.75$ $formfac = 1.064$ $knt := 1.69\cdot\frac{ft}{sec}$

$Ca := .0004$ $ro := 1.9905\cdot\frac{lbf\cdot sec^2}{ft^4}$

$V := 12\cdot knt$

$$RN := \frac{LOA\cdot V}{1.2817\times10^{-5}\cdot\frac{ft^2}{sec}}$$ $RN = 4.076\times10^{8}$ $CF := \frac{.075}{(\log(RN)-2)^2}$ $CF = 1.716\times10^{-3}$

$$R := \frac{(Ca + CF\cdot formfac)}{2}\cdot ro\cdot SS\cdot V^2$$ $R = 8.6731ton$ snorkel resistance?

$PEBH := R\cdot V$ $PEBH = 716.329\,hp$ $PET := 1.3\cdot PEBH$ $EHP := 1.25\cdot PET$

$PC := .7$ $SHP := \frac{EHP}{PC}$ $eta := .92$ $BHP := \frac{SHP}{eta}$ $BHP = 1.808\times10^{3}\,hp$

$BHP = 1.348\times10^{3}\,kW$

$$formfac := 1 + .5\cdot\frac{B}{LOA} + 3\cdot\left(\frac{B}{LOA}\right)^{7-n_f-\frac{n_a}{2}}$$ $n_f = 2.15$ $n_a = 2.75$ $formfac = 1.064$ $knt := 1.69\cdot\frac{ft}{sec}$

$Ca := .0004$ $ro := 1.9905\cdot\frac{lbf\cdot sec^2}{ft^4}$

$V := 12\cdot knt$

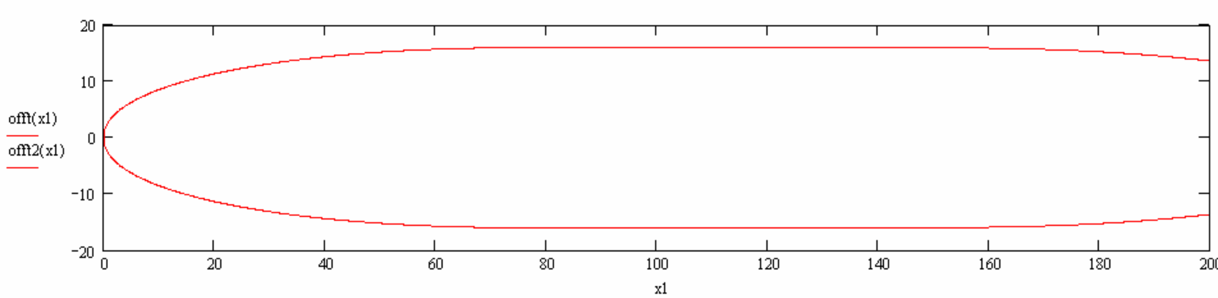
$$RN := \frac{LOA\cdot V}{1.2817\times10^{-5}\cdot\frac{ft^2}{sec}}$$ $RN = 4.076\times10^{8}$ $CF := \frac{.075}{(\log(RN)-2)^2}$ $CF = 1.716\times10^{-3}$

$$R := \frac{(Ca + CF\cdot formfac)}{2}\cdot ro\cdot SS\cdot V^2$$ $R = 8.6731ton$ snorkel resistance?

$PEBH := R\cdot V$ $PEBH = 716.329\,hp$ $PET := 1.3\cdot PEBH$ $EHP := 1.25\cdot PET$

$PC := .7$ $SHP := \frac{EHP}{PC}$ $eta := .92$ $BHP := \frac{SHP}{eta}$ $BHP = 1.808\times10^{3}\,hp$

$BHP = 1.348\times10^{3}\,kW$

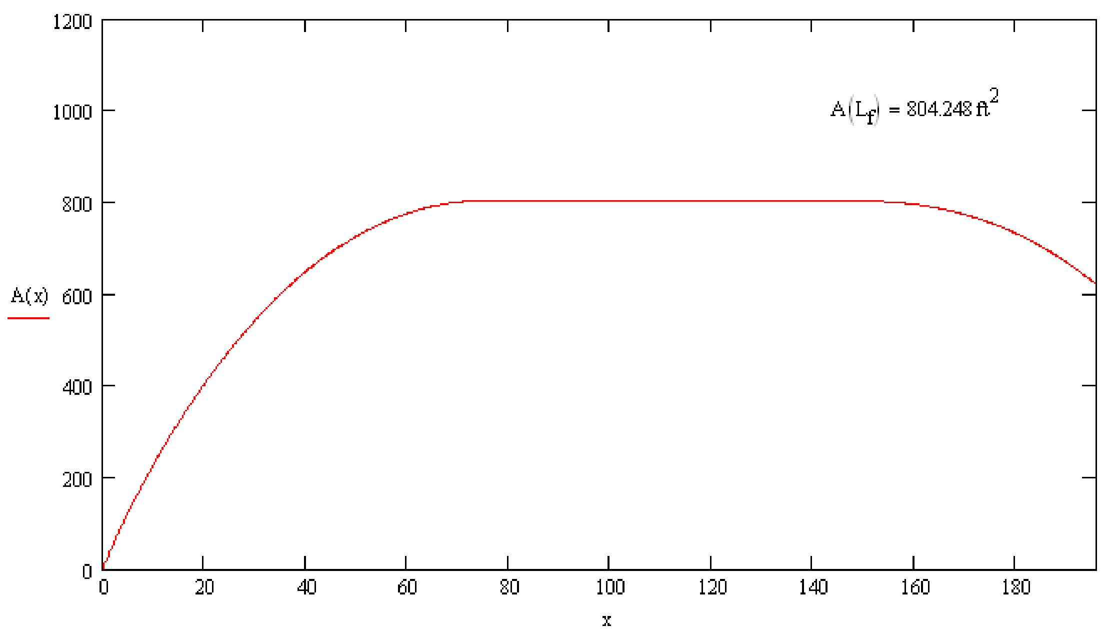


$D = 32\,ft$ $LOD = 8.05$ $BtoD = 1$ $LOA = 257.6\,ft$ $B = 32\,ft$ $L_{pmb} = 65.6\,ft$ $n_f = 2.15$ $n_a = 2.75$ $formfac = 1.064$

$L_f = 76.8\,ft$ $L_f + L_{pmb} = 142.4\,ft$ $\frac{D}{2} = 16\,ft$ $LOA = 257.6\,ft$ $offt(LOA) = 5.329 \times 10^{-15}\,ft$

$x1 := 0 \cdot ft, \frac{L_f}{10} .. L_f$ $x2 := (L_f + L_{pmb}), \left(L_f + L_{pmb} + \frac{L_a}{10}\right) .. LOA$

x1 = (ft)	offt(x1) = (ft)	x2 = (ft)	offt(x2) = (ft)
0	0	142.4	16
7.68	7.616	153.92	15.972
15.36	10.215	165.44	15.809
23.04	11.967	176.96	15.416
30.72	13.249	188.48	14.712
38.4	14.209	200	13.622
46.08	14.92	211.52	12.073
53.76	15.429	223.04	10
61.44	15.764	234.56	7.338
69.12	15.947	246.08	4.025
76.8	16	257.6	$-3.908 \cdot 10^{-14}$



Appendix H – Power and Propulsion Calculations

Units definition and Physical Parameters

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

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

$\delta_F = 42.6 \cdot \frac{ft^3}{lton}$ $days := 24hr$ $RPM := \frac{1}{min}$

Input Module:

Principal characteristics: $LOA := 257.5 \cdot ft$ $B := 32 \cdot ft$ $D := 32 \cdot ft$ $S := 21316.68 \cdot ft^2$ $C_A := .0004$

$n_f := 2.0$ $n_a := 2.8$ $V_e := 5 \cdot knt$ $V_{esnork} := 12knt$ $W_{fsnk} := 220lton$ $Wfaip := 133lton$

$KW_{24AVG} := 346.2113 \cdot kW$ $D_P := 5.97 \cdot m$ $D_P = 19.587\,ft$ $N_P := 1$ $V_{env} := 153203 \cdot ft^3$ $V_S := 21.23 \cdot knt$

Propulsion Margin Factors and Efficiencies: $FMF_e := 1.1$ $PMF_S := 1.25$ $\eta_{elec} := .93$ $PMF := 1.1$

DFM in diesel engine: $SFC_{snk} := .476 \cdot \frac{lbf}{kW \cdot hr}$ $SFC_{aip} := 0.410 \cdot \frac{kgf}{kW \cdot hr}$ $SFC_{aip} = 0.904 \frac{lbf}{kW \cdot hr}$ $SFC_{aip} = 4.035 \times 10^{-4} \frac{lton}{kW \cdot hr}$

Battery Capacity: $E_{battery} := 6000 \cdot kW \cdot hr$

$E_{FC} := \frac{Wfaip}{SFC_{aip}}$

Sprint Battery Power: $P_{battery} := 7200 \cdot kW$

Diesel Brake Power: $P_{main} := 1000 \cdot kW$

$E_{FC} = 3.296 \times 10^5\, kW \cdot hr$

Sprint Available Brake Propulsion Power: $P_{IPRP} = P_{main} + .5P_{battery} - KW_{24AVG}$

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

Viscous Resistance

Form Factor adapted from Gilmer and Johnson: $formfac := 1 + .5 \cdot \frac{B}{LOA} + 3 \cdot \left(\frac{B}{LOA}\right)^{\left(7 - n_f - \frac{n_a}{2}\right)}$ $formfac = 1.064$

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

Bare Hull Resistance

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

Effective Horsepower

Power, Bare hull: $P_{EBH_i} := R_{T_i} \cdot V_i$

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

MIT Method (for comparison and validation to VT method):

C_r calculation: using equation developed for $\frac{C_f + C_r}{C_f}$ (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: $A_s := 400 \cdot ft^2$ $\quad C_{Ds} := .009$ $\quad A_s \cdot C_{Ds} = 3.6\,ft^2$

For the remaining appendages, use the expression for $A_{other} \cdot C_{dother}$ = $App := \frac{LOA \cdot D}{1000}$ $\quad App = 8.243\,ft^2$

$$EHPMIT_i := 0.5 \cdot \rho SW \cdot (V_i)^3 \cdot \left[S \cdot \left(C_{F_i} \cdot C_{frf} + C_A\right) + \left[\left(A_s \cdot C_{Ds}\right) + App\right]\right] \qquad EHPMIT_1 = 70.781\,hp$$

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

$$C_{ws} := \frac{S}{\pi \cdot LOA \cdot D} \qquad C_{ws} = 0.823$$

$$w := 1 - .371 - 1.7151 \cdot \frac{\frac{D_p}{D}}{\sqrt{C_{ws} \cdot \frac{LOA}{D}}} \qquad w = 0.221$$

wake fraction $\quad w := if(w < 0.1, 0.1, w) \quad w = 0.221$

$$t := 1 - .532 - 1.3756 \cdot \frac{\frac{D_p}{D}}{\sqrt{C_{ws} \cdot \frac{LOA}{D}}} \qquad t = 0.041$$

thrust deduction fraction - prop changes pressure distribution around hull which effectively changes the resistance of towed hull

$t := if(t < .15, .15, t) \quad t = 0.15$

$V_A := V \cdot (1 - w)$

speed of advance - average wake velocity seen by prop

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

$\eta_H := \frac{1-t}{1-w}$ $\eta_H = 1.091$ hull efficiency $THP := \frac{EHP}{\eta_H}$

V = (knt)

	1
1	5
2	6
3	7
4	8
5	9
6	10
7	11
8	12
9	13
10	14
11	15
12	16
13	17
14	18
15	19
16	20
17	21
18	22
19	23
20	24
21	25

THP = (hp)

	1
1	68
2	115
3	180
4	264
5	371
6	504
7	663
8	853
9	1075
10	1332
11	1627
12	1961
13	2337
14	2758
15	3225
16	3742
17	4310
18	4932
19	5610
20	6347
21	7144

T = (lbf)

	1
1	$4.376\cdot10^3$
2	$6.17\cdot10^3$
3	$8.252\cdot10^3$
4	$1.062\cdot10^4$
5	$1.326\cdot10^4$
6	$1.618\cdot10^4$
7	$1.938\cdot10^4$
8	$2.285\cdot10^4$
9	$2.659\cdot10^4$
10	$3.059\cdot10^4$
11	$3.486\cdot10^4$
12	$3.94\cdot10^4$
13	$4.419\cdot10^4$
14	$4.925\cdot10^4$
15	$5.457\cdot10^4$
16	$6.014\cdot10^4$
17	$6.598\cdot10^4$
18	$7.207\cdot10^4$
19	$7.841\cdot10^4$
20	$8.501\cdot10^4$
21	$9.186\cdot10^4$

V_A = (knt)

	1
1	3.894
2	4.673
3	5.452
4	6.231
5	7.009
6	7.788
7	8.567
8	9.346
9	10.125
10	10.903
11	11.682
12	12.461
13	13.24
14	14.019
15	14.797
16	15.576
17	16.355
18	17.134
19	17.913
20	18.692
21	19.47

$T_1 = 1.947\times10^4$ newton $V_1 = 5$ knt AIP $D_P = 5.97$ m $DEPTH_{aip} := 100\cdot m$ $DEPTH_{snrk} := 18m$

$T_{17} = 2.935\times10^5$ newton $V_{17} = 21$ knt Sprint Thrust Endurance AIP, Sprint, Snorkel $w = 0.221$

$T_8 = 1.016\times10^5$ newton $V_8 = 12$ knt Snorkel

For B series, 7-bladed prop optimized for max open water eff at AIP speed: (EAR=1.05, P/D=1.4, w=.31)

$\eta_{Oaip} := .768$ $n_{aipSHAFT} := 17.44\cdot RPM$

$\eta_{Osprint} := .794$ $n_{sprintSHAFT} := 71.23\cdot RPM$

$\eta_{Osnork} := .784$ $n_{snrkSHAFT} := 41.11\cdot RPM$

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

$\eta_{Baip} := \eta_{Oaip}\cdot\eta_R$ $\eta_{Baip} = 0.791$ AIP prop efficiency behind ship = THP/DHP

$\eta_{Bsprint} := \eta_{Osprint}\cdot\eta_R$ $\eta_{Bsprint} = 0.818$ Sprint prop efficiency behind ship = THP/DHP

$\eta_{Bsnrk} := \eta_{Oaip}\cdot\eta_R$ $\eta_{Bsnrk} = 0.791$ AIP prop efficiency behind ship = THP/DHP

$DHP_{aip} := \frac{THP_1}{\eta_{Baip}}$ $DHP_{sprint} := \frac{THP_{17}}{\eta_{Bsprint}}$ $DHP_{snrk} := \frac{THP_8}{\eta_{Bsnrk}}$

$DHP_{Oaip} := \eta_R \cdot DHP_{aip}$ $DHP_{Osprint} := \eta_R \cdot DHP_{sprint}$ $DHP_{Osnrk} := \eta_R \cdot DHP_{snrk}$

quasi-propulsive efficiency

$\eta_{Daip} := \eta_H \cdot \eta_{Baip}$ $\eta_{Daip} = 0.863$

$\eta_{Dsprint} := \eta_H \cdot \eta_{Bsprint}$ $\eta_{Dsprint} = 0.893$

$\eta_{Dsnrk} := \eta_H \cdot \eta_{Bsnrk}$ $\eta_{Dsnrk} = 0.863$

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

Shaft Power - delivered at hull/stern tube

$SHP_{aip} := \frac{DHP_{aip}}{\eta_S}$ $SHP_{sprint} := \frac{DHP_{sprint}}{\eta_S}$ $SHP_{snrkv} := \frac{DHP_{snrk}}{\eta_S}$ (viscous component of snorkel resistance only)

$SHP_{aip} = 64.17\,kW$ $SHP_{sprint} = 3.93 \times 10^3\,kW$ $SHP_{snrkv} = 804.115\,kW$

propulsive efficiency (Propulsive Coefficient, PC)

$\eta_{Paip} := \eta_S \cdot \eta_{Daip}$ $\eta_{Paip} = 0.863$

$\eta_{Psprint} := \eta_S \cdot \eta_{Dsprint}$ $\eta_{Psprint} = 0.893$

$\eta_{Psnrk} := \eta_S \cdot \eta_{Dsnrk}$ $\eta_{Psnrk} = 0.863$

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

Endurance Brake Power:

$BHP_{aipreq} := \frac{PMF_e \cdot SHP_{aip}}{\eta_{elec}}$ $BHP_{aipreq} = 76\,kW$ delivered by prime movers or motors

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

$V_{17} = 21\,knt$ $SHP_{sprint} = 3930\,kW$ $BHP_{req} = 5283\,kW$ $P_{IPRP} = 4254\,kW$ $n_{sprintSHAFT} = 71.23\,RPM$

Average Endurance Brake Power Required: $P_{eBAVG} := \frac{SHP_{aip}}{\eta_{elec}}$ $P_{eBAVG} := \frac{SHP_{aip}}{\eta_{elec}}$ $P_{eBAVG} = 69\,kW$

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

$f_1 = 1.04$

$EHP_{req} = 5.283 \times 10^3\,kW$

Specified fuel rate: $FR_{SP} := f_1 \cdot SFC_{aip}$ $FR_{SP} = 0.94 \frac{lbf}{kW \cdot hr}$

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

$FR_{AVG} = 0.987 \frac{lbf}{kW \cdot hr}$

Tailpipe allowance: $TPA := 0.95$

$Wfaip = 1331 ton$

Endurance Range AIP:

$Wfaip = 1331 ton$

$P_{aipavg} := \frac{KW_{24AVG}}{\eta_{elec}} + BHP_{aipreq}$ $P_{aipavg} = 448.17 kW$ $E_{faip} := Wfaip \cdot \frac{1.}{SFC_{aip}}$ $E_{faip} = 3.296 \times 10^5 kW \cdot hr$

$E_{aip} := \frac{E_{faip}}{(f_1 \cdot 1.05 \cdot P_{aipavg})}$ $E_{aip} = 28.061 days$ $f_1 \cdot 1.05 \cdot P_{aipavg} = 489.402 kW$ $E_A := E_{aip} \cdot V_1$ $E_A = 3.367 \times 10^3 nm$

Sprint Range:

$E_{sprint} := \frac{E_{battery}}{BHP_{req} - 500kW}$ $E_{sprint} = 1.255 hr$

$E_S := (E_{sprint}) \cdot V_{17}$ $E_S = 26 nm$

500 kW are subtracted from BHPreq to correspond the use of fuel cells while performing spring operations. Since fuel cell output is unknown, the power used for AIP Endurance was used.

Snorkel Range:

$SHP_{snrkv} = 804.115 kW$

Froude # for Cdw Coef Calc:

$Fn := \frac{V_{esnork}}{(g \cdot LOA)^{.5}}$ $Fn = 0.223$

$C_{DW} := 3561.3 \cdot Fn^6 - 8812.6 \cdot Fn^5 + 8148.4 \cdot Fn^4 - 3454.3 \cdot Fn^3 + 654.09 \cdot Fn^2 - 40.235 \cdot Fn + .12$

$C_{DW} = 1.097$

$C_W := \frac{C_{DW}}{4 \cdot \left[\left(\frac{LOA}{D}\right) - 1.3606\right]\left(\frac{LOA}{D}\right)^2}$ $C_W = 6.326 \times 10^{-4}$

Wave Induced:

$SHP_W := C_W \cdot S \cdot \rho_{SW} \cdot V_{esnork}^3$ $SHP_W = 303.531 kW$

SHP Snorkel:

$SHP_{snrk} := SHP_{snrkv} + SHP_W$ $SHP_{snrk} = 1108 kW$

Endurance Snork Calculation:

$FR_{SPsnk} := f_1 \cdot SFC_{snk}$ $FR_{SPsnk} = 0.495 \frac{lbf}{kW \cdot hr}$ $BHP_{snrkreq} := PMF \cdot \frac{SHP_{snrk}}{.93}$

$FR_{AVGsnk} := 1.05 \cdot FR_{SPsnk}$ $FR_{AVGsnk} = 0.52 \frac{lbf}{kW \cdot hr}$ $BHP_{snrkreq} = 1.31 \times 10^3 kW$

$P_{snkAVG} := \frac{SHP_{snrk} + KW_{24AVG}}{\eta_{elec}}$ $P_{snkAVG} = 2096 hp$

$E_{snork} := \frac{(W_{fsnk} \cdot V_{esnork} \cdot TPA)}{P_{snkAVG} \cdot FR_{AVGsnk}}$ $E_{snork} = 6914 nm$

Appendix I - Cost Calculation

SUBMARINE COST MODEL (Follow-Ship BCC):

based on Capt Jackson's notes as revised by Ms. Smith, PMS 350P in 1995

Establish Cost units: $Mdol := coul$ $lton := 2240 \cdot lb$

$Cost_C := 1000 \cdot Mdol$ $Bdol := 1000 \cdot Mdol$ $Kdol := \frac{Mdol}{1000}$ $dol := \frac{Kdol}{1000}$

Weight Inputs:

$W_1 := 1084 \cdot lton$ $W_5 := 200 \cdot lton$

$W_2 := 564 \cdot lton$ $W_6 := 74 \cdot lton$

$W_3 := 79 \cdot lton$ $W_7 := 51.1 \cdot lton$

$W_4 := 182 \cdot lton$

A. Additional characteristics:

Ship Service Life: $L_S := 30$ **Initial Operational Capability:** $Y_{IOC} := 2015$

#

Total Ship Acquisition: $N_S := 10$ **Production Rate (per year):** $R_P := .5$

#

B. Inflation:

Base Year: $Y_B := 2010$ $iy := Y_B - 1995$

#

Average Inflation Rate (%): $R := 2$ $F_I := \left(1 + \frac{R}{100}\right)^{iy}$ $F_I = 1.346$
(from 1995)

#

C. Lead Ship Shipbuilder Labor Cost:

Update Man Hour Rate (fully burdened): $Mh := \frac{75 \cdot dol}{hr}$

#

Structure $K_{N1} := \frac{400 \cdot hr}{lton}$ $CL_1 := K_{N1} \cdot W_1 \cdot Mh$ $CL_1 = 32.5\,Mdol$

+ Propulsion $K_{N2} := \frac{800 \cdot hr}{lton}$ $CL_2 := K_{N2} \cdot W_2 \cdot Mh$ $CL_2 = 33.8\,Mdol$

+ Electric $K_{N3} := \frac{1000 \cdot hr}{lton}$ $CL_3 := K_{N3} \cdot W_3 \cdot Mh$ $CL_3 = 5.9\,Mdol$

+ Command, Control, Surveillance

$K_{N4} := \frac{3649 \cdot hr}{lton}$ $CL_4 := K_{N4} \cdot W_4 \cdot Mh$ $CL_4 = 49.8\,Mdol$

+ Auxiliary $K_{N5} := \frac{1500 \cdot hr}{lton}$ $CL_5 := K_{N5} \cdot W_5 \cdot Mh$ $CL_5 = 22.5\,Mdol$

+ Outfit $K_{N6} := \frac{1300 \cdot hr}{lton}$ $CL_6 := K_{N6} \cdot W_6 \cdot Mh$ $CL_6 = 7.2\,Mdol$

+ Armament $K_{N7} := \frac{2607 \cdot hr}{lton}$ $CL_7 := K_{N7} \cdot W_7 \cdot Mh$ $CL_7 = 10\,Mdol$

D. Lead Ship Shipbuilder Material Cost:

Structure $K_{M1} := \frac{18 \cdot Kdol}{1ton}$ $C_{M_1} := F_I \cdot K_{M1} \cdot W_1$ $C_{M_1} = 26.3\,Mdol$

+ Propulsion $K_{M2} := \frac{150 \cdot Kdol}{1ton}$ $C_{M_2} := F_I \cdot K_{M2} \cdot W_2$ $C_{M_2} = 113.9\,Mdol$

+ Electric $K_{M3} := \frac{200 \cdot Kdol}{1ton}$ $C_{M_3} := F_I \cdot K_{M3} \cdot W_3$ $C_{M_3} = 21.3\,Mdol$

+ Command, Control, Surveillance

$K_{M4} := \frac{782 \cdot Kdol}{1ton}$ $C_{M_4} := F_I \cdot K_{M4} \cdot W_4$ $C_{M_4} = 191.5\,Mdol$

+ Auxiliary $K_{M5} := \frac{80 \cdot Kdol}{1ton}$ $C_{M_5} := F_I \cdot K_{M5} \cdot W_5$ $C_{M_5} = 21.5\,Mdol$

+ Outfit $K_{M6} := \frac{40 \cdot Kdol}{1ton}$ $C_{M_6} := F_I \cdot K_{M6} \cdot W_6$ $C_{M_6} = 4\,Mdol$

+ Armament $K_{M7} := \frac{417 \cdot Kdol}{1ton}$ $C_{M_7} := F_I \cdot K_{M7} \cdot W_7$ $C_{M_7} = 28.7\,Mdol$

E. Integration & Assembly:

+ Integration (40% of labor and 0.1% of Material)

$$C_{L_8} := .40 \cdot \sum_{i=1}^{7} C_{L_i} \qquad C_{L_8} = 64.7\,Mdol$$

$$C_{M_8} := .001 \cdot \sum_{i=1}^{7} C_{M_i} \qquad C_{M_8} = 0.4\,Mdol$$

+ Assembly (20% of labor and 0.5% of Material)

$$C_{L_9} := .20 \cdot \sum_{i=1}^{7} C_{L_i} \qquad C_{L_9} = 32.4\,Mdol$$

$$C_{M_9} := .005 \cdot \sum_{i=1}^{7} C_{M_i} \qquad C_{M_9} = 2\,Mdol$$

F. Direct Costs:

1. Labor Cost:

$$C_L := \sum_{i=1}^{9} C_{L_i} \qquad C_L = 258.9\,Mdol$$

2. Material Cost:

$$C_M := \sum_{i=1}^{9} C_{M_i} \qquad C_M = 409.6\,Mdol$$

3. Direct Cost:

$$DC := C_L + C_M \qquad DC = 668.5\,Mdol$$

G. Overhead: **Enter Overhead Rate:** $ovhd := .25$

$IC := DC \cdot ovhd$ $IC = 167.1\,Mdol$

H. Profit: **Enter Profit Rate:** $profit := .10$

$Profit := profit \cdot (IC + DC)$ $Profit = 83.6\,Mdol$

I. Total Lead Ship Construction Cost: (BCC):

$C_{BCC} := (1 + profit) \cdot (DC + IC)$ $C_{BCC} = 919.1\,Mdol$

Compare to cost constraint:

$$\frac{C_{BCC} - Cost_C}{C_{BCC}} = -8.8\%$$

+ Over constraint
- Under constraint

Appendix J – Final Weight and Volume Summary and Spreadsheet

Volume	Volume (ft3)	Vol % of sub disp	Disp (LT)
Pressure Hull	100088.8	0.72	2859.7
Outboard Volume	21256.3	0.15	607.3
Everbouyant Volume	121345.1	0.88	3467.0
Main Ballast	16982.2	0.12	485.2
Submerged Displacement Volume	138327.4	1.00	3952.2
Freeflood Volume	14875.9	0.11	425.0
Envelope Volume	153203.3	1.11	4377.2

Weights		% of NSC
Group 1	1084.42	0.31
Group 2	563.53	0.16
Group 3	79.42	0.02
Group 4	194.78	0.06
Group 5	188.23	0.05
Group 6	74.04	0.02
Group 7	52.50	0.02
Condition A-1	2236.907137	0.65
Lead Ballast	505.00	0.15
Condition A	2741.907137	0.79
Variable Loads	725.13	0.21
Normal Surface Condition	3467.032869	

SWBS Group	Weight (lton)	VCG (ft) (above center-line)	LCG(ft) (fwd LCB)
100	1084.42	0.23	-3.92
200	563.53	-4.52	-13.00
300	79.42	3.06	-38.79
400	194.78	1.74	85.47
500	188.23	-0.04	-16.60
600	74.04	1.23	11.28
700	52.50	-3.56	49.74
8 (lead)	505.00	-9.55	33.67
F10	5.53	6.00	-2.47
F20	208.24	4.28	36.86
F30	10.11	-3.00	16.03
F40	479.62	-9.39	-57.96
F50	21.63	-12.79	17.75
900	725.13	-5.36	-26.25
Condition A-1	2236.91	-0.81	1.03
Condition A	2741.91	-2.42	7.04
NSC	3467.03	-3.04	0.08

SWBS	COMPONENT	From Synthesis	WT-lton	VCG-ft	Moment	LCG-ft (fwdFP)	LCG-ft (fwdLCB)	Moment (fwdFP)	TCG-ft	Moment	Moment (LCB)
9	FULL LOADS	W9	725.13	-5.36	-3886.96	-152.28	-26.25	-110420.57	0.00	0.00	-23397.69
A	LIGHTSHIP WEIGHT + LEAD	Wa	2741.91	-2.42	-6639.28	-118.98	7.04	-326234.21	0.00	0.00	24866.05
8	Total Lead	W8 (total)	505.00	-9.55	-4822.51	-92.36	33.67	-46640.55			17343.68
8	LEAD Margin	W8 (Margin)	173.35	0.88	152.22	-127.00	-0.97	-22015.66	0.00	0.00	172.38
8	Lead Stability/trim	W8 (Stability)	331.65	-15.00	-4974.73	-74.25	51.78	-24624.89			17171.30701
A-1	LIGHTSHIP WEIGHT SWBS 1-7	Wa1	2236.91	-0.81	-1816.77	-124.99	1.03	-279593.66	0.00	0.00	7522.368604
100	**HULL STRUCTURES**	**W1**	**1084.42**	**0.23**	**249.70**	**-129.94**	-3.92	**-140912.80**	**0.00**	**0.00**	959.9375248
110	SHELL + SUPPORTS		781.98	0.00	0.00	-132.69	-6.66	-103758.42	0.00	0.00	
111	PRESSURE HULL	Wph	571.94	0.00	0.00	**-130.00**	-3.97	-74351.68	0.00	0.00	-2273.077665
112	NON-PRESSURE ENVELOPE	W112	175.04	0.00	0.00	-140.00	-13.97	-24505.61	0.00	0.00	-2446.072792
118	NON-PRESSURE FRAMES	W118	35.01	0.00	0.00	-140.00	-13.97	-4901.12	0.00	0.00	-489.2145583
120	PRESSURE HULL STRUCTURAL BULKHDS		25.17	-5.03	-126.56	-137.16	-11.14	-3452.96	0.00	0.00	-280.4102988
123	TRUNKS	W123	6.21	-10.00	-62.07	-128.50	-2.47	-797.57	0.00	0.00	-15.35783707
125&6	SOFT AND HARD TANKS	Wtanks	18.97	-3.40	-64.49	-140.00	-13.97	-2655.39	0.00	0.00	-265.0524617
140	PRESSURE HULL PLATFORMS/FLATS	Wdecks	13.03	-9.50	-123.80	-150.00	-23.97	-1954.78	0.00	0.00	-312.4309394
160	SPECIAL STRUCTURES		94.81	5.27	500.06	-77.21	48.82	-7319.83	0.00	0.00	4628.565178
161	COMBAT SYS STRUCTURE SUPPORT	WP100	73.72	2.69	198.30	-70.55	55.48	-5200.73	0.00	0.00	4089.495779
163	SEA CHESTS	Wsea	0.99	-10.00	-9.87	-110.00	16.03	-108.58	0.00	0.00	15.81941572
167	HULL CLOSURES	Wclose	20.11	15.50	311.63	-100.00	26.03	-2010.52	0.00	0.00	523.2499832
180	FOUNDATIONS	W180	161.01	0.00	0.00	-145.00	-18.97	-23345.75	0.00	0.00	-3054.970093
190	SPECIAL PURPOSE SYSTEMS	Wweld	8.41	0.00	0.00	-128.50	-2.47	-1081.05	0.00	0.00	-20.81632235
200	**PROPULSION PLANT**		**563.53**	**-4.52**	**-2544.53**	**-139.03**	-13.00	**-78345.53**	**0.00**	**0.00**	-7326.434757
220	ENERGY GENERATING SYSTEM		122.97	1.96	240.48	-172.27	-46.24	-21184.38	0.00	0.00	-5686.481505
	DIESEL GENERATOR	1.5*Wbmdg	80.16	3.00	240.48	-166.00	-39.97	-13306.42	0.00	0.00	-3204.311453
	FUEL CELL	1.5*Wbmeip	42.81	0.00	0.00	-184.00	-57.97	-7877.95	0.00	0.00	-2482.170052
230	PROPULSION UNITS	Wprop	50.10	0.00	0.00	-245.00	-118.97	-12273.40	0.00	0.00	-5960.081075
240	PROPULSION POWER TRANSMISSION		0.00	0.00	0.00	0.00	126.03	0.00	0.00	0.00	0
		Wshaft	0.00	0.00	0.00	0.00	126.03	0.00	0.00	0.00	0
		Wbearing	0.00	0.00	0.00	0.00	126.03	0.00	0.00	0.00	0
		Wmotor	0.00	0.00	0.00	0.00	126.03	0.00	0.00	0.00	0
250	SUPPORT SYSTEMS		387.01	-7.15	-2767.76	-114.47	11.55	-44301.29	0.00	0.00	4471.830296
	ARGON TANKS	Wars	0.00	0.00	0.00	0.00	126.03	0.00	0.00	0.00	0
	OXYGEN TANKS	1.5*Wo2s	107.01	-2.00	-214.02	**-143.00**	-16.97	-15302.74	0.00	0.00	-1816.463083
	H2 TANKS	Wfeips	0.00	-9.39	0.00	-114.49	11.54	0.00	0.00	0.00	0
	BATTERY	Wbattery	234.00	-9.39	-2197.26	**-91.00**	35.03	-21294.00	0.00	0.00	8196.000536
256	SALTWATER CIRC	Wswc	34.50	-8.00	-275.98	-170.00	-43.97	-5864.65	0.00	0.00	-1517.025158
257	FRESH WATER CIRC	Wfwc	11.50	-7.00	-80.50	-160.00	-33.97	-1839.89	0.00	0.00	-390.6819993
290	SPECIAL PURPOSE SYSTEMS		3.45	-5.00	-17.25	-170.00	-43.97	-586.46	0.00	0.00	-151.7024718
298	FLUIDS	W2fluids	2.30	-5.00	-11.50	-170.00	-43.97	-390.98	0.00	0.00	-101.1349959
299	PARTS	W2parts	1.15	-5.00	-5.75	-170.00	-43.97	-195.49	0.00	0.00	-50.56747596
300	**ELECTRIC PLANT, GENERAL**		**79.42**	**3.06**	**242.64**	**-164.81**	-38.79	**-13088.54**	**0.00**	**0.00**	-3080.149343
310	ELECTRIC POWER GENERATION		35.48	2.00	70.96	-175.00	-48.97	-6208.90	0.00	0.00	-1737.580791
312	EMERGENCY DIESEL GENERTOR	Wemerg	0.00	3.00	0.00	0.00	126.03	0.00	0.00	0.00	0
314	POWER CONVERSION	Wconv	35.48	2.00	70.96	-175.00	-48.97	-6208.90	0.00	0.00	-1737.580791
320	ELECTRICAL DISTRIBUTION SYSTEM		28.92	1.26	36.56	-160.00	-33.97	-4627.65	0.00	0.00	-982.6338633
321	POWER CABLE	Wcab	18.28	2.00	36.56	-160.00	-33.97	-2924.64	0.00	0.00	-621.0169261
324	SWITCH GEAR	Wswitch	10.64	0.00	0.00	-160.00	-33.97	-1703.01	0.00	0.00	-361.6169372
330	LIGHTING SYSTEM	Wlight	15.01	9.00	135.12	-150.00	-23.97	-2252.00	0.00	0.00	-359.9346887
340	POWER GENERATION SUPPORT SYS		0.00	0.00	0.00	0.00	126.03	0.00	0.00	0.00	0
390	SPECIAL PURPOSE SYSTEMS		0.00	0.00	0.00	0.00	126.03	0.00	0.00	0.00	0
400	**COMMAND + SURVEILLANCE**		**194.78**	1.74	**339.34**	-40.56	85.47	**-7900.34**	0.00	**0.00**	16647.06633
420	NAVIGATION SYSTEMS	Wco	20.02	6.00	120.11	-70.55	55.48	-1412.25	0.00	0.00	1110.498114
430	INTERIOR COMMUNICATIONS	Wic	8.50	8.00	68.04	-128.50	-2.47	-1092.82	0.00	0.00	-21.04301549
440	EXTERIOR COMMUNICATIONS	Want	1.60	16.00	25.60	-80.00	46.03	-128.00	0.00	0.00	73.6410293
450	SURF SURVEILLANCE SYS (RADAR)	Wradar	7.10	16.00	113.60	-80.00	46.03	-568.00	0.00	0.00	326.7820675
460	UNDERWATER SURVEILLANCE SYS	Wsonar	125.95	0.00	0.00	**-15.00**	111.03	-1889.25	0.00	0.00	13983.67978
475	DEGAUSSING	Wdegaus	10.01	0.00	0.00	-128.50	-2.47	-1286.14	0.00	0.00	-24.76553913
480	FIRE CONTROL SYSTEMS	Wcc	4.00	3.00	12.00	-70.55	55.48	-282.20	0.00	0.00	221.9025733
490	SPECIAL PURPOSE SYSTEMS	Wper	17.60	0.00	0.00	-70.55	55.48	-1241.68	0.00	0.00	976.3713224
500	**AUXILIARY SYSTEM, GENERAL**		**188.23**	-0.04	**-8.16**	-142.63	-16.60	**-26846.47**	0.00	**0.00**	-3124.798659
510	CLIMATE CONTROL		51.83	5.83	302.06	-133.82	-7.80	-6935.64	0.00	0.00	-404.1630947
512	VENTILATION	Wvent	13.72	3.00	41.15	-125.00	1.03	-1714.59	0.00	0.00	14.06843141
514	AIR CONDITIONING	Wac	13.72	8.00	109.73	-137.00	-10.97	-1879.19	0.00	0.00	-150.5318486
515	AIR REVITALIZATION	Warevit	8.79	3.00	26.38	-137.00	-10.97	-1204.67	0.00	0.00	-96.4997132
516	REFRIGERATION	Wrefer	15.60	8.00	124.80	-137.00	-10.97	-2137.20	0.00	0.00	-171.1999643
520	SEA WATER SYSTEMS		29.39	-14.13	-415.11	-168.75	-42.73	-4958.84	0.00	0.00	-1255.536332
524	AUXILIARY SALTWATER	Wauxsw	3.67	-8.00	-29.33	-160.00	-33.97	-586.65	0.00	0.00	-124.5695269
528	DRAINAGE	Wdrain	25.72	-15.00	-385.78	-170.00	-43.97	-4372.19	0.00	0.00	-1130.966805
530	FRESH WATER SYSTEMS		12.07	-7.90	-95.30	-158.00	-31.97	-1906.44	0.00	0.00	-385.8056253
531	DISTILLERS	Wdist	4.02	-8.00	-32.14	-158.00	-31.97	-634.85	0.00	0.00	-128.4742441
532	FW COOLING	Wcool	6.82	-8.00	-54.55	-158.00	-31.97	-1077.37	0.00	0.00	-218.025944
533	POTABLE WATER SYSTEM	Wpotw	1.23	-7.00	-8.60	-158.00	-31.97	-194.23	0.00	0.00	-39.30543719
540	FUELS/LUBRICANTS, HANDLING+STOWAGE		3.08	3.00	9.24	-150.00	-23.97	-462.15	0.00	0.00	-73.86448948
541	FUEL SERVICE TANKS	Wfuelt	3.08	3.00	9.24	-150.00	-23.97	-462.15	0.00	0.00	-73.86448948
550	AIR,GAS+MISC FLUID SYSTEM		26.84	4.46	119.66	-160.45	-34.43	-4306.83	0.00	0.00	-924.0962914
551	NITROGEN BOTTLES	WcN2	0.59	-5.00	-2.96	-128.50	-2.47	-76.10	0.00	0.00	-1.465292997
554	MBT BLOW AIR	Wmbtblow	5.51	-4.00	-22.03	-160.00	-33.97	-881.24	0.00	0.00	-187.1231803
555	FIREFIGHTING SYSTEMS	Wfire	4.26	3.00	12.77	-128.50	-2.47	-546.80	0.00	0.00	-10.52898401
556	HYDRAULIC SYSTEMS	Whyd	16.49	8.00	131.89	-170.00	-43.97	-2802.69	0.00	0.00	-724.978834
560	SHIP CNTL SYS		35.23	0.32	11.28	-137.23	-11.21	-4834.52	0.00	0.00	-394.8469965
561	STEERING	Wsteer	5.79	0.00	0.00	-220.00	-93.97	-1274.39	0.00	0.00	-544.3616849
563	DEPTH CONTROL	Wdepth	2.36	0.00	0.00	-128.50	-2.47	-302.62	0.00	0.00	-5.827109992
564	TRIM SYSTEMS	Wtrim	0.00	-9.93	0.00	-165.00	-38.97	0.00	0.00	0.00	0
566	DIVING PLANES	Wplanes	25.20	0.00	0.00	-124.00	2.03	-3124.88	0.00	0.00	51.04758899
569	CONTROL	Wcont	1.88	6.00	11.28	-70.55	55.48	-132.63	0.00	0.00	104.2942094
580	ANCHOR, MOORING, HANDLING+STOWAGE		6.90	8.70	60.00	-53.91	72.11	-372.00	0.00	0.00	497.5769389
581	ANCHOR HANDLING	Wanchor	1.20	-5.00	-6.00	-5.00	121.03	-6.00	0.00	0.00	145.230772
582	MOORING	Wmoor	1.20	-5.00	-6.00	-5.00	121.03	-6.00	0.00	0.00	145.230772
585	MAST	Wmast	4.50	16.00	72.00	-80.00	46.03	-360.00	0.00	0.00	207.1153949
590	ENVIRONMENTAL + AUX SYSTEMS		22.90	0.00	0.00	-134.06	-8.04	-3070.05	0.00	0.00	-184.0627681
591	MISCELANEOUS MISSION AUX SYSTEMS	Wp500	19.60	0.00	0.00	-135.00	-8.97	-2646.00	0.00	0.00	-175.897391
592	DIVING SYSTEMS	Wdiver	1.30	0.00	0.00	-128.50	-2.47	-167.05	0.00	0.00	-3.21666369
593	ENVIRONMENTAL SYSTEMS	Wenv	2.00	0.00	0.00	-128.50	-2.47	-257.00	0.00	0.00	-4.948713369
600	**OUTFIT + FURNISHING, GENERAL**		74.04	**1.23**	91.12	**-114.74**	11.28	-8494.97	0.00	0.00	835.4012362
610&620	HULL OUTFIT	Woh	40.04	0.00	0.00	-140.00	-13.97	-5604.97	0.00	0.00	-559.4706365
630-650	PERSONAL OUTFIT	Wotp	34.00	2.68	91.12	**-85.00**	41.03	-2890.00	0.00	0.00	1394.871873

700	**ARMAMENT**		52.50	**-3.56**	-186.87	**-76.29**	49.74	-4005.00	0.00	0.00	2611.346274
740	VLS	**Wvls**	0.00	3.74	0.00	-108.50	17.53	0.00	0.00	0.00	0
750	TORPEDOES HANDLING	Wtorp	51.00	-3.87	-197.37	**-75.00**	51.03	-3825.00	0.00	0.00	2602.307809
760	LOCKOUT	Wlock	1.50	7.00	10.50	-120.00	6.03	-180.00	0.00	0.00	9.038464973
											0
	FULL LOAD SUBMERGED CONDITION										0
F00	LOADS		725.13	**-5.36**	-3886.96	**-152.28**	-26.25	-110420.57	0.00	0.00	-23397.68973
F10	SHIP PERSONNEL	WF10	5.53	6.00	33.17	-128.50	-2.47	-710.42	0.00	0.00	-13.67965908
F20	MISSION EXPENDABLES		208.24	**4.28**	891.90	**-89.17**	36.86	-18568.24	0.00	0.00	-5721.660483
F22	ORDNANCE DELIVERY - torpedoes	Wtorp	13.20	-4.00	-52.80	**-82.00**	44.03	-1082.40	0.00	0.00	581.1384918
F22	ORDNANCE DELIVERY - missiles	Wmis	0.00	3.74	0.00	-108.50	17.53	0.00	0.00	0.00	0
F29	MISCELANEOUS ORDNANCE	Wcounter	0.04	0.00	0.00	-128.50	-2.47	-5.14	0.00	0.00	-0.098974267
F30	STORES		10.11	**-3.00**	-30.34	**-110.00**	16.03	-555.46	0.00	0.00	719.1632565
F31	PROVISIONS+PERSONNEL STORES	WF31	7.64	-3.00	-22.93	-55.55	70.48	-424.62	0.00	0.00	538.7158175
F32	GENERAL STORES	WF32	2.47	-3.00	-7.41	-52.97	73.06	-130.84	0.00	0.00	180.447439
F40	FUEL AND LUBRICANTS		479.62	**-9.39**	-4505.11	**-183.99**	-57.96	-88244.89	0.00	0.00	-18765.3787
F41	DIESEL FUEL	Wf	242.50	**-16.12**	-3909.09	**-177.07**	-51.05	-42940.08	0.00	0.00	-12378.08546
	DIESEL FUEL - compensated	Wfcomp	217.17	-9.00	-1954.54	**-189.00**	-62.97	-41045.40	0.00	0.00	-13676.231
	DIESEL FUEL - clean	Wfclean	25.33	-9.39	-237.85	**-74.80**	51.23	-1894.68	0.00	0.00	1297.545545
F46	LUBE OIL	WF46	1.00	0.00	0.00	-162.00	-35.97	-162.00	0.00	0.00	-35.97435668
F49	SPECIAL FUELS AND FUEL GASES		236.12	**-2.52**	-596.02	**-191.19**	-65.16	-45142.81	0.00	0.00	-6350.718879
	Ethanol - clean	Wethanol/2	**30.65**	-9.39	-287.83	**-67.40**	58.63	-2065.97	0.00	0.00	1797.013371
	Ethanol - compensated	Wethanol/2	**102.35**	-9.39	-961.04	**-154.00**	-27.97	-15761.54	0.00	0.00	-2863.109842
	O2	Wo2	205.46	-1.50	-308.20	**-143.00**	-16.97	-29381.27	0.00	0.00	-3487.609037
	ARGON	War	0.00	0.00	0.00	0.00	126.03	0.00	0.00	0.00	0
F50	LIQUIDS AND GASES		21.63	**-12.79**	-276.58	**-108.28**	17.75	-2341.56	0.00	0.00	383.865847
F51	SEA WATER		10.85	**-16.00**	-173.55	**-115.00**	11.03	-1247.42	0.00	0.00	119.5965864
	SEA WATER - trim	Wtrimbal	**0.00**	-9.93	0.00	-111.10	14.93	0.00	0.00	0.00	0
	SEAWATER - residual	Wresidual	10.85	-16.00	-173.55	-115.00	11.03	-1247.42	0.00	0.00	119.5965864
F52	FRESH WATER	WF52	7.80	-9.39	-73.24	-91.20	34.83	-711.36	0.00	0.00	271.6400179
F55	SEWAGE	Wsew	2.98	-10.00	-29.79	-128.50	-2.47	-382.78	0.00	0.00	-7.370757205
	OUTBOARD PAYLOAD	Wpob	54.00	0.00	0.00	-207.00	-80.97	-11178.00			-4372.615261
	Manta	MANTA	141.00	6.70	944.70	-44.70	81.33	-6302.70			-6302.7