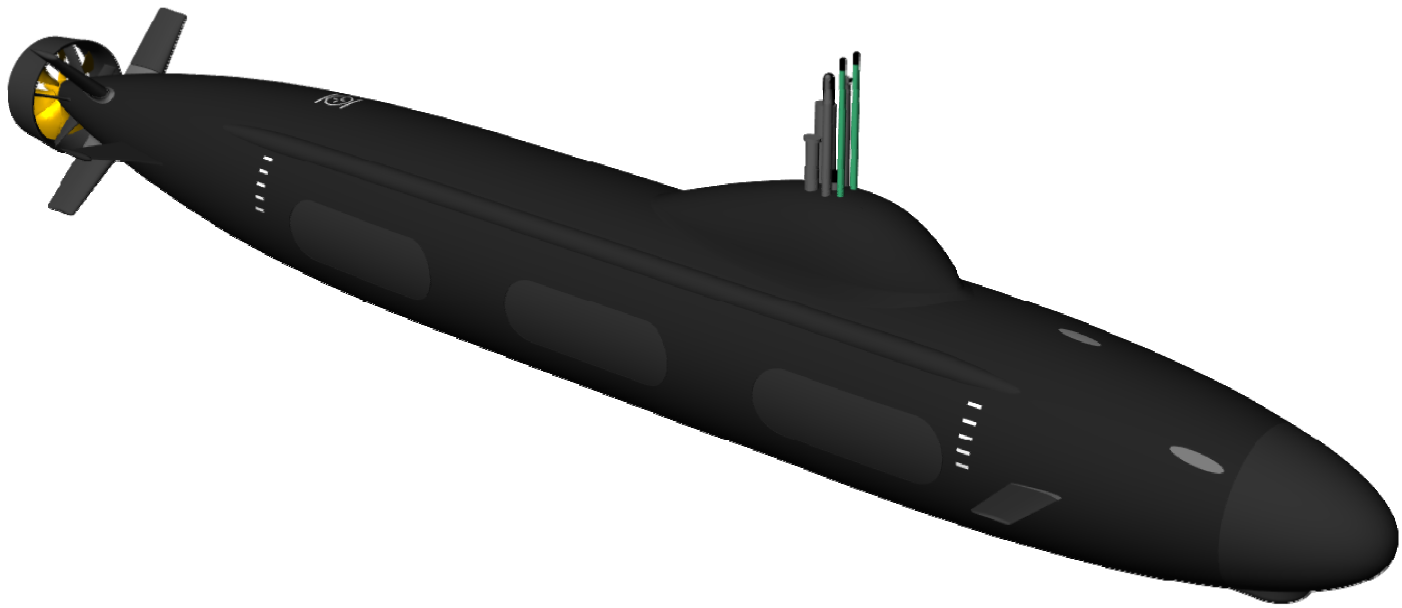
Virginia Tech Aerospace & Ocean Engineering

# Design Report

## Ballistic Missile Defense Submarine

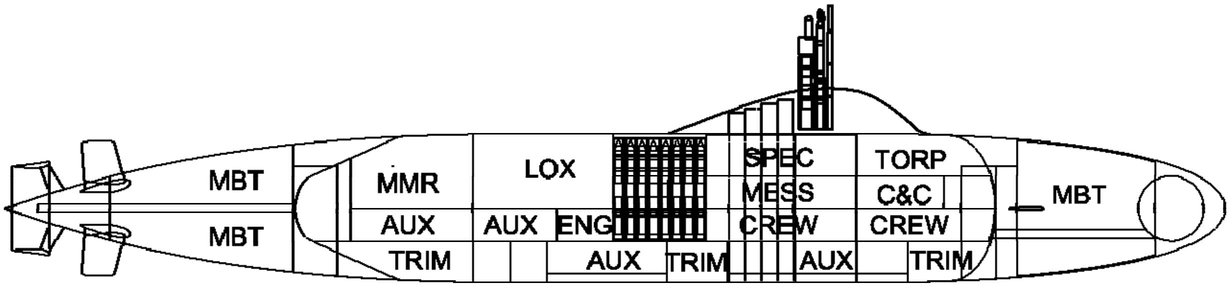
## SSBMD



Ocean Engineering Design Project
AOE 4066 Spring 2008
Virginia Tech Team 1


| | | |
|---|---|---|
| Christopher R. Blizzard – Team Leader | | 27537 |
| Kyle Colantonio | | 27666 |
| Van Jones | | 25922 |
| Mike Toris | | 25654 |
| David Riegel | | 27540 |
| Matt Wichgers | | 13591 |

# Executive Summary




This report describes the Concept Exploration and Development of a Diesel/ AIP Ballistic Missile Defense Submarine (SSBMD) for the United States Navy. This concept design was completed in a two-semester ship design course at Virginia Polytechnic Institute and State University.

The SSBMD requirement is based on the SSBMD Initial Capabilities Document (ICD) and Virginia Tech SSBMD Acquisition Decision Memorandum (ADM). The submarine addresses the need to provide a sea-based ballistic missile defense launch capability to guard against rogue and hostile nation missile attack.

The submarine platform allows for covert positioning near potential enemy launch sites and provides a favorable launch angle for missile interception with guidance from surface or air bourne assets. By utilizing a diesel-electric/AIP design, a ballistic missile defense capability is achieved without endangering US nuclear assets or incurring the diplomatic risk inherent to nuclear submarine operations in or near foreign waters. The submarine is expected to operate in littoral and open ocean environments.

The primary threats expected to be encountered include operating in areas of dense contact with high levels of civilian vessels present (near international shipping lanes).

The primary missions carried out by the submarine are Ballistic Missile Defense (BMD), Intelligence, Reconnaissance & Surveillance Operations, Inland Missile Strike, as well as anti-submarine (ASW) and anti-surface ship (ASuW) capability (primarily for self defense).

SSBMD is a high effectiveness and moderate risk, high end alternative selected from the non-dominated frontier. This design was chosen to provide a ground-breaking, challenging project in which modern, innovative technologies such as PEM fuel cells for air-independent propulsion, two five torpedo rotary launch systems, and four Kinetic Energy Interceptor (KEI) missiles contained in an advanced composite sail were utilized. SSBMD has many other attractive qualities including high maneuverability, an axi-symmetric hullform for producibility, and a sonar system capable of both active and passive sonar ASW missions.

The basic cost of construction of SSBMD is $1.575 billion. This satisfies the goal of a lead ship BCC less than $1.6 billion. The final concept design satisfies key performance requirements in the CDD within cost and risk constraints. The basic characteristics of SSBMD are listed in the table below.

| Ship Characteristic | Value |
|---|---|
| LOA | 261.2 ft |
| Beam | 32 ft |
| Diameter | 32 ft |
| Submerged Displacement | 3962 lton |
| Submerged Displaced Volume | 138027 $ft^3$ |
| Sprint Speed | 22 knt |
| Snorkel Range @ 12 knt | 5356 nm |
| AIP Endurance @ 5 knt | 24 days |
| AIP Sprint Endurance | 56 minutes (21 nm) |
| Propulsion and Power | Open Cycle Diesel/AIP, 2xCAT 3512 V12 + 2x500kW PEM; 5000kW-hr Zebra batteries, Shrouded Propeller |
| Weapon Systems | 4 KEI in sail, Reconfigurable torpedo room, 2x21" tubes, 8 reloads; 24 Cell VLS (16 SM-3, 8TLAM), |
| Sensors | BSY-2 w/ CCSM EDO Arrays |
| $P_{req}$ for AIP 5knt | 76 kW |
| $P_{req}$ for Sprint Speed | 6010 kW |
| $P_{req}$ for Snorkel | 1136 kW |
| Battery Capacity | 5000 kW-hr |
| Diving Depth | 570 ft |
| Total Officers | 8 |
| Total Enlisted | 47 |
| Total Manning | 55 |
| Basic Cost of Construction | $1.6 billion |

# Table of Contents

# 1 Introduction, Design Process and Plan

## 1.1 Introduction

This report describes the concept exploration and development of a Ballistic Missile Defense Submarine (SSBMD) for the United States Navy. The SSBMD requirements are based on the SSBMD Initial Capabilities Document (ICD) and the Virginia Tech SSBMD Acquisition Decision Memorandum (ADM) (provided in Appendix A and Appendix B). The SSBMD concept design was completed during a two-semester senior design course at Virginia Tech.

The overarching capability gap addressed by this ICD is to provide a robust/covert ballistic missile interceptor platform, SSBMD. The SSBMD ICD requires a primary capability of ballistic missile defense. SSBMD must be capable of projecting a missile defense screen to protect regional allied forces and assets. In addition to missile defense, the submarine must be capable of performing ISR missions and deploying special operations forces. SSBMD must be able to implement these primary capabilities without unduly reducing the submarine's performance in its core attributes of stealth, mobility, ASW, and ASuW. Furthermore, in order to adapt to changing threats throughout the submarine's operational lifetime, SSBMD must be designed with the ability to reconfigure mission spaces.

The primary Joint Functional Area for SSBMD is Force and Homeland Protection.
SSBMD must provide force capability as follows:

- Project defense around friends, joint forces, and critical bases of operations at sea.
- Provide a covert sea-based layer of homeland defense.

SSBMD's covert nature would allow it to undertake missions which would be infeasible for surface based BMD platforms. Foremost among these capabilities is BMD interceptor launch operations in or near a hostile nation's waters. This positioning would allow for an advantageous launch angle (similar launch points between target missile and interceptor would allow for similar trajectories and reduced closing speeds). Furthermore, in the case of missiles launched relatively near to the coast, SSBMD's close proximity would allow for possible "boost-phase" interception. Boost-phase interception attempts to strike the target missile when it is ascending, providing a slower, larger target which is more easily tracked by radar and infrared targeting. Additionally, debris from ballistic missiles intercepted in boost phase would likely fall back to earth within the hostile nation, reducing the risk of radioactive contamination in friendly areas.

Because of its covert nature, SSBMD would have limited -if any- launch detection and guidance capability. Instead, it would rely on external cueing, receiving targeting information when an asset –such as a satellite or land/sea based radar system- detects a ballistic missile launch. Because of its heavy reliance on external communications SSBMD must possess very robust, high-bandwidth communication capability.

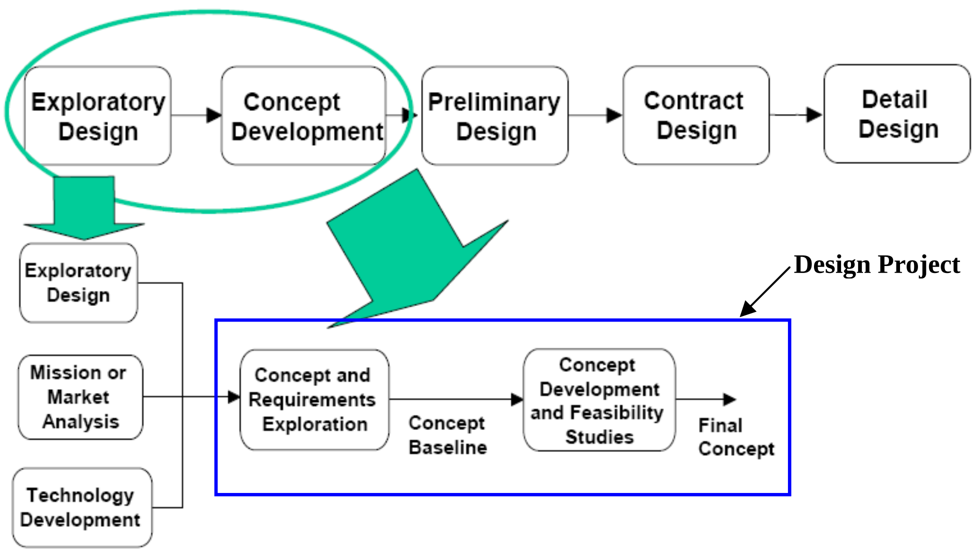



**Figure 1.1: Design Process**

Because SSBMD is non-nuclear, it could operate in enemy waters without endangering key nuclear secrets should a submarine be lost. Additionally, SSBMD would not pose the risk of fallout –radiological or political- which would ensue should a nuclear vessel be damaged while operating in foreign waters.

## 1.2 Design Philosophy, Process, and Plan

The overall design process is shown in Figure 1.1. This design project comprises only the concept exploration and development stages of the full design process. Exploratory design results are provided by the ICD and ADM documents. The concept exploration stage at Virginia Tech breaks with traditional "rule of thumb" design techniques; instead it utilizes a Multi Objective Genetic Optimizer (MOGO) to generate a range of candidate baseline concept designs. Once a baseline design has been selected, a preliminary Capability Development Document (CDD) is created. The CDD specifies key performance requirements, design constraints, concepts to be explored and serves as the primary requirements document for concept development.

The Concept and Requirements Exploration process (Figure 1.2) is used to identify baseline designs from the ICD and ADM. 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 SSBMD missions. The ROCs may require future technologies in the areas of power and propulsion, combat systems, electronics and automation that will become available by the time of the lead ship acquisition. With a list of the technologies expected to be available at lead-ship construction, Design Variables (DVs) are chosen to represent technology selections for each submarine system. Further DVs are chosen to represent continuous numeric values such as vessel dimensions or fuel capacity. Together the DVs represent the design space from which a baseline submarine design will be chosen. With the design space defined by the available and future technologies; metrics for risk, cost, and effectiveness are developed for comparison. The MOGO generates a range of non-dominated designs (that meet all feasibility requirements) which together comprise a non dominated frontier. From this non-dominated frontier, a baseline submarine design is chosen.

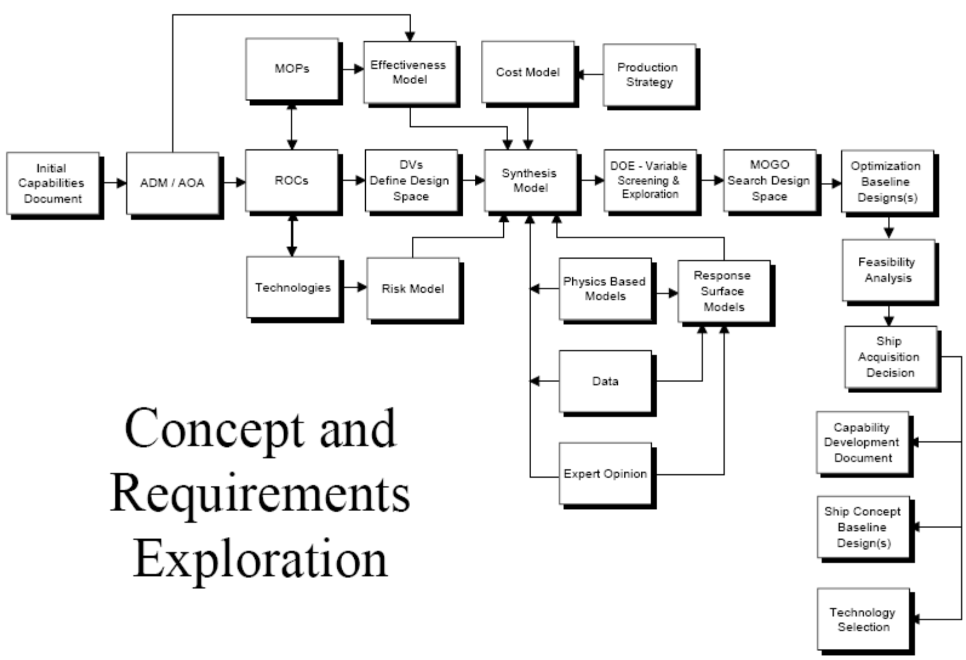



**Figure 1.2: Concept and Requirements Exploration**

To search the design space for optimal designs, the MOGO uses a genetic algorithm. Each submarine design in the design space is evaluated based on several objective attributes: feasibility, effectiveness, risk, and cost (with the final goal being a feasible submarine design with maximum effectiveness, minimum risk, and minimum cost). Various attributes (DVs) of successful submarine designs are then combined, generating new designs for inclusion into the next generation for the next optimization iteration. The MOGO method allows for a total systems approach to be integrated into a design process. This allows for the efficient comparison of many more possible designs than would be possible using traditional means alone.

The design spiral is used in concept development as presented in Figure 1.3. 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.

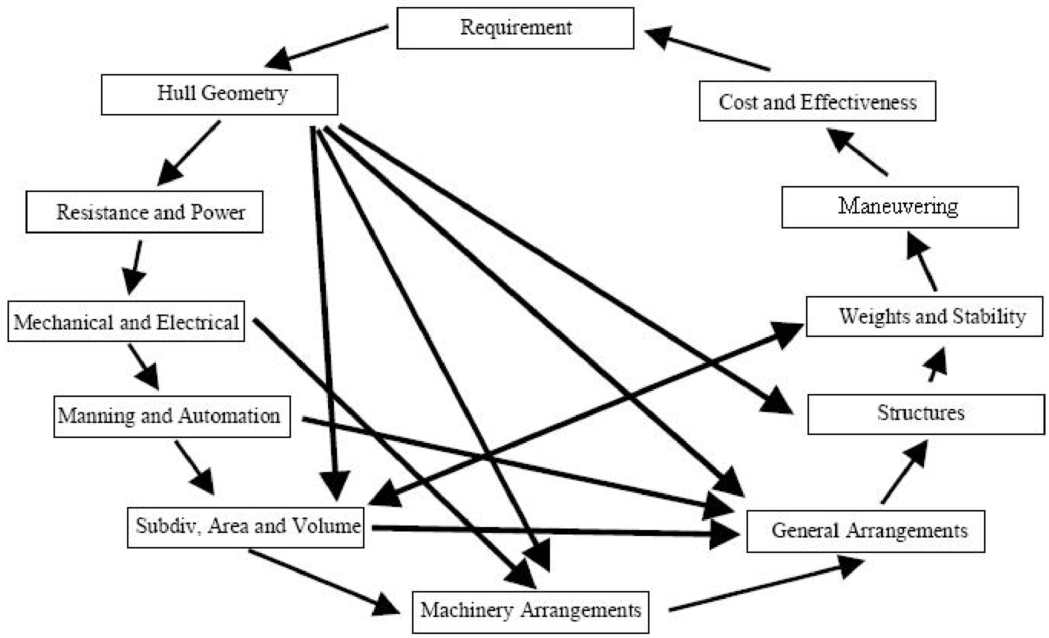



**Figure 1.3: Virginia Tech Concept Development Spiral**

## 1.3 Work Breakdown

SSBMD Team 1 consists of six students from Virginia Tech. Each student is assigned areas of work according to his interests and special skills as listed in Table 1.1.

**Table 1.1: Work Breakdown**

| Name | Specialization |
|---|---|
| Christopher Blizzard (Team Leader) | Optimization, Hydrostatics, Power and Propulsion Analysis, Final Cost and Risk Analysis |
| Van Jones | Optimization, 2D Arrangements<br>Torpedo Room Arrangement and Modeling |
| Michael Toris | Optimization, Structural Analysis |
| Kyle Colantonio | Optimization, Structural Analysis |
| Matthew Wichgers | Powering and Machinery Arrangement<br>Balance, Lead Rhino Modeler |
| David Riegel | Propeller Modeling, Sail Arrangement and Modeling |

## 1.4 Resources

Computational and modeling tools used in this project are listed in Table 1.2.

**Table 1.2: Software Tools**

| Analysis | Software Package |
|---|---|
| Arrangement Drawings | Rhino |
| Hull form Development | Rhino |
| Hydrostatics | Rhino/Rhino Marine |
| Resistance/Power | Mathcad |
| Dynamics and Control | MATLAB |
| Ship Synthesis Model | Mathcad/Model Center/Fortran |
| Structure Model | MAESTRO/Jackson SUBSTRUK |
| Balance/Trim | Rhino/Excel |

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

# 2 Mission Definition

The SSBMD requirement is based on the SSBMD Initial Capabilities Document (ICD), and Virginia Tech SSBMD Acquisition Decision Memorandum (ADM), Appendix A and Appendix B, with elaboration and clarification obtained by discussion and correspondence with the customer, and reference to pertinent documents and web sites referenced in the following sections.

## 2.1 Concept of Operations

The concept of operations is based on the SSBMD Initial Capabilities Document and Analysis of Alternatives (AOA) guidelines. The concept entails a SSBMD submarine designed to operate in littoral seas and blue water in sensitive and vulnerable remote regions, while surviving anti-submarine (ASW) and surface engagements. The submarine's primary mission while in a target area will be to provide timely ballistic missile interceptor launch, targeting ICBMs or medium/short range ballistic missiles in boost, early ascent, or mid-flight phase. SSBMD will be equipped with very fast interceptor missiles not currently employed by the US Navy, making this possible. The advantage of a submarine is that the missiles can be launched from a position inaccessible to space and ground interceptor systems. The submarine can operate forward-deployed in international waters without foreign permission. SSBMD will be able to operate close in while covering a large target territory without jeopardizing nuclear submarine technology. In addition, the submerged and hidden SSBMD will be less provocative to foreign governments than a large surface vessel in the same geographical position. If the ballistic missile threat changes to a new country or area, the submarine could quietly and quickly move to the new location without detection. A potential limitation of the SSBMD is the ability for interceptor missiles to be queued in a timely manner from a surface ship or other asset. Possible solutions are to have an autonomous underwater vehicle relay communications from the surface or a robust command and control connectivity to support targeting.

When the threat of ballistic missile launch is low, the submarine could instead function as a platform to launch unmanned reconnaissance vehicles, thus adding intelligence gathering capability. The small crew size and limited logistics requirement called for will facilitate efficient forward deployment. Furthermore, when acting in conjunction with joint forces, the submarine will be capable of providing ballistic missile defense for friendly assets.

**Table 2.1: BMD Mission Scenario**

| Day | **Mission scenario for Ballistic Missile Defense (BMD)** |
|---|---|
| | *Evidence of a large military buildup near a US ally leads intelligence to believe that hostile military action may be imminent. A CVBG is ordered to the region to discourage hostile action and defend the US ally.* |
| 1-8 | Transit with CVBG from forward base to area of hostilities. |
| 8-10 | Detach from CVBG. Engage AIP systems and submerge. Proceed independently to within 15 nm of enemy coastline. |
| | *Diplomatic negotiations break down.* |
| 10-16 | Loiter in hostile waters. |
| 16-17 | *Accidental explosion on hostile naval vessel mistaken for attack by US ally. Hostile nation mobilizes invasion forces.* |
| | Multiple ballistic missile launches detected, submarine receives targeting information. Launches SM-3 and KEI missiles successfully intercepting ballistic missiles. Submarine launches TLAMs at sources of ballistic missiles and other high value targets. |
| 17-20 | Launch AUV acoustic decoys, relocate to secondary loiter area, evading hostiles. |
| | *Political infighting in hostile nation halts invasion, ceasefire agreement is signed.* |
| 20-22 | SSBMD-09 relieves submarine, Rejoin CVBG. |
| 22-27 | Transit from area of hostilities to forward base. Rearm missiles and resupply at forward base. |

The submarine would also be capable of carrying out inland strikes and support amphibious operations using Tomahawk Land Attack Missiles (TLAMS). As part of its primary mission requirements, the submarine must be capable of transiting to a target area covertly, and once on station, loiter undetected for extended periods of time. Because of the covert nature of ballistic missile defense operations, the submarine must be highly independent; requiring only minimal re-supply while underway. In addition, because the submarine itself will likely have little or no ability to detect a ballistic missile launch, a robust and reliable communications system will be required to insure constant command and control connectivity.

## 2.2 Projected Operational Environment (POE) and Threat

The POE of the SSBMD is littoral and blue water areas off the coast of countries that can develop the capability to launch ballistic missiles in the next five years. The submarine will be expected to operate in sea states one through nine. The asymmetric threat comes from both rogue nations and groups whose mission is not an accurate strike but maximum devastation to civilian and military infrastructure. Threats may include a conventional explosive, biological, chemical or nuclear warhead. The current threat comes from China, North Korea and Iran.

## 2.3 Specific Operations and Missions

The primary mission of the SSBMD is to loiter covertly off of areas believed threatening by military intelligence in the case of a hostile ballistic missile launch. Secondary missions include ISR and inland missile strikes and support of amphibious operations support with TLAMs. In addition, in a primarily defensive nature, the submarine will perform ASM and ASuW.

## 2.4 Mission Scenarios

Mission scenarios for the primary SSBMD missions are provided in Tables 2.1 and 2.2.

**Table 2.2: Strike & SPW Mission Scenario**

| Day | Mission Scenario for Land Attack/Amphibious Operations |
|---|---|
| 1-8 | Depart CONUS, Transit with CVBG from forward base to area of hostilities. |
| 8-10 | Detach from CVBG. Engage AIP systems and submerge. Proceed independently to within 15 nm of enemy coastline. |
| 10-16 | Loiter in hostile waters. Deploy AUV communications/decoy vehicles. Maintain AUVs on rotating duty schedules. |
| 17-19 | Receive targeting information via AUV comm link. Support initial airstrike operations, launch TLAMs at high priority surface targets. |
| 19-20 | TLAM attack has compromised covert location of SSBM, enemy ASW helicopter locates SSBM vectors enemy ASW surface assets to SSBM. Enable decoy mode of AUV remotes, evade enemy ASW helicopter. Reencounter enemy ASW surface asset, engage with MK-48 ADCAP torpedoes if evasion tactics fail. |
| 21 | Transit from area of hostilities to forward base or CONUS. |
| 21-27 | Rearm missiles and resupply. |

## 2.5 Required Operational Capabilities

In order to support the missions and mission scenarios described in Section 2.4, the capabilities listed in Table 2.3 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 SSBMD's ability to perform these functional capabilities is measured by explicit Measures of Performance (MOPs). SSBMD will have focused mission capabilities of BMD, Strike, ASW, and ASuW.

**Table 2.3: Required Operational Capabilities (ROCs)**

| ROCs | Description |
|---|---|
| AAW 3 | Support theater ballistic missile defense |
| AAW 3.1 | Support theater ballistic missile defense during launch phase |
| AAW 3.2 | Support theater ballistic missile defense during mid-flight phase |
| AAW 9 | Engage airborne threats using sub-to-air armament |
| AMW 6 | Conduct airborne autonomous vehicle (AAV) operations |
| ASU 1 | Engage surface threates with anti-surface armaments |
| ASU 1.1 | Engage surface ships at long range |
| ASU 1.2 | Engage surface ships and medium range |
| ASU 4.2 | Detect and track a surface target using sonar |
| ASU 6 | Disengage, evade and avoid surface attack |
| ASW 1 | Engage submarines |
| ASW 1.2 | Engage submarines at medium range |
| ASW 1.3 | Engage subarmines at close range |
| ASW 7 | Attack submarines with antisubmarine armament |
| ASW 7.6 | Engage submarines with torpedoes |
| ASW 8 | Disengage, evade, avoid and deceive submarines |
| CCC 3 | Provide own unit Command and control |
| CCC 4 | Maintain data link capability |
| CCC 6 | Provide communications for own unit |
| CCC 21 | Perform cooperative engagement |
| FSO 7 | Provide explosive ordinance disposal services |
| FSO 9 | Provide routine health care |
| FSO 10 | Provide first aid assistance |
| INT 3 | Conduct surveillance and reconnaissance |
| MIW 3 | Conduct mine neutralization/destruction |
| MIW 3.1 | Deploy AUVs and UUVs for mine detection and neutralization |
| MIW 4 | Conduct mine avoidance |
| MIW 6 | Conduct magnetic silencing (degaussing, deperming) |
| MIW 6.7 | Maintain magnetic signature limits |
| MOB 1 | Steam to design capacity in most fuel efficient manner |
| MOB 3 | Prevent and control damage |
| MOB 7 | Perform seamanship, airmanship, and navigation tasks (navigate, anchor, mooring, scuttle, life boat/raft capacity, tow/be-towed) |
| MOB 10 | Replenish at sea |
| MOB 12 | Maintain health and well being of crew |
| MOB 13 | Operate and sustain self as a forward deployed unit for an extended period of time during peace and war without shored based support |
| MOB 16 | Operate in day and night environments |
| MOB 17 | Operate in heavyweather |
| MOB 18 | Operate in full compliance of existing US and international pollution control laws and regulations |
| MOB 19 | Operate submerged using AIP and batteries |
| MOB 20 | Operate and transit on snorkel |
| MOB 21 | Operate in littoral zones |
| MOB 22 | Operate covertly |
| NCO 3 | Provide upkeep and maintenance of own unit |
| SEW 2 | Conduct sensor and ECM operations |
| SEW 5 | Conduct coordinated SEW operations and other units |
| STW 3 | Support/conduct multiple cruise missile strikes |

# 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).

## 3.1 Trade-Off Studies, Technologies, Concepts and Design Variables

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

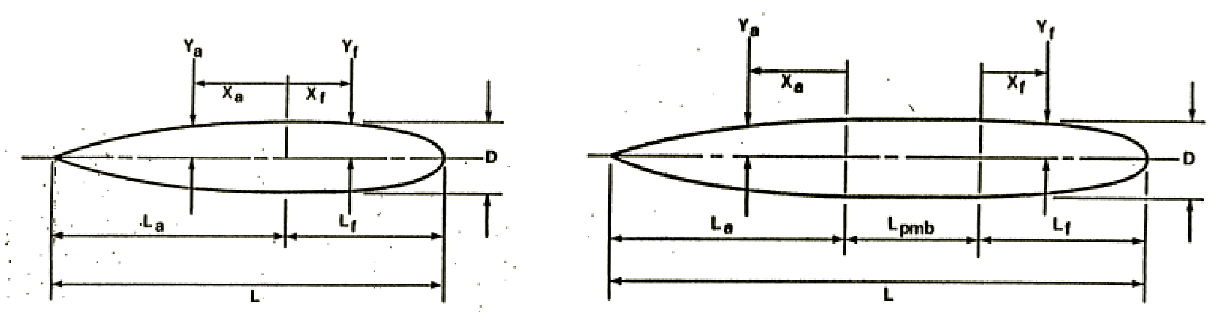
### 3.1.1 Hullform Alternatives

The hullform technology selection process considered performance metrics, hullform options, and modeling alternatives. Design lanes specify hullform design parameter ranges and initial hullform point designs. Applicable alternatives for consideration in the Concept Exploration design space are selected. Important hullform characteristics include:

- High speed resistance (sustained speed): 15-22 knots
- Low speed resistance (endurance / snorkeling): 5000 nm at 12 knots
- Stability and maneuverability: teardrop with parallel midbody
- Cost and producibility: modularization, COTS
- Volume for large object spaces (machinery spaces, mission spaces)
- Number of decks: 3 decks
- Hull depth: 32 feet
- Structural efficiency (pressure hull)
- Number of hulls: 1 or 2 hulls

The two primary hullform alternatives are axisymmetric tear drop with parallel mid body and non-axisymmetric types. Advantages of the axisymmetric hull are low resistance, producibility, and structural efficiency. The non-axisymmetric hull is more expensive, less stable, but has an increased payload and arrangement area. Types of hulls considered are single hull, double hull, and a catamaran pressure hull. The axisymmetric option was chosen in order to keep unit cost to a minimum.

The hullform model used is based on the MIT model shown in Figure 3.1




$$L = L_a + L_f$$

$$\frac{L_a + L_f}{D} = 6$$

$$L_a = 0.6L = 3.6D$$

$$L_f = 0.4L = 2.4D$$

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

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

$$L = L_a + L_{pmb} + L_f$$

$$L_a = 3.6D$$

$$L_f = 2.4D$$

**Figure 3.1: MIT Teardrop Hull Model; without Parallel Midbody (left), with Parallel Midbody (right)**

Hull diameter for this design is driven by the sizing requirements of the VLS systems. The threshold design specifies the BMD interceptor missile suite and consists of SM3 type missiles only. The goal design includes the much larger KEI interceptor missiles. The hull diameter is fixed at 32 feet for the genetic optimization, which is less than the KEI length but allows the installation of VLS tubes with SM3 missiles. A design option that includes an advanced composite sail will provide room for four KEI missiles in the sail area, extending out of the hull. The platform arrangements are varied based on the addition of a 4 foot double hull varying from 7 to 9 feet as shown in Figure 3.2. To minimize resistance and allow for the constraints, the forward fullness exponent ($n_{fopt}$) is 2.0 to 2.5, aft fullness exponent ($n_{aopt}$) is 2.5 to 3.0, and length to diameter ratio is between 6 and 8.

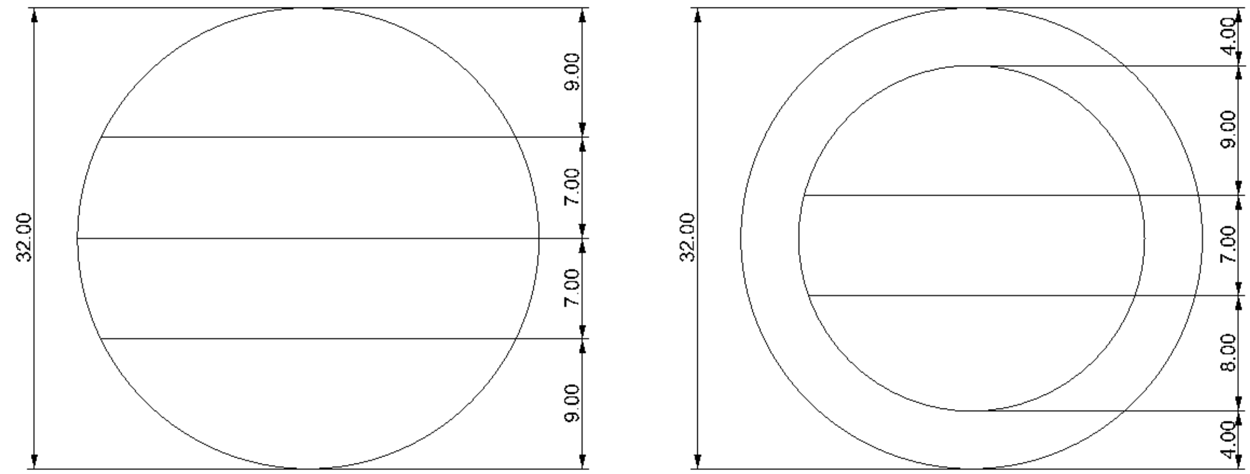



**Figure 3.2: Initial Cross-Sectional Designs for Single and Double Hull Designs**

### 3.1.2 Propulsion and Electrical Machinery Alternatives

#### 3.1.2.1 Machinery Requirements

Based on the ICD and expert guidance the propulsion requirements are:

*General Requirements*

The propulsion must be non-nuclear and capable of traveling to an area of conflict under its own power on snorkel. Once on site the SSBMD must be able to operate on AIP and remain unnoticed in a littoral environment.

*Sustained Speed and Propulsion Power*

Based on the ICD, the threshold sprint speed is 15 knots with a goal speed of 22 knots. The threshold snorkel distance is 5000 nm at 12 knots with a goal of 6000 nm at 12 knots. While running on AIP the threshold duration is 20 days at 5 knots and the goal is 30 days at 5 knots.

*Submarine Control and Machinery Plan Automation:*

To minimize the cost, maximum effective automation must be used. Whenever feasible, Commercial off the Shelf (COTS) hardware will be used. COTS allows for reduced costs, easier upgrades, and greater compatibility.

*Propulsion Engine and Ship Service Generator Certification*

Due to the nature of combat the submarine must carry Grade A shock-certified machinery. To minimize signature a shrouded propeller and fuel cells will be considered.

#### 3.1.2.2 Machinery Plant Alternatives

General machinery requirements given in Section 3.1.2.1 allowed for developing propulsion alternatives. System trade-off alternatives are consistent with the General Machinery Requirements and Guidelines and the preliminary power guidelines given in Table 2.3. The final propulsion alternatives are listed in Table 3.1.

**Table 3.1: Propulsion Systems Design Variable Alternatives**

| DV Name | Description | Design Space |
|---|---|---|
| PSYS | Propulsion system alternative | Option 1) CCD, 2xCAT 3512 V12<br>Option 2) CCD, 2xCAT 3516 V16<br>Option 3) CCD, 2xCAT 3608 1L8<br>Option 4) OCD, 2xCAT 3512 V12 - 2 AIP 250KW PEM<br>Option 5) OCD, 2xCAT 3512 V12 - 2 AIP 500KW PEM<br>Option 6) OCD, 2xCAT 3516 V16 - 2 AIP 250KW PEM<br>Option 7) OCD, 2xCAT 3516 V16 - 2 AIP 500KW PEM<br>Option 8) OCD, 2xCAT 3608 1L8 - 2 AIP 250KW PEM<br>Option 9) OCD, 2xCAT 3608 1L8 - 2 AIP 500KW PEM<br>Option 10) OCD, 2xCAT 3512 V12 - 2 AIP 250KW PEM w/reformer<br>Option 11) OCD, 2xCAT 3512 V12 - 2 AIP 500KW PEM w/reformer<br>Option 12) OCD, 2xCAT 3516 V16 - 2 AIP 250KW PEM w/reformer<br>Option 13) OCD, 2xCAT 3516 V16 - 2 AIP 500KW PEM w/reformer<br>Option 14) OCD, 2xCAT3608 1L8 - 2 AIP 250KW PEM w/reformer<br>Option 15) OCD, 2xCAT3608 1L8 - 2 AIP 500KW PEM w/reformer |
| PROPtype | Propulsion Prop Type | Option 1) Water Jet<br>Option 2) RDP, Rim Driven Prop<br>Option 3) Shrouded |
| BATtype | Battery system type alternative | Option 1) Nickel Cadmium<br>Option 2) Lead Acid (2.75xNickel Cadmium)<br>Option 3) Zebra (1.67xNickel Cadmium) |
| Ebat | Battery Capacity | 2500-5000 kwhr |

Batteries, AIP systems, reactant storage, propulsors, hydrogen storage, oxygen storage, reformers, fuel cells, closed cycle diesels, and open cycle diesels were all considered to determine their advantages and disadvantages.

Hydrogen reformers allow for the use of methanol to produce H2. Diesel fuel is difficult to reform. Reformers require high temperatures and risk contamination problems with CO and S. Figure 3.3 shows the process of the hydrogen reformer, which converts steam and methanol to CO2 and H2.

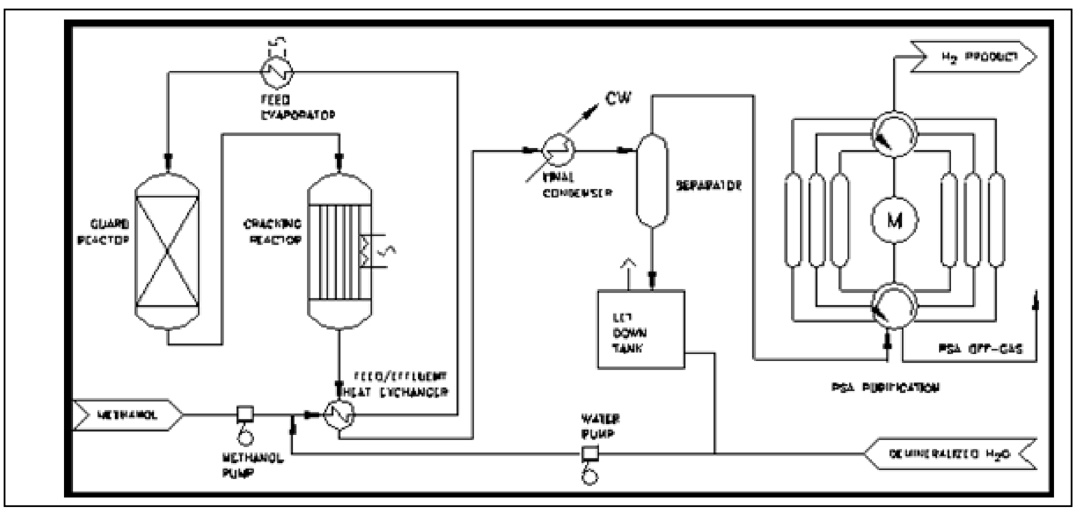



**Figure 3.3: Schematic of Hydrogen Reformer**

Closed cycle diesel systems can be used for AIP and snorkeling. The closed cycle uses liquid cryogenic oxygen for the system. The exhaust gases are then scrubbed and argon is reused in the system and the excess gases are discharged. The Cosworth System is used to absorb and discharge the CO2. Figure 3.4 illustrates the flow pattern of the closed cycle diesel Cosworth System where the system absorbs the CO2 into the seawater and pumps it overboard to eliminate a trail of exhaust.

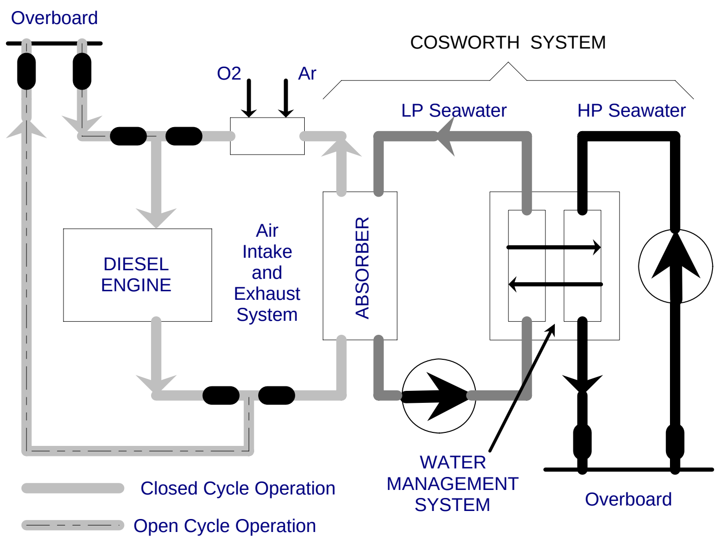



**Figure 3.4: Schematic of Closed Cycle Diesel System**

Closed cycle diesel engines offer advantages with risk, cost, safety, and power. Risk associated with maintenance and use is low due to the time in service of the engines. Closed cycle diesels run on diesel fuel making them safer compared to systems running on hydrogen which is more dangerous to store and transport.

Three types of Caterpillar diesel engines were considered for the diesel engine propulsion options. Information on the types of engines, Caterpillar 3512, Caterpillar 3516, and Caterpillar 3608 is given in Table 3.2.

**Table 3.2: 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 |

Fifteen various combinations of open cycle diesels (OCDs) with fuel cells and closed cycle diesels (CCDs) were compared for trade-offs as shown in Table 3.1. Table 3.3 and Table 3.4 describe the characteristics of the propulsion alternatives.

**Table 3.3: 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 3516 +2xCAT 3512 | 4 | 1 | 4288 | 4288 | 0.000 | 0.000 | 0.735 | 0.130 | 0.021 | 0.037 | 89.000 |
| 2xCAT 3512 V12 w/ 2 AIP 250KW PEM | 5 | 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 | 6 | 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 | 7 | 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 | 8 | 2 | 2536 | 1000 | 0.634 | 0.250 | 0.390 | 0.058 | 0.000 | 0.000 | 64.000 |
| 2xCAT3608 1L8 w/ 2 AIP 250KW PEM | 9 | 2 | 5056 | 500 | 0.634 | 0.250 | 0.390 | 0.058 | 0.000 | 0.000 | 64.000 |

**Table 3.4: 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 | 0.0 | 0 | 0 | 0.84 | 0.317 | 0.030 | 0.002 | 34 | 0 | 0.216 | 0.93 |
| 2xCAT 3516 V16 | 0.0 | 0 | 0 | 0.84 | 0.317 | 0.030 | 0.002 | 34 | 0 | 0.216 | 0.93 |
| 2xCAT3608 1L8 | 0.0 | 0 | 0 | 0.84 | 0.317 | 0.030 | 0.002 | 34 | 0 | 0.189 | 0.93 |
| 2xCAT 3516 +2xCAT 3512 | 0.0 | 0 | 0 | 0.84 | 0.317 | 0.030 | 0.002 | 34 | 0 | 0.216 | 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 |

**Table 3.5: Acronyms for Propulsion Spreadsheet**

| 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 | Wolume 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 Consumption |
| MarS | Mass Argon Stowage |
| MBMaip | Machinery Box Mass AIP (kg/kw) |
| MBMdg | Machinery Box Mass Diesel (kg/kw) |
| SFC | Specific Fuel Consumption |

#### 3.1.2.2.1 AIP Fuel Cells

Four types of fuel cells were researched for the AIP option of the SSBMD. Fuel cells are classified by their electrolyte. The fuel cells considered were Molten Carbonate (MCFC), Phosphoric Acid (PAFC), Polymer Electrolyte Membrane (PEMFC), and Solid Oxide (SOFC). Characteristics of each fuel cell are listed in Table 3.6.

**Table 3.6: Fuel Cell Data**

| | MOFC | PAFC | PEMFC | SOFC |
|---|---|---|---|---|
| Electrolyte | Molten Carbonate Salt | Liquied Phosphoric Acid | Polymer 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 | $CO_2/0_2$/Air | $0_2$/Air | $0_2$/Air | $0_2$/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 produce high-pressure steam |

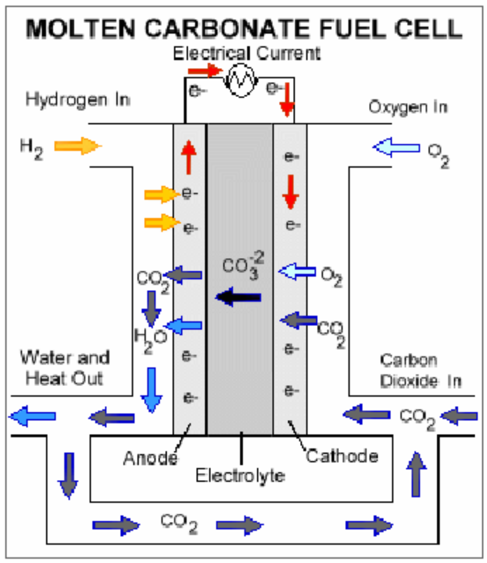



**Figure 3.5: MCFC Fuel Cell Schematic**

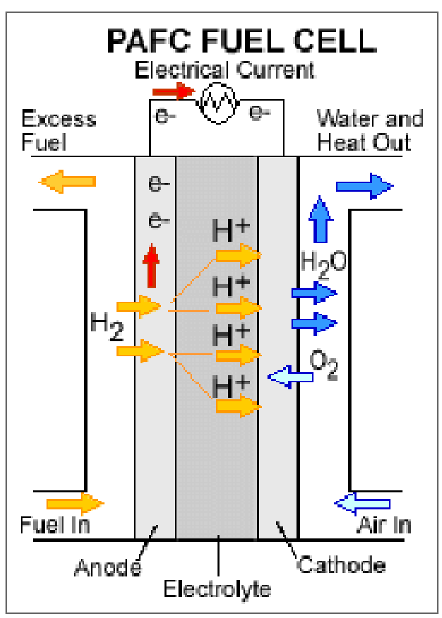



**Figure 3.6: PAFC Fuel Cell Schematic**

Molten Carbonate fuel cells have a high efficiency (85% with cogeneration) and do not require an external reformer. They are less expensive than the other fuel cells because they do not require a precious metal for the catalyst. However, the MCFC fuel cells require high operating temperatures (1100°F), which can cause problems in a submarine environment.

Phosphoric Acid fuel cells also have a high efficiency (80% with cogeneration). However, there are many risks associated with the PAFC. The fuel cell is expensive to produce due to the use of a platinum catalyst. Further, the fuel cells produce less power than fuel cells of a similar size and are high risk due to the recent development of the technology.

Polymer Electrolyte Membrane fuel cells (PEMFC) are proven to be reliable. There is less risk and corrosion associated with the PEMFC than the other fuel cells. However, the PEMFC requires pure reactants and can be poisoned by impurities. Also, the fuel cell requires hydrogen as a reactant which is difficult to store or it can be reformed with an external reformer.

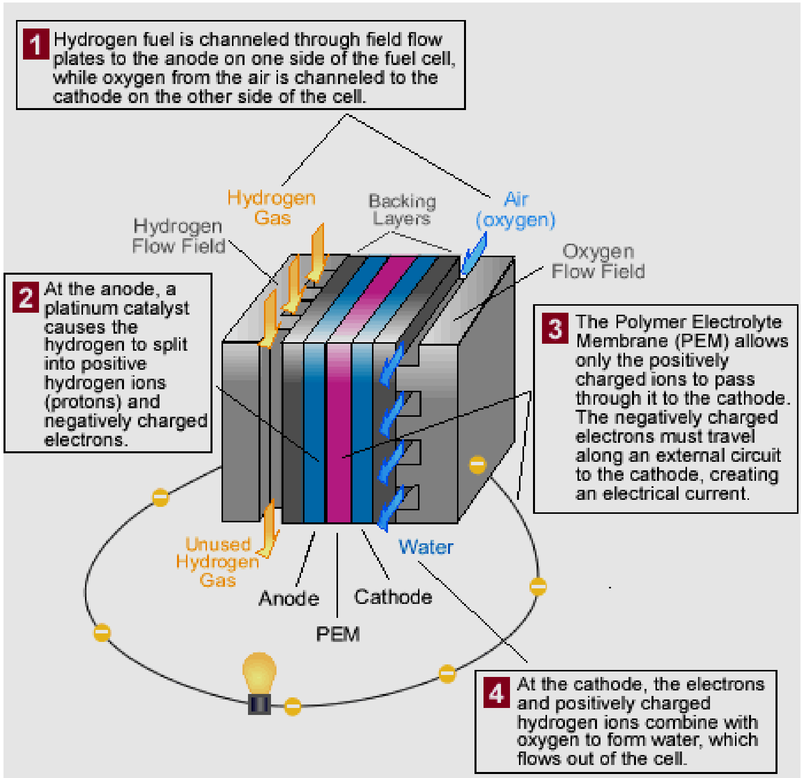



**Figure 3.7: PEMFC Fuel Cell Schematic**

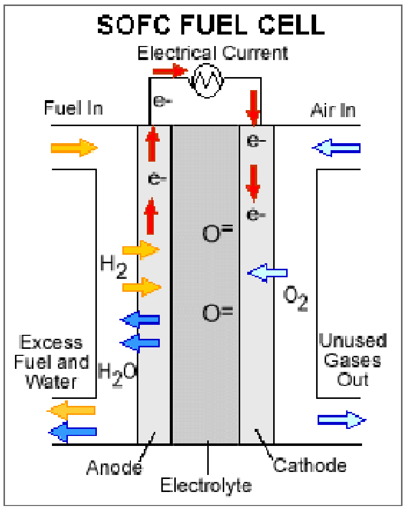



**Figure 3.8: SOFC Fuel Cell Schematic**

Solid Oxide fuel cells have a high efficiency (85% with cogeneration) and do not require an external reformer. They are less expensive than the other fuel cells because they do not require a precious metal for the catalyst. However, the SOFC fuel cells require high operating temperatures (1100°F), which can cause problems in a submarine environment. SOFC fuel cells are also vulnerable to shock damage and require a long start up time. As shown in Table 3.1 PEM fuel cells were chosen for use in the SSBMD.

##### 3.1.2.2.2 Hydrogen and Oxygen Storage

Hydrogen is used for many propulsion systems considered for the SSBMD. There are four main methods to store or produce hydrogen: as a gas, liquid, hydride, or hydrocarbon fuel. When stored as a gas, hydrogen has a low energy density, requires a large volume, high pressure, and storage is heavy. The uses of gas hydrogen are also limited. As a liquid, hydrogen must be stored at -253°C and has three times the energy density of diesel fuel. The storage tanks are required to be super insulated with two walls. Liquid hydrogen is hard to shock proof and evaporates at a rate of 1-2% per day.

Hydrides pressurize hydrogen and store it in the hydride and release it through heating. Hydrogen is produced at a rate of 1-2% per weight of the hydride. Hydrides are safe but heavy and can be located either inside or outside the hull. Finally, hydrogen can be reformed from either methanol or diesel. The methanol combines with water to produce $CO_2$ and $H_2$ gas which passes through a membrane to separate the hydrogen and carbon dioxide. The use of diesel requires high temperature steam and can have problems associated with carbon monoxide and sulfur contamination.

Oxygen is also necessary for use with the AIP system. Oxygen can be stored either as a gas or as a liquid. Storing oxygen as a gas requires high pressures and a large volume to store it. Liquid oxygen is safe and effective. The technology is well established and it can be stored either inside or outside the hull. However, the most common location of storage is outside the hull.

##### 3.1.2.2.3 Batteries

Batteries provide back-up power and determine the sprint speed of the submerged submarine. Batteries provide the back-up power for submerged propulsion, system power including payload systems, command and control, and habitability systems. Lead-Acid, Nickle/Cadmium, and ZEBRA batteries are compared in Table 3.7 and Table 3.8. Batteries are charged by either a generator or AIP systems. The storage of batteries must be watertight and redundant with two or three compartments that are rubber lined to prevent acid spills. Ventilation of the compartments is necessary to eliminate the buildup of excess gasses.

**Table 3.7: Battery Type Comparison Data**

| Classification | Lead-Acid | Alakaline | Molten Salt |
|---|---|---|---|
| Battery Type | Lead Acid | Nickel/Cadmium | ZEBRA |
| Maturity | Mature | Mature | Immature |
| Energy Density (Wh/kg) | 20-35 | 20-37 | 90 |
| Power Density (kW/kg) | 0.02-0.175 | 0.1-0.6 | 0.15 |
| Cycle Life (# of cycles) | 200-2000 | 500-2000 | 1000-3000 |
| Service Life (years) | 3-10 | 5-10 | 5-10 |
| Battery Effluent | H2 Gas | None | None |
| Ease of Operation | Good, frequent monitoring required | Very Good | Projected to be maintenance free |

#### 3.1.2.3 Propulsors

Five options were considered for propulsors in SSBMD. Propulsors can be single stern mounted or mounted in multiple locations to allow vectored thrust. There are advantages and disadvantages of each orientation and option for propulsors as shown in Table3.9.

**Table 3.8: Battery Type Advantages and Disadvantages**

| | Advantages | Disadvantages |
|---|---|---|
| Lead Acid | Proven technology<br>Long cell life<br>Recent improvements | Least energy dense<br>Evolves hydrogen when charging<br>Requires frequent monitoring |
| Nickel/Cadmium | High energy density compared to lead acid<br>Longer cell life compared to lead acid<br>Rapid charging<br>Reduced maintenance | Unproven at sea<br>Abrupt cut-off when fully charge<br>Memory effects<br>Expensive relative to lead acid |
| ZEBRA | 50% lighter weight than lead acid<br>No emission gasses<br>Rapid discharge for max sprint speed<br>Tolerant of short circuits | High operating temperatures<br>Battery must be heated before operating<br>Thermal management needed<br>Only produced by one factory in the world |

**Table 3.9: Propulsor Summary Data**

| Propulsor Type | Summary |
|---|---|
| Open Shaft-Driven Propellers | Typically 6 or 7 blade |
| Open Shaft-Driven Propellers with Shrouds | Improvement over un-shrouded propeller designs in efficiency and acoustic signature; reduces tip cavitation and losses<br>Costs more |
| Rim-Driven Propulsor | Integral motor<br>Rim/shroud stator<br>Propeller rotor<br>More technology risk |
| Ducted Pump Jet Propulsion (DPJP) | Ducts intake seawater, accelerate it through a reducing cross-section of ducts into a pump that quietly moves the water out the rear of the boat; able to direct thrust in almost any direction<br>Pumps can be “tuned” to reduce vibration and signatures; not as efficient as open prop |
| Tunnel Thrusters | Commercial off the shelf (COTS) technology<br>Small propeller mounted in tube, powered by a hydraulic motor in the hub<br>Operate in the transverse and vertical directions<br>Dynamic positioning<br>Commercially available: 40 to 2500 lbs thrust |

### 3.1.3 Automation and Manning

Reduction in manning levels requires a corresponding increase in automation. Increasing automation levels increases the cost of the vessel, and usually increases the risk level. These costs must be compared to the personnel cost that the automation technology replaces. Increased automation requires a greater upfront cost which needs to be compared to the cost of the crew over their career. Utilizing established technologies for the automation greatly reduces the risk, while using unproven automation increases the risk. Another risk inherent in increased automation levels is the loss of the human factor in damage control situations.

Increasing automation reduces response time. Fewer crew are in harms way during damage control situations. The crew is afforded greater job enrichment and computer literacy from the added technical skills gained by operating the automated equipment. The manning and automation factor, $C_{man}$, shows the amount of crew that can be eliminated due to the increased use of automation.

**Manning Calculations:**

$NE =$ Enlisted Manning

$C_{man} =$ Manning and Automation Factor

$KW_{snork} =$ Total Snorkel Power

$V_{env} =$ Envelope Volume

$NT =$ Total Crew Manning

$NO =$ Number of Officers

$$NE = C_{man}\left(\frac{KW_{snork}}{100} + \frac{V_{env}}{4500}\right)$$

$$NT = NE + NO$$

Simple Parameters for number of enlisted crew

### 3.1.4 Combat System Alternatives

#### 3.1.4.1 Sonar and Combat Control Systems

The sonar and combat systems in this design must be balanced between cost effectiveness and performance. The primary mission tasking calls for extensive loitering undetected on-station, instead of a hunter-killer mission. Since the vessel is primarily defensive, the sonar and combat systems can be less capable than current US SSNs. Significant cost savings may be realized in this design area, without sacrificing operational capability. The sonar and combat system options considered in the optimization are given in the SONARSYS design variable options and are as follows:

**Table 3.10: SONARSYS System Alternative Components**

| DV Name | Description | Design Space |
|---|---|---|
| SONARSYS (SSYS) | Sonar/Combat System Alternatives | Option 1: BQQ-5E Bow Dome/Passive structure and access, BQQ-10 sonar electronics and software, LWWAA, BQS-24 high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29; BSY-2/CCSM; AN/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: BQQ-5E Bow Dome/Passive structure and access, BQQ-5 sonar dome hull damping, AN/BQG-5 WAA, BQS-24 high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; BSY-2/CCSM; AN/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 3: EDO Model 1122 Bow Dome/Passive structure and access, EDO Model 1122 MF Passive bow array, MFA, PRS, EDO Model 1121 flank array, HF MOA 3070 high frequency mine detection sonar, Scout HF Chin Array, EDO Model 1123 towed array, ISUS-90 CCS; AN/WLY-1 acoustic interception and countermeasures system , AN/WLQ-4, AN/BLQ-10 Electronic Support Measure (ESM) System; 2x3" countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube |
| | | Option 4: ATLAS Electronik DBQS 40 MF cylindrical bow array, MFA, PRS, TAS-3 low-frequency towed array , FAS-3 flank array sonar, and HF MOA 3070 high frequency mine detection sonar; ISUS-90 CCS, Scout HF Chin Array; AN/WLY-1 acoustic interception and countermeasure system; AN/WLQ-4, AN/BLQ-10 Electronic Support Measure (ESM) System; 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube |
| | | Option 5: EDO Model 1122 Bow Dome/Passive structure and access, EDO Model 1122 MF Passive bow array, MFA, PRS, EDO Model 1121 flank array, Scour mine detection sonar, SUBICS 900 CCS; Scout HF Chin Array, AN/WLY-1 acoustic interception and countermeasure system; AN/WLQ-4, AN/BLQ-10 Electronic Support Measures (ESM) System; 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube |

SONARSYS Option 1 includes an AN/BQQ-10 bow mounted spherical sonar array with passive and active capabilities. Figure 3.9 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. The BQS-24 is a high frequency sail and chin array which is used for mine, ice, and obstacle avoidance. 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.

**Figure 3.9: US Navy Submarine Sonar Dome**

SONARSYS Option 2 includes an AN/BQQ-5E digital, multibeam system which includes a bow mounted spherical sonar array with passive and active capabilities. The AN/BQQ-5E provides improvement over the AN/BQQ-5 system in the areas of detection, tracking, and classification of low frequency data. The system features LF active interference rejection, dual towed array processing and full spectrum processing.

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 utilizes an EDO Model 1122 MF Passive bow array instead of the AN/BQQ-10 Active/Passive array with ISUS-90 CCS. 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 can also be used to detect other moving or stationary underwater objects. It can be used as a navigation sonar during a submarines surfacing maneuver, or as a navigational aid in narrow or dangerous waters. Figure 3.10 shows the coverage of the Scout sonar.

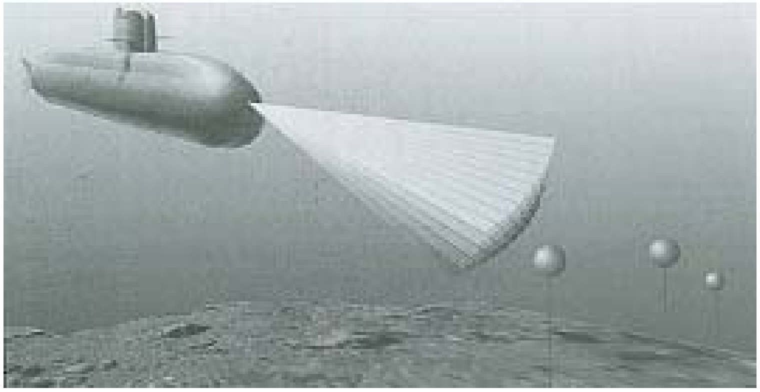


**Figure 3.10: Coverage of the Scout Sonar**

SONARSYS Option 4 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 5 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 3.11 shows a block schematic of the SUBICS 900 system.

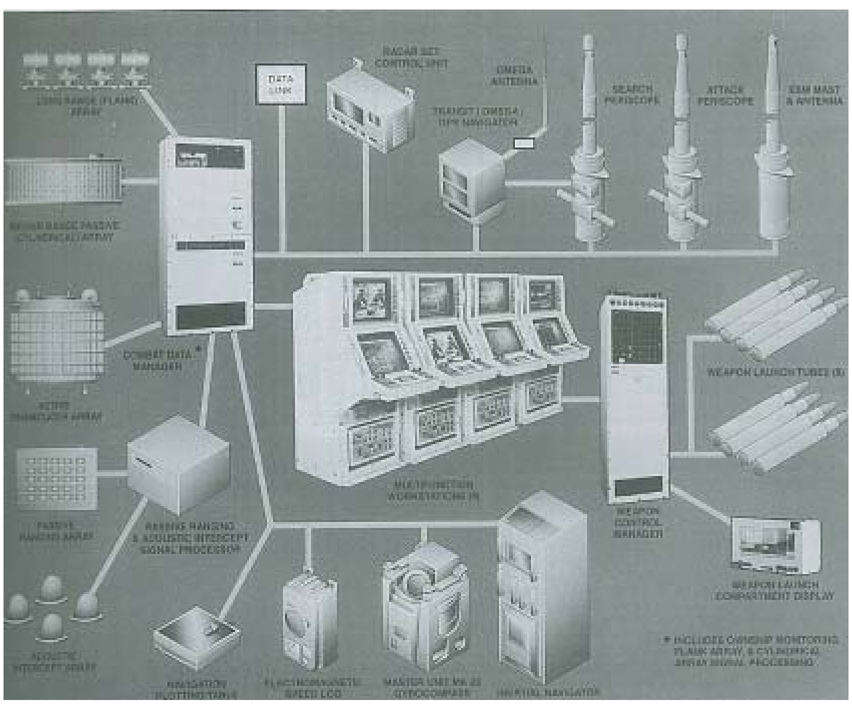



**Figure 3.11: Block Schematic of SUBICS 900 System**

All SONARSYS Options include AN/WLY-1 acoustic interception and countermeasures system, AN/WLQ-4, AN/BLQ-10 Electronic Support Measures (ESM) system, 2x3" Countermeasure Launcher w/ Reloads, and 2x6.75" Countermeasure Tubes. 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. 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.

#### 3.1.4.2 Sail

The SAIL design variable options are listed in Table 3.11 below. There are distinct differences between the four options. SAIL Option 1 is based upon an advanced composite sail capable of storing four Kinetic Energy Interceptor (KEI) ballistic missiles, whereas the remaining SAIL options are based upon a small version of the current Virginia Class sail.

Both sail designs contain radar, visual, and communication equipment of the submarine, where each option includes two photonics mast and radar equipment, the necessary snorkel equipment, and a Seal Locker.

**Table 3.11: SAIL system with alternative components**

| DV Name | Description | Design Space |
|---|---|---|
| SAIL | Sail (KEI VLS, Radar, Masts and Periscopes, and communication) | Option 1: Advanced Composite Sail, 4xKEI missile cells, BPS-16 Radar; 2x AN/BRA-34 Multiband; AN/BVS-1 Photonics mast; Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA (buoy system), AN/BRD-7/BLD-1 |
| | | Option 2: BPS-16 Radar; 2x AN/BRA-34 Multiband; AN/BVS-1 Photonics mast; Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA (buoy system), AN/BRD-7/BLD-1 |
| | | Option 3: BPS-16 Radar; 2x AN/BRA-34 Multiband; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA (buoy system), AN/BRD-7/BLD-1 |
| | | Option 4: BPS-16 Radar; 2x AN/BRA-34 Multiband; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry Seal Locker; Shrike, AN/BRD-7/BLD-1 |

SAIL Option 1, the advanced composite sail, includes four KEIs, 2x AN/BVS-1 Phototonics mast, 2x AN/BRA-34 Multiband Radar, 2x EHF/SHF HDR Multiband, a BPS-16 Radar, and an OE-315 HSBCA. The BVS-1 Phototonics 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. 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. The AN BRD-7/BLD-1 is as a submarine based precision radar direction finding system. It detects passively and tracks airborne, surface and land-based threats, employing a mast-mounted antenna that is raised just above the sea surface operation. The system delivers precise threat bearing information, which is integrated with other sensor data for tactical surveillance and over-the-horizon targeting for vertically launched missiles. 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. The sail is composed of a composite material for corrosion resistance characteristics, ease of manufacturing three-dimensional complex curvatures, and a low CG when surfacing. Figure 3.12 shows the communications capabilities required in the 4 different modes of operation: stealth, covert, low risk, and overt.

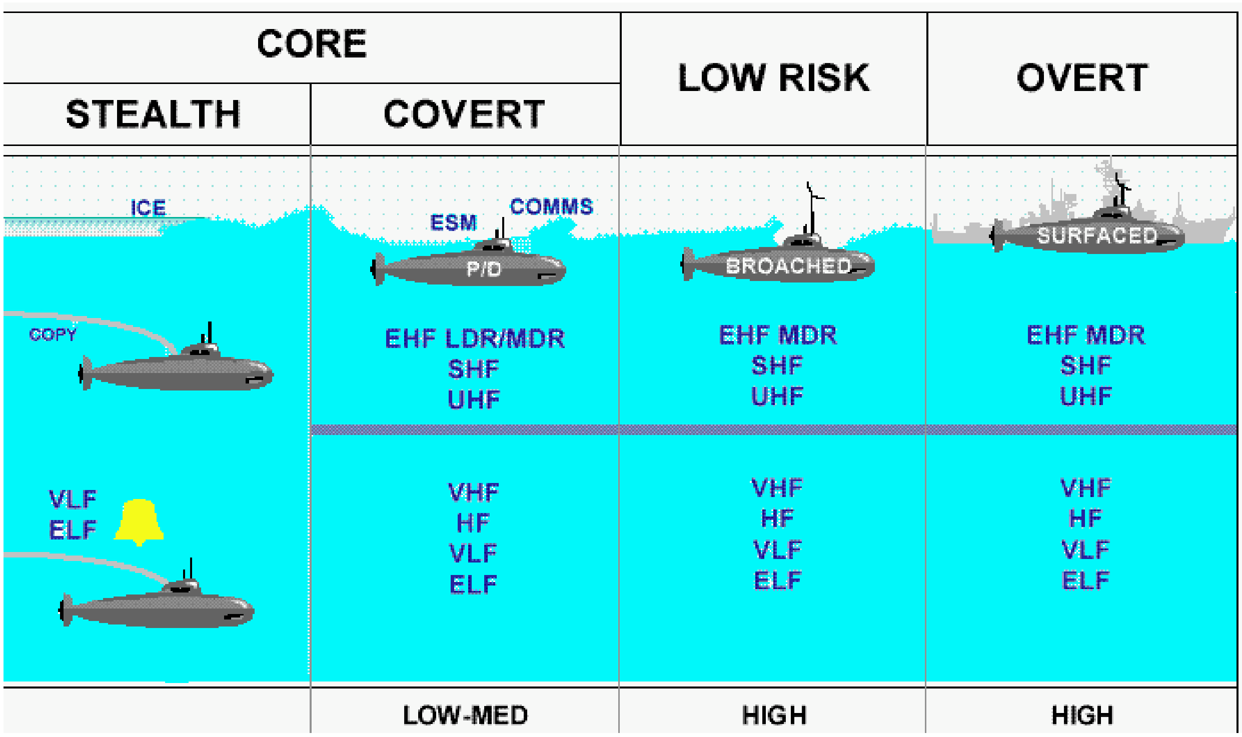



**Figure 3.12: Communications capabilities required by mode of operation**

SAIL Option 2 is also equipped with 2x, AN/BVS-1 Photonics Mast, 2x AN/BRA-34 Multiband, a BPS-16 radar, and an OE-315 HSBCA, however, the sail is fabricated from steel.

SAIL Option 3-4 are equipped with BPS-16 Radar, 2x AN/BRA-34 Multiband, Type 8 Mod 3 Periscope, Type 18 Mod 3 Persicope, and AN/BRD-/BLD-1.

All options include snorkel, Integrated Electronics Mast (IEM), Sea Sentry, and a Seal Locker. 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 3.13 shows the Sea Sentry in flight.

**Figure 3.13: 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 3.14 shows the arrangement for the Virginia Class sail configuration.

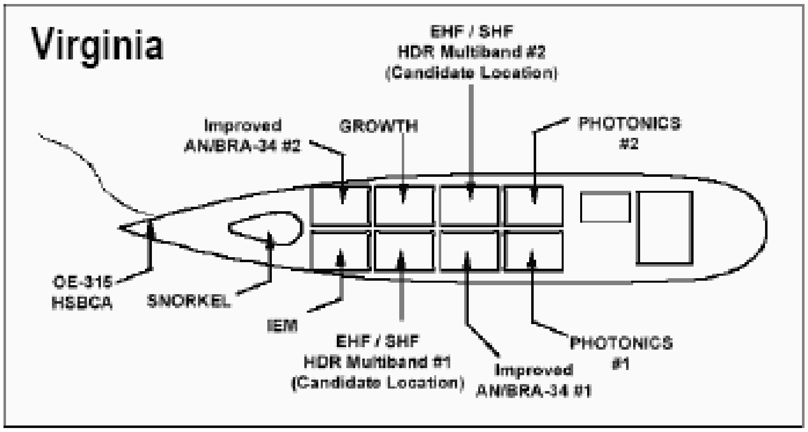



**Figure 3.14: Virginia Class Sail Configuration**

The advanced composite sail will be capable of storing up to four KEIs, and will offer approximately 4 times the volume of a typical sail and improve the hydrodynamics. Below in Figure 3.15 is an artist's rendition of what the advanced composite sail may look like.

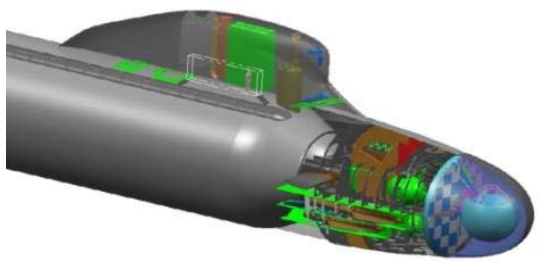


Figure 3.15: Concept of advanced composite sail

#### 3.1.4.3 Torpedo/UUV

The torpedo options are shown in Table 3.12 below. All configuration options have the capability of carrying Mk 48 ADCAP, Mk 46 and Mk 50 torpedoes. Options 1-3 consist of a reconfigurable torpedo room with varying reload numbers. Options 4-5 are externally encapsulated torpedoes that cannot be reloaded.

**Table 3.12: TORP System Alternative Components**

| DV Name | Description | Design Space |
|---|---|---|
| TORP | Torpedo system alternative | Option 1: Full 2 x 21" Tubes, 12 reloads |
| | | Option 2: Full 2 x 21" Tubes, 8 reloads |
| | | Option 3: Full 2 x 21" Tubes, 6 reloads |
| | | Option 4: No torpedo room, 8 external encapsulated torpedoes |
| | | Option 5: No torpedo room, 4 external encapsulated torpedoes |

The Mk 48 ADCAP or advanced capability is a $3.5 million dollar torpedo with a 650 lbs. high explosive warhead. It is 19 ft long with a 21 inch diameter, weighs 3,695 lbs and has a ranger over 5 miles. The ADCAP version has improved target acquisition range, reduced vulnerability to countermeasures, reduced shipboard constraints like warmup, and enhanced effectiveness against surface ships.

The Mk 46 torpedo is designed to attack high performance submarines, and is presently identified as the NATO standard. The MK-46 Mod 5 torpedo is the backbone of the Navy's lightweight ASW torpedo inventory and is expected to remain in service until the year 2015. It is 102 in long with a diameter of 12.75 in, weighs 518 lbs and has a range of 8000 yards. The weapon has a minimum search and attack depth of 20 yards and a maximum of 1500 yards and uses a 98 lb high explosive warhead.

The Mk 50 lightweight torpedo is the eventual replacement for the Mk 46 as the fleet's lightweight torpedo. It has a length of 112 inches, diameter of 12.75 in, weighs 750 lbs and has a range of approximately 2000 yards. Powered by a stored chemical energy propulsion system it has a maximum speed of over 40 knots.

The first three options include a re-configurable torpedo room shown in Figure 3.16. A reconfigurable torpedo room gives the advantage of the options for torpedo and horizontal missile launch operations and other uses such as a bunk room. The disadvantage of a torpedo room is the space taken up by the torpedoes and the machinery required for firing. Encapsulated torpedoes solve this problem by being placed outboard of the pressure hull.

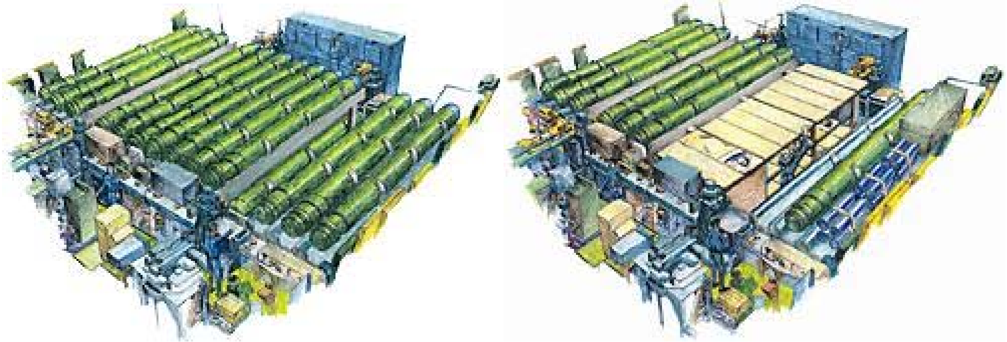


**Figure 3.16: Reconfigurable Torpedo Room**

#### 3.1.4.4 VLS

The Vertical Launching System (VLS) options are listed in Table 3.13. The three options allow for 16 VLS cells, 12 VLS cells, or 8 VLS cells.

**Table 3.13: VLS System Alternative Components**

| DV Name | Description | Design Space |
|---|---|---|
| VLS | Vertical Launching System Alternatives | Option 1: 16 Cell VLS |
| | | Option 2: 12 Cell VLS |
| | | Option 3: 8 Cell VLS |

Table 3.14 lists the weight, center of gravity, area, outboard volume, and power consumption ratings for the VLS components.

**Table 3.14: Component List for the VLS System**

| ID | NAME | WARAREA | ID | SingleD SWBS | WT lton | VCD ft+CL | AREA ft2 | Vob ft3 | KW |
|---|---|---|---|---|---|---|---|---|---|
| 21 | 6 cell VLS | VLS | 21 | 7 | 7.20 | -10.00 | 0.00 | 420.00 | 0.00 |
| 22 | 6 TLAM | VLS | 22 | 20 | 11.85 | -10.00 | 0.00 | 0.00 | 0.00 |
| 23 | VLS machinery 6 cells | VLS | 23 | 5 | 2.00 | 0.00 | 30.00 | 0.00 | 5.40 |

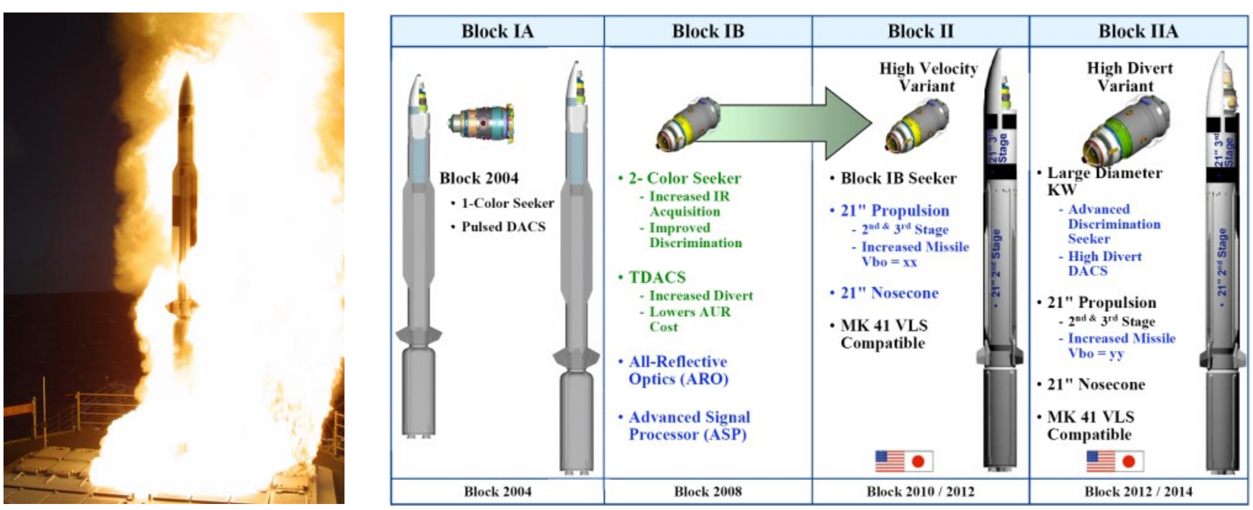




**Figure 3.17: SM-3 Missile**

VLS is a missile launch system aboard submarines. The VLS allows for the use of Tomahawk, Harpoon, and Standard Missile 2 (SM2) or Standard Missile 3 (SM3) AAW/BMD Missile (Figure 3.17). The system allows for added storage of weapons in addition to the torpedo room. The VLS system also allows more weapons to be ready for use than with other launching systems.

There are many different options for the payload that can be used in the VLS system in order to perform the mission of BMD. The SM-3 Block IA missile is equipped with a kinetic, non-explosive, warhead designed to destroy a ballistic missile's warhead by colliding with it outside the atmosphere, during the midcourse phase of flight. It is intended to intercept short range ballistic missiles (SRBMs) and medium range ballistic missiles (MRBMs). An improved version, the Block IB, will offer some capability for intercepting intermediate-range ballistic missiles (IRBMs). The Block IA and IB do not fly fast enough to offer a substantial capability for intercepting ICBMs. A faster-flying version of the SM-3, the Block II/IIA, is being developed. Block II/IIA is intended to give Aegis BMD ships a capability for intercepting certain ICBMs. In contrast to the Block IA/1B version of the SM-3, which has a 21-inchdiameter booster stage but is 13.5 inches in diameter along the remainder of its length, the Block II/IIA version would have a 21-inch diameter along its entire length. The increase in diameter to a uniform 21 inches gives the missile a burnout velocity that is 45% to 60% greater than that of the Block IA/IB version. The Block IIA version also includes an improved kinetic warhead.

The newest technology that could be used for ballistic missile defense is the Kinetic Energy Interceptor (KEI) (Figure 3.18). KEI's are much larger compared to the SM-3 and have a much higher burnout velocity. This higher burnout velocity could possibly make it possible to attack the missiles during boost and early ascent phases of flight giving more opportunities to destroy the missiles. In addition, if the missile is destroyed in the early phases, there is a a better chance of the debris falling back on the attacker.

**Figure 3.18: Kinetic Energy Interceptor Missile**

#### 3.1.4.5 SPW

The special warfare options allow for either a nine or four man lockout chamber as shown in Table 3.115.

**Table 3.15: SPW System Alternative Components**

| DV Name | Description | Design Space |
|---|---|---|
| SPW | SPW Alternatives | Option 1: 9 Man Lock out chamber |
| | | Option 2: 4 Man Lock out chamber |

Table 3.96 lists the weight, center of gravity, area, outboard volume, and power consumption ratings for the lockout chamber.

**Table 3.96: Component List for the SPW System**

| ID | NAME | WARAREA | ID | SingleD SWBS | WT lton | VCD ft+CL | AREA ft2 | Vob ft3 | KW |
|---|---|---|---|---|---|---|---|---|---|
| 48 | 4 man lockout trunk | SPW | 48 | 1 | 8.62 | 8.00 | 0.00 | 301.59 | 1.00 |

The lockout chamber, shown in Figure 3.19, allows for the submerged delivery of Special Warfare Units. The chamber will allow a nine man SEAL team to enter or leave the submarine at one time. Access to the chamber would be allowed through the composite sail.

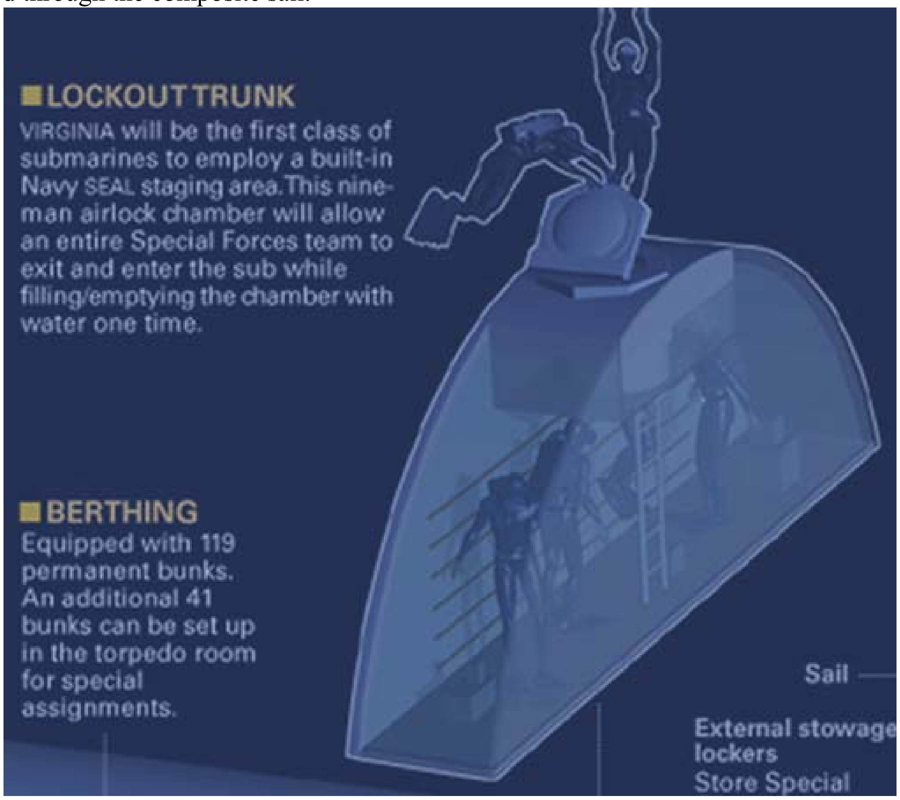



**Figure 3.19: Virginia Class Lockout Chamber**

#### 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 3.17 below are included in the submarine synthesis model data base.

## 3.2 Design Space

The twenty Design Variables (DVs) in Table 3.17 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 Multi-Objective Genetic Optimization (MOGO). The best option for each DV is designated option 1. The MOGO assigns a value to each variable, as given by an expert, and uses the synthesis results to search for non-dominated designs.

**Table 3.17: Design Variable Options**

| DV # | DV Name | Description | Design Space |
|---|---|---|---|
| 1 | D | Diameter | 24-34ft |
| 2 | LtoD | Length to Depth Ratio | 7-10 |
| 3 | BtoD | Beam to Depth Ratio | 1-1.2 |
| 4 | $n_a$ | Fullness factor aft | 2.5-4.0 |
| 5 | $n_f$ | Fullness factor forward | 2.0-3.5 |
| 6 | Depth | Diving Depth | 500-1000ft |

| DV # | DV Name | Description | Design Space |
|---|---|---|---|
| 7 | PSYS | Propulsion system alternative | Option 1) CCD, 2xCAT 3512 V12<br>Option 2) CCD, 2xCAT 3516 V16<br>Option 3) CCD, 2xCAT 3608 1L8<br>Option 4) OCD, 2xCAT 3512 V12 - 2 AIP 250KW PEM<br>Option 5) OCD, 2xCAT 3512 V12 - 2 AIP 500KW PEM<br>Option 6) OCD, 2xCAT 3516 V16 - 2 AIP 250KW PEM<br>Option 7) OCD, 2xCAT 3516 V16 - 2 AIP 500KW PEM<br>Option 8) OCD, 2xCAT 3608 1L8 - 2 AIP 250KW PEM<br>Option 9) OCD, 2xCAT 3608 1L8 - 2 AIP 500KW PEM<br>Option 10) OCD, 2xCAT 3512 V12 - 2 AIP 250KW PEM w/reformer<br>Option 11) OCD, 2xCAT 3512 V12 - 2 AIP 500KW PEM w/reformer<br>Option 12) OCD, 2xCAT 3516 V16 - 2 AIP 250KW PEM w/reformer<br>Option 13) OCD, 2xCAT 3516 V16 - 2 AIP 500KW PEM w/reformer<br>Option 14) OCD, 2xCAT3608 1L8 - 2 AIP 250KW PEM w/reformer<br>Option 15) OCD, 2xCAT3608 1L8 - 2 AIP 500KW PEM w/reformer |
| 8 | PROPtype | Propulsion Prop Type | Option 1) Water Jet<br>Option 2) RDP, Rim Driven Prop<br>Option 3) Shrouded |
| 9 | BATtype | Battery system type alternative | Option 1) Nickel Cadmium<br>Option 2) Lead Acid (2.75xNickel Cadmium)<br>Option 3) Zebra (1.67xNickel Cadmium) |
| 10 | Ebat | Battery Capacity | 2500-5000 kwhr |
| 11 | Wfsnork | Weight Fuel Snorkel | 100-200lton |
| 12 | Wfaip | Weight Fuel AIP | 100-200lton |
| 13 | Ndegaus | Degaussing | 0=none; 1=degaussing |
| 14 | Cman | Manpower Reduction | 0.5-1.0 |
| 15 | TORP | Torpedo system alternative | Option 1: Full 2 x 21” Tubes, 12 torpedoes |
| | | | Option 2: Full 2 x 21” Tubes, 8 torpedoes |
| | | | Option 3: Full 2 x 21” Tubes, 6 torpedoes |
| | | | Option 4: No torpedo room, 8 external encapsulated torpedoes |
| | | | Option 5: No torpedo room, 4 external encapsulated torpedoes |
| 16 | VLS | Vertical Launching System Alternatives | Option 1: 16 Cell VLS |
| | | | Option 2: 12 Cell VLS |
| | | | Option 3: 8 Cell VLS |
| 17 | SONARSYS (SSYS) | Sonar/Combat System Alternatives | Option 1: BQQ-5E Bow Dome/Passive structure and access, BQQ-10 sonar electronics and software, LWWAA, BQS-24 high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29; BSY-2/CCSM; AN/WLY-1 acoustic interception and countermeasures system; AN/WLQ-4, AN/BLQ-10 Electronic Support Measures (ESM) system; |

| DV # | DV Name | Description | Design Space |
|---|---|---|---|
| | | | 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube |
| | | | Option 2: BQQ-5E Bow Dome/Passive structure and access, BQQ-5 sonar dome hull damping, AN/BQG-5 WAA, BQS-24 high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; BSY-2/CCSM; AN/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 3: EDO Model 1122 Bow Dome/Passive structure and access, EDO Model 1122 MF Passive bow array, MFA, PRS, EDO Model 1121 flank array, HF MOA 3070 high frequency mine detection sonar, Scout HF Chin Array, EDO Model 1123 towed array, ISUS-90 CCS; AN/WLY-1 acoustic interception and countermeasures system , AN/WLQ-4, AN/BLQ-10 Electronic Support Measure (ESM) System; 2x3" countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube |
| | | | Option 4: ATLAS Electornik DBQS 40 MF cylindrical bow array, MFA, PRS, TAS-3 low-frequency towed array , FAS-3 flank array sonar, and HF MOA 3070 high frequency mine detection sonar; ISUS-90 CCS, Scout HF Chin Array; AN/WLY-1 acoustic interception and countermeasure system; AN/WLQ-4, AN/BLQ-10 Electronic Support Measure (ESM) System; 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube |
| | | | Option 5: EDO Model 1122 Bow Dome/Passive structure and access, EDO Model 1122 MF Passive bow array, MFA, PRS, EDO Model 1121 flank array, Scour mine detection sonar, SUBICS 900 CCS; Scout HF Chin Array, AN/WLY-1 acoustic interception and countermeasure system; AN/WLQ-4, AN/BLQ-10 Electronic Support Measures (ESM) System; 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube |
| 18 | SPW | SPW Alternatives | Option 1: 9 Man Lock out chamber |
| | | | Option 2: 4 Man Lock out chamber |
| 19 | SAIL | Sail (KEI VLS, Radar, Masts and Periscopes, and communication) | Option 1: Advanced Composite Sail, 4xKEI missile cells, BPS-16 Radar; 2x AN/BRA-34 Multiband; AN/BVS-1 Photonics mast; Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA (buoy system), AN/BRD-7/BLD-1 |
| | | | Option 2: BPS-16 Radar; 2x AN/BRA-34 Multiband; AN/BVS-1 Photonics mast; Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA (buoy system), AN/BRD-7/BLD-1 |
| | | | Option 3: BPS-16 Radar; 2x AN/BRA-34 Multiband; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA (buoy system), AN/BRD-7/BLD-1 |
| | | | Option 4: BPS-16 Radar; 2x AN/BRA-34 Multiband; Type 8 Mod 3 Periscope, Type 18 Mod 3 Periscope, Snorkel; IEM; Sea Sentry Seal Locker; Shrike, AN/BRD-7/BLD-1 |

### 3.3 Ship 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 3.20. 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. 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.

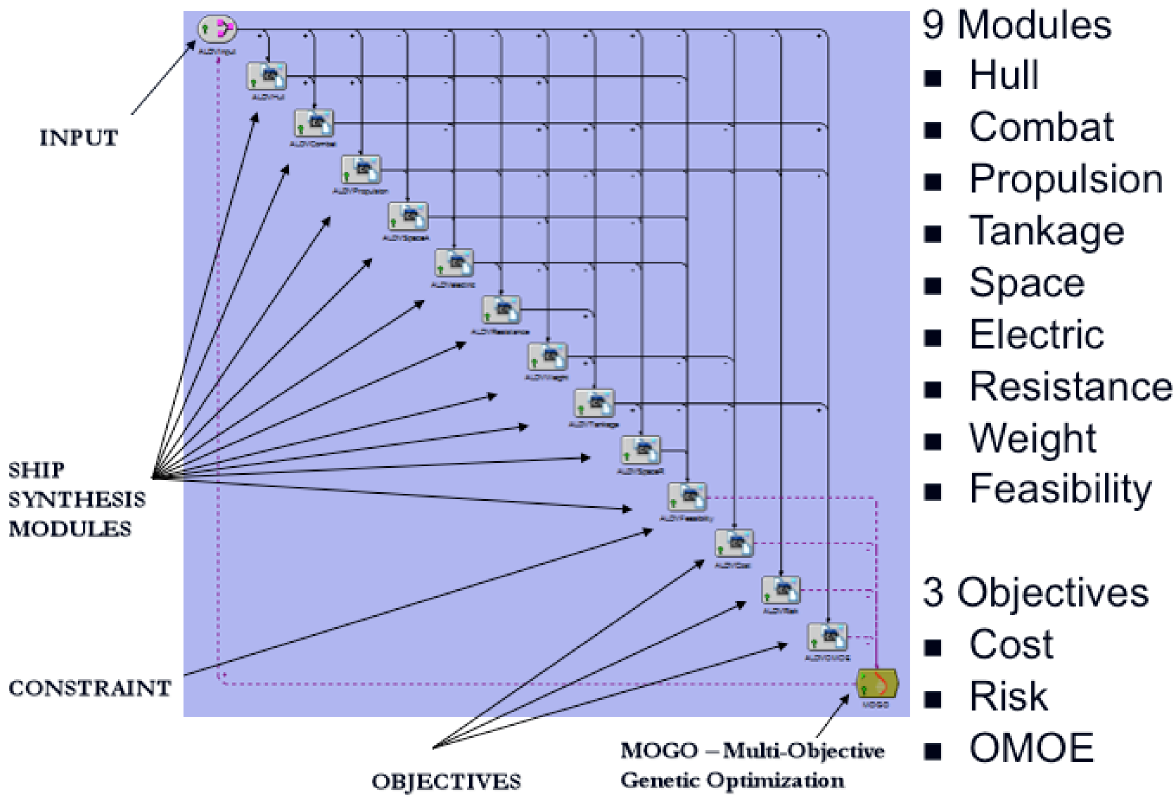



**Figure 3.20: Submarine Synthesis Model in Model Center**

The following modules are used in the submarine synthesis model:

- Input Module**:** This module's specific function is to collect the values of the input variables before providing them to specific modules. The input module then parses the values of all of the input variables and sends them to the module that requests them. 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 by summing the components from the combat systems data table. The total VCG is calculated using a moment about the baseline of the submarine and dividing by the total weight.
- Propulsion Module: The propulsion module determines battery specifications (weight, volume, and power), prop specifications, fuel weights and volumes and total propulsion machinery space. An Excel spreadsheet is used as a database in which all parametric data is read from. 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: An algorithm, developed by MIT's Captain Jackson, is implemented in this module to determine the optimum "tear drop" shape hullform (which includes parallel mid-body). The optimum tear drop shape 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). The total surface area is also determined.

- 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, and calculates manning. 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 a regression's equation for 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) found in the combat systems database. 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. Resistance is calculated for both snorkel and fully-submerged AIP scenarios. The total resistance of the sub is estimated based on its size using industry-standard parametric equations such as: ITTC, Gilmer/Johnson drag coefficient, and Jackson wave which have been modified to be submarine specific. For the snorkel-depth calculation wave-making resistance is added to the resistance value. Total resistance is obtained by adding a correlation allowance to the viscous and wave-making resistance. The total resistance is then used to obtain bare hull power, which is then used to determine shaft power. From the power values aforementioned, 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 3.21. 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.
- Feasibility Module: This module compares available values to required values using a feasibility ratio, (avail-req)/req. Characteristics such as endurance range and duration, GM, GB, and arrangeable area are all examined to determine feasibility. Free flood volume and lead are critical slack variables. 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.

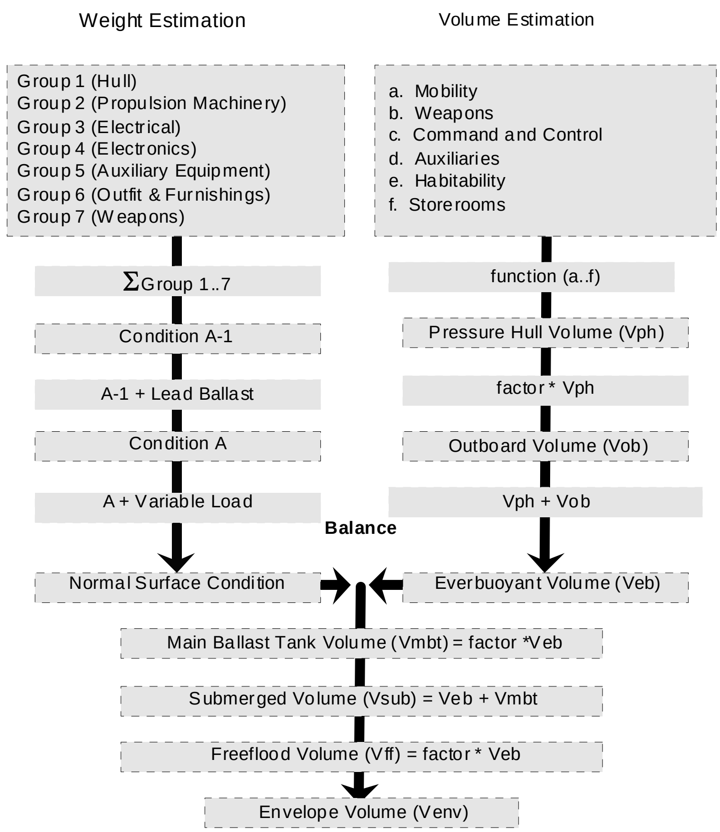



**Figure 3.21: Weight and Volume Balance**

- 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 SSBMD include the use of PEMs, reformer, RDP, NiCd battery, Zebra battery, SONARSYS, and automation.
- MOGO Module: The multi-objective genetic optimizer module is used to identify 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)

When comparing different submarine designs, it is necessary to have a single numerical value representing the mission effectiveness of a submarine. This Overall Measure of Effectiveness (OMOE) is a value (0-1.0) which represents the submarine's overall ability to perform in its required missions. To understand how OMOE is calculated, it is necessary to first define several terms:

- Mission Specific Measures of Effectiveness (MOEs) - Figure of merit index (0-1.0) for specific mission scenario's or mission types.
- Mission Capability Groups or Mission Areas
- Measures of Performance (MOPs) - Specific ship or system performance metric in required capabilities, independent of mission (i.e. speed, range, number of missiles)
- 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.

OMOE takes into account defense policy, threats, operational environment, missions, mission scenarios, and force structures. Ideally these parameters would be included in a war-game module that would evaluate the effectiveness of the design using a range of randomly generated missions. However, due to the complexity and computational resources required to perform such an evaluation; such a system is beyond the means of this study. The alternative to this system is to use expert opinion to determine measures of effectiveness (MOEs) for each design variable option under each mission type. Pair wise comparison is used to generate a relative effectiveness value normalized (0-1.0) on the most effective option in the design space (pairwise comparison results are listed in Appendix D). For each MOP critical to the submarine mission, goal and threshold values are assigned. The MOPs are organized into an OMOE hierarchy (Figure 3.22). Figure 3.23 shows the weighting of each MOP and how important they are compared to each other.

$$OMOE = \sum w_i (VOP_i)(MOP_i)$$

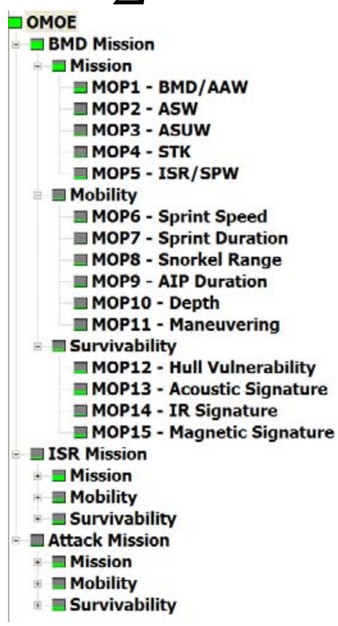



**Figure 3.22: MOP Hierarchy**

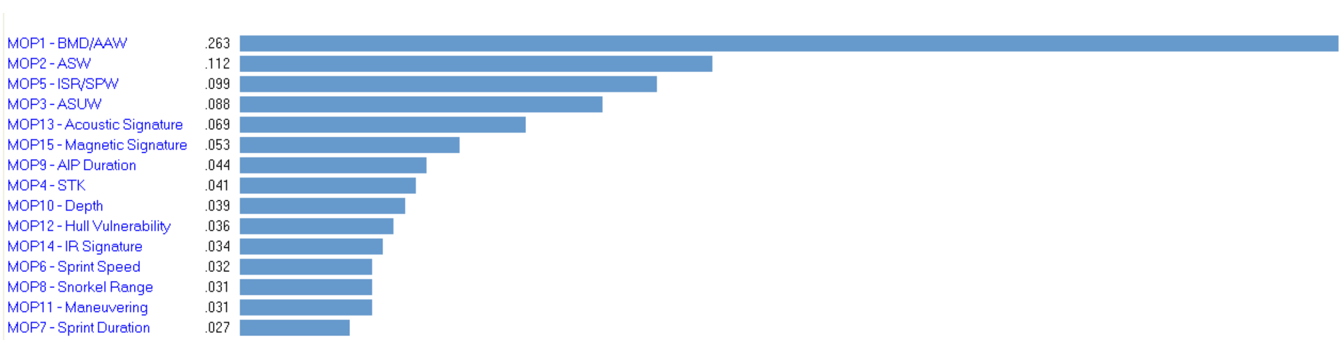



**Figure 3.23: Pairwise Comparison Results – MOP Weights**

### 3.4.2 Overall Measure of Risk (OMOR)

The purpose of the overall measure of risk (OMOR) is to provide a quantitative measure of the risk associated with technologies used in a design. These technologies are specified by the design variables in Table 3.17. The calculation of the value of risk for any given variable, *i*, is the probability of failure, $P_i$, multiplied by the consequence of the failure $C_i$.

$$R_i = P_i C_i$$

Three different types of risk are considered: performance, cost, and schedule. Risk events of each type are associated with specific design variable options. $P_i$ and $C_i$ are estimated using Table 3.18 and Table 3.19. In order to be considered in the risk factors the event must have major impact on performance, cost, or schedule.

**Table 3.18: Event Probability Estimate**

| *Probability* | Probability of Event |
|---|---|
| 0.1 | Remote |
| 0.3 | Unlikely |
| 0.7 | Highly Likely |
| 0.5 | Likely |
| 0.9 | Near Certain |

**Table 3.19: Event Consequence Estimate**

| *Consequence* | Performance Consequence | Schedule Consequence | Cost Consequence |
|---|---|---|---|
| 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 | Acceptable with significant reduction in margin | Minor slip in key milestones; not able to meet need date | 5-7% |
| 0.7 | Acceptable: No remaining margin | Major slip in key milestone or critical path impacted | 7-10% |
| 0.9 | Unacceptable | Can't achieve key team or major program milestone | >10% |

Failure events associated with each design variable are then assigned values of risk. Weight values for each risk type ($W_{pref}$, $W_{cost}$, and $W_{sched}$) are calculated using a pair-wise comparison based on information provided by an expert. The value for OMOR is then determined using the following equation:

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

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 ($W_{sched}$) is 0.2. The final risk register is presented in Table 3.20.

### 3.4.3 Cost

Figure 3.24 below is the cost module diagram which shows the process used to calculate the Basic Cost of Construction (BCC) for the SSBMD. The first step of the process is to input the cost module variables. These are defined in Table 3.21.

As shown in Figure 3.24 above, the process to produce the Basic Cost of Construction for the SSBMD involves an inflation factor, labor cost, material cost, total direct, 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%).

**Table 3.20: Risk Register**

| SWBS | Risk Type | Related DV # | DV Options | DV Description | Risk Event Ei | Event # | Pi | Ci | Ri |
|---|---|---|---|---|---|---|---|---|---|
| 2 | Performance | DV6 | 1-7 | PSYS | PEM does not meet performance TLRs | 1 | 0.5 | 0.7 | 0.35 |
| 2 | Schedule | DV6 | 1-7 | PSYS | PEM schedule delays impact program | 2 | 0.4 | 0.8 | 0.32 |
| 2 | Cost | DV6 | 1-7 | PSYS | PEM development and acquisition cost overruns | 3 | 0.5 | 0.3 | 0.15 |
| 2 | Performance | DV6 | 8-11 | PSYS | CCD does not meet performance TLRs | 1 | 0.2 | 0.7 | 0.14 |
| 2 | Schedule | DV6 | 8-11 | PSYS | CCD schedule delays impact program | 2 | 0.3 | 0.8 | 0.24 |
| 2 | Cost | DV6 | 8-11 | PSYS | CCD development and acquisition cost overruns | 3 | 0.2 | 0.3 | 0.06 |
| 2 | Performance | DV8 | 1 | Prop Type | Pump Jet does not meet performance TLRs | 4 | 0.3 | 0.8 | 0.24 |
| 2 | Schedule | DV8 | 1 | Prop Type | Pump Jet schedule delays impact program | 5 | 0.3 | 0.5 | 0.15 |
| 2 | Cost | DV8 | 1 | Prop Type | Pump Jet development and acquisition cost overruns | 6 | 0.4 | 0.3 | 0.12 |
| 2 | Performance | DV8 | 2 | Prop Type | RDP does not meet performance TLRs | 4 | 0.4 | 0.8 | 0.32 |
| 2 | Schedule | DV8 | 2 | Prop Type | RDP schedule delays impact program | 5 | 0.4 | 0.5 | 0.2 |
| 2 | Cost | DV8 | 2 | Prop Type | RDP development and acquisition cost overruns | 6 | 0.6 | 0.3 | 0.18 |
| 3 | Performance | DV9 | 1 | Battery Type | NiCd Batteries do not meet performance TLRs | 7 | 0.2 | 0.6 | 0.12 |
| 3 | Schedule | DV9 | 1 | Battery Type | NiCd Batteries' schedule delays impact program | 8 | 0.3 | 0.2 | 0.06 |
| 3 | Cost | DV9 | 1 | Battery Type | NiCd Battery development and acquisition cost overruns | 9 | 0.3 | 0.2 | 0.06 |
| 4 | Performance | DV14 | 0.5 | Cman | Increased automation and reduced manning may not work | 13 | 0.4 | 0.6 | 0.24 |
| 4 | Schedule | DV14 | 0.5 | Cman | Increased automation and reduced manning may cause delays | 14 | 0.3 | 0.3 | 0.09 |
| 4 | Cost | DV14 | 0.5 | Cman | Increased automation and reduced manning may have cost overuns | 15 | 0.5 | 0.5 | 0.25 |
| 7 | Performance | DV19 | 1 | Sail Type | KEI VLS System underwater launch does not meet performance requirements | 16 | 0.2 | 0.8 | 0.16 |
| 7 | Schedule | DV19 | 1 | Sail Type | KEI System R&D schedule delays impact program | 17 | 0.3 | 0.5 | 0.15 |
| 7 | Cost | DV19 | 1 | Sail Type | KEI deployment cost-overuns impact program | 18 | 0.5 | 0.3 | 0.15 |

## 3.5 Multi-Objective Optimization

A Multi-Objective Genetic Optimization (MOGO) is used to determine the optimal set of feasible designs for the SSBMD. MOGO utilizes a genetic algorithm to improve on a population of potential designs. The process randomly chooses models from the design space which are then evaluated for their feasibility, effectiveness, risk, and cost. Next, the designs are compared to each other to determine their dominance and a probability of selection for the next generation is assigned to each design based on this dominance. The dominance and probability of selection are used to select a new population of designs. Crossover and mutation are then used to ensure a spread of design options. Crossover is the combination of half of the options of one design with half of those from other designs. Mutation randomly changes the value of one DV in a selected design. Once the new design space is set up the process runs again and the designs are analyzed. The MOGO process is shown in Figure 3.25.

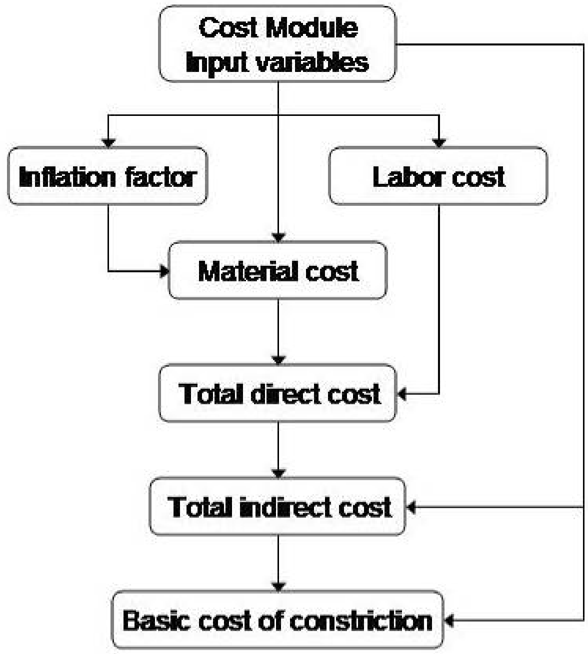



**Figure 3.24: Cost Module Diagram**

**Table 3.21: 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 |

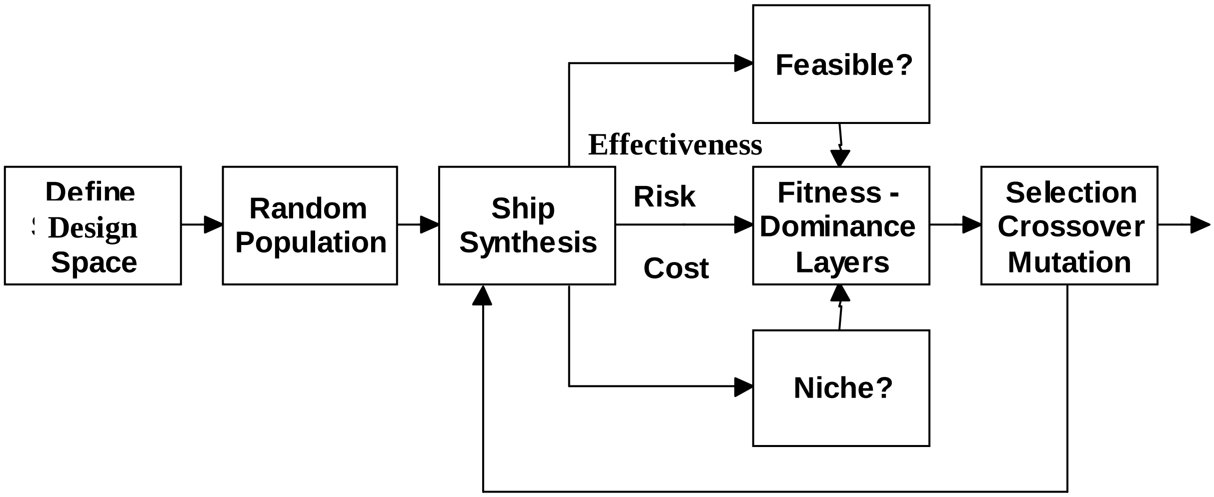



**Figure 3.25: Multi-Objective Genetic Optimization Process**

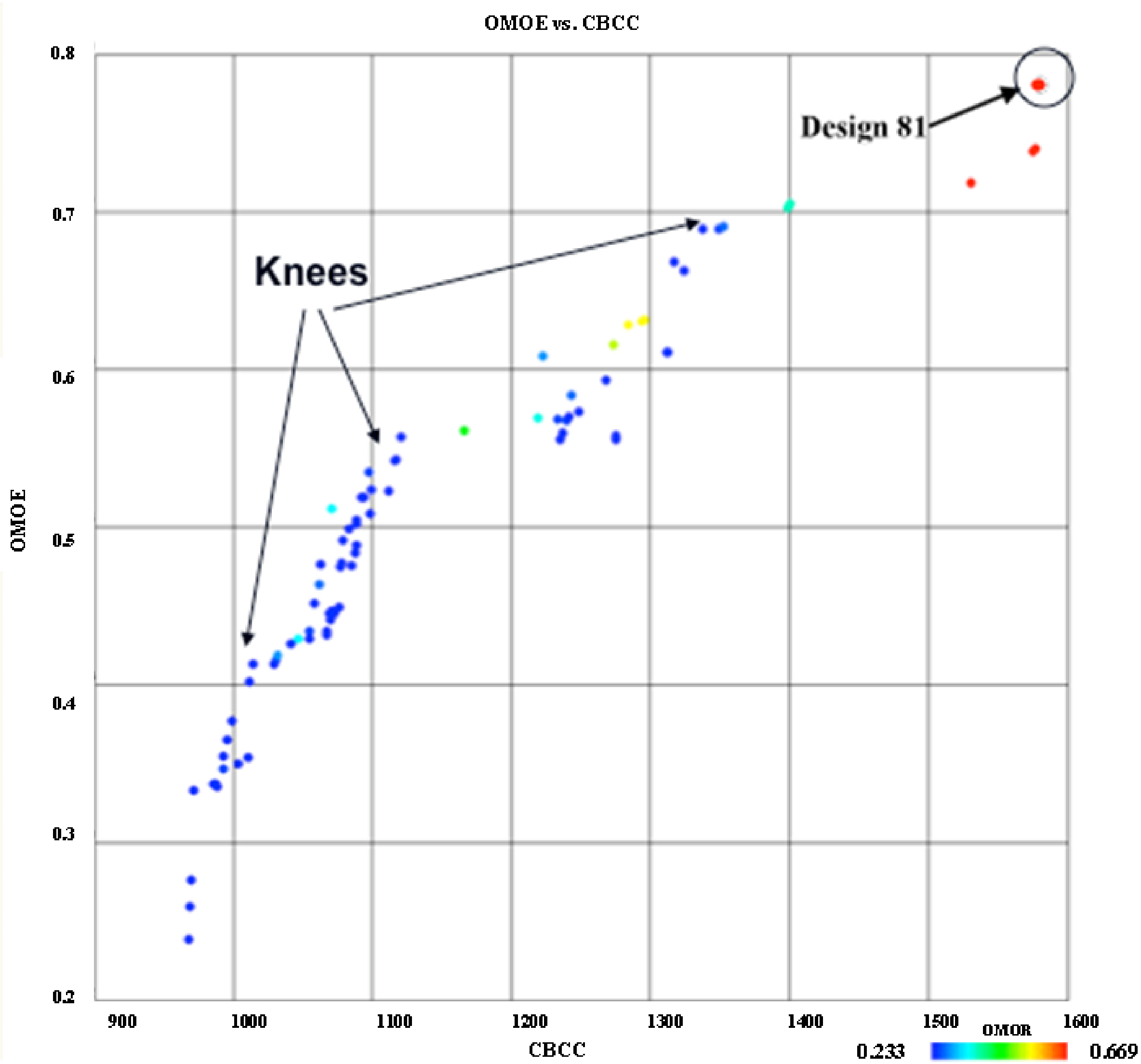



**Figure 3.26: Non Dominated Frontier of Designs (2D)**

### 3.6 Optimization Results

Figure 3.26 shows the initial non-dominated frontier developed by the MOGO. "Knees" are designs that are associated with a significant increase in overall effectiveness for a slight increase in cost and/or risk. Design 81, highlighted with a black circle was chosen as the baseline design. It is a design with high effectiveness, moderate risk, and moderate cost. Design 81 has a cost of $1.579 billion, an overall measure of risk (OMOR) of 0.669, and an overall measure of effectiveness (OMOE) of 0.78. The selected design incorporates new and innovative technologies such as four KEI missiles in the sail of the submarine and an air-independent system that is fueled by methanol reformers. This technology is not currently used by the US Navy, however, it has been proven to be reliable in foreign, non-nuclear submarines.

### 3.7 Baseline Concept Design

Design 81 was further optimized using ModelCenter's gradient optimization tool to fine tune the continuous design parameters (i.e. hull length) by: maximizing OMOE, minimizing feasibility limits, constraining design variables, and by limiting the cost to $1.579 billion. The gradient optimization tool was successful in finding the best set of continuous design parameters and options for the given set of criteria. The gradient optimization design has a cost of $1.574 billion (0.32% improvement), an overall measure of risk (OMOR) of 0.663 (0.91% improvement), and an overall measure of effectiveness (OMOE) of 0.80 (2.56% improvement).

The baseline concept particulars are as follows:

- LOA: 261.2 feet
- Diameter: 32 feet
- Displacement (normal surface condition): 3961 ltons
- Maximum depth: 574.50 feet
- Stores and provisions: 74.2 days

The propulsion machinery system chosen includes 2x Caterpillar 3512 with 2x PEM fuel cells (at 500kW). Hydrogen from reformed methanol was chosen as the fuel for the AIP system. The battery system selected was the advanced Zebra lead-acid battery. The propulsion system has the following performance characteristics:

- Submerged sprint speed: 22 knots
- AIP Endurance speed: 5 knots
- Snorkel speed: 12 knots
- AIP Endurance (at 5 knots): 24.8 days
- Snorkel Endurance range: 5180 nautical miles

The shrouded propeller option was determined to be the propulsor type chosen from the optimization program. The shrouded propeller has several advantages compared to an open propeller in certain flow regimes. The propeller shroud is known to increase thrust and efficiency of restricted diameter propellers at static and low-speed states of operation. The shroud is also known to reduce acoustic signatures if designed properly. Refer to *3.1.2.3 Propulsors* for more information.

The sail type chosen is an advanced composite sail that is capable of storing four KEI ballistic missiles that penetrate the pressure hull. The sail also includes 2x AN/BVS-1 Phototonics mast, 2x AN/BRA -34 Radar, 2x EHF/SHF HDR Multiband, a BPS-16 Radar, and an OE-315 HSBCA. The BVS-1 Phototonics 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-art multi-spectral devices to ensure dominance of the submarine battle force. The advanced composite sail will offer approximately 4 times the volume of a typical sail and improve the hydrodynamics. Refer to *3.1.4.2 Sail* for more information.

The torpedo system used has the capability of a full torpedo room containing two 21" tubes with eight torpedo reloads. The torpedo system has the capacity of carrying Mk 48 ADCAP, Mk 46 and Mk 50 torpedoes.

The VLS system chosen has 16 cells. Sixteen SM-3 missiles will be stored in these cells, with the option to swap out SM-3s for TLAM strike missiles. Refer to *3.1.4.5 VLS* for more information.

A special warfare lockout trunk is included to facilitate deployment of special warfare teams. The lockout chamber will allow a nine man SEAL team to enter or leave the submarine at one time. Access to the chamber would be allowed through the composite sail.

An X-tail stern plane arrangement is chosen for the concept baseline design. This design allows for possible "bottoming" of the vessel for ultra-quiet loitering. The forward dive planes are positioned on the hull as opposed to the sail.

The automation level for the baseline concept is 0.925. This represents a relatively conventional level of automation for this size vessel. Designs employing greater automation are penalized with excessive risk levels with decreasing returns on performance or cost savings.

# 4 Concept Development (Feasibility Study)

## 4.1 Hull Form

### 4.1.1 Final Hull Form Design

The design considerations and process of the hull design is described in Section 3.1.1. The MIT hullform model utilizes a teardrop shape with parallel midbody. For improved producibility and stability an axisymetric hull was chosen. The multi-objective genetic optimization program (MOGO) gives the baseline characteristics. The offsets where then calculated using the MIT model equations and then revolved in Rhino to create the hullform. Expert critiques were used to determine that the hull diameter should be no less than 32 feet to allow for the deck spacing shown in Figure 4.1.

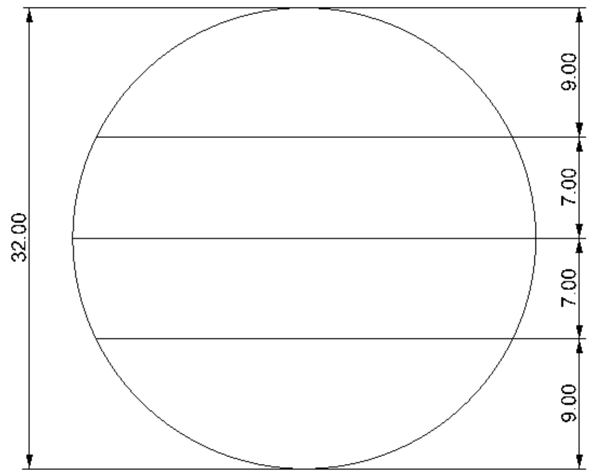



**Figure 4.1: Cross-section of Final Hullform**

Using the 32 foot diameter the hull was optimized and the hullform characteristics where determined. Table 4.1 shows a summary of characteristics used to determine the final hullform.

**Table 4.1: Final Concept Hullform Characteristics**

| DV | Value |
|---|---|
| LOA | 261.2 ft |
| D | 32 ft |
| LtoD | 8.16 |
| $n_f$ | 2.75 |
| $n_a$ | 2.6 |

The full calculations for the hullform are shown in Appendix G-Hullform Model. The offsets were determined from these calculations and revolved in Rhino to construct a 3-D rendering shown in Figure 4.2.

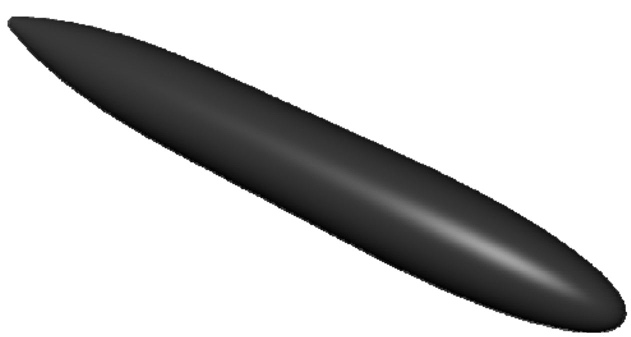


**Figure 4.2: Final Hullform in Rhino**

The hullform was then used to calculate the envelope volume and surface area of the hull. The calculated values in Table 4.2 are determined from those shown in Figure 4.3. The Rhino and synthesis model values differ by less than 1%.

**Units definition**

$MT := 1000 \cdot kg \cdot g$

Physical Parameters

Sea water properties: $\rho_{SW} := 1.9905 \cdot \frac{slug}{ft^3}$

**Input**

$D := 32$ $BtoD := 1.0$ $LtoD := 8.16$ $n_f := 2.2$ $n_a := 2.5$

**Process**

$D := D \cdot ft$ $B := BtoD \cdot D$ $B = 32\,ft$ $LOA := LtoD \cdot D$ $LOA = 261.12\,ft$

Calculate teardrop forebody and run L/D: $LtoD_{td} := 6.0$ $L_{td} := LtoD_{td} \cdot D$ $L_{td} = 192\,ft$

Select LOA including PMB: $L_{pmb} := LOA - L_{td}$ $L_{pmb} = 69.12\,ft$

$L_f := 2.4 \cdot D$ $L_f = 76.8\,ft$

(resistance optimum)

$L_a := 3.6 \cdot D$ $L_a = 115.2\,ft$

B. VOLUME CALCULATIONS TO SUPPORT ARRANGENMENTS:

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

$$zf1(x) := \left[1 - \left(\frac{L_f - x}{L_f}\right)^{n_f}\right]^{\frac{1}{n_f}} \cdot \frac{D}{2} \qquad zf(x) := if\left(x < L_f, zf1(x), \frac{D}{2}\right)$$

**Figure 4.3: Hullform Calculations**

## 4.2 Initial Balance and Trim

Submarine balance and trim is critical for the safe operation of the boat over all mission regimes. The ability to reach equilibrium buoyancy overall operating depths and under all anticipated loading conditions is fundamental to the operation of a submarine. Non-nuclear submarines have unique trim requirements arising from the requirement to use large quantities of consumable fuel and oxidizer. Displacement weight of fuel consumed must be adjusted for along with the change in moment (trim) that results while the submarine is operating. Careful internal and external arrangement of tankage is necessary to minimize the volume of variable ballast tanks. Minimizing variable ballast system size is desirable because internal pressure hull volume must be sacrificed for the trim and variable ballast system.

The balance and trim of the submarine is developed concurrently with the general and machinery arrangements. Arrangement constraints drive the variable ballast system development. For example, placement of internal Liquid Oxygen (LOX) tanks as well as clean diesel and methanol tanks is critical to minimizing the change in moment that results in changing liquid loads. Weapons placement is also extremely influential on the volume required for the variable ballast system. Further constraints include:

- Survivability
- Propulsion and machinery arrangements
- Structural design considerations
- Producibility (tanks and structures assembled from simple shapes only)

The process over which required balance and equilibrium is reached is outlined below:

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

$$za(x) := \left[1 - \left[\frac{x - (L_f + L_{pmb})}{L_a}\right]^{n_a}\right] \cdot \frac{D}{2} \qquad z(x) := if\left(x \le L_f + L_{pmb}, zf(x), za(x)\right)$$

3. Total Ship:

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

$$V_{env} := \int_{0 \cdot ft}^{LOA} A(x)\,dx \qquad V_{env} = 1153772\ gal$$

$$S := \int_{0 \cdot ft}^{LOA} p(x)\,dx \qquad S = 21496.82\ ft^2$$

$$L_f = 76.8\ ft \qquad L_f + L_{pmb} = 145.92\ ft \qquad \frac{D}{2} = 16\ ft \qquad LOA = 261.12\ ft \qquad z(LOA) = 0\ ft$$

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

| x1 = (ft) | z(x1) = (ft) | x2 = (ft) | z(x2) = (ft) |
|---|---|---|---|
| 0 | 0 | 145.92 | 16 |
| 7.68 | 7.818 | 157.44 | 15.949 |
| 15.36 | 10.404 | 168.96 | 15.714 |
| 23.04 | 12.129 | 180.48 | 15.211 |
| 30.72 | 13.382 | 192 | 14.381 |
| 38.4 | 14.311 | 203.52 | 13.172 |
| 46.08 | 14.993 | 215.04 | 11.538 |
| 53.76 | 15.475 | 226.56 | 9.441 |
| 61.44 | 15.787 | 238.08 | 6.841 |
| 69.12 | 15.954 | 249.6 | 3.705 |
| 76.8 | 16 | 261.12 | -0 |
| | | | |

**Cont'd Figure 4.3: Hullform Calculations**

**Table 4.2: Calculated Values of Envelope Volume and Surface Area**

| | Synthesis Model | RhinoMarine | Rhino |
|---|---|---|---|
| Envelope Volume ($ft^3$) | 154327 | 154726 | 154722 |
| Surface Volume ($ft^2$) | 21497 | 21737 | 21785 |

The initial volumes and weights are obtained from the optimizer results. These results are based on empirical calculation and "rule of thumb" guidelines. Significant fine tuning of the initial volumes is needed due to arrangement constraints. SWBS weights estimated by the optimizer are collected into a table of values, from which the main SWBS weight groups are found. The initial three-dimensional model is created in Rhinoceros which is an extension of the two-dimensional arrangement "Flounder Diagram" cartoon developed during concept exploration as seen in Figure 4.5 below.

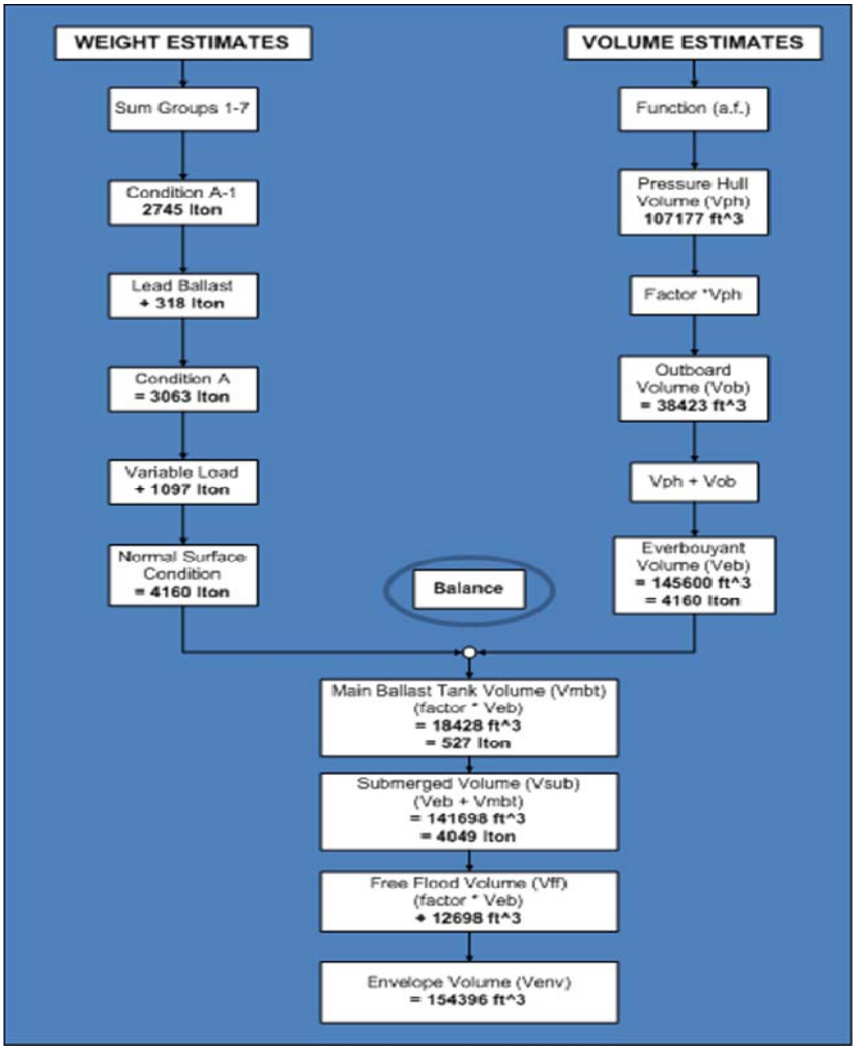



Figure 4.4: Initial Balance

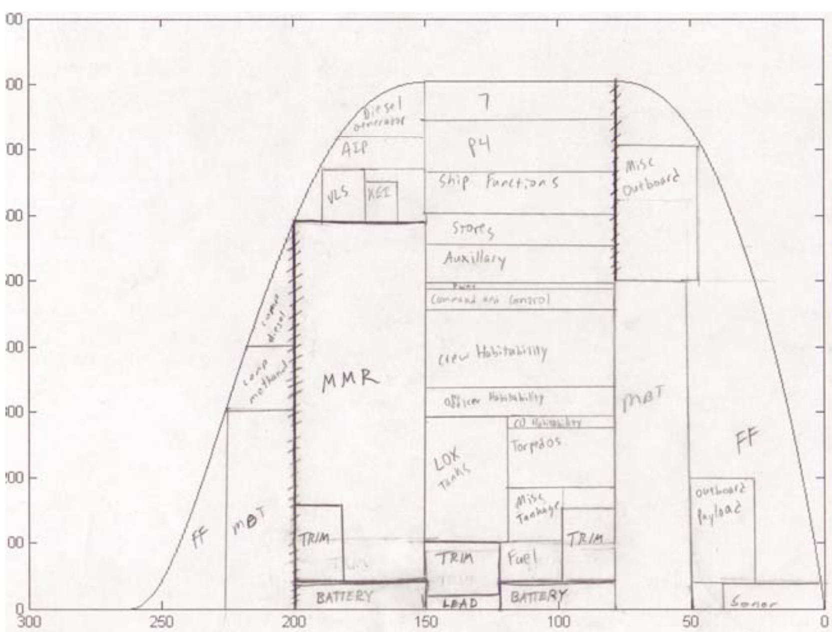



Figure 4.5: Flounder Diagram

All weights included in the SWBS hierarchy are modeled spatially in Rhino along with all internal and external tanks and volumes including the pressure hull. The Rhino model development process is as follows:

1. Model envelope hull by importing profile curve station points
2. Size and locate pressure hull inside the envelope hull (end cap length approximately 1/3 hull diameter)
3. Model all external (to pressure hull) displacing tanks and volumes from Model Center: Main Ballast Tanks, sonar dome, weapons and torpedo tubes, propulsion shafting, escape trunks, structure, etc.
    a. total submerged external volume must equal required submerged displacement
4. Model all decks, bulkheads, internal tanks, primary machinery components, batteries, stores
5. Develop and maintain SWBS weights spreadsheet as described above
6. Check surfaced hydrostatics using RhinoMarine
    a. adjust MBT size to ensure adequate reserve buoyancy when surfaced
    b. reserve buoyancy is calculated by dividing MBT volume by total submerged displacement
    c. target reserve buoyancy is 15-25%
7. Check submerged trim by evaluating Equilibrium Polygon (Section 13.3.5 below)
8. Adjust placement of displacing volumes and weight positions
9. Iterate process

### 4.2.1 Displacing Volumes

Buoyancy is derived from displacing fluid. Although the internal pressure hull and main ballast tanks are the primary sources of displaced volume (and therefore buoyancy), all components that displace water must be accounted for. Other sources of displaced fluid include: sonar dome and access tunnel, compensated fuel tanks, outboard VLS components, outboard payload items, torpedo tubes, propulsor, and ship structures. Components accounted for during displaced volume are displayed graphically below. Omitted for clarity in Figure 4.7 below are the miscellaneous outboard volumes including: propulsor, propulsor shroud, external payload volumes, and external structure (such as envelope hull).

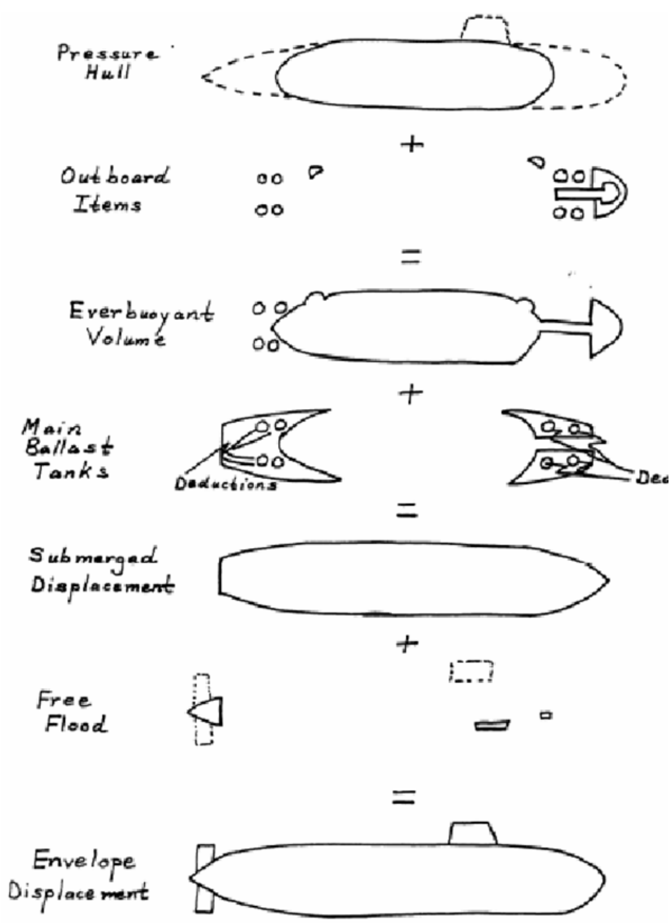



**Figure 4.6: Displaced Volume Breakdown [7]**

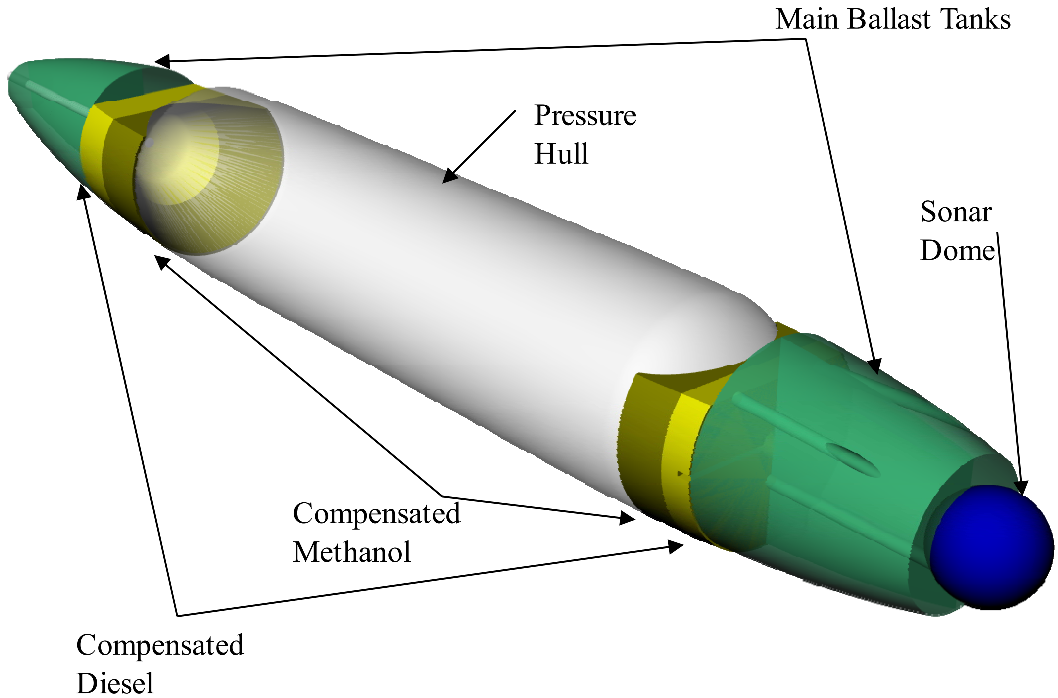



**Figure 4.7: Displaced Volumes**

Pressure hull development begins with locating the pressure hull within the envelope hull fore/aft. Pressure hull diameter is determined during optimization. Pressure hull hemispherical end caps are modeled, with height of hemisphere approximately 1/3 of pressure hull diameter. Departure from pure hemispherical end caps used to provide "saddle tank" position for external fuel tanks. This will locate compensated fuel tanks closer to internal clean fuel tanks, thus reducing shift of CG aft when external tanks are filled with seawater. Care was taken to maintain structural integrity of pressure hull; no sharp knuckles or concavities that may act as stress concentrations are allowed.

Main ballast tanks are sized to ensure correct waterline height and trim when surfaced which creates hydrostatic stability and reserve buoyancy. Main ballast tanks are flooded completely to submerge (achieve negative buoyancy).

### 4.2.2 Internal and External Tanks

All internal and external tankage is modeled and accounted for in the equilibrium balance process. External tankage is devoted to liquid fuel (diesel and methanol). As fuel is used from the external tanks, they are compensated with seawater. Simultaneously fuel is used from the internal clean fuel tanks to compensate for the fuel/water density difference. Fuel from the external tanks is coalesced to remove water contamination, filtered and transferred to internal service tanks. The volume that has been vacated in the external tanks is filled with seawater. The compensated tanks are of the membrane type, which physically isolates the fuel from the seawater. The internal and external fuel tank sizes are based on the respective difference in density between the fuel and seawater with the goal of having no net change in effective weight as fuel is burned. For example, the density of diesel fuel marine (DFM) is 52.1 lb/ft$^3$. This is 81% the density of seawater at 64 lb/ft$^3$. The target distribution of tankage between clean internal and compensated internal is thus 19% internal and 81% external. Distributing the fuel in this manner results in the desired zero net change in effective weight from the fuel system. Once the external compensated fuel tanks are filled with seawater, this will shift the resultant CG aft. This shift in CG (and corresponding requirement to trim out the moment with the variable ballast tanks) can be minimized by placing compensated fuel tanks as close to the clean fuel tanks as possible. Consumption of oxidizer (LOX) weight must be compensated for by the variable ballast system.

The variable ballast system inboard of the pressure hull is of the three tank type, with a main aux tank amidships feeding the trim tanks fore and aft. The fore and aft tanks are placed at the extreme ends of the pressure hull on the lowest deck. This allows the trim tanks to compensate for the maximum amount of moment with the smallest possible amount of ballast volume. The size of these tanks is adjusted using the equilibrium polygon.

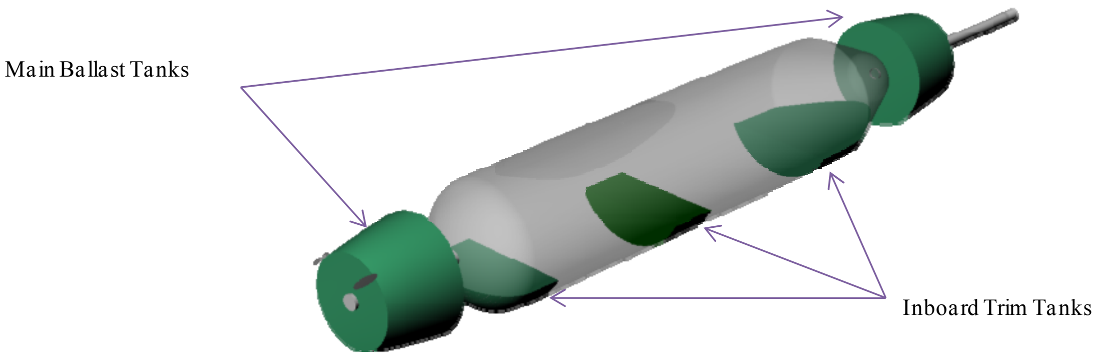



**Figure 4.8: Main and Variable Ballast System**

### 4.2.3 Weights

Component weights for all subsystems are taken from the optimizer results. A Ship's Work Breakdown Structure (SWBS) common to naval vessels is utilized to organize and tabulate all fixed weights and variable weights. SEE Appendix F for tabulated list of SWBS weights.

### 4.2.4 Load Conditions

Loading conditions are developed in accordance with Dept. of the Navy publication S9086-C6-STM-010/CH-096R1 which provides guidance for non-nuclear submarine loading conditions and operating conditions. These loading conditions attempt to emulate the extremes in variable loads the submarine may encounter over the course of a mission. Once the variable ballast system is known to be able to account for any extremes of loading conditions, any intermediate loading condition will be able to be compensated for. Variable loading conditions are the primary driver for trim and variable ballast system sizing along with operating environment considerations. The amount of buoyancy available from the surrounding water varies with the water density. Thus the submarine will be essentially heavier in brackish water near the mouth of a river than it will operating in the Red Sea. The range of seawater density studied is from 63.6 lb/ft$^3$ to 64.3 lb/ft$^3$. The extreme cases of variable loads are paired with the "worst case" water densities to ensure that the variable ballast system is able to correct any possible loading situation. The load conditions studied are summarized in Table 4.3. Complete load condition information is included in Appendix

**Table 4.3: Load Conditions**

| Load Condition | Description | Weight | Moment |
|---|---|---|---|
| Normal | Normal surface condition. All tanks 100%. Weapons stores 100%. 100% provisions | 11.33 | 562 |
| Light #1 | 75% LO, 50% potable water, 75% provision, weapons stores expended | 31.05 | 1657 |
| Heavy #1 | 50% LO, 50% provisions, AIP gases expended, 100% compensated fuel tanks (SW), clean fuel expended, missiles/torpedoes 100% | 150.62 | -5762 |
| Heavy #1 (Mines) | 50% LO, 50% provisions, AIP gases expended, 100% compensated fuel tanks (SW), clean fuel expended, missiles/mines 100% | 139.52 | -3576 |
| Heavy FWD #1 | 75% LO, 75% provisions, weapons stores 100% | 32.47 | 618 |
| Heavy FWD #2 | 75% LO, 50% provisions, 50% AIP gases, 50% compensated fuel tanks | 45.97 | -981 |
| Heavy Aft (Diesel) | 75% LO, 50% provisions, 50% potable water, 50% AIP gases, 50% clean fuel, 50% compensated fuel tanks, missiles 100%, torpedoes expended | 126.66 | 4649 |

### 4.2.5 Initial Equilibrium Polygon

The equilibrium polygon is a graphical method to ensure adequate variable ballast is available for all anticipated loading conditions. The polygon is plotted with fore-aft trim moment (lton-ft) on the X-axis and change in weight (lton) on the Y-axis. The loading conditions found earlier are plotted as points in this system, reflecting the amount of weight and moment that need to be compensated for by the variable ballast system. The variable ballast tanks each are plotted with respective weights and moments when both full and empty. A polygon is constructed using the full/empty points for each variable ballast tank. Tank size and position is then "fine tuned" to contain within the polygon boundaries all the loading condition points. The polygon is constantly revisited throughout the design spiral as the general and machinery arrangements are altered.

The initial equilibrium polygon constructed after roughly locating all SWBS weight components in the model and sizing all tanks and pressure hull to the initial volumes specified by the optimizer is shown in Figure 4.9.

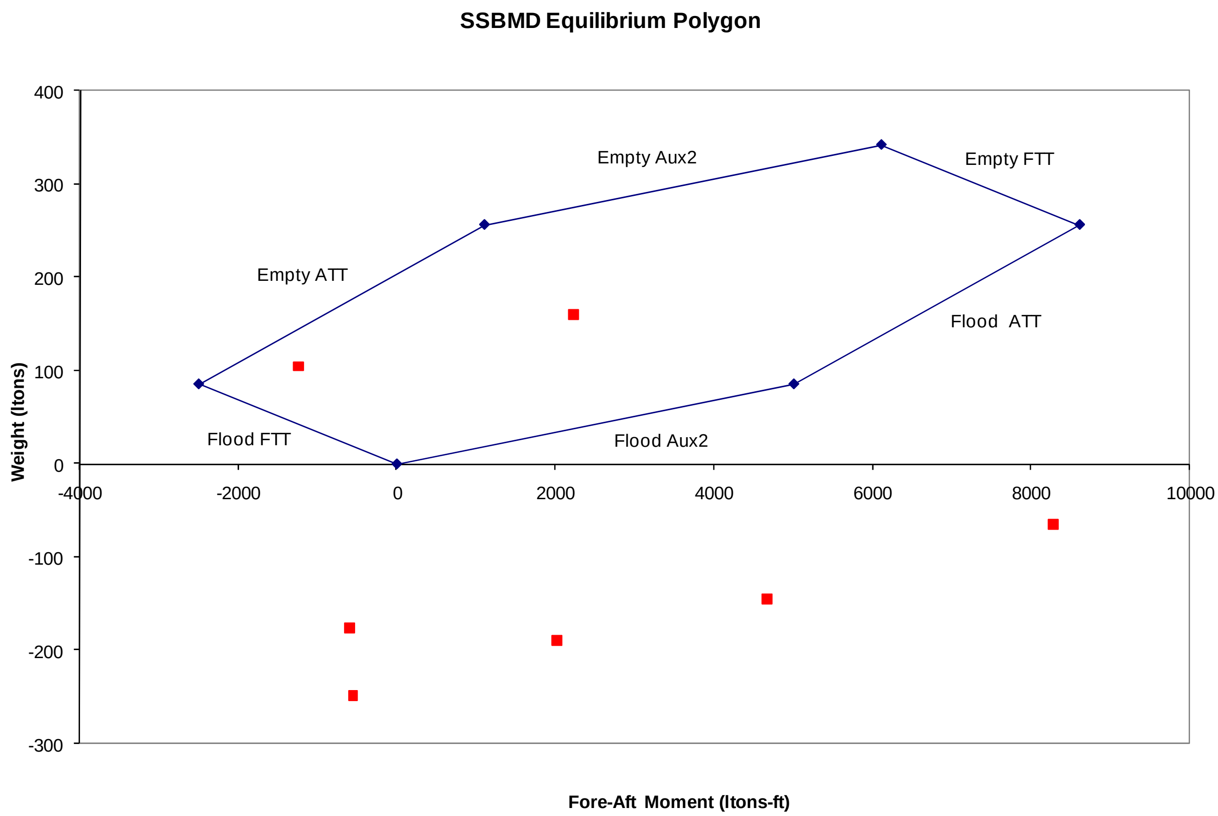



**Figure 4.9: Initial Equilibrium Polygon**

### 4.2.6 Necessary Modifications and Baseline Equilibrium Polygon

As can be seen in Figure 4.9 above, the initial loading condition and displacing volumes were not balanced. Five out of seven loading conditions are unacceptable as they are below the X-axis, which corresponds to a "sinking" condition. The initial pressure hull volume was increased to compensate for the excessive weight. Increasing the pressure hull volume shifts the loading condition points upwards. The same effect can be had by decreasing the amount of lead ballast carried, however this approach is less desirable because reducing the lead weight may negatively affect hydrostatic stability or lead margins if too much is removed. Figure 4.9 above also indicates that the variable ballast system volume must be increased to encompass all loading condition points. After increasing the pressure hull volume from 103385 $ft^3$ to 118785 $ft^3$ and increasing the variable ballast total volume from 11972 $ft^3$ to 18500 $ft^3$ the submarine was balanced over all loading conditions. The loading condition spreadsheet was also updated with revised weights. Figure 4.10 below shows the baseline polygon.

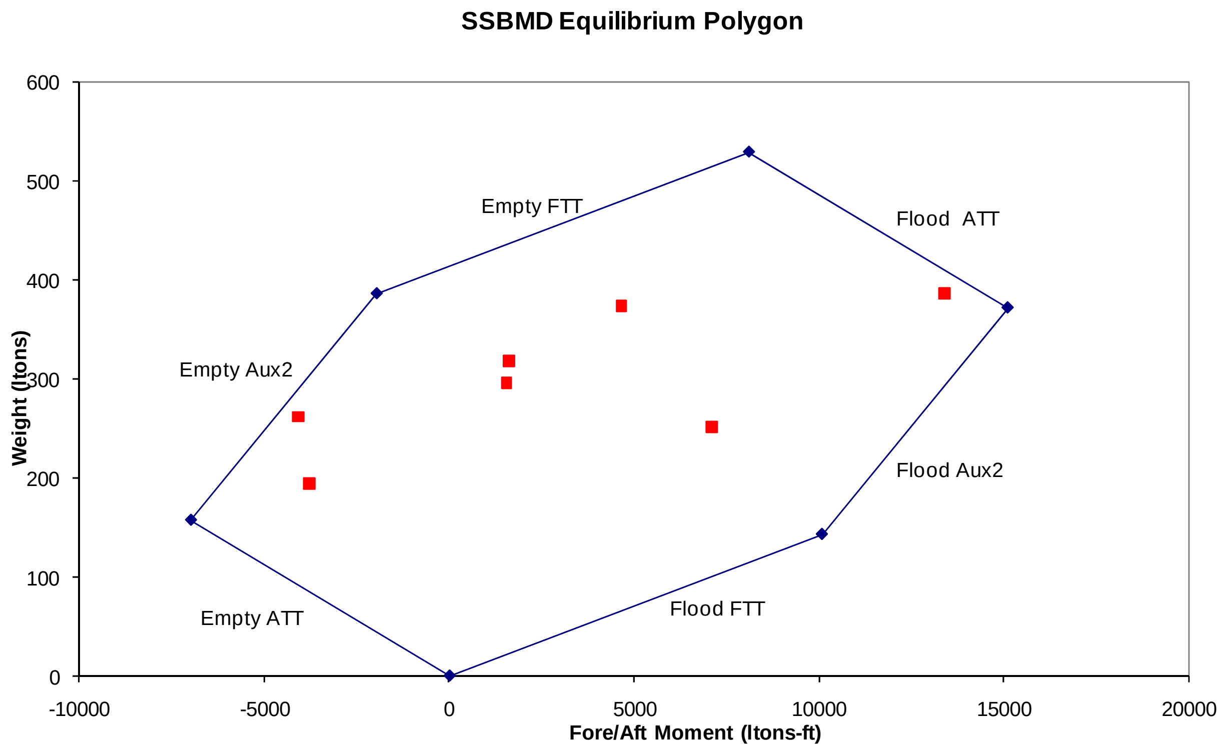



**Figure 4.10: Baseline Equilibrium Polygon**

### 4.2.7 Normal Surface Condition

Hydrostatic stability while surfaced is determined by water plane area, waterline location (reserve buoyancy), center of buoyancy, and center of gravity. Center of buoyancy is determined by displaced volume while surfaced. RhinoMarine hydrostatics is used to determine waterline at Normal Surface Condition (NSC). Weight at NSC is taken from the SWBS weights spreadsheet with the main ballast tanks empty. The weights spreadsheet also gives the vertical center of gravity (VCG) which is 0.71 ft below the axis of the pressure hull. RhinoMarine generates hydrostatic curves by varying the draft at which the submarine floats on the surface. Appendix M shows the hydrostatic curves.

Main ballast tank size is altered to obtain sufficient reserve buoyancy. Initial MBT tank volume obtained from optimizer results was found to be too small as the freeboard was approximately 2 ft. This is due to the optimizer assuming all displaced volumes are contributing to buoyant force while surfaced. While at the surface, a significant amount of structure and payload is above the free surface. Figure 4.11 below shows the submarine at the calculated surface condition detailed in Table 4.4 below.

**Table 4.4: Initial NSC values**

| Description | Normal Surface Condition |
|---|---|
| Displacement | 4252 lton |
| LWL | 205 ft |
| T | 26 |
| B | 32 |
| Trim | 0.96° (down by stern) |
| Reserve Buoyancy | 20.70% |

## 4.3 Structural Design and Analysis

The iterative process of structural design, shown in Figure 4.12, was performed using both manual calculations and a finite element analysis (FEA) program.

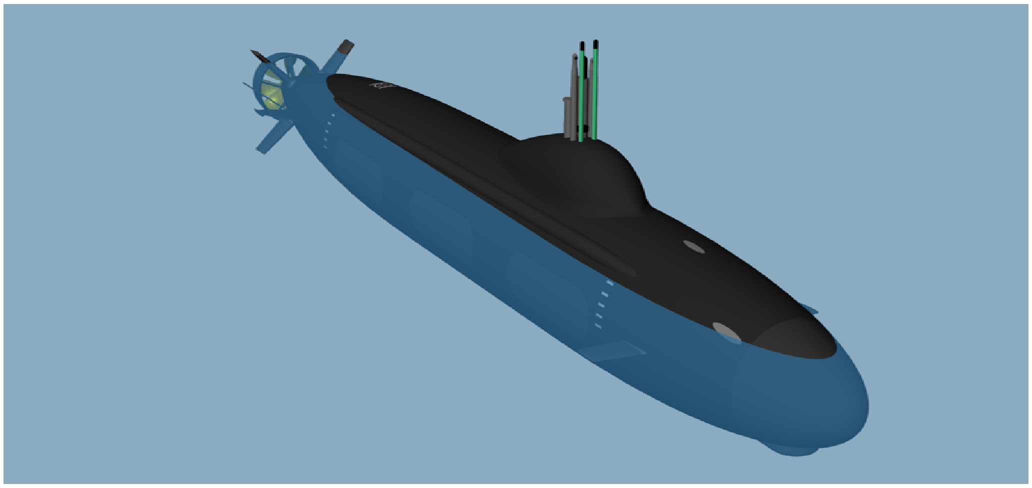


**Figure 4.11: Surfaced Waterline**

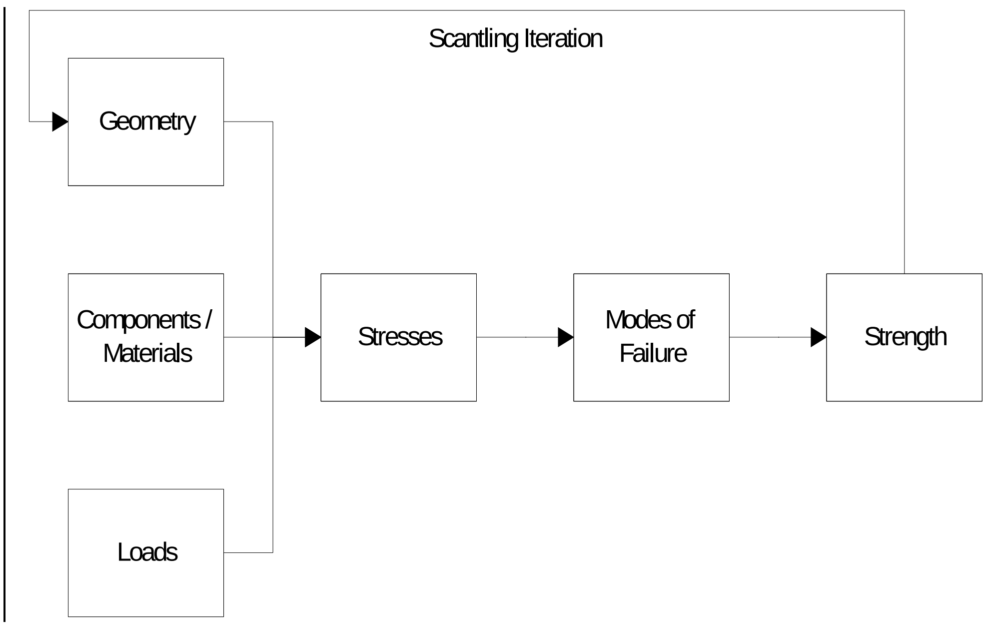



**Figure 4.12: Structural Design Process**

The first step in the process is using a sketch of the pressure hull with principal dimensions and deciding where to place king frames and bulkheads. Manual calculations are then performed using a MathCAD interpretation of Captain Jackson's structural calculation for submarines. The program is then run through a Model Center Optimization which minimizes weight for given enclosed volume to obtain initial scantlings that are plugged into the finite element analysis program, MAESTRO, which assesses the strength limit states. The pressure hull model in MAESTRO includes all materials, loads and geometry while calculating stresses and limit state values. The final step is to iterate the scantlings in MAESTRO. Limited stress results were acquired in MAESTRO, however, results for the main failure mode of submarines, stiffener buckling, could not be calculated in MAESTRO and the manual calculations were used. This report will present the manual calculations and stress results acquired in MAESTRO.

### 4.3.1 Geometry, Components and Materials

Figure 4.13 shows the pressure hull as it was modeled in MAESTRO. The blue represents plate, the red represents frames and yellow represents king frames. The dimensions of the elements are shown in Table 4.5. Each king frame defines a module in the Model Center optimization. This spacing was determined by various internal arrangements. Descriptions of the modules can be seen in Table 4.6. Although some modules mention bulkheads, king frames were used to model the bulkheads. Note in Module 6, where the pressure hull forms an angle, there are king frames were used for additional support on each end of the frustum where stress concentrations form at geometric discontinuities. Frame spacing was chosen to be 2 feet through out the entire pressure hull in order stay with current submarine construction conventions.

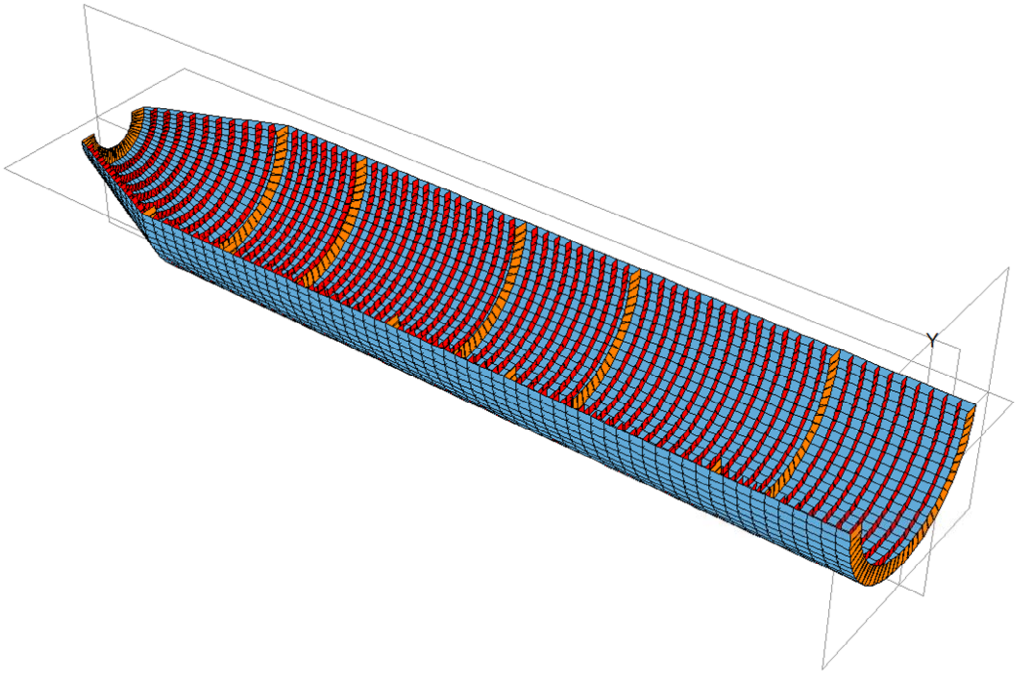


**Figure 4.13: Hull Model in MAESTRO**

**Table 4.5: Element Dimensions**

| Element | Part | Size(in) |
|---|---|---|
| Plate | NA | 1.00 |
| Frame | flange width | 5.01 |
| | flange thickness | 0.375 |
| | web height | 15.94 |
| | web thickness | 0.375 |
| King Frame | flange width | 10.04 |
| | flange thickness | 2.00 |
| | web height | 31.92 |
| | web thickness | 0.75 |

**Table 4.6: Module Descriptions**

| Module | Length | Division |
|---|---|---|
| 1 | 20 | Forward end cap to bulkhead aft of torpedo room |
| 2 | 32 | Torpedo room bulkhead to front of VLS cells |
| 3 | 20 | Brackets the VLS cells |
| 4 | 30 | Bulkhead forward of LOX tanks to bulkhead aft of LOX tanks |
| 5 | 16 | Aft bulkhead to max diameter before hull slopes |
| 6 | 22 | Aft end cap |

The material chosen for all plating and frames in the pressure hull is HY-100 steel, a high strength steel alloy with a yield stress of 100,000 psi.

### 4.3.2 Failure Modes and Safety Factors

Captain Jackson's method was coded into MathCAD and an optimization was run for plating thickness and frame scantlings. The ratio of weight to buoyancy was minimized. The maximum depth hydrostatic pressure was used in considering the limit states or failure modes: shell yielding (SY), lobar buckling (LB), general instability (GI), frame yielding (fy), and frame instability (FI). The stress factor, r, is determined by dividing the stress by the failure stress for each mode of failure. The results are normalized by the adequacy parameter (1-r)/(1+r). The values of the adequacy parameter vary between negative one and positive one. The desired value is zero with negative one correlating to an under designed parameter and positive one correlating to over designed parameters. At zero the parameter meets the design requirements with the given factor of safety. The goal is to remain close to zero or positive.

**Global Variable Inputs:**

Operating depth: $D_t := D_t \cdot ft$ $D_t = 575\ ft$

Geometry Variables: $D := D \cdot ft$ shell diam $D = 32\ ft$ $R := \frac{D}{2}$

Frame spacing $L_f := L_f \cdot ft$ $L_f = 24\ in$

Material:(HY80) $\sigma_y \equiv 100000 \cdot \frac{lbf}{in^2}$ $\rho_{st} \equiv 7.8 \cdot 10^3 \cdot \frac{kg}{m^3}$ $E \equiv 30 \cdot 10^6 \cdot \frac{lbf}{in^2}$ $\nu \equiv 0.3$ $\rho \equiv 1030 \cdot \frac{kg}{m^3}$

**Define input variables:**

Bulkhead spacing $L_s := L_s \cdot ft$ $L_s = 192\ in$

shell thickness $t_p := t_p \cdot in$ $t_p = 1\ in$

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

flange tickness $t_f := t_f \cdot in$ $t_f = 0.376\ in$

flange width $w_f := w_f \cdot in$ $w_f = 5.02\ in$

web thickness $t_w := t_w \cdot in$ $t_w = 0.375\ in$

web height $h_w := h_w \cdot in$ $h_w = 15.935\ in$

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

flange,web $A_f := t_f \cdot w_f$ $A_w := t_w \cdot h_w$ $A := A_f + A_w$ $A = 7.861\ in^2$

Compute structural efficiency (buoyancy factor):

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

$BF = 0.103$ $BF \cdot 100 = 10.305$

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

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{sy}$ $P = 385.135\ psi$

Area ratio $B := \frac{t_w \cdot t_p}{A + t_w \cdot t_p}$ $B = 0.046$

Slenderness parameter: $\theta := L_f \cdot \left[\frac{3 \cdot (1 - \nu^2)}{(R \cdot t_p)^2}\right]^{\frac{1}{4}}$ $\theta = 2.226$

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

**Figure 4.14: Structural Adequacy Calculation Input**

The factors of safety used in the calculations are: SY (1.5), fy (1.5), FI (1.8), LB (2.25), GI (3.75). The factors of safety are set to allow for yielding to be the limiting factor in the pressure hull not buckling.

Figure 4.14 shows the hand calculations for one module, the length of the submarine between king frames, and is representative to that of the other five modules. The pressure hull is divided into 6 modules in the optimization shown in Figure 4.15. The optimization occurs over a continuous range for the frame and plate scantlings.

Frame flexability parameter:

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

$$\beta = 2.581$$

Frame deflection parameter:

$$\Gamma := \frac{\left(1-\frac{\nu}{2}\right) - B}{1+\beta}$$

$$\Gamma = 0.225$$

Bending effect (mem):

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

$$H_M = -0.787$$

Bending effect (bend):

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

$$H_E = 0.617$$

Bending efffect near frame:

$$K := \frac{\sinh(\theta)-\sin(\theta)}{\sinh(\theta)+\sin(\theta)}$$

Midbay shell stress is calculated:

outer

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

inner

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

Shell stress at frames is:

outer

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

inner

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

$$j := 1..8$$

$$\sigma_{sy} := \begin{pmatrix}\sigma_{\phi\phi so}\\ \sigma_{\phi\phi si}\\ \sigma_{xxso}\\ \sigma_{xxsi}\\ \sigma_{\phi\phi fo}\\ \sigma_{\phi\phi fi}\\ \sigma_{xxfo}\\ \sigma_{xxfi}\end{pmatrix} \qquad \sigma_{sy} = \begin{pmatrix}-6.396\times10^4\\ -5.78\times10^4\\ -4.722\times10^4\\ -2.672\times10^4\\ -5.096\times10^4\\ -6.371\times10^4\\ -1.571\times10^4\\ -5.823\times10^4\end{pmatrix}\text{psi}$$

**Cont'd Figure 4.14: Structural Adequacy Calculation Input**

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

This represents how much of the safety factor was actually used:

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

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

$$\sigma_{SYM} = 5.745 \times 10^4 \, psi$$

$$\sigma_{SYF} = 6.116 \times 10^4 \, psi \qquad \sigma_{SY} := \max\left(\begin{pmatrix} \sigma_{SYM} \\ \sigma_{SYF} \end{pmatrix}\right) \qquad \sigma_{SY} = 6.116 \times 10^4 \, psi$$

$$r_{SY} := \frac{\sigma_{SY}}{\sigma_y} \qquad r_{SY} = 0.764$$

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

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{lb}$ $P = 577.702 \, psi$

Collapse pressure:

$$P_{cLB} := \frac{2.42 \cdot E \cdot \left(\frac{t_p}{D}\right)^{2.5}}{\left(\frac{L_f}{D} - 0.45 \cdot \sqrt{\frac{t_p}{D}}\right) \cdot \left(1 - \nu^2\right)^{0.75}} \qquad P_{cLB} = 682.079 \, psi$$

$$r_{LB} := \frac{P}{P_{cLB}} \qquad r_{LB} = 0.847$$

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

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{gi}$ $P = 962.837 \, psi$

Compute effective frame spacing: $\gamma := \frac{P}{2 \cdot E} \cdot \left(\frac{R}{t_p}\right)^2 \cdot \sqrt{3 \cdot \left(1 - \nu^2\right)}$ $\gamma = 0.977$

Compute clear length:

$$L_c := L_f - t_w \qquad n_1 := 0.5 \cdot \sqrt{1 - \gamma} \qquad n_1 = 0.075$$

$$n_2 := 0.5 \cdot \sqrt{1 + \gamma} \qquad n_2 = 0.703$$

**Cont'd Figure 4.14: Structural Adequacy Calculation Input**

$t_w = 0.375\,in$

Effective plate length:

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

$$L_{eff} := L_c\cdot F_1 + t_w$$

$$L_{eff} = 19.551\,in$$

$F_1 = 0.812$ must be less than 1.00

Theoretical critical lobe number values are:

$i := 0..2$

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

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

Effective plate area: $A_{eff} := L_{eff}\cdot t_p$

Frame-plate neutral axis (ref web centre+ toward flange):

$$y_{na} := \frac{\left(\frac{h_w + t_f}{2}\right)\cdot A_f - \left(\frac{h_w + t_p}{2}\right)\cdot A_{eff}}{A_{eff} + A_w + A_f}$$

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

$$I_{pcor} := I_p + A_{eff}\cdot\left[\left(\frac{t_p + h_w}{2}\right) + y_{na}\right]^2$$

$$I_{wcor} := I_w + A_w\cdot(y_{na})^2$$

$$I_{fcor} := I_f + A_f\cdot\left(\frac{t_f + h_w}{2} - y_{na}\right)^2$$

Total: $I_{eff} := I_{pcor} + I_{wcor} + I_{fcor}$

The critical pressure is:

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

$$P_{cGI} = \begin{pmatrix}1.041\times 10^4\\4.481\times 1\\3.347\times 10^3\end{pmatrix}$$

$P_{cGI} := \min(P_{cGI})$ $P_{cGI} = 3.347\times 10^3\,psi$

$r_{GI} := \frac{P}{P_{cGI}}$ $r_{GI} = 0.288$

**Cont'd Figure 4.14: Structural Adequacy Calculation Input**

PART 4 FRAME YIELDING

Safety factor is: $SF_{fy} := 1.5$

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{fy}$ $P = 385.135\ \text{psi}$

Compute direct stress:

$$\beta_f := \frac{t_w}{L_f}$$

Radius to frame NA: $R_{fna} := \frac{D}{2} - t_p - \frac{h_w}{2} - y_{na}$

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

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

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

Stress adjuster: $SA := 1 - \frac{\alpha_p}{\alpha_p + \beta_f + (1 - \beta_f) \cdot F_1}$ $SA = 0.723$

$$\sigma_{direct} := \frac{\left(1 - \frac{\nu}{2}\right) \cdot P \cdot \left(\frac{D}{2} - \frac{t_p}{2}\right)^2}{t_p \cdot \left(\frac{D}{2} - t_p - h_w - t_f\right)} \cdot SA \qquad \sigma_{direct} = 4.966 \times 10^4\ \text{psi}$$

Compute bending stress due to eccentricity:

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

Bending stress: $\sigma_{bend} := \frac{E \cdot c \cdot e \cdot \left[(n)^2 - 1\right]}{R^2} \cdot \frac{P}{P_{cGl} - P}$ $\sigma_{bend} = 4.099 \times 10^3\ \text{psi}$

**Cont'd Figure 4.14: Structural Adequacy Calculation Input**

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

This must be less than one:

$\sigma_{fr} = 5.376 \times 10^{4}\ \text{psi}$ $\quad r_{fy} := \dfrac{\sigma_{fr}}{\sigma_y}$ $\quad r_{fy} = 0.672$

PART 5 FRAME INSTABILITY

Safety factor is: $SF_{fy} := 1.8$

Pressure loading is: $P := \rho \cdot g \cdot D_r \cdot SF_{fy}$ $\quad P = 462.162\ \text{psi}$

Area of plate: $A_p := t_p \cdot L_f$

Frame-plate neutral axis (ref web centre+ toward flange):

$$y_{na2} := \frac{\left(\frac{t_f}{2} + \frac{h_w}{2}\right) \cdot A_f - \left(\frac{t_p}{2} + \frac{h_w}{2}\right) \cdot A_p}{A_p + A_w + A_f} \qquad y_{na2} = -5.896\ \text{in}$$

Moments of inertia for plate,flange,web (compute Ip using actual plate length:

$$I_p := \frac{L_f \cdot t_p^{\,3}}{12} \qquad I_p = 2\ \text{in}^4$$

Correct the individual moments from the na:

$$I_{pcor} := I_p + A_p \cdot \left(\frac{t_p}{2} + \frac{h_w}{2} + y_{na2}\right)^2$$

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

Then total plate, frame moment of inertia is:

$$I := I_{pcor} + I_{wcor} + I_{fcor}$$

Diameter to NA is: $D_{na} := D - 2t_p - h_w - 2y_{na2}$ $\quad D_{na} = 31.488\ \text{ft}$

Compute pressure limit:

$$P_{cFI} := \frac{25 \cdot E \cdot I}{D_{na}^{\,3} \cdot L_f} \qquad P_{cFI} = 502.32\ \text{psi} \qquad r_{FI} := \frac{P}{P_{cFI}} \qquad r_{FI} = 0.92$$

Load ratio must be less than 1:

**Cont'd Figure 4.14: Structural Adequacy Calculation Input**

### 4.3.3 Optimization Results, Adequacy, Loads and MAESTRO Results

The calculation results are shown in Figure 4.16. The stress factor values, r, all fell below 1.0 as required.

**Results:**

$r_{SY} = 0.764$ $\quad BF = 0.103$

$r_{LB} = 0.847$

$r_{GI} = 0.288$

$r_{fy} = 0.672$

$r_{FI} = 0.92$

**Figure 4.16: Structural optimization results**

The adequacy results, calculated as (1-r)/(1+r) are shown in Table 4.7. All adequacies were between zero and one. Since the values were all over one, the scantlings output by the MathCAD file are overdesigned, however, this is a good starting place for MAESTRO where the dimensions can be altered to save weight and bring the adequacies closer to zero. Frame instability and lobar buckling were the critical limit states (or modes of failure).

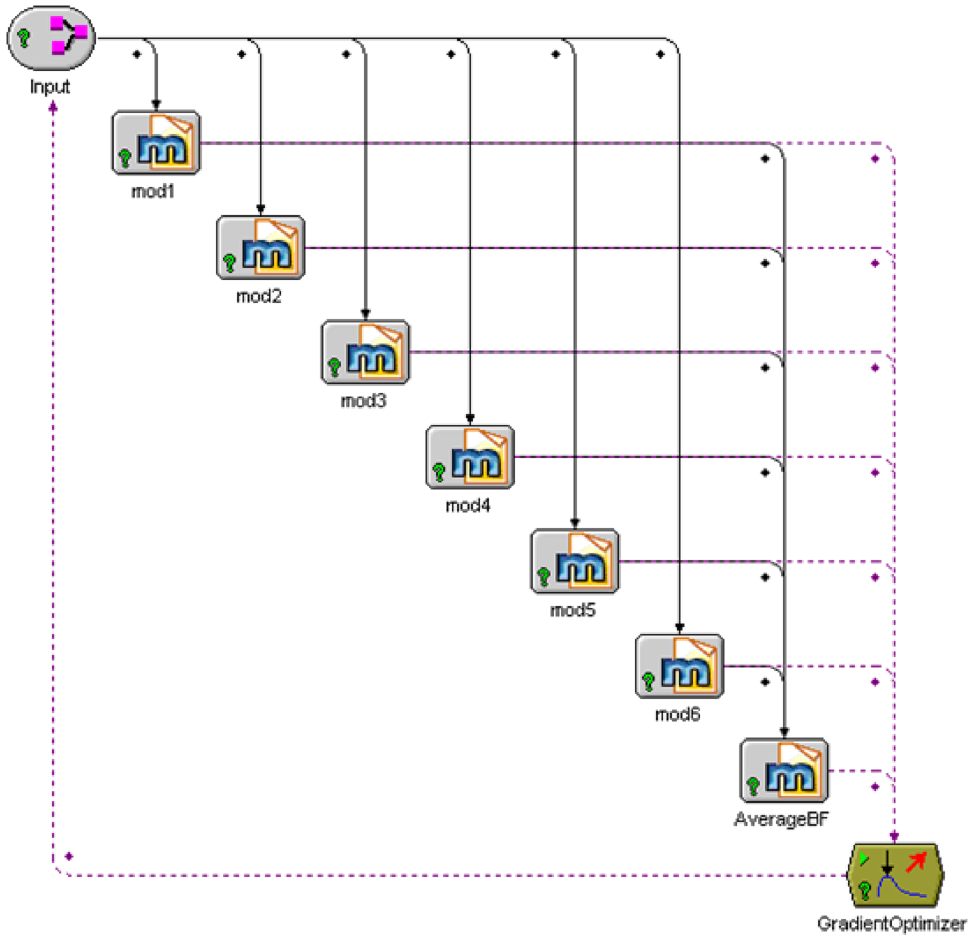



**Figure 4.15: Model Center Optimization Model**

**Table 4.7: Adequacy results**

| Mode | r | Adequacy |
|---|---|---|
| SY | 0.764 | 0.1338 |
| LB | 0.847 | 0.0828 |
| GI | 0.288 | 0.5528 |
| fy | 0.672 | 0.1962 |
| FI | 0.922 | 0.0406 |

The results shown in Table 4.5 for frames were then input in MAESTRO as the base frame dimensions. Dimensions for the king frames were doubled from the general frames and then input into MAESTRO. Once the hull was been modeled, a uniform pressure of 256, psi which is equal to a pressure at 575 feet was applied to the plates. In addition, point loads are added to each node on both ends to model the hull end caps.

Once the loads were applied a course mesh FEA is run using the MAESTRO COM Solver, which outputs the stress results. Figure 4.17 shows the Von Mises Stress which is the stress combination at a given point that will cause failure, however, it is not the limiting mode of failure in this submarine. Although the stresses appear in red, they are still approximately one-third of the yield stress. Frame instability and lobar buckling were only calculated manually and remained the critical limit states.

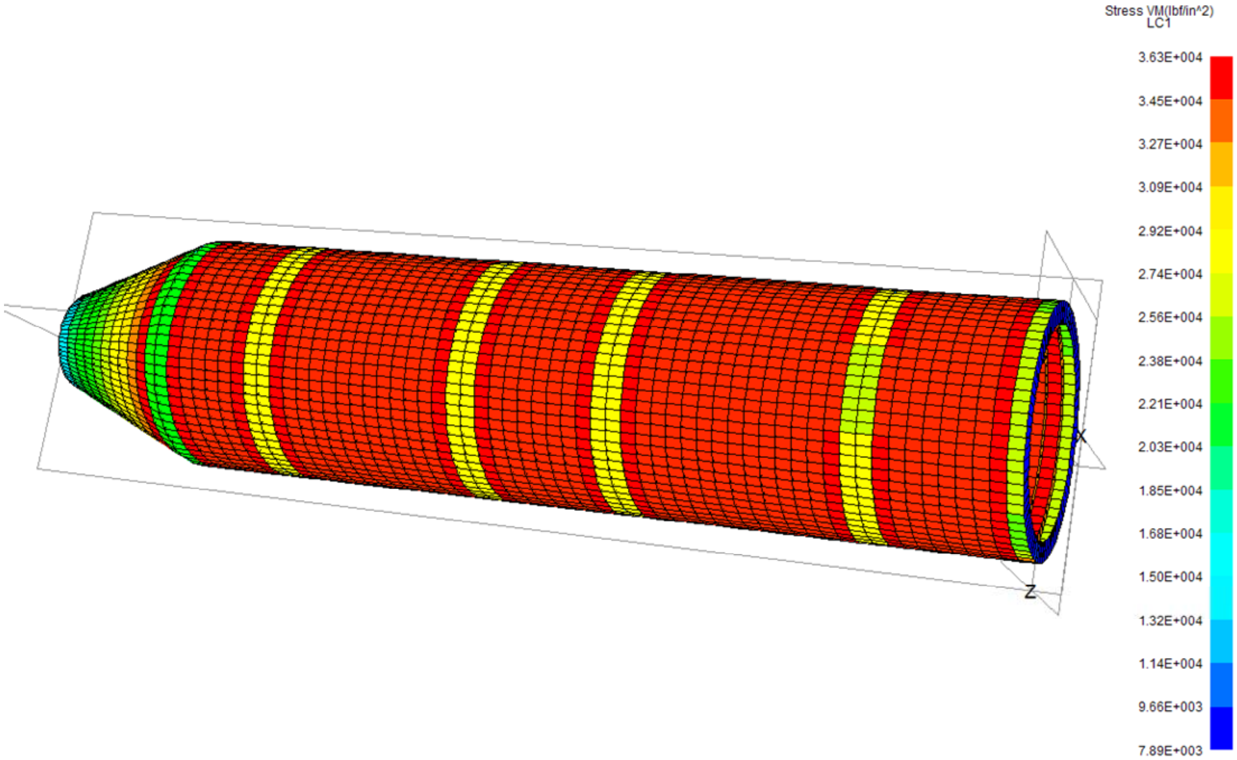



**Figure 4.17: Von Mises Stress output by MAESTRO**

Figure 4.18 shows the axial stress in the X-direction which is positive to the right in this model.

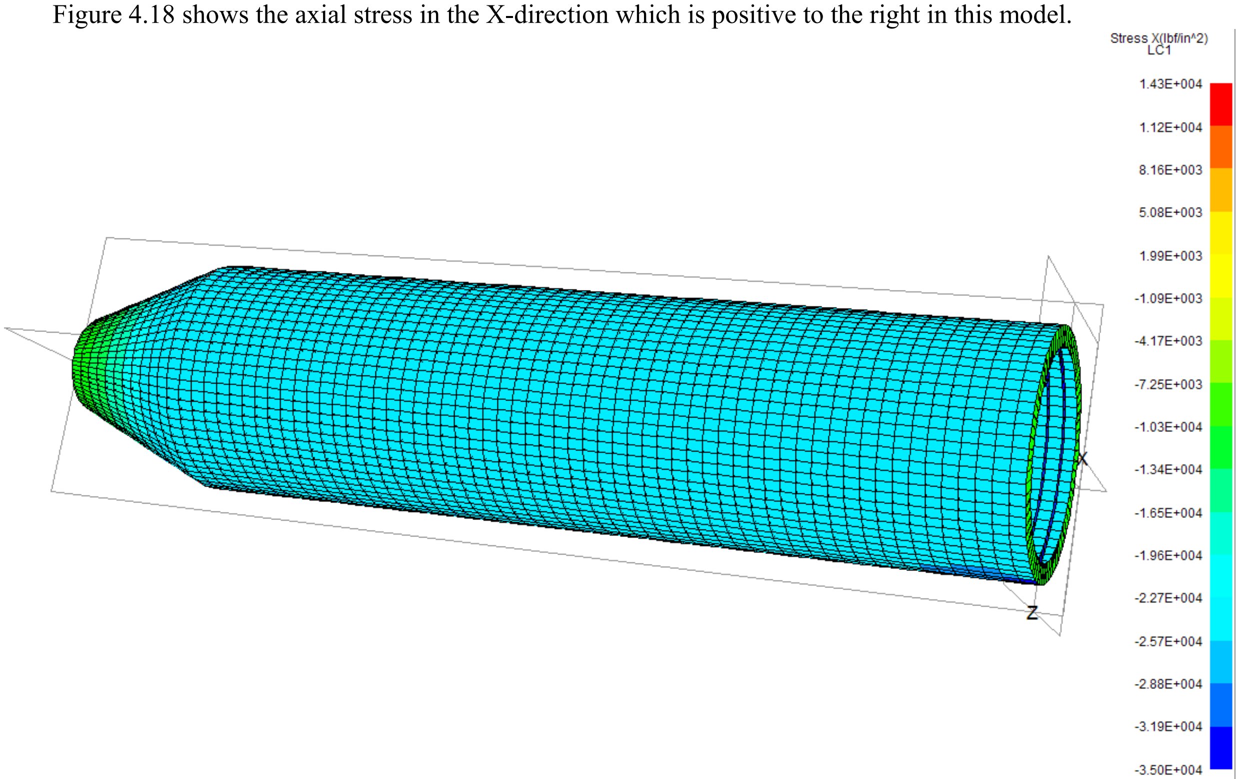



**Figure 4.18: X-axial stress out by MAESTRO**

Figure 4.19 shows the "Panel Collapse Membrane Yield", or PCMY, as calculated by MAESTRO. PCMY is when in-plane loads on a panel of plating cause yielding through the thickness of the plating. The minimum value for PCMY is 0.0. The one inch plating used in this model gives a minimum PCMY value of 0.33 along most of the hull.

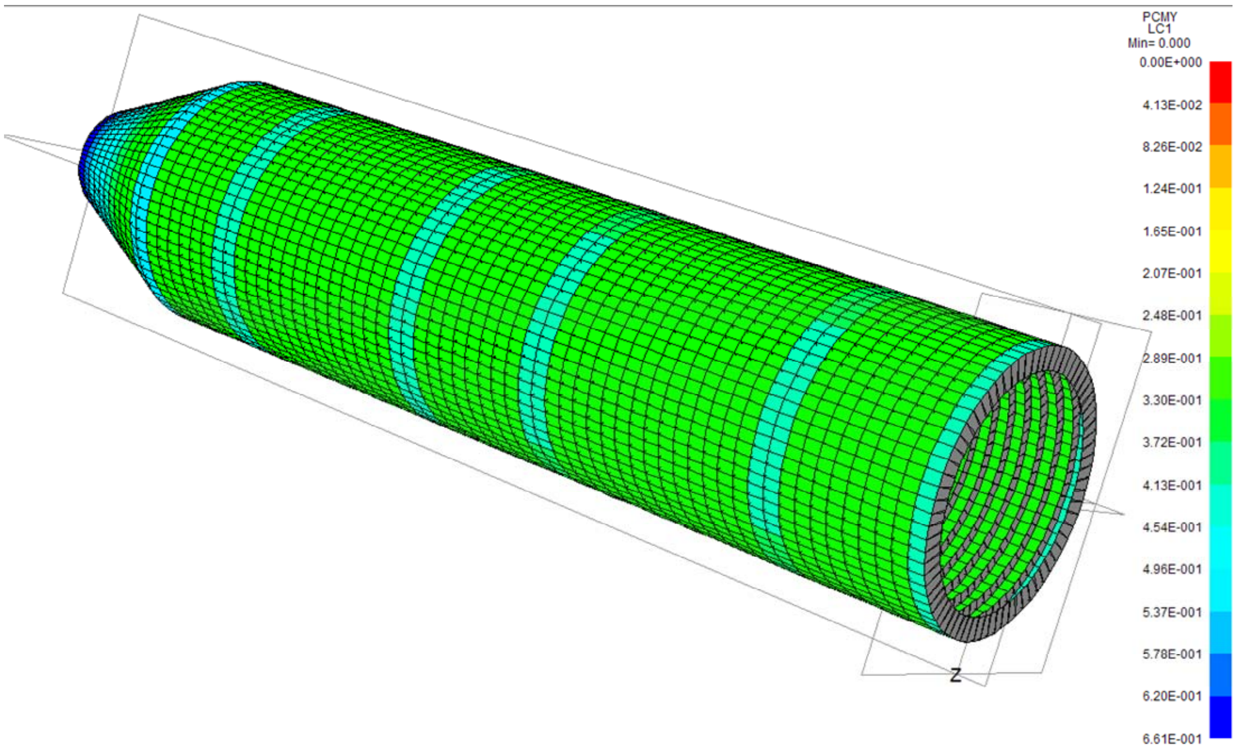



**Figure 4.19: Panel Collapse Membrane Yield computed by MAESTRO.**

## 4.4 Power and Propulsion

The SSBMD propulsion system consists of two CAT 3512 V12 diesel engines for use during snorkel, two 500KW PEM fuel cells used during submerged operations, two methanol reformers, and lead-acid batteries. The PEM fuel cells use hydrogen from the methanol reformers, and pure liquid oxygen, stored in cryogenic tanks inside the pressure hull. SSBMD has an Integrated Power System (IPS) to distribute power throughout the ship. During snorkel operations the CAT diesel engines power the motor through the IPS, while in submerged operation fuel cells and batteries power the motor through the IPS.

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 produces by the MOGO. After endurance calculations were determined to be consistent with the MOGO, a propeller optimization was run. The propeller was initially optimized based on AIP, but adjusted to ensure no cavitation at other speed conditions. Adjustment was made by changing the pitch to diameter ratio. Propeller 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.

### 4.4.1 Resistance and Effective Horsepower

Submerged bare hull resistance calculations performed were based on empirical formulations of Gilmer and Johnson method with additional modifications for waved induced drag using Captain Jackson's wave induced resistance curves. Figure 4.20 shows the VT method. The initial values used in this method correlate closely with those from 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 4.21) The MIT method includes the sail directly and other appendages using a percentage. Figure 4.22 shows the submerged bare hull resistance curves. Figure 4.23 shows a comparison of the VT and MIT methods for calculating EHP. There is good agreement between the methods. Figure 4.24 shows the SSBMD EHP curve.

## Resistance and Power

$iii := 22$

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: $formfac := 1 + .5\cdot\frac{B}{LOA} + 3\cdot\left(\frac{B}{LOA}\right)^{\left(7-n_f-\frac{n_a}{2}\right)}$ $formfac = 1.063$

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

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

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 4.20: Resistance Calculations**

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

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

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

Appendage drag (including sail) calculation:

Surface area of the sail: $A_s := 1222\cdot ft^2$ $C_{Ds} := .009$ $A_s\cdot C_{Ds} = 10.998\,ft^2$

For the remaining appendages, use the expression for $A_{other}$*$C_{dother}$ = $App := \frac{LOA\cdot D}{1000}$ $App = 8.358\,ft^2$

$$EHPMIT_i := 0.5\cdot\rho_{SW}\cdot(V_i)^3\cdot\left[S\cdot\left(C_{F_i}\cdot C_{ff} + C_A\right) + \left[(A_s\cdot C_{Ds}) + App\right]\right] \qquad EHPMIT_1 = 79.339\cdot hp$$

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

**Figure 4.21: MIT Method Resistance Calculations**

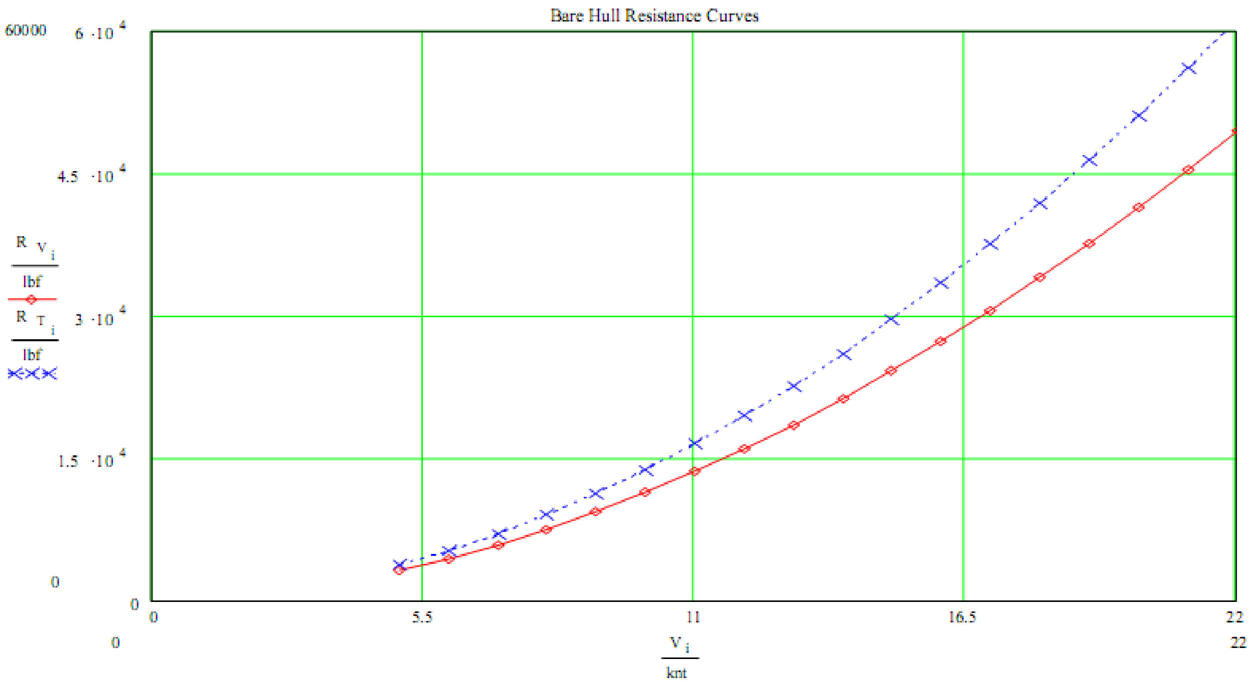



**Figure 4.22: Submerged Bare Hull Resistance vs. Speed**

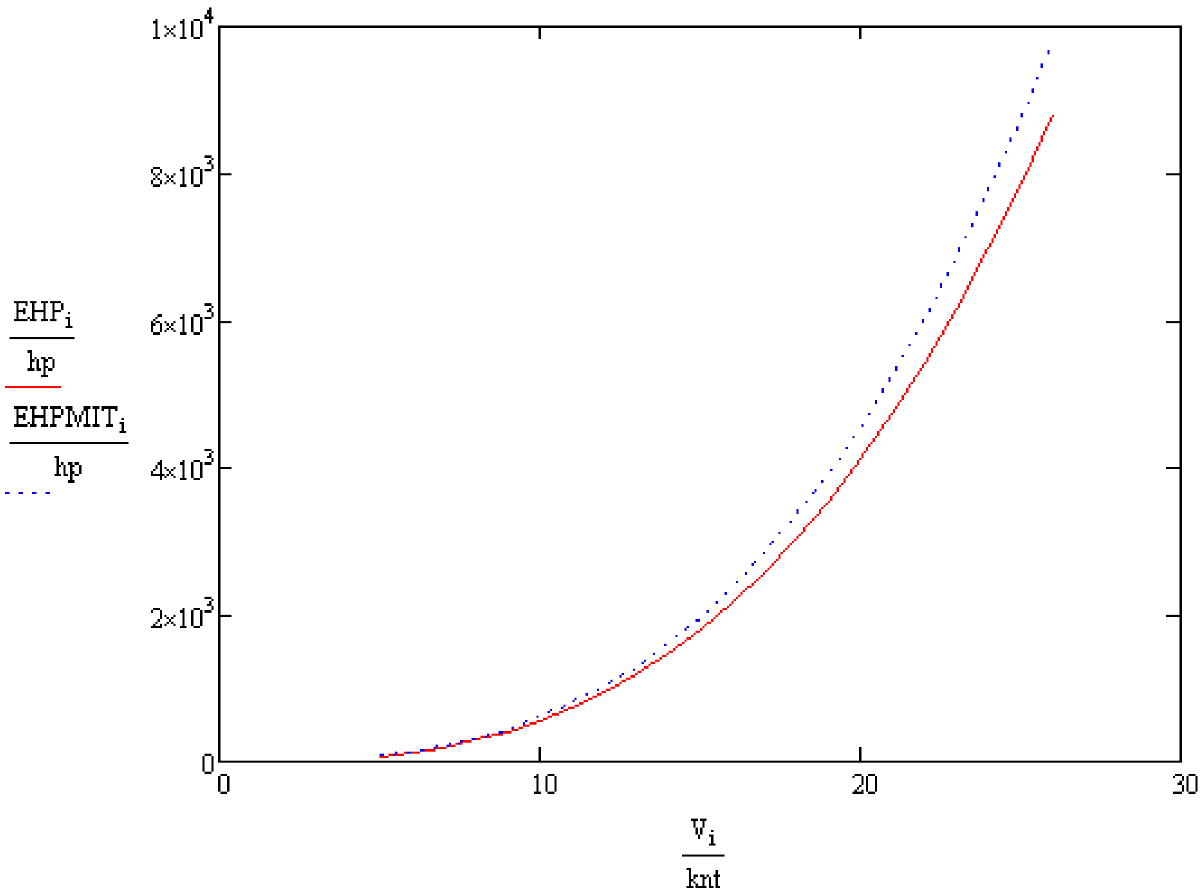



**Figure 4.23: Comparison of VT and MIT Methods**

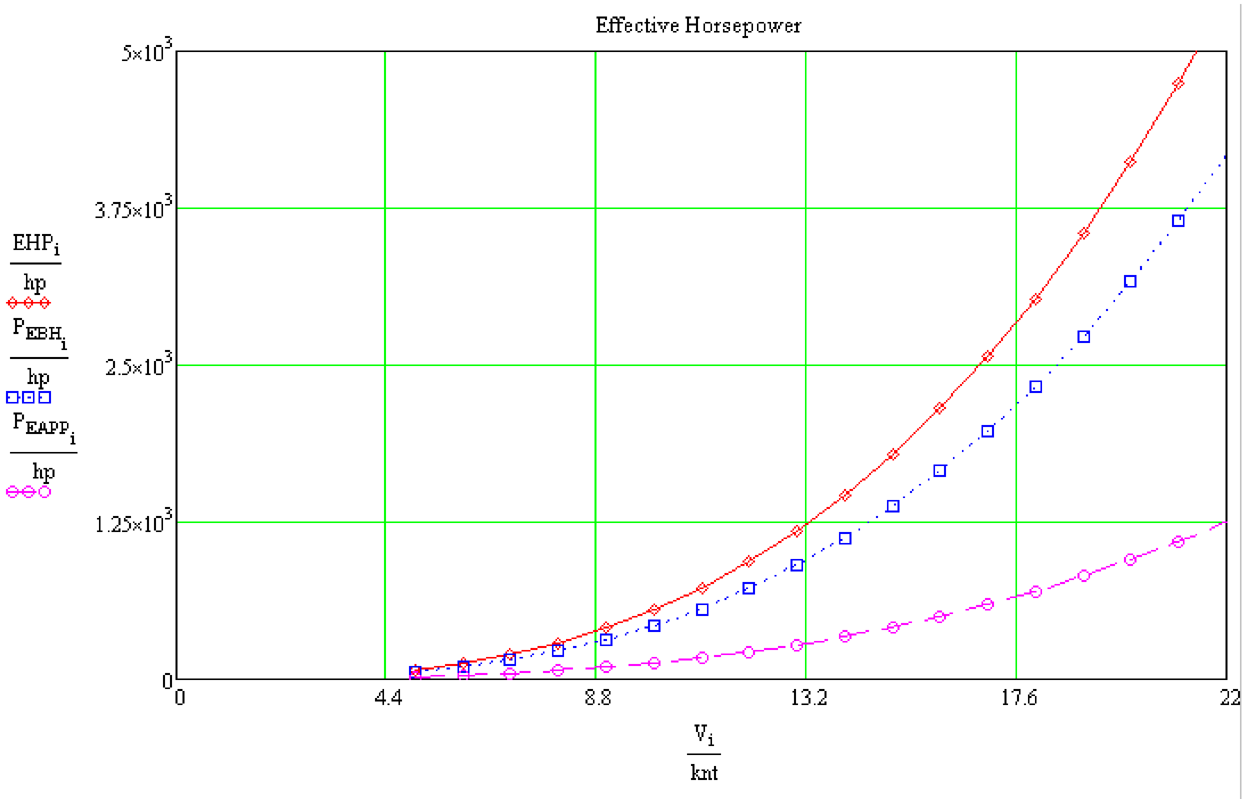



**Figure 4.24: Submerged EHP vs. Speed**

### 4.4.2 Propulsion

Additional calculations provided values for the wake fraction, thrust deduction factor and thrust. Figure 4.25 shows the calculations for these values. These values were necessary for optimization of the propeller.

Optimization of the propeller is performed using the Michigan Propeller Optimization Program (POP). 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. Re-optimization took place by adjusting the pitch to diameter ratio. Table 4.8 below shows the input values for the propeller analysis.

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 4.26; 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% Burrrill 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 the P/D ratio.

The iteration process is repeated until all CDD efficiencies are satisfied and the propeller does not cavitate during snorkel and sprint speeds. Figure 4.27 and Figure 4.28 show the propeller curves for AIP endurance and AIP sprint respectively. Figure 4.29 shows the propeller curves for snorkel endurance.

The propeller characteristics after optimization are summarized in Table 4.9 below. The propeller is 7-bladed with a diameter of 5.25 m.

$$C_{ws} := \frac{S}{\pi \cdot LOA \cdot D} \quad C_{ws} = 0.819$$

$$w := 1 - .371 - 1.7151 \cdot \frac{\frac{D_P}{D}}{\sqrt{C_{ws} \cdot \frac{LOA}{D}}} \quad w = 0.272$$ wake fraction $$w := if(w < 0.1, 0.1, w) \quad w = 0.272$$

$$t := 1 - .632 - 1.3766 \cdot \frac{\frac{D_P}{D}}{\sqrt{C_{ws} \cdot \frac{LOA}{D}}} \quad t = 0.081$$

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

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

$$\eta_H := \frac{1 - t}{1 - w} \quad \eta_H = 1.168$$ hull efficiency $$THP := \frac{EHP}{\eta_H}$$

**Figure 4.25: Calculation of Wake Fraction, Thrust Deduction Factor and Thrust**

**Table 4.8: Input Values for Propeller Optimization**

| Description | Value |
|---|---|
| Thrust AIP endurance @ 5 knt | 19.60 kN |
| Thrust AIP Sprint @ 22 knt | 322.9 kN |
| Thrust Snorkel (submerged) @ 12 knt | 102.4 kN |
| Propeller Diameter (Dp) (optimized) | 5.25 m |
| Wake fraction (based on Prop Dia) | 0.272 |
| Depth of shaft centerline (SSBMD submerged) | 30 m |
| Depth of shaft center line (SSBMDsurfaced) | 2.5 m |
| Number of blades | 7 |
| Burrill Percent of Back Cavitation | 5% |
| Weight fuel AIP | 100 lton |
| Weight fuel Diesel | 167.74 lton |

182 PRINCIPLES OF NAVAL ARCHITECTURE

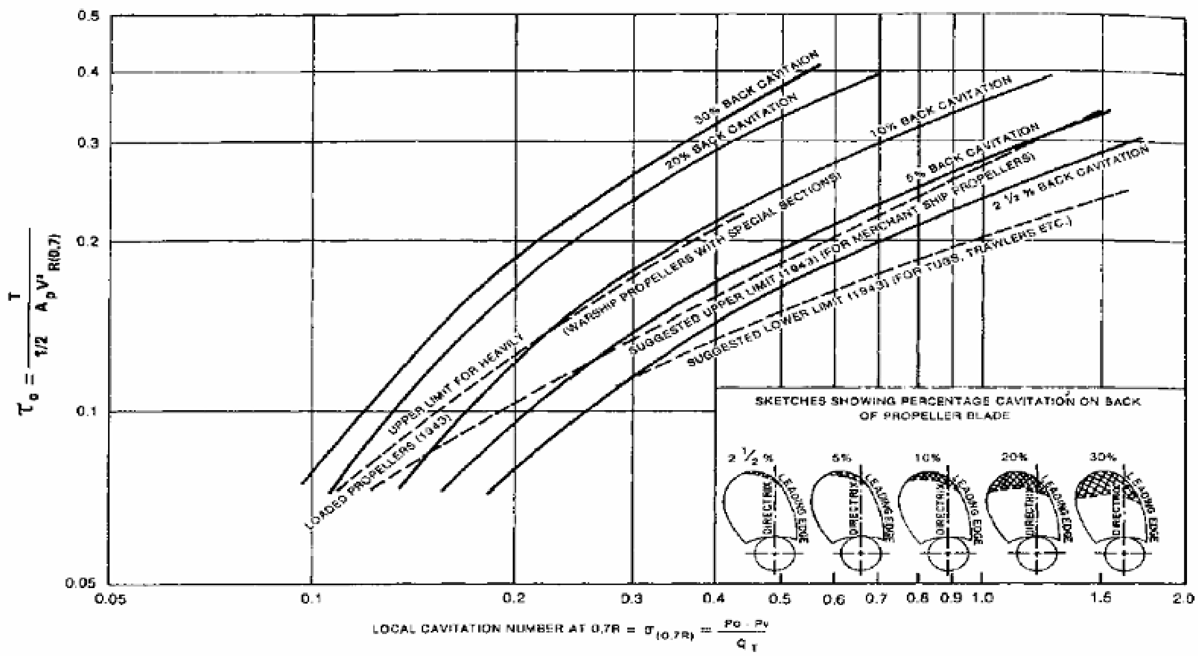



Fig. 45 Simple cavitation diagram (Burrill, et al, 1943, 1962-63)

**Figure 4.26: Burrill's Simple Cavitation Diagram [Principles of Naval Architecture]**

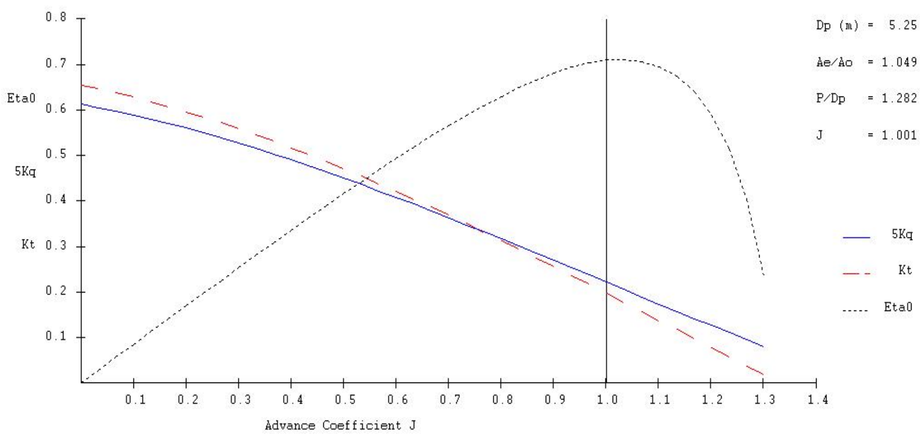



**Figure 4.27: Propeller Curve for AIP Endurance (5 knt)**

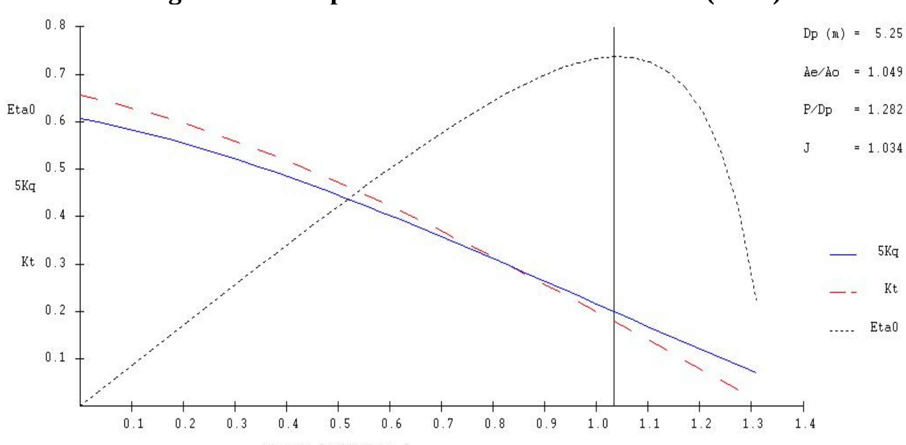



**Figure 4.28: Propeller Curve for AIP Sprint (22 knt)**

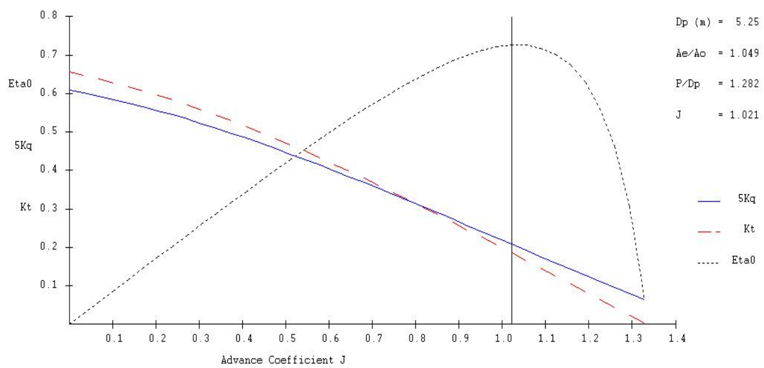



**Figure 4.29: Propeller Curve for Snorkel Endurance (12 knt)**

**Table 4.9: Summary of Optimized Propeller Characteristics**

| Description | Optimization Result |
|---|---|
| P/D | 1.282 |
| Pitch(P) | 6.73 m |
| EAR | 1.0485 |
| # Blades | 7 |
| $D_P$ | 5.25 m |
| Wake Fraction | 0.272 |

### 4.4.3 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 4.10 summarizes the input values.

**Table 4.10: Summary of Input Values for Speed and Endurance Calculations**

| Condition | V (knot) | SFC ($lb_f$/ (hp*hr)) | Weight Fuel (lton) | Battery Capacity (kW*hr) | PMF | Eta Electric | KW24Avg (kW) |
|---|---|---|---|---|---|---|---|
| AIP Endurance | 5 | 0.674 | 100 | 5000 | 1.1 | 0.93 | 295.27 |
| AIP Sprint | 22 | n/a (battery) | n/a (battery) | 5000 | 1.25 | 0.93 | 295.27 |
| Snorkel | 12 | 0.355 | 167.74 | 5000 | - | 0.93 | 295.27 |

The Shaft Horsepower (SHP) and Brake Horsepower (BHP) are calculated for each condition to determine the endurance. Figure 4.30 shows the AIP endurance and sprint calculations. It was necessary to determine a submerged SHP for these conditions.

\The total SHP for the snorkel condition is the sum of the submerged SHP and the wave-induced SHP. To obtain an accurate wave induce 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 31.

**Calculate AIP Endurance:**

$$P_{aipavg} := \frac{KW_{24AVG}}{\eta_{elec}} + BHP_{aipreq} \qquad P_{aipavg} = 393.181 \cdot kW \qquad E_{faip} := Wfaip \cdot \frac{1.}{SFC_{aip}} \qquad E_{faip} = 2.478 \times 10^{5} \cdot kW \cdot hr$$

$$E_{aip} := \frac{E_{faip}}{\left(f_1 \cdot 1.05 \cdot P_{aipavg}\right)} \qquad E_{aip} = 24.051 \cdot days$$

Yellow Values must be within CDD Requirements

**Calculate BHPreq:**

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

$V_{18} = 22 \cdot knt$ $SHP_{sprint} = 4471 \cdot kW$ $BHP_{req} = 6010 \cdot kW$ $P_{IPRP} = 5642 \cdot kW$

**Calculate AIP Sprint:**

$E_{sprint} := \frac{E_{battery}}{BHP_{req}}$ $E_{sprint} = 0.832 \cdot hr$

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

**Figure 4.30: AIP Endurance and Sprint Calculations**

**Calculate Submerged SHPsnrk:**

$DHP_{snrk} := \frac{THP_s}{\eta_{Bsnrk}}$ $SHP_{snrkv} := \frac{DHP_{snrk}}{\eta_S}$

**Calculate Wave Induced Drag SHPw:**

$SHP_{snrkv} = 801.966 kW$

Froude # for Cdw Coef Calc:

$Fn := \frac{V_{esnork}}{(g \cdot LOA)^{.5}}$ $Fn = 0.221$

$C_{DW} := 3561.3Fn^6 - 8812.6Fn^5 + 8148.4Fn^4 - 3454.3Fn^3 + 654.09Fn^2 - 40.235Fn + .272$

$C_{DW} = 1.249$

$C_W := \frac{C_{DW}}{4 \cdot \left[\left(\frac{LOA}{D}\right) - 1.3606\right]\left(\frac{LOA}{D}\right)^2}$ $C_W = 6.888 \times 10^{-4}$

Wave Induced:

$SHP_W := C_W \cdot S \cdot \rho_{SW} \cdot V_{esnork}^3$ $SHP_W = 333.568 kW$

SHP Snorkel:

$SHP_{snrk} := SHP_{snrkv} + SHP_W$ $SHP_{snrk} = 1136 kW$

**Endurance Snorkel Range:**

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

$FR_{AVGsnk} := 1.05 FR_{SPsnl}$ $FR_{AVGsnk} = 0.52 \frac{lbf}{kW \cdot hr}$

$P_{snkAVG} := \frac{SHP_{snrk} + KW_{24AVG}}{\eta_{elec}}$ $P_{snkAVG} = 2063 hp$

$E_{snork} := \frac{(W_{fsnk} V_{esnork} TPA)}{P_{snkAVG} FR_{AVGsnk}}$ $E_{snork} = 5356 nm$

**Figure 4.31: Calculations for Snorkel**

Table 4.11 is a summary of the speed and durance calculated values. The range for each condition meets the CDD requirements.

**Endurance Calculated Values**

| Condition | Thrust (kN) | Overall SHP (kW) | RPM | Eta Prop Efficiency THP/DHP | Eta PC (Propulsion Coefficient) | Range | CDD Requirement |
|---|---|---|---|---|---|---|---|
| AIP Endurance | 4406 (19.6) | 86.2 (64.3) | 21.4 | 0.747 | 0.872 | 24.05 days | 24 days |
| AIP Sprint | 72591 (322.9) | 5996 (4471) | 91.1 | 0.775 | 0.904 | 0.832 hr/18 nm | 0.6 hr |
| Snorkel | 23020 (102.4) | 1523 (1136) | 50.3 | 0.747 | 0.872 | 5356 nm | 5180 nm |

### 4.4.4 Propulsor

In concept development, a Wageningen B series was used, but for the final design, because the primary SSBMD mission occurs while under 5 kt AIP propulsion, an accelerating duct was chosen to increase thrust and efficiency under the lightly-loaded, low-speed propulsion condition. A Marin-19A Kort nozzle was chosen and slightly modified to remove the blunted trailing edges (typically added to aid in backing maneuvers –deemed unnecessary for a combat submarine-). The corresponding Ka5-75 series propeller was modified to a seven blade configuration for acoustic considerations. The Ka5-75 blade curves and resulting duct are shown in Figure 32.

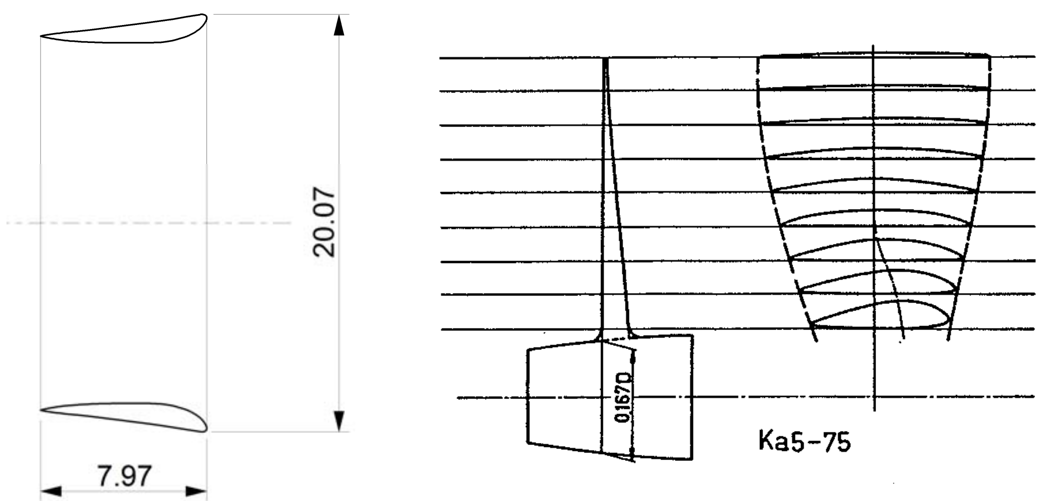



**Figure 4.32: Modified Marin 19A Nozzle and Ka5-75 Propeller Curves**

A five-blade stator was chosen to support the shroud. The propulsor is shown in Figure 33 below.

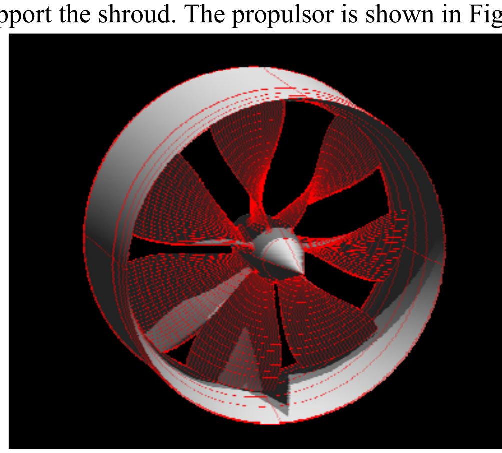


**Figure 4.33: Propulsor**

### 4.4.5 Electric Load Analysis (ELA)

Table 4.12 below is a summary of the Electric Load Analysis (ELA) for SSBMD. AIP, snorkel, and sprint were the electric load conditions analyzed. A partial Machinery Equipment List is shown in Table 4.13 with the full list in Appendix G. 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 4.12 and is greater than power required in all conditions.

**Table 4.12: Electric Load Analysis**

| SWBS | DESCRIPTION | Connected (kW) | AIP (kW) | Snorkel (kW) | Sprint (kW) |
|---|---|---|---|---|---|
| **100** | Deck | 64 | 0 | 0 | 0 |
| **200** | **Propulsion** | 7.6 | 1000 | 1752 | 9875 |
| 220 | Battery | 500 | 1 | 1 | 1 |
| 235 | Electric Propulsion Drive | 6050 | 1000 | 1086 | 6050 |
| 250/260 | Support | 31.4 | 31.4 | 31.4 | 31.4 |
| **300** | **Electric** | 20.7 | 20.7 | 20.7 | 20.7 |
| 310 | Power Generation | 15.7 | 15.7 | 15.7 | 15.7 |
| 330 | Switch Board | 5 | 5 | 5 | 5 |
| 400 | **Combat Systems** | 291 | 291 | 291 | 291 |
| 500 | Combat Systems | 291 | 291 | 291 | 291 |
| 500 | Aux Machinery | 27.5 | 27.5 | 27.5 | 27.5 |
| 510 | HVAC | 36.5 | 36.5 | 36.5 | 36.5 |
| 520 | Seawater Systems | 11 | 11 | 11 | 11 |
| 530 | Fresh Water Systems | 25 | 25 | 25 | 25 |
| 550 | Air & Gas | 50 | 50 | 50 | 50 |
| 560 | Ship Control | 15 | 15 | 15 | 15 |
| 593 | Environmental | 12 | 12 | 12 | 12 |
| **500** | **Overall** | 468 | 468 | 468 | 468 |
| **700** | **Payload** | 291 | 291 | 291 | 291 |
| | Max Functional Load | 546 | 546 | 546 | 546 |
| | MFL with Margins | 602.5 | 602.5 | 602.5 | 602.5 |
| | 24 hr Average (with margins) | 295 | 295 | 295 | 295 |
| **Number** | **Generator** | **Rating (kW)** | **AIP** | **Snorkel** | **Sprint** |
| 2 | CAT 3512 Genset | 1752 | 0 | 1752 | 0 |
| 2 | 500 kW PEM Fuel Cell | 500 | 1000 | 0 | 1000 |
| 1 | Zebra Lead Acid Battery Bank | 9875 | 0 | 0 | 9875 |

## 4.5 Mechanical and Electrical Systems

The main components of the mechanical and electrical systems are shown in the MEL. Table 4.13. Appendix E is a complete MEL. This section describes the location, quantity, size, weight, and power requirements for each component. Whenever possible commericial off the shelf (COTS) systems are used to reduce the cost and make repairs less costly. Primary systems for the SSBMD include hydraulics, compressed air, salt water, ventilation and air, and electrical power distribution. The arrangements of these systems are found in Section 4.8.2.

**Table 4.13: Machinery Equipment List**

| ITEM | QTY | DESCRIPTION | LOCATION | SWBS |
|---|---|---|---|---|
| | | **Propulsion and Power** | | |
| 1 | 2 | PEM Fuel Cell | Fuel cell room | 235 |
| 2 | 2 | Caterpillar 3512 V12 Diesel Generator (AC) | Main Prop Diesel room | 230 |
| 3 | 1 | Machinery Control/Switchboard | Engineering Control Center | 310 |
| 4 | 1 | Battery Bank | Aux 3 | 220 |
| 5 | 1 | Main DC Switchboard (557v) | Engineering Control Center | 320 |
| 6 | 1 | Emergency Switchboard | Reformer room | 320 |
| 7 | 6 | Cryogenic Liquid Oxygen Tank | LOX tank rooms | 520 |
| 8 | 2 | AC to DC transformers | Reformer room | 310 |
| 9 | 1 | AC Permanent Magnet Main Motor | Main Motor room | 300 |
| 10 | 1 | LED Lighting Panel | Engineering Control Center | 300 |
| 11 | 2 | Start Air Receiver | Main Prop Diesel room | 250 |
| 12 | 1 | Degaussing | - | 475 |
| | | **Fuel Transfer** | | |
| 13 | 2 | Diesel FO Transfer Pump | Aux 4 | 250 |
| 14 | 2 | Methanol Transfer Pump | Aux 4 | 250 |
| 15 | 1 | Diesel FO Coalescer/Purifier | Aux 4 | 250 |
| 16 | 1 | Methanol Coalescer/Purifier | Aux 4 | 250 |
| | | **Lube/Dirty Oil Purifcation** | | |
| 17 | 2 | LO Purifier | Main Prop Diesel room | 250 |
| 18 | 1 | Oily Water Separator | Aux 4 | 250 |
| | | **Control Surfaces** | | |
| 19 | 1 | X-tail Hydraulics | aft- external to pressure hull | 560 |
| 20 | 1 | Forward Planes | fwd- external to pressure hull | 560 |
| | | **Compressed Air Systems** | | |
| 21 | 2 | High Pressure Air Compressor | Fuel Cell room | 550 |
| 22 | 2 | High Pressure Air Receiver | Fore/Aft Main Ballast Tanks | 550 |
| 23 | 1 | Low Pressure Sevice Air Compressor | Fuel Cell room | 550 |
| | | **Hydraulic Systems** | | |
| 24 | 2 | Hydraulic Pump | Aux 3 | 550 |
| 25 | 2 | Hydraulic Pressure Actuator | Aux 3 | 550 |
| 26 | 1 | Hydraulic Sump | Aux 3 | 550 |
| | | **Potable Water** | | |
| 27 | 1 | Potable Water Pump | Aux 3 | 530 |
| 28 | 1 | Hot Water Pump | Aux 3 | 530 |
| 29 | 1 | Reverse Osmosis Water Purifier | Aux 3 | 530 |

The Integrated Power System (IPS) is used to provide the submarine with ship service power, and propulsion power. Figure 4.34 shows the one-line diagram of the IPS system. When surfaced or snorkeling, power is generated by 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 connected to the SWB. During sprint operation, the main batteries, which are also connected to the SWB provide another 5000 kW of power to the propulsor for 0.6 hr. 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.

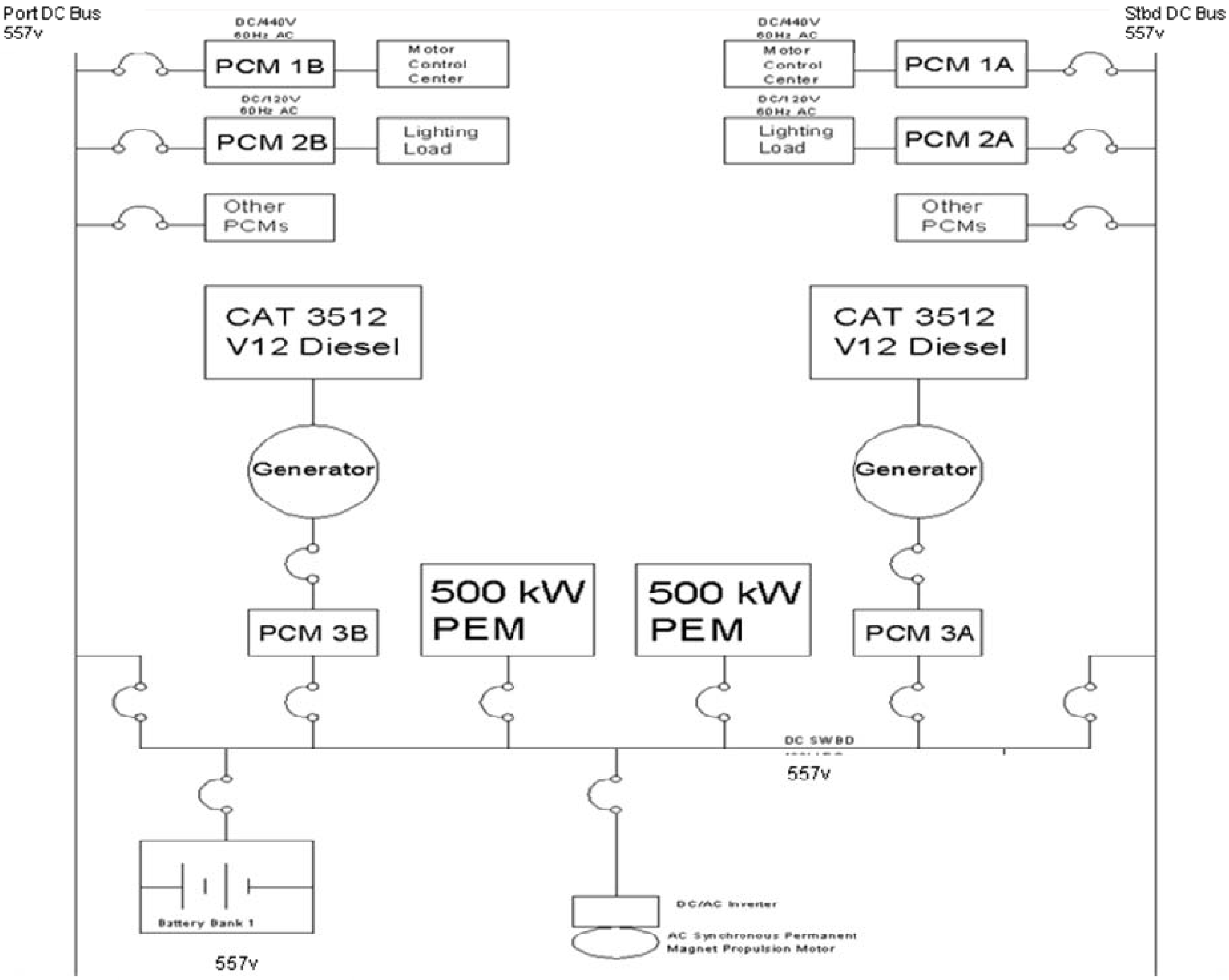



**Figure 4.34: Electric One-Line Diagram**

## 4.6 Manning

The manning estimate starts with developing a hierarchy chart and table to assign personnel to divisions and departments. Next, an estimate from the concept exploration is set as a goal and adjusted as necessary and the results are validated. Submarine manning is broken into five departments and then further broken down into divisions. The first department is Engineering, which breaks down into the divisions: main machinery, abbreviated MM, auxiliary machinery, abbreviated AUX, and electric, abbreviated E. The second department is Combat Systems, which breaks down into: Weapons, abbreviated WEPS, and Sonar Technicians (ST). The third department is Navigations/Operations which breaks down into: Communication, abbreviated COMS, and Navigation, abbreviated as NAV. The fourth department is Supply which is abbreviated as S. The final department is Executive, abbreviated as EXEC, which includes the CO, XO and COB. Table 4.14 shows the rates associated with each department. The abbreviations are MM is machinist mate, EM is electricians mate, ET is electronics technician, STS is sonar tech submarine, and SK is store keeper. Table 4.15 shows the manning breakdown computed for the SSBMD and rationales for those numbers. Table 4.16 shows the accommodations and spacing required for the crew.

**Table 4.14: Associated Rates for each department**

| Department | Division | Rate |
|---|---|---|
| Engineering | AUX | MM |
| Engineering | MM | MM |
| Engineering | E | EM |
| Combat Systems | WEPS | MM |
| Combat Systems | ST | STS |
| Executive | Exec | Any |
| Navigation/Operations | COM | ET |
| Navigation/Operations | NAV | ET |
| Supply | S | SK |

**Table 4.15: SSBMD Manning Breakdown**

| Departments | Division | Officers | CPO | Enlisted | Total Department | Rationale |
|---|---|---|---|---|---|---|
| | CO/XO | 2 | | | **2** | required |
| | Department Heads | 4 | | | **4** | 1 officer per department |
| Executive/ Admin | Executive/ Admin | | 1 | 1 | **2** | 1 Chief of Boat, 1 yeoman, 1 personnel man |
| Engineering | Auxiliary | | 1 | 4 | **20** | minimum for workload and expertise, 3x1 enlisted watch standers |
| | Main Machinery | 1 | 1 | 7 | | minimum for workload and expertise, 3x2 enlisted watch standers |
| | Electrical | | 1 | 5 | | minimum for workload and expertise, 3x1 enlisted watch standers |
| Combat Systems | Weapons | 1 | 1 | 5 | **13** | minimum for workload and expertise |
| | Sonar Technician | | 1 | 5 | | minimum for workload and expertise |
| Navigation/ Operations | Communications | | 1 | 4 | **9** | 3x1 enlisted watch standers, CPO, officer required |
| | Navigation/ Control | | 1 | 3 | | CPO navigator, 3x1 enlisted watch standers |
| Supply | Supply | | 2 | 3 | **5** | minimum for workload and expertise |
| | **Total** | **8** | **10** | **37** | **55** | |

**Table 4.16: Spacing requirements for accommodations**

| Item | Accommodation Quantity | Per Space | Number of Spaces | Average Area Each (ft^2) | Total Area (ft^2) |
|---|---|---|---|---|---|
| CO | 1 | 1 | 1 | 81 | 81 |
| XO | 1 | 1 | 1 | 65 | 65 |
| Officer | 4 | 2 | 2 | 45 | 90 |
| Enlisted | 48 | 6 | 8 | 70 | 560 |
| Officer Sanitary | 6 | 6 | 1 | 132 | 132 |
| Enlisted Sanitary | 48 | 16 | 3 | 78 | 234 |
| **Total** | | | 16 | | 1162 |

## 4.7 Space and Arrangements

Rhino is used to generate and validate subdivision and arrangements in 3D space. A simplified profile view of SSBMD arrangements is shown in Figure 4.35.

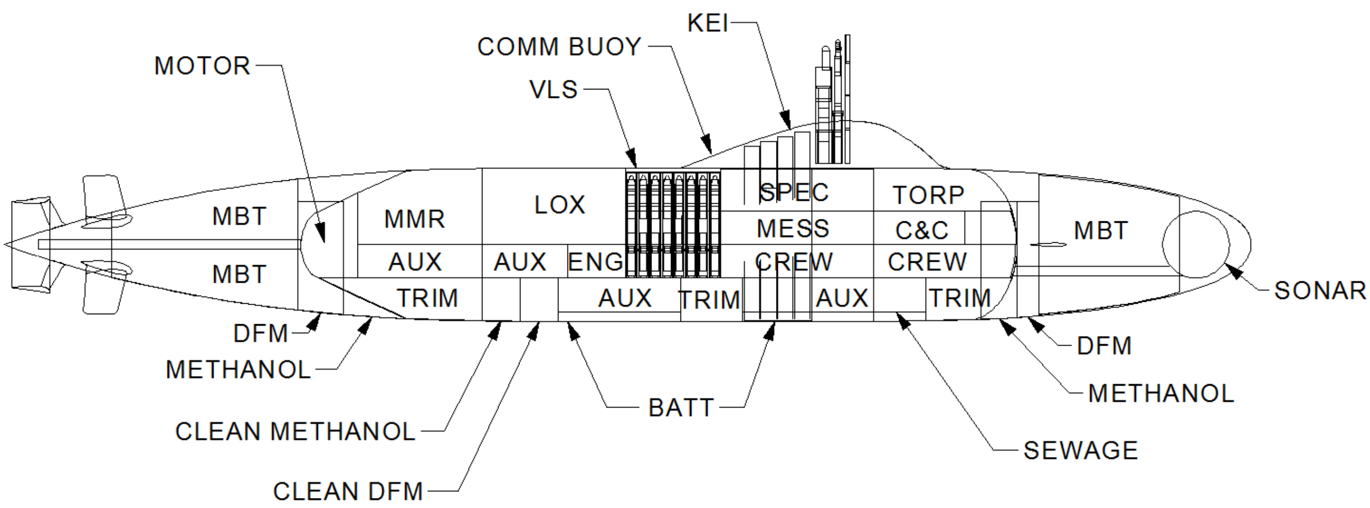



**Figure 4.35: Profile View of Arrangements**

**Table 4.17: Initial Required vs. Final Concept Tankage Volume**

| Tankage | Required (ft^3) | Final Concept (ft^3) |
|---|---|---|
| Main Ballast Tanks | 18491 | 22644 |
| Trim Tanks | 11972 | 8894 |
| Compensated Diesel | 6106 | 6447 |
| Compensated Methanol | 3492 | 3972 |
| Cryogenic Oxygen | 5377 | 5394 |
| Fresh Water | 303 | 366 |
| Clean Diesel | 1312 | 1483 |
| Clean Methanol | 2939 | 1467 |
| Sewage | 110 | 118 |
| Lube Oil | 42 | 48 |

### 4.7.1 Volume

Initial volume requirements are determined in the ship synthesis model. Arrangeable area estimates and requirements are updated in the concept development stage. Arrangeable areas are discussed in Sections 4.82 through 4.8.4. Table 4.17compares the initial required tankage volumes and the final design tankage volumes. The difference in initial and final methanol tank volumes was caused by an error in methanol density in the ship synthesis model which has been corrected.

The initial longitudinal arrangements of required systems were developed using the submarine cartoon and flounder diagram. The weight and balance and equilibrium polygon were used to help make adjustments on arrangements, and check the feasibility under all the design loading conditions. The initial main ballast tankage volume given from the ship synthesis model was too small to create a feasible equilibrium polygon. The final concept main ballast tankage volume is larger than the initial estimate.

The main machinery rooms, trim tanks, clean fuel tank, batteries, clean ethanol tank, cryogenic oxygen tanks, command and control, VLS, habitability spaces, miscellaneous machinery rooms, stores, and torpedo room are located inside the pressure hull. The main ballast tanks, compensated diesel, compensated methanol, torpedo tubes, sonar dome, UUVs, UAVs, and countermeasures are all located outside of the pressure hull.

### 4.7.2 Main and Auxiliary Machinery Spaces and Machinery Arrangement

The location of the main machinery rooms is shown in Figure 4.36. The equipment in the main machinery rooms is highlighted in gold.

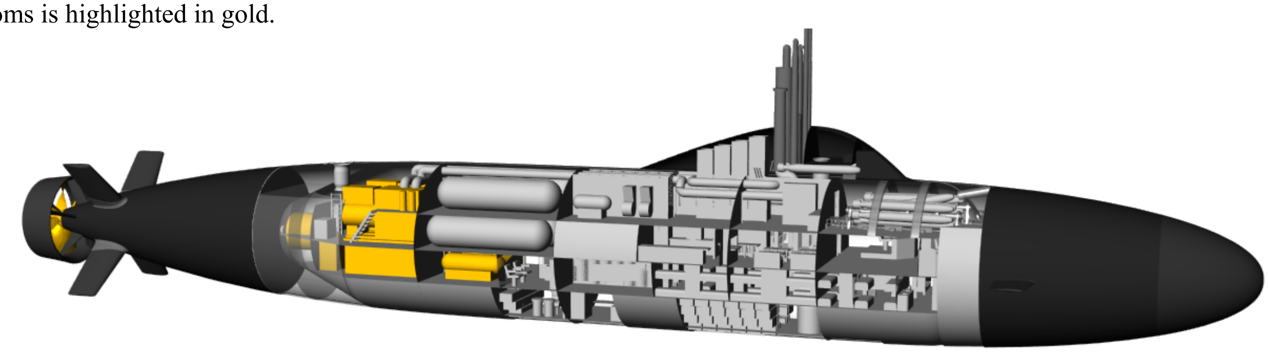


**Figure 4.36: Locations of Main Machinery Rooms**

The volume for the main machinery room was taken from the ship synthesis model and then adjusted by arrangements and balance process. Figure 4.37 shows the layout of the main machinery rooms. The inlet and exhaust are then run from the engines and generators through a gap in the VLS and then up through the sail.

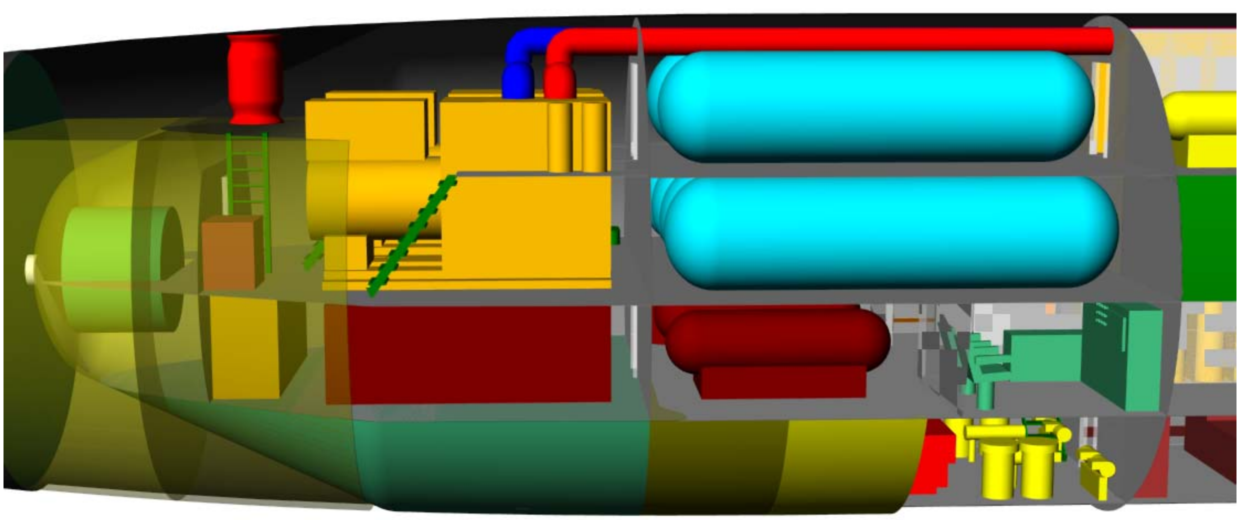


**Figure 4.37: Main Machinery Rooms**

The uppermost deck (deck 1) contains the upper level of the engine room (Figure 4.38), HVAC machinery (Figure 4.39) and reconfigurable space. The second uppermost deck (deck 2) contains the motor room and the lower level of the engine room. The second lowest deck (deck 3) contains the PEM fuel cells, the sea chest, and the methanol reformers. The bottom deck (deck 4) contains the battery banks, the potable water system (Figure 4.40), the sanitary system (Figure 4.41), and the methanol and fuel transfer pumps (Figure 4.42) and filters.

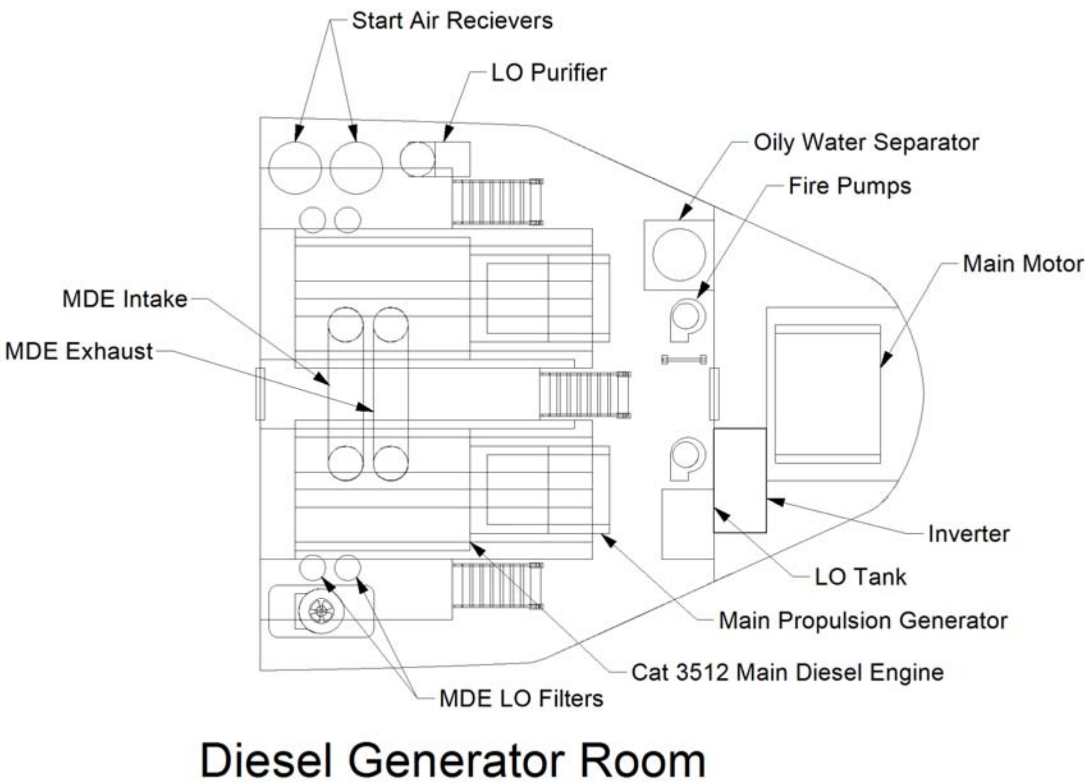



**Figure 4.38: Main Machinery Room**

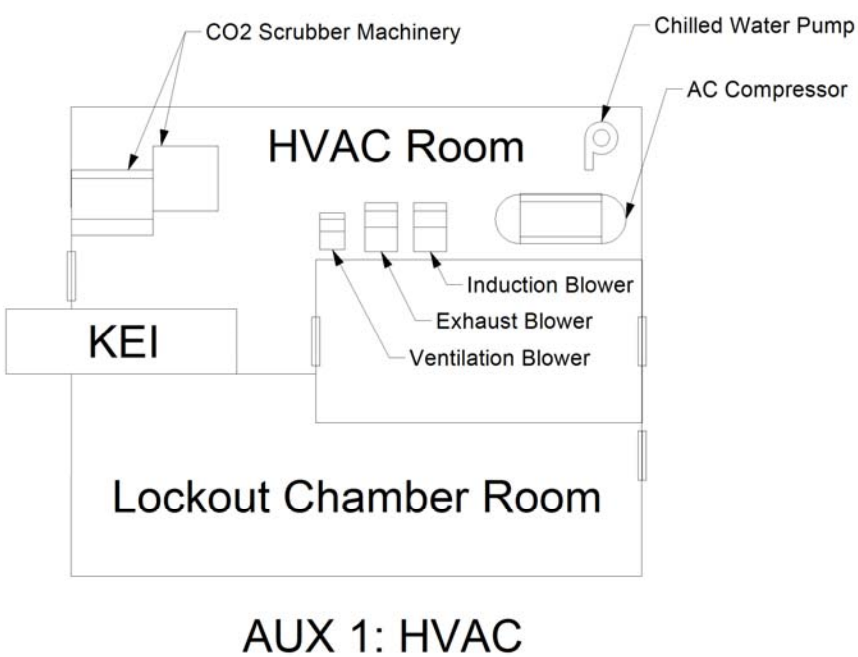



**Figure 4.39: Auxilary HVAC Room**

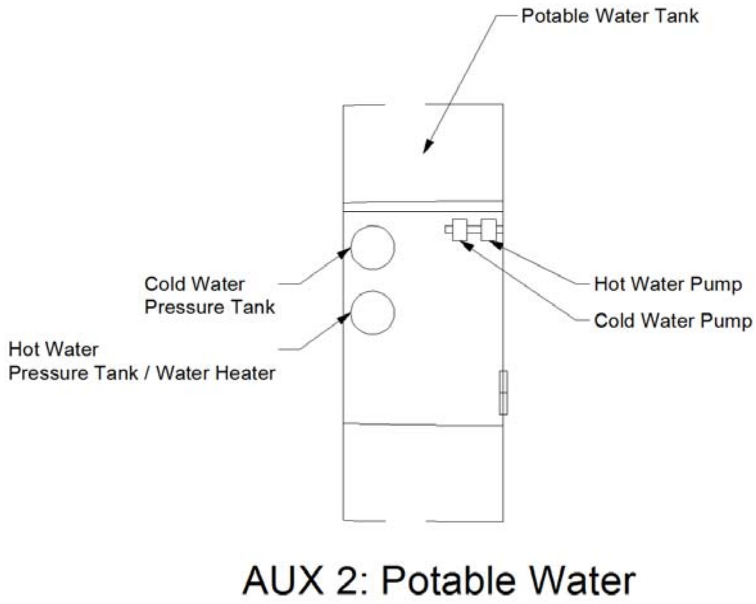



**Figure 4.40: Auxilary Potable Water Room**

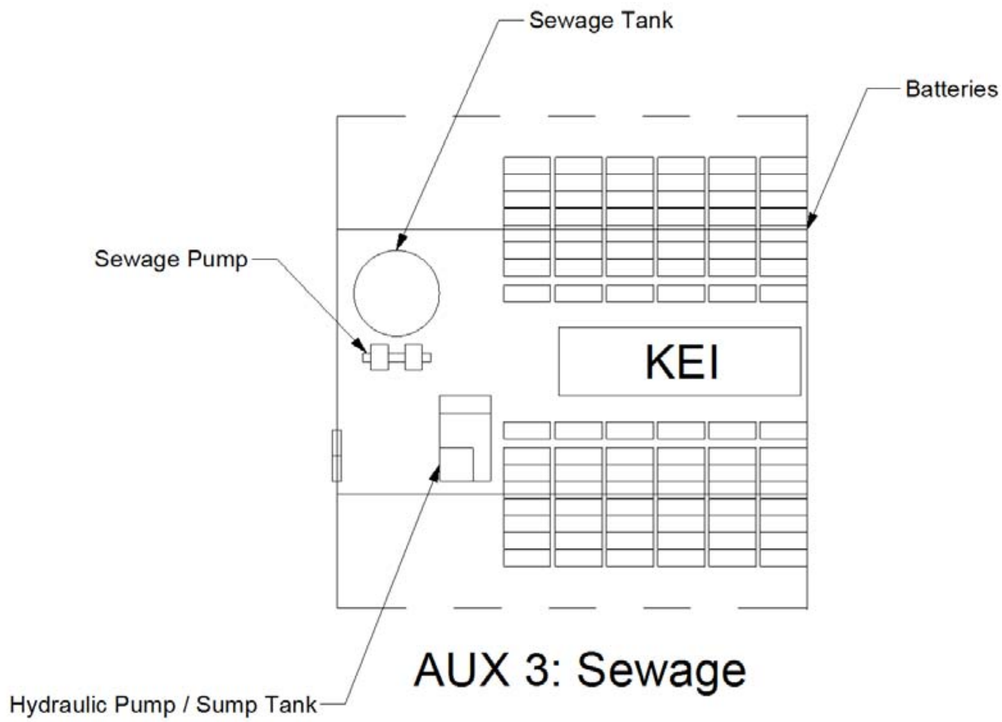



**Figure 4.41: Auxilary Sewage Room**

### 4.7.3 Internal Arrangements

The pressure hull is divided into two inner 7 foot decks and two outer 9 foot decks. The volume is divided to accommodate combat systems, habitability, stores, machinery and tankage. The required volumes of the spaces are determined from the ship synthesis model and the arrangements are obtained from the Rhino model. Figures 4.43 and 4.44 shows a profile view of the internal arrangements.

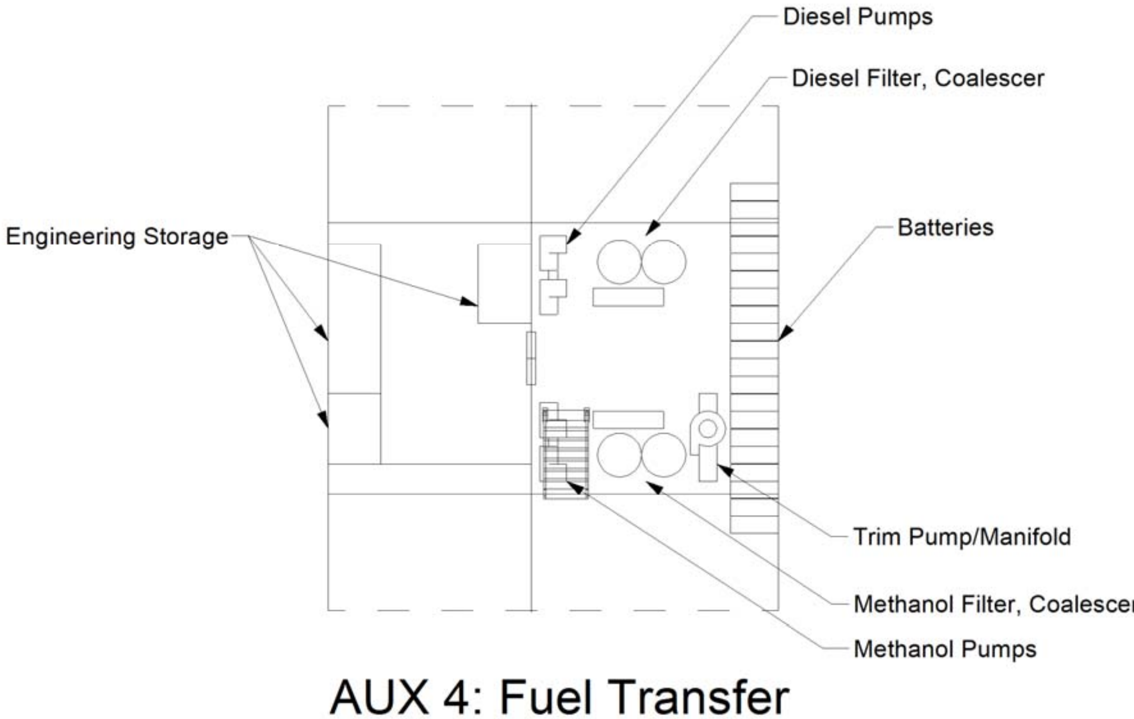



**Figure 4.42: Auxilary Fuel Transfer Room**

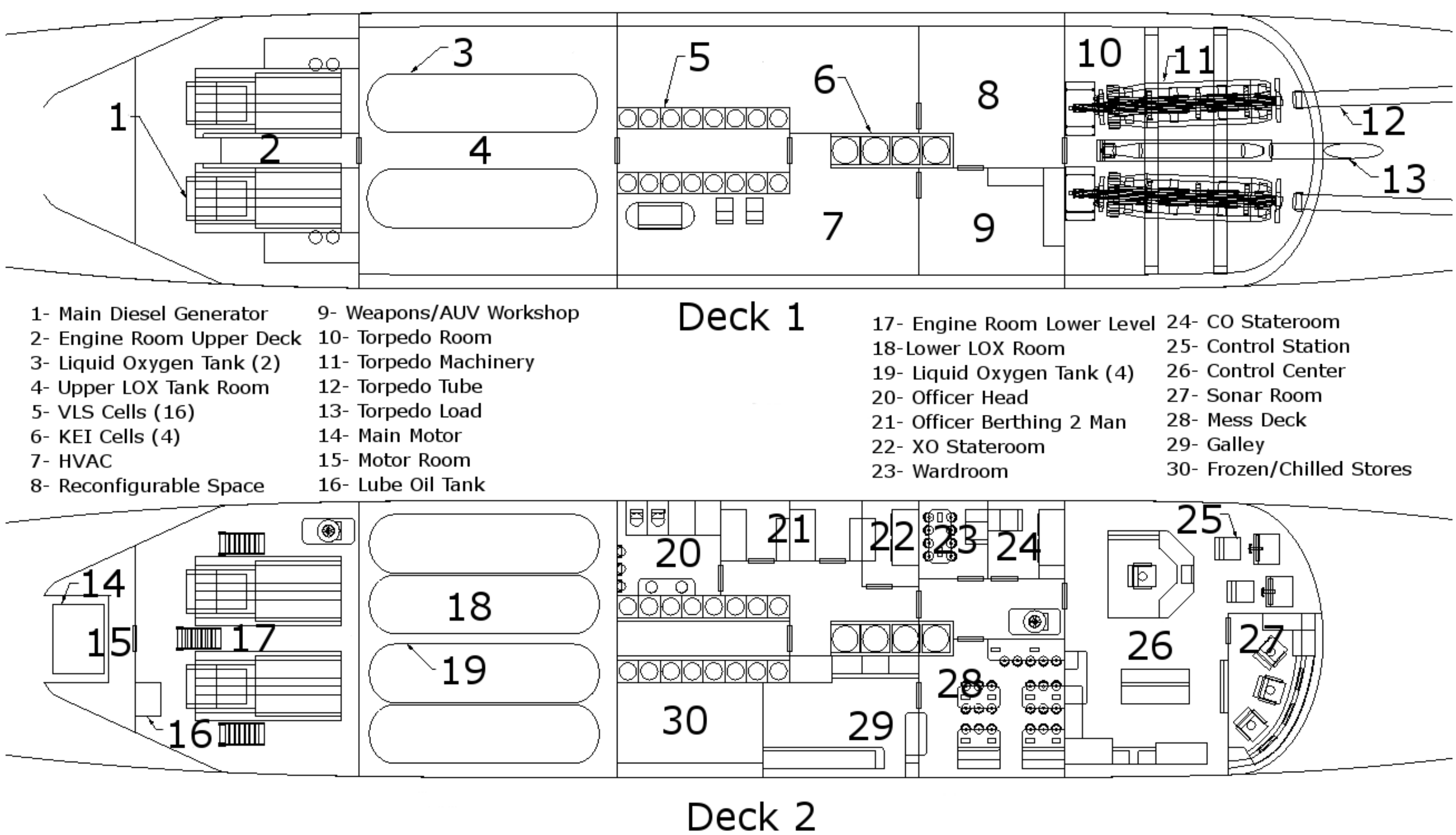



**Figure 4.43: General Arrangements (Decks 1 and 2)**

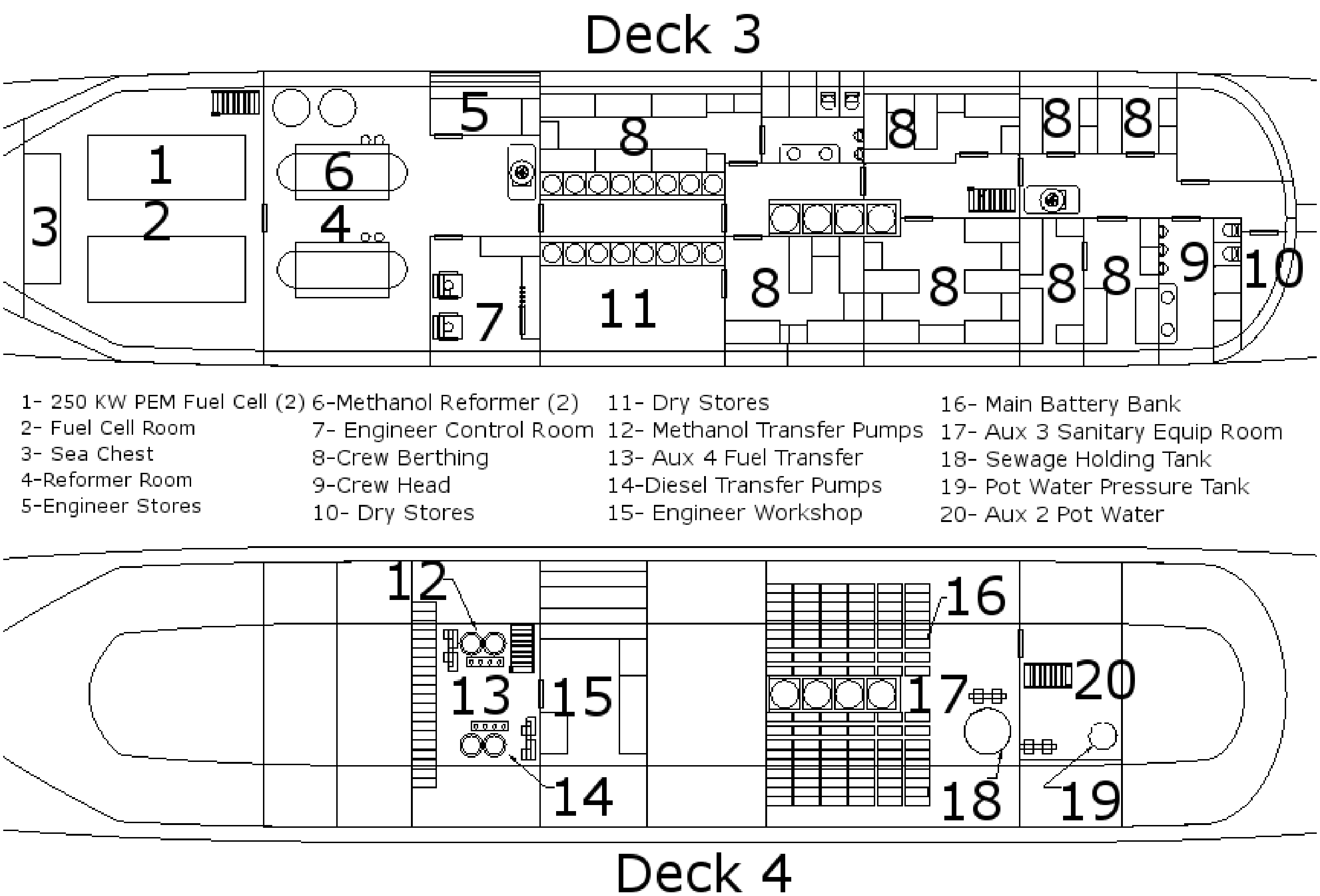



**Figure 4.44: General Arrangements (Decks 3 and 4)**

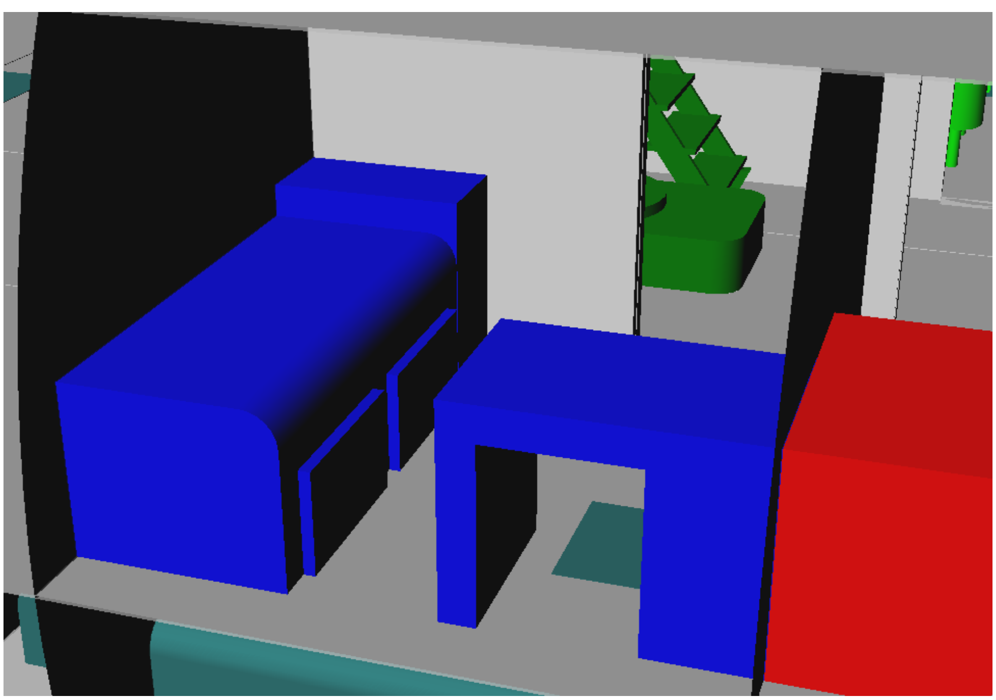


**Figure 4.45: The CO Stateroom**

### 4.7.4 Living Arrangements

The volume required for both the officer and enlisted berthing is determined from the ship synthesis model, and the arrangements are created in Rhino. The arrangements of the SSBMD living arrangements are driven by human space requirements and US Navy tradition.

Both the CO and the XO have private state rooms. The other officers have berthings that accommodate two people per room. The officers share a communal head that is separate from the enlisted head. The officers also have a separate mess facility in the wardroom. Figures 4.45-4.47 show the CO stateroom, officer head, and the wardroom in that order.

The enlisted living arrangements provide sleeping, mess and sanitary area for all of the enlisted personnel. Enlisted bunks range from accommodating 2 to 12 crewmembers in a single room. Figures 4.48-4.50 illustrate enlisted berthing, enlisted sanitary, and the messdeck.

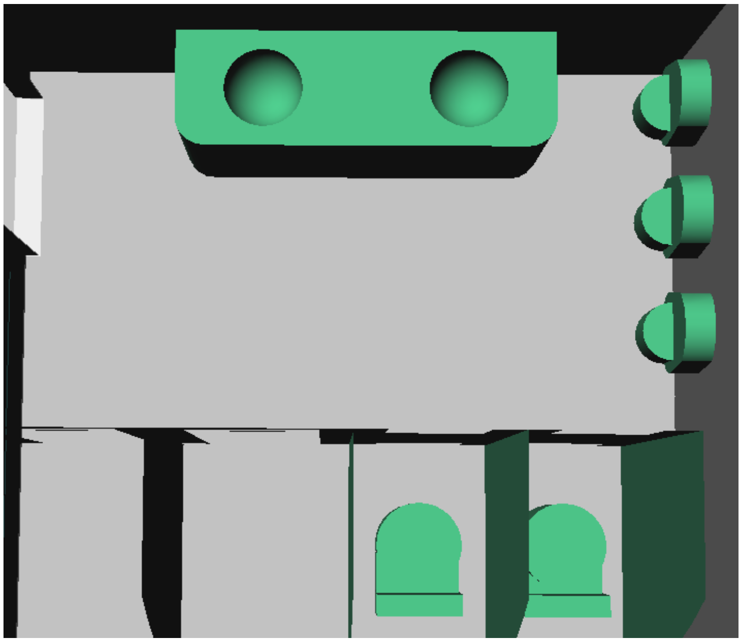


**Figure 4.46[A]: Officer Head**

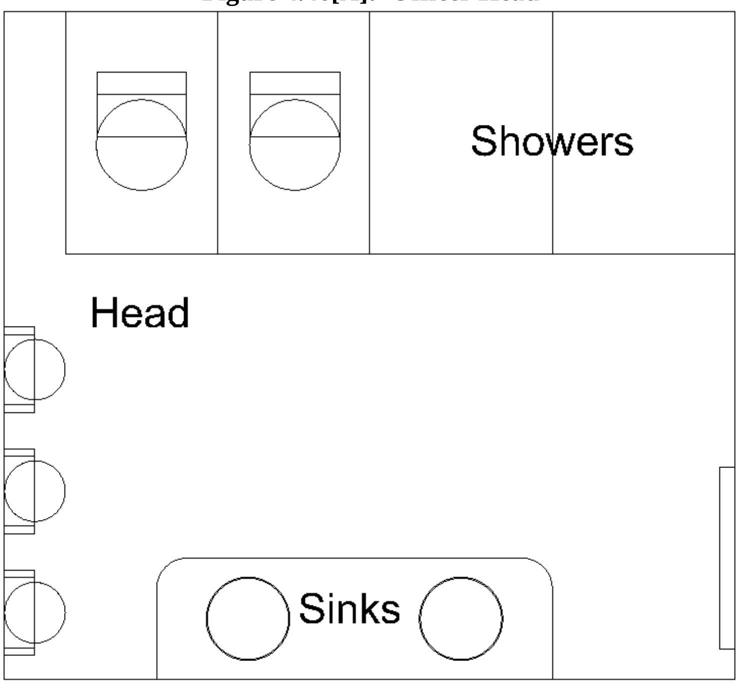



**Figure 4.46[B]: Officer Head**

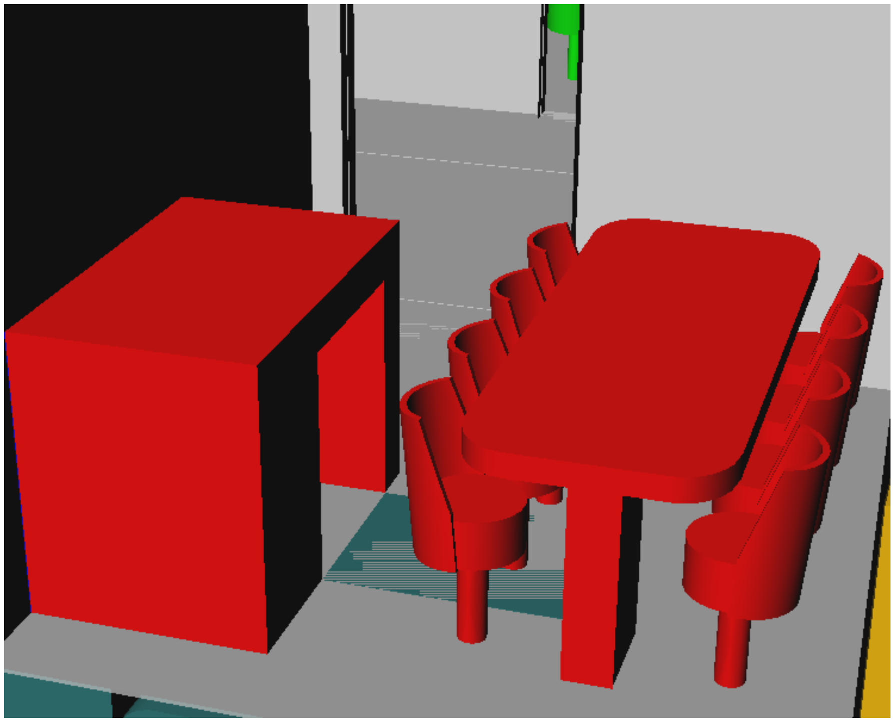


**Figure 4.47[A]: Wardroom**

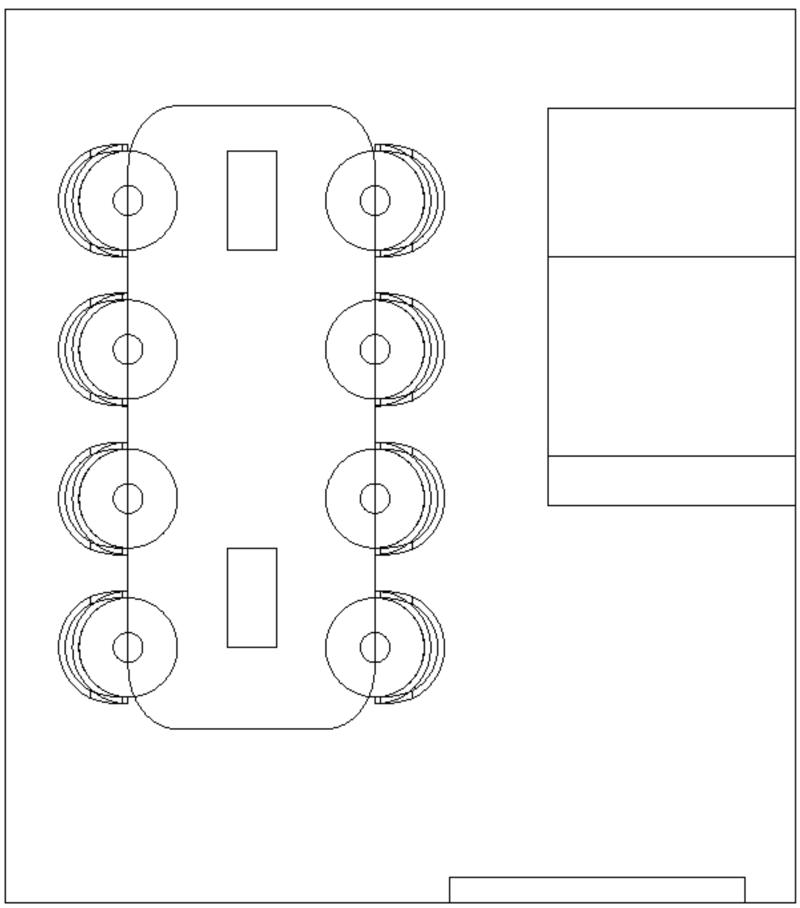


**Figure 4.47[B]: Wardroom**

Figure 4.48[A]: Enlisted Berthing

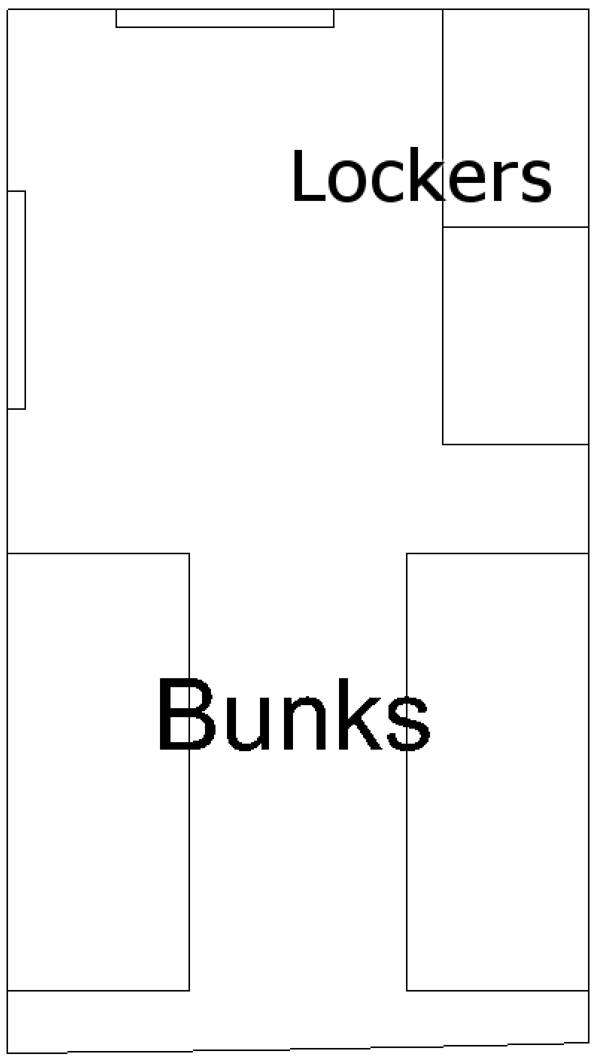



Figure 4.48[B]: Enlisted Berthing

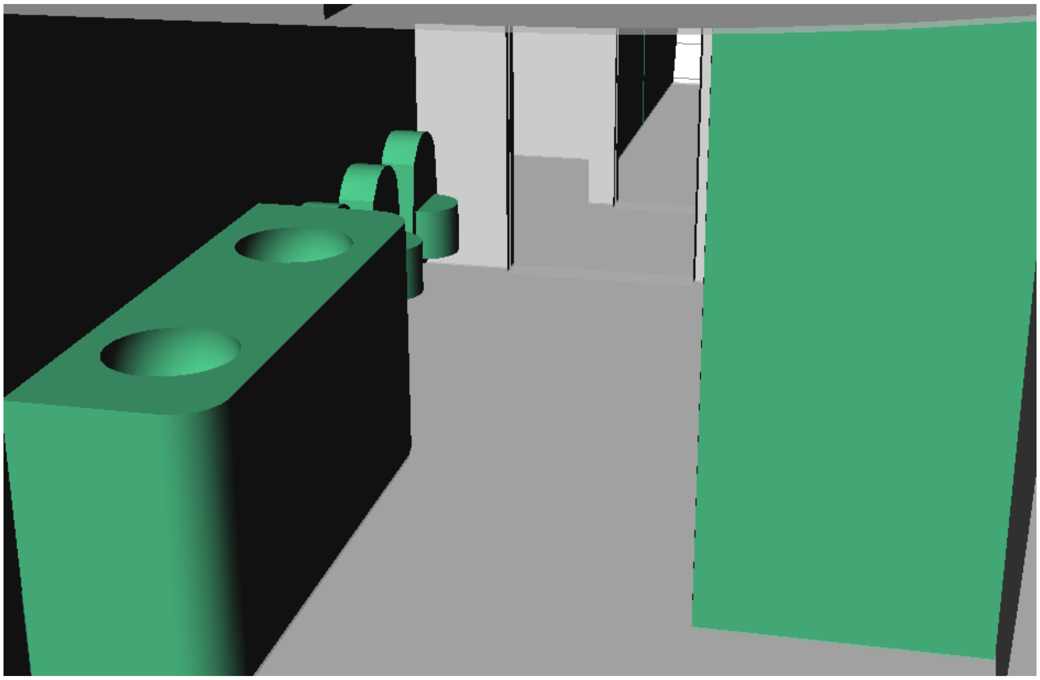


Figure 4.49[A]: Enlisted Head

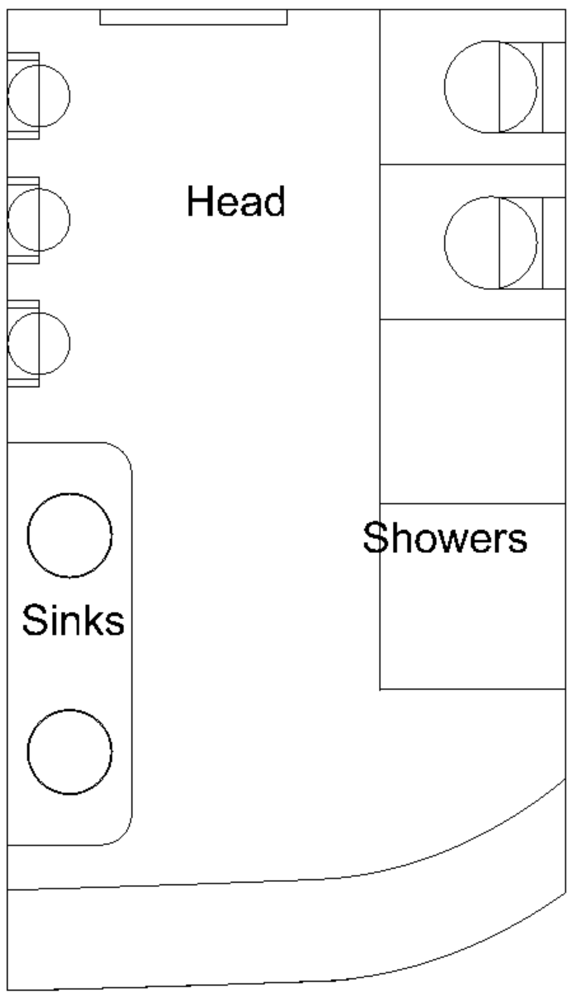



Figure 4.49[B]: Enlisted Head

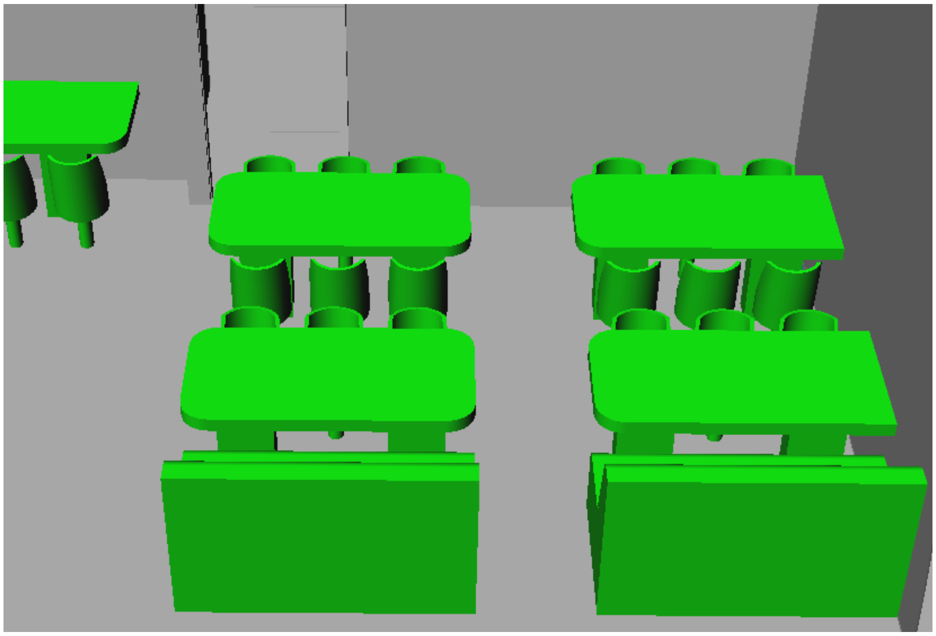


Figure 4.50[A]: Enlisted messdeck

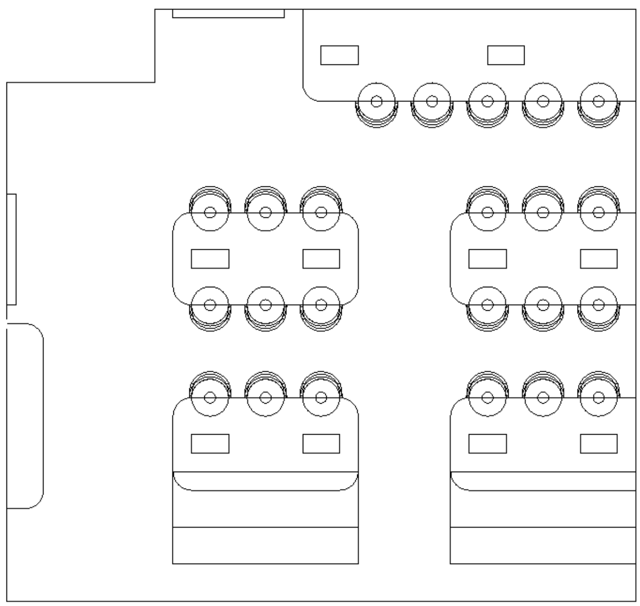


Figure 4.50[B]: Enlisted messdeck

### 4.7.5 Combat System Arrangements

The combat system choices were obtained from the ship synthesis model. The arrangement of individual components was selected to utilize space in the most effective way possible (Figure 4.51). The torpedo room is located on the top deck to allow for easy torpedo loading (Figure 4.52). The sail houses the following combat system components (Figure 4.53):

- Kinetic Energy Interceptor cells are hull penetrating
- Sea Sentry UAVs and the UUVs
- 16 Vertical Launch cells
- 9 man lockout chamber

The sonar equipment is placed according to positional requirements (i.e. flank arrays must be located on the side of the hull).

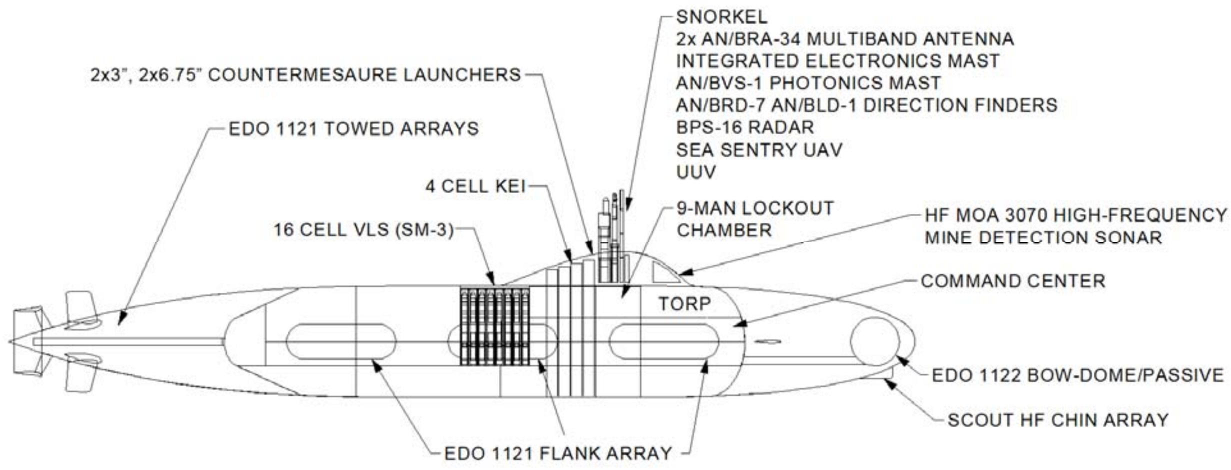



**Figure 4.51: Profile View of Combat Systems**

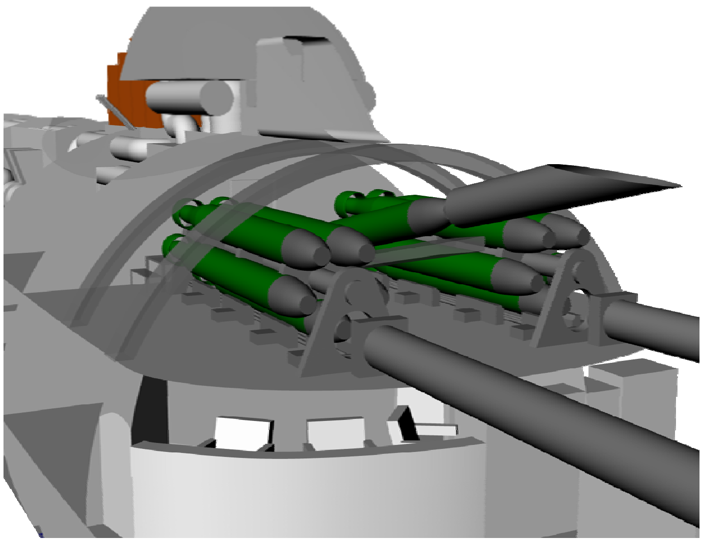


**Figure 4.52[A]: 3D View of Torpedo Revolver System**

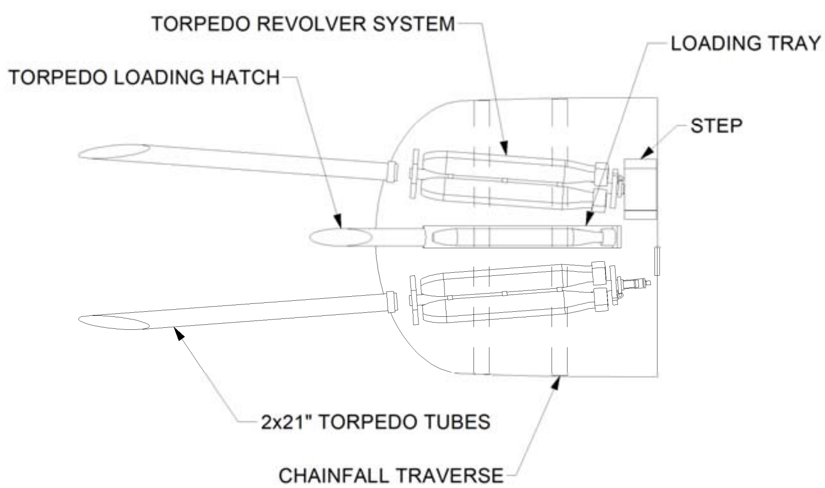



**Figure 4.52[B]: 2D View of Torpedo Revolver System**

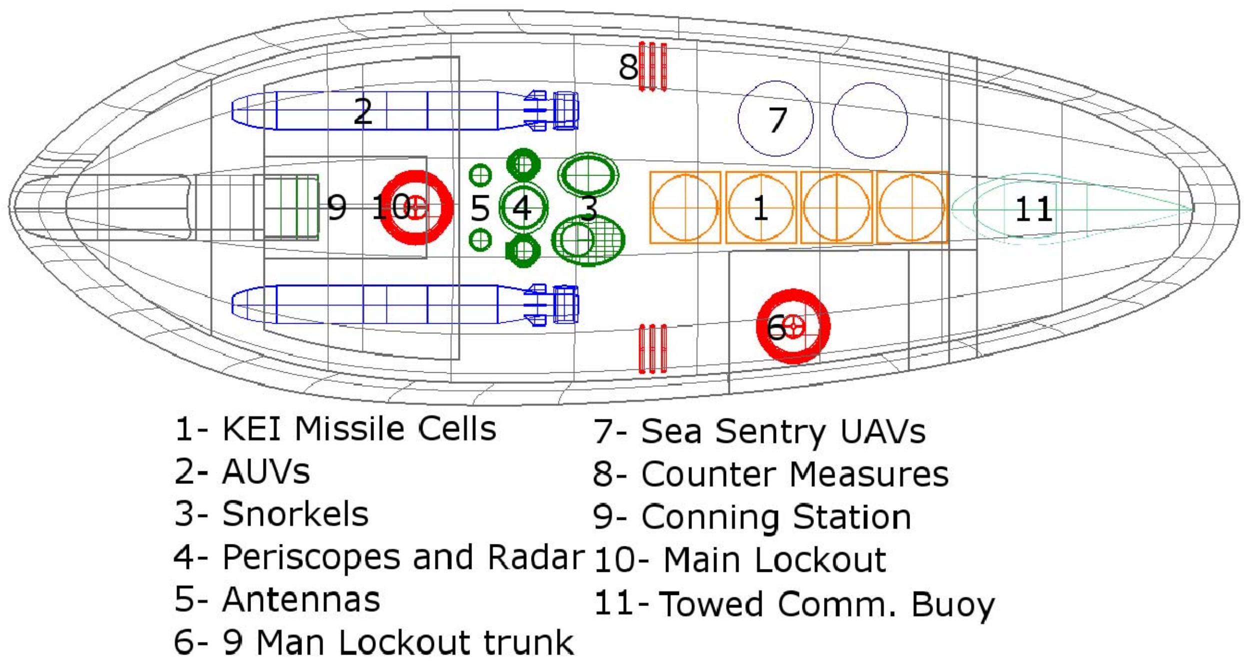



**Figure 4.53: Sail Combat Systems**

Figure 4.54 is a 2D view of the Command and Control Room and the adjoining Sonar Control Room. The Conn/officer station is an elevated platform that has sightlines to all watch stations in Command and Control. Paperless plotting and navigation station is located to starboard of the Conn station. Communications and Weapons control stations include dedicated stations for VLS tasking, UUV/AUV control, and traditional weapon control. Multiple multi-function flat screen monitors are able to display any image including periscope, weapons, and sonar information.

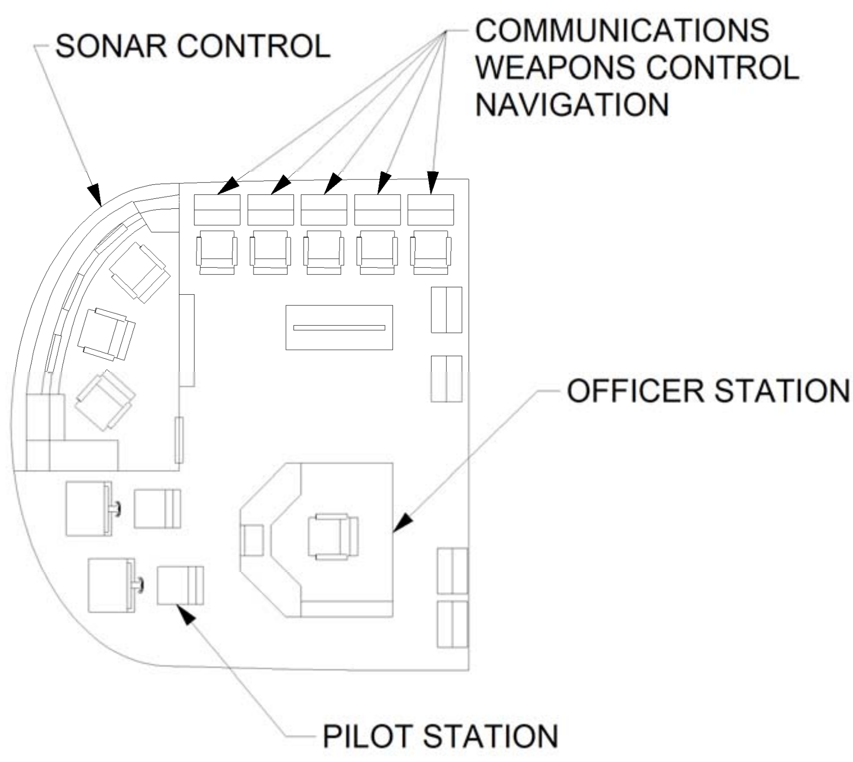



**Figure 4.54: 2D View of Command and Control Room**

## 4.8 Final Weights, Loading and Equilibrium

### 4.8.1 Summary of Concept Development Equilibrium Changes

Once initial equilibrium and balance was reached during baseline concept development, additional work was done to further optimize the arrangements and variable ballast tanks. The primary goal during the concept development phase was to reduce the requirement for variable ballast. This reduction would increase the amount of volume available inside the pressure hull for arrangements. Different approaches towards machinery and internal tankage arrangements were explored at this time. A critical design change was the decision to split the external compensated methanol and diesel fuel tanks into fore and aft tanks. This decision was reached when a review of the baseline balance revealed that the compensated fuel tanks were causing excessive range in the loading condition moments. The percentage of pressure hull volume devoted to variable ballast tanks was reduced from 19% at baseline design to 8% at final concept design.

Pressure hull volume increased as discussed in 3.3.6. The aft pressure hull endcap shape was altered from a reduced neck style to a conical style. This was mainly due to structural concerns but also resulted in changes to the equilibrium condition.

### 4.8.2 Final Weights

Final SWBS weight groups are listed in Appendix F. No significant changes were made to the baseline weights. Main SWBS groups are displayed in Table 4.18 below. SWBS Group 800 (Lead) is further subdivided into stability lead and margin lead. Margin lead allows expansion and upgrade of submarine systems over the lifetime of the vessel. Margin lead weight is typically 2-3% of total lightship weight. Stability lead is used to ensure that the CG of the submarine is low enough to provide transverse stability while submerged and at the surface. Stability lead longitudinal position is altered during the design cycle to ensure trim of the submarine is at the design angle.

**Table 4.18: Main SWBS Groups**

| Main SWBS Groups | |
|---|---|
| **Weight/Loading Condition** | **Weight (lton)** |
| SWBS 100- Hull Structures | 940 |
| SWBS 200- Propulsion Plant | 370 |
| SWBS 300- Electrical Plant, General | 70 |
| SWBS 400- Command, Surveillance | 269 |
| SWBS 500- Auxiliary System, General | 364 |
| SWBS 600- Outfit + Furnishing, General | 78 |
| SWBS 700- Armament | 752 |
| SWBS A-1 Lightship Weight | 2843 |
| SWBS 800- Lead | 310 |
| SWBS A- Lightship Weight + Lead | 3161 |
| SWBS 9- Full Variable Loads | 1097 |
| Normal Surface Condition | 4258 |

### 4.8.3 Final Loading Conditions

Final loading conditions were altered from baseline to reflect the design change to split fore/aft compensated fuel tanks. Other changes included increasing the size of the main ballast tanks, shifting the battery bank, clean diesel and methanol tanks, and various minor arrangement changes. Main weapons system locations were not changed from baseline.

### 4.8.4 Final Displaced Volumes

Final displaced volumes are summarized in Table 4.19.

**Table 4.19: Final Displaced Volumes**

| Component | Displaced Volume (ft^3) |
|---|---|
| Pressure Hull | 110650 |
| Sonar Dome & Access Tunnel | 1800 |
| Main Ballast Tank (fore) | 18755 |
| Main Ballast Tank (aft) | 15315 |
| Compensated Methanol Tank | 3500 |
| Compensated Diesel Tank | 6107 |
| VLS (outboard components) | 110 |
| Payload (outboard) | 1820 |
| Torpedo Tubes | 189 |
| Propulsor | 600 |
| Miscellaneous Outboard | 6000 |

### 4.8.5 Final Equilibrium Polygon

Performing the changes to the design outlined in Section 13.9.1 resulted in a greatly reduced requirement for variable ballast volume. The variable ballast volume required was reduced from 18500 $ft^3$ to 9000 $ft^3$. The final equilibrium polygon is shown in Figure 4.55.

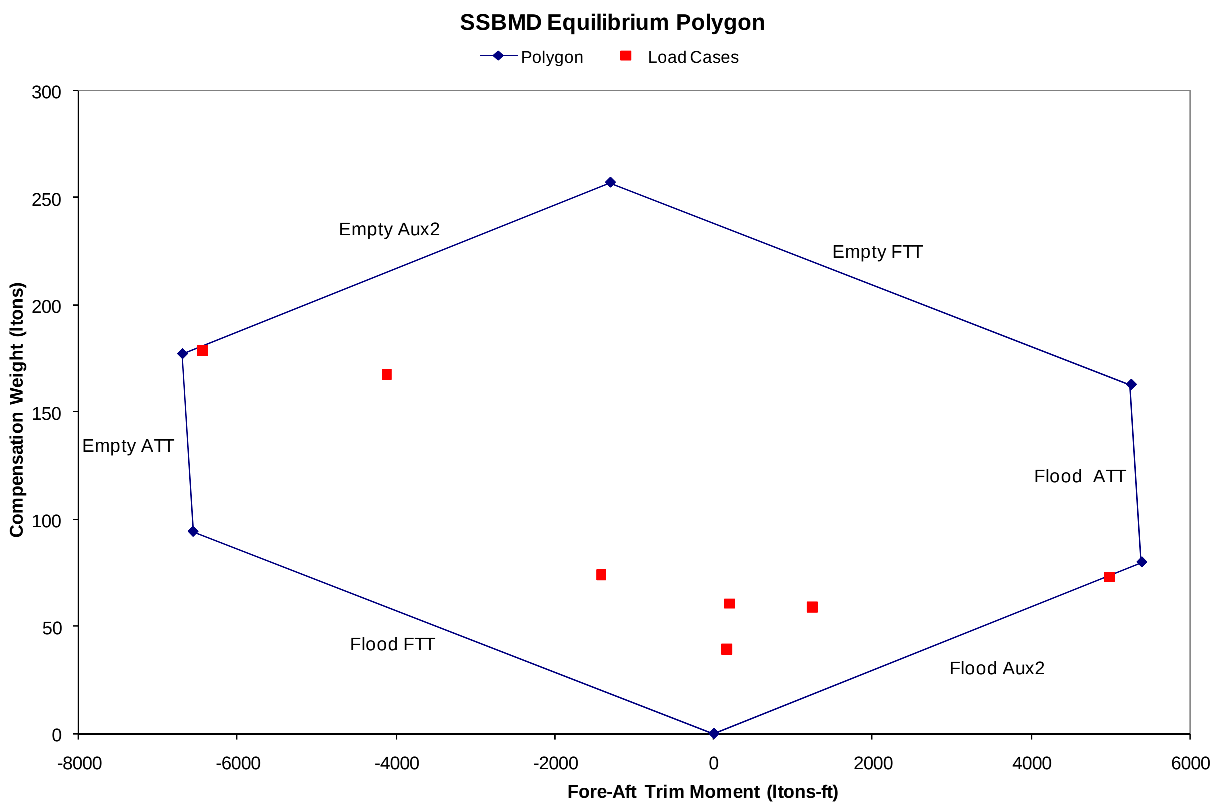



**Figure 4.55: Final Equilibrium Polygon**

Comparing the initial and baseline equilibrium polygons in Section 3.3.5/6 with the final equilibrium polygon above, a large reduction in the required moment to trim may be seen. The required moment to trim fore-aft in the baseline design was approximately 22500 ltons-ft. The required moment to trim fore-aft in the final concept design is approximately 11500 ltons-ft, a reduction of about 50%. This reduction in internal volume allowed the final internal arrangements to be more spacious, especially the main machinery spaces in the aft portion of the submarine (Figure 4.56).

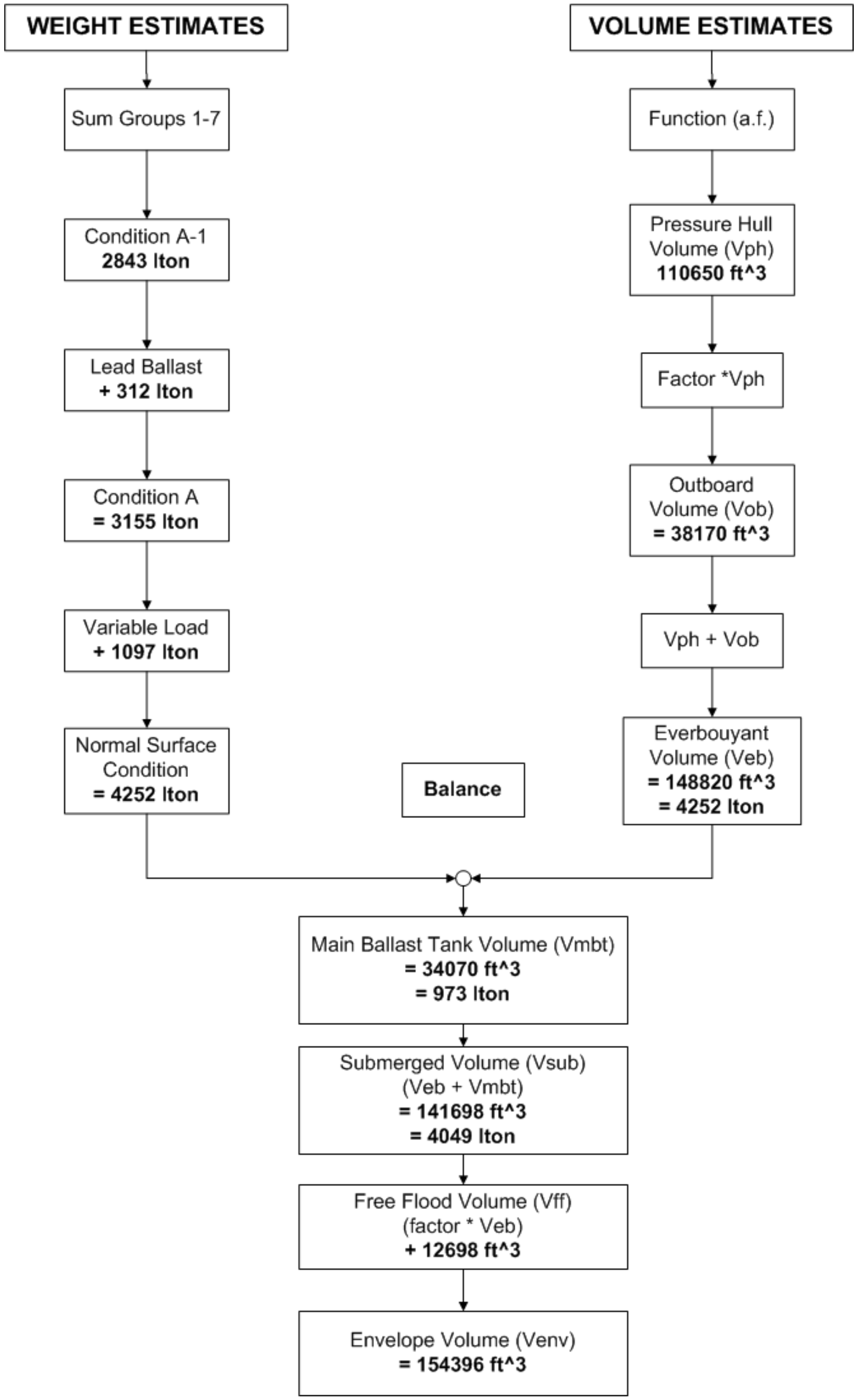



**Figure 4.56: Final Balance**

## 4.9 Dynamic Stability and Maneuverability

Two competing characteristics must be considered when designing control surfaces for a submarine; stability and maneuverability. Stability is a measure of a submarine's tendency to return to equilibrium after a perturbation. Maneuverability is a measure of a submarine's ability to rapidly change heading or depth.

A dynamically stable submarine (Figure 4.57) will –without any control inputs- tend to return to equilibrium after a short period of oscillation. A dynamically unstable submarine (Figure 4.57) will –without any control inputs- experience ever increasing oscillations after perturbation, making course keeping impossible.

Very stable submarines will exhibit favorable course keeping characteristics, but will tend to maneuver poorly (Figure 4.58). Conversely, a low stability (or unstable) submarine will tend towards increased maneuverability at the cost of course keeping (Figure 4.58).

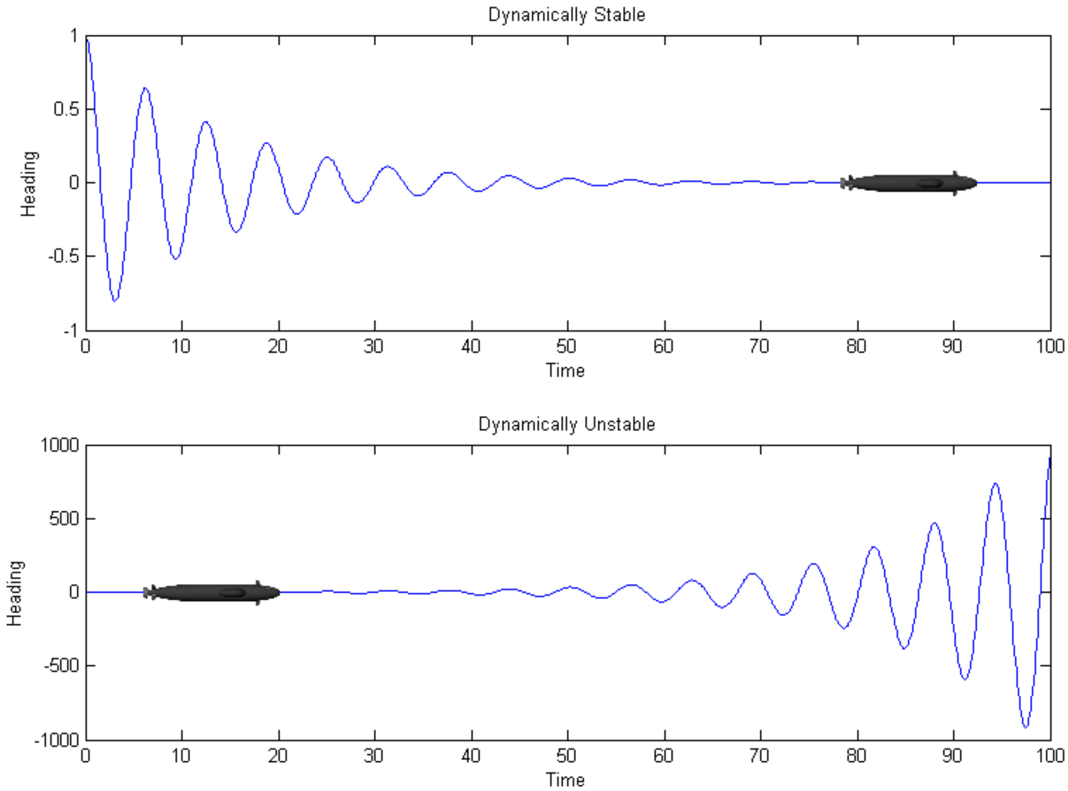



**Figure 4.57: Dynamic Stability**

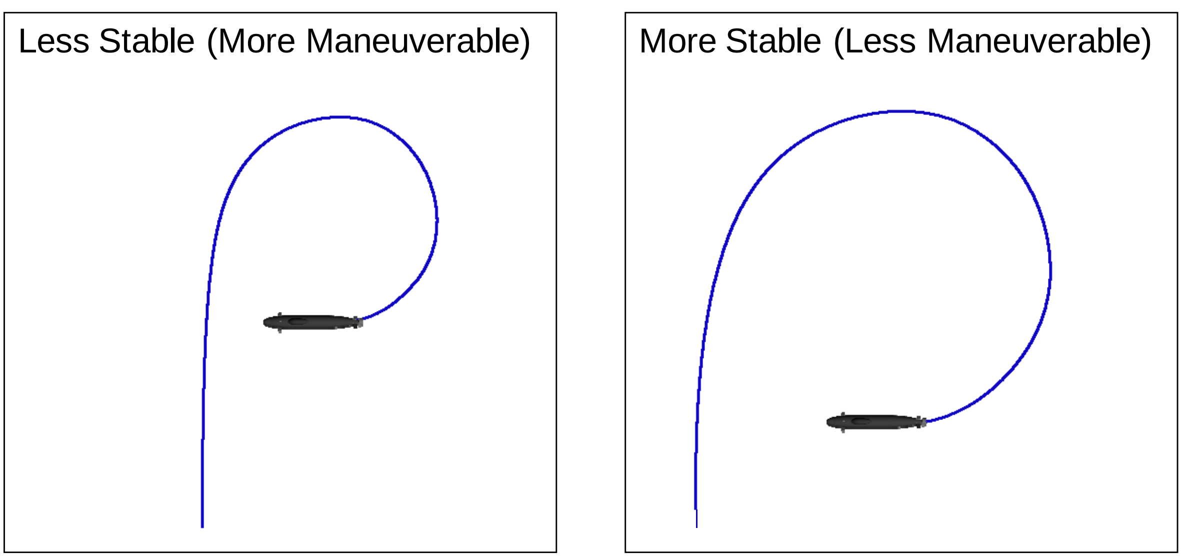
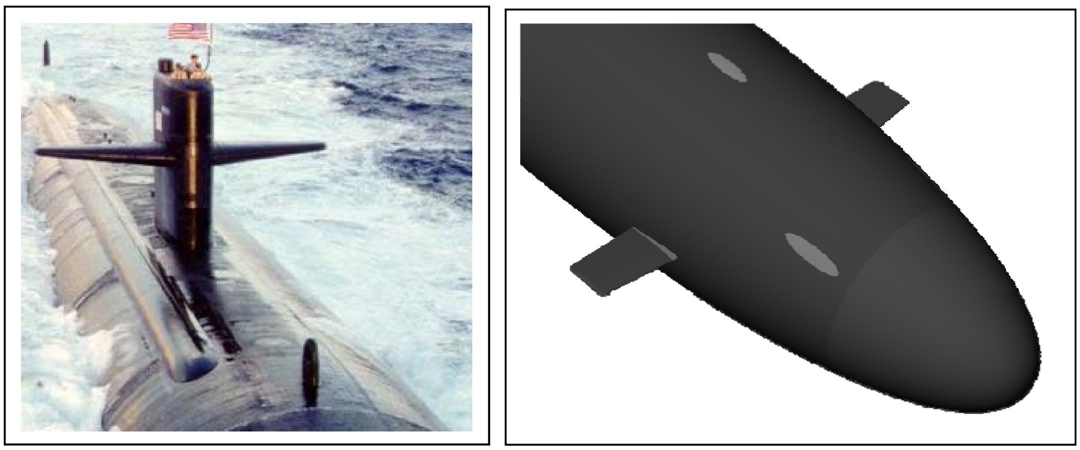



**Figure 4.58: Maneuverability**

In order to function effectively, a submarine must be capable of maneuvering rapidly during combat situations while at the same time expressing the directional-stability and depth-keeping necessary for normal operation. This leads to a tradeoff between maneuverability and stability. Historically, submarines have chosen a compromise which has favored more stable designs. However, modern advances in computer control systems –namely "fly by wire" have reduced the necessity for stability; allowing less stable (and even unstable) submarine's to be created. A fly-by-wire system breaks the traditional direct connection between pilots and control surfaces. Instead, a pilot inputs any desired directional and depth changes and the computer system calculates the corresponding control surface actuations. This has the advantage of both reducing piloting difficulty and, by virtue of a computers ability to respond very rapidly to small perturbations, allowing for dynamically unstable submarines to be easily controlled. Modern submarines which implement computerized control systems can exhibit both favorable maneuvering and favorable course keeping characteristics.

Two factors still place limits on how unstable a submarine may be made. If a submarine is made to be very unstable, control surface machinery may not be capable of reacting quickly enough to make the necessary corrections to maintain stable operation. Additionally, the small –constant- control surface actions required to control an unstable submarine require electrical power. For non-nuclear submarines especially, this power draw must be considered when designing control surfaces.

Control surface design typically follows one of a few set configurations: Dive planes (which aid in vertical maneuvers and depth control) can be placed either on the hull in a "bow plane" configuration, or high on the sail as "fairwater planes" (Figure 4.59).



Fairwater Planes Bow-Planes

**Figure 4.59: Dive Plane Configurations**

Fairwater planes facilitate docking, in that they are typically raised high enough to avoid a dock or other obstacles. Fairwater planes however pose a broaching hazard when a submarine is traveling close to the surface. Because fairwater planes are also typically located closer to a submarine's longitudinal center of gravity their ability to affect the pitch of a submarine is less than that of an equivalent bow plane system (the bow planes being located farther from the $L_{CG}$ act with a larger moment arm and greater pitching moment).

Bow Planes typically result in superior pitch authority, but because of their placement on the sides of a submarine's hull must be retracted before docking.

Stern control surface configurations exhibit a much greater degree of variability. However there exist two dominant themes in modern submarine design; fixed "cruciform" control surfaces equipped with flaps, and fully movable control surfaces in X shape known as an X-Tail (Figure 4.60).

"Cruciform" Tail X-Tail

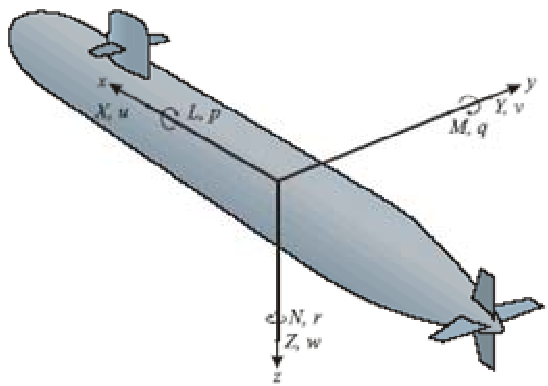
**Figure 4.60: Stern Control Surface Configurations**

Flapped cruciform tails typically result in more stable submarine designs. The simple correlation between rudder/elevator controls and yaw/pitch control allows for simple manual control systems to be implemented. The fixed portions of the foils tend to provide damage resilient characteristics to cruciform tails. However the vertical orientation of the rudder of a cruciform tail results in a greater draft, reducing the ability for cruciform tails to operate in shallow water.

X-Tails tend to result in highly maneuverable systems (especially at high speeds). As a result of the slanted orientation of the control surfaces, each individually actuated control surface contributes to both pitch and yaw control. This results in a highly redundant control system which –while not damage resilient- is highly damage tolerant (due to its inherent redundancy). Because X-Tails are not oriented vertically, they typically allow for a much lower draft and facilitate shallow water operations. Because of the complexity of the X-Tail configuration, a computerized control system is almost always required.

In order to estimate control surface dimensions and calculate approximate maneuverability and stability characteristics for any control surface configuration, a least-squares curve fit developed at Virginia Tech by Lisa Minnick for a Master's thesis was utilized. To obtain the curve fit, Lisa Minnick first used the program GEORGE to calculate estimated maneuvering coefficients for ten US submarines. These maneuvering coefficients appear in the dynamic equations of motion for a submarine, and may be used to predict or simulate maneuvering characteristics (see Figure 4.61).

$$m(\dot{v} + ru) = Y_v + Y_{\dot{v}} + Y_r + Y_{control} \qquad I_{zz}\dot{r} = N_v + N_r + N_{\dot{r}} + N_{control}$$




$$Y_* = \frac{\partial Y}{\partial *} \qquad N_* = \frac{\partial N}{\partial *} \qquad v = SwayRate \qquad r = YawRate$$

$$\dot{v} = SwayAcceleration \qquad \dot{r} = YawAcceleartions$$

$$control = ControlSurfaceInputs \qquad u = ForwardVelocity$$

**Figure 4.61: Horizontal Equations of Motion and Maneuvering Coefficients**

Lisa Minnick then used these maneuverability coefficients to calculate vertical and horizontal stability indices; $G_v$ and $G_h$ (Equations 1&2). $G_v$ and $G_h$ are unit normalized stability indices taken at a theoretical ∞ velocity. Theory predicts that submarine's stability at infinite speed is proportional to its stability at any finite speed. Thus the stability indices can be used to evaluate a submarine's overall stability/maneuverability. The traditional desired range for $G_h$ is 0.15 – 0.3 and $G_v$ is 0.5 – 0.7. However, provided a fly-by-wire control system is utilized, the acceptable range of stability indices may stray well below these traditional ranges.

$$G_v = 1 - M_w\left(\frac{Z_q + m}{Z_w M_q}\right) \qquad (1)$$

$$G_h = 1 - N_v\left(\frac{Y_r + m}{Y_v N_r}\right) \qquad (2)$$

By relating the hull and control surface characteristics of each of the ten submarines to the resulting stability indices, Lis Minnick was able to create a least squares regression relating submarine characteristics directly to stability indices. The hull and control surface characteristics used by Lisa Minnick for the curve fit were: Bow/Fairwater-Planes, Cruciform/X-Tail, Hull diameter, Length to diameter ratio, and the Hull fullness coefficients $n_a$, $n_f$. The resulting curve fits are shown in Figure 4.62.

```
Gh= -.8710153E+01 + 0.3172744E+00*D + 0.6818338E+00*LtoD + 0.1626116E+00*na + -.3260974E+00*nf +
-.3504993E-02*D**2 + -.2365368E-01*LtoD**2 + -.1080688E-01*na**2 + 0.1645568E-01*nf**2 + -.3114843E-02*D*LtoD +
-.1786924E-01*D*na + -.2145144E-02*D*nf + 0.3072456E-01*LtoD*na + 0.1348954E-01*LtoD*nf + 0.3955147E-01*na*nf

Gv= -.1422074E+02 + 0.3810203E+00*D + 0.1456368E+01*LtoD + 0.3417729E+00*na + 0.2548777E+00*nf + -.3532465E-02*D**2 +
-.5131522E-01*LtoD**2 + -.3715690E-01*na**2 + 0.4040887E-02*nf**2 + -.8089447E-02*D*LtoD + -.2325680E-01*D*na +
-.2950826E-02*D*nf + 0.3943816E-01*LtoD*na + -.2947461E-01*LtoD*nf + 0.3464663E-01*na*nf
```

**Figure 4.62: Stability-Index Curve Fits (Lisa Minnick)**

For SSBMD, A bow-plane configuration was chosen due to concerns over the questionable compatibility between fairwater planes and a Virginia Class style advanced composite sail. An X-Tail stern configuration was chosen to maximize the submarines shallow water performance, as well as to facilitate possible “bellying down” operations for the submarine. For comparison; an additional Fairwater-planes/Cruciform-Stern configuration was also included. By plugging in the hull characteristics and control surface configurations for SSBMD into Lisa Minnick’s curve fit, the following stability indices (Table 4.20) were obtained.

**Table 4.20: Summary of Stability Indices Obtained**

| | | |
|---|---|---|
| Fairwater Planes / Cruciform Stern | $G_v = 0.5867536$ | $G_h = 0.2249016$ |
| Bow-Planes / X-Tail | $G_v = 0.1867722$ | $G_h = 0.05881127$ |

As expected, the Cruciform Stern configuration resulted in mid-range stability indices, characteristic of a traditional pre-Virginia Class submarine. The Bow-Planes/X-Tail configuration chosen for SSBMD resulted in highly maneuverable stability indices, further reinforcing the need for a fly-by-wire control system on SSBMD.

### 4.9.1 SSBMD Control Surfaces

Once the basic control surface configurations were chosen, visual approximation techniques were utilized to position and size the control surfaces for SSBMD. The results are summarized in Table 4.21.

**Table 4.21: Summary of SSBMD Control Surface Characteristics**

| Control System | Planform Area ($ft^2$) | Mean Chord (ft) | Position ($F_{PP}$ to ¼ Chord) (ft) |
|---|---|---|---|
| Bow Planes | 61.5 (per plane) | 6.6 | 51.22 |
| Stern Planes | 92.03 (per control surface) | 7.5 | 240.9 |

Figure 4.63 below shows the final control surface arrangement for the SSBMD.

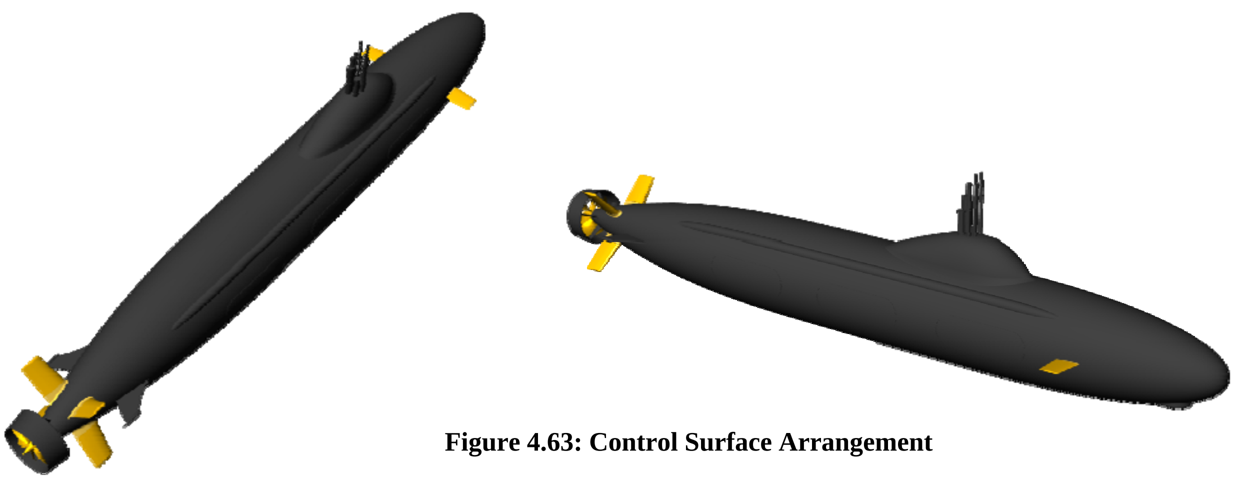


**Figure 4.63: Control Surface Arrangement**

## 4.10 Cost and Risk Analysis

### 4.10.1 Cost and Producibility

The SSBMD pressure hull structure is constructed of HY-100 steel. This steel was first used on the US Seawolf submarine 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 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 4.64 for weight groups 1 and 2. It should be noted that the calculations are used for weight groups 1-8.

**C. Lead Ship Shipbuilder Labor Cost:**

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

| | | | |
|---|---|---|---|
| **Structure** | $K_{N1} := \frac{400 \cdot hr}{1ton}$ | $C_{L_1} := K_{N1} \cdot W_1 \cdot Mh$ | $C_{L_1} = 28.2 \cdot Mdol$ |
| **+ Propulsion** | $K_{N2} := \frac{700 \cdot hr}{1ton}$ | $C_{L_2} := K_{N2} \cdot W_2 \cdot Mh$ | $C_{L_2} = 23 \cdot Mdol$ |

**D. Lead Ship Shipbuilder Material Cost:**

| | | | |
|---|---|---|---|
| **Structure** | $K_{M1} := \frac{18 \cdot Kdol}{1ton}$ | $C_{M_1} := F_I \cdot K_{M1} \cdot W_1$ | $C_{M_1} = 23.7 \cdot Mdol$ |
| **+ Propulsion** | $K_{M2} := \frac{120 \cdot Kdol}{1ton}$ | $C_{M_2} := F_I \cdot K_{M2} \cdot W_2$ | $C_{M_2} = 73.7 \cdot Mdol$ |

**Figure 4.64: Cost Calculation Example**

**E. Direct Costs:**

**1. Labor Cost:**

$$C_L := \sum_{i=1}^{9} C_{L_i} \qquad C_L = 413.7 \cdot Mdol$$

**2. Material Cost:**

$$C_M := \sum_{i=1}^{9} C_{M_i} \qquad C_M = 731.7 \cdot Mdol$$

**3. Direct Cost:**

$$DC := C_L + C_M \qquad DC = 1145.4 \cdot Mdol$$

**F. Overhead:** **Enter Overhead Rate:** $ovhd := 0.25$

$$IC := DC \cdot ovhd \qquad IC = 286.3 \cdot Mdol$$

**Cont'd Figure 4.64: Cost Calculation Example**

The basic cost of construction of the SSBMD is $1.575 billion. This satisfies the goal of a lead ship BCC of less than $1.6 billion. Figure 4.65 illustrates the total cost breakdown including all SWBS groups. The SSBMD is a cost efficient and producible supplement to today's United State Navy.

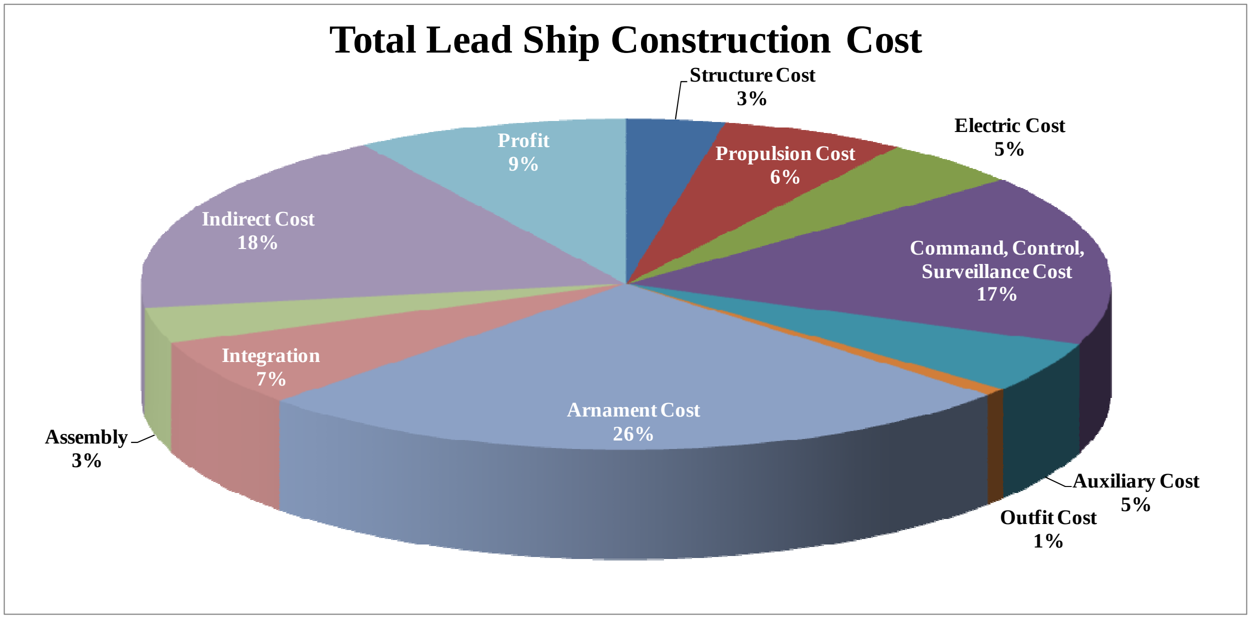



**Figure 4.65: Direct Cost Breakdown**

### 4.10.2 Risk Analysis

The selected baseline design for the SSBMD is a moderate risk design with an OMOR of 0.663. The systems that are associated with the highest risk are the use of the reformers for hydrogen, the PEM fuel cells, and the KEIs themselves and integration of those into the advance composite sail. The risk associated with many of these systems comes from the United State 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 2018. This ten year time period allows for further testing and development of all systems to be used onboard. This ten 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

**Table 1: Compliance with Operational Requirements**

| Technical Performance Measure | Threshold | Goal | Concept Exploration BL/ CDD KPP | Final Concept Development BL |
|---|---|---|---|---|
| Mission payload | Passive/Active ranging sonar, 2 IB torpedo tubes, countermeasure Launchers, Virginia Class Sail masts, 12 VLS cells | Advanced Passive/Active ranging sonar, 4IB torpedo tubes, countermeasure launchers, Advanced Composite Sail masts, degaussing, 9 man lock-out trunk, 24 VLS cells, 4 KEIs in Sail | Advanced Passive/Active ranging sonar, 2 IB torpedo tubes, countermeasure Launchers, Advance Composite Sail masts, degaussing, 9 man lock-out trunk, 16 VLS cells, 4 KEIs in Sail | Advanced Passive/Active ranging sonar, 2 IB torpedo tubes, countermeasure Launchers, Advance Composite Sail masts, degaussing, 9 man lock-out trunk, 16 VLS cells, 4 KEIs in Sail |
| Propulsion | CCD, 2xCAT 3512 V12, Lead Acid batteries | OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM, Zebra batteries | OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM, Zebra batteries | OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM, Zebra batteries |
| Snorkel Endurance (nm) | 5000 | 6000 | 5180 | 5356 |
| Sprint Endurance (hr) | 0.5 | 1.0 | 0.6 | 0.832 |
| AIP Endurance (days) | 20 | 30 | 24 | 24 |
| Snorkel Speed (knots) | 12 | 12 | 12 | 12 |
| Sprint Speed Vs (knots) | 15 | 22 | 22 | 22 |
| AIP Speed (knots) | 5 | 5 | 5 | 5 |
| Crew size | 54 | 54 | 54 | 54 |
| Diving Depth (ft) | 500 | 1000 | 560 | 570 |

## 5.2 Summary of Changes Made in Concept Development

The design was refined during several internal steps between baseline design and final concept development. Major components that underwent several design cycles were the pressure hull volume and shape and the external and internal tankage and ballast systems. Systems that were altered or refined during concept development are summarized below.

- Compensated Fuel Tanks - The external compensated methanol and diesel tanks underwent extensive redesign and alteration over the course of concept development. Compensated methanol tank sizing was adjusted to reflect more accurate data on methanol density. The external tanks were also terminated at the anticipated free surface level due to concerns from overflowing in the full condition while surfaced. The primary alteration to the tanks was the decision to go to fore/aft split compensated tanks. This decision was due to balance concerns (see Section 4.9.1 for details)
- Pressure Hull - The pressure hull volume was increased over the concept development phase. This was due to higher than anticipated weights for the combat systems, primarily the KEI missile system. The pressure hull end cap shape aft was altered from a necked-down type to a conical type due to structural concerns.
- Torpedo Machinery - A novel machinery system for loading torpedoes was developed during concept development. The goal was to reduce manning requirements and decrease cycle time during torpedo reload exercises
- Clean fuel tanks - The internal clean fuel tank configuration was changed as the variable ballast tank aft had priority from a design standpoint. Efforts were made to locate the clean methanol and diesel tanks close to the main machinery spaces, particularly the reformer room and the main propulsion diesel room.
- Main Ballast and Variable Ballast Tanks - The Variable Ballast system was reduced in size significantly as discussed in Section 3.9.5. The Main Ballast system was increased in size significantly from baseline design to increase the reserve buoyancy to an acceptable level.

- 9 Man Lockout Trunk - The lockout trunk layout was changed from an integral structure occupying a partial section of the hull curvature which involved heavily reinforced bulkheads. The lockout trunk was changed to an internal cylindrical pressure vessel to simplify hull structure design. This change was made possible due to efficient habitability arrangements freeing up arrangeable space on the upper deck.
- VLS System Layout - The 16-cell 21" diameter VLS system was originally arranged in an 8x2 array along the centerline of the hull. Diesel intake and exhaust routing considerations forced the array to be split into two 8x1 parallel arrays spaced four feet apart off centerline. VLS system hatch arrangements required that a partial turtleback be placed over the 16 cell array.
- Deck Layout - Primary deck spacing remained unchanged at 7 ft, 9 ft, 7ft. Inserting a partial half deck with 7 ft deck height under the third deck allowed locating auxiliary machinery such as fuel transfer and sanitary systems near the tankage they serve. This approach was enabled once the variable ballast system size was reduced.
- Battery - The battery bank layout was altered from a bilge level arrangement to being located on the fully accessible partial deck. Volume originally devoted to stores was converted to the primary battery bank space. Additional space for batteries was required in the aft portion of the fuel transfer room.

## 5.3 Future Work

Due to the finite timeframe and limited scope of this project, a complete concept development, including several design spiral iterations, proved to be untenable. The primary points of interest which were identified for further analysis during the next iteration of the design spiral are outlined below.

- Evaluate Propeller Alternatives
    - Rim Driven Propulsor – Investigate shaftless propulsor. Because of timeframe for construction of SSBMD, SSBMD is positioned well to be the first to prototype the new technology.
    - Open Bladed Propeller - Because the acoustic advantages of a shrouded propeller are marginal at very low speed, the extra cost and weight incurred by the shrouded propulsor casts doubt on it as the optimal propulsor alternative. Additionally the efficiency gained at low speeds –while large- only amounts to a very small total power reduction (as the majority of low speed power consumption is devoted to sensors). A simple open bladed propeller should be analyzed for cost/benefit tradeoffs.
- Switch from Methanol Fuel to Ethanol Fuel for AIP - Ethanol is more power dense and much more readily available then methanol. Ethanol –like methanol- is easily reformable. Together this makes ethanol a much more desirable fuel for the AIP system.
- Investigate Benefits of Increasing Number/Subdivision of Internal Trim Tanks
- Research and Evaluate Diesel Reforming Systems - Improvements in Diesel Reforming Technology may allow such a system to be adopted by the construction time of SSBMD. Implementing such a system would allow for a single fuel to be used for both AIP and snorkel operation.
- Analyze benefits of relocating VLS to Forward MBT - The size of the VLS system (for the SM-3 missiles) conflicts with the desired stiffener spacing of 2 ft. Additionally, there are safety concerns anytime munitions are stored within the pressure hull. Moving the VLS to the forward ballast tank (as in the Virginia Class and 688 submarines) would likely alleviate both of these issues. The primary difficulty with such a move is the impact it would have on the balance the submarine.
- Reanalyze Structural Scantlings - Several points of interest have been identified for reanalysis relating to structural issues. First among these is the number of kingframes, which was initially chosen to be perhaps lower than optimal. This lead to possible overdesign of hull plating and stiffener thickness. A complete FEA structural analysis, including buckling failure analysis, must be performed in order to adequately design the structural components of the pressure hull.
- Arrange and Model Additional Combat Systems
    - Towed Array Fairing
    - Towed Array Supports
    - Towed Array Machinery
    - External Seal Equipment Lockers (in Sail)
- Perform In-Depth analysis of Comm. System Alternatives - Because the communication system represents a critical path system for the SSBMD concept, a full analysis of alternative communications including optical, acoustic, buoy, and UUV communication alternatives must be performed.
- Evaluate Benefits of an Increase in Hull Diameter to 33' or 34' - With the current loading, a very large portion of the submarine's envelope volume outside the pressure hull is devoted to main ballast tanks. While this may reflect a highly optimized design it leaves very little margin for future expansion. An increase to a larger

diameter would allow for more flexibility in arranging equipment, and allow for a greater growth margin to be built into the submarine.

- Possible KEI Size Correction - Because the KEI system is still in development there is some confusion as to the final dimensions of the missiles. Initial estimates hinted at a 38.8 ft length, while further sources stated a length of 36 ft. The 36 ft length was used in the modeling and arranging of the submarine.
- Increase Sail size
    - (Possible KEI Size Correction)
    - Allow for KEI Hatch Machinery
    - Allow for HF Anti Mine Sonar
- Consider replacing HF Anti Mine Sonar and Chin Array sonar with high performance AUV network.
- Investigate Benefits of External to Pressure Hull Cryogenic Oxygen Tanks
- Perform Full Hull Drag CFD Analysis
- Examine Acoustics Impact of any Shed Vortices from Sail Interacting with the Propulsor.
- Perform Buckling Structural Failure Analysis of Pressure-Hull Plating
- Evaluate Possible Reduction of Propeller Diameter
- Determine Maneuvering Coefficients (using GEORGE) and Perform Full Maneuverability Simulation,
    - Obtaining: horizontal and vertical turning radius, zig-zag performance, and turn reach.
- Evaluate radioactive AIP extreme endurance propulsion system alternative (as utilized on other US submarines)

## 5.4 Conclusions

The SSBMD platform provides the United States with a critical component in ballistic missile defense strategy. As an inherently stealthy platform the SSBMD adds close-in boost phase and mid phase ballistic missile interception capability. The selection of a quiet fuel cell based AIP propulsion system enhances the covertness of the submarine while removing the risk of losing classified nuclear technology to foreign countries. In addition, utilizing a submarine based asset in addition to surface based assets for BMD gives an immediate strategic advantage as it is extremely difficult for the aggressor country to locate and track stealthy underwater vehicles such as SSBMD. Due to the forward projected force that a submarine asset gives to the United States Defense Department, SSBMD also adds capability as a low risk surface strike and intelligence platform. In addition to being an extremely capable platform, the SSBMD manning level is 40% of the Virginia Class attack submarine which is extremely important when considering lifecycle costs. The SSBMD design is the pinnacle of capability within the current worldwide fleet of non-nuclear submarines.

## References


1. *AIP Selection: The Importance of Submarine Integration and Other Non-Headline Discriminations*. 1999. Warship '99: Naval Submarines 6.

2. Brown, Dr. Alan and LCDR Mark Thomas, USN. "Reengineering the Naval Ship Concept Design Process." 1998.

3. Brown, A.J., "Ship Design Notes", Virginia Tech AOE Department, 2006.

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

5. Clancy, Tom. "SUBMARINE: A guided Tour Inside a Nuclear Warship." Berkley; New York, New York. 1993.

6. *Federation of American Scientists*. Federation of American Scientists. 10/05-12/05 <http://www.fas.org/main/home.jsp>.

7. Jackson, Captain. "Submarine Design Notes," MIT.

8. "Military.com." Equipment Guide. 10/05-12/05 <www.military.com>

9. Minnick, Lisa. "A Parametric Model for Predicting Submarine Dynamic Stability in Early Stage Design", Unpublished Master's Thesis, Virginia Tech AOE Department, 2006.

10. *Naval Source*. Naval History. 10/05-12/05 <www.navsource.org>

11. Pearson and Walters. "Warship '99: Naval Submarines 6"

12. "US Navy Shipboard Combat Systems." 2004. Global Security.org. 10/04-12/04 <http://www.globalsecurity.org/military/systems/ship/systems/index.html>.

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

14. Van Blarcom, et al. "Scale Model Testing of a Commercial Rim-Driven Propulsor Pod", *Journal of Ship Production*, Vol. 19, No. 2, May 1, 2003.

15. Watts, Anthony J. "Janes Underwater Warfare Systems 2005-2006." Biddles Limited. Alexandria, Virginia. 2005.

16. *Zebra Battery Fact Sheet*. 2002. www.rolls-royce.com

## Appendix A – Initial Capabilities Document (ICD)

UNCLASSIFIED

# INITIAL CAPABILITIES DOCUMENT

FOR A

# Ballistic Missile Defense Submarine (SSBMD)

## 1. PRIMARY JOINT FUNCTIONAL AREA

Force and Homeland Protection - The range of military application for the functions in this ICD includes: force protection; and protection of homeland and critical bases from the sea. Timeframe considered: 2015-2050. This extended timeframe demands flexibility in upgrade and capability over time.

## 2. REQUIRED FORCE CAPABILITY(S)

- Project defense around friends, joint forces and critical bases of operations at sea.
- Provide a covert sea-based layer of homeland defense.

## 3. CONCEPT OF OPERATIONS SUMMARY

A covert missile interceptor/strike platform would deploy on-station in sensitive and vulnerable remote regions, ready to provide immediate, time sensitive BMD, anti-air, anti-surface and inland missile strikes, using TLAM, anti-air, anti-ship, and BMD interceptor missiles, in support of battle groups, amphibious operations, homeland ballistic missile defense, and other national objectives.

Current Aegis surface ships are to be configured to intercept short and medium-range BM threats, but can not counter long-range intercontinental ballistic missiles that could target the US from China, North Korea and Iran. Land-based and space-based sensors and defense systems may not be in advantageous positions to launch intercept missiles to counter ballistic missile threats including ICBMs.

Potential strengths of SSBMD include the ability to launch intercept missiles from advantageous locations at sea that are inaccessible to ground and space-based systems, the ability to operate in forward locations in international waters without permission from foreign governments, and the ability to readily move to new maritime locations as needed. SSBMD would operate submerged and quiet, making it very difficult to detect and less provocative. SSBMD could readily move to respond to changing demands for BMD capabilities or to evade detection and targeting by enemy forces, and could do so without placing demands on other assets. Better locations might lie along a ballistic missile's potential flight path which can facilitate tracking and intercepting the attacking missile. If a potential adversary's ballistic missile launchers are relatively close to its coast, SSBMD could defend a large down-range territory against potential attack by ballistic missiles fired from those launchers. SSBMD could be equipped with very fast interceptors (i.e., interceptors faster than those the Navy is currently deploying), and could intercept ballistic missiles fired from launchers during the missiles' boost phase of flight — the initial phase, during which the ballistic missiles' rocket engines are burning. A ballistic missile in the boost phase of flight is a relatively large, hot-burning target, is easier to intercept (in part because the missile is flying relatively slowly and is readily seen by radar), and the debris from a missile intercepted during its boost phase is more likely to fall on the adversary.

Potential limitations of SSBMD include the requirement for radar queing from surface ship, land-based or space-based sensors and adequate command and control connectivity to support targeting.

Critical capabilities for SSBMD include adequate capacity for missiles with robust ICBM BMD terminal, mid-course, and potentially boost-phase capability, and effective command and control connectivity. The SM-3 Block IA missile is equipped with a kinetic (i.e., non-explosive) warhead designed to destroy a ballistic missile's warhead by colliding with it outside the atmosphere, during the enemy missile's midcourse phase of flight. It is intended to intercept SRBMs and MRBMs. An improved version, the Block IB, is to offer some capability for intercepting intermediate-range ballistic missiles (IRBMs). The Block IA and IB do not fly fast enough to offer a substantial capability for intercepting ICBMs. A faster-flying version of the SM-3, the Block II/IIA, is being developed. Block II/IIA is intended to give Aegis BMD ships a capability for intercepting certain ICBMs. The Block II version of the SM-3 will be available around 2013, and the Block IIA version in 2015. In contrast to the Block IA/1B version of the SM-3, which has a 21-inchdiameter booster stage but is 13.5 inches in diameter along the remainder of its length, the Block II/IIA version would have a 21-inch diameter along its entire length. The increase in diameter to a uniform 21 inches gives the missile a burnout velocity (a maximum velocity, reached at the time the propulsion stack burns out) that is 45% to 60% greater than that of the Block IA/IB version. The Block IIA version also includes an improved kinetic warhead. MDA states that the Block II/IIA version will "engage many [ballistic missile] targets that would outpace, fly over, or be beyond the engagement range" of earlier versions of the SM-3, and that the net result, when coupled with enhanced discrimination capability, is more types and ranges of engageable [ballistic missile] targets; with greater probability of kill, and a large increase in defended "footprint".

A more robust ICBM defense missile capability could include a system using a modified version of the Army's Patriot Advanced Capability-3 (PAC-3) interceptor or a system using a modified version of the SM-6 Extended Range Active Missile (SM-6 ERAM) air defense missile being developed by the Navy. These missiles could also provide a terminal phase capability. A full capability for intercepting missiles in the terminal phase could prove critical for intercepting missiles such as SRBMs or ballistic missiles fired along depressed trajectories that do not fly high enough to exit the atmosphere and consequently cannot be intercepted by the SM-3. They could also provide a more robust ability to counter potential Chinese TBMs equipped with maneuverable reentry vehicles (MaRVs) capable of hitting moving ships at sea.

The Kinetic Energy Interceptor (KEI) is a potential ballistic missile interceptor that, although large, could be used as a sea-based interceptor. Compared to the SM-3, the KEI would be much larger (perhaps 40 inches in diameter and 36 feet in length) and would have a much higher burnout velocity. Because of its much higher burnout velocity, it might be possible to use a KEI to intercept ballistic missiles during the boost and early ascent phases of their flights.

It would be advantageous for SSBMD to be non-nuclear to avoid placing nuclear assets in sensitive and potentially exposed locations and to minimize the acquisition cost of a submarine asset designed primarily to sit quiet and wait with minimal need for multi-mission capabilities.

# 4. CAPABILITY GAP(S)

The overarching capability gap addressed by this ICD is to provide a robust/covert ballistic missile interceptor platform, SSBMD:

Specific capability gaps and requirements include:

| Priority | Capability Description | Threshold Systems or metric | Goal Systems or metric |
|---|---|---|---|
| 1 | Missile Cells | SM-3 capable | KEI capable |
| 2 | BMD Missile Capacity | 16 SM-3 | 16 SM-3, 4 KEI |
| 3 | C4I / Data Link | Current Virginia Class | More capable |
| 4 | Mobility | Depth=500ft<br>Sprint speed=15knt<br>Snorkel range=5000nm@12knt<br>AIP=20days@5knt<br>Sprint Duration=1 hour | Depth=1000ft<br>Sprint speed=22knt<br>Snorkel range=6000nm@12knt<br>AIP=30days@5knt<br>Sprint Duration=1.5 hours |
| 5 | ASW, ASUW – primarily self defense | SUBTICS (Thales): Passive Cylindrical bow array, PVDF planar flank arrays, sail and chin-arrays; 4 external encapsulated torpedoes | BQQ-10 Bow Dome Passive/Active, LWWAA, BSY-2, sail and chin-arrays; torpedoes; 2x21inch tubes, 8 reloads |

# 5. THREAT AND OPERATIONAL ENVIRONMENT

Ballistic missiles armed with WMD payloads pose a strategic threat to the United States. This is not a distant threat. A new strategic environment now gives emerging ballistic missile powers the capacity, through a combination of domestic development and foreign assistance, to acquire the means to strike the U.S. within about five years of a decision to acquire such a capability. During several of those years, the U.S. might not be aware that such a decision had been made. Available alternative means of delivery can shorten the warning time of deployment nearly to zero. The threat is exacerbated by the ability of both existing and emerging ballistic missile powers to hide their activities from the U.S. and to deceive the U.S. about the pace, scope and direction of their development and proliferation programs.

Twenty-first-century threats to the United States, its deployed forces, and its friends and allies differ fundamentally from those of the Cold War. An unprecedented number of international actors have now acquired – or are seeking to acquire – missiles. These include not only states, but also non-state groups interested in obtaining missiles with nuclear or other payloads. The spectrum encompasses the missile arsenals already in the hands of Russia and China, as well as the emerging arsenals of a number of hostile states. The character of this threat has also changed. Unlike the Soviet Union, these newer missile possessors do not attempt to match U.S. systems, either in quality or in quantity. Instead, their missiles are designed to inflict major devastation without necessarily possessing the accuracy associated with the U.S. and Soviet nuclear arsenals of the Cold War.

The warning time that the United States might have before the deployment of such capabilities by a hostile state, or even a terrorist actor, is eroding as a result of several factors, including the widespread availability of technologies to build missiles and the resulting possibility that an entire system might be acquired. Would-be possessors do not have to engage in the protracted process of designing and building a missile. They could purchase and assemble components or reverse-engineer a missile after having purchased a prototype, or immediately acquire a number of assembled missiles. Even missiles that are primitive by U.S. standards might suffice for a rogue state or terrorist organization seeking to inflict extensive damage upon the United States.

A successfully launched short or long range ballistic missile has a high probability of delivering its payload to its target compared to other means of delivery. Emerging powers therefore see ballistic missiles as highly effective deterrent weapons and as an effective means of coercing or intimidating adversaries, including the United States. The basis of most missile developments by emerging ballistic missile powers is the Soviet Scud missile and its derivatives. The Scud is derived from the World War II-era German V-2 rocket. With the external help now readily available, a nation with a well-developed, Scud-based ballistic missile infrastructure would be able to achieve first flight of a long range missile, up to and including intercontinental ballistic missile (ICBM) range (greater than 5,500 km), within about five years of deciding to do so. During several of those years the U.S. might not be aware that such a decision had been made. Early production models would probably be limited in number. They would be unlikely to meet U.S. standards of safety, accuracy and reliability. But the purposes of these nations would not require such standards. A larger force armed with scores of missiles and warheads and meeting higher operational standards would take somewhat longer to test, produce and deploy. But meanwhile, even a few of the simpler missiles could be highly effective for the purposes of those countries.

The extraordinary level of resources North Korea and Iran are now devoting to developing their own ballistic missile capabilities poses a substantial and immediate danger to the U.S., its vital interests and its allies. While these nations' missile programs may presently be aimed primarily at regional adversaries, they inevitably and inescapably engage the vital interests of the U.S. as well. Their targeted adversaries include key U.S. friends and allies. U.S. deployed forces are already at risk from these nations' growing arsenals. Each of these nations places a high priority on threatening U.S. territory, and each is even now pursuing advanced ballistic missile capabilities to pose a direct threat to U.S. territory.

Since many potentially unstable nations are located on or near geographically constrained (littoral) bodies of water, the tactical picture may be at smaller scales relative to open ocean warfare. Threats in such an environment include:

- 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).

The sea-based environment for BMD varies greatly depending on the most strategic and effective location necessary to counter a particular threat. It includes:

- Open ocean (sea states 0 through 9) and littoral
- Shallow and deep water
- Noisy and reverberation-limited

- Crowded shipping
- Dense contacts and threats with complicated targeting
- Biological, chemical and nuclear weapons
- All-Weather

# 6. FUNCTIONAL SOLUTION ANALYSIS SUMMARY.

Non-Materiel Approaches (DOTMLPF Analysis).

- Use surface-ship SPY-3/MK-57 VLS DDG1000 technology; use space-based and land-based systems for terminal phase and robust ICBMD, no submarine assets
- Increase reliance on foreign BMD support (Japan, etc.) to meet the interests of the U.S.

Materiel Approaches.

- Design and build new large (25000 lton) nuclear CGNX for BMD
- Design and build modified LPD-17 for BMD
- Upgrade and extend service life of CG-52 ships with increased BMD capability
- Design and build entire new CGX/BMD ship with limited multi-mission capability
- Design and build new CGX/BMD ship with maximum DDG1000 commonality
- Use/modify existing SSN and SSBN assets for BMD
- Design and build a new SSBMD

# 7. FINAL RECOMMENDATIONS.

a. Non-material solutions are not consistent with national policy.
b. Surface ship options to not provide covert platform with potential for optimum targeting angles and proximity.
c. SSN and SSBN options put nuclear, high value, high manning assets in sensitive and vulnerable locations with a high acquisition / conversion cost.
d. SSBMD offers potential for a covert, relatively low cost, low manning, non-nuclear platform, able to deliver BMD interceptor missiles with external cueing, able to respond to changing demands for BMD capabilities or to evade detection and targeting by enemy forces.

# Appendix B - Acquisition Decision Memorandum (ADM)

Virginia Tech

VIRGINIA POLYTECHNIC INSTITUTE
AND STATE UNIVERSITY

Aerospace and Ocean Engineering

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: SSBMD Design Teams

Subject: ACQUISITION DECISION MEMORANDUM FOR a Ballistic Missile Defense Submarine

Ref: (a) Virginia Tech SSBMD 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 21 August 2007. 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 and launch ballistic missile defense interceptor missiles. 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. Basic cost of construction (BCC) shall not exceed $1.5B ($FY2012). It is expected that 10 ships of this type will be built with IOC in 2018.
3. The AOA shall be conducted in accordance with the Virginia Tech Concept Exploration process.

A.J. Brown
VT Acquisition Executive

## Appendix C - Operational Requirements Document (ORD)

# CAPABILITY DEVELOPMENT DOCUMENT

FOR

# Ballistic Missile Defense Submarine (SSBMD)

## 1. Capability Discussion

The Initial Capabilities Document (ICD) associated with this CDD was issued by the Virginia Tech Acquisition Authority on 21 August 2007. The required functions in this ICD include: Sea-based ballistic missile defense for protection of homeland and critical bases without endangering US nuclear assets. SSBMD will support ballistic missile defense around allies, joint forces, and critical bases of operations at sea. In addition, SSBMD will act as a platform for covert sea-based homeland defense. It will have modular functionality in order to upgrade technologies as mission requirements change throughout the submarine's operational lifetime. All of these requirements must be met while maintaining a self-defense capability from surface and submarine threats. Specific Capability Gaps specified in the ICD with goals and thresholds are summarized in Table 1.

**Table 1 - Specific Capability Gaps**

| Priority | Capability Description | Threshold Systems or metric | Goal Systems or metric |
|---|---|---|---|
| 1 | Missile Cells | SM-3 capable | KEI capable |
| 2 | BMD Missile Capacity | 8 SM-3 | 16 SM-3, 2 KEI |
| 3 | C4I / Data Link | Current Virginia Class | More capable |
| 4 | Mobility | Depth=500ft<br>Sprint speed=15knt<br>Snorkel range=5000nm@12knt<br>AIP=20days@5knt<br>Sprint Duration=0.5 hour | Depth=1000ft<br>Sprint speed=22knt<br>Snorkel range=6000nm@12knt<br>AIP=30days@5knt<br>Sprint Duration=1.0 hours |
| 5 | ASW, ASUW – primarily self defense | SUBTICS (Thales): Passive Cylindrical bow array, PVDF planar flank arrays, sail and chin-arrays; 4 external encapsulated torpedoes | BQQ-10 Bow Dome Passive/Active, LWWAA, BSY-2, sail and chin-arrays; torpedoes; 4x21inch tubes, 12 reloads |

## 2. Acquisition Decision Memorandum

An SSBMD Acquisition Decision Memorandum was issued on 21 August 2007 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 ballistic missile defense. Required capabilities are BMD, stealth, ISR, mobility, ASW, ASUW. The design must minimize personnel vulnerability in combat through automation, innovative concepts for minimum crew size, and signature reduction.

Concept Exploration was conducted from 4 September 2007 through 5 December 2007. 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 submarine 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 submarine 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. Effectiveness is represented by an Overall Measure of Effectiveness (OMOE), cost by Basic Cost of Construction (CBCC, $M), and risk by an Overall Measure of Risk (OMOR).

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 preferred non-dominated **design selected for Virginia Tech Team 1, and specified in this CDD, is the high end design shown with a circle in Figure 1**. Selection of a point on the non-dominated frontier specifies requirements, technologies and the baseline design.

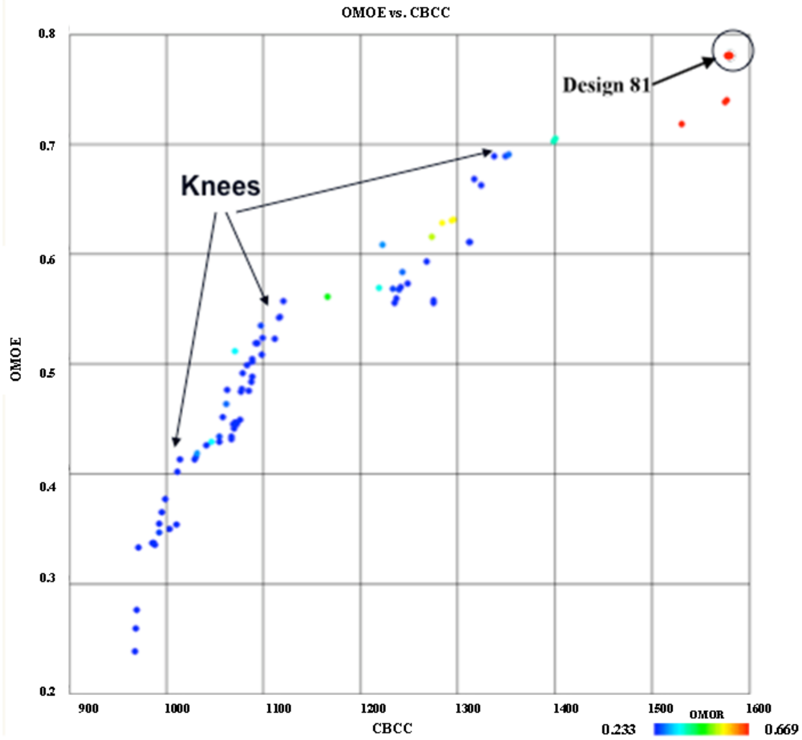



**Figure 1 – SSBMD Non-Dominated Frontier**

## 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: 2015-2050. 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.

SSBMD must: protect homeland, critical bases, and US forces with effective cued ballistic missile engagement; and leverage information technology in the execution and support of flexible BMD missions. SSBMD must also be able to support, maintain and conduct persistent surveillance operations with the most technologically advanced unmanned/remotely controlled tactical and $C^4$/I reconnaissance vehicles. SSBMD must possess sufficient mobility, self-defense capabilities, and endurance to perform all missions on extremely short notice, at locations far removed from home port. To accomplish this, SSBMD must be pre-deployed, virtually on station, in sufficient numbers around the world.

Missions specified for SSBMD include:

- Ballistic Missile Defense (BMD)
- Strike (TLAM)
- Intelligence, Surveillance and Reconnaissance (ISR)
- Anti-submarine (ASW) and Anti-surface (ASuW) Warfare

- Special Warfare (SPW)

## 4. Threat Summary

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:

- 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).
- Unstable or rogue nations and terrorists able to easily access missiles capable of inflicting extensive damage on the United States. Three main threats include: (1) biological, (2) chemical, and (3) nuclear weapons attached to missiles. 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 sea-based environment for BMD varies greatly depending on the most strategic and effective location necessary to counter a particular threat. It includes:

- Open ocean (sea states 0 through 9) and littoral
- Shallow and deep water
- Noisy and reverberation-limited
- Crowded shipping
- Dense contact and threat with complicated targeting
- Biological, chemical, and nuclear weapons
- All-Weather

## 5. Required System Capabilities and Characteristics

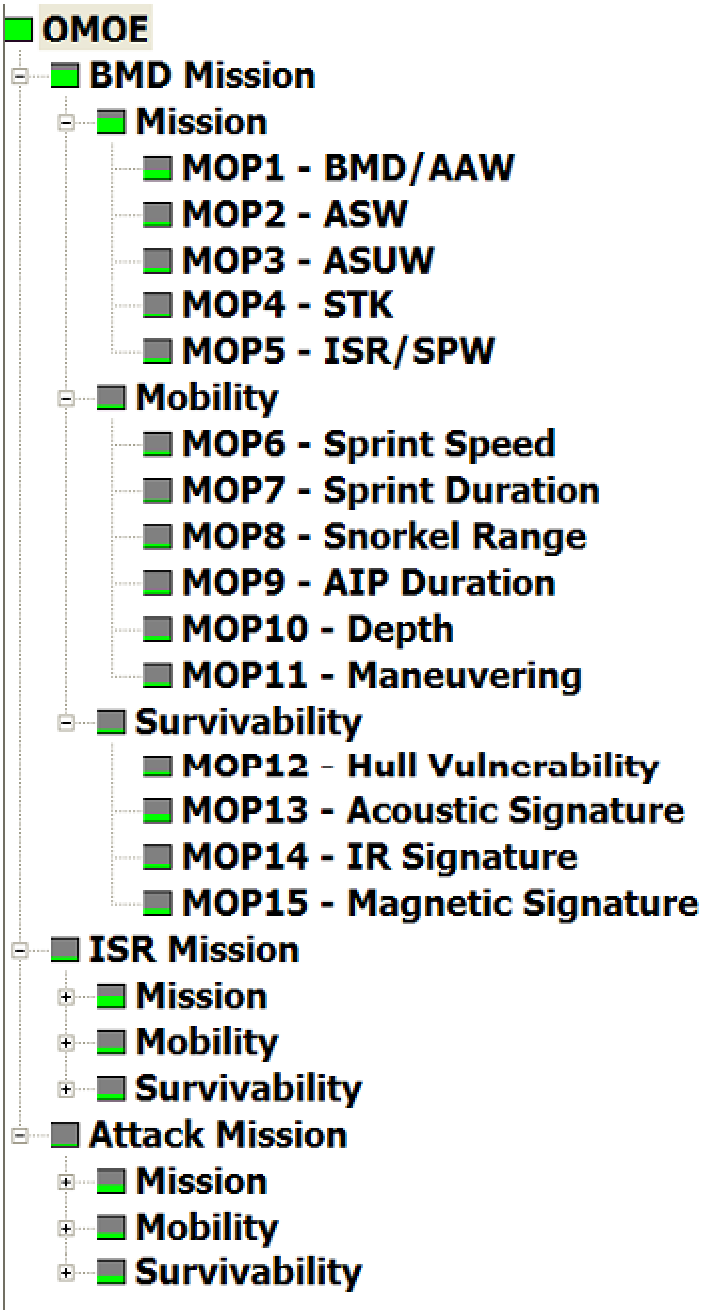
**Table 2 System Capabilities and Characteristics**

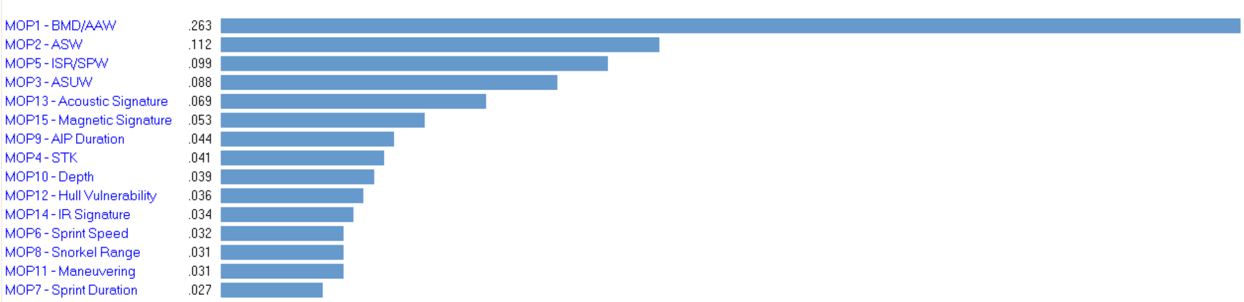
| Key Performance Parameter (KPP) | Development Threshold or Requirement |
|---|---|
| Mission Payload | Reconfigurable torpedo room, 2x21” tubes, 8 reloads; 16 Cell VLS (16 SM-3) + 4 KEI missile cells |
| Propulsion | Open Cycle Diesel w/AIP, 2xCAT 3512 V12 + 2x500kW PEM fuel cells w/methanol reformers; 5000kW-hr Zebra batteries, Shrouded Propeller |
| Mobility | Depth = 570 feet<br>Sprint speed = 22 knots<br>Snorkel range = 5180 nm @ 12 knots<br>AIP = 24 days @ 15 knots<br>Sprint duration = 0.6 hour |
| Combat Systems | ISUS-90 Combat System; EDO bow dome, towed and flank arrays; sail and chin arrays |
| SAIL | 4xKEI in sail, BPS-16 Radar; 2xAN/BRA-34 radar; 2xAN/BVS-1 Photonics mast; 2xEHF/SHF HDR Multiband; Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA |

## 6. Program Requirements

The basic cost of construction will not exceed $1.6B. It is expected that initial operational capability for SSBMD will be 2018.

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



# Appendix E – Machinery Equipment List

| QTY | DESCRIPTION | LOCATION | SWBS | UNIT WEIGHT (lton) | POWER REQD (kW) | REMARKS | DIMENSIONS (ft) |
|---|---|---|---|---|---|---|---|
| | **Propulsion and Power** | | | | | | |
| 2 | PEM Fuel Cell | Fuel cell room | 235 | 8.5 | - | PEM type | 8x8x7 |
| 2 | Caterpillar 3512 V12 Diesel Generator (AC) | Main Prop Diesel room | 230 | 54 | - | Open Cycle | 16x14x12 |
| 1 | Machinery Control/Switchboard | Engineering Control Center | 310 | 1.5 | 6 | | 3x7x6 |
| 1 | Battery Bank | Aux 3 | 220 | 78.5 | - | Zebra Lead Acid | 22x17x7 |
| 1 | Main DC Switchboard (557v) | Engineering Control Center | 320 | 5 | 2 | | |
| 1 | Emergency Switchboard | Reformer room | 320 | 1 | 2 | | |
| 6 | Cryogenic Liquid Oxygen Tank | LOX tank rooms | 520 | 35 | - | Cylindrical tank | 7 DIA x 27 |
| 2 | AC to DC transformers | Reformer room | 310 | 6 | 4 | | 3x4x4 |
| 1 | AC Permanent Magnet Main Motor | Main Motor room | 300 | 67 | 6 | Includes Inverters | 8 DIA x 6 |
| 1 | LED Lighting Panel | Engineering Control Center | 300 | 0.05 | 1 | | 1x2x3 |
| 2 | Start Air Receiver | Main Prop Diesel room | 250 | 0.33 | - | | 3 DIA x 4 |
| 1 | Degaussing | - | 475 | 10.43 | 10 | | distributed |
| | **Fuel Transfer** | | | | | | |
| 2 | Diesel FO Transfer Pump | Aux 4 | 250 | 0.06 | 1 | | 1x2x1 |
| 2 | Methanol Transfer Pump | Aux 4 | 250 | 0.06 | 1 | | 1x2x1 |
| 1 | Diesel FO Coalescer/Purifier | Aux 4 | 250 | 0.25 | - | | 1x4x4 |
| 1 | Methanol Coalescer/Purifier | Aux 4 | 250 | 0.25 | - | | 1x4x4 |
| | **Lube/Dirty Oil Purifcation** | | | | | | |
| 2 | LO Purifier | Main Prop Diesel room | 250 | 0.5 | 3 | pneumatic transfer pump | 2x3x3 |
| 1 | Oily Water Separator | Main Prop Diesel room | 250 | 0.5 | 2 | pneumatic transfer pump | 2 DIA x 3 |
| | **Control Surfaces** | | | | | | |
| 1 | X-tail Hydraulics | aft- external to pressure hull | 560 | 4 | - | actuator and linkage | 5x5x5 |
| 1 | Forward Planes | fwd- external to pressure hull | 560 | 2 | - | actuator and linkage | 5x5x5 |
| | **Compressed Air Systems** | | | | | | |
| 2 | High Pressure Air Compressor | Fuel Cell room | 550 | 0.5 | 7 | for MBT blow | 3x4x4 |
| 2 | High Pressure Air Receiver | Fore/Aft Main Ballast Tanks | 550 | 0.5 | - | for MBT blow | 2x6x5 |
| 1 | Low Pressure Sevice Air Compressor | Fuel Cell room | 550 | 0.5 | 5 | LP air for service, general | 3x4x4 |
| 1 | Low Pressure Sevice Air Receiver | Fuel Cell room | 550 | 0.33 | - | LP air for service, general | 3 DIA x 5 |
| | **Hydraulic Systems** | | | | | | |
| 2 | Hydraulic Pump | Aux 3 | 550 | 0.5 | 15 | | 2 DIA x 3 |
| 2 | Hydraulic Pressure Actuator | varies | 550 | varies | - | Actuators throughout boat | varies |
| 1 | Hydraulic Sump | Aux 3 | 550 | 0.1 | - | | 3x4x3 |

| QTY | DESCRIPTION | LOCATION | SWBS | UNIT WEIGHT (lton) | POWER REQD (kW) | REMARKS | DIMENSIONS (ft) |
|---|---|---|---|---|---|---|---|
| | **Potable Water** | | | | | | |
| 1 | Potable Water Pump | Aux 3 | 530 | 0.05 | 1.5 | | 1x2x2 |
| 1 | Hot Water Pump | Aux 3 | 530 | 0.05 | 1.5 | | 1x2x2 |
| 1 | Reverse Osmosis Water Purifier | Aux 3 | 530 | 0.33 | 4 | | 3x4x4 |
| 2 | Potable Water Pressure Tank | Aux 3 | 530 | 0.1 | - | 1 each for hot/cold water | 2 DIA x 4 |
| | **Salt Water** | | | | | | |
| 1 | Variable Ballast Manifold | Aux 4 | 520 | 0.05 | - | | 2x4x3 |
| 2 | Variable Ballast Pump | Aux 4 | 520 | 0.1 | 3 | | 1x2x2 |
| 2 | Bilge Pump | Aux 4, Aux 3 | 500 | 0.05 | 1.5 | | 1x1x2 |
| 2 | Main Diesel Salt Water Circ Pump | Main Prop Diesel room | 250 | 0.05 | - | Engine driven | 1x2x2 |
| 2 | Fire Pump | Main Prop Diesel room | 550 | 1.5 | 10 | | 3 DIA x 3 |
| | **Ventilation and Air Purification** | | | | | | |
| 2 | Main Induction Blower | Sail | 500 | 0.2 | 2.5 | operated while snorkeling | |
| 2 | Main Exhaust Fan | HVAC room | 500 | 0.2 | 2.5 | operated while snorkeling | |
| 2 | Ventilation Fan | HVAC room | 510 | 0.1 | 1.75 | operated while submerged | |
| 2 | CO2 Scrubber System | HVAC room | 510 | 0.25 | 0.75 | operated while submerged | |
| | **AC and Refrigeration** | | | | | | |
| 2 | AC Compressor Unit | HVAC room | 510 | 1.5 | 2 | | 3x5x4 |
| 2 | Chilled Water Pump | HVAC room | 510 | 0.1 | 0.5 | | 1x2x2 |
| 1 | Refrigeration Unit | Engineers Stores | 530 | 1.75 | 3 | Located beneath C/F stores | 4x5x4 |
| 1 | Chilled/Frozen Stores | Galley | 500 | - | - | Built into structure | 17x11x7 |
| | **Environmental Systems** | | | | | | |
| 1 | Trash Disposal Unit | Galley | 593 | 0.25 | 1.5 | | 3x3x3 |
| 1 | Sewage Vacuum System | Aux 3 | 593 | 2 | 0.5 | | 5 DIA x 6.5 |
| 2 | Waste Discharge Pump | Aux 3 | 593 | 0.05 | 0.5 | | 1x1x2 |

# Appendix F - Weights and Centers

| SWBS | COMPONENT | From Synthesis | WT-lton | VCG-ft | Moment | LCG-ft (fwdFP) | LCG-ft (fwdLCB) | Moment (fwdFP) | Moment (LCB) | TCG-ft | Moment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NSC | FULL LOAD WEIGHT | Wnsc | 4251.61 | -0.69 | -2938.36 | -116.01 | 2.38 | -493229.25 | 10131.36 | 0.00 | 0.00 |
| 9 | FULL LOADS | W9 | 1096.73 | 0.23 | 248.88 | -110.52 | 7.87 | -121213.27 | 8631.24 | 0.00 | 0.00 |
| A | LIGHTSHIP WEIGHT + LEAD | Wa | 3154.89 | -1.01 | -3187.24 | -117.92 | 0.48 | -372015.98 | 1500.11 | 0.00 | 0.00 |
| 8 | LEAD | W8 | 312.00 | -15.00 | -4680.00 | -85.00 | 33.39 | -26520.00 | 10418.57 | 0.00 | 0.00 |
| A-1 | LIGHTSHIP WEIGHT SWBS 1-7 | Wa1 | 2842.89 | 0.53 | 1492.76 | -121.53 | -3.14 | -345495.98 | -8918.46 | 0.00 | 0.00 |
| **100** | **HULL STRUCTURES** | **W1** | **939.82** | **-0.40** | **-380.62** | **-115.72** | 2.68 | **-108751.97** | 2515.98 | **0.00** | **0.00** |
| 110 | SHELL + SUPPORTS | | 557.73 | 0.00 | 0.00 | -116.96 | 1.44 | -65229.51 | 801.29 | 0.00 | 0.00 |
| 111 | PRESSURE HULL | Wph | 339.53 | 0.00 | 0.00 | -115.00 | 3.39 | -39045.56 | 1151.97 | 0.00 | 0.00 |
| 112 | NON-PRESSURE ENVELOPE | W112 | 181.83 | 0.00 | 0.00 | -120.00 | -1.61 | -21819.96 | -292.23 | 0.00 | 0.00 |
| 118 | NON-PRESSURE FRAMES | W118 | 36.37 | 0.00 | 0.00 | -120.00 | -1.61 | -4363.99 | -58.45 | 0.00 | 0.00 |
| 120 | PRESSURE HULL STRUCTURAL BULKHDS | | 20.45 | -0.66 | 70.05 | -124.21 | -5.82 | -2539.80 | -119.00 | 0.00 | 0.00 |
| 123 | TRUNKS | W123 | 6.29 | 18.60 | 116.92 | -128.50 | -10.11 | -807.76 | -63.53 | 0.00 | 0.00 |
| 125&6 | SOFT AND HARD TANKS | Wtanks | 14.16 | -3.31 | -46.87 | -122.31 | -3.92 | -1732.04 | -55.47 | 0.00 | 0.00 |
| 140 | PRESSURE HULL PLATFORMS/FLATS | Wdecks | 16.82 | -2.28 | -38.36 | -128.50 | -10.11 | -2161.77 | -170.03 | 0.00 | 0.00 |
| 160 | SPECIAL STRUCTURES | | 105.50 | 4.93 | 520.32 | -76.47 | 41.92 | -8067.89 | 4422.59 | 0.00 | 0.00 |
| 161 | COMBAT SYS STRUCTURE SUPPORT | WP100 | 84.50 | 2.69 | 227.31 | -70.55 | 47.84 | -5961.48 | 4042.72 | 0.00 | 0.00 |
| 163 | SEA CHESTS | Wsea | 0.64 | -3.50 | -2.23 | -110.00 | 8.39 | -70.22 | 5.36 | 0.00 | 0.00 |
| 167 | HULL CLOSURES | Wclose | 20.36 | 14.50 | 295.25 | -100.00 | 18.39 | -2036.20 | 374.51 | 0.00 | 0.00 |
| 180 | FOUNDATIONS | W180 | 233.16 | -4.00 | -932.63 | -128.50 | -10.11 | -29960.81 | -2356.56 | 0.00 | 0.00 |
| 190 | SPECIAL PURPOSE SYSTEMS | Wweld | 6.16 | 0.00 | 0.00 | -128.50 | -10.11 | -792.19 | -62.31 | 0.00 | 0.00 |
| **200** | **PROPULSION PLANT** | | **370.03** | **-1.46** | **-540.65** | **-178.86** | -60.47 | **-66183.23** | -22374.44 | **0.00** | **0.00** |
| 220 | MAIN PROPULSOR | Wbm | 81.98 | 2.26 | 185.09 | -192.00 | -73.61 | -14022.70 | -6034.52 | 0.00 | 0.00 |
| | DIESEL GENERATOR | Wbmdg | 53.44 | 5.60 | 299.26 | -170.00 | -51.61 | -9084.71 | -2757.86 | 0.00 | 0.00 |
| | FUEL CELL | Wbmaip | 28.54 | -4.00 | -114.17 | -173.00 | -54.61 | -4937.99 | -1558.67 | 0.00 | 0.00 |
| 230 | PROPULSION UNITS | Wprop | 12.68 | 0.00 | 0.00 | -256.00 | -137.61 | -3245.39 | -1744.49 | 0.00 | 0.00 |
| 240 | PROPULSION POWER TRANSMISSION | | 97.85 | 0.00 | 0.00 | -249.28 | -130.89 | -24393.11 | -12807.98 | 0.00 | 0.00 |
| | | Wshaft | 24.77 | 0.00 | 0.00 | -229.00 | -110.61 | -5671.87 | -2739.52 | 0.00 | 0.00 |
| | | Wbearing | 5.82 | 0.00 | 0.00 | -229.00 | -110.61 | -1332.89 | -643.79 | 0.00 | 0.00 |
| | | Wmotor | 67.26 | 0.00 | 0.00 | -194.00 | -75.61 | -13049.36 | -5085.70 | 0.00 | 0.00 |
| 250 | SUPPORT SYSTEMS | | 174.44 | -4.10 | -715.47 | -138.28 | -19.89 | -24121.72 | -3469.71 | 0.00 | 0.00 |
| | ARGON TANKS | Wars | 0.00 | 0.00 | 0.00 | 0.00 | 118.39 | 0.00 | 0.00 | 0.00 | 0.00 |
| | OXYGEN TANKS | Wo2s | 54.88 | 5.80 | 318.29 | -145.00 | -26.61 | -7957.32 | -1460.15 | 0.00 | 0.00 |
| | HYDROGEN TANKS | Wh2s | 0.00 | 0.00 | 0.00 | 0.00 | 118.39 | 0.00 | 0.00 | 0.00 | 0.00 |
| | BATTERY | Wbattery | 78.50 | -9.90 | -777.15 | -117.00 | 1.39 | -9184.50 | 109.34 | 0.00 | 0.00 |
| 256 | SALTWATER CIRC | Wswc | 30.79 | -5.00 | -153.97 | -170.00 | -51.61 | -5234.93 | -1589.17 | 0.00 | 0.00 |
| 257 | FRESH WATER CIRC | Wfwc | 10.26 | -10.00 | -102.65 | -170.00 | -51.61 | -1744.98 | -529.72 | 0.00 | 0.00 |
| 290 | SPECIAL PURPOSE SYSTEMS | | 3.08 | -3.33 | -10.26 | -130.00 | -11.61 | -400.32 | -35.74 | 0.00 | 0.00 |
| 298 | FLUIDS | W2fluids | 2.05 | 0.00 | 0.00 | -128.50 | -10.11 | -263.80 | -20.75 | 0.00 | 0.00 |
| 299 | PARTS | W2parts | 1.03 | -10.00 | -10.26 | -133.00 | -14.61 | -136.52 | -14.99 | 0.00 | 0.00 |
| **SWBS** | **COMPONENT** | **From Synthesis** | **WT-lton** | **VCG-ft** | **Moment** | **LCG-ft (fwdFP)** | **LCG-ft (fwdLCB)** | **Moment (fwdFP)** | **Moment (LCB)** | **TCG-ft** | **Moment** |
| **300** | **ELECTRIC PLANT, GENERAL** | | **70.39** | **-1.71** | **-120.50** | **-133.87** | -15.48 | **-9423.69** | -1089.54 | **0.00** | **0.00** |
| 310 | ELECTRIC POWER GENERATION | | 30.12 | -4.00 | -120.50 | -140.00 | -21.61 | -4217.45 | -650.91 | 0.00 | 0.00 |
| 312 | EMERGENCY DIESEL GENERTOR | Wemerg | 0.00 | 0.00 | 0.00 | 0.00 | 118.39 | 0.00 | 0.00 | 0.00 | 0.00 |
| 314 | POWER CONVERSION | Wconv | 30.12 | -4.00 | -120.50 | -140.00 | -21.61 | -4217.45 | -650.91 | 0.00 | 0.00 |
| 320 | ELECTRICAL DISTRIBUTION SYSTEM | | 24.76 | 0.00 | 0.00 | -129.78 | -11.38 | -3212.75 | -281.84 | 0.00 | 0.00 |
| 321 | POWER CABLE | Wcab | 15.72 | 0.00 | 0.00 | -128.50 | -10.11 | -2019.82 | -158.87 | 0.00 | 0.00 |
| 324 | SWITCH GEAR | Wswitch | 9.04 | 0.00 | 0.00 | -132.00 | -13.61 | -1192.93 | -122.97 | 0.00 | 0.00 |
| 330 | LIGHTING SYSTEM | Wlight | 15.51 | 0.00 | 0.00 | -128.50 | -10.11 | -1993.49 | -156.80 | 0.00 | 0.00 |
| 340 | POWER GENERATION SUPPORT SYS | | 0.00 | 0.00 | 0.00 | 0.00 | 118.39 | 0.00 | 0.00 | 0.00 | 0.00 |
| 390 | SPECIAL PURPOSE SYSTEMS | | 0.00 | 0.00 | 0.00 | 0.00 | 118.39 | 0.00 | 0.00 | 0.00 | 0.00 |
| **400** | **COMMAND + SURVEILLANCE** | | **269.38** | 1.18 | **318.06** | -34.00 | 84.40 | **-9158.00** | 22734.18 | 0.00 | **0.00** |
| 420 | NAVIGATION SYSTEMS | Wco | 20.68 | 3.00 | 62.05 | -88.00 | 30.39 | -1820.25 | 628.67 | 0.00 | 0.00 |
| 430 | INTERIOR COMMUNICATIONS | Wic | 8.67 | 0.00 | 0.00 | -125.00 | -6.61 | -1083.90 | -57.29 | 0.00 | 0.00 |
| 440 | EXTERIOR COMMUNICATIONS | Want | 1.65 | 20.00 | 33.00 | -91.00 | 27.39 | -150.15 | 45.20 | 0.00 | 0.00 |
| 450 | SURF SURVEILLANCE SYS (RADAR) | Wradar | 7.10 | 20.00 | 142.00 | -78.00 | 40.39 | -553.80 | 286.79 | 0.00 | 0.00 |
| 460 | UNDERWATER SURVEILLANCE SYS | Wsonar | 201.00 | 0.00 | 0.00 | -12.00 | 106.39 | -2412.00 | 21384.97 | 0.00 | 0.00 |
| 475 | DEGAUSSING | Wdegaus | 10.34 | 0.00 | 0.00 | -130.00 | -11.61 | -1344.20 | -120.02 | 0.00 | 0.00 |
| 480 | FIRE CONTROL SYSTEMS | Wcc | 2.33 | -3.00 | -6.99 | -90.00 | 28.39 | -209.70 | 66.16 | 0.00 | 0.00 |
| 490 | SPECIAL PURPOSE SYSTEMS | Wper | 17.60 | 5.00 | 88.00 | -90.00 | 28.39 | -1584.00 | 499.71 | 0.00 | 0.00 |

| SWBS | COMPONENT | From Synthesis | WT-lton | VCG-ft | Moment | LCG-ft (fwdFP) | LCG-ft (fwdLCB) | Moment (fwdFP) | Moment (LCB) | TCG-ft | Moment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **500** | **AUXILIARY SYSTEM, GENERAL** | | **363.75** | -0.89 | **-324.50** | -118.19 | 0.20 | **-42993.12** | 72.17 | 0.00 | **0.00** |
| 510 | CLIMATE CONTROL | | 59.04 | 4.52 | 267.01 | -121.04 | -2.64 | -7145.73 | -156.15 | 0.00 | 0.00 |
| 512 | VENTILATION | Wvent | 14.69 | 10.40 | 152.81 | -130.00 | -11.61 | -1910.13 | -170.55 | 0.00 | 0.00 |
| 514 | AIR CONDITIONING | Wac | 14.69 | 9.00 | 132.24 | -130.00 | -11.61 | -1910.13 | -170.55 | 0.00 | 0.00 |
| 515 | AIR REVITALIZATION | Warevit | 9.30 | 9.00 | 83.70 | -130.00 | -11.61 | -1209.07 | -107.95 | 0.00 | 0.00 |
| 516 | REFRIGERATION | Wrefer | 20.35 | -5.00 | -101.75 | -104.00 | 14.39 | -2116.40 | 292.89 | 0.00 | 0.00 |
| 520 | SEA WATER SYSTEMS | | 31.26 | -13.81 | -431.82 | -68.00 | 50.39 | -2125.91 | 1575.45 | 0.00 | 0.00 |
| 524 | AUXILIARY SALTWATER | Wauxsw | 3.71 | -5.00 | -18.57 | -68.00 | 50.39 | -252.51 | 187.13 | 0.00 | 0.00 |
| 528 | DRAINAGE | Wdrain | 27.55 | -15.00 | -413.25 | -68.00 | 50.39 | -1873.40 | 1388.32 | 0.00 | 0.00 |
| 530 | FRESH WATER SYSTEMS | | 12.46 | 0.43 | 5.38 | -102.79 | 15.60 | -1280.37 | 194.32 | 0.00 | 0.00 |
| 531 | DISTILLERS | Wdist | 4.25 | 0.00 | 0.00 | -68.00 | 50.39 | -288.99 | 214.16 | 0.00 | 0.00 |
| 532 | FW COOLING | Wcool | 6.91 | 3.00 | 20.72 | -130.00 | -11.61 | -897.76 | -80.16 | 0.00 | 0.00 |
| 533 | POTABLE WATER SYSTEM | Wpotw | 1.30 | -11.80 | -15.34 | -72.00 | 46.39 | -93.61 | 60.32 | 0.00 | 0.00 |
| 540 | FUELS/LUBRICANTS, HANDLING+STOWAGE | | 28.50 | -10.70 | -304.95 | -172.00 | -53.61 | -4902.00 | -1527.80 | 0.00 | 0.00 |
| 541 | FUEL SERVICE TANKS | Wfuelt | 28.50 | -10.70 | -304.95 | -172.00 | -53.61 | -4902.00 | -1527.80 | 0.00 | 0.00 |
| 550 | AIR,GAS+MISC FLUID SYSTEM | | 25.32 | 2.20 | 55.78 | -130.00 | -11.61 | -3291.35 | -293.87 | 0.00 | 0.00 |
| 551 | NITROGEN BOTTLES | WcN2 | 0.00 | 0.00 | 0.00 | -130.00 | -11.61 | 0.00 | 0.00 | 0.00 | 0.00 |
| 554 | MBT BLOW AIR | Wmbtblow | 5.58 | 10.00 | 55.78 | -130.00 | -11.61 | -725.16 | -64.75 | 0.00 | 0.00 |
| 555 | FIREFIGHTING SYSTEMS | Wfire | 3.04 | 0.00 | 0.00 | -130.00 | -11.61 | -395.59 | -35.32 | 0.00 | 0.00 |
| 556 | HYDRAULIC SYSTEMS | Whyd | 16.70 | 0.00 | 0.00 | -130.00 | -11.61 | -2170.61 | -193.80 | 0.00 | 0.00 |
| 560 | SHIP CNTL SYS | | 44.37 | -0.88 | -38.90 | -103.42 | 14.97 | -4589.16 | 664.46 | 0.00 | 0.00 |
| 561 | STEERING | Wsteer | 5.87 | 0.00 | 0.00 | -255.00 | -136.61 | -1495.99 | -801.43 | 0.00 | 0.00 |
| 563 | DEPTH CONTROL | Wdepth | 2.37 | 0.00 | 0.00 | -255.00 | -136.61 | -604.35 | -323.76 | 0.00 | 0.00 |
| 564 | TRIM SYSTEMS | Wtrim | 4.28 | -10.40 | -44.54 | -144.00 | -25.61 | -616.66 | -109.66 | 0.00 | 0.00 |
| 566 | DIVING PLANES | Wplanes | 29.98 | 0.00 | 0.00 | -57.00 | 61.39 | -1708.60 | 1840.28 | 0.00 | 0.00 |
| 569 | CONTROL | Wcont | 1.88 | 3.00 | 5.64 | -87.00 | 31.39 | -163.56 | 59.02 | 0.00 | 0.00 |
| 580 | ANCHOR, MOORING, HANDLING+STOWAGE | | 6.90 | 15.57 | 107.40 | -69.65 | 48.74 | -480.60 | 336.31 | 0.00 | 0.00 |
| 581 | ANCHOR HANDLING | Wanchor | 1.20 | -8.00 | -9.60 | -36.00 | 82.39 | -43.20 | 98.87 | 0.00 | 0.00 |
| 582 | MOORING | Wmoor | 1.20 | 15.00 | 18.00 | -57.00 | 61.39 | -68.40 | 73.67 | 0.00 | 0.00 |
| 585 | MAST | Wmast | 4.50 | 22.00 | 99.00 | -82.00 | 36.39 | -369.00 | 163.77 | 0.00 | 0.00 |
| 590 | ENVIRONMENTAL + AUX SYSTEMS | | 155.90 | 0.10 | 15.60 | -123.01 | -4.62 | -19178.00 | -720.55 | 0.00 | 0.00 |
| 591 | MISCELANEOUS MISSION AUX SYSTEMS | Wp500 | 152.60 | 0.00 | 0.00 | -123.00 | -4.61 | -18769.80 | -703.05 | 0.00 | 0.00 |
| 592 | DIVING SYSTEMS | Wdiver | 1.30 | 12.00 | 15.60 | -114.00 | 4.39 | -148.20 | 5.71 | 0.00 | 0.00 |
| 593 | ENVIRONMENTAL SYSTEMS | Wenv | 2.00 | 0.00 | 0.00 | -130.00 | -11.61 | -260.00 | -23.21 | 0.00 | 0.00 |
| **600** | **OUTFIT + FURNISHING, GENERAL** | | 77.77 | **-2.34** | -182.00 | **-108.00** | 10.39 | -8399.22 | 808.12 | 0.00 | 0.00 |
| 610&620 | HULL OUTFIT | Wofh | 41.37 | 0.00 | 0.00 | -130.00 | -11.61 | -5378.02 | -480.18 | 0.00 | 0.00 |
| 630-650 | PERSONAL OUTFIT | Wofp | 36.40 | -5.00 | -182.00 | -83.00 | 35.39 | -3021.20 | 1288.30 | 0.00 | 0.00 |
| **700** | **ARMAMENT** | | 751.75 | **3.62** | 2722.97 | **-133.80** | -15.41 | -100586.76 | -11584.92 | 0.00 | 0.00 |
| 740 | VLS (KEI and SM3) | **Wvls** | 738.46 | 3.50 | 2584.61 | -135.00 | -16.61 | -99692.10 | -12263.70 | 0.00 | 0.00 |
| 750 | TORPEDOES HANDLING | Wtorp | 13.20 | 10.40 | 137.28 | -67.00 | 51.39 | -884.40 | 678.39 | 0.00 | 0.00 |
| 760 | LOCKOUT | Wlock | 0.09 | 12.00 | 1.08 | -114.00 | 4.39 | -10.26 | 0.40 | 0.00 | 0.00 |

| SWBS | COMPONENT | From Synthesis | WT-lton | VCG-ft | Moment | LCG-ft (fwdFP) | LCG-ft (fwdLCB) | Moment (fwdFP) | Moment (LCB) | TCG-ft | Moment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **FULL LOAD SUBMERGED CONDITION** | | | | | | | | 0.00 | | |
| F00 | LOADS | | 1096.73 | **0.23** | 248.88 | **-110.52** | 7.87 | -121213.27 | 8631.24 | 0.00 | 0.00 |
| F10 | SHIP PERSONNEL | WF10 | 5.84 | -2.00 | -11.69 | -100.00 | 18.39 | -584.46 | 107.50 | 0.00 | 0.00 |
| F20 | MISSION EXPENDABLES | | 555.78 | **4.19** | 2328.56 | **-109.30** | 9.09 | -60749.34 | 5051.05 | 0.00 | 0.00 |
| F22 | ORDNANCE DELIVERY - torpedoes | Wtorp | 55.50 | 10.40 | 577.20 | -67.00 | 51.39 | -3718.50 | 2852.30 | 0.00 | 0.00 |
| F22 | ORDNANCE DELIVERY - missiles | Wmis | 500.24 | 3.50 | 1750.84 | -114.00 | 4.39 | -57027.36 | 2197.49 | 0.00 | 0.00 |
| F29 | MISCELANEOUS ORDNANCE | Wcounter | 0.04 | 13.00 | 0.52 | -87.00 | 31.39 | -3.48 | 1.26 | 0.00 | 0.00 |
| F30 | STORES | | 13.13 | **-2.48** | -32.58 | **-104.00** | 14.39 | -1365.59 | 188.99 | 0.00 | 0.00 |
| F31 | PROVISIONS+PERSONNEL STORES | WF31 | 9.97 | -2.00 | -19.94 | -104.00 | 14.39 | -1037.04 | 143.52 | 0.00 | 0.00 |
| F32 | GENERAL STORES | WF32 | 3.16 | -4.00 | -12.64 | -104.00 | 14.39 | -328.56 | 45.47 | 0.00 | 0.00 |
| F40 | FUEL AND LUBRICANTS | | 429.56 | **-0.54** | -232.15 | **-110.24** | 8.15 | -47354.92 | 3502.37 | 0.00 | 0.00 |
| F41 | DIESEL FUEL | Wf | 170.51 | **-3.55** | -605.87 | **-142.54** | -24.15 | -24304.84 | -4117.09 | 0.00 | 0.00 |
| | DIESEL FUEL - compensated | Wfcomp | 142.00 | -2.12 | -300.76 | -136.22 | -17.83 | -19343.24 | -2531.45 | 0.00 | 0.00 |
| | DIESEL FUEL - aft compensated | | 83.78 | -2.20 | -184.32 | -201.00 | | | 0.00 | | |
| | DIESEL FUEL - fwd compensated | | 58.22 | -2.00 | -116.44 | -43.00 | | | 0.00 | | |
| | DIESEL FUEL - clean | Wfclean | 28.51 | -10.70 | -305.11 | -174.00 | -55.61 | -4961.60 | -1585.64 | 0.00 | 0.00 |
| F46 | LUBE OIL | WF46 | 1.00 | 2.00 | 2.00 | -133.00 | -14.61 | -133.00 | -14.61 | 0.00 | 0.00 |
| F49 | SPECIAL FUELS AND FUEL GASES | | 258.05 | **1.44** | 371.72 | **-88.81** | 29.58 | -22917.08 | 7634.06 | 0.00 | 0.00 |
| | H2 | Wh2 | 0.00 | 0.00 | 0.00 | -114.49 | 3.90 | 0.00 | 0.00 | 0.00 | 0.00 |
| | O2 | Wo2 | 158.05 | 5.80 | 916.68 | -145.00 | -26.61 | -22917.08 | -4205.23 | 0.00 | 0.00 |
| | ~~ARGON~~ | ~~War~~ | ~~0.00~~ | ~~0.00~~ | ~~0.00~~ | ~~0.00~~ | ~~118.39~~ | ~~0.00~~ | 0.00 | ~~0.00~~ | ~~0.00~~ |
| | ~~METHANOL~~ | | ~~100.00~~ | | | | | | | | |
| | METHANOL- compensated | Wfaip*0.772 | 77.20 | -3.90 | -301.00 | -129.07 | -10.68 | -9964.20 | -824.27 | | |
| | METHANOL- aft compensated | | 44.00 | -4.20 | -184.82 | -194.00 | | | 0.00 | | |
| | METHANOL- fwd compensated | | 33.20 | -3.50 | -116.19 | -43.00 | | | 0.00 | | |
| | METHANOL- clean (inboard) | Wfaip*0.228 | 22.80 | -10.70 | -243.96 | -174.00 | -55.61 | -3967.20 | -1267.84 | | |
| F50 | LIQUIDS AND GASES | | 92.41 | **-19.51** | -1803.26 | **-120.76** | -2.37 | -11158.95 | -218.66 | 0.00 | 0.00 |
| F51 | SEA WATER | | 81.01 | **-11.13** | -901.63 | **-124.78** | -6.39 | -10108.14 | -517.61 | 0.00 | 0.00 |
| | SEA WATER - trim | Wtrimbal | 70.44 | -10.40 | -732.58 | -124.00 | -5.61 | -8734.56 | -394.97 | 0.00 | 0.00 |
| | SEAWATER - residual | Wresidual | 10.57 | -16.00 | -169.06 | -130.00 | -11.61 | -1373.58 | -122.64 | 0.00 | 0.00 |
| F52 | FRESH WATER | WF52 | 8.25 | -9.70 | -80.03 | -93.00 | 25.39 | -767.25 | 209.49 | 0.00 | 0.00 |
| F55 | SEWAGE | Wsew | 3.15 | -11.00 | -34.66 | -90.00 | 28.39 | -283.56 | 89.46 | 0.00 | 0.00 |

# Appendix G – Electric Loads Analysis

| SWBS | DESCRIPTION | Connected (kW) | AIP (kW) | Snorkel (kW) | Sprint (kW) |
|---|---|---|---|---|---|
| **100** | Deck | 64 | 0 | 0 | 0 |
| **200** | **Propulsion** | 7.6 | 1000 | 1752 | 9875 |
| 220 | Battery | 500 | 1 | 1 | 1 |
| 235 | Electric Propulsion Drive | 6050 | 1000 | 1086 | 6050 |
| 250/260 | Support | 31.4 | 31.4 | 31.4 | 31.4 |
| **300** | **Electric** | 20.7 | 20.7 | 20.7 | 20.7 |
| 310 | Power Generation | 15.7 | 15.7 | 15.7 | 15.7 |
| 330 | Switch Board | 5 | 5 | 5 | 5 |
| 400 | **Combat Systems** | 291 | 291 | 291 | 291 |
| 500 | Combat Systems | 291 | 291 | 291 | 291 |
| 500 | Aux Machinery | 27.5 | 27.5 | 27.5 | 27.5 |
| 510 | HVAC | 36.5 | 36.5 | 36.5 | 36.5 |
| 520 | Seawater Systems | 11 | 11 | 11 | 11 |
| 530 | Fresh Water Systems | 25 | 25 | 25 | 25 |
| 550 | Air & Gas | 50 | 50 | 50 | 50 |
| 560 | Ship Control | 15 | 15 | 15 | 15 |
| 593 | Environmental | 12 | 12 | 12 | 12 |
| **500** | **Overall** | 468 | 468 | 468 | 468 |
| **700** | **Payload** | 291 | 291 | 291 | 291 |
| | Max Functional Load | 546 | 546 | 546 | 546 |
| | MFL with Margins | 602.5 | 602.5 | 602.5 | 602.5 |
| | 24 hr Average (with margins) | 295 | 295 | 295 | 295 |

| Number | Generator | Rating (kW) | AIP | Snorkel | Sprint |
|---|---|---|---|---|---|
| 2 | CAT 3512 Genset | 1752 | 0 | 1752 | 0 |
| 2 | 500 kW PEM Fuel Cell | 500 | 1000 | 0 | 1000 |
| 1 | Zebra Lead Acid Battery Bank | 9875 | 0 | 0 | 9875 |

# Appendix H– Hullform Calculations

## Units definition

$MT := 1000 \cdot kg \cdot g$

Physical Parameters

Sea water properties: $\rho_{SW} := 1.9905 \cdot \frac{slug}{ft^3}$

## Input

$D := 32$ $BtoD := 1.2$ $LtoD := 9.0$ $n_f := 2.5$ $n_a := 2.75$

## Process

$D := D \cdot ft$ $B := BtoD \cdot D$ $B = 38.4\,ft$ $LOA := LtoD \cdot D$ $LOA = 288\,ft$

Calculate teardrop forebody and run L/D: $LtoD_{td} := 6.0$ $L_{td} := LtoD_{td} \cdot D$ $L_{td} = 192\,ft$

Select LOA including PMB: $L_{pmb} := LOA - L_{td}$ $L_{pmb} = 96\,ft$ $del := B - D$ $del = 6.4\,ft$

$L_f := 2.4 \cdot D$ $L_f = 76.8\,ft$

(resistance optimum)

$L_a := 3.6 \cdot D$ $L_a = 115.2\,ft$

B. VOLUME CALCULATIONS TO SUPPORT ARRANGENMENTS:

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

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

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

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

3. Total Ship:

$$\int_{0 \cdot ft}^{LOA} offt(x)^2 \cdot \pi \, dx = 1354160.469\,gal$$

$$V_{env} := \int_{0 \cdot ft}^{LOA} offt(x)^2 \cdot \pi \, dx + 2 \cdot (B - D) \cdot \int_{0 \cdot ft}^{LOA} offt(x)\, dx \qquad V_{env} = 1730107\,gal$$

$$2 \cdot (B - D) \cdot \int_{0 \cdot ft}^{LOA} offt(x)\, dx = 375946.349\,gal$$

$$S := \int_{0 \cdot ft}^{LOA} offt(x) \cdot 2 \cdot \pi \, dx + 2 \cdot del \cdot \int_{0 \cdot ft}^{LOA} \sqrt{1 + \left(\frac{d}{dx} offt(x)\right)^2}\, dx \qquad S = 28452\,ft^2$$

$$\int_{0 \cdot ft}^{LOA} offt(x) \cdot 2 \cdot \pi \, dx = 24669.709\,ft^2$$

$$2 \cdot del \cdot \int_{0 \cdot ft}^{LOA} \sqrt{1 + \left(\frac{d}{dx} offt(x)\right)^2}\, dx = 3782.048\,ft^2$$

$$V_{f1} := \int_{0 \cdot ft}^{L_f} offt(x)^2 \cdot \pi \, dx \qquad V_{f1} = 346546\,gal$$

$$V_{a1} := \int_{L_f + L_{pmb}}^{LOA} offt(x)^2 \cdot \pi \, dx \qquad V_{a1} = 430056\,gal$$

$S = 28451.757\,ft^2$

$$V_{f2} := \left(\int_{0 \cdot ft}^{L_f} offt(x)\, dx\right) \qquad V_{f2} = 1039\,ft^2 \qquad S_{f1} := 2 \cdot \pi \cdot V_{f2} \qquad S_{f1} = 6525.865\,ft^2$$

$V_{f2} := 2 \cdot V_{f2} \cdot (B - D)$ $= 99448.889\,gal$

$$V_{a2} := \left(\int_{L_f + L_{pmb}}^{LOA} offt(x)\, dx\right) \qquad V_{a2} = 1352\,ft^2 \qquad S_{a1} := 2 \cdot \pi \cdot V_{a2} \qquad S_{a1} = 8492.856\,ft^2$$

$V_{a2} := 2 \cdot V_{a2} \cdot del$ $V_{a2} = 129424.231\,gal$

# Appendix I - Structures Calculations

## Global Variable Inputs:

Operating depth: $D_t := D_t \cdot ft$ $D_t = 575\ ft$

Geometry Variables: $D := D \cdot ft$ shell diam $D = 32\ ft$ $R := \frac{D}{2}$

Frame spacing $L_f := L_f \cdot ft$ $L_f = 24\ in$

Material:(HY80) $\sigma_y \equiv 100000 \cdot \frac{lbf}{in^2}$ $\rho_{st} \equiv 7.8 \cdot 10^3 \cdot \frac{kg}{m^3}$ $E \equiv 30 \cdot 10^6 \cdot \frac{lbf}{in^2}$ $\nu \equiv 0.3$ $\rho \equiv 1030 \cdot \frac{kg}{m^3}$

## Define input variables:

Bulkhead spacing $L_s := L_s \cdot ft$ $L_s = 192\ in$

shell thickness $t_p := t_p \cdot in$ $t_p = 1\ in$

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

flange tickness $t_f := t_f \cdot in$ $t_f = 0.376\ in$

flange width $w_f := w_f \cdot in$ $w_f = 5.02\ in$

web thickness $t_w := t_w \cdot in$ $t_w = 0.375\ in$

web height $h_w := h_w \cdot in$ $h_w = 15.935\ in$

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

flange,web $A_f := t_f \cdot w_f$ $A_w := t_w \cdot h_w$ $A := A_f + A_w$ $A = 7.861\ in^2$

Compute structural efficiency (buoyancy factor):

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

$BF = 0.103$ $BF \cdot 100 = 10.305$

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

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{sy}$ $P = 385.135\ psi$

Area ratio $B := \frac{t_w \cdot t_p}{A + t_w \cdot t_p}$ $B = 0.046$

Slenderness parameter: $\theta := L_f \cdot \left[\frac{3 \cdot (1 - \nu^2)}{(R \cdot t_p)^2}\right]^{\frac{1}{4}}$ $\theta = 2.226$

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

Frame flexability parameter:

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

$\beta = 2.581$

Frame deflection parameter:

$$\Gamma := \frac{\left(1-\frac{\nu}{2}\right) - B}{1+\beta}$$

$\Gamma = 0.225$

Bending effect (mem):

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

$H_M = -0.787$

Bending effect (bend):

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

$H_E = 0.617$

Bending efffect near frame:

$$K := \frac{\sinh(\theta)-\sin(\theta)}{\sinh(\theta)+\sin(\theta)}$$

Midbay shell stress is calculated:

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

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

Shell stress at frames is:

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

$$\sigma_{\phi\phi fi} := \frac{-P\cdot R}{t_p}\cdot\left[1-\Gamma\cdot\left[1-\nu\cdot\left(\frac{3}{1-\nu^2}\right)^{0.5}\cdot K\right]\right] \quad \text{inner} \qquad \sigma_{xxfi} := \frac{-P\cdot R}{t_p}\cdot\left[0.5+\Gamma\cdot\left(\frac{3}{1-\nu^2}\right)^{0.5}\cdot K\right]$$

$j := 1..8$

$$\sigma_{sy} := \begin{pmatrix}\sigma_{\phi\phi so}\\ \sigma_{\phi\phi si}\\ \sigma_{xxso}\\ \sigma_{xxsi}\\ \sigma_{\phi\phi fo}\\ \sigma_{\phi\phi fi}\\ \sigma_{xxfo}\\ \sigma_{xxfi}\end{pmatrix} \qquad \sigma_{sy} = \begin{pmatrix}-6.396\times10^4\\ -5.78\times10^4\\ -4.722\times10^4\\ -2.672\times10^4\\ -5.096\times10^4\\ -6.371\times10^4\\ -1.571\times10^4\\ -5.823\times10^4\end{pmatrix}\text{psi}$$

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

This represents how much of the safety factor was actually used:

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

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

$\sigma_{SYM} = 5.745 \times 10^4 \text{ psi}$

$\sigma_{SYF} = 6.116 \times 10^4 \text{ psi}$ $\quad \sigma_{SY} := \max\left(\begin{pmatrix} \sigma_{SYM} \\ \sigma_{SYF} \end{pmatrix}\right)$ $\quad \sigma_{SY} = 6.116 \times 10^4 \text{ psi}$

$r_{SY} := \frac{\sigma_{SY}}{\sigma_y}$ $\quad r_{SY} = 0.764$

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

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{lb}$ $\quad P = 577.702 \text{ psi}$

Collapse pressure:

$$P_{cLB} := \frac{2.42 \cdot E \cdot \left(\frac{t_p}{D}\right)^{2.5}}{\left(\frac{L_f}{D} - 0.45 \cdot \sqrt{\frac{t_p}{D}}\right) \cdot \left(1 - \nu^2\right)^{0.75}} \qquad P_{cLB} = 682.079 \text{ psi}$$

$r_{LB} := \frac{P}{P_{cLB}}$ $\quad r_{LB} = 0.847$

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

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{gi}$ $\quad P = 962.837 \text{ psi}$

Compute effective frame spacing: $\gamma := \frac{P}{2 \cdot E} \cdot \left(\frac{R}{t_p}\right)^2 \cdot \sqrt{3 \cdot \left(1 - \nu^2\right)}$ $\quad \gamma = 0.977$

Compute clear length:

$L_c := L_f - t_w$ $\quad n_1 := 0.5 \cdot \sqrt{1 - \gamma}$ $\quad n_1 = 0.075$

$n_2 := 0.5 \cdot \sqrt{1 + \gamma}$ $\quad n_2 = 0.703$

$t_w = 0.375\,in$

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

Effective plate length:

$$L_{eff} := L_c\cdot F_1 + t_w$$

$L_{eff} = 19.551\,in$

$F_1 = 0.812$ must be less than 1.00

Theoretical critical lobe number values are:

$i := 0..2$

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):

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

$$y_{na} := \frac{\left(\frac{h_w + t_f}{2}\right)\cdot A_f - \left(\frac{h_w + t_p}{2}\right)\cdot A_{eff}}{A_{eff} + A_w + A_f}$$

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

$$I_{pcor} := I_p + A_{eff}\cdot\left[\left(\frac{t_p + h_w}{2}\right) + y_{na}\right]^2$$

$$I_{wcor} := I_w + A_w\cdot(y_{na})^2$$

$$I_{fcor} := I_f + A_f\cdot\left(\frac{t_f + h_w}{2} - y_{na}\right)^2$$

Total: $I_{eff} := I_{pcor} + I_{wcor} + I_{fcor}$

The critical pressure is:

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

$$P_{cGI} = \begin{pmatrix} 1.041\times 10^4 \\ 4.481\times 1 \\ 3.347\times 10^3 \end{pmatrix}$$ $P_{cGI} := \min(P_{cGI})$ $P_{cGI} = 3.347\times 10^3\,psi$

$r_{GI} := \frac{P}{P_{cGI}}$ $r_{GI} = 0.288$

PART 4 FRAME YIELDING

Safety factor is: $SF_{fy} := 1.5$

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{fy}$ $P = 385.135\ psi$

Compute direct stress:

$$\beta_f := \frac{t_w}{L_f}$$

Radius to frame NA: $R_{fna} := \frac{D}{2} - t_p - \frac{h_w}{2} - y_{na}$

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

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

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

Stress adjuster: $SA := 1 - \frac{\alpha_p}{\alpha_p + \beta_f + (1 - \beta_f) \cdot F_1}$ $SA = 0.723$

$$\sigma_{direct} := \frac{\left(1 - \frac{\nu}{2}\right) \cdot P \cdot \left(\frac{D}{2} - \frac{t_p}{2}\right)^2}{t_p \cdot \left(\frac{D}{2} - t_p - h_w - t_f\right)} \cdot SA \qquad \sigma_{direct} = 4.966 \times 10^4\ psi$$

Compute bending stress due to eccentricity:

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

Bending stress: $\sigma_{bend} := \frac{E \cdot c \cdot e \cdot \left[(n)^2 - 1\right]}{R^2} \cdot \frac{P}{P_{cGI} - P}$ $\sigma_{bend} = 4.099 \times 10^3\ psi$

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

This must be less than one:

$\sigma_{fr} = 5.376 \times 10^4 \text{psi}$  $r_{fy} := \dfrac{\sigma_{fr}}{\sigma_y}$  $r_{fy} = 0.672$

PART 5 FRAME INSTABILITY

Safety factor is: $SF_{fy} := 1.8$

Pressure loading is: $P := \rho \cdot g \cdot D_t \cdot SF_{fy}$  $P = 462.162\,\text{psi}$

Area of plate: $A_p := t_p \cdot L_f$

Frame-plate neutral axis (ref web centre+ toward flange):

$$y_{na2} := \frac{\left(\frac{t_f}{2} + \frac{h_w}{2}\right) \cdot A_f - \left(\frac{t_p}{2} + \frac{h_w}{2}\right) \cdot A_p}{A_p + A_w + A_f} \qquad y_{na2} = -5.896\,\text{in}$$

Moments of inertia for plate,flange,web (compute Ip using actual plate length:

$$I_p := \frac{L_f \cdot t_p^{\,3}}{12} \qquad I_p = 2\,\text{in}^4$$

Correct the individual moments from the na:

$$I_{pcor} := I_p + A_p \cdot \left(\frac{t_p}{2} + \frac{h_w}{2} + y_{na2}\right)^2$$

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

Then total plate, frame moment of inertia is:

$$I := I_{pcor} + I_{wcor} + I_{fcor}$$

Diameter to NA is: $D_{na} := D - 2t_p - h_w - 2y_{na2}$  $D_{na} = 31.488\,\text{ft}$

Compute pressure limit:

$$P_{cFI} := \frac{25 \cdot E \cdot I}{D_{na}^{\,3} \cdot L_f} \qquad P_{cFI} = 502.32\,\text{psi} \qquad r_{FI} := \frac{P}{P_{cFI}} \qquad r_{FI} = 0.92$$

Load ratio must be less than 1:

**Results:**

$r_{SY} = 0.764$  $BF = 0.103$

$r_{LB} = 0.847$

$r_{GI} = 0.288$

$r_{fy} = 0.672$

$r_{FI} = 0.92$

# Appendix J – Power and Propulsion Calculations

## Units definition and Physical Parameters

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

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

$rev := 1$ $\delta_F := 43.6 \cdot \frac{ft^3}{lton}$ $days := 24hr$ $RPM := \frac{1}{min}$

## Input Module:

Principal characteristics: $LOA := 261.2 \cdot ft$ $B := 32 \cdot ft$ $D := 32 \cdot ft$ $S := 21514.36 \cdot ft^2$ $C_A := .0004$

$n_f := 2.19891$ $n_a := 2.54251$ $V_e := 5 \cdot knt$ $V_{esnork} := 12knt$ $W_{fsnk} := 167.74lton$ $Wfaip := 100lton$

$KW_{24AVG} := 295.27 \cdot kW$ $D_P := 5.25 \cdot m$ $D_P = 17.224\, ft$ $N_P := 1$ $V_{env} := 154459.0 \cdot ft^3$

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

SFC: H2 in PEM fuel cell: $SFC_{aip} := .674 \cdot \frac{lbf}{(hp \cdot hr)}$ DFM in diesel engine: $SFC_{snk} := .355 \cdot \frac{lbf}{hp \cdot hr}$

Battery Capacity: $E_{battery} := 5000 \cdot kW \cdot hr$

Sprint Battery Power: $P_{battery} := 9875.00 \cdot kW$

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

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

## Resistance and Power

$iii := 22$

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: $formfac := 1 + .5 \cdot \frac{B}{LOA} + 3 \cdot \left(\frac{B}{LOA}\right)^{\left(7 - n_f - \frac{n_a}{2}\right)}$ $formfac = 1.063$

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

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

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:

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

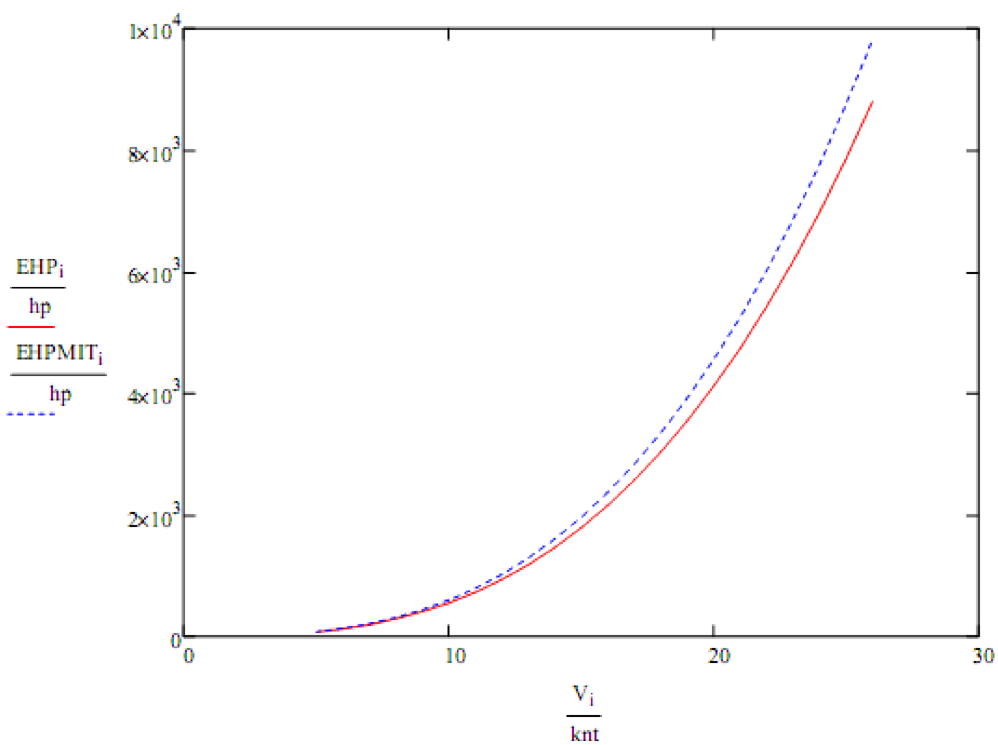
Appendage drag (including sail) calculation:

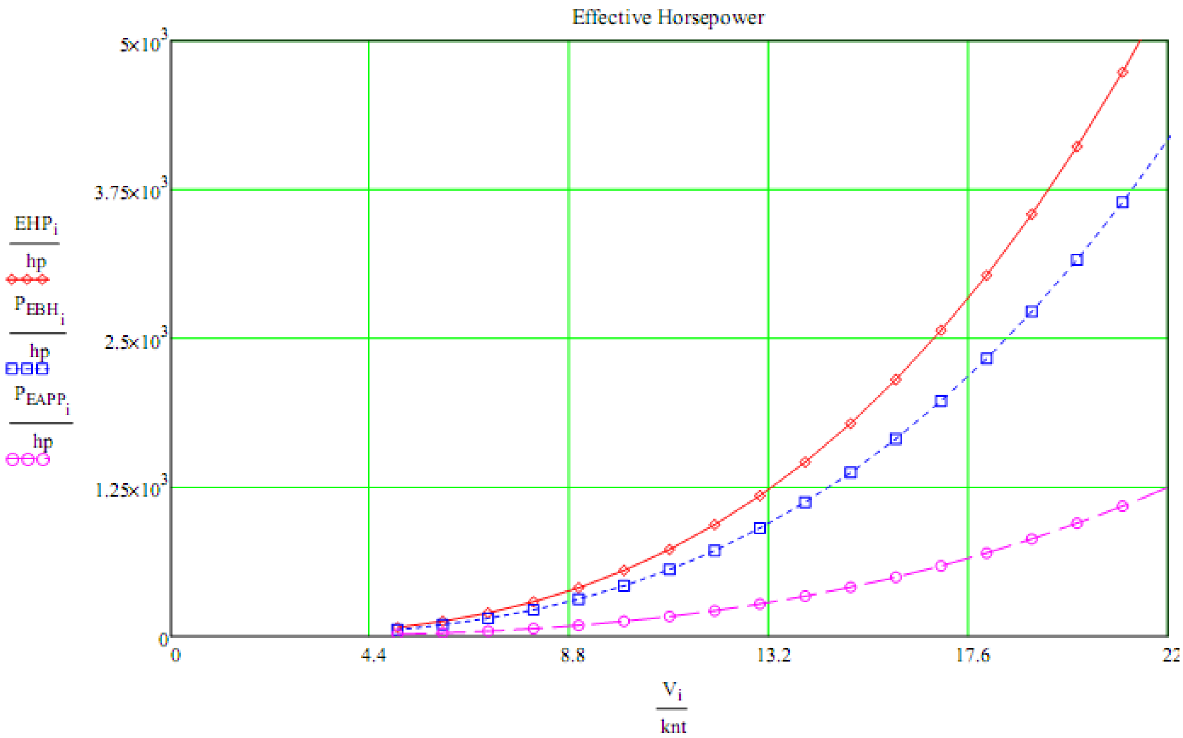
Surface area of the sail: $A_s := 1222 \cdot ft^2$ $\quad C_{Ds} := .009$ $\quad A_s \cdot C_{Ds} = 10.998\, ft^2$

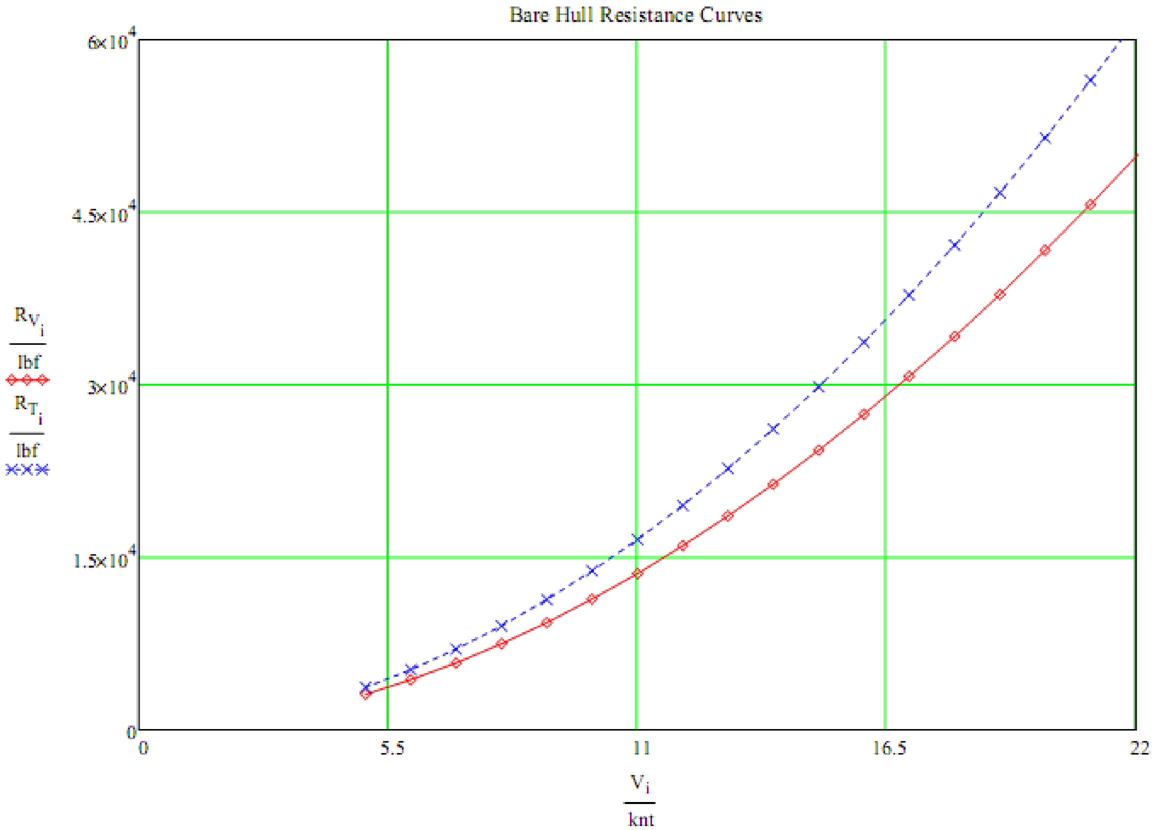
For the remaining appendages, use the expression for $A_{other} * C_{dother}$ = $App := \frac{LOA \cdot D}{1000}$ $\quad App = 8.358\, ft^2$

$$EHPMIT_i := 0.5 \cdot \rho_{SW} \cdot (V_i)^3 \cdot \left[S \cdot \left(C_{F_i} \cdot C_{frf} + C_A\right) + \left[(A_s \cdot C_{Ds}) + App\right]\right] \qquad EHPMIT_1 = 79.339 \cdot hp$$

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




Effective Horsepower
5×10^3
3.75×10^3
2.5×10^3
1.25×10^3
0
EHP_i / hp
P_EBH_i / hp
P_EAPP_i / hp
0
4.4
8.8
13.2
17.6
22
V_i / knt


Bare Hull Resistance Curves
6×10^4
4.5×10^4
3×10^4
1.5×10^4
0
R_V_i / lbf
R_T_i / lbf
0
5.5
11
16.5
22
V_i / knt

$C_{ws} := \dfrac{S}{\pi \cdot LOA \cdot D}$ $C_{ws} = 0.819$

$w := 1 - .371 - 1.7151 \cdot \dfrac{\dfrac{D_P}{D}}{\sqrt{C_{ws} \cdot \dfrac{LOA}{D}}}$ $w = 0.272$ wake fraction $w := if(w < 0.1, 0.1, w)$ $w = 0.272$

$t := 1 - .632 - 1.3766 \cdot \dfrac{\dfrac{D_P}{D}}{\sqrt{C_{ws} \cdot \dfrac{LOA}{D}}}$ $t = 0.081$ thrust deduction fraction - prop changes pressure distribution around hull which effectively changes the resistance of towed hull

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

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

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

$\eta_H := \dfrac{1 - t}{1 - w}$ $\eta_H = 1.168$ hull efficiency $THP := \dfrac{EHP}{\eta_H}$

| | V (·knt) | THP (·hp) | T (·lbf) | $V_A$ (·knt) |
|---|---|---|---|---|
| 1 | 5 | 64 | $4.407 \cdot 10^3$ | 3.64 |
| 2 | 6 | 108 | $6.214 \cdot 10^3$ | 4.368 |
| 3 | 7 | 169 | $8.311 \cdot 10^3$ | 5.096 |
| 4 | 8 | 249 | $1.069 \cdot 10^4$ | 5.824 |
| 5 | 9 | 350 | $1.336 \cdot 10^4$ | 6.552 |
| 6 | 10 | 474 | $1.63 \cdot 10^4$ | 7.28 |
| 7 | 11 | 624 | $1.952 \cdot 10^4$ | 8.008 |
| 8 | 12 | 803 | $2.301 \cdot 10^4$ | 8.736 |
| 9 | 13 | 1012 | $2.678 \cdot 10^4$ | 9.464 |
| 10 | 14 | 1254 | $3.081 \cdot 10^4$ | 10.192 |
| 11 | 15 | 1532 | $3.511 \cdot 10^4$ | 10.92 |
| 12 | 16 | 1846 | $3.968 \cdot 10^4$ | 11.648 |
| 13 | 17 | 2201 | $4.451 \cdot 10^4$ | 12.376 |
| 14 | 18 | 2597 | $4.961 \cdot 10^4$ | 13.104 |
| 15 | 19 | 3037 | $5.497 \cdot 10^4$ | 13.832 |
| 16 | 20 | 3523 | $6.058 \cdot 10^4$ | 14.56 |
| 17 | 21 | 4058 | $6.646 \cdot 10^4$ | 15.288 |
| 18 | 22 | 4644 | $7.259 \cdot 10^4$ | 16.016 |
| 19 | 23 | 5283 | $7.898 \cdot 10^4$ | 16.744 |
| 20 | 24 | 5976 | $8.563 \cdot 10^4$ | 17.472 |
| 21 | ... | ... | ... | ... |

$T_1 = 1.96 \times 10^4 \cdot newton$ $V_1 = 5 \cdot knt$ AIP $D_P = 5.25 \cdot m$ $DEPTH_{aip} := 30 \cdot m$ $DEPTH_{snrk} := 2.5m$

$T_{18} = 3.229 \times 10^5 \cdot newton$ $V_{18} = 22 \cdot knt$ Sprint Thrust Endurance AIP, Sprint, Snorkel

$T_8 = 1.024 \times 10^5 \cdot newton$ $V_8 = 12 \cdot knt$ Snorkel

**For B series, 7-bladed prop optimized for max open water eff at AIP speed: (EAR=1.0485, P/D=1.282, w=.272)**

$\eta_{Oaip} := .725$ $n_{aipSHAFT} := 21.39 \cdot RPM$

$\eta_{Osprint} := .752$ $n_{sprintSHAFT} := 91.11 \cdot RPM$

$\eta_{Osnork} := .741$ $n_{snrkSHAFT} := 50.32 \cdot RPM$

Inputted from blade optimization

Itterated wake fraction with Dp (ie if Dp changes from initial guess after optimization then wake fraction changes and another optimization or iteration is necessarry)

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

$\eta_{Baip} := \eta_{Oaip} \cdot \eta_R$ $\eta_{Baip} = 0.747$ AIP prop efficiency behind ship = THP/DHP

$\eta_{Bsprint} := \eta_{Osprint} \cdot \eta_R$ $\eta_{Bsprint} = 0.775$ Sprint prop efficiency behind ship = THP/DHP

$\eta_{Bsnrk} := \eta_{Oaip} \cdot \eta_R$ $\eta_{Bsnrk} = 0.747$ AIP prop efficiency behind ship = THP/DHP

$DHP_{aip} := \frac{THP_1}{\eta_{Baip}}$ $DHP_{sprint} := \frac{THP_{18}}{\eta_{Bsprint}}$ $DHP_{snrk} := \frac{THP_8}{\eta_{Bsnrk}}$

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

quasi-propulsive efficiency

$\eta_{Daip} := \eta_H \cdot \eta_{Baip}$ $\eta_{Daip} = 0.872$

$\eta_{Dsprint} := \eta_H \cdot \eta_{Bsprint}$ $\eta_{Dsprint} = 0.904$

$\eta_{Dsnrk} := \eta_H \cdot \eta_{Bsnrk}$ $\eta_{Dsnrk} = 0.872$

$\eta_S := 1.0$ 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 ) propulsive efficiency (Propulsive Coefficient, PC)

$\eta_{Paip} := \eta_S \cdot \eta_{Daip}$ $\eta_{Paip} = 0.872$

$\eta_{Psprint} := \eta_S \cdot \eta_{Dsprint}$ $\eta_{Psprint} = 0.904$

$\eta_{Psnrk} := \eta_S \cdot \eta_{Dsnrk}$ $\eta_{Psnrk} = 0.872$

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

**Endurance Brake Power:**

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

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

$V_{18} = 22 \cdot knt$ $SHP_{sprint} = 4471 \cdot kW$ $BHP_{req} = 6010 \cdot kW$ $P_{PRP} = 5642 \cdot kW$ $n_{sprintSHAFT} = 91.11 \cdot \frac{rev}{min}$

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

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

Specified fuel rate: $FR_{SP} := f_l \cdot SFC_{aip}$ $FR_{SP} = 0.701 \cdot \frac{lbf}{hp \cdot hr}$

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

$FR_{AVG} = 0.736 \cdot \frac{lbf}{hp \cdot hr}$

Tailpipe allowance: $TPA := 0.95$

**Endurance Range AIP:**

$P_{aipavg} := \frac{KW_{24AVG}}{\eta_{elec}} + BHP_{aipreq}$ $P_{aipavg} = 393.181 \cdot kW$ $E_{faip} := Wfaip \cdot \frac{1.}{SFC_{aip}}$ $E_{faip} = 2.478 \times 10^5 \cdot kW \cdot hr$

$E_{aip} := \frac{E_{faip}}{(f_l \cdot 1.05 \cdot P_{aipavg})}$ $E_{aip} = 24.051 \cdot days$ Yellow Values must be within ORD

**Sprint Range:**

$E_{sprint} := \frac{E_{battery}}{BHP_{req}}$ $E_{sprint} = 0.832 \cdot hr$

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

**Snorkel Range:**

$SHP_{snrkv} = 801.966 \cdot kW$

Froude # for Cdw Coef Calc:

$Fn := \frac{V_{esnork}}{(g \cdot LOA)^{.5}}$ $Fn = 0.221$

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

$C_{DW} = 1.249$

$C_W := \frac{C_{DW}}{4 \cdot \left[\left(\frac{LOA}{D}\right) - 1.3606\right]\left(\frac{LOA}{D}\right)^2}$ $C_W = 6.888 \times 10^{-4}$

Wave Induced:

$SHP_W := C_W \cdot S \cdot \rho_{SW} \cdot V_{esnork}^3$ $SHP_W = 333.568 \cdot kW$

SHP Snorkel:

$SHP_{snrk} := SHP_{snrkv} + SHP_W$ $SHP_{snrk} = 1136 \cdot kW$

Endurance Snork Calculation:

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

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

$P_{snkAVG} := \frac{SHP_{snrk} + KW_{24AVG}}{\eta_{elec}}$ $P_{snkAVG} = 2063 \cdot hp$

$E_{snork} := \frac{(W_{fsnk} \cdot V_{esnork} \cdot TPA)}{P_{snkAVG} \cdot FR_{AVGsnk}}$ $E_{snork} = 5356 \cdot nm$

## Appendix K – Cost Calculation

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

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

$Cost_C := 600 \cdot Mdol$  $Bdol := 1000 \cdot Mdol$  $Kdol := \frac{Mdol}{1000}$  $dol := \frac{Kdol}{1000}$

**Weight Inputs:**

$W_1 := 940.31 \cdot lton$  $W_5 := 348.16 \cdot lton$

$W_2 := 438.46 \cdot lton$  $W_6 := 77.77 \cdot lton$

$W_3 := 70.39 \cdot lton$  $W_7 := 534.16 \cdot lton$

$W_4 := 196.48 \cdot lton$

**A. Additional characteristics:**

**Ship Service Life:** $L_S := 30$  **Initial Operational Capability:** $Y_{IOC} := 2018$

**Total Sub Acquisition:** $N_S := 10$  **Production Rate (per year):** $R_P := 0.5$

**B. Inflation:**

**Base Year:** $Y_B := 2012$  $iy := Y_B - 1995$

**Average Inflation Rate (%): (from 1995)** $R := 2.0$  $F_I := \left(1 + \frac{R}{100}\right)^{iy}$  $F_I = 1.4$

**C. Lead Ship Shipbuilder Labor Cost:**

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

**Structure** $K_{N1} := \frac{400 \cdot hr}{lton}$  $C_{L_1} := K_{N1} \cdot W_1 \cdot Mh$  $C_{L_1} = 28.2 \cdot Mdol$

**+ Propulsion** $K_{N2} := \frac{700 \cdot hr}{lton}$  $C_{L_2} := K_{N2} \cdot W_2 \cdot Mh$  $C_{L_2} = 23 \cdot Mdol$

**+ Electric** $K_{N3} := \frac{1000 \cdot hr}{lton}$  $C_{L_3} := K_{N3} \cdot W_3 \cdot Mh$  $C_{L_3} = 5.3 \cdot Mdol$

**+ Command, Control, Surveillance**

$K_{N4} := \frac{3582.8 \cdot hr}{lton}$ $C_{L_4} := K_{N4} \cdot W_4 \cdot Mh$ $C_{L_4} = 52.8 \cdot Mdol$

**+ Auxiliary** $K_{N5} := \frac{1500 \cdot hr}{lton}$ $C_{L_5} := K_{N5} \cdot W_5 \cdot Mh$ $C_{L_5} = 39.2 \cdot Mdol$

**+ Outfit** $K_{N6} := \frac{1300 \cdot hr}{lton}$ $C_{L_6} := K_{N6} \cdot W_6 \cdot Mh$ $C_{L_6} = 7.6 \cdot Mdol$

**+ Armament** $K_{N7} := \frac{2559.1 \cdot hr}{lton}$ $C_{L_7} := K_{N7} \cdot W_7 \cdot Mh$ $C_{L_7} = 102.5C$

## D. Lead Ship Shipbuilder Material Cost:

**Structure** $K_{M1} := \frac{18 \cdot Kdol}{lton}$ $C_{M_1} := F_I \cdot K_{M1} \cdot W_1$ $C_{M_1} = 23.7 \cdot Mdol$

**+ Propulsion** $K_{M2} := \frac{120 \cdot Kdol}{lton}$ $C_{M_2} := F_I \cdot K_{M2} \cdot W_2$ $C_{M_2} = 73.7 \cdot Mdol$

**+ Electric** $K_{M3} := \frac{700 \cdot Kdol}{lton}$ $C_{M_3} := F_I \cdot K_{M3} \cdot W_3$ $C_{M_3} = 69 \cdot Mdol$

**+ Command, Control, Surveillance**

$K_{M4} := \frac{768 \cdot Kdol}{lton}$ $C_{M_4} := F_I \cdot K_{M4} \cdot W_4$ $C_{M_4} = 211.3 \cdot Mdol$

**+ Auxiliary** $K_{M5} := \frac{80 \cdot Kdol}{lton}$ $C_{M_5} := F_I \cdot K_{M5} \cdot W_5$ $C_{M_5} = 39 \cdot Mdol$

**+ Outfit** $K_{M6} := \frac{40 \cdot Kdol}{lton}$ $C_{M_6} := F_I \cdot K_{M6} \cdot W_6$ $C_{M_6} = 4.4 \cdot Mdol$

**+ Armament** $K_{M7} := \frac{409.5 \cdot Kdol}{lton}$ $C_{M_7} := F_I \cdot K_{M7} \cdot W_7$ $C_{M_7} = 306.3 \cdot Mdol$

**E. Integration & Assembly:**

**+ Integration (40% of labor and .1% of Material)**

$$C_{M_8} := .001 \cdot \sum_{i=1}^{7} C_{M_i} \qquad C_{M_8} = 0.7 \cdot Mdol$$

**+ Assembly (20% of labor and .5% of Material)**

$$C_{L_9} := .20 \cdot \sum_{i=1}^{7} C_{L_i} \qquad C_{L_9} = 51.7 \cdot Mdol$$

$$C_{M_9} := .005 \cdot \sum_{i=1}^{7} C_{M_i} \qquad C_{M_9} = 3.6 \cdot Mdol$$

**F. Direct Costs:**

1. **Labor Cost:**

$$C_L := \sum_{i=1}^{9} C_{L_i} \qquad C_L = 413.7 \cdot Mdol$$

2. **Material Cost:**

$$C_M := \sum_{i=1}^{9} C_{M_i} \qquad C_M = 731.7 \cdot Mdol$$

3. **Direct Cost:**

$$DC := C_L + C_M \qquad DC = 1145.4 \cdot Mdol$$

$$C_{L_8} := .40 \cdot \sum_{i=1}^{7} C_{L_i}$$ $$C_{L_8} = 103.4 \cdot \text{Mdol}$$

**G. Overhead: Enter Overhead Rate:** $ovhd := 0.25$

$$IC := DC \cdot ovhd$$ $$IC = 286.3 \cdot \text{Mdol}$$

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

$$Profit := profit \cdot (IC + DC)$$ $$Profit = 143.2 \cdot \text{Mdol}$$

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

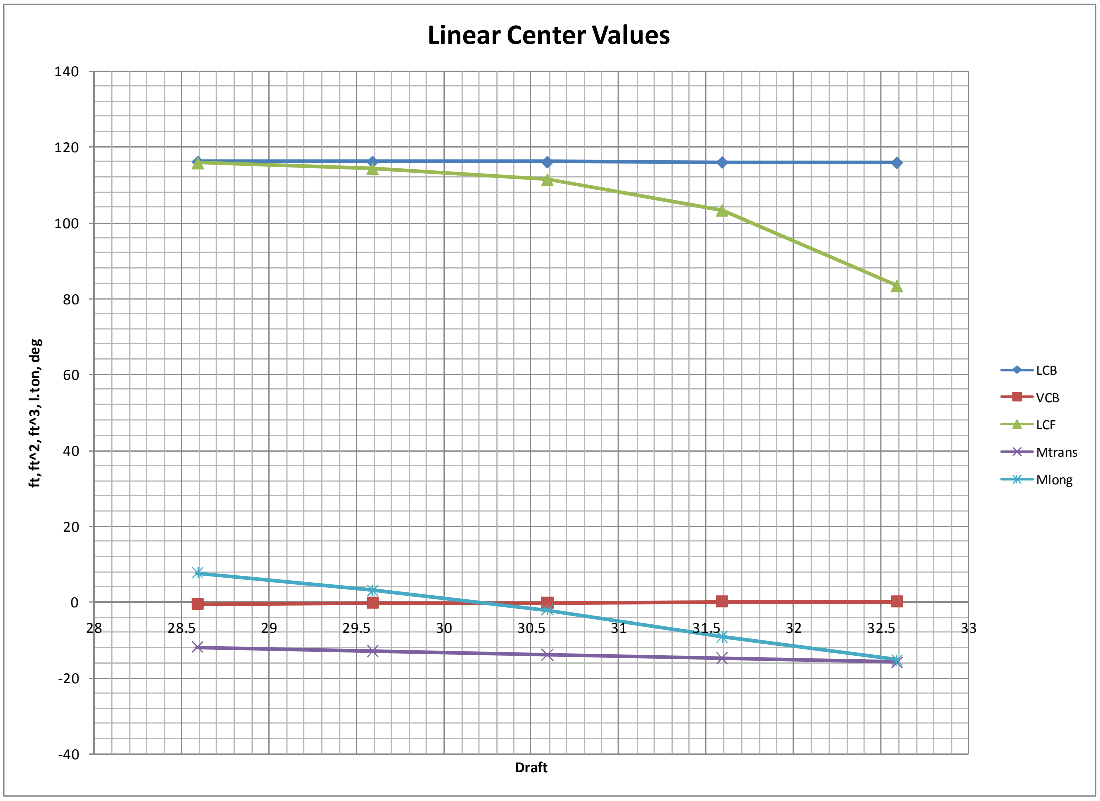
$$C_{BCC} := (1 + profit) \cdot (DC + IC)$$ $$C_{BCC} = 1574.9 \cdot \text{Mdol}$$

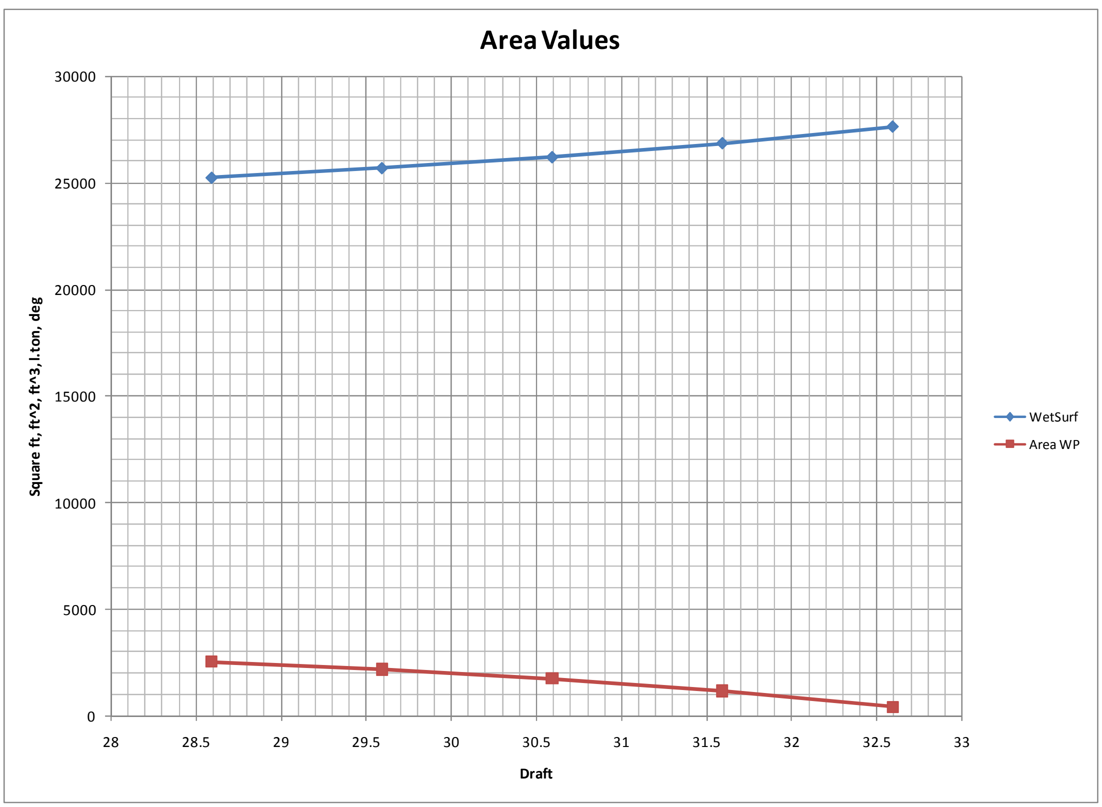
**Compare to cost constraint:**

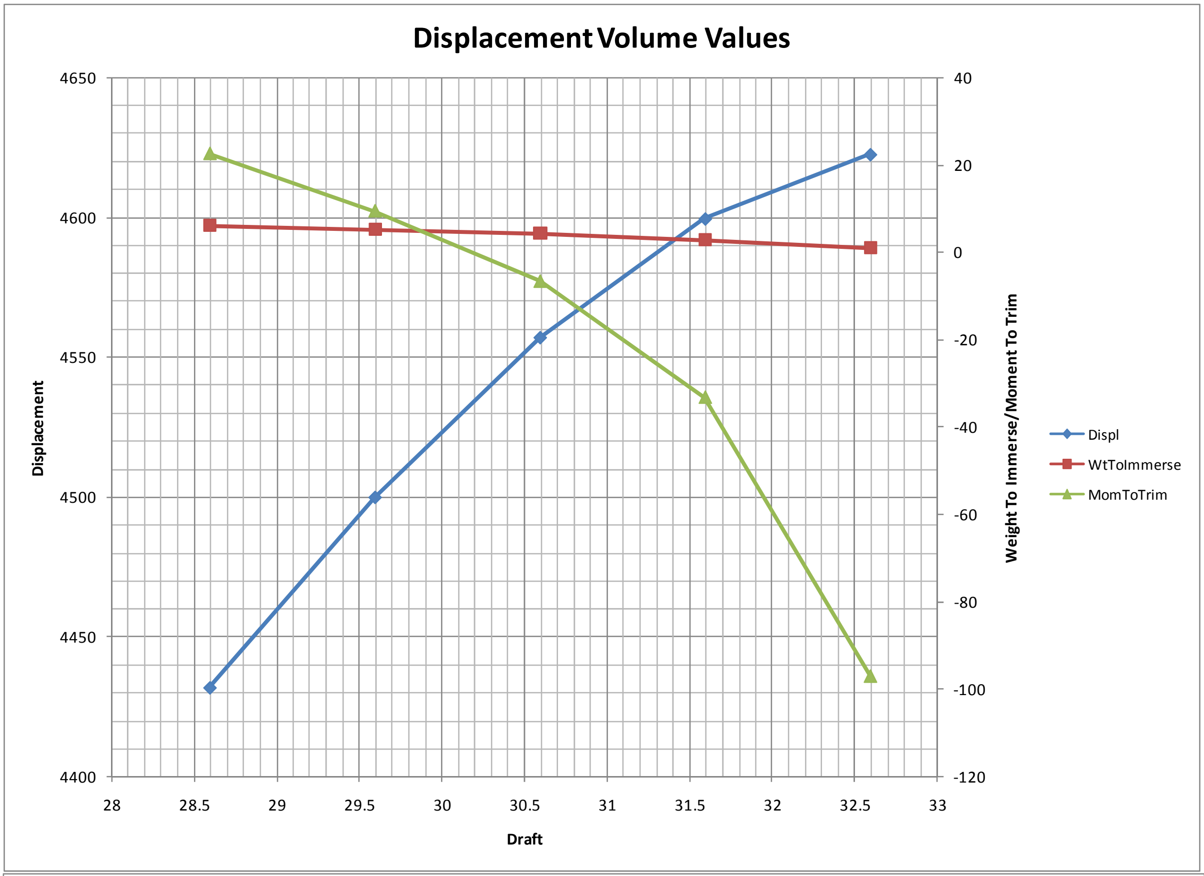
$$\frac{C_{BCC} - Cost_C}{C_{BCC}} = 61.9 \cdot \%$$

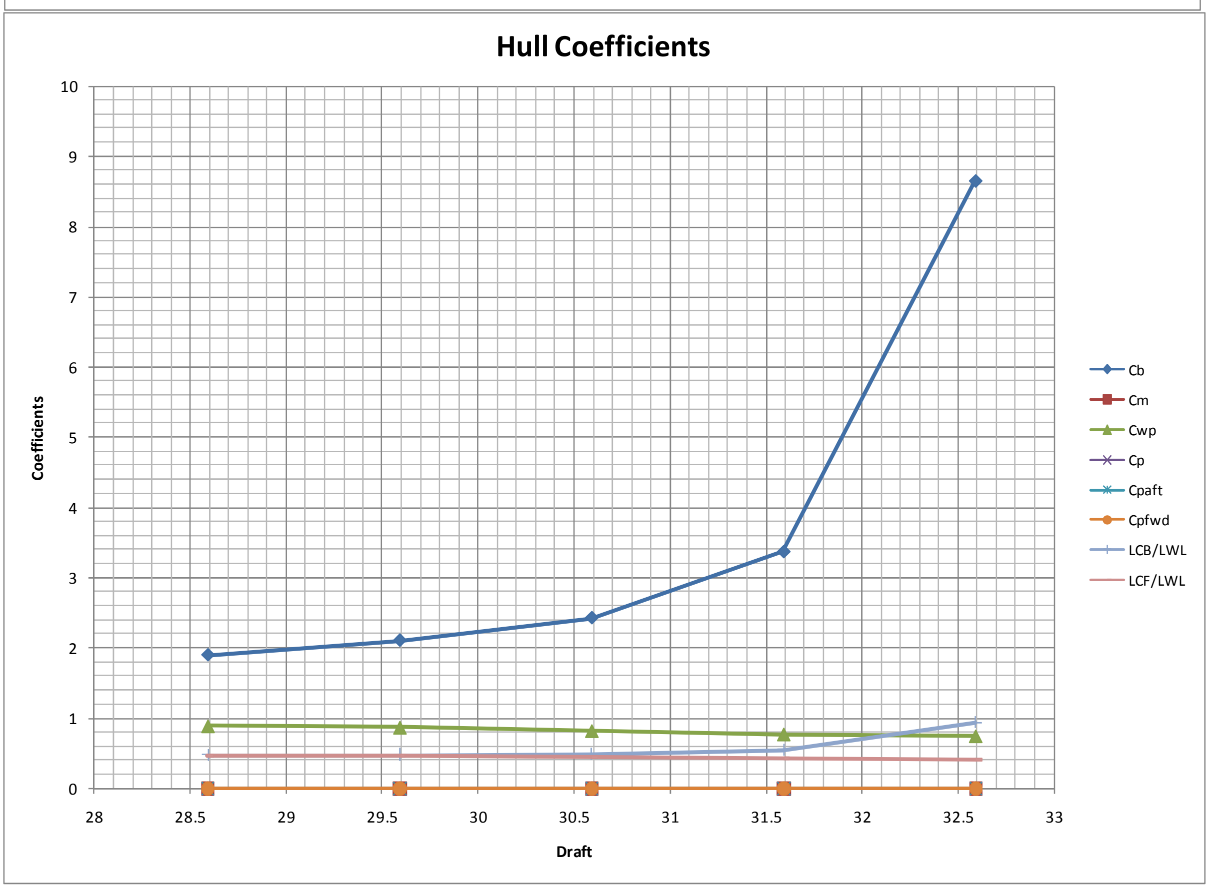
**+ Over constraint**
**- Under constraint**

# Appendix L – Hydrostatic Curves




Displacement Volume Values
4650
4600
4550
4500
4450
4400
Displacement
40
20
0
-20
-40
-60
-80
-100
-120
Weight To Immerse/Moment To Trim
28
28.5
29
29.5
30
30.5
31
31.5
32
32.5
33
Draft
Displ
WtToImmerse
MomToTrim


Hull Coefficients
10
9
8
7
6
5
4
3
2
1
0
Coefficients
28
28.5
29
29.5
30
30.5
31
31.5
32
32.5
33
Draft
Cb
Cm
Cwp
Cp
Cpaft
Cpfwd
LCB/LWL
LCF/LWL

# Appendix M – Loading Conditions

| Group | Item | Ship Synthesis | | | Normal Condition N | | | Light #1 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Water Density (lbf/ft3) | 64 | | | 64 | | | 64.3 | | |
| | | Equation | Value | LCG (fwdLCB) | % Full | Weight | Moment | % Full | Weight | Moment |
| Condition A | | Wa | 3154.89 | 0.48 | | 3154.89 | 1500.11 | | 3154.887 | 1500.1147 |
| Disp sub (adjusted for density, lton) | | Disp' | 4709.89 | 0.00 | | 4709.89 | 0.00 | | 4732 | 0 |
| Main Ballast Tanks (adjusted for density, lton) | | Wmbt' | 924.76 | 2.58 | | 924.76 | 2386.81 | | 929 | 2397.9946 |
| Weight to Submerge (lton) adjusted for density | | Ws' | 1555.00 | -0.96 | | 1555.00 | -1500.11 | | 1577 | -1500.11 |
| 1,2,3 | Fixed Loads: crew and effects, ballistic missiles, sanitary, lube oil sumps, candles | WF10+ Wsew+ 0.1*WF46 | 9.10 | 21.49 | 100.00 | 9.10 | 195.50 | 100.00 | 9.10 | 195.50 |
| 1 | Crew | WF10 | 5.84 | 18.39 | 100.00 | 5.84 | 107.50 | 100.00 | 5.84 | 107.50 |
| 2 | Sewage | Wsew | 3.15 | 28.39 | 100.00 | 3.15 | 89.46 | 100.00 | 3.15 | 89.46 |
| 3 | Lube oil in sumps | 0.1*WF46 | 0.10 | -14.61 | 100.00 | 0.10 | -1.46 | 100.00 | 0.10 | -1.46 |
| 4 | Gases: oxgen and hydrogen | Wo2 | 158.05 | -26.61 | 100.00 | 158.05 | -4205.23 | 100.00 | 158.05 | -4205.23 |
| | | Wh2 | 0.00 | 118.39 | 100.00 | 0.00 | 0.00 | 100.00 | 0.00 | 0.00 |
| 5 | Torpedoes, missiles, mines and Ammunition | Wvp | 116.55 | 40.92 | 100.00 | 55.50 | 2852.30 | 0.00 | 58.28 | 2384.42 |
| | Torpedo | Wtorp | 55.50 | 51.39 | 100.00 | 55.50 | 2852.30 | 50.00 | 27.75 | 1426.15 |
| | Missile (after flood) | Wmis | 0.00 | 4.39 | 100.00 | 0.00 | 0.00 | 100.00 | 0.00 | 0.00 |
| | Mines | Wmines | 61.05 | 31.39 | 0.00 | 0.00 | 0.00 | 50.00 | 30.53 | 958.27 |
| 6 | Potable and fresh water | WF52 | 8.25 | 25.39 | 100.00 | 8.25 | 209.49 | 50.00 | 4.13 | 104.75 |
| 7 | Provisions and general stores | WF31+ WF32 | 13.13 | 14.39 | 100.00 | 13.13 | 188.99 | 75.00 | 9.85 | 141.74 |
| | | WF31 | 9.97 | 14.39 | | | | | | |
| | | WF32 | 3.16 | 14.39 | | | | | | |
| 8 | Lube oil in storage tanks | 0.9*WF46 | 0.90 | -14.61 | 100.00 | 0.90 | -13.15 | 75.00 | 0.68 | -9.86 |
| 9 | Compensating fuel tanks (no fuel ballast tanks) | Wfcomp | 142.00 | -17.83 | 100 fuel | 142.00 | -2531.45 | 100 fuel | 142.00 | -2531.45 |
| 10 | Fuel in clean fuel tanks | Wfclean | 28.51 | -55.61 | 100.00 | 28.51 | -1585.64 | 100.00 | 28.51 | -1585.64 |
| | Compensated Methanol (outboard) | 0.772*Wfaip | 77.20 | -10.68 | 100.00 | 77.20 | -824.27 | 100.00 | 77.20 | -824.27 |
| | Methanol (inboard) | 0.228*Wfaip | 22.80 | -55.61 | 100.00 | 22.80 | -1267.84 | 100.00 | 22.80 | -1267.84 |
| 11 | Cargo | | | | | 0.00 | 0.00 | | 0.00 | 0.00 |
| 12 | Passengers | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 13 | Residual SW | Wresidual | 10.57 | -11.61 | 100.00 | 10.57 | -122.64 | 100.00 | 10.57 | -122.64 |
| Total | VLI | WF00 | 1096.73 | -110.52 | | 590.60 | -4056.14 | | 588.52 | -5140.61 |
| Variable Balast Required | Ws'-Wmbt'-VLI | Wtrimbal | | | | 39.64 | 169 | | 59.47 | 1243 |

| Group | Item | Ship Synthesis | | | Heavy #1 | | | Heavy #1 (mines) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Water Density (lbf/ft3) | 64 | | | 63.6 | | | 63.6 | | |
| | | Equation | Value | LCG (fwdLCB) | % Full | Weight | Moment | % Full | Weight | Moment |
| Condition A | | Wa | 0.00 | 0.00 | | 3154.887 | 1500.1147 | | 3154.89 | 1500.11 |
| Disp sub (adjusted for density, lton) | | Disp' | 0.00 | 0.00 | | 4680 | 0 | | 4680.45 | 0.00 |
| Main Ballast Tanks (adjusted for density, lton) | | Wmbt' | 0.00 | 0.00 | | 919 | 2371.8889 | | 918.98 | 2371.89 |
| Weight to Submerge (lton) adjusted for density | | Ws' | 1525.56 | 0.00 | | 1526 | -1500.11 | | 1525.56 | -1500.11 |
| 1,2,3 | Fixed Loads: crew and effects, ballistic missiles, sanitary, lube oil sumps, candles | WF10+ Wsew+ 0.1*WF46 | #VALUE! | #VALUE! | 100.00 | 9.10 | 195.50 | 100.00 | 9.10 | 195.50 |
| 1 | Crew | WF10 | = | 0.00 | 100.00 | 5.84 | 107.50 | 100.00 | 5.84 | 107.50 |
| 2 | Sewage | Wsew | 0.00 | 0.00 | 100.00 | 3.15 | 89.46 | 100.00 | 3.15 | 89.46 |
| 3 | Lube oil in sumps | 0.1*WF46 | 0.00 | 0.00 | 100.00 | 0.10 | -1.46 | 100.00 | 0.10 | -1.46 |
| 4 | Gases: oxgen and hydrogen | Wo2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Wh2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 5 | Torpedoes, missiles, mines and Ammunition | Wvp | 0.00 | #DIV/0! | Torp and Missile | 55.50 | 3080.25 | Mine and Missile | 61.05 | 1916.53 |
| | Torpedo | Wtorp | 0.00 | 0.00 | 100 | 56 | 3080.25 | 0 | 0 | 0 |
| | Missile (after flood) | Wmis | 0.00 | 0.00 | 100 | 0 | 0.00 | 100 | 0 | 0 |
| | Mines | Wmines | 0.00 | 0.00 | 0 | 0 | 0.00 | 100 | 61 | 1916.5345 |
| 6 | Potable and fresh water | WF52 | 0.00 | 0.00 | 100.00 | 8.25 | 209.49 | 100.00 | 8.25 | 209.49 |
| 7 | Provisions and general stores | WF31+ WF32 | #VALUE! | #VALUE! | 50.00 | 6.57 | 94.49 | 50.00 | 6.57 | 94.49 |
| | | WF31 | 0.00 | 0.00 | | | | | | |
| | | WF32 | = | 0.00 | | | | | | |
| 8 | Lube oil in storage tanks | 0.9*WF46 | 0.00 | 0.00 | 50.00 | 0.45 | -6.57 | 50.00 | 0.45 | -6.57 |
| 9 | Compensating fuel tanks (no fuel ballast tanks) | Wfcomp | 0.00 | 0.00 | 100 SW | 173.40 | -3091.14 | 100 SW | 173.40 | -3091.14 |
| 10 | Fuel in clean fuel tanks | Wfclean | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Compensated Methanol (outboard) | 0.772*Wfaip | 0.00 | 0.00 | 100 SW | 99.38 | -1061.04 | 100 SW | 99.38 | -1061.04 |
| | Methanol (inboard) | 0.228*Wfaip | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 11 | Cargo | | | | | 0.00 | 0.00 | | 0.00 | 0.00 |
| 12 | Passengers | | | | | 0.00 | 0.00 | | 0.00 | 0.00 |
| 13 | Residual SW | Wresidual | 0.00 | 0.00 | 100.00 | 10.57 | -122.64 | 100.00 | 10.57 | -122.64 |
| Total | VLI | WF00 | 0.00 | 0.00 | | 427.79 | 2574.09 | | 438.89 | 246.65 |
| Variable Balast Required | Ws'-Wmbt'-VLI | Wtrimbal | | | | 178.79 | -6446 | | 167.69 | -4119 |

| Group | Item | Ship Synthesis | | | Heavy Fwd #1 | | | Heavy Fwd #2 | | | Heavy Aft (diesel) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Water Density (lbf/ft3) | 64 | | | 64.3 | | | 63.6 | | | 63.6 | | |
| | | Equation | Value | LCG (fwdLCB) | % Full | Weight | Moment | % Full | Weight | Moment | % Full | Weight | Moment |
| Condition A | | Wa | 0.00 | 0.00 | | 3154.89 | 1500.11 | | 3154.89 | 1500.11 | | 3154.89 | 1500.11 |
| Disp sub (adjusted for density, ltons) | | Disp' | 0.00 | 0.00 | | 4731.96 | 0.00 | | 4680.45 | 0.00 | | 4680.45 | 0.00 |
| Main Ballast Tanks (adjusted for density, lton) | | Wmbt' | 0.00 | 0.00 | | 929.09 | 2397.99 | | 918.98 | 2371.89 | | 918.98 | 2371.89 |
| Weight to Submerge (lton) adjusted for density | | Ws' | 1577.08 | 0.00 | | 1577.08 | -1500.11 | | 1525.56 | -1500.11 | | 1525.56 | -1500.11 |
| 1,2,3 | Fixed Loads: crew and effects, ballistic missiles, sanitary, lube oil sumps, candles | WF10+ Wsew+ 0.1*WF46 | 0.00 | #DIV/0! | 100.00 | 9.10 | 195.50 | 100.00 | 9.10 | 195.50 | 100.00 | 9.10 | 195.50 |
| 1 | Crew | WF10 | 0.00 | 0.00 | 100.00 | 5.84 | 107.50 | 100.00 | 5.84 | 107.50 | 100.00 | 5.84 | 107.50 |
| 2 | Sewage | Wsew | 0.00 | 0.00 | 100.00 | 3.15 | 89.46 | 100.00 | 3.15 | 89.46 | 100.00 | 3.15 | 89.46 |
| 3 | Lube oil in sumps | 0.1*WF46 | 0.00 | 0.00 | 100.00 | 0.10 | -1.46 | 100.00 | 0.10 | -1.46 | 100.00 | 0.10 | -1.46 |
| 4 | Gases: oxgen and hydrogen | Wo2 | 0.00 | 0.00 | 100.00 | 158.05 | -4205.23 | 50.00 | 79.02 | -2102.61 | 50.00 | 79.02 | -2102.61 |
| | | Wh2 | 0.00 | 0.00 | 100.00 | 0.00 | 0.00 | 50.00 | 0.00 | 0.00 | 50.00 | 0.00 | 0.00 |
| 5 | Torpedoes, missiles, mines and Ammunition | Wvp | 0.00 | #DIV/0! | aft expanded | 55.50 | 2852.30 | aft expended | 55.50 | 2852.30 | fore expended | 0.00 | 0.00 |
| | Torpedo | Wtorp | 0.00 | 0.00 | 100 | 56 | 2852.3041 | 100 | 56 | 2852.30411 | 0 | 0 | 0 |
| | Missile (after flood) | Wmis | 0.00 | 0.00 | 100 | 0 | 0 | 100 | 0 | 0 | 100 | 0 | 0 |
| | Mines | Wmines | 0.00 | 0.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | Potable and fresh water | WF52 | 0.00 | 0.00 | 100.00 | 8.25 | 209.49 | 100.00 | 8.25 | 209.49 | 50.00 | 4.13 | 104.75 |
| 7 | Provisions and general stores | WF31+ WF32 | 0.00 | #DIV/0! | 75.00 | 9.85 | 141.74 | 50.00 | 6.57 | 94.49 | 50.00 | 6.57 | 94.49 |
| | | WF31 | 0.00 | 0.00 | | | | | | | | | |
| | | WF32 | 0.00 | 0.00 | | | | | | | | | |
| 8 | Lube oil in storage tanks | 0.9*WF46 | 0.00 | 0.00 | 75.00 | 0.68 | -9.86 | 75.00 | 0.68 | -9.86 | 75.00 | 0.68 | -9.86 |
| 9 | Compensating fuel tanks (no fuel ballast tanks) | Wfcomp | 0.00 | 0.00 | 100 fuel | 142.00 | -2531.45 | 50 fuel | 158.26 | -2821.39 | 50 fuel | 158.26 | -2821.39 |
| 10 | Fuel in clean fuel tanks | Wfclean | 0.00 | 0.00 | 100.00 | 28.51 | -1585.64 | 100.00 | 28.51 | -1585.64 | 50.00 | 14.26 | -792.82 |
| | Compensated Methanol (outboard) | 0.772*Wfaip | 0.00 | 0.00 | 100.00 | 77.20 | -824.27 | 50 fuel | 88.59 | -945.93 | 50 fuel | 218.88 | -2336.96 |
| | Methanol (inboard) | 0.228*Wfaip | 0.00 | 0.00 | 100.00 | 22.80 | -1267.84 | 100.00 | 22.80 | -1267.84 | 100.00 | 22.80 | -1267.84 |
| 11 | Cargo | | | | | 0.00 | 0.00 | | 0.00 | 0.00 | | 0.00 | 0.00 |
| 12 | Passengers | | | | | 0.00 | 0.00 | | 0.00 | 0.00 | | 0.00 | 0.00 |
| 13 | Residual SW | Wresidual | 0.00 | 0.00 | 100.00 | 10.57 | -122.64 | 100.00 | 10.57 | -122.64 | 100.00 | 10.57 | -122.64 |
| Total | VLI | WF00 | 0.00 | 0.00 | | 587.09 | -4100.10 | | 532.44 | -2456.33 | | 533.34 | -8863.89 |
| Variable Balast Required | Ws'-Wmbt'-VLI | Wtrimbal | | | | 60.89 | 202 | | 74.14 | -1416 | | 73.24 | 4992 |