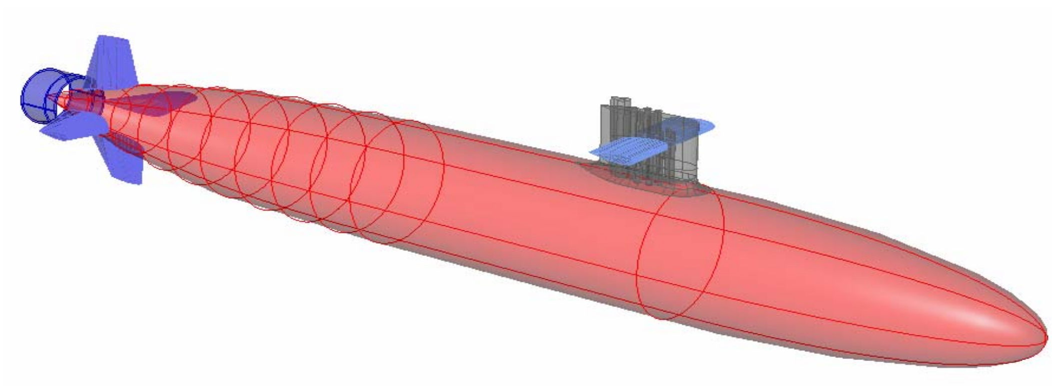
Virginia Tech
Aerospace & Ocean Engineering

Design Report

Guided Missile Submarine

SSG(X)

VT Total Ship Systems Engineering



SSG(X) Variant 2-44
Ocean Engineering Design Project
AOE 4065/4066
Fall 2005 – Spring 2006
Virginia Tech Team 3

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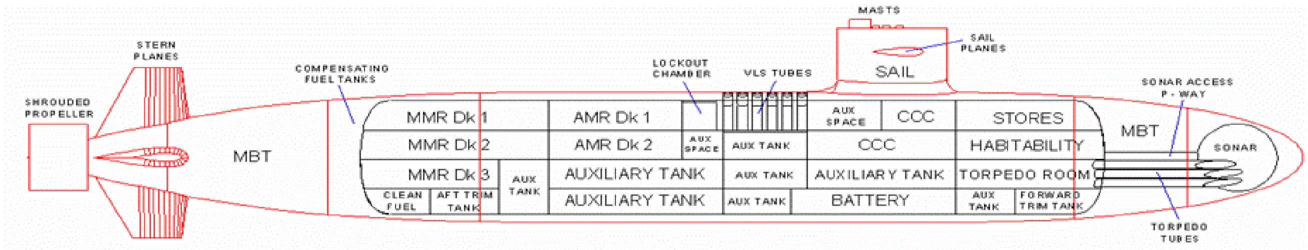
Executive Summary



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

The SSG(X) requirement is based on the need for a technologically advanced, covert non-nuclear missile launch platform. Mission requirements include the time-sensitive launch of anti-air, anti-surface, and anti-ship weapons in littoral regions in support of the battle group. The SSG(X) is capable of ISR missions and mine countermeasures.

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

SSG(X) is a high effectiveness, high risk, and low cost alternative from the non-dominated frontier. This design was chosen to provide a challenging design project, with modern technologies including PEM fuel cells and a Rim-Driven Propulsor (RDP). The SSG(X) houses a capable missile platform with 24 VLS cells and six torpedo tubes with 24 reloads. The small size of the SSG(X) when compared to vessels with similar capabilities and high maneuverability allows the submarine to operate in ports and close littoral regions. The SSG(X) has an axis-symmetric hullform for producibility. An advanced sonar system and AUV and UAV capabilities make the SSG(X) fully capable of ISR missions. The main characteristics of SSG(X) are listed in the table to the right.

Concept Development included hullform development and analysis, structural finite element analysis, propulsion and power system development and arrangement, general arrangements, machinery arrangements, combat system definition and arrangement, maneuvering and control analysis, cost and producibility analysis and risk analysis. The final concept design satisfies critical operational requirements in the ORD within cost and risk constraints with additional work required to improve the VLS and torpedo arrangements, and shape the bow for delayed boundary layer transition and transition noise reduction.

Ship Characteristic	Value
LOA	257.3 ft
Beam	31 ft
Diameter	31 ft
Submerged Displacement	3320 lton
Submerged Displaced Volume	133800 ft^3
Sprint Speed	22 knt
Snorkel Range @ 12 knt	5160 nm
AIP Endurance @ 5 knt	26 days
Sprint Endurance	1.05 hours
Propulsion and Power	Open Cycle Diesel/AIP, 2xCAT 3512 V12 + 2x500kW PEM; 5820kW-hr Zebra batteries, 1x14.75ft RDP
Weapon Systems	Reconfigurable torpedo room, 6x21" tubes, 24 reloads; 24 Cell VLS
Sensors	BQQ-10 Bow Dome Passive/Active, AN/BQG-5 WAA, high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; BSY-2
P_{req} for Sprint Speed	6570 kW
P_{req} for Snorkel	1332 kW
Battery Capacity	5820 kW-hr
Diving Depth	1000 ft
Total Officers	8
Total Enlisted	21
Total Manning	29
Basic Cost of Construction	$635M

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1 Introduction, Design Process and Plan

1.1 Introduction

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

1. Time sensitive and covert missile and torpedo launch.
2. Covert Intelligence, Surveillance, and Reconnaissance (ISR) operations.

The importance of action against regional powers is stressed in “Forward from the Sea” as published by the Department of the Navy in December 1996. This action requires rapid response to developing crises in order to protect U.S. interests and defend allies. “Naval Transformational Roadmap,” a Quadrennial Defense Review Report, identified seven critical U.S. military operation goals, of which the SSG(X) design must meet the first, third, fourth and fifth. These are: 1) protecting critical bases of operation; 3) protecting and sustaining U.S. forces while defeating denial threats; 4) denying enemy sanctuary by persistent surveillance; and 5) tracking and rapid engagement. Further concepts of operation for the SSG(X) design provide eight requirements. These are: 1) operating in littoral regions; 2) engage threats in cooperation with other forces by providing a covert missile launch platform; 3) launching time-sensitive and covert anti-air, anti-submarine, and anti-surface warfare; 4) projecting power ashore using Tomahawk Land Attack Missiles (TLAM); 5) conducting ongoing ISR; 6) conducting mine detection, neutralization, and avoidance; 7) snorkeling during transit and using Air Independent Propulsion (AIP) and batteries on station; and 8) supporting a single SEAL team.

The SSG(X) should be designed for minimum cost; the lead-ship acquisition cost should be less than \$1B and the follow-ship acquisition cost should be no more than \$700M. The platform must be highly producible to minimize time from concept to delivery. It should also be flexible enough to support variants. The platform must operate within current logistics support capabilities and it must consider inter-service and C^4/I. The design should also focus on survivability in a high-threat environment and operation in all warfare areas. The platform should be non-nuclear since the SSG(X) will operate in enemy littoral regions.

1.2 Design Philosophy, Process, and Plan

Submarine design is rooted in tradition, using experience and rules of thumb. The SSG(X) design does not follow the standard design process. A Multi-Objective Genetic Optimizer (MOGO) uses a genetic algorithm to find optimal feasible designs. It considers three objective attributes: effectiveness, risk, and cost. The MOGO searches for designs with maximum effectiveness and minimum risk and cost. Innovation is important in this design to develop a non-nuclear covert missile launch platform that meets the goals laid out in the SSG(X) MNS and ADM. The design process uses a total system approach; all submarine systems are evaluated for their effectiveness, risk, and cost.

This project covers Concept and Requirements Exploration in the Fall semester and Concept Development in the Spring. This is illustrated in Figure 1. The Concept and Requirements Exploration process used in this project is illustrated in Figure 2. Concept and Requirements Exploration results in a baseline design; from this, a preliminary Operational Requirements Document (ORD) is developed. The ORD is provided in Appendix C and specifies performance requirements, design constraints, and concepts to be explored. It serves as the primary requirements document for Concept Development.

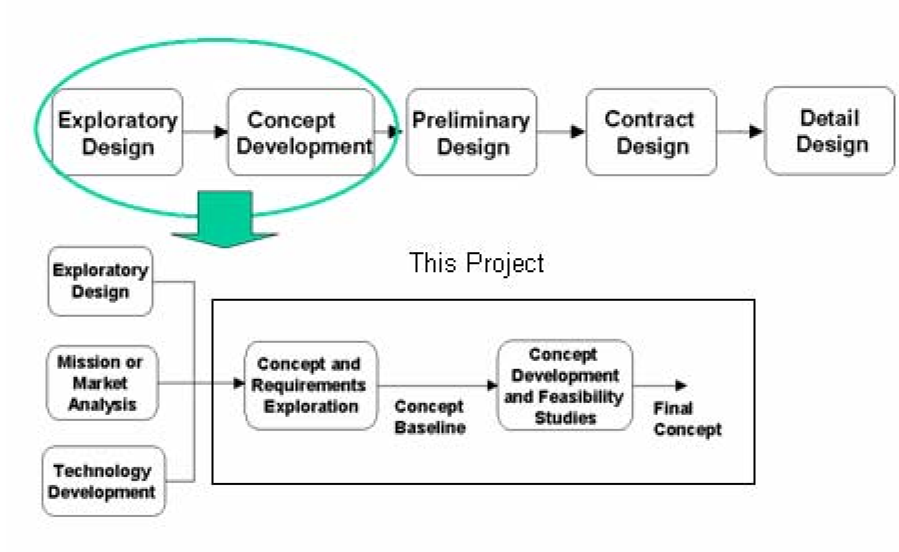


Figure 1 - Design Process

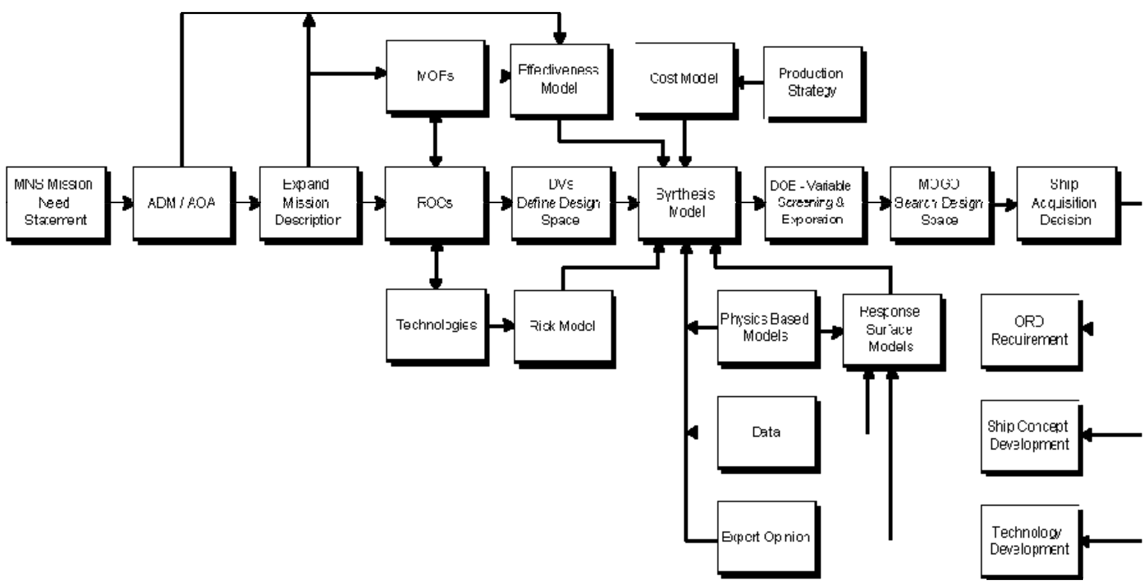


Figure 2 - Concept and Requirements Exploration

From the MNS and ADM, the Concept of Operations (CONOPs), Projected Operational Environment (POE), mission scenarios, and Required Operational Capabilities (ROCs) are defined for the SSG(X) missions. Technologies necessary for the ROCs are identified; these include hullform, power and propulsion, combat systems, and automation. From the available technologies, a design space is defined. Metrics for effectiveness, risk and cost are developed to consider the alternatives in the non-dominated design space. A submarine synthesis model is built and used to perform a MOGO. The optimization results in the selection of the baseline design from the non-dominated design space.

Figure 3 illustrates the design spiral used in the concept development stage of this project. Each time around the design spiral improves the quality and balance of the design by increasing effectiveness and lowering risk and cost.

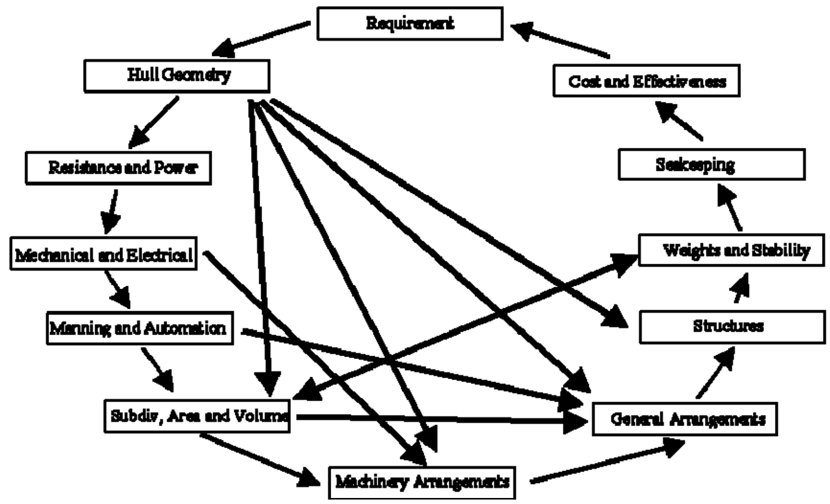


Figure 3 - VT Concept Development Design Spiral

1.3 Work Breakdown

SSG(X) Team 3 consists of six students from Virginia Tech. Each student is assigned areas of work according to his or her interests and special skills as listed in Table 1.

Table 1 - Work Breakdown

Name	Specialization
Desta Alemayehu	Hydrostatics
Robert B. Boyle	Modeling/Balance
Elizabeth Eaton	Maneuvering and Control
Timothy Lynch	Structures
Justin Stepanchick	Powering and Machinery Arrangements
Ronda Yon	Arrangements/Modeling

1.4 Resources

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

Table 2 - Tools

Analysis	Software Package
Arrangement Drawings	Rhino
Hull form Development	Rhino
Hydrostatics	Rhino/Rhino Marine
Resistance/Power	MathCad
Dynamics and Control	VT Sub Stab
Ship Synthesis Model	MathCad/Model Center/Fortran
Structure Model	MAESTRO/Jackson SUBSTRUK

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

2 Mission Definition

The SSG(X) requirement is based on the SSG(X) MNS and Virginia Tech SSG(X) ADM in Appendix A and Appendix B respectively 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 MNS and ADM for the Guided Missile Submarine to provide a non-nuclear platform for covert strike and ISR. It will snorkel using open-cycle during transit and operate on AIP and batteries on station. The SSG(X) must be able to operate in vulnerable remote littoral regions. This vulnerability requires a non-nuclear platform. The submarine will engage in threats in cooperation with other forces; it will function as a platform for time sensitive and covert strike. The SSG(X) will support Anti-Air Warfare (AAW) by launching missiles cued by surface platform; the SSG(X) will conduct Anti-Submarine Warfare (ASW) using torpedoes with detection from sonar and tracking; the platform will launch Harpoon missiles and torpedoes for Anti-Surface Warfare (ASuW) and use sonar detection and tracking for identification of enemy surface ships. In accordance with "Forward from the Sea," the submarine will project power ashore for Strike operations using TLAM. The SSG(X) will support a single SEAL team.

The SSG(X) will perform ongoing ISR. The submarine will need to perform mine countermeasures involving detection, avoidance and neutralization. This will be done with Unmanned Underwater Vehicles (UUVs) and Autonomous Underwater Vehicles (AUVs). During ISR operations, it will be necessary for the submarine to avoid and neutralize attack from enemy submarines and avoid detection from patrol craft.

2.2 Projected Operational Environment (POE) and Threat

The projection of force against enemy nations near geographically constrained bodies of water requires the SSG(X) to operate using AIP in littoral regions worldwide. During the mission, the submarine may encounter dense contact by the enemy. The submarine will need to protect itself from 1) conventional and nuclear weapons, 2) anti-ship mines, 3) contact with and attack from surface ships and diesel and nuclear submarines, and 4) attack from air or land. The SSG(X) will be able to perform evasive or defensive measures in littoral regions in response to these threats.

The SSG(X) must be able to transit in the open ocean while snorkeling. The submarine should be suitable for all weather and be able to withstand sea states 0 through 9. Compromises will need to be made in the design to produce a submarine seaworthy enough for transoceanic tours and agile enough to effectively perform missions in littoral regions.

2.3 Specific Operations and Missions

The SSG(X) is required to perform two major missions. Under each of these missions, the SSG(X) is required to conduct MIW, ASW, ASuW and AAW scenarios. AAW capabilities are limited to launch; the SSG(X) will work in concert with surface ships that detect and track enemy aircraft. The SSG(X) is capable of performing all four warfare types with a high degree of stealth by utilizing AIP. The first major mission is to conduct ISR, which includes Special Operations. These missions can include conducting visual reconnaissance, recovering assets (human or electronic), and eliminating targets. The intelligence sides of ISR entails gathering information by intercepting electronic conversations or tapping into hardwire lines. The other major mission the SSG(X) will perform is a missile launch. The objective of this mission will concentrate on a land attack; however, the SSG(X) will not be limited to land attack missile launches. The SSG(X) is also capable of targeting ships with an ASuW missile launch, missiles with an AAW missile launch, and a submarine with an ASW torpedo launch. No matter what type of missile launch scenario, the SSG(X) is designed to launch in a time sensitive scenario as well as being covert.

2.4 Mission Scenarios

Mission scenarios for the primary SSG(X) missions are provided in Table 3 and Table 4. The ISR Mission departs from the continental United States and covertly travels to a hostile area to conduct intelligence, surveillance and reconnaissance. While conducting ISR, the submarine engages and neutralizes an enemy submarine and conducts mine counter warfare. The missile mission uses air, surface and land attack weapons to neutralize enemies. An enemy submarine is again neutralized and mine counter warfare is conducted. This mission also uses the ability of the submarine to replenish at a sea base.

Table 3 – ISR Mission

Day	Mission scenario
1-15	Depart from CONUS on snorkel to area of hostilities
15-16	Proceed independently to within 10 nautical miles (nm) of enemy mainland
16-20	Conduct ISR
16	Avoid/neutralize enemy submarine attack
17	Conduct mine counter warfare. Launch counter mine AUVs that will detect and neutralize threat.
20-30	Continue ISR
28	Engage enemy patrol craft using Harpoon cruise missile
30	Return to sea base for rearming and refueling

Table 4 - Missile Mission

Day	Mission scenario
1-15	Depart from home base submerged. Transit at snorkel depth, having batteries charged upon arrival.
15	Launch strike missiles against land target. Launch anti-air defense against an enemy ASW helicopter.
16	Kill incoming cruise missile salvo against CBG in cooperation with DDG.
17	Avoid/neutralize enemy submarine attack
18	Receive re-targeting information and perform cruise missile strike against updated targets.
19-20	Conduct mine counter warfare. Launch counter mine AUVs that will detect and neutralize threat.
15-30	Conduct EM, visual and radio reconnaissance
20	Replenish fuel and stores at sea base
25	Cooperatively, with Aegis unit, detect, engage, and kill incoming cruise missile salvo on CBG unit
26	Engage and destroy enemy surface ships using Harpoon cruise missiles
30	Return to sea base for rearming and refueling

2.5 Required Operational Capabilities

To support the missions and mission scenarios described in Section 2.4, the capabilities listed in Table 5 are required. Each of these can be related to functional capabilities required in the ship design, and, if within the scope of the Concept Exploration design space, the ship's ability to perform these functional capabilities is measured by explicit Measures of Performance (MOPs).

Table 5 - List of Required Operational Capabilities (ROCs)

ROCs	Description
AAW 1.2	Support area anti-air defense
AAW 2	Provide anti-air defense in cooperation with other forces
AMW 6	Conduct unmanned aerial vehicle (UAV) operations
ASU 1	Engage surface threats with anti-surface armaments
ASU 1.1	Engage surface ships at long range
ASU 1.2	Engage surface ships at medium range
ASU 2	Engage surface ships in cooperation with other forces
ASU 4.2	Detect and track a surface target using sonar
ASU 6	Disengage, evade and avoid surface attack
ASW 1	Engage submarines

ROCs	Description
ASW 1.2	Engage submarines at medium range
ASW 1.3	Engage submarines at close range
ASW 2	Engage submarines in cooperation with other forces
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 9	Relay communications
CCC 21	Perform cooperative engagement
FSO 3	Provide support services to other units
FSO 5	Conduct towing/search/salvage rescue operations
FSO 6	Conduct SAR operations
FSO 7	Provide explosive ordnance disposal services
FSO 9	Provide routine health care
FSO 10	Provide first aid assistance
INT 1	Support/conduct intelligence collection
INT 3	Conduct surveillance and reconnaissance
INT 9	Disseminate surveillance and reconnaissance information
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)
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 shore-based support
MOB 16	Operate in day and night environments
MOB 17	Operate in heavy weather
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
NCO 3	Provide upkeep and maintenance of own unit
SEW 2	Conduct sensor and ECM operations
SEW 5	Conduct coordinated SEW operations with 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 Hull Form Alternatives

SSG(X) hull alternatives are chosen based on a set of performance metrics and other considerations. From these a list of general requirements for the submarine hull is formed and initial design variables and parameter ranges are specified. This defines the design space from which hull form alternatives are selected for consideration.

The performance metrics are selected based on the mission needs of the SSG(X). Efficiency in transit dictates the selection of a hydrodynamic hull for low resistance. However, the submarine will not only transit, but must be able to operate agilely in littoral regions; therefore, dynamic stability and maneuverability are important factors in the design. To maintain structural efficiency, weight is kept to a minimum. The SSG(X) must be producible and affordable. The diameter of the submarine must be greater than 22 feet to carry the missile payload and accommodate the Vertical Launch System (VLS).

A traditional teardrop shape was selected for the hull of SSG(X). The teardrop shape has an elliptical bow and parabolic stern and was chosen based on its low submerged resistance. This shape is modified by the addition of parallel midbody for arrangements and machinery and mission spaces. The traditional teardrop and modified teardrop shapes are shown in Figure 4. The pressure hull will be axis-symmetric for structural efficiency and producibility. The hydrodynamic envelope may have a slightly larger beam than depth. Two or three decks may be included in the pressure hull; these decks will have a height between 7 and 8 feet. A lower bilge for batteries and tankage with a height between 6 and 8 feet will also be included in the pressure hull. The ranges for the diameter, length, beam, and fore and aft body characteristics are shown in Table 6. The parameters η_f and η_a are exponents that describe the fullness of the fore and aft bodies as shown in Figure 4.

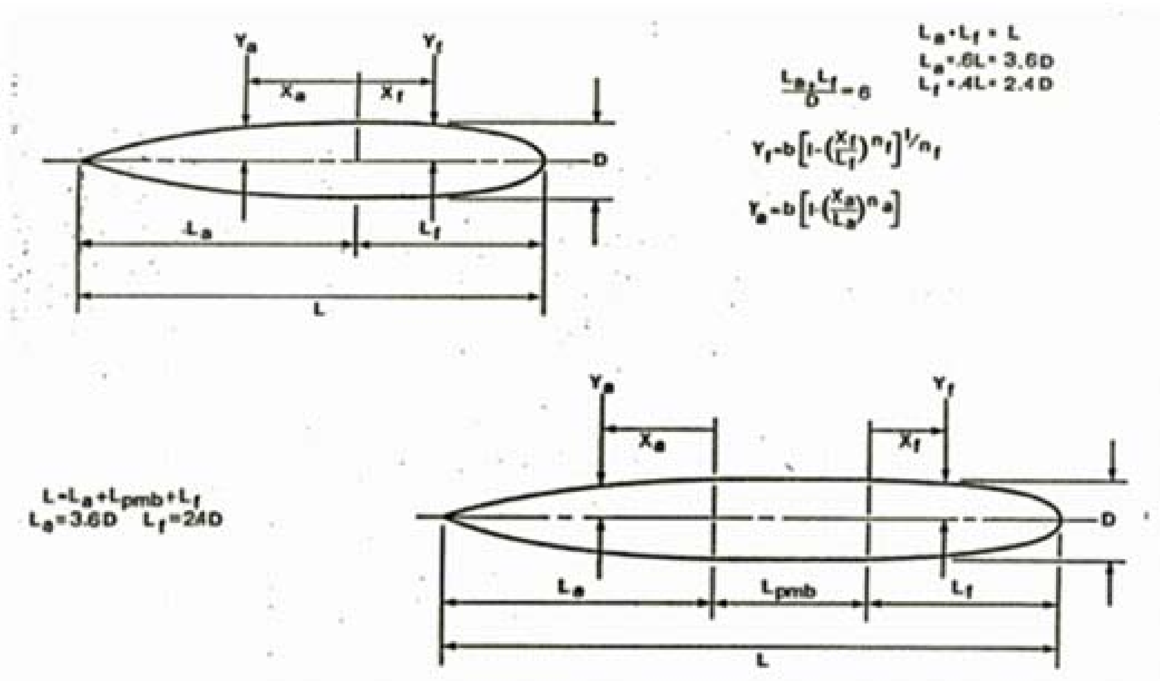


Figure 4 - Teardrop and Modified Teardrop Hull Forms [MIT Jackson Notes]

Table 6 - Hull Form Design Space

Parameter	Range
D	22 – 34 feet
L/D	7 – 10
B/D	1 – 1.2
L_{fwd}	2.4D
L_{aft}	3.6D
η_f	2.0 – 3.5
η_a	2.5 – 4.0

3.1.2 Propulsion and Electrical Machinery Alternatives

The propulsion section is broken down into requirements and alternatives. The final propulsion alternative hierarchy for SSG(X) is shown in Figure 5. The propulsor type will either be a shrouded single shaft propeller or a Rim Driven Pod.

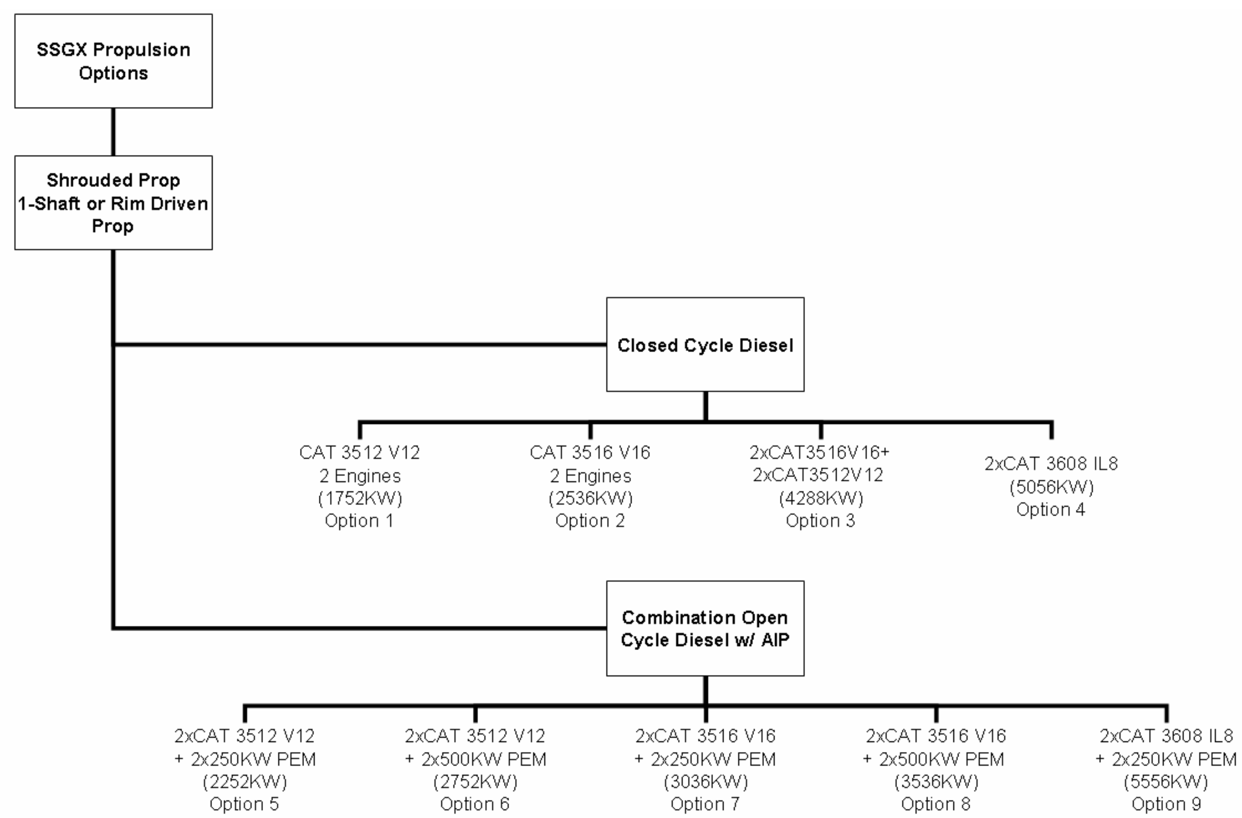


Figure 5 - SSG(X) propulsion system alternatives

3.1.2.1 Machinery Requirements

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

General Requirements –

The propulsion and power must be non-nuclear. The submarine must be capable of transiting from base to area of conflict under its own power. While in areas of hostility SSG(X) must be capable of covert littoral maneuvering. The SSG(X) will operate in two modes: AIP and snorkel.

Sustained Speed and Propulsion Power –

The goal sprint speed for SSG(X) is 22 knots, with a threshold of 15 knots. For the propulsor to accomplish this speed, preliminary calculations were made by varying the hull characteristics to create a best and worst case scenario for hull resistance. The power requirement was also calculated to propel the SSG(X) at 12 knots under snorkel. The propulsive power requirement varies from 1750 KW to 5560 KW. SSG(X) has a threshold endurance range of 4000 miles for snorkel transit, threshold endurance duration of 20 days at 5 knots for AIP transit, and sprint duration of 1 hour also under AIP at a velocity no less than 15 knots.

Ship Control and Machinery Plant Automation –

One of the main goals for SSG(X) is to keep manning requirements to a minimum. To achieve this goal, a high level of automation is required. Utilizing Commercial off the Shelf (COTS) hardware will reduce cost, improve logistics support and provide larger customer base for improvements and upgrades.

Propulsion Engine and Ship Service Generator Certification –

Because of the criticality of propulsion and ship service power to many aspects of the ship's mission and survivability, this equipment shall be Navy-qualified, Grade A shock certified, and non-nuclear. To reduce signatures a shrouded prop and an Integrated Propulsion System (IPS) is proposed.

3.1.2.2 Machinery Plant Alternatives

Propulsion system trade-off alternatives are selected to be consistent with speed, endurance, payload, and mission requirements. From this a hierarchy of machinery alternatives is created. An excel spreadsheet is created and filled with characteristics of data on each power plant from the manufacturer and technical papers. Table 6 lists the data collected for each propulsion configuration. Table 7 - Table 8 display this data for the SSG(X) propulsion options. [Pearson and Walters, Warship '99: Naval Submarines 6]

SSG(X) Concept Exploration considers fuel cells and closed cycle diesel engines for AIP alternatives. The propulsion system will either be an open cycle diesel or a closed cycle diesel that can run open cycle while snorkeling. The battery options are limited to low to moderate risk Lead Acid, Ni-Cd, and Zebra batteries. Depending on the pressure hull design, hydrocarbon fuels, oxygen, and argon will be stored inboard or outboard of the pressure hull. Hydrogen will be stored outboard.

Table 6 – Propulsion System Data [AIP Selection]

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

Table 7 – Data for SSG(X) propulsion options

Description	Propulsion Option (PSYS)	AIP Type (AIPtype) (1=CCD, 2=fuel cell)	Esnorkel (hr)	Eaip (hr)	VH2C (m3/kw-hr)	VH2S (m3/kw-hr)	VO2C (m3/kw-hr)	VO2S (m3/kw-hr)	VAC (m3/kw-hr)	VAS (m3/kw-hr)	VBMdp (m3/hr)
2xCAT3512 V12	1	1	1752	1752	0.000	0.000	0.135	0.130	0.021	0.037	60.000
2xCAT3516 V16	2	1	2536	2536	0.000	0.000	0.135	0.130	0.021	0.037	60.000
2xCAT3608 IL8	3	1	3036	3036	0.000	0.000	0.135	0.130	0.021	0.037	60.000
2xCAT3516 +2xCAT3512	4	1	4288	4288	0.000	0.000	0.135	0.130	0.021	0.037	60.000
2xCAT3512 V12 w/2 AIP 250KW PEM	5	2	1752	500	0.484	0.280	0.390	0.058	0.000	0.000	65.000
2xCAT3512 V12 w/2 AIP 500KW PEM	6	2	1752	1000	0.484	0.280	0.390	0.058	0.000	0.000	65.000
2xCAT3516 V16 w/2 AIP 250KW PEM	7	2	2536	500	0.484	0.280	0.390	0.058	0.000	0.000	65.000
2xCAT3516 V16 w/2 AIP 500KW PEM	8	2	2536	1000	0.484	0.280	0.390	0.058	0.000	0.000	65.000
2xCAT3608 IL8 w/2 AIP 250KW PEM	9	2	3036	500	0.484	0.280	0.390	0.058	0.000	0.000	65.000

Table 8 - Data for SSG(X) propulsion options (continued)

Description	VBMdg (m3/hr)	MH2C (kg/kw-hr)	MH2S (kg/kw-hr)	MO2C (kg/kw-hr)	MO2S (kg/kw-hr)	MAC (kg/kw-hr)	MAS (kg/kw-hr)	MBMdp (kg/hr)	MBMdg (kg/hr)	SFC (kg/kw-hr)	Transmission efficiency
2xCAT3512 V12	0.0	0	0	0.84	0.337	0.030	0.008	34	0	0.216	0.98
2xCAT3516 V16	0.0	0	0	0.84	0.337	0.030	0.008	34	0	0.216	0.98
2xCAT3608 IL8	0.0	0	0	0.84	0.337	0.030	0.008	34	0	0.189	0.98
2xCAT3516 +2xCAT3512	0.0	0	0	0.84	0.337	0.030	0.008	34	0	0.216	0.98
2xCAT3512 V12 w/2 AIP 250KW PEM	303	3480	0.874	0.44	0.165	0.000	0.008	19	3099	0.216	0.96
2xCAT3512 V12 w/2 AIP 500KW PEM	303	3480	0.874	0.44	0.165	0.000	0.008	19	3099	0.216	0.96
2xCAT3516 V16 w/2 AIP 250KW PEM	260	3480	0.874	0.44	0.165	0.000	0.008	19	2290	0.216	0.96
2xCAT3516 V16 w/2 AIP 500KW PEM	260	3480	0.874	0.44	0.165	0.000	0.008	19	2290	0.216	0.96
2xCAT3608 IL8 w/2 AIP 250KW PEM	176	3480	0.874	0.44	0.165	0.000	0.008	19	1730	0.189	0.96

The AIP fuel cell options are classified by their electrolyte. The options researched were Molten Carbonate (MCFC), Phosphoric Acid (PAFC), Polymer Electrolyte Membrane (PEM), Solid Oxide, Direct Methanol, Alkaline, and Regenerative (Reversible). The best alternative for SSG(X) was found to be the PEM cell, providing reduced signatures and safe and proven technology. Reformers were also researched, but not considered due to their immature development.

PEM fuel cells have multiple advantages. They offer a quiet low temperature operating condition, thereby reducing the thermal signature. The only byproduct is clean pure water. The technology is proven and safe; therefore, PEM fuel cells are a low risk option. PEM cells are stackable, providing a range of space options. Their disadvantage is that pure Hydrogen and Oxygen reactants must be carried. Cell impurities also reduce efficiency and output. Figure 6 displays how a PEM fuel cell operates.

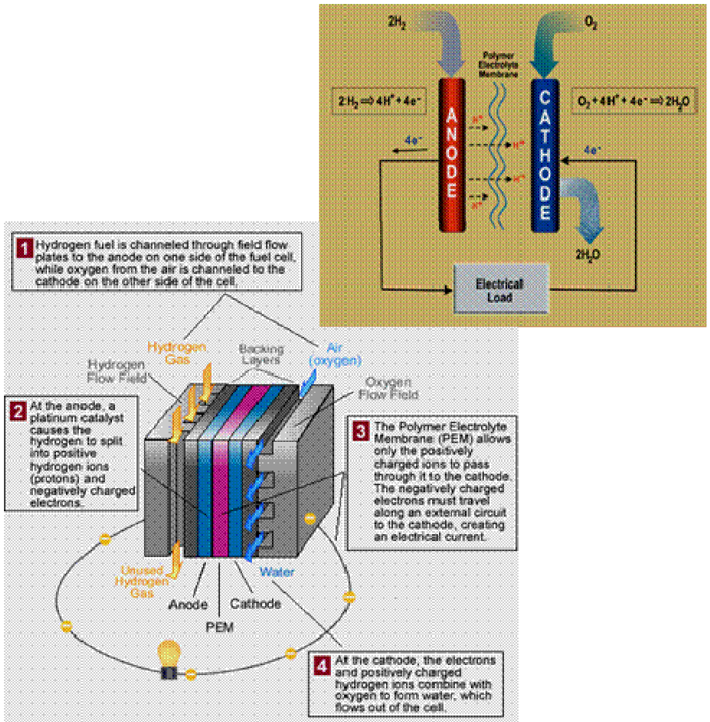


Figure 6 - PEM fuel cell description [Dr. Brown, Ship Design Notes]

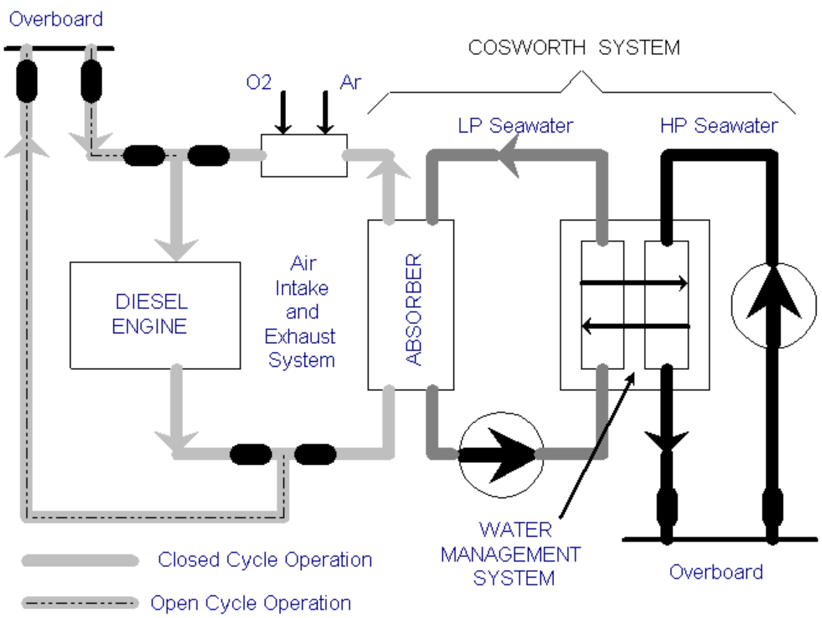


Figure 7 - Outline of a closed cycle diesel engine [Dr. Brown, Ship Design Notes]

The closed cycle diesel (CCD) option can be integrated with any diesel engine. The process for a CCD is to use an inert gas (e.g. Argon) and oxygen to provide an atmosphere for the diesel engine. Exhaust gases are separated from the argon which is recycled. Exhaust gases, are then dissolved into seawater using a Water Management System (Cosworth System), and dumped. The diesel engine can operate in an open cycle (using a snorkel) or a closed cycle (using stored oxygen) modes. Some additional efficiency is gained by using an AC generator in propulsion vice DC. The CCD system is proven technology. A diesel engine is a low cost, high power density option. A CCD is a more simplistic option needing only one system to provide both AIP and snorkeling propulsion. Some disadvantages of the CCD are noise associated with the moving parts and high volume density. The system also requires the COSWORTH system to function and is affected by any contamination of gases. Figure 7 is a schematic of how a CCD system works.

The batteries on a non-nuclear submarine are essential equipment. Batteries provide stored energy for all systems and supply the primary power for sustained or sprint speed. Three types of batteries were researched and considered; the first of which is lead-acid. Advantages of the lead acid battery are a high cell life and proven reliability provided by many improvements. A disadvantage of the lead acid battery is their lower energy density. Lead acid batteries also require frequent monitoring and emit hydrogen while charging. The second battery considered is the Nickel Cadmium. Its advantages are a high energy density and enhanced cell life. Nickel cadmium batteries are charged rapidly, and require less maintenance. Their primary disadvantage is a lack of experience at sea. They are also expensive and have a dangerous abrupt cut-off when fully discharged. Table 9 lists the data associated with these battery options. The third battery option is the Zebra battery. Zebra batteries store energy by transferring sodium ions through a beta-alumina ceramic solid electrolyte. This no emission battery is a product of Rolls Royce and manufactured in Switzerland. The primary advantage of the Zebra is its higher energy density (50 percent lighter than lead acid). Its disadvantage is its reliability. [Zebra Battery Fact Sheet, Rolls-Royce]

Table 9 - Data for battery options

batteries	weight (ton/kwhr)	vol(ft^3/kwhr)	kw/kwhr
lead acid	0.04	0.53	1.2
nickel cadmium	0.033	0.141	3.33
Zebra	0.0157	0.29	1.975

A key component to any AIP system is fuel storage. For the PEM fuel cell pure hydrogen must be stored. Hydrogen can be stored as a gas, liquid or in a hydride. Storing hydrogen as a gas provides low energy density and demands large amounts of volume. Hydrogen storage as a cryogenic liquid provides a fuel three times more energy dense than diesel fuel at the same weight. However, the hydrogen must be maintained at -253 degrees C, and consequently the storage tanks needs to be super-insulated using two walls. One to two percent evaporation per day can be expected, which causes venting issues. The overall system also becomes complicated when shock proofing the submarine. Hydride storage uses an iron titanium matrix or powder as a solid matrix for the hydrogen. Hydrogen is captured in the hydride and is released by heating. This form of hydrogen storage is safe, but heavy. However, this weight can be stored maintenance free low in the hull to add stability. Out of the three options researched, the hydride method is chosen for its proven safety and reliability advantages. During the concept development phase of this project an additional disadvantage of using hydrogen was also better appreciated. Hydrogen tanks cannot be salt water compensated as with external compensated diesel tanks. This requires internal ballast (aux) tanks for fuel weight compensation which has a major impact on pressure hull volume.

Oxygen and argon storage is required for both the fuel cell and CCD options. Oxygen storage is best done by storing it as a cryogenic liquid. This method uses safe and effective proven technology. It can be stored inboard or outboard of the pressure hull. Argon is only necessary if the propulsion system is a closed cycle diesel. Since argon is an inert gas, its storage is relatively easy and safe as a gas.

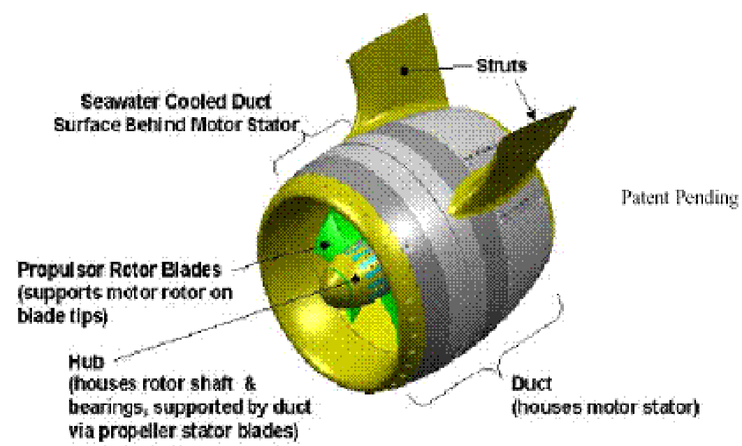


Figure 8 - Rim Driven Podded Propulsor (RDP) [Van Blarcom et al.]

Two options for the propulsor were researched and considered. This first option researched was the Rim Driven Podded Propulsor (RDP). The RDP option was a shrouded prop with an AC synchronous permanent magnet motor stator in the rim. Inside the shroud are guide vanes fore and aft of the rotor to set the flow and reduce swirl. Rim Driven Pods offer high efficiency maneuverability, and arrangement flexibility with motor volume outside of the pressure hull. RDPs can be water lubricated and cooled. Figure 8 shows an RDP.

A simple shrouded prop driven by an internal propulsion motor is the second option researched for the SSG(X) propulsor. The shrouded prop is an open-shaft-driven propeller enclosed by a shroud. The advantages over an open shaft prop are increased efficiency, lower acoustic signature, and reduced cavitation. The efficiency is increased through a reduction in losses from tip-vortex drag. With SSG(X) intended for littoral regions, a shroud will also provide some prop protection. The main disadvantage to a shroud over a non shroud is the increase in cost and weight.

3.1.3 Automation and Manning

In concept exploration it is difficult to deal with automation manning reductions explicitly, so a ship manning and automation factor is used. This factor represents reductions from "standard" manning levels resulting from automation. The manning factor, C_{MAN}, varies from 0.5 to 1.0. It is used in a regression based manning equation shown in Figure 9.

KWsnork: total snorkel power
Cman: manning and automation factor
Venv: envelope volume
NO: number of officers
NE: enlisted manning
NT: total crew manning
NE=INT(Cman*(KWsnork/150.+Venv/5000.))
NT=NO+NE

Figure 9 - "Standard" Manning Calculation

A manning factor of 1.0 corresponds to a "standard" fully-manned ship. A ship manning factor of 0.5 results in a 50% reduction in manning and implies a large increase in automation. The manning factor is also applied using simple expressions based on expert opinion for automation cost, automation risk, damage control performance and repair capability performance.

For the lower end variants (volume limited), a lower manning factor is preferred. In the higher end variants where the submarine was weight limited especially with the iron hydrde AIP fuel option, a higher manning factor was more easily accommodated. Lower manning is possible through the use of computers onboard to perform functions previously assigned to the crew.

3.1.4 Combat System Alternatives

3.1.4.1 SONARSYS

The SONARSYS design variable options are listed in Table 10 below. SONARSYS consists of sonar and combat system options. [Jane's Underwater Warfare Systems 2005-2006]

Table 10 – SONARSYS system alternative components

Design Variable	Options	Components
SONARSYS system alternative	Option 1: BQQ-10 Bow Dome Passive/Active, LWWAA, high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; CCSM	1, 2, 3, 4, 6, 7, 9, 10, 11, 44, 45, 46, 47
	Option 2: BQQ-10 Bow Dome Passive/Active, AN/BQG-5 WAA, high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; BSY-2	1, 2, 3, 5, 6, 7, 9, 10, 13, 44, 45, 46, 47
	Option 3: BQQ-10 Bow Dome Passive/Active, AN/BQG-5 WAA, high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; BSY-1 CCS MK 2 Block 1C	1, 2, 3, 5, 6, 7, 9, 10, 12, 44, 45, 46, 47
	Option 4:SUBTICS (Thales): Passive Cylindrical bow array, PVDF planar flank arrays, sail array, hydrophones	8, 44, 45, 46, 47

Table 11 - Components list for SONARSYS system

ID	NAME	WARAREA	ID	SingleD SWBS	WT lton	VCD ft+CL	AREA ft2	Vol ft3	KW
1	BQQ-10 bow sonar dome passive/active structure and access	SONARSYS	1	1	85.70	0.00	0.00	2200.00	0.00
2	BQQ-10 sonar electronics	SONARSYS	2	4	67.40	0.00	600.00	0.00	75.00
3	BQQ-10 bow sonar dome hull damping	SONARSYS	3	6	20.10	0.00	0.00	0.00	0.00
4	LWWAA	SONARSYS	4	4	25.10	-4.00	150.00	250.00	20.00
5	BQG-5 WAA	SONARSYS	5	4	29.00	-4.00	150.00	275.00	18.00
6	high frequency sail array	SONARSYS	6	4	3.20	14.00	16.67	30.60	2.00
7	chin array	SONARSYS	7	4	3.20	-12.00	16.67	30.60	2.00
8	SUBTICS Sonar and Combat Control System Suite	SONARSYS	8	4	100.00	-3.00	8.82	2153.00	119.00
9	TB-16	SONARSYS	9	4	2.50	7.00	16.67	87.30	4.00
10	TB-29A	SONARSYS	10	4	0.62	7.00	16.67	21.80	4.00
11	CCSM (Total Combat Control System)	SONARSYS	11	4	0.53	0.00	238.00	0.00	37.50
12	BSY-1 CCS Mk 2 Block 1C	SONARSYS	12	4	0.53	0.00	250.00	0.00	39.00
13	BSY-2	SONARSYS	13	4	0.53	0.00	250.00	0.00	39.00
44	underwater comms	SONARSYS	44	4	0.05	11.00	2.00	1.20	1.00
45	navigation echo sounders	SONARSYS	45	4	0.10	0.00	0.00	1.30	1.00
46	communications electronics and equipment	SONARSYS	46	4	1.25	0.00	20.00	0.00	5.00
47	ISR control and processing	SONARSYS	47	4	0.50	0.00	50.00	0.00	2.00

The sonar system for a submarine provides the ears and brains for the vessel. The bow sonar dome is the most critical piece of sonar equipment. The bow sonar dome is mounted in the bow and is usually spherical. The outer portion is covered with transducers for listening. The BQQ-10 is the most current and effective dome used on USN submarines today, specifically the Virginia class. The dome provides low frequency passive and active search sonar capabilities. The BQQ-10 is an upgrade from the BQQ-5 which is on the Los Angeles class submarines. Utilizing COTS software has allowed the BQQ-10 to stay more current, keep costs down, and improve the acoustic performance. The BQQ-10 can be integrated with any of the control systems and works in conjunction with the flank side arrays and the towed arrays.

Another significant element in the sonar suite includes the Light-Weight Wide Aperture Array (LWWAA) and the BQG-5 Wide Aperture Array (WAA) options, which are flank side arrays. Both options consist of large panels mounted along the side of the hull providing major sonar sensor input into the combat system. The LWWAA is a newer more advanced system than the BQG-5. Instead of traditional ceramic hydrophone sensors, LWWAA uses fiber-optic and laser technologies to convert acoustic energy into information that can be used to track and shoot. LWWAA also provides weight and cost savings of 54% and 37% respectively. The weight savings are attributed to the upgraded transducers.

High frequency sail and chin arrays are also important components of the sonar system suite. They are located on the sail and bottom of the bow respectively. These systems are specifically designed for littoral warfare operations. The chin array is mainly used for mine and ice detection. Figure 10 illustrates where the different sonar suite systems are located.

Figure 10 - Overall sonar system [navsource.org]

The thick and thin towed arrays complete the sonar system suite. The towed array options for SSG(X) are TB-29A and TB-16. Both are currently used on Virginia Class submarines. The TB-29A is the most advanced thin line array and works well in combination with the BQQ-10 and any combat system. The TB-16 is a proven thick line array on the modern USN submarines. Figure 11 shows various parts of a towed line array.

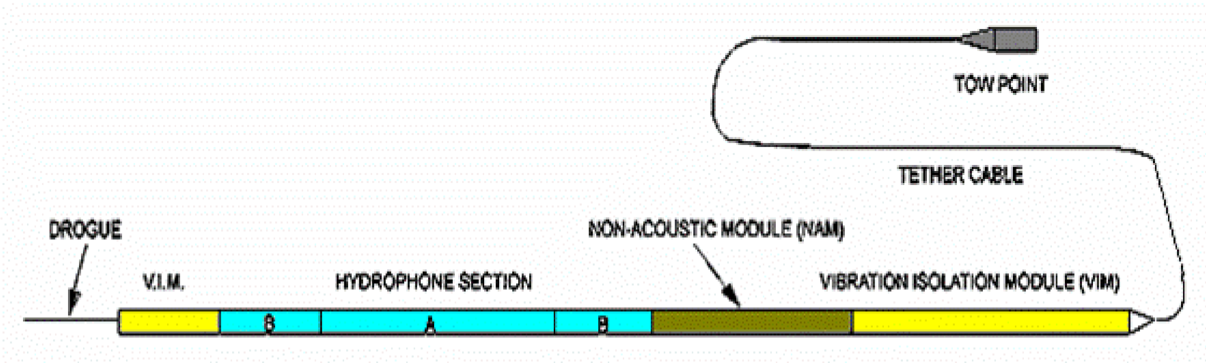


Figure 11 - Towed line array [Dr. Brown, Ship Design Notes]

The fourth option for SONARSYS is the sonar suite manufactured by Thales and found on foreign submarines. Thales is designed for multi-missions and long and short range ASW. The suite includes passive bow cylindrical arrays, planar flank arrays, intercept arrays, passive ranging arrays, and a self-noise monitoring system. The system is also capable of mine and obstacle avoidance. The use of COTS helps keep costs low and the system up-to-date. Thales claims improvements of weak signal resolution, an increase in S/N ratio, and improved detection at high speeds.

The brain of a USN submarine is the combat system. The SSG(X) has three options for its "brains" or combat systems. The BSY 1 CCS MK 2, BSY-2 and CCSM are all proven and fully capable systems, shown in Figure 12. These systems control sonar, combat control, electronics, and major subsystems. The CCSM utilizes COTS as an upgrade from the BSY-2 system found on the Seawolf class of submarines. The BSY-2 is an improvement from BSY-1 and allows for integration of future missions and upgraded capacity.

Figure 12 - BSY system [Dr. Brown, Ship Design Notes]

Each SSG(X) option includes underwater communication, communication electronics and equipment, navigation echo sounders, ISR control and processing. These components work in cooperation with the CCSM, BSY, or Thales suite. [Jane's Underwater Warfare Systems, 2005-2006]

3.1.4.2 SAIL

Table 12 lists the components for each of the sail system alternatives. The sail contains the radar, visual, and communication equipment of the submarine. Each option includes two of either a photonics or traditional mast and radar equipment. Each option also includes the necessary snorkel equipment and an Unmanned Aerial Vehicle

(UAV) for ISR. This UAV is the Sea Sentry and is stored in the sail. The sail may contain a SEAL Locker. [Jane's Underwater Warfare Systems, 2005-2006]

Table 12 - SAIL system alternative components

Design Variable	Options	Components
SAIL system alternatives	Option 1: Virginia Class Sail plus: BPS-16 Radar; 2xAN/BRA-34 Radar; 2xAN/BVS-1 Photonics masts; 2xEHF/SHF HDR Multiband; Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA	24, 25, 26, 27, 28, 29, 30, 31, 32, 43
	Option 2: Virginia Class Sail: BPS-16 Radar; 2xAN/BRA-34; 2xAN/BVS-1 Photonics Masts; 2xEHF/SHF HDR Multiband; Snorkel; IEM; Sea Sentry; OE-315 HSBCA	24, 25, 26, 27, 28, 29, 30, 32, 43
	Option 3: Seawolf Class Sail: BPS-16 radar; 2xAN/BRA-34; 2xAN/BVS-1 Photonics Masts; Type 8 Mod 3 Periscope; Type 18 Mod 3 Periscope; Sea Sentry; Snorkel; OE-315 HSBCA	24, 25, 26, 28, 30, 32, 33, 34, 43
	Option 4: 688I Class Sail: BPS-16 Radar; 2xAN/BRA-34; Type 8 Mod 3 Periscope; Type 18 Mod 3 Periscope; Snorkel; Sea Sentry; OE-315 HSBCA	24, 25, 28, 30, 32, 33, 34, 43

Table 13 lists the sail components with their related weight, vertical center, area, outboard volume, and power consumption rates. The radar system provides navigation and surface surveillance.

Table 13 - Components lists for SAIL system

ID	NAME	WARAREA	ID	SingleD SWBS	WT lton	VCD ft+CL	AREA ft2	Vob ft3	KW
24	BPS 16 radar	SAIL	24	4	2.90	14.00	16.67	24.00	2.00
25	2 x AN/BRA 34 radar	SAIL	25	4	2.90	14.00	16.67	24.00	2.00
26	2 x AN/BVS 1 photonics mast	SAIL	26	4	8.80	12.00	8.00	22.00	10.00
27	2 x EHF/SHF HDR multiband	SAIL	27	4	2.20	12.00	4.20	11.00	6.60
28	snorkel	SAIL	28	2	6.00	10.00	2.36	11.80	0.10
29	IEM	SAIL	29	4	1.10	12.00	2.10	5.50	3.30
30	Sea Sentry	SAIL	30	4	0.50	12.00	0.00	6.00	0.00
31	Seal Locker	SAIL	31	7	0.50	12.00	0.00	6.00	6.00
32	OE 315 HSBCA	SAIL	32	4	0.50	14.00	0.00	10.00	7.00
33	Type 8 Mod 3 periscope	SAIL	33	4	4.40	12.00	4.00	11.00	5.00
34	Type 18 Mod 3 periscope	SAIL	34	4	4.40	12.00	4.00	11.00	5.00
43	distress beacon	SAIL	43	4	0.05	12.00	0.00	1.00	0.50

The AN/BPS 16 is the latest upgrade to the BPS 15 radar. It is currently used on the Ohio, Seawolf, and Virginia Class submarines. SSG(X) uses the AN/BPS 16 radar for navigation and surface surveillance. It has a range of 50 kilometers. The upgrade from the BPS 15 includes a 50 kilowatt frequency-agile transmitter in the I-band.

The AN/BRA-34 mast is used for navigation, communications, IFF, and receiving VLF and GPS frequencies, two-way HF, and UH.

The OE-315 is a rope buoy system included in every option. It is a towed buoy that operates on the surface and relays visual images to the submarine while it is submerged at cruise depth. It uses a real-time fiber-optic data link to transfer images. This system provides the functionality of a periscope without required transit at periscope depth

Figure 13 shows communications capabilities required of SSG(X) operating in stealth, covert, low risk, and overt modes.

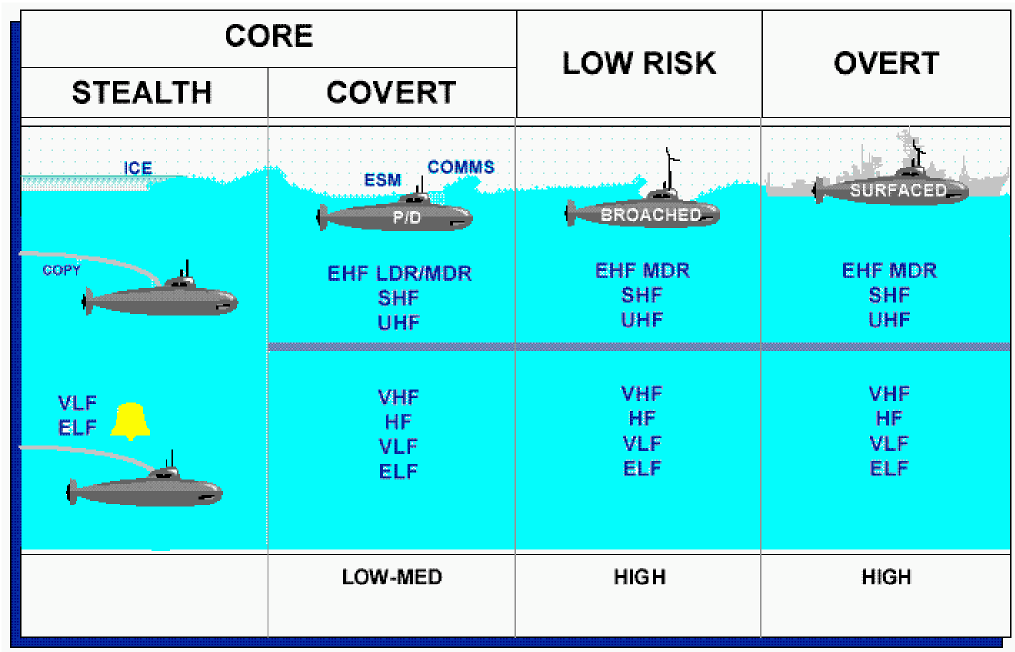


Figure 13 – SSG(X) required communications capabilities [FAS.org]

SSG(X) options include a traditional periscope mast or a non-hull-penetrating optics/photonics mast. The periscope mast is optical. Kollmorgen is the current manufacturer of all periscope masts for the U.S. Navy. The Type 8 and Type 18 masts are electro-optical masts used on the Los Angeles Class and Seawolf. These masts have high performance and use well-proven technology. They are effective for day and night use and can be integrated with the combat system. The Type 18 is an upgraded version of the Type 8. Improvements include color TV and a digital camera. The AN/BVS-1 is in use on the Virginia Class. It is a non-hull-penetrating and uses an electronic imaging system.

The non-hull-penetrating mast offers several advantages over the traditional periscope. It does not require a puncture hole in the pressure hull and it does not require volume in the pressure hull that is needed for other arrangements. Figure 14 shows cross-sections of submarines using hull-penetrating and non-hull penetrating masts.

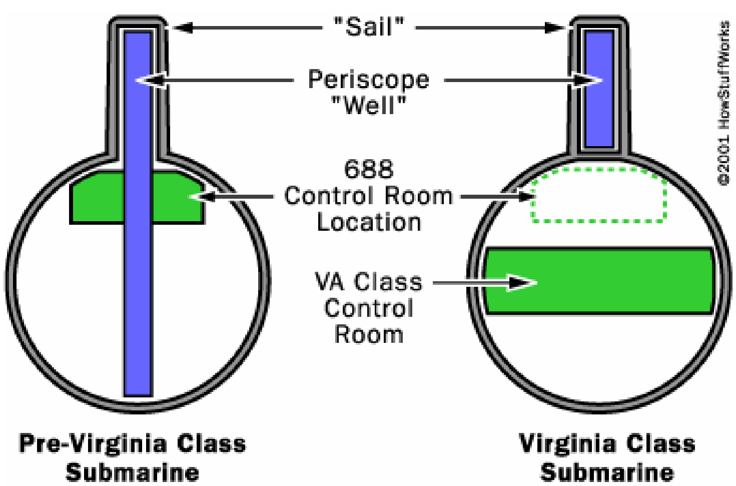


Figure 14 - Traditional and non-hull-penetrating masts [HowStuffWorks.com]

The non-hull-penetrating masts also do not require specific placement of the control center. It can be located on the middle deck, allowing enlargement of the control center, and does not need to be located below the conning tower. This allows the conning tower placement for the best hydrodynamic performance of the submarine.

Figure 15 Shows the Kollmorgen Photonics Mast System (PMP) and its control console. The PMP is the AN/BVS-1. It is non-hull-penetrating. Its sensors include infrared (IR), black and white (B&W), color; various modules can be mounted on the PMP to customize radio sensing capabilities. It is capable of depluming, RAS, and thermal signature control. The PMP uses a rotary seal and pressure compensation for rotation.

Figure 15 - Kollmorgen PMP and Control Center [Kollmorgen]

The Sea Sentry is an Unmanned Aerial Vehicle that launches from a canister in the sail and performs ISR. The wing and tail are folded against the fuselage during storage in the canister and extend to full span during launch. Figure 16 shows the sea sentry in flight and Figure 17 illustrates launch.

Figure 16 - Sea Sentry in flight [Kollmorgen]

Figure 17 - Launch of Sea Sentry [Kollmorgen]

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 18 shows arrangements for four sail configurations – the 688, 688I, Virginia Class, and SSN 21.

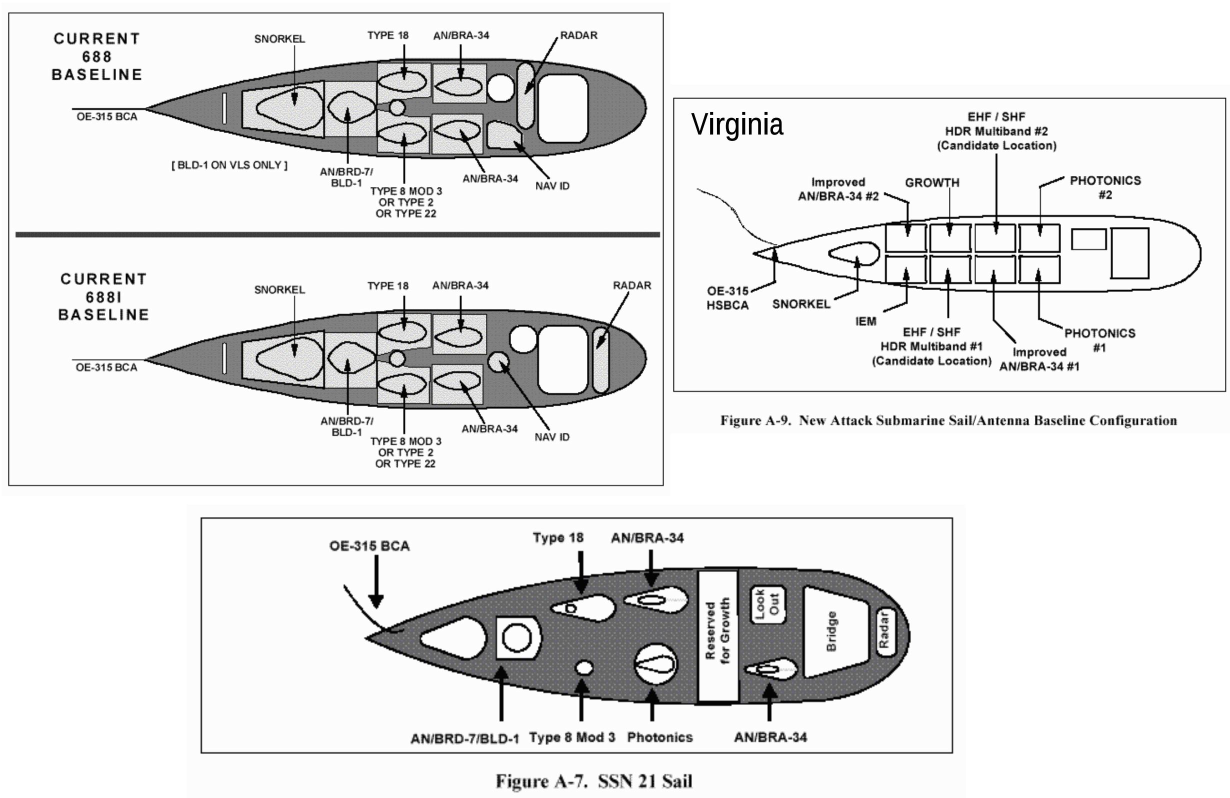


Figure 18 – SSG(X) Sail Configuration Alternatives [FAS.org]

3.1.4.3 ESM

Table 14 lists components for the Electronic Support Measures system alternatives. Both alternatives include the SHRIKE ESM system, two sets of 3” Countermeasure/XBT launcher with 3” countermeasure reloads (10), and a 6.75” external countermeasure launcher with reloads (4). The first alternative includes a WLY-1 acoustic interception and countermeasure system and a AN/BLQ-10 ESM system; the second alternative includes a AN/BRD-7/BLD-1 ESM direction finding system and WLR-8(v)2 interceptors. [FAS.org]

Table 14 - ESM system alternative components

Warfighting System	Options	Components
ESM - system alternative	Option 1: Shrike ESM; WLY-1 acoustic interception and countermeasures system; AN/BLQ-10 Electronic Support Measures (ESM) system; 2x3” Countermeasure Launcher w/ Reloads, 2x6.75” Countermeasure Tube Option 2: Shrike ESM; AN/BRD-7/BLD-1; WLR-8(v)2 interceptors; 2x3” Countermeasure Launcher w/ Reloads, 2x6.75” Countermeasure Tube	35, 36, 37, 40, 40, 41, 41, 42 35, 38, 39, 40, 40, 41, 41, 42

Table 15 shows the components with their weight, vertical center of gravity, arrangeable area, outboard volume, and power consumption.

Table 15 - Component table for ESM system

ID	NAME	WARAREA	ID	SingleD SWBS	WT lton	VCD ft+CL	AREA ft2	Vob ft3	KW
35	SHRIKE ESM	ESM	35	4	1.50	10.00	4.00	3.00	5.00
36	WLY-1 acoustics interception and countermeasures system	ESM	36	4	1.75	10.00	9.00	3.00	5.00
37	AN/BLQ-10 (ESM)	ESM	37	4	1.20	12.00	4.00	4.00	4.50
38	AN/BRD-7/BLD-1	ESM	38	4	1.10	12.00	4.00	4.00	4.00
39	WLR-8(V)2 interceptors	ESM	39	4	1.50	10.00	8.00	3.00	4.50
40	3" Countermeasure/XBT launcher	ESM	40	7	0.09	6.00	1.00	0.00	0.10
41	3" Countermeasure reloads x 10 (locker)	ESM	41	F20	0.04	6.00	3.00	0.00	0.00
42	6.75" external Countermeasure launcher w/4cannisters ea	ESM	42	7	0.22	6.00	0.00	0.69	0.10

SHRIKE is a low cost, lightweight naval ESM system. It rapidly intercepts and identifies radar signals and associated threats. SHRIKE features low unit count for easy installation, high probability of intercept, detection over the horizon, operation in a high pulse density environment, full threat identification with user definable libraries, pulse Doppler detection, instantaneous frequency measurement, monopulse direction finding, extensive built-in test facilities, and full recording and playback. SHRIKE has a frequency range of 2 to 18 GHz (option of 2 - 40 GHz), direction finding accuracy of 5º, spatial coverage of 360º in the azimuth plane with ± 30º elevation, pulse density of 2.5 million pulses/sec with up to 54 levels of stagger, frequency resolution of 1.25 MHz, sensitivity rating of -65 dBm, amplitude resolution of 0.3 dB, and a pulse width range of 80 ns to 204 µs. It has many available options: laser warning, UV sensors and interface, ECM interface, 0. 7 to 2 GHz and 18 to 40 GHz frequency ranges, 2° RMS direction finding accuracy, CMS interface, LPI receiver (including DF), and multiple displays.

WLY-1 provides acoustic interception and countermeasures capabilities. The WLY-1 system has the following duties: threat platform sonar and torpedo recognition for early detection/classification/tracking and control system for all countermeasure devices and launchers.

The AN/BLQ-10 ESM system (formerly, Advanced Submarine Tactical ESM Combat System (ASTECS)) consists of signal receivers, displays, and advanced processing and analysis equipment. It provides detection, identification, and direction-finding for radar and communication signals emanating from ships, aircraft, submarines, and other emitters. The system provides: analysis and reporting of signals that are of immediate tactical importance as well as full-spectrum radar processing. The design of the AN/BLQ-10 system has been optimized for the littoral environment that the SSG(X) will operate in.

The AN/BRD-7/BLD-1 system provides direction finding capability. It is currently used on Los Angeles class submarines. WLR-8(v)2 interceptors (currently installed on Ohio class submarines) act as ESM receivers. They provide interception, surveillance and analysis of electromagnetic signals.

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

TORP Table 16 lists components for each of the torpedo system alternatives. The alternatives include a reconfigurable torpedo room with either 6 or 4 twenty-one inch tubes or an alternative for no torpedo room with all of the weapons encapsulated external to the pressure hull. [Jane's Underwater Warfare Systems, 2005-2006 and Clancy]

Table 16 - TORP system alternative components

Warfighting System	Options	Components
TORP system alternative	Option 1: Reconfigurable torpedo room, 6x21" tubes, 24 reloads	14, 14, 14, 16, 16, 16, 18, 18, 18, 19, 19, 19
	Option 2: Reconfigurable torpedo room, 6x21" tubes, 18 reloads	14, 14, 14, 15, 15, 15, 17, 17, 17, 19, 19, 19
	Option 3: Reconfigurable torpedo room, 6x21" tubes, 12 reloads	14, 14, 14, 16, 16, 18, 18, 19, 19, 19
	Option 4: Reconfigurable torpedo room, 4x21" tubes, 16 reloads	14, 14, 16, 16, 18, 18, 19, 19
	Option 5: Reconfigurable torpedo room, 4x21" tubes, 12 reloads	14, 14, 15, 15, 17, 17, 19, 19
	Option 6: Reconfigurable torpedo room, 4x21" tubes, 8 reloads	14, 14, 16, 18, 19, 19
	Option 7: No torpedo room, 24 external encapsulated	20, 20, 20, 20
	Option 8: No torpedo room, 18 external encapsulated	20, 20, 20
	Option 9: No torpedo room, 12 external encapsulated	20, 20

Table 17 shows the components with their related weight, vertical center, area, outboard volume, and power consumption. Twenty-one inch tubes allow the launch of Unmanned Underwater Vehicles (UUVs), torpedoes, mine launchers and other weapons. The model for all torpedo tube loads is the Mk 48 Advanced Capability (ADCAP) torpedo. Other components important to the completion of missions in this combat area are torpedo racks to hold the reloads and associated torpedo machinery to operate the tubes and move the weapons into place. The last component in the table is the external encapsulated torpedoes.

Table 17 - Components Table for TORP system

ID	NAME	WARAREA	ID	SingleD SWBS	WT lton	VCD ft+CL	AREA ft2	Vob ft3	KW
14	2 x 21" torpedo tubes and doors	TORP	14	7	3.00	-4.00	0.00	88.00	3.60
15	6 x Mk 48(Adcap) torpedoes	TORP	15	20	9.90	-4.00	0.00	0.00	0.00
16	8 x Mk48(Adcap) Torpedoes	TORP	16	20	13.20	-4.00	0.00	0.00	0.00
17	6 x Torpedo Racks	TORP	17	7	3.00	-4.00	132.00	0.00	0.00
18	8 x Torpedo Racks	TORP	18	7	4.00	-4.00	176.00	0.00	0.00
19	2 x Torpedo Machinery	TORP	19	5	1.50	-4.00	44.00	0.00	1.80
20	6 external encapsulated torpedoes (Mk 48Adcap)	TORP	20	20	12.00	-10.00	0.00	420.00	3.60

Torpedo arrangements and load out are as follows: a full torpedo room with six 21 inch tubes and 24, 18, or 12 torpedoes; full torpedo room with four 21 inch tubes and 16, 12, or 8 torpedoes; no torpedo room and 24, 18, or 12 external encapsulated torpedoes. Payload Options include the Mk 48 ADCAP for ASW operations, Tomahawk missile for strike (STK) missions, Harpoon for ASUW missions, the Mk 60 Mine Launcher and various UUVs for other ASW tasks. The torpedo room options are all reconfigurable. Figure 19 shows the torpedo room in a standard configuration and another configuration with the center weapons and their stowage structures removed to accommodate Special Forces troops.

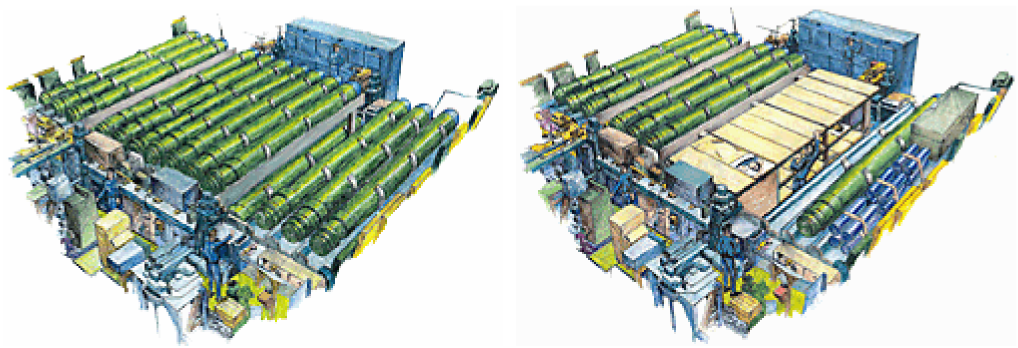


Figure 19 - Torpedo room in two configurations [Dr. Brown, Ship Design Notes]

The SCOUT mine detection and obstacle avoidance sonar will conduct mine warfare (MIW) using versatile active and passive sonar. Duties include navigation, detection, and collision, mine and obstacle avoidance when employing its dual frequency, forward looking sonar with long range and high resolution. Frequency ranges between 30kHz to 70kHz (LF – HF). Detection range is 850m to 3600m and power consumption is approximately 800VA. It is 549m high by 515m wide by 388m deep and weighs about 54kg. Figure 20 displays the system configuration.

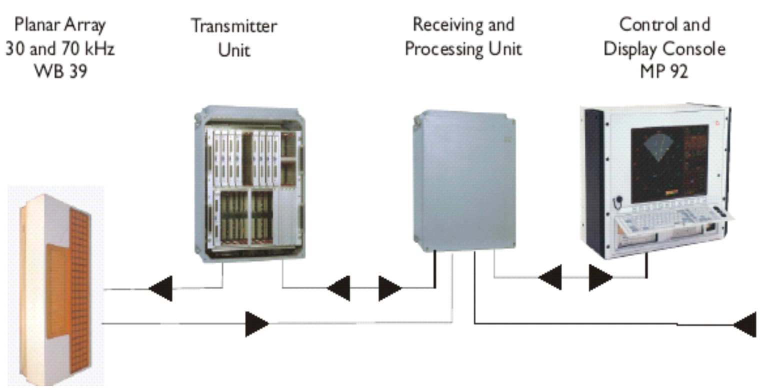


Figure 20 - SCOUT mine detection and obstacle avoidance sonar [Dr. Brown, Ship Deisgn Notes]

Unmanned Underwater Vehicles (UUVs) reduce personnel risk. Some UUVs are expendable and do not need to be recovered to obtain data from them. They are a multi-mission platform and can execute ISR, Mine Counter-Measures (MCM) and Anti-Submarine Warfare (ASW) missions. Figure 21 shows a UUV working in conjunction with a submarine, satellite and other platforms to conduct a mission. REMUS and other comparable UUVs, as in Figure 22, can perform oceanographic profiling (ISR) and MCM missions.

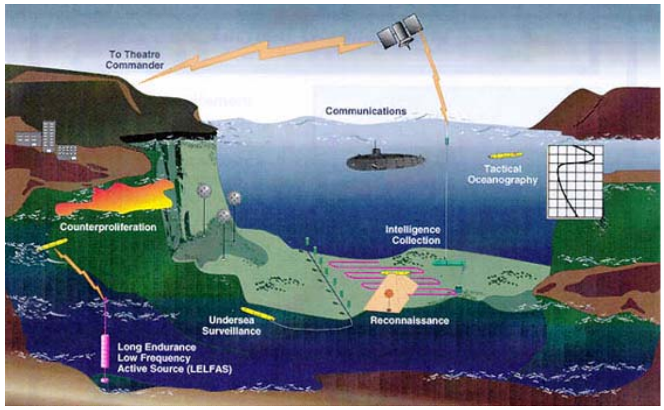


Figure 21 - UUV working in conjunction with other platforms [Dr. Brown, Ship Deisgn Notes]

Figure 22 - REMUS UUV [military.com]

3.1.4.4 VLS

Table 18 lists the alternatives for vertical launch system (VLS). The three alternatives include a four module, three module, and two module VLS system. All three alternatives are configured to carry the Tomahawk Land – Attach Missile (TLAM).

Table 18 - VLS system alternatives

Warfighting System	Options	Components
VLS system alternative	Option 1: 24 Cell VLS	21, 21, 21, 21, 22, 22, 22, 22, 23, 23, 23, 23
	Option 2: 18 Cell VLS	21, 21, 21, 22, 22, 22, 23, 23, 23
	Option 3: 12 Cell VLS	21, 21, 22, 22, 23, 23

Table 19 lists the components for each option of the VLS system with their weight, vertical center of gravity, area, outboard volume and the required power for each component. Each module contains six canisters, six TLAM's, and machinery required to operate the module. [Jane's Underwater Warfare Systems, 2005-2006]

Table 19 - Components list for 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 23 shows a module for a vertical launch system (VLS) consisting of eight canisters measuring 6.7 m tall.

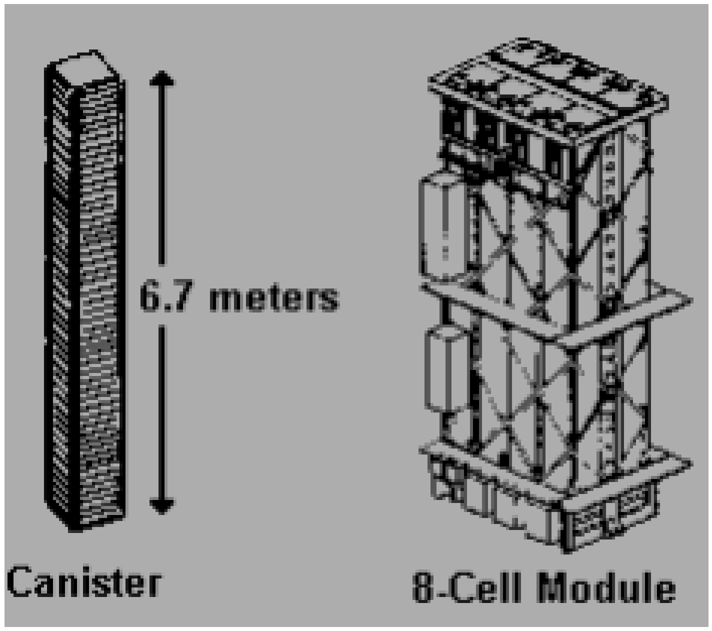
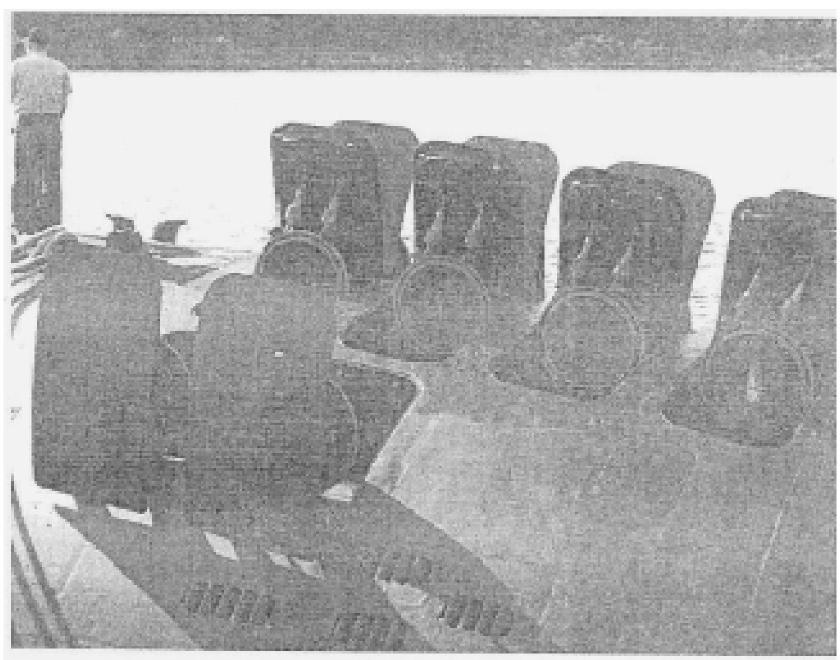


Figure 23 - Vertical launch system (VLS) module [Dr. Brown, Ship Design Notes]

Figure 24 shows the arrangement of the VLS system on the USS Miami. This system consists of one eight cell module and one two cell module.



The twelve hydraulically operated doors of the *Miami*'s vertical launch system for Tomahawk cruise missiles. Note the pressure caps to protect the missiles.
JOHN D. GERSMAN

Figure 24 - USS Miami VLS system [Clancy]

3.1.4.5 SPW

Table 20 lists the components for the special warfare options. The alternatives are to have a 4 man lockout chamber for the special warfare operatives or not to have the lockout chamber.

Table 20 - SPW Alternatives

Warfighting System	Options	Components
SPW system alternative	Option 1: 4 Man Lock out chamber Option 2: None	48

Table 21 lists the lock out chamber weight, vertical center, area, outboard volume, and power consumption if it was added to the submarine.

Table 21 - Components list for SPW

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

Figure 25 shows the lockout chamber included in the submarine design.

Figure 25 – SPW lockout chamber [navsource.org]

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 22 are included in the ship synthesis model data base.

3.2 Design Space

Twenty design variables (Table 23) describe potential SSG(X) designs as discussed in Section 3.1. The optimizer chooses values for each variable in the allowable range and the ship synthesis model uses these values to evaluate the design. The ship synthesis model balances the design, checks for feasibility, and calculates measures of effectiveness, risk, and cost. Hull design parameters (DV1-6) are described in Section 3.1.1. Propulsion system alternatives (DV7-12) are described in Section 3.1.2. Manpower reduction options (DV14) are described in Section 3.1.3. Combat systems alternatives (DV13, 15-20) are described in Section 3.1.4.

Table 22 - Combat System Ship Synthesis Characteristics

ID	NAME	WARAREA	ID	SingleD SWBS	WT lton	VCD ft+CL	AREA ft2	Vob ft3	KW
1	BQQ-10 bow sonar dome passive/active structure and access	SONARSYS	1	1	85.70	0.00	0.00	2200.00	0.00
2	BQQ-10 sonar electronics	SONARSYS	2	4	67.40	0.00	600.00	0.00	75.00
3	BQQ-10 bow sonar dome hull damping	SONARSYS	3	6	20.10	0.00	0.00	0.00	0.00
4	LWWAA	SONARSYS	4	4	25.10	-4.00	150.00	250.00	20.00
5	BQG-5 WAA	SONARSYS	5	4	29.00	-4.00	150.00	275.00	18.00
6	high frequency sail array	SONARSYS	6	4	3.20	14.00	16.67	30.60	2.00
7	chin array	SONARSYS	7	4	3.20	-12.00	16.67	30.60	2.00
8	SUBTICS Sonar and Combat Control System Suite	SONARSYS	8	4	100.00	-3.00	8.82	2153.00	119.00
9	TB-16	SONARSYS	9	4	2.50	7.00	16.67	87.30	4.00
10	TB-29A	SONARSYS	10	4	0.62	7.00	16.67	21.80	4.00
11	CCSM (Total Combat Control System)	SONARSYS	11	4	0.53	0.00	238.00	0.00	37.50
12	BSY-1 CCS Mk 2 Block 1C	SONARSYS	12	4	0.53	0.00	250.00	0.00	39.00
13	BSY-2	SONARSYS	13	4	0.53	0.00	250.00	0.00	39.00
14	2 x 21" torpedo tubes and doors	TORP	14	7	3.00	-4.00	0.00	88.00	3.60
15	6 x Mk 48(Adcap) torpedoes	TORP	15	20	9.90	-4.00	0.00	0.00	0.00
16	8 x Mk48(Adcap) Torpedoes	TORP	16	20	13.20	-4.00	0.00	0.00	0.00
17	6 x Torpedo Racks	TORP	17	7	3.00	-4.00	132.00	0.00	0.00
18	8 x Torpedo Racks	TORP	18	7	4.00	-4.00	176.00	0.00	0.00
19	2 x Torpedo Machinery	TORP	19	5	1.50	-4.00	44.00	0.00	1.80
20	6 external encapsulated torpedoes (Mk 48Adcap)	TORP	20	20	12.00	-10.00	0.00	420.00	3.60
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
24	BPS 16 radar	SAIL	24	4	2.90	14.00	16.67	24.00	2.00
25	2 x AN/BRA 34 radar	SAIL	25	4	2.90	14.00	16.67	24.00	2.00
26	2 x AN/BVS 1 photonics mast	SAIL	26	4	8.80	12.00	8.00	22.00	10.00
27	2 x EHF/SHF HDR multiband	SAIL	27	4	2.20	12.00	4.20	11.00	6.60
28	snorkel	SAIL	28	2	6.00	10.00	2.36	11.80	0.10
29	IEM	SAIL	29	4	1.10	12.00	2.10	5.50	3.30
30	Sea Sentry	SAIL	30	4	0.50	12.00	0.00	6.00	0.00
31	Seal Locker	SAIL	31	7	0.50	12.00	0.00	6.00	6.00
32	OE 315 HSBCA	SAIL	32	4	0.50	14.00	0.00	10.00	7.00
33	Type 8 Mod 3 periscope	SAIL	33	4	4.40	12.00	4.00	11.00	5.00
34	Type 18 Mod 3 periscope	SAIL	34	4	4.40	12.00	4.00	11.00	5.00
35	SHRIKE ESM	ESM	35	4	1.50	10.00	4.00	3.00	5.00
36	WLY-1 acoustics interception and countermeasures system	ESM	36	4	1.75	10.00	9.00	3.00	5.00
37	AN/BLQ-10 (ESM)	ESM	37	4	1.20	12.00	4.00	4.00	4.50
38	AN/BRD-7/BLD-1	ESM	38	4	1.10	12.00	4.00	4.00	4.00
39	WLR-8(V)2 interceptors	ESM	39	4	1.50	10.00	8.00	3.00	4.50
40	3" Countermeasure/XBT launcher	ESM	40	7	0.09	6.00	1.00	0.00	0.10
41	3" Countermeasure reloads x 10 (locker)	ESM	41	20	0.04	6.00	3.00	0.00	0.00
42	6.75" external Countermeasure launcher w/4cannisters ea	ESM	42	7	0.22	6.00	0.00	0.69	0.10
43	distress beacon	SAIL	43	4	0.05	12.00	0.00	1.00	0.50
44	underwater comms	SONARSYS	44	4	0.05	11.00	2.00	1.20	1.00
45	navigation echo sounders	SONARSYS	45	4	0.10	0.00	0.00	1.30	1.00
46	communications electronics and equipment	SONARSYS	46	4	1.25	0.00	20.00	0.00	5.00
47	ISR control and processing	SONARSYS	47	4	0.50	0.00	50.00	0.00	2.00

Table 23 - SSG(X) Design Variables (DVs)

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
5	n_f	Fullness factor forward	2.0-3.5
6	Depth	Diving Depth	500-1010ft
7	PSYS	Propulsion system alternative	Option 1) CCD, CAT 3512 V12 x2 Engines Option 2) CCD, CAT 3516 V16 x2 Engines Option 3) CCD, 2xCAT3516V16 + 2xCAT3512V12 Option 4) CCD, 2xCAT 3608 IL8 Option 5) OCD/AIP, 2xCAT 3512 V12 + 2x250KW PEM Option 6) OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM Option 7) OCD/AIP, 2xCAT 3516 V16 + 2x250KW PEM Option 8) OCD/AIP, 2xCAT 3516 V16 + 2x500KW PEM Option 9) OCD/AIP, 2x CAT 3608 IL8 + 2x250KW PEM
8	PROPtype	Propulsion Prop Type	Option 1) RDP, Rim Driven Prop Option 2) Shrouded
9	BATtype	Battery system type alternative	Option 1) Nickel Cadmium Option 2) Lead Acid Option 3) Zebra

DV #	DV Name	Description	Design Space
10	Ebat	Battery Capacity	5000-12000 kwhr
11	Wfsnork	Weight Fuel Snorkel	50-150lton
12	Wfaip	Weight Fuel AIP	300-900lton
13	Ndegaus	Degaussing	0=none; 1=degaussing
14	Cman	Manpower Reduction	0.5-1.0
15	TORP	Torpedo system alternative	Option 1: Reconfigurable torpedo room, 6x21” tubes, 24 reloads Option 2: Reconfigurable torpedo room, 6x21” tubes, 18 reloads Option 3: Reconfigurable torpedo room, 6x21” tubes, 12 reloads Option 4: Reconfigurable torpedo room, 4x21” tubes, 16 reloads Option 5: Reconfigurable torpedo room, 4x21” tubes, 12 reloads Option 6: Reconfigurable torpedo room, 4x21” tubes, 8 reloads Option 7: No torpedo room, 24 external encapsulated Option 8: No torpedo room, 18 external encapsulated Option 9: No torpedo room, 12 external encapsulated
16	VLS	Vertical Launching System Alternatives	Option 1: 24 Cell VLS Option 2: 18 Cell VLS Option 3: 12 Cell VLS
17	SONARSYS	Sonar/Combat System Alternatives	Option 1: BQQ-10 Bow Dome Passive/Active, LWWAA, high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; CCSM Option 2: BQQ-10 Bow Dome Passive/Active, AN/BQG-5 WAA, high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; BSY-2 Option 3: BQQ-10 Bow Dome Passive/Active, AN/BQG-5 WAA, high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; BSY-1 CCS MK 2 Block 1C Option 4:SUBTICS (Thales): Passive Cylindrical bow array, PVDF planar flank arrays, sail array, hydrophones
18	SPW	SPW Alternatives	Option 1: 4 Man Lock out chamber Option 2: None
19	SAIL	Sail (Radar, Masts and Periscopes, and communication)	Option 1: Virginia Class Sail plus: BPS-16 Radar; 2xAN/BRA-34 Radar; 2xAN/BVS-1 Photonics masts; 2xEHF/SHF HDR Multiband; Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA Option 2: Virginia Class Sail: BPS-16 Radar; 2xAN/BRA-34; 2xAN/BVS-1 Photonics Masts; 2xEHF/SHF HDR Multiband; Snorkel; IEM; Sea Sentry; OE-315 HSBCA Option 3: Seawolf Class Sail: BPS-16 radar; 2xAN/BRA-34; 2xAN/BVS-1 Photonics Masts; Type 8 Mod 3 Periscope; Type 18 Mod 3 Periscope; Sea Sentry; Snorkel; OE-315 HSBCA Option 4: 688I Class Sail: BPS-16 Radar; 2xAN/BRA-34; Type 8 Mod 3 Periscope; Type 18 Mod 3 Periscope; Snorkel; Sea Sentry; OE-315 HSBCA
20	ESM	Electronic Support Measure Alternatives	Option 1: Shrike ESM; WLY-1 acoustic interception and countermeasures system; AN/BLQ-10 Electronic Support Measures (ESM) system; 2x3” Countermeasure Launcher w/ Reloads, 2x6.75” Countermeasure Tube Option 2: Shrike ESM; AN/BRD-7/BLD-1; WLR-8(v)2 interceptors; 2x3” Countermeasure Launcher w/ Reloads, 2x6.75” Countermeasure Tube

3.3 Ship Synthesis Model

The ship synthesis model (see Figure 26) defines and balances designs selected by the optimizer and assesses their feasibility, effectiveness, risk, and cost. The ship synthesis model in Model Center (MC) integrates modules written in Fortran using file wrappers and input\output files for each module. The modules were modified and updated specifically for optimization of the SSG(X) platform. One of the main tasks of the synthesis model is to balance the design (see Figure 27). The Weight Module calculates lead weight based on an estimation of the hull volume (provided by the Hull Module) and an estimation of the weights for the various SWBS groups (calculated in the Weight Module). The amount of lead weight is calculated to achieve balance in Condition A. Lead weight is the slack variable in the optimization and balance. It must be within specified limits for feasibility.

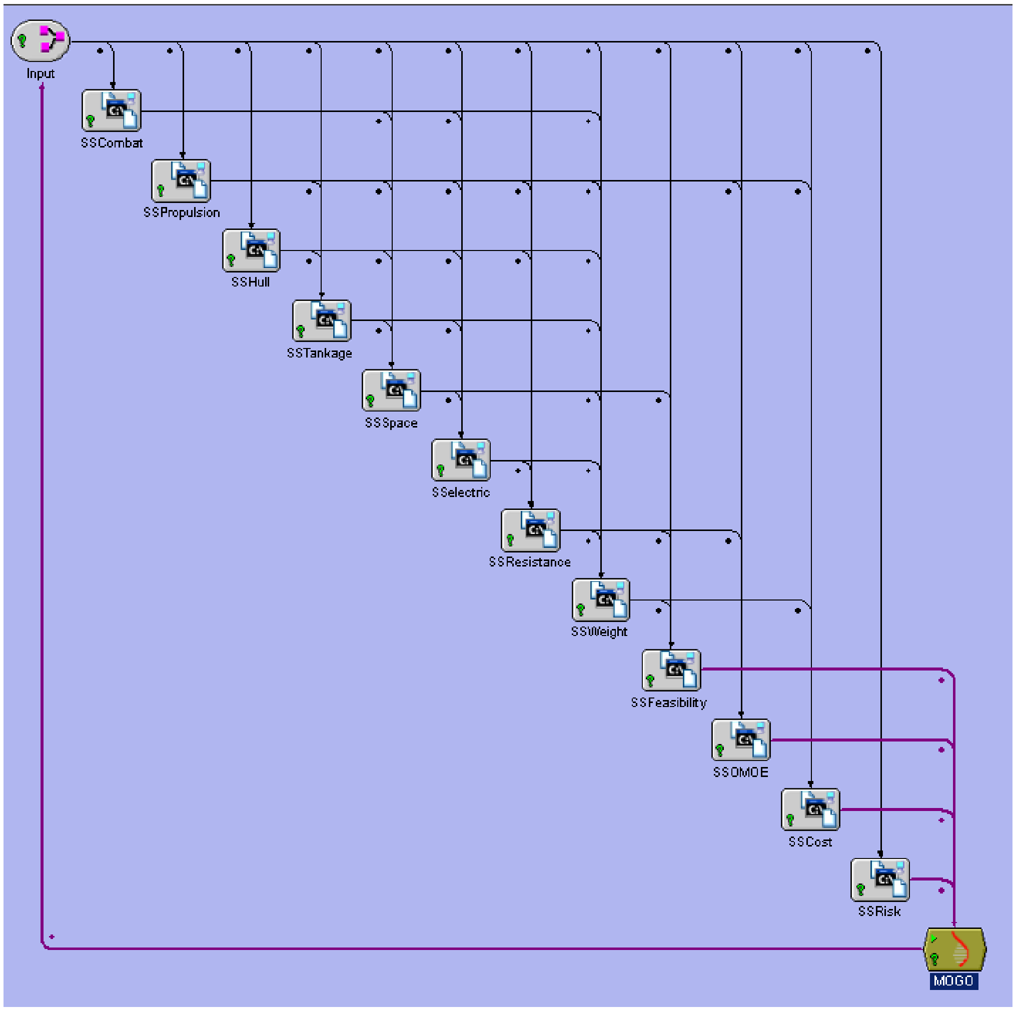


Figure 26 - Ship Synthesis Model in Model Center (MC)

The Ship Synthesis Model is organized into the following modules:

- Input Module: Stores the design variable values and other design parameters which are provided as input to the other modules.
- Combat Module: Sums payload characteristics (weights, vertical centers of gravity (VCGs), arrangeable areas, and electric power consumption) using the combat system alternatives selected and an Excel file containing data for each system. The weights, arrangeable areas and electric power consumption are simple summations; vertical centers of gravity are calculated using moments of weights. The combat module outputs weights summarized by SWBS groups as well as a total, arrangeable area, power consumption, and the required payload outboard volume.
- Propulsion Module: Calculates propulsion and generator system characteristics (weights and stowage volumes) using the propulsion "subsystems" (propulsion system, propulsor type, battery type)

alternatives and capacities (battery capacity, fuel weight (AIP), fuel weight (snorkel)) and an Excel file containing data (stowage and machinery room volumes, fuel consumption rates, and transmission efficiency). It also uses the battery type to determine battery and performance characteristics. The Propulsion Module outputs the battery power, weight and volume of the basic propulsion machinery, batteries and fuels, the volume of the prop, specific fuel consumption (SFC), power provided by AIP and snorkeling, AIP diesel fuel energy capacity, overall propulsive coefficient (PC), and transmission efficiency.

- Hull Module: Calculates hull characteristics (volumes and lengths of the three hull parts and the total bare hull surface area) using hull input quantities (diameter, beam-to-diameter ratio, length-to-diameter ratio and forward and aft fullness exponents). These quantities are used to find a shape parameterized by an MIT model (see Figure 4) which is composed of an ellipsoidal forebody, parallel midbody, parabolic aftbody, and transverse midbody; this hull form is a modified form of the hydrodynamically optimized teardrop hullform which adds parallel midbody (length) and transverse midbody (beam) which provides more arrangeable area. The Hull Module calculates lengths and offsets based on this model and integrates over the lengths to determine the volumes of each part. The module outputs the width of the transverse insertion, the bare hull surface area, the envelope volume, the length of each part of the hull, the beam, and the length overall.

- Tankage Module: Calculates the tankage volumes and liquid weights and crew manning numbers. The diesel fuel is split between clean (17%) and compensated (83%) tanks. Compensated tanks external to the pressure hull use ballast water to replace diesel fuel as it is used; this allows easier management of ballast and an overall more efficient design. Soft tanks ballast open to the sea and have a lower weight. The tankage weights (including AIP liquids) are based on the specific volumes for the tankage contents. The Tankage Module calculates manning numbers using a parameterized model based on the ship size, power consumption, and manning and automation factor; these are calculated in the Tankage Module as this is a convenient place (the Hull Module is the first module to use these numbers). Additional (habitability) tankage volumes and weights are calculated using the crew numbers. The tankage module outputs the total inboard tankage volume and the outboard compensated tankage volume, enlisted and total crew numbers, and the weights for lube oil, fresh water, sewage, and clean and compensated fuel.

- Space Module: Calculates available and required arrangeable areas and hull volumes (including free flood and free flood min\max) using the stores and provisions duration, average deck height, crew numbers (enlisted, officers and total), the pressure hull arrangeable area margin, and the required area for payload (CCC and ordnance delivery system). The arrangeable area is calculated using parametric models; arrangeable area and average deck height are used to calculate the arrangeable volume; the hull volumes are based on their definitions and previously calculated volumes. The Space Module outputs various volumes (pressure hull, outboard displacement, everbuoyant, main ballast tank, submerged displaced, free flood (including min\max) and auxiliary space; it also outputs the total required and total available arrangeable area.

- Electric Module: Calculates (with applicable margins) the maximum electric power load and the 24-hour average load. The Electric Module inputs the margins (electric functional margin factor, electric design margin factor and average electric power margin factor), payload weight, volumes of the pressure hull, machinery box and auxiliary box, the power provided while snorkeling, overall length and diameter, the required power for the payload, the total crew number and whether or not there is a degaussing system. It then calculates the power required using a parameterized model which uses the hull dimensions, the ship service power based on the total crew number and the total load.

- Resistance Module: Calculates sustained speed, ranges and endurances (sustained, snorkel and AIP), and the total mission length. The Resistance Module calculates resistance over a range of speeds using frictional resistance (from the bare hull surface area) form factor and a correlation allowance. The endurances are based on battery and fuel capacities and usage rates, the Propulsion Margin Factor (PMF), Overall Propulsive Coefficient (PC), and the transmission efficiency (η). The mission length is based on the endurances that are calculated.

- Weight Module: Calculates total weights and VCGs for SWBS groups, overall VCG, stability (GB and GM), and minimum and maximum values for lead ballast. The Weight Module calculates SWBS subgroups' (systems, subsystems, shafting, cabling, etc.) weights and VCGs based on inputs. The group weights are found by summing the individual components and VCGs are calculated using weight moments. The hull geometry determines the center of buoyancy which is used with the overall VCG to calculate GB (the submerged stability condition). The surface stability condition (GM) is calculated using stability formula which considers the waterplane's contribution to the stability. This module also calculates lead weight as difference between NSC weight and ever-buoyant displacement. The feasibility module assesses the feasibility of this weight to satisfy minimum design and stability lead requirements.

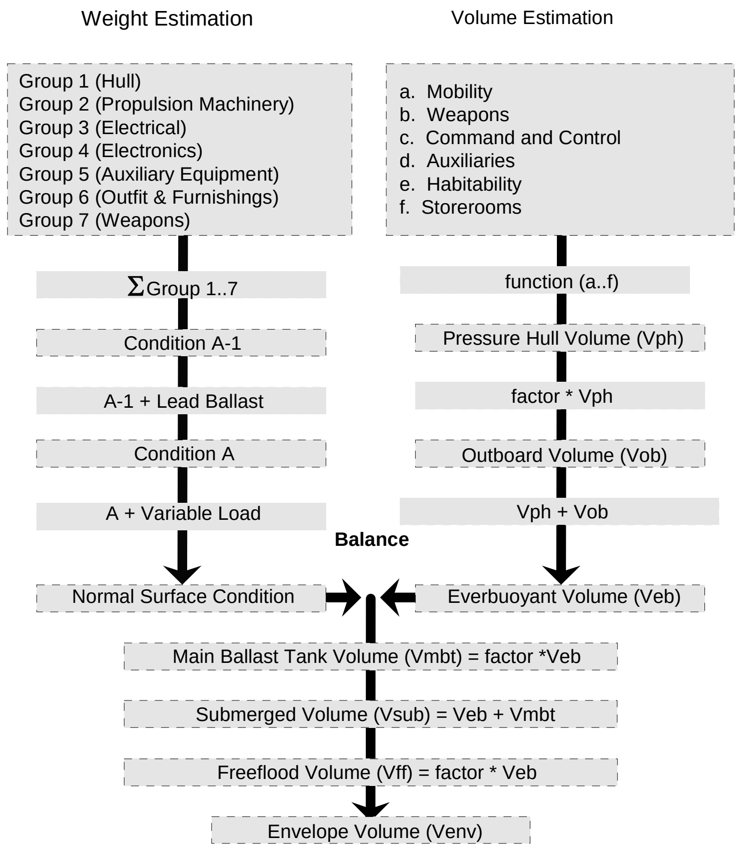


Figure 27 - Submarine balance diagram [MIT Jackson Notes]

- Feasibility Module: Calculates ratios comparing the actual values of snorkel endurance range, AIP endurance duration, sustained speed, spring duration, submerged GB, surfaced GM, weight of lead, free flood, arrangeable area, and the stores and provisions duration to applicable minimums and\or maximums. Each ratio must be positive for a feasible design. Each of these ratios are output to the MOGO Module to determine if the design is feasible.
- OMOE Module: Calculates a Value of Performance (VOP) for each Measure of Performance (MOP) using the actual values calculated and an Overall Measure of Effectiveness (OMOE). Each VOP is calculated based on weights provided by a previously-completed pair-wise comparison process. The OMOE (the only output) is calculated using each VOP added together using weights provided by the pair-wise comparison. The calculation of the OMOE is further described in 3.4.1.
- Cost Module: Calculates the basic cost of construction (CBCC). The Cost Module calculates labor costs for each SWBS group using complexity factors and SWBS groups' weights, material costs using SWBS groups' weights, direct and indirect (using overhead) costs, and the basic cost of construction using the direct and indirect cost and a profit margin. The calculation of cost is further described in 3.4.3.
- Risk Module: Calculates an Overall Measure of Risk. The OMOR is found by first calculating a performance, cost, and schedule risk for each system (DVs) based on risk factors determined

previously. The OMOR is a weighted summation of each total risk for each risk type. The calculation of risk is further described in 3.4.2.

- MOGO Module: The Multi-Objective Genetic Optimizer maximizes the OMOE while complying with the constraints produced by the ratios found in the Feasibility Module and minimizing the CBCC and OMOR.

3.4 Objective Attributes

3.4.1 Overall Measure of Effectiveness (OMOE)

Important terminology used in describing the process to develop the SSG(X) OMOE includes:

- Overall Measure of Effectiveness (OMOE) - Single overall figure of merit index (0-1.0) describing ship effectiveness in specified missions

- Mission or Mission Type Measures of Effectiveness (MOEs) - Figure of merit index (0-1.0) for specific mission scenarios or mission types

- Measures of Performance (MOPs) - Specific ship or system performance metric in required capabilities independent of mission (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

There are several considerations to determine overall mission effectiveness in a naval submarine: MOPs, defense policy and goals, threat, environment, missions, mission scenarios, force structure, modeling and simulation or war gaming results and expert opinion. A master war gaming model includes all information about the problem to predict resulting measures of effectiveness for a matrix of submarine performance inputs in a series of probabilistic scenarios. The application of regression analysis to the results defines a mathematical relationship between input submarine MOPs and output effectiveness. The accuracy of such a simulation depends on modeling the detailed interactions of the complex human and physical system and its response to a broad range of quantitative and qualitative variables and conditions including submarine MOPs. Each set of discrete input variables requires a statistically significant number of full simulations since the majority of the inputs and responses are probabilistic. This extensive modeling capability is not yet available for practical applications.

An alternative to modeling and simulation is to use expert opinion to incorporate these diverse inputs and assess the value or utility of submarine MOPs in an OMOE function. This is usually structured as a multi-attribute decision problem. Two methods for structuring these problems are Multi-Attribute Utility Theory (MAUT) and the Analytical Hierarchy Process (AHP). In the past, supporters of these theories have been critical of each other, but recently efforts to identify similarities and blend the best of both for application in Multi-Attribute Value (MAV) functions. This approach is adapted here for deriving an OMOE.

The process begins with the Mission Need Statement (Appendix A) and mission description (Chapter 2). Required Operational Capabilities (ROCs) identified to perform the ship's mission(s) and measures of performance (MOPs) specify those capabilities that will vary in the designs as a function of the submarine Design Variables (DVs). Each MOP is assigned a threshold and goal value. ROCs and applicable restraints to all designs are specified in Table 24. Table 24 summarizes the ROCs, DVs, and MOPs as defined for SSG(X). Goal and threshold values are assigned to MOPs critical to submarine mission in Table 25. An OMOE hierarchy is then developed (Figure 28). Next, AHP and pair-wise comparison calculate MOP weights. Multi-Attribute Value Theory (MAVT) develops individual MOP value functions. The result is a weighted overall effectiveness function (OMOE) used as an objective in the multi-objective optimization. Expert and customer opinion are required to calculate AHP weights using pair-wise comparison questionnaires. MOP and VOP values calculate VOP functions, usually S-curves, for use in the ship synthesis model. A particular VOP with a value of 0 corresponds to the MOP threshold, while a value of 1.0 corresponds to the MOP goal.

Figure 28 is the OMOE hierarchy for SSG(X) derived from Table 25 Two missions (ISR and Missile Launch) depend on the same four MOP categories (War Fighting, Mobility, Sustainability, and Susceptibility). Each of four categories has associated MOPs.

Table 24 - ROC/MOP/DV Summary

ROCs	Description	Applicable Systems and Technology	MOP	Related DV	Goal	Threshold
AAW 1.2	Support area anti-air defense	VLS; Sea Sentry; BPS-16 Radar; BPS-15 Radar; BSY-1; BSY-2; SUBTICS	AAW C4I/SPW	SAIL VLS SONARSYS	SAIL=1 VLS=1 SONARSYS=1	SAIL=4 VLS=3 SONARSYS=4
AAW 2	Provide anti-air defense in cooperation with other forces	VLS; Sea Sentry; BPS-16 Radar; BPS-15 Radar; BSY-1; BSY-2; SUBTICS; AN/BRAi-34	AAW C4I/SPW	SAIL VLS SONARSYS	SAIL=1 VLS=1 SONARSYS=1	SAIL=4 VLS=3 SONARSYS=4
AAW 9	Engage airborne threats using surface-to-air armament	VLS; Sea Sentry; BPS-16 Radar; BPS-15 Radar; BSY-1; BSY-2; SUBTICS	AAW C4I/SPW	SAIL VLS SONARSYS	SAIL=1 VLS=1 SONARSYS=1	SAIL=4 VLS=3 SONARSYS=4
AMW 6	Conduct airborne autonomous vehicle (AAV) operations	Sea Sentry; BPS-16 Radar; BPS-15 Radar; BSY-1; BSY-2; SUBTICS	AAW C4I/SPW	SAIL SONARSYS	SAIL=1 SONARSYS=1	SAIL=3 SONARSYS=4
ASU 1	Engage surface threats with anti-surface armaments	Full 6 or 4 21” tubes; Sea Sentry; BPS-16 Radar; BPS-15 Radar; BQQ-10 Sonar; BQQ-5 Sonar; BQQ-6 Sonar; Thales Suite Sonar; BSY-1; BSY-2; SUBTICS	ASuW	TORP SONARSYS SAIL VLS	TORP=1 SONARSYS=1 SAIL=1 VLS =1	TORP=9 SONARSYS=4 SAIL=4 VLS =3
ASU 1.1	Engage surface ships at long range	Full 6 or 4 21” tubes; Sea Sentry; BPS-16 Radar; BPS-15 Radar; BQQ-10 Sonar; BQQ-5 Sonar; BQQ-6 Sonar; Thales Suite Sonar; BSY-1; BSY-2; SUBTICS	ASuW	TORP SONARSYS SAIL VLS	TORP=1 SONARSYS=1 SAIL=1 VLS =1	TORP=9 SONARSYS=4 SAIL=4 VLS =3
ASU 1.2	Engage surface ships at medium range	Full 6 or 4 21” tubes; Sea Sentry; BPS-16 Radar; BPS-15 Radar; BQQ-10 Sonar; BQQ-5 Sonar; BQQ-6 Sonar; Thales Suite Sonar; BSY-1; BSY-2; SUBTICS	ASuW	TORP SONARSYS SAIL VLS	TORP=1 SONARSYS=1 SAIL=1 VLS =1	TORP=9 SONARSYS=4 SAIL=4 VLS =3
ASU 2	Engage surface ships in cooperation with other forces	Full 6 or 4 21” tubes; Sea Sentry; BPS-16 Radar; BPS-15 Radar; BQQ-10 Sonar; BQQ-5 Sonar; BQQ-6 Sonar; Thales Suite Sonar; BSY-1; BSY-2; SUBTICS	ASuW C4I/SPW	TORP SONARSYS SAIL VLS	TORP=1 SONARSYS=1 SAIL=1 VLS =1	TORP=9 SONARSYS=4 SAIL=4 VLS =3
ASU 4.2	Detect and track a surface target using sonar	Full 6 or 4 21” tubes; Sea Sentry; BPS-16 Radar; BPS-15 Radar; BQQ-10 Sonar; BQQ-5 Sonar; BQQ-6 Sonar;	ASuW	TORP SONARSYS SAIL VLS	TORP=1 SONARSYS=1 SAIL=1 VLS =1	TORP=9 SONARSYS=4 SAIL=4 VLS =3

ROCs	Description	Applicable Systems and Technology	MOP	Related DV	Goal	Threshold
		Thales Suite Sonar; BSY-1; BSY-2; SUBTICS				
ASU 6	Disengage, evade and avoid surface attack	Full 6 or 4 21" tubes; Sea Sentry; BPS-16 Radar; BPS-15 Radar; BQQ-10 Sonar; BQQ-5 Sonar; BQQ-6 Sonar; Thales Suite Sonar; BSY-1; BSY-2; SUBTICS ;Shrike ESM; WLY-1 system; AN/BLQ-10 (ESM); WLR-8(V)2 ESM; AN/BRD-7/BLD-1	ASuW	TORP SONARSYS SAIL VLS ESM	TORP=1 SONARSYS=1 SAIL=1 VLS =1 ESM = 1	TORP=9 SONARSYS=4 SAIL=4 VLS =3 ESM = 2
ASW 1	Engage submarines	Full 4-6x21" tubes w/ Reloads, Encapsulated Torpedoes; Sea Sentry; LWWAA, WAA, BQQ-10 Sonar, BQQ-5, BQQ-6, BQR-19 Navigation, BQR-13 Active, Chin-Array, TB-16, TB-29A, Thales Sonar Suite; BSY-1, BSY-2, SUBTICS	ASW	TORP VLS SONARSYS	TORP =1 VLS =1 SONARSYS =1	TORP =9 VLS =3 SONARSYS=4
ASW 1.2	Engage submarines at medium range	Full 4-6x21" tubes w/ Reloads, Encapsulated Torpedoes; Sea Sentry; LWWAA, WAA, BQQ-10 Sonar, BQQ-5, BQQ-6, BQR-19 Navigation, BQR-13 Active, Chin-Array, TB-16, TB-29A, Thales Sonar Suite; BSY-1, BSY-2, SUBTICS	ASW	TORP VLS SONARSYS	TORP =1 VLS =1 SONARSYS =1	TORP =9 VLS =3 SONARSYS=4
ASW 1.3	Engage submarines at close range	Full 4-6x21" tubes w/ Reloads, Encapsulated Torpedoes; Sea Sentry; SPAT; LWWAA, WAA, BQQ-10 Sonar, BQQ-5, BQQ-6, BQR-19 Navigation, BQR-13 Active, Chin-Array, TB-16, TB-29A, Thales Sonar Suite; BSY-1, BSY-2, SUBTICS	ASW	TORP VLS SONARSYS	TORP =1 VLS =1 SONARSYS =1	TORP =9 VLS =3 SONARSYS=4
ASW 2	Engage submarines in cooperation with other forces	Full 4-6x21" tubes w/ Reloads, Encapsulated Torpedoes; Sea Sentry; SPAT; LWWAA, WAA, BQQ-10 Sonar, BQQ-5, BQQ-6, BQR-19 Navigation, BQR-13	ASW C4I/SPW	TORP VLS SONARSYS	TORP =1 VLS =1 SONARSYS =1	TORP =9 VLS =3 SONARSYS=4

ROCs	Description	Applicable Systems and Technology	MOP	Related DV	Goal	Threshold
		Active, Chin-Array, TB-16, TB-29A, Thales Sonar Suite; BSY-1, BSY-2, SUBTICS; AN/BRAi-34				
ASW 7	Attack submarines with antisubmarine armament	Full 4-6x21" tubes w/ Reloads, Encapsulated Torpedoes; Sea Sentry; SPAT; LWWAA, WAA, BQQ-10 Sonar, BQQ-5, BQQ-6, BQR-19 Navigation, BQR-13 Active, Chin-Array, TB-16, TB-29A, Thales Sonar Suite; BSY-1, BSY-2, SUBTICS, MK 60 Mine Launcher	ASW MIW	TORP VLS SONARSYS	TORP =1 VLS =1 SONARSYS =1	TORP =9 VLS =3 SONARSYS=4
ASW 7.6	Engage submarines with torpedoes	Full 4-6x21" tubes w/ Reloads, Encapsulated Torpedoes; Sea Sentry; SPAT; LWWAA, WAA, BQQ-10 Sonar, BQQ-5, BQQ-6, BQR-19 Navigation, BQR-13 Active, Chin-Array, TB-16, TB-29A, Thales Sonar Suite; BSY-1, BSY-2, SUBTICS	ASW	TORP VLS SONARSYS	TORP =1 VLS =1 SONARSYS =1	TORP =9 VLS =3 SONARSYS=4
ASW 8	Disengage, evade, avoid and deceive submarines	Full 4-6x21" tubes w/ Reloads, Encapsulated Torpedoes; Sea Sentry; SPAT; LWWAA, WAA, BQQ-10 Sonar, BQQ-5, BQQ-6, BQR-19 Navigation, BQR-13 Active, Chin-Array, TB-16, TB-29A, Thales Sonar Suite; BSY-1, BSY-2, SUBTICS; 3"-6.75" Countermeasure Launcher w/ Reloads;	ASW ESM IR Acoustic	TORP VLS SONARSYS PSYStype PROPtype	TORP =1 VLS =1 SONARSYS =1 PSYStype =6 PROPtype =1	TORP =9 VLS =3 SONARSYS =4 PSYStype =4 PROPtype =2
CCC 3	Provide own unit Command and Control	BSY-1, BSY-2, SUBTICS	C4I/SPW	SONARSYS	SONARSYS =1	SONARSYS =4
CCC 4	Maintain data link capability	BSY-1, BSY-2, SUBTICS	C4I/SPW	SONARSYS	SONARSYS =1	SONARSYS =4
CCC 6	Provide communications for own unit	BSY-1, BSY-2, SUBTICS	C4I/SPW	SONARSYS	SONARSYS =1	SONARSYS =4
CCC 9	Relay communications	BSY-1, BSY-2, SUBTICS; BPS-16 Radar; AN/BRAi-34; EHF/SHF HDR Multiband; IEM; OE-315 HSBCA	C4I/SPW	SONARSYS	SONARSYS =1	SONARSYS =4
CCC 21	Perform cooperative	BSY-1, BSY-2,	C4I/SPW	SONARSYS	SONARSYS =1	SONARSYS =4

ROCs	Description	Applicable Systems and Technology	MOP	Related DV	Goal	Threshold
	engagement	SUBTICS; BPS-16 Radar; AN/BRAi-34; EHF/SHF HDR Multiband; IEM; OE-315 HSBCA				
FSO 3	Provide support services to other units	All Designs	N/A			
FSO 5	Conduct towing/search/salvage rescue operations	All Designs	N/A			
FSO 6	Conduct SAR operations	All Designs	N/A			
FSO 7	Provide explosive ordnance disposal services	All Designs	N/A			
FSO 9	Provide routine health care	All Designs	N/A			
FSO 10	Provide first aid assistance	All Designs	N/A			
INT 1	Support/conduct intelligence collection	Sea Sentry; Full 4-6x21" tubes w/ Reloads; BSY-1, BSY-2, SUBTICS; 4-man lock out	C4I/SPW	TORP SAIL SONARSYS SPW	TORP =1 SAIL =1 SONARSYS =1 SPW =1	TORP =9 SAIL =4 SONARSYS=4 SPW =2
INT 3	Conduct surveillance and reconnaissance	Sea Sentry; Full 4-6x21" tubes w/ Reloads; BSY-1, BSY-2, SUBTICS; 4-man lock out	C4I/SPW	TORP SAIL SONARSYS SPW	TORP =1 SAIL =1 SONARSYS =1 SPW =1	TORP =9 SAIL =4 SONARSYS=4 SPW =2
INT 9	Disseminate surveillance and reconnaissance information	Sea Sentry; Full 4-6x21" tubes w/ Reloads; BSY-1, BSY-2, SUBTICS; 4-man lock out	C4I/SPW	TORP SAIL SONARSYS SPW	TORP =1 SAIL =1 SONARSYS =1 SPW =1	TORP =9 SAIL =4 SONARSYS=4 SPW =2
MIW 3	Conduct mine neutralization/ destruction	Full 4-6x21" tubes w/Reloads; BSY-1, BSY-2, SUBTICS;	MIW	TORP SONARSYS	TORP =1 SONARSYS =1	TORP =9 SONARSYS=4
MIW 3.1	Deploy AUVs and UUVs for mine detection and neutralization	Full 4-6x21" tubes w/Reloads; Sea Sentry; UUV's; BSY-1, BSY-2, SUBTICS;	MIW	TORP SONARSYS	TORP =1 SONARSYS =1	TORP =9 SONARSYS=4
MIW 4	Conduct mine avoidance	Full 4-6x21" tubes w/Reloads; BSY-1, BSY-2, SUBTICS;	MIW	TORP SONARSYS	TORP =1 SONARSYS =1	TORP =9 SONARSYS=4
MIW 6	Conduct magnetic silencing (Degaussing, deperming)	Degaussing	Magnetic Signature		NDEGAUS=1	NDEGAUS =0
MIW 6.7	Maintain magnetic signature limits	Degaussing	Magnetic Signature		NDEGAUS =1	NDEGAUS =0
MOB 1	Steam to design capacity in most fuel efficient manner	Hull, Propulsion	Speed Sprint, End; End Range Snorkel, AIP,	Hullform, PSYStype, PROPtype	Esnork =4000 nm Eaip =30 days Vs=22 knt Es=2hr	Esnork=3000 nm Eaip=20 days Vs=15 knt Es=1hr

ROCs	Description	Applicable Systems and Technology	MOP	Related DV	Goal	Threshold
			Sprint			
MOB 3	Prevent and control damage	All Designs	N/A			
MOB 7	Perform seamanship, airmanship and navigation tasks (navigate, anchor, mooring, scuttle, life boat/raft capacity, tow/be-towed)	All Designs	N/A			
MOB 10	Replenish at sea	All Designs	N/A			
MOB 12	Maintain health and well being of crew	All Designs	N/A			
MOB 13	Operate and sustain self as a forward deployed unit for an extended period of time during peace and war without shore-based support	All Designs	N/A	Ts	45days	25days
MOB 16	Operate in day and night environments	All Designs	N/A			
MOB 17	Operate in heavy weather	Hullform	STABI	Depth	1000 ft	500 ft
MOB 18	Operate in full compliance of existing US and international pollution control laws and regulations	All Designs	N/A			
MOB 19	Operate submerged using AIP and batteries	Propulsion, Batteries	End AIP	PSYStype, BAT, BATC, WFAIP	Ebat =9000kwhr WFaip=200lt	Ebat =2500kwhr WFaip=100lt
MOB 20	Operate and transit on snorkel	Propulsion; Snorkel	End Snorkel and Speed	SAIL, PSYStype, WFS	SAIL=1 WFsnork=200lt	SAIL=2 WFsnork=100lt
NCO 3	Provide upkeep and maintenance of own unit	All Designs	N/A			
SEW 2	Conduct sensor and ECM operations	Shrike ESM; WLY-1; AN/BLQ-10 (ESM); WLR-8(v)2 interceptors; AN/BRD-7/BLD-1	AAW, ASuW, MIW, ASW,	ESM	ESM =1	ESM =2
SEW 5	Conduct coordinated SEW operations with other units	Shrike ESM; WLY-1; AN/BLQ-10 (ESM); WLR-8(v)2 interceptors, AN/BRD-7/BLD-1; EHF/SHF HDR Multi-band; AN/BRAi-34; OE-315 HSBCA	AAW, ASuW, MIW, ASW, C4I/SPW	ESM SAIL	ESM =1 SAIL=1	ESM =2 SAIL=2
STW 3	Support/conduct multiple cruise missile strikes	VLS, BSY-1, BSY-2, SUBTICS	STK	VLS, SONARSYS	VLS =1 SONARSYS =1	VLS =3 SONARSYS=4

Table 25 - MOP Table

MOP #	MOP	Metric	Goal	Threshold
1	AAW	VLS Option SONARSYS Option SAIL Option ESM Option	VLS =1 SONARSYS =1 SAIL =1 ESM =1	VLS =3 SONARSYS=4 SAIL =4 ESM =2
2	ASW	TORP Option VLS Option SONARSYS Option SAIL Option ESM Option	TORP =1 VLS =1 SONARSYS =1 SAIL =1 ESM =1	TORP =9 VLS =3 SONARSYS=4 SAIL =4 ESM =2
3	ASuW	SONARSYS Option SAIL Option TORP Option ESM Option VLS Option	SONARSYS =1 SAIL =1 TORP =1 ESM =1 VLS =1	SONARSYS=4 SAIL =4 TORP =9 ESM =2 VLS =3
4	C4I/SPW	SONARSYS Option SAIL Option TOR Option SPW Option	SONARSYS =1 SAIL =1 TOR =1 SPW =1	SONARSYS=4 SAIL =4 TOR =9 SPW =2
5	STK	SONARSYS Option SAIL Option VLS Option	SONARSYS =1 SAIL =1 VLS =1	SONARSYS=4 SAIL =4 VLS =3
6	MIW	SONARSYS Option SAIL Option TORP Option	SONARSYS =1 SAIL =1 TORP =1	SONARSYS=4 SAIL =4 TORP =9
7	Vs (Sprint Speed)	Knots	22knts	15knts
8	Es (Sprint Duration)	Hr	2hr	1hr
9	Esnork (@ 12 knts)	nm	4000nm	3000nm
10	Eaip (AIP Duration @ 5 knts)	Days	30days	20days
11	Depth	Feet	1000ft	500ft
12	STABI	Index	4	1
13	Hull Vulnerability	Depth (ft)	1000	500
14	Acoustic Signature	PSYStype PROPtype	PSYStype =5 PROPtype =1	PSYStype =3 PROPtype =2
15	IR Signature	PROPtype	PROPtype =1	PROPtype =2
16	Magnetic Signature	DEGAUS	Ndegaus =1	Ndegaus =0

Table 25 lists the MOPs. MOP weights are calculated using pair-wise comparison as illustrated in Figure 29. Results are shown in Figure 30. Figure 31 is an example of VOP weights. A single OMOE function assembles MOP weights and value functions, as shown in the following equation. Other VOP weights are listed in Appendix D.

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

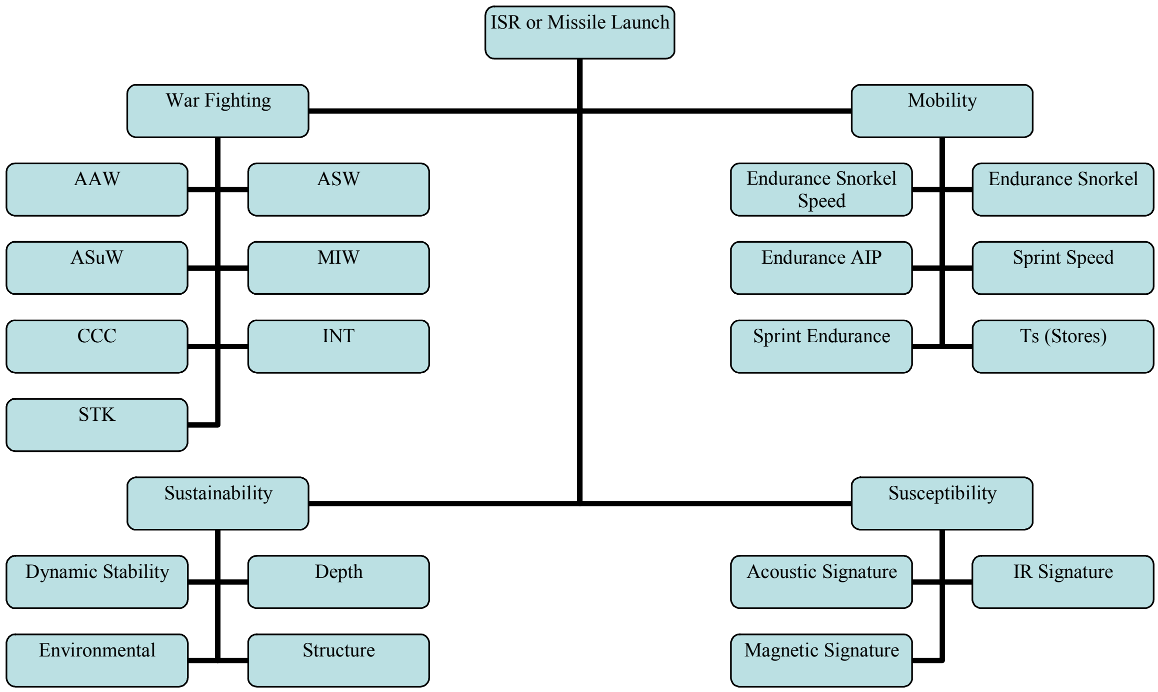


Figure 28 - OMOE Hierarchy

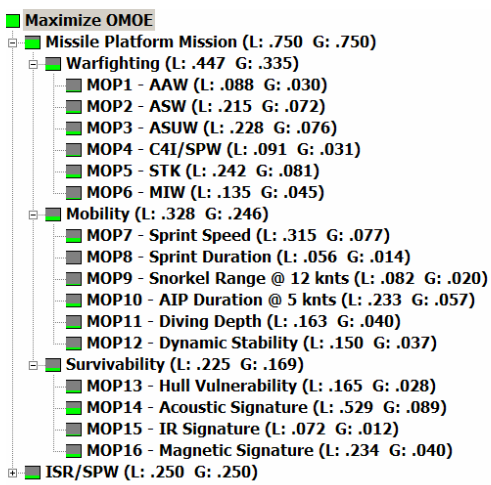


Figure 29 – MOP Weights in Warfighting area

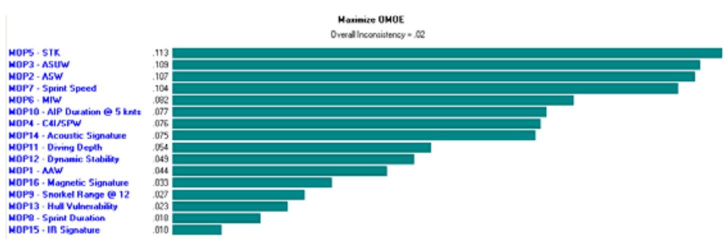


Figure 30 – Bar chart showing MOP weights in order of priority

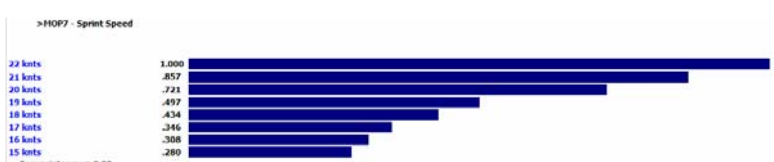


Figure 31 - Value of performance weights for sprint speed

3.4.2 Overall Measure of Risk (OMOR)

In the submarine design process, there has to be a quantitative way to evaluate the technology risk of developing the ship. The OMOR calculates a quantitative measure of risk based on the technologies selected for the submarine. The technology risks associated with SSG(X) include performance, scheduling, and cost risks. Performance risk is the chance that the system will not perform as predicted. Cost risk is the chance that the cost will be significantly more than expected. Schedule risk is the chance that a technology will not be ready in time for the application as planned.

The process for performing an OMOR calculation begins with identifying the risk events associated with each of the design variables, required capabilities, schedule, and cost. The next step is to calculate the risk associated with each event. Table 27 and expert opinion estimate the probability (Pi) that the event will occur. Next, Table 28 and expert opinion estimate the consequence of that event occurring. To calculate the risk for each event (Ri), multiply the probability by the consequence. Finally, pair-wise comparison is used to calculate the OMOR hierarchy weights and the OMOR is calculated in the risk module using the following equation:

$$OMOR = W_{perf}\frac{\sum_i P_i C_i}{\sum_i (P_i C_i)_{\max}} + W_{\cos t}\frac{\sum_j P_j C_j}{\sum_j (P_j C_j)_{\max}} + W_{sched}\frac{\sum_k P_k C_k}{\sum_k (P_k C_k)_{\max}}$$

The overall weight of the performance risk is 0.5, the weight of the cost risk is 0.3, and the weight of the scheduling risk is 0.2.

Table 26 - Risk Register

SWBS	Risk Type	Related DV #	DV Options	DV Description	Risk Event Ei	Event #	Pi	Ci	Ri
2	Performance	DV6	5-9	PSYS	PEM does not meet performance TLRs	1	0.5	0.7	0.35
2	Schedule	DV6	5-9	PSYS	PEM schedule delays impact program	2	0.4	0.8	0.32
2	Cost	DV6	5-9	PSYS	PEM development and acquisition cost overruns	3	0.5	0.3	0.15
2	Performance	DV7	1	Prop Type	RDP does not meet performance TLRs	4	0.4	0.8	0.32
2	Schedule	DV7	1	Prop Type	RDP schedule delays impact program	5	0.4	0.5	0.2
2	Cost	DV7	1	Prop Type	RDP development and acquisition cost overruns	6	0.6	0.3	0.18
3	Performance	DV8	1	Battery Type	NiCd Batteries do not meet performance TLRs	7	0.3	0.7	0.21
3	Schedule	DV8	1	Battery Type	NiCd Batteries' schedule delays impact program	8	0.3	0.2	0.06
3	Cost	DV8	1	Battery Type	NiCd Battery development and acquisition cost overruns	9	0.3	0.2	0.06
3	Performance	DV8	3	Battery Type	Zebra batteries do not meet performance TLRs	10	0.3	0.7	0.21
3	Schedule	DV8	3	Battery Type	Zebra batteries schedule delays impact program	11	0.3	0.2	0.06

3	Cost	DV8	3	Battery Type	Zebra battery may be very expensive compared to alternatives	12	0.5	0.5	0.25
4	Performance	DV13	0.5	Manning reduction	Increased automation and reduced manning may not work	13	0.6	0.6	0.36
4	Schedule	DV13	0.5	Manning reduction	Increased automation and reduced manning may cause delays	14	0.5	0.3	0.15
4	Cost	DV13	0.5	Manning reduction	Increased automation and reduced manning may have cost overruns	15	0.5	0.5	0.25
4	Performance	DV14	1	Sonar	LWWAA Does not meet performance TLRs	16	0.3	0.5	0.15
4	Schedule	DV14	1	Sonar	LWWAA Schedule delays impact program	17	0.3	0.3	0.09
4	Cost	DV14	1	Sonar	LWWAA Development and acquisition cost overruns	18	0.3	0.3	0.09
4	Performance	DV14	4	Sonar	SUBTICS/ Thales Suite does not meet performance TLRs	19	0.3	0.7	0.21
4	Schedule	DV14	4	Sonar	SUBTICS/ Thales Suite schedule delays impact program	20	0.3	0.5	0.15
4	Cost	DV14	4	Sonar	SUBTICS/ Thales Suite development and acquisition cost overruns	21	0.1	0.2	0.02

Table 27 - Event Probability Estimate

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

Table 28 - Event Consequence Estimate

Consequence Level	Given the Risk is Realized, What Is the Magnitude of the Impact?		
	Performance	Schedule	Cost
0.1	Minimal or no impact	Minimal or no impact	Minimal or no impact
0.3	Acceptable with some reduction in margin	Additional resources required; able to meet need dates	<5%
0.5	Acceptable with significant reduction in margin	Minor slip in key milestones; not able to meet need date	5-7%
0.7	Acceptable; no remaining margin	Major slip in key milestone or critical path impacted	7-10%
0.9	Unacceptable	Can't achieve key team or major program milestone	>10%

3.4.3 Cost

Figure 32 – Cost module diagram shows the process used to calculate the Basic Cost of Construction (BCC) for the SSG(X). The input variables required for the module are listed in Table 29.

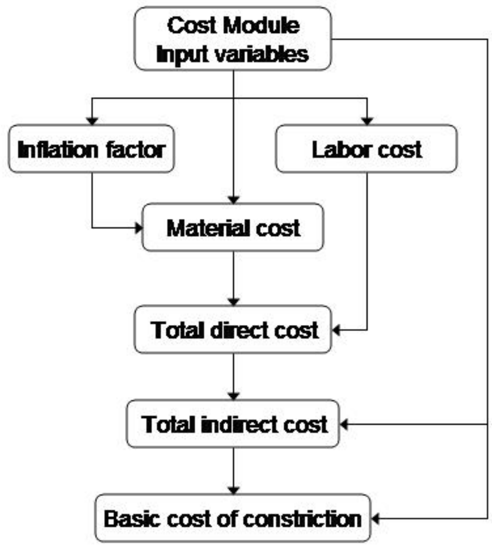


Figure 32 – Cost module diagram

Table 29 – 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 command and control weight
W5	SWBS 500 auxiliaries weight
W6	SWBS 600 outfit weight
W7	SWBS 700 ordnance weight
Yioc	Initial operational capability year
Rp	Shipbuilding rate per year after lead ship
Mh	Average 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

The process of determining the BCC of the submarine is broken into several components. As shown in Figure 32, the inflation factor, labor cost, material cost, total direct and indirect costs are the components used to determine the BCC. The cost for each of the component used to determine the BCC is calculated as follows:

- The inflation factor is determined using the average inflation rate and the number of years between the initial estimate and the base year. This provides a factor to multiply by a given year estimate to produce a current estimate.
- The labor cost is determined using the ship work breakdown structure (SWBS) weights, complexity factors, and the man-hour rate. First, the labor cost for SWBS 100 – 700 is determined by multiplying the man-hour rate by the complexity factor and weight. Second, the labor costs for the production support, and design and integration are determined using half by the sum of the SWBS labor costs. The total labor cost

is then determined through summing SWBS labor costs, production support labor cost, and design and integration labor cost.

- 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 determined by summing the total labor cost with the total material cost.
- The total indirect cost is determined by multiplying the total direct cost with the overhead rate.
- The BCC is determined by summing the total direct and indirect costs and multiplying by one plus the profit margin.

3.5 Multi-Objective Optimization

The Multi-Objective Optimizer uses a genetic algorithm to find the most effective feasible designs while minimizing cost and risk and maximizing effectiveness. The Multi-Objective Genetic Optimizer (MOGO) chooses a random population from this design space. Each individual design of the population is defined by its values of the design variables. The synthesis model evaluates the effectiveness, cost, and risk of all individual designs in the population. It determines the feasibility of each design and the fitness-dominance layers. After evaluation of the initial population, the MOGO performs selection crossover mutation to define a new population. This new population is influenced by the designs in the former population that performed favorably. Figure 33 shows a flow chart of the MOGO process.

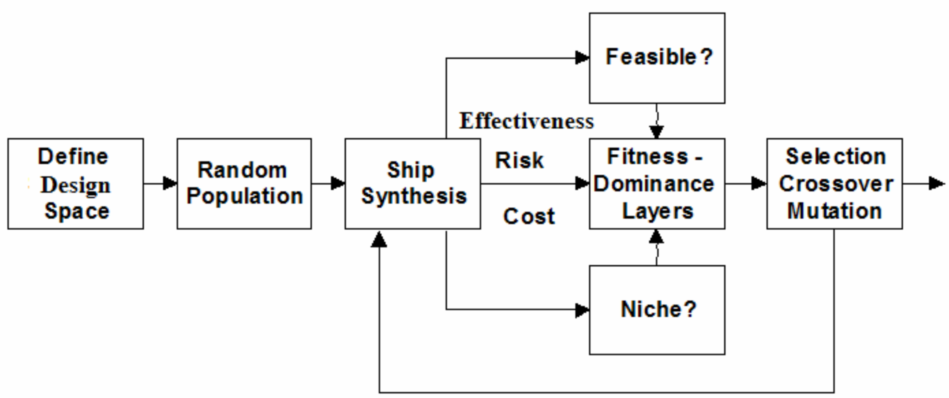


Figure 33 - Multi-Objective Genetic Optimization (MOGO)

The MOGO is implemented using the Darwin optimizer and it is integrated into Model Center along with the synthesis model. The objectives, design variables, and constraints must be identified before use of the MOGO. The objectives are to maximize the effectiveness (OMOE) and minimize the cost (CBCC) and risk (OMOR). The feasibility ratios are the constraints and are given lower and upper bounds. The lower bound for the feasibility ratios is set to zero. The design variables are added from the Input Module and lower and upper bounds are set for the continuous variables.

The MOGO is added to the synthesis model as a new component. Before the optimization is run, the parameters are adjusted so the population size is 200 with 60 preserved designs and the maximum number of generations is 1,000. Evaluation of 100 populations without improvement defines convergence. For discrete variables, the crossover probability is 1 and the mutation probability is 0.15; for continuous variables, the crossover probability is 1 and the mutation probability is 0.1. The maximum constraint violation is 0.02 with a percent penalty of 0.5 for violation.

The result of the MOGO is the non-dominated frontier; these designs are known as the Pareto designs. Figure 34 shows a three-dimensional representation of the non-dominated frontier.

3.6 Optimization Results

Figure 34 shows the non-dominated frontier from the optimization results and the chosen design, run number 44. The selected design has a cost of $633 million and an OMOE of 0.896. All non-dominated designs have the highest effectiveness for a given cost and risk. Figure 34 is a 2-D representation of the Non-Dominated Frontier with several visible knees (the circled designs). Knees in the curve are the top of a region where there is a substantial increase in effectiveness for a slight increase in cost. Design 44, a high risk, moderate cost, but very effective design is a knee in the curve, as indicated. Design 44 was chosen because of its dominance of effectiveness at a moderate cost. The design also contains higher risk systems that were more interesting and appealing. (Unlike program managers, students like risk).

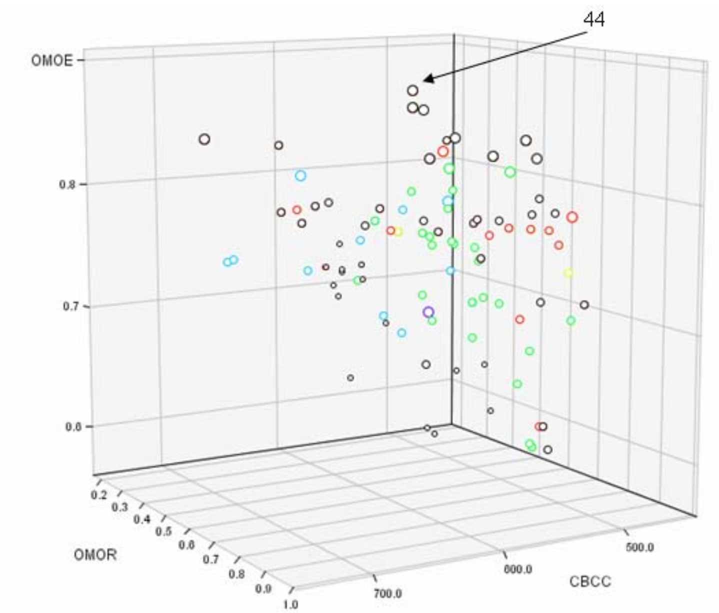


Figure 34 - Non-Dominated Frontier.

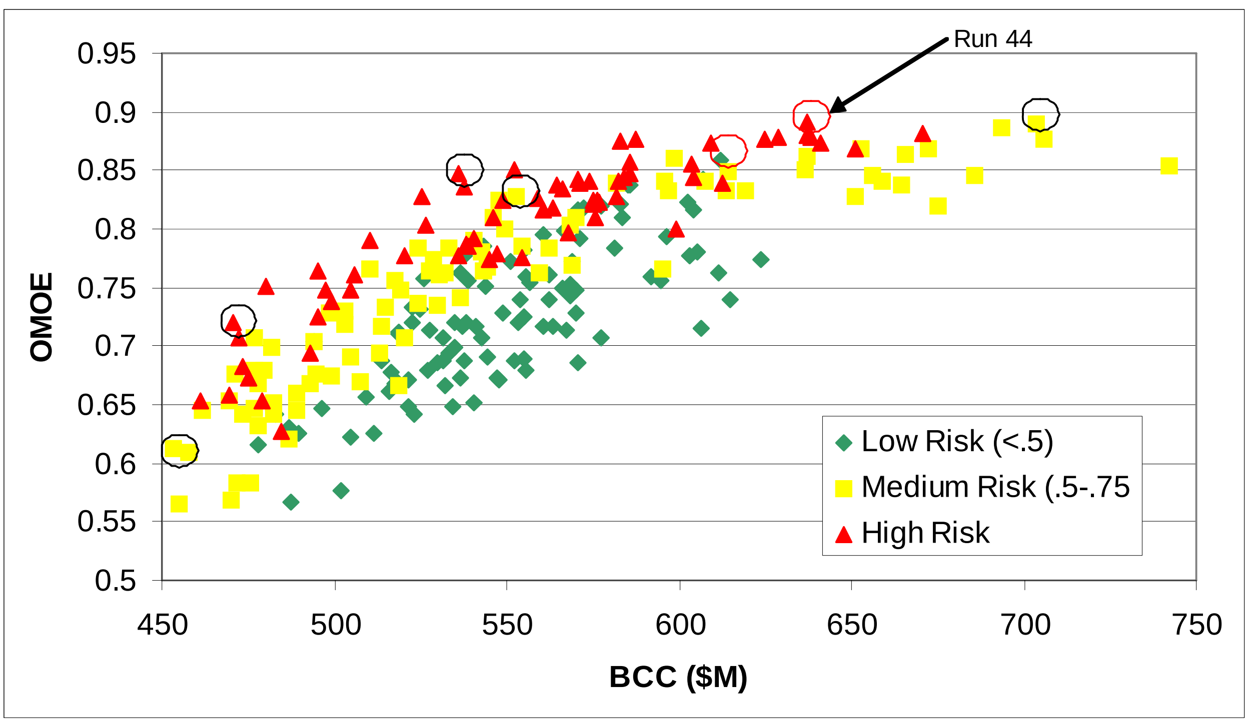


Figure 35 - 2-D Non-Dominated Frontier

Design 44 is a high risk option with an OMOR of 0.842. The factors influencing risk were the selection of PEM cells for AIP, RDP, and Zebra batteries. These options are not currently used by the U.S. Navy; however, these are tested technologies and are proving sound.

After design 44 was selected, the variant was re-optimized to achieve maximum efficiency. The re-optimization was based on maximizing OMOE with cost as an Independent Variable (CAIV) and risk (OMOR) as upper constraints, which restricted the variant to not increase in cost or risk from the initial design 44 optimization. The discrete variables (i.e. TORP, VLS, PROPtype, etc.) were held constant. The new optimization varied only the continuous variables (i.e. LtoD, Diameter, Depth, etc.) to find the highest OMOE. The re-optimization techniques were consistent with the ones described in Section 3.5. In Figure 36 the re-optimization results are shown. Run Number 5 was selected as the final optimized variant. Run number 3 was not selected because it violated some feasibility constraints and cost 20 million dollars more than the original design 44. Constraint violations less than 5% were allowed by the optimizer.

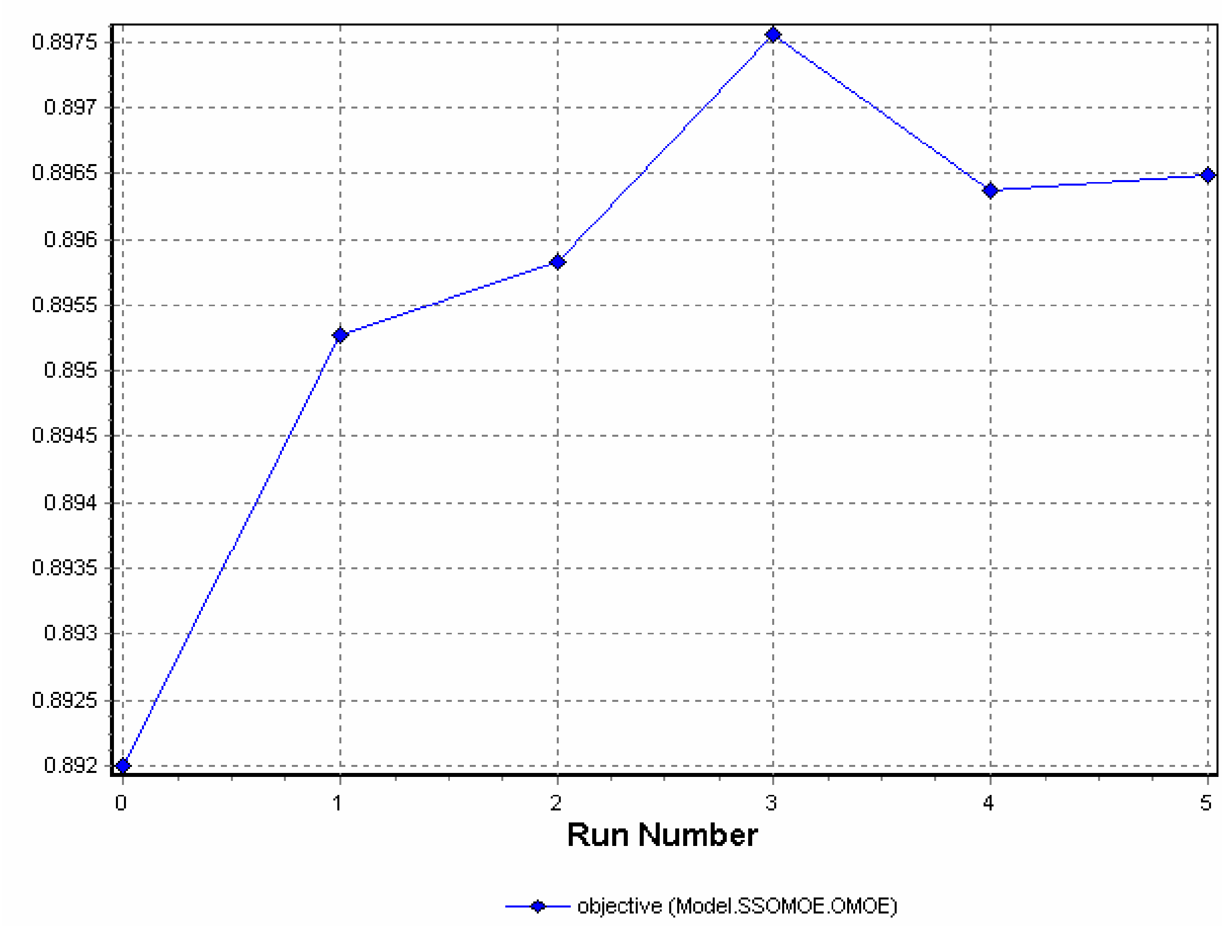


Figure 36 - Re-optimization Results

3.7 Baseline Concept Design

The result of Design 44 with the Variant 2 re-optimization is summarized in Table 30 through Table 35.

The goal diving depth of 1000 ft was achieved while still maintaining high speed and endurance. The propulsion system uses an Open Cycle Diesel (OCD) for transit and AIP while on station. The propulsor is a rim-driven permanent magnet motors with low signature. A degaussing system and significant automation are present onboard. The goal reconfigurable torpedo room, VLS option, and lockout chamber are also included in this design.

Table 30 - Design Variables Summary

Design Variable	Description	Trade-off Range	Baseline Design Values
1	D Diameter	24-34ft	31 ft
2	LtoD Length to Depth Ratio	7-10	8.3
3	BtoD Beam to Depth Ratio	1-1.2	1.01
4	n_a Fullness factor aft	2.5-4	2.71
5	n_f Fullness factor forward	2.0-3.5	2.11
6	Depth Diving Depth	500-1000 ft	1000 ft
7	PSYS Propulsion system alternative	Option 1) CCD, CAT 3512 V12 x2 Engines Option 2) CCD, CAT 3516 V16 x2 Engines Option 3) CCD, 2xCAT3516V16 + 2xCAT3512V12 Option 4) CCD, 2xCAT 3608 IL8 Option 5) OCD/AIP, 2xCAT 3512 V12 + 2x250KW PEM Option 6) OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM Option 7) OCD/AIP, 2xCAT 3516 V16 + 2x250KW PEM Option 8) OCD/AIP, 2xCAT 3516 V16 + 2x500KW PEM Option 9) OCD/AIP, 2x CAT 3608 IL8 + 2x250KW PEM	Option 6) OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM
8	PROPtype Propulsion Prop Type	Option 1) RDP, Rim Driven Prop Option 2) Shrouded	Option 1) RDP, Rim Driven Prop
9	BATtype Battery system type alternative	Option 1) Nickel Cadmium Option 2) Lead Acid Option 3) Zebra	Option 3) Zebra
10	Ebat Battery Capacity	5000-12000 kwhr	5820 kwhr
11	Wfsnork Weight Fuel Snorkel	50-150lton DFM	118 lton
12	Wfaip Weight Fuel AIP	300-900lton Hydrogen in hydride	621 lton
13	Ndegaus Degaussing	0=none; 1=degaussing	1=degaussing
14	Cman Manpower Reduction	0.5-1.0	0.54
15	TORP Torpedo system alternative	Option 1: Reconfigurable torpedo room, 6x21” tubes, 24 reloads Option 2: Reconfigurable torpedo room, 6x21” tubes, 18 reloads Option 3: Reconfigurable torpedo room, 6x21” tubes, 12 reloads Option 4: Reconfigurable torpedo room, 4x21” tubes, 16 reloads Option 5: Reconfigurable torpedo room, 4x21” tubes, 12 reloads Option 6: Reconfigurable torpedo room, 4x21” tubes, 8 reloads Option 7: No torpedo room, 24 external encapsulated Option 8: No torpedo room, 18 external encapsulated Option 9: No torpedo room, 12 external encapsulated	Option 1: Reconfigurable torpedo room, 6x21” tubes, 24 reloads
16	VLS Vertical Launching System Alternatives	Option 1: 24 Cell VLS Option 2: 18 Cell VLS Option 3: 12 Cell VLS	Option 1: 24 Cell VLS

Design Variable	Description	Trade-off Range	Baseline Design Values
17	SONARSYS Sonar/Combat System Alternatives	Option 1: BQQ-10 Bow Dome Passive/Active, LWWAA, high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; CCSM Option 2: BQQ-10 Bow Dome Passive/Active, AN/BQG-5 WAA, high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; BSY-2 Option 3: BQQ-10 Bow Dome Passive/Active, AN/BQG-5 WAA, high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; BSY-1 CCS MK 2 Block 1C Option 4:SUBTICS (Thales): Passive Cylindrical bow array, PVDF planar flank arrays, sail array, hydrophones	Option 2: BQQ-10 Bow Dome Passive/Active, AN/BQG-5 WAA, high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; BSY-2
18	SPW Alternatives	Option 1: 4 Man Lock out chamber Option 2: None	Option 1: 4 Man Lock out chamber
19	SAIL (Radar, Masts and Periscopes, and communication)	Option 1: Virginia Class Sail plus: BPS-16 Radar; 2xAN/BRA-34 Radar; 2xAN/BVS-1 Photonics masts; 2xEHF/SHF HDR Multiband; Snorkel; IEM; Sea Sentry; Seal Locker; OE-315 HSBCA Option 2: Virginia Class Sail: BPS-16 Radar; 2xAN/BRA-34; 2xAN/BVS-1 Photonics Masts; 2xEHF/SHF HDR Multiband; Snorkel; IEM; Sea Sentry; OE-315 HSBCA Option 3: Seawolf Class Sail: BPS-16 radar; 2xAN/BRA-34; 2xAN/BVS-1 Photonics Masts; Type 8 Mod 3 Periscope; Type 18 Mod 3 Periscope; Sea Sentry; Snorkel; OE-315 HSBCA Option 4: 688I Class Sail: BPS-16 Radar; 2xAN/BRA-34; Type 8 Mod 3 Periscope; Type 18 Mod 3 Periscope; Snorkel; Sea Sentry; OE-315 HSBCA	Option 2: Virginia Class Sail: BPS-16 Radar; 2xAN/BRA-34; 2xAN/BVS-1 Photonics Masts; 2xEHF/SHF HDR Multiband; Snorkel; IEM; Sea Sentry; OE-315 HSBCA
20	ESM Electronic Support Measure Alternatives	Option 1: Shrike ESM; WLY-1 acoustic interception and countermeasures system; AN/BLQ-10 Electronic Support Measures (ESM) system; 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube Option 2: Shrike ESM; AN/BRD-7/BLD-1; WLR-8(v)2 interceptors; 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube	Option 1: Shrike ESM; WLY-1 acoustic interception and countermeasures system; AN/BLQ-10 Electronic Support Measures (ESM) system; 2x3" Countermeasure Launcher w/ Reloads, 2x6.75" Countermeasure Tube

Table 31 - Concept Exploration Weights and Vertical Center of Gravity Summary

Group	Weight (lton)	VCG
SWBS 100	1230	15.6
SWBS 200	319	15.7
SWBS 300	44.6	20.1
SWBS 400	159	20.6
SWBS 500	187	20.1
SWBS 600	57.7	20.1
SWBS 700	49.9	20.1
Condition A-1	2040	16.8
Lead Ballast	284	10.3
Condition A	2330	16.0
Variable Loads	997	4.43
Normal Surface Condition (NSC)	3320	11.5

Table 32 - Concept Exploration Volume/Area Summary

Volume/Area	Required	Available
Mobility (ft^3)	Vtk+Vbat+Vmb	36400
Weapons (inboard) (ft^3)	A7*HDK	5460
Command and Control (ft^3)	(Acont+Ap4)*HDK	6770
Auxiliaries and Ship Functions (ft^3)	Vaux+(Asf+Aphpassage)*HDK	10200
Habitability (ft^3)	Abm*HDK	4760
Storerooms	Vstores	1520
Volume Margin	5%	-
Pressure Hull Volume	Vph	84100
Outboard Volume	Vob	32200
Everbuoyant Volume	Veb	116000
Everbuoyant Displacement (lton)	Wnsc	3320
Main Ballast Tank Volume	Vmbt	17500
Submerged Volume	Veb+Vmbt	133000
Free Flood Volume	Vff	7040
Envelope Volume	Venv	145000
Total Arrangeable Area	3775.62	6780

Table 33 – Concept Exploration Electric Power Summary

Group	Description	Power
SWBS 200	Propulsion	7.59
SWBS 300	Electric Plant, Lighting	16.8
SWBS 430, 475	Miscellaneous	5.40
SWBS 521	Firemain	5.89
SWBS 540	Fuel Handling	8.41
SWBS 530, 550	Miscellaneous Auxiliary	14.5
SWBS 561	Steering	7.72
SWBS 600	Services	8.70
KWdegaus	Degaussing	42.1
KW_{NP}	Non-Payload Functional Load	75.0
KWac	AC and Heating	43.9
KWv	Ventilation	19.2
KWmfl	Max. Functional Load	323
KW_{MFLM}	Max. Functional Load w/Margins	356
KW_{24avg}	Average 24 Hour Electrical Load	178

Table 34 - MOP/ VOP/ OMOE/ OMOR Summary

Measure	Description	Value of Performance	Actual Values and Options
MOP 1	AAW	0.963	VLS =1 SAIL = 2 ESM = 1 SONARSYS = 2
MOP 2	ASW	0.942	VLS =1 ESM = 1 SONARSYS = 2 TORP = 1
MOP 3	ASuW	0.947	VLS =1 ESM = 1 SONARSYS = 2 TORP = 1 SAIL = 2
MOP 4	C4I/SPW	0.947	ESM = 1 SONARSYS = 2 SAIL = 2 SPW = 1
MOP 5	STK	0.950	VLS =1 SONARSYS = 2 SAIL = 2
MOP 6	MIW	0.913	SONARSYS = 2 TORP = 1 SAIL = 2
MOP 7	Vs (Sprint Speed)	1.0	22.0 knts
MOP 8	Es (Sprint Duration)	0.491	0.917 hrs
MOP 9	Esnork (@ 12 knts)	1.00	5160 nm
MOP 10	Eaip (AIP Duration @ 5 knts)	0.631	26.6 hrs
MOP 11	Depth	1.00	1000 ft
MOP 12	STABI	1.00	1 (highest rating)
MOP 13	Hull Vulnerability	1.00	Depth = 1000 ft
MOP 14	Acoustic Signature	0.890	AIP Type = Fuel Cell Prop Type = Rim
MOP 15	IR Signature	1.00	AIP Type = Fuel Cell
MOP 16	Magnetic Signature	0.822	Degaussing Prop Type = Rim
OMOE	Overall Measure of Effectiveness	0.896	-
OMOR	Overall Measure of Risk	0.842	-

Table 35 - Concept Exploration Baseline Design Principal Characteristics

Characteristic	Baseline Value
Normal Surface Condition Weight (lton)	3320
Submerged Displacement (ft^3)	133800
L (ft)	258
Depth Diameter (ft)	31.1
Beam (ft)	31.4
KG (ft)	11.5
GM (ft) (normal surface condition)	3.66
BG (ft) (normal surface condition)	3.05
Lead weight (lton)	284
KG (m)	3.50
GM/B (surface condition)	0.111
Propulsion and power system and AIP type	OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM
Propulsor	Rim Driven Pods
Total Power Required for Sprint Speed (kW)	6350
Total Power Required for Snorkel (kW)	1150
Sprint Speed (knt)	22.0
Snorkel Range @ 12 knts (nm)	5160
AIP Endurance (days)	26.6
Sprint Endurance (hours)	0.917
Battery Capacity (kwhr)	5820
Diving Depth (ft)	1000
TORP system	Reconfigurable torpedo room, 6x21” tubes, 24 reloads
VLS system	24 Cell VLS
Sonar and CS system	BQQ-10 Bow Dome Passive/Active, AN/BQG-5 WAA, high frequency sail and chin-array (mine and obstacle avoidance), TB-16, TB-29A; BSY-2
SPW system	4 Man Lock out chamber
SAIL	Virginia Class Sail: BPS-16 Radar; 2xAN/BRA-34; 2xAN/BVS-1 Photonics Masts; 2xEHF/SHF HDR Multiband; Snorkel; IEM; Sea Sentry; OE-315 HSBCA
ESM	Shrike ESM; WLY-1 acoustic interception and countermeasures system; AN/BLQ-10 Electronic Support Measures (ESM) system; 2x3” Countermeasure Launcher w/ Reloads, 2x6.75” Countermeasure Tube
Total Officers	8
Total Enlisted	21
Total Manning	29
Basic Cost of Construction ($M)	634

4 Concept Development (Feasibility Study)

Concept Development of SSG(X) follows Concept Exploration. In Concept Development the general concepts for the hull, systems, and arrangements are developed. These general concepts are refined into specific systems and subsystems that meet the ORD requirements. Design risk is reduced by this analysis and parametrics used in Concept Exploration are validated.

4.1 Hull Form

4.1.1 Envelope Hull

Section 3.1.1 describes the hullform alternatives. Table 36 provides a summary of the optimization results and the baseline characteristics of the SSG(X). The overall diameter of the envelope hull is 31 feet; the length is 257.3 feet, giving a length to diameter ratio of 8.3. The beam was adjusted to 31 feet so that the beam to diameter ratio is 1. The symmetrical submarine is more producible and structurally efficient.

Table 36 – SSG(X) Envelope Hullform Characteristics

	MOGO	Baseline
D	31 ft	31 ft
B	31.3 ft	31 ft
L	257.3 ft	257.3 ft
n_f	2.71	2.71
n_a	2.11	2.11
Δ	144401 ft^3	135811 ft^3

The MIT teardrop hullform model was used to generate offsets for the outer hull; these hand calculations are shown in Figure 39. The length of the forebody is 74.4 ft; the length of the parallel midbody is 71.3 ft; the length of the aft body is 111.6 ft. Figure 37 - Figure 39 show the calculations of the hullform offsets, volume and surface area.

SS Hullform Module

Units definition

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

Physical Parameters

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

Input

$D := 31$ $BtoD := 1.0$ $LtoD := 8.3$ $n_f := 2.11$ $n_a := 2.71$

Process

$D := D \cdot ft$ $B := BtoD \cdot D$ $B = 31\,ft$ $LOA := LtoD \cdot D$ $LOA = 257.3\,ft$

Calculate teardrop forebody and run L/D: $LtoD_{td} := 6.0$ $L_{td} := LtoD_{td} \cdot D$ $L_{td} = 186\,ft$

Select LOA including PMB: $L_{pmb} := LOA - L_{td}$ $L_{pmb} = 71.3\,ft$

$L_f := 2.4 \cdot D$ $L_f = 74.4\,ft$

(Resistance optimum)

$L_a := 3.6 \cdot D$ $L_a = 111.6\,ft$

Figure 37 - Hullform Calculations

B. VOLUME CALCULATIONS TO SUPPORT ARRANGENMENTS:

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

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

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

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

3. Total Ship:

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

$$V_{env} := \int_{0\cdot ft}^{LOA} A(x)\,dx \qquad V_{env} = 144401\,ft^3$$

$$S := \int_{0\cdot ft}^{LOA} p(x)\,dx \qquad S = 20688.13\,ft^2$$

Figure 38 - Hullform Calculations (cont.)

$L_f = 74.4\,ft$ $L_f + L_{pmb} = 145.7\,ft$ $\frac{D}{2} = 15.5\,ft$ $LOA = 257.3\,ft$ $z(LOA) = -0\,ft$

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

x1 = (ft)	z(x1) = (ft)	x2 = (ft)	z(x2) = (ft)
0	0	145.7	15.5
7.44	7.217	156.86	15.47
14.88	9.744	168.02	15.302
22.32	11.461	179.18	14.907
29.76	12.726	190.34	14.206
37.2	13.68	201.5	13.131
44.64	14.394	212.66	11.617
52.08	14.908	223.82	9.604
59.52	15.252	234.98	7.033
66.96	15.443	246.14	3.85
74.4	15.5	257.3	0

Figure 39 - Hullform Calculations (cont.)

The offsets obtained from the calculations are used to create the envelope hull in Rhino shown in Figure 40.

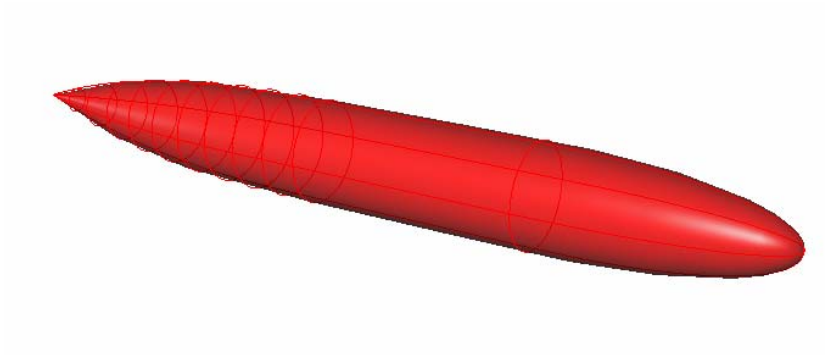


Figure 40 - SSG(X) Envelope Hull Created from Offsets

4.2 Preliminary Arrangement (Flounder Diagram and Cartoon)

As a preliminary step in finalizing hull form geometry and inboard and outboard general arrangements, an arrangement cartoon was developed for areas supporting mission operations, propulsion, and other critical constrained functions. Figure 41 shows the SSG(X) Flounder diagram, the first step to arrange the submarine. This is a plot of cross-sectional area against length, within the envelope hull sectional area curve; areas in the Flounder diagram represent volumes in the submarine. Required areas from Concept Exploration are placed inside the outer hull boundaries. This method provides a rough longitudinal arrangement to check and maintain the necessary volume balance.

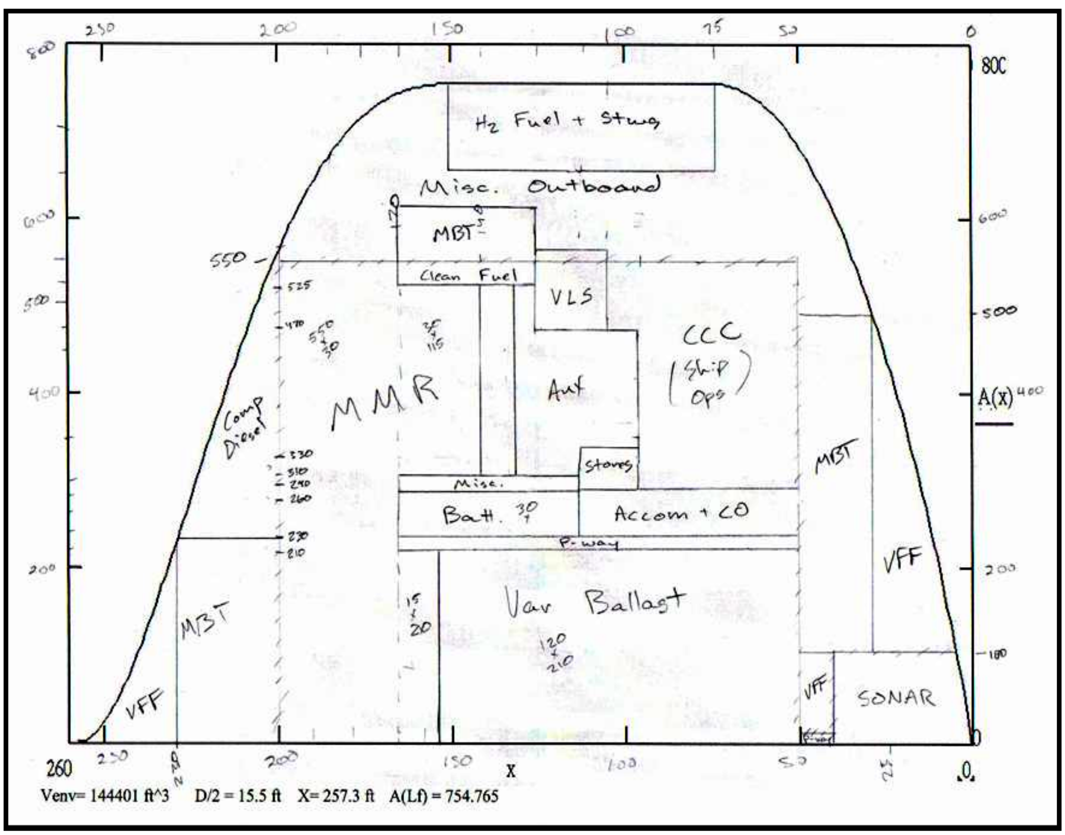


Figure 41 – SSG(X) Flounder Diagram

Figure 42 shows a preliminary arrangement cartoon. This cartoon was developed from the Flounder diagram and provides a profile and midship cross-sectional view of the SSG(X). The general arrangements inboard of the pressure hull are driven by the large required volume of variable ballast (VB). The volume of VB results from the use of PEM fuel cells and hydrogen hydride. Hydrogen tanks cannot be used for salt water which necessitates inboard compensating ballast. The SSG(X) is divided into three decks: the area of the top deck forward of the VLS holds stores and area for command and control; the forward area of the second deck serves as the primary location for command and control and contains habitability; a torpedo room is located at the forward-most section of the lower deck. The main and auxiliary machinery rooms are contained in the area of these decks aft of the VLS system. The remaining volume in the pressure hull below the lowest deck contains variable ballast and the Zebra batteries. These arrangements were somewhat modified during concept development.

The cartoon shows main ballast tanks (MBT) forward and aft of the pressure hull with an additional MBT around the pressure hull at amidships. A compensating diesel tank is located just aft of the pressure hull. The hydride for the PEM fuel cells lines the bottom of the envelope hull. The sonar dome is in the bow of the submarine and a passageway extends from the pressure hull to the dome. The remaining outboard volume is used for free flood and miscellaneous volume.

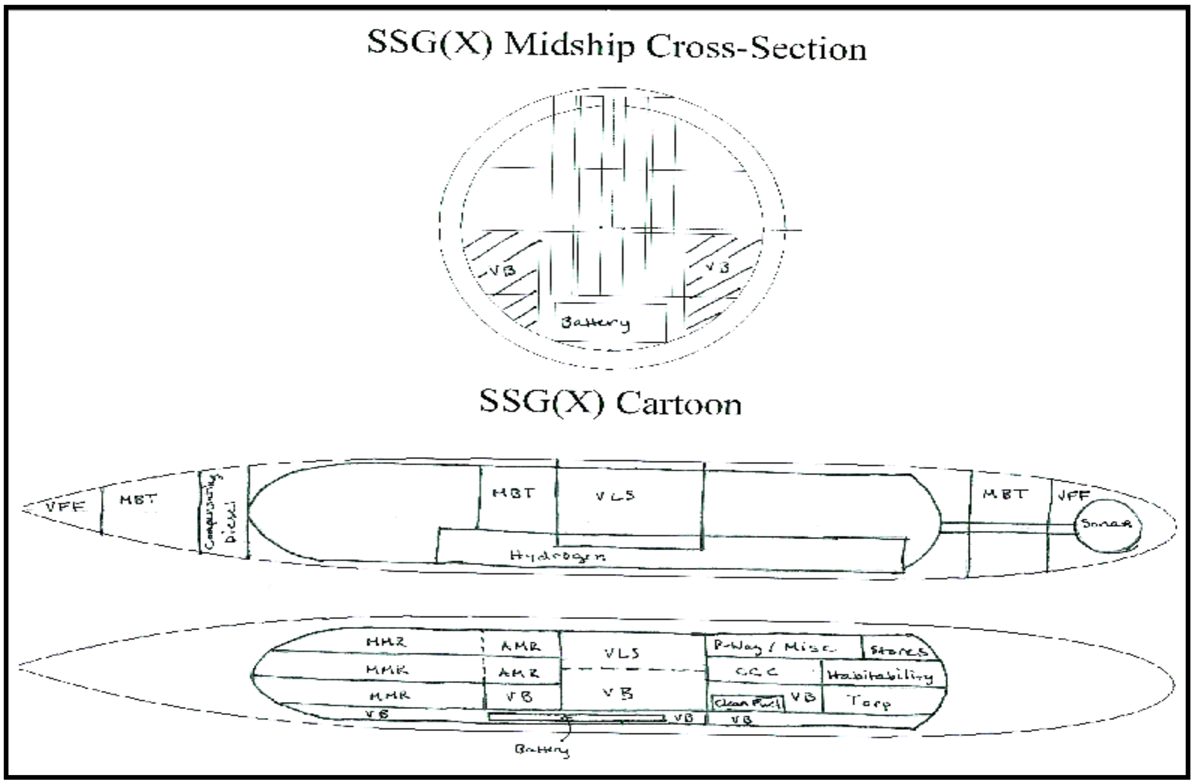


Figure 42 - SSG(X) Cartoon

4.2.1 Mission Operations Arrangements

The mission components for the SSG(X) are as follows: Passive/Active BQQ-10 Bow Dome, AN/BQG-5 Wide Aperture Array (WAA), TB-16 and TB-29A line arrays, high frequency sail and chin arrays, the BSY-2 combat system; a WLY-1 acoustic interception and countermeasure system, an AN/BLQ-10 ESM system, two sets of 3" Countermeasure/XBT launcher with 3" countermeasure reloads (10), a 6.75" external countermeasure launcher with reloads (4); two photonics masts (AN/BVS-1), two AN/BRA-34 radars, two EHF/SHF HDR multibands, IEM, an AN/BPS-16 radar, a Sea Sentry UAV; a reconfigurable torpedo room with six 21'' torpedo tubes and 24 reloads; a 24 cell VLS system; and a 4 man lock out chamber.

The mission operations include missile launch and ISR. Those components playing directly into the mission of the ship are a main concern for arrangements. These include the VLS cells, torpedo room and tubes, and CCC. The VLS cells are located inboard of the pressure hull at amidships. This is a result of space limitations discovered while arranging spaces in the Flounder diagram and cartoon. The inboard torpedo room is located on the foremost part of the lower deck in the pressure hull. Six tubes extend from the torpedo tube out the bow of the submarine.

CCC space is located on the upper and second decks ahead of the VLS system. Section 0 presents further detail of the internal combat systems arrangements.

4.2.2 Propulsion and Machinery Arrangements

The preliminary arrangement for the propulsion and machinery equipment was primarily driven by the volume requirements determined by the optimization. As with all modern submarines the habitability and torpedo spaces are located in the bow or forward somewhere. The stern and aft portions of the boat consequently are designated for the main machinery room (MMR) and the auxiliary machinery room (AMR). For stability purposes the variable ballast tanks must be kept in the bilge. The compensating fuel tank was located between the pressure and envelope hull around the MMR for quicker distribution to the CAT 3512 diesel engines. The clean fuel tank was also placed next the MMR only in the bilge inside the pressure hull. Also to increase stability the heavy Zebra batteries are distributed in the bilge and symmetrically along the center line. The heavy hydrogen hydride was determined to not be any higher than half the diameter of the submarine. Due to the limited pressure hull space and safety purposes the hydrogen hydride is located outboard.

4.2.3 Equilibrium Polygon

An equilibrium Polygon provides the boundary for the operational envelope for trim and ballast for SSG(X). The loads at different loading conditions are calculated and the plotted with the polygon. If the loading conditions are all within the polygon, they are feasible. If the loading conditions are outside of the polygon, the locations of the weights must be changed to get all loading conditions inside of the polygon.

The first step in creating an equilibrium polygon with loading conditions is to arrange the tanks and displacing volumes in the arrangements drawings. The next step is to use the drawings to calculate the longitudinal center of buoyancy (LCB). In order for the submarine to balance, the longitudinal center of gravity (LCG) must be as close to the LCB as possible. The next step in the process is to use the drawings to determine the LCG of the entire submarine. Then, use the drawings to determine the LCGs and volumes for each of the variable ballast tanks. Starting at the forward-most trim tank and moving aft, fill each tank. Each time a tank is filled, it creates an edge of the polygon. Once all of the tanks are filled, the tanks are emptied. Starting at the forward-most trim tank, each tank is the emptied. This creates the other half of the polygon. The last step in the process is to determine the weights and moments for each condition. The feasibility of the conditions is determined by plotting the loading conditions onto the equilibrium polygon.

4.3 Initial Balance and Trim

4.3.1 Displacing Volumes

All volumes external to the pressure hull were considered to be a displacing volume. Figure 43 shows all displacing volumes for SSG(X).

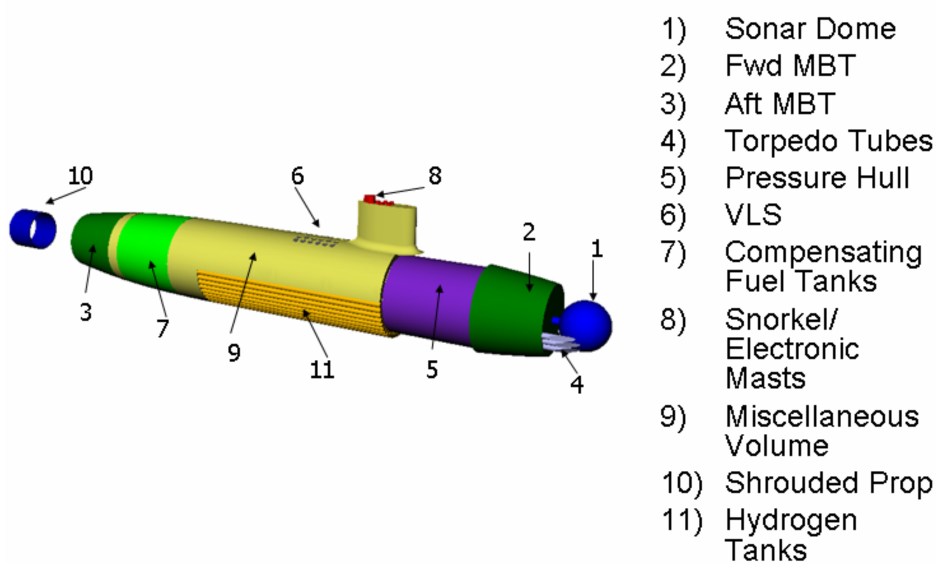


Figure 43 - Displacing Volumes

All of these volumes were used in calculating the submerged LCB of the submarine. For the LCB calculation all centers of buoyancy were taken with respect to the forward most point of the envelope hull. Table 37 summarizes the LCB calculation of SSG(X).

Table 37 - Longitudinal Center of Buoyancy Calculation

Description	Volume – ft^3	Buoyancy - lton	LCB - ft	VCB - ft
Pressure Hull	83796	2394	-115	16
H2 Tanks (Mid)	5655	162	-115	7
Sonar	2302	66	-14	15
MBT(fore)	9925	284	-34	16
MBT(aft)	10303	294	-206	16
Comp Diesel Fuel	5095	146	-182	16
VLS (outboard)	161	5	-109	30
Torpedo Tubes (Outboard)	474	14	-29	12
Propulsor	900	26	-260	16
Miscellaneous	17199	491	-122	25
total (Vsub)	**135811**	**3880**	**-119**	**16**

4.3.2 Internal and External Tanks

Figure 44 and Figure 45 show the initial tank locations.

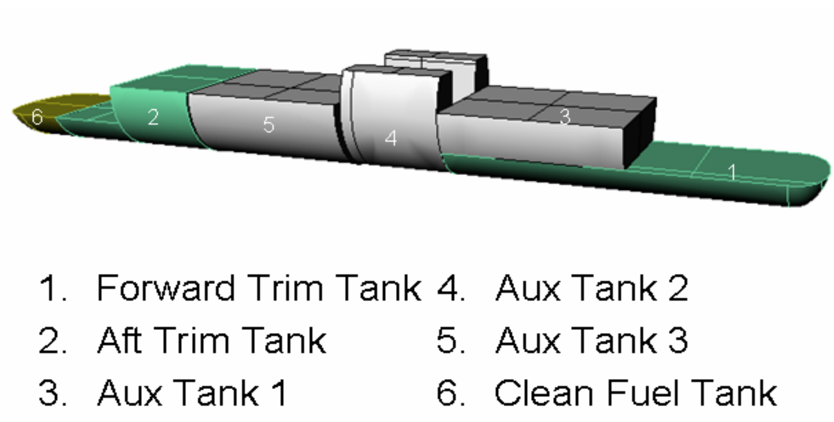


Figure 44 - Initial Inboard Tanks

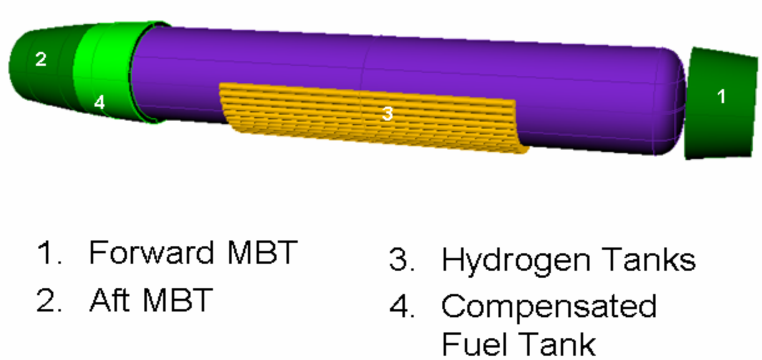


Figure 45 - Initial Outboard Tanks

4.3.3 Weights

Ship weights are grouped by SWBS. The components list was obtained from the Model Center optimization. The weight for each component was compiled into an Excel spreadsheet. In addition to the weights, their centers of gravity (vertical and longitudinal) were entered. These centers of gravity were estimated using the ship's arrangements. The weights and centers of gravity (CG) were used to find the lightship load and CG of the submarine. To make sure that the submarine was balanced, the longitudinal CG (LCG) needed to be as close to the longitudinal center of buoyancy (LCB) as possible. In order to facilitate this need, the centers of all of the components were taken with reference to the LCB of the submarine. The LCB of the ship was taken to be at the volumetric center of the buoyant volumes of the submarine. The LCB turned out to be 119 ft. from the bow. A summary of the weights by SWBS code and the lightships weight are listed in table (insert ref). The complete weights spreadsheet is provided in the appendix (whatever).

Table 38 - Lightship Weight Summary

SWBS Group	Weight (lton)	VCG (ft)	LCG (ft)
100	1220.51	-0.29	3.66
200	334.58	-2.55	-50.05
300	44.59	-2.40	-33.40
400	159.74	1.52	76.46
500	178.12	1.09	-0.62
600	57.65	0.73	9.52
700	49.89	0.55	32.03
8 (Lead)	315.00	-15.00	26.98
Total (LS+8)	2360.08	-2.34	3.80

4.3.4 Load Conditions

The arrangements drawings, weights spreadsheet, and the variable loads are used in creating the extreme loading conditions in the different water densities that the submarine will encounter. The loading conditions used are the Normal Condition, Light #1, Heavy #1, Heavy #2 (mines), Heavy Forward #1, Heavy Forward #2, and Heavy Aft. Table 39 illustrates each of the loading conditions and the water density used for each loading condition. Once the loading conditions were positioned on the plot with the polygon, the next task was to get all of the points inside of the polygon. To do this, ballast tanks were changed, components were moved, and lead was added and taken away. Figure 92 shows the final equilibrium polygon with all of the loading conditions inside of it.

Table 39 - Variable Load Summary

Group	Items	Ship Synthesis	Normal Condtion (N)	Light (Diesel)	Heavy (Diesel)	Heavy (Mines)	Heavy Fwd #1 (Diesel)	Heavy Fwd #2 (Diesel)	Heavy Aft (Diesel)
No Arctic	Water Density (lb_f/ft^3)	64	64	64.3	63.6	63.6	64.3	64.3	64.3
Condition A			A						
Disp. Sub			A'						
MBT (ltons)			MBT'						
Weight to Submerge			Ws'						
1, 2, 3	Fixed Loads: crew and effects, ballistic missiles, sanitary, lube oil,	WF10+ Wsew+ 0.1·WF46	Normal						
4	Gases: Nitrogen, Oxygen, Hydrogen, Argon	WArgon+ WO_2+ WH_2	Full		None		Full	½ to ¾ full; max fwd moment	½ to ¾ full; max aft moment
5	Torpedoes, Missiles, Mines, Ammunition	Wvp	Full	None	Torpedoes and Missiles	Mines and Missiles	Aft Expended	Aft Expended	Fwd Expended

Group	Items	Ship Synthesis	Normal Condtion (N)	Light (Diesel)	Heavy (Diesel)	Heavy (Mines)	Heavy Fwd #1 (Diesel)	Heavy Fwd #2 (Diesel)	Heavy Aft (Diesel)
6	Potable and Fresh Water	WF52	Full	½ Full	Full		Full to ½ Full, max fwd moment		Full to ½ Full, max aft moment
7	Provisions and General Stores	WF31+ WF32	Normal	¾ Normal	½ Normal		¾ Normal	½ Normal	
8	Lube Oil and Storage Tanks	0.9·WF46	Full	¾ Full	½ Full		¾ Full, max fwd moment	½ to ¾ Full, max fwd moment	½ to ¾ Full, max aft moment
9	Compensating Fuel Tanks (no fuel ballast tanks)	Wf_{comp}	Fuel		SW		Fuel	½ to ¾ Full, max fwd moment	½ to ¾ Full, max aft moment
10	Fuel in Clean Fuel Tanks	Wf_{clean}	Full		None		Full	½ to ¾ Full, max fwd moment	½ to ¾ Full, max aft moment
11	Cargo		Normal						
12	Passengers		Normal						
13	Residual SW	$W_{residual}$	Normal						
Total	VLI	WF00	VLI						
Variable Ballast	Ws'-Wmbt'-VLI	$W_{trimbal}$	Ws'-Wmbt'-VLI						

4.3.5 Initial Equilibrium Polygon

The equilibrium polygon is a graphical representation of the possible ballast and moments that can be achieved with variable ballast compensation. The polygon is created in a plot of the weight vs. the moment. The boundary of the polygon are composed of the weights and moments created by the variable ballast tanks. This polygon is used in tandem with certain extreme loading conditions. If the loading conditions lie within the boundaries of the polygon, then the submarine will be able to maintain neutral buoyancy and level trim under all operational conditions.

To create the boundary of the polygon, the volumetric center of each ballast tank is identified using the arrangements drawings. The variable ballast tanks are filled starting with the forward trim tank and ending with the aft trim tank, and then the tanks are emptied in the same order. The weights and moments created after filling or emptying each ballast tank are what compose the polygon boundaries.

Table 40 – Construction of Polygon Boundaries

Tanks Filled	Volume (ft3)	Weight (lton)	Moment
Empty	0	0	0
Forward Trim Tank (FTT)	5445	156	10215
FTT + Aux 1 (A1)	11191	320	18737
FTT + A1 + A2	13397	383	20528
FTT + A1 + A2 + A3	20137	575	21473
FTT + A1 + A2 + A3 + ATT	25582	731	18076
A1 + A2 + A3 + ATT	20137	575	7861
A2 + A3 + ATT	14391	411	-661
A3 + ATT	12185	348	-2452
Aft Trim Tank (ATT)	5445	156	-3397
Empty	0	0	0

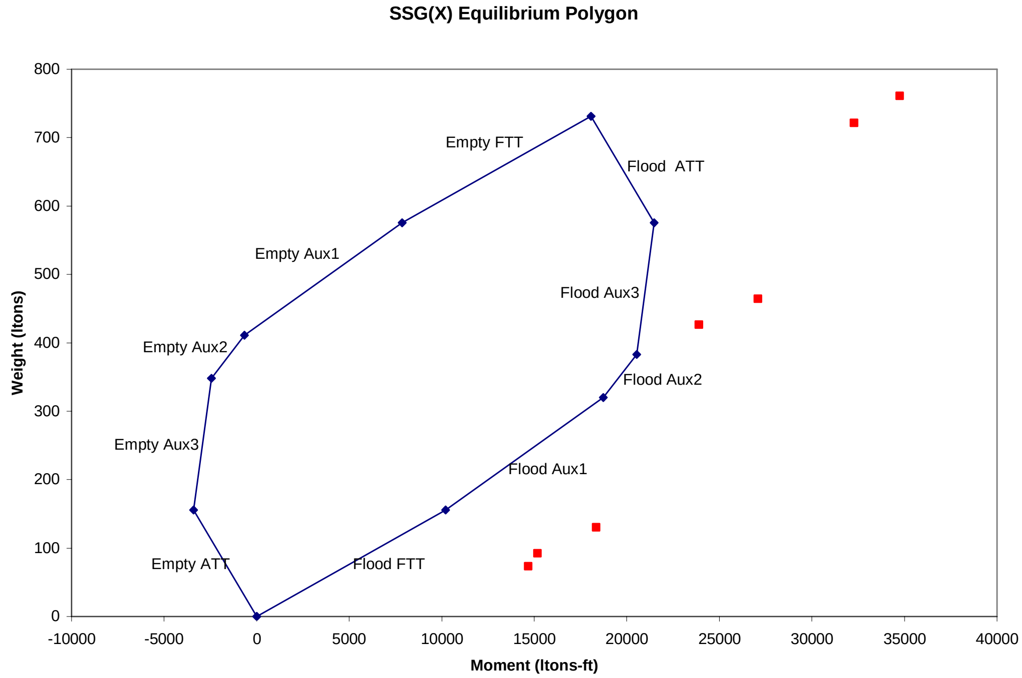


Figure 46 - SSG(X) Initial Equilibrium Polygon

4.3.6 Necessary Modifications and Baseline Equilibrium Polygon

All of the loading conditions need to be inside of the polygon. The CGs of all of the components can be moved to accomplish this task. The compensating fuel tank and the clean fuel tank must be moved so that their CGs are the same. This needs to be done so that when all of the fuel was used, there would be no extra moment created by having salt water in the compensating diesel tank and an empty clean fuel tank. The amount and position of the lead can also be altered to move all of the loading conditions inside of the equilibrium polygon. The position and size of all external and internal tanks can also be changed.

4.3.7 Normal Surface Condition

Table 41 summarizes the normal surface condition. The normal surface calculations are computed using the displacing volume of the submarine. This displacing volume includes the pressure hull, ballast tanks, hydrogen tanks, sonar dome, propulsion system, torpedo tubes, and any other miscellaneous outboard volume. The envelope hull is not included in the displacement calculations. Due to the complex shapes of the displacing volumes, the Rhino Marine plug-in is used to calculate the transverse and longitudinal stabilities. Rhino Marine is also used to plot the curves of form for SSG(X). The reserve buoyancy calculations are determined by how much buoyancy is not in use by the MBTs (Main Ballast Tanks) when SSG(X) is on the surface. The reserve buoyancy for the SSG(X) is 3.6%, with a draft of 26 ft and a length on the waterline (LWL) of 233 ft. The submarine exhibits transverse stability with a metacenter 3.3 ft above the center of gravity and longitudinal stability with a metacenter 103 ft above the center of gravity. Figure 47 shows the curves of form.

Table 41 - Summary of SSG(X) Surface Condition

Description	Surface Condition
Δ	3312 lton
LWL	233 ft
T	26 ft
B	31 ft
GMT	3.3 ft
GML	103 ft
Reserve Buoyancy	3.6%

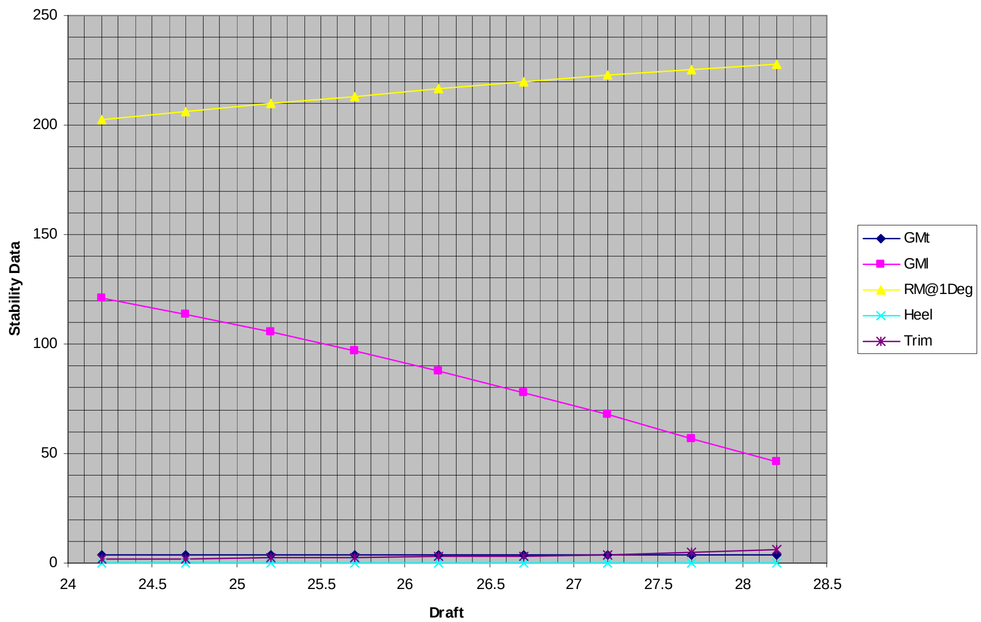


Figure 47 - Curves of form Normal Surface Condition

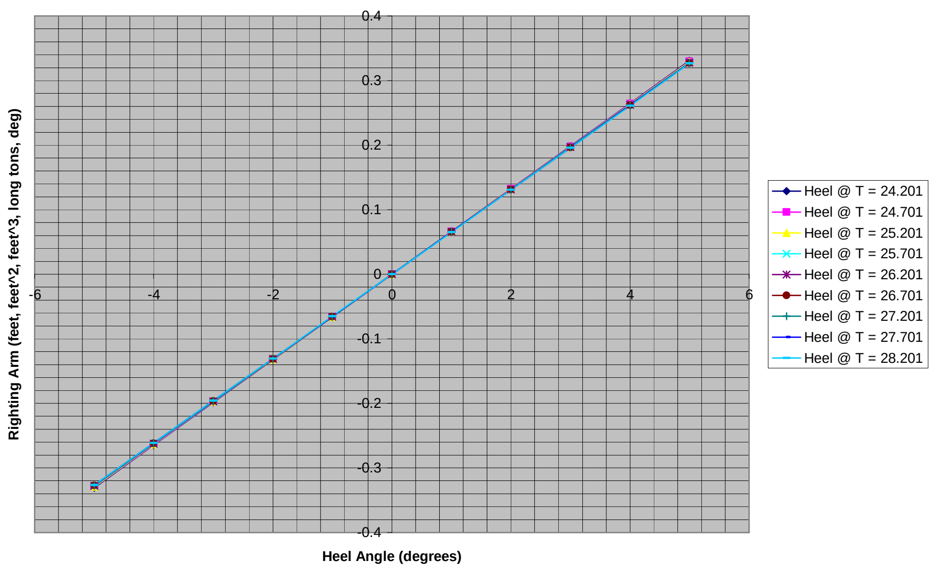
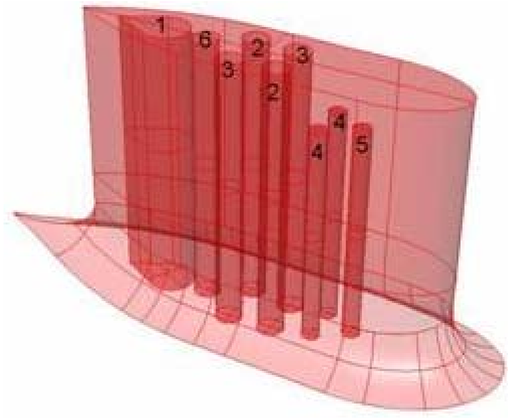


Figure 48 - Righting Arm Curves

4.3.8 Sail

Figure 49 shows the sail with internal components labeled. The cross-section is a NACA 0020 airfoil, with the leading edge 70 feet aft of the nose of the submarine. The distance from the foremost point to the aftermost point (the chord) is 22 feet. The height of the sail is 15 feet. Section 4.10.2 presents further details about the sizing of the sail.

The sail contains the snorkel, two photonics masts (AN/BVS-1), two AN/BRA-34 radars, two EHF/SHF HDR multibands, IEM, a AN/BPS-16 radar, and the Sea Sentry UAV. These items were determined from Concept Exploration.



#	Item
1	Snorkel
2	EHF/SHF HDR Multiband
3	AN/BRA-34
4	AN/BVS-1 Photonics Mast
5	AN/BPS-16 Radar
6	IEM
Not Pictured	Sea Sentry (very small)

Figure 49 - SSG(X) Sail

4.4 Structural Design and Analysis

Structural analysis focuses on the pressure hull as it is the primary load bearer. The first phase involves determination of initial scantling values. Calculations are performed in ModelCenter using two MathCAD files – one for internal frames (Appendix G) and one for external frames (Appendix G) – to give values for the buoyancy factor, which is a measure of structural efficiency. Figure 50 shows the calculation of buoyancy factor for internal frames; Figure 51 shows the calculation of buoyancy factor for external frames.

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

Figure 50 - Buoyancy Factor for Internal Frames

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

Figure 51- Buoyancy Factor for External Frames

The ModelCenter file (see Figure 52) is composed of seven modules:

- Input: Provides common values of shell plating, flange and web thicknesses, flange width, and web height.
- Mod1, Mod2, Mod3, Mod4: Calculate adequacy parameters and buoyancy factor for each module (see 4.4.1 for an explanation of module definition). These values differ between modules due to varying quantities for length between frames and length between bulkheads
- BFwgtavg: Calculates an average buoyancy factor for the entire pressure hull weighted by the length of the module.
- Optimizer: Minimizes structural weight by minimizing the weighted average buoyancy factor while maintaining sufficient adequacy parameters in each module. The values of web height, flange width, web thickness, and flange thickness are varied in order to optimize the structure. Figure 53 shows the dialog box in which options for the optimization are set.

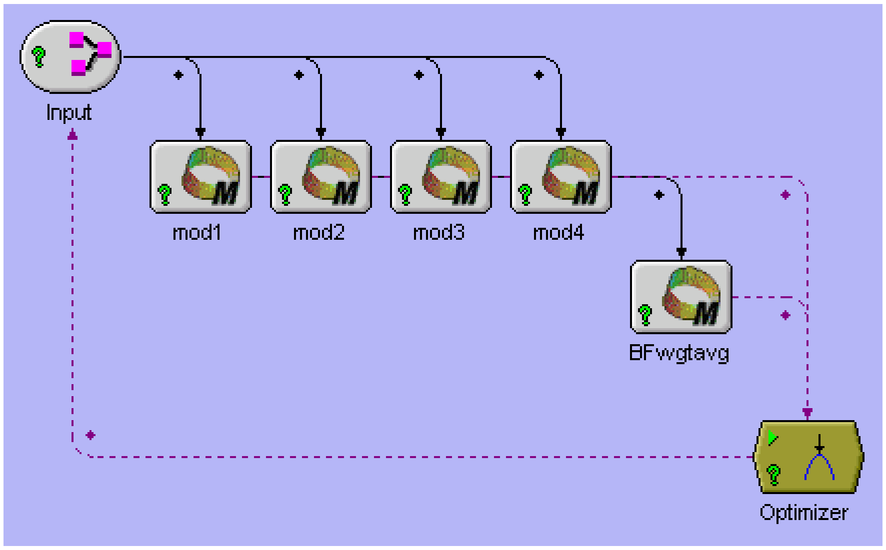


Figure 52 - ModelCenter File

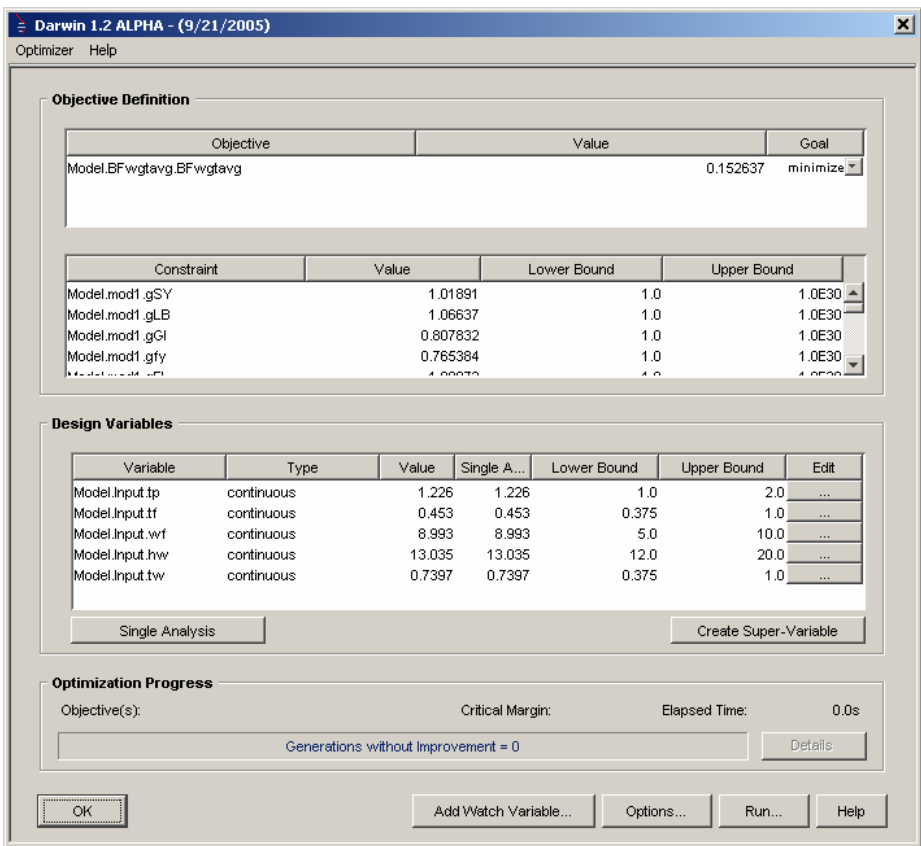


Figure 53 - Optimization Dialog Box

The second phase of the analysis involves modeling the structure in the finite element program MAESTRO. The MAESTRO model (see Figure 54) is constructed according to the geometry described in 4.4.1 using the initial scantlings provided by the MathCAD calculations. Since the bulkheads and end caps are not the focus of this level of analysis, the bulkheads are modeled as king frames, and the end caps are modeled as bulkheads.

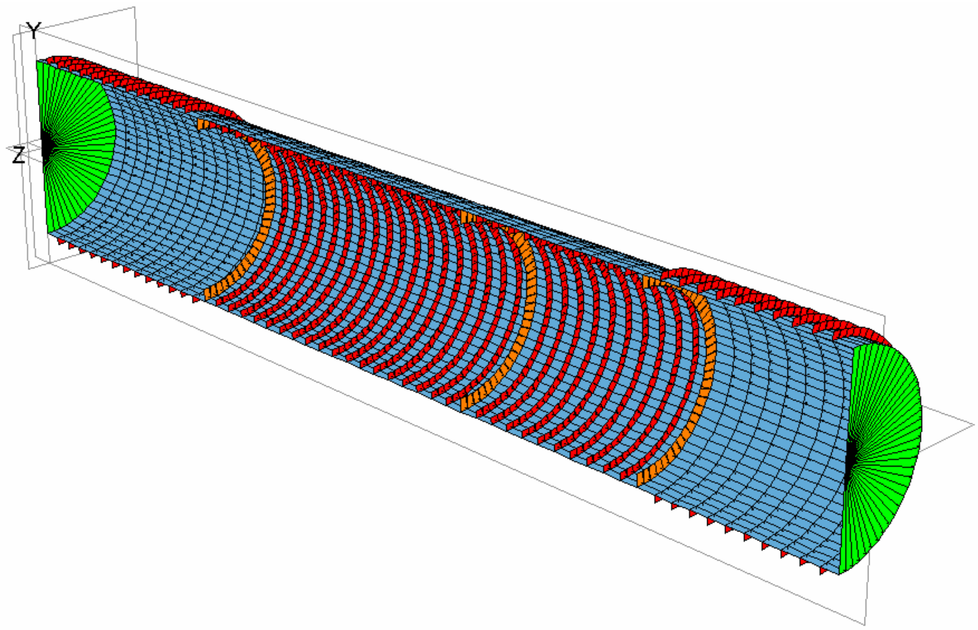


Figure 54 - Pressure Hull Model in MAESTRO

Once the geometry and composition of the structure is determined using the optimized results from ModelCenter, the loads are placed on the structure. The MAESTRO Solver analyzes the structure to determine adequacy. If inadequate structure is found, the structural model is modified by adjusting the plating thickness or frame scantlings. The iterative process of defining the structure, determining structural adequacy, and adjusting the scantlings is outlined in Figure 55.

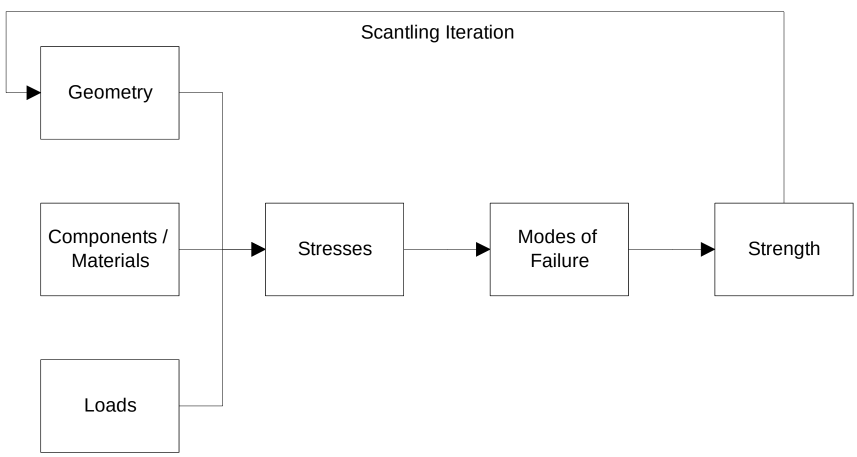


Figure 55 - Iterative Structural Design Process in MAESTRO

4.4.1 Geometry, Components and Materials

In the case of a non-nuclear submarine which has more outboard volume, external frames allow more arrangeable area within the pressure hull. These external frames can run through tanks which are enclosed by transverse outboard bulkheads; however, along the portion of the pressure hull which has outboard cylindrical hydride tanks, internal frames must be employed.

It is desirable to isolate portions of the submarine which contain potential flood or fire hazards. The machinery room is considered both a fire and flood hazard; therefore, a watertight bulkhead forward is placed forward of the machinery room. The torpedo room is also considered a potential flood hazard; therefore, a watertight bulkhead is placed aft of the torpedo room. A general structural rule for bulkhead placements suggests a bulkhead or king frame spacing of one to two diameters. Based on this rule, an additional king frame divides the distance between the two bulkheads.

Constraints provided by the arrangements fix the bulkhead and king frame locations. An aft section (38 ft. in length – Module 1) with external framing contains the machinery room; a watertight bulkhead separates this section from the next. Forward of this bulkhead are two sections (52 ft. and 30 ft. in length – Module 2 and 3, respectively) with internal framing which are separated by a king frame; a watertight bulkhead separates the third section from the forward most section. The forward most section (30 ft. in length – Module 4) with external framing contains the torpedo room. Figure 57 shows the modular divisions and frame locations.

A rule for ring frame spacing suggests one tenth to one fifth of the diameter between ring frames. One tenth of the diameter is 32.4 inches. Initial optimization runs indicated that this is an optimum frame spacing. In order to achieve equal frame spacing along the length of the module, the frame spacing was calculated and fixed for the MathCAD calculations and within MAESTRO.

HY-80 steel, which is the most common steel used in the construction of US Navy submarines, is used for the pressure hull shell plating and all framing. The framing consists of standard T-shapes.

4.4.2 Loads and Failure Modes

The primary load on the pressure hull is the pressure at maximum operating depth. The MathCAD calculations use the nominal pressure in order to consider the following failure modes: shell yielding (SY), lobar buckling (LB), general instability (GI), frame yielding (fy), and frame instability (FI).

MAESTRO assumes pressure is applied to plating on the side opposite of any frames attached to the plating. In order to correctly simulate pressure on the plating, artificial strakes with internal frames (with negligible scantlings) are placed at the same nodes as the actual strakes. Pressure is applied to the artificial strakes. As the nodes connected to the artificial strakes move in response to the pressure, the stress is transferred to the actual strakes via the displacement of the nodes. The axial compression caused by the pressure at the ends is simulated by placing equivalent point forces at the nodes on each end. MAESTRO considers the following failure modes: panel collapse membrane yield (PCMY), cylindrical local buckling (CCLocB), and cylindrical general buckling (CCGenB).

4.4.3 Safety Factors, Optimization Results, and Adequacy

The following safety factors are used in determining adequacy in the MathCAD calculations: shell yielding (1.5), lobar buckling (2.25), general instability (3.75), frame yielding (1.5), and frame instability (1.8). Optimization is performed over continuous values; a final optimization with producible values is used to determine final adequacy values. Figure 56 shows the value of the weighted average buoyancy factor during the optimization; eliminating infeasible designs yielded Run #7 as the most efficient set of scantlings. Table 42 lists final adequacy parameters (normalized around one) by module and mode before and after conversion to standard size scantlings. Table 43 lists final frame scantlings.

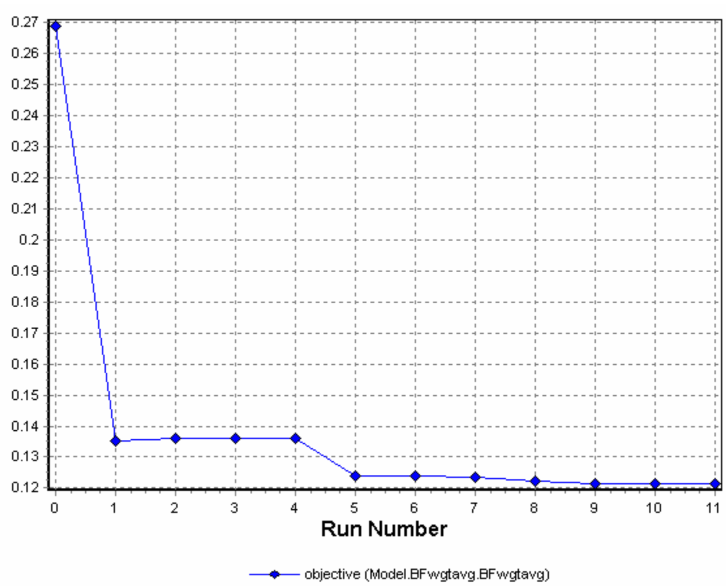


Figure 56 - MathCAD Optimization Results

Table 42 - Module Adequacy Parameters

Mode	Module 1	Module 2	Module 3	Module 4
Final Adequacy Parameters Before Standardization				
Shell Yielding	1.28853	1.29033	1.2896	1.2896
Lobar Buckling	1.83517	1.85542	1.84717	1.84717
General Instability	1.99523	2.45622	1.415	1.415
Frame Yielding	2.11642	21.1956	1.24424	1.15088
Frame Instability	1.53919	1.43055	1.42653	1.54506
Final Adequacy Parameters After Standardization				
Shell Yielding	1.285	1.287	1.286	1.286
Lobar Buckling	1.840	1.860	1.852	1.852
General Instability	1.969	2.420	1.391	1.39
Frame Yielding	2.035	11.717	1.234	1.139
Frame Instability	1.552	1.443	1.439	1.558

Table 43 - Optimized frame scantlings

Frame Type	Flange Thickness	Flange Width	Web Thickness	Web Height
Ring Frame	5/8 (0.625) in.	6.0 in.	9/16 (0.5625) in.	12.0 in.
King Frame	5/8 (0.625) in.	8.0 in.	5/8 (0.625) in.	24.0 in.

The following safety factors are used in determining adequacy in the MAESTRO model: PCMY (1.5), CCLocB (2.25), and CCGenB (3.75). The initial result using the scantlings selected using the MathCAD calculations is an inadequate structure (see
Table 44). Changes to the ring and king frame scantlings as well as frame spacing and shell thickness produce only minor changes to the adequacy parameters. In order to make the design feasible in MAESTRO, large changes have to be made which deviate from the results from the MathCAD calculations.

Table 44 - Initial MAESTRO Adequacy Parameters

Mode	Module 1	Module 2	Module 3	Module 4	Mean
CCGenB	-0.602	-0.582	-0.565	-0.596	-0.586
PCMY	0.035	0.039	0.039	0.035	0.037
CCLocB	-0.350	-0.351	-0.351	-0.351	-0.351

Because the MAESTRO results differ so greatly from the results from the MathCAD calculations and are only slightly affected by major changes in the hull geometry, the results from the MathCAD calculations are used until further work on developing a finite element model can be done. The scantlings listed in Table 43 are used to develop the structural profile in Figure 57. A midship section drawing is presented in Figure 58.

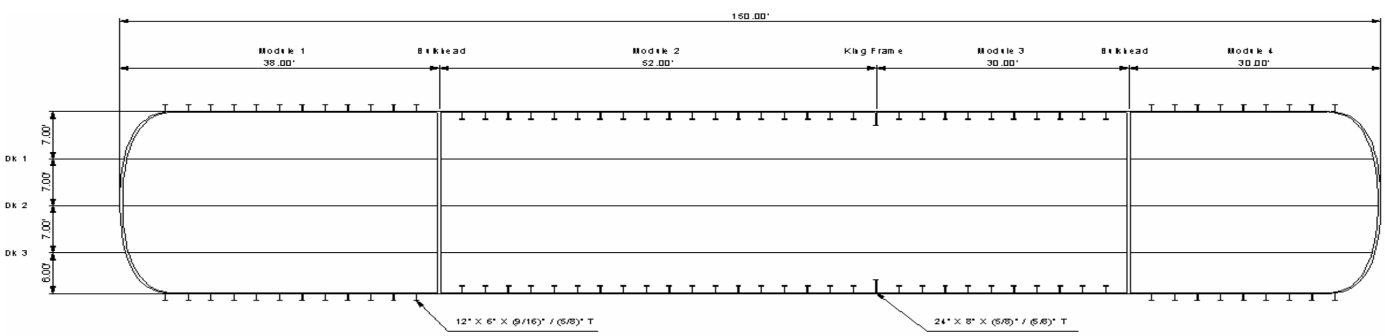


Figure 57 - Longitudinal Structural Profile

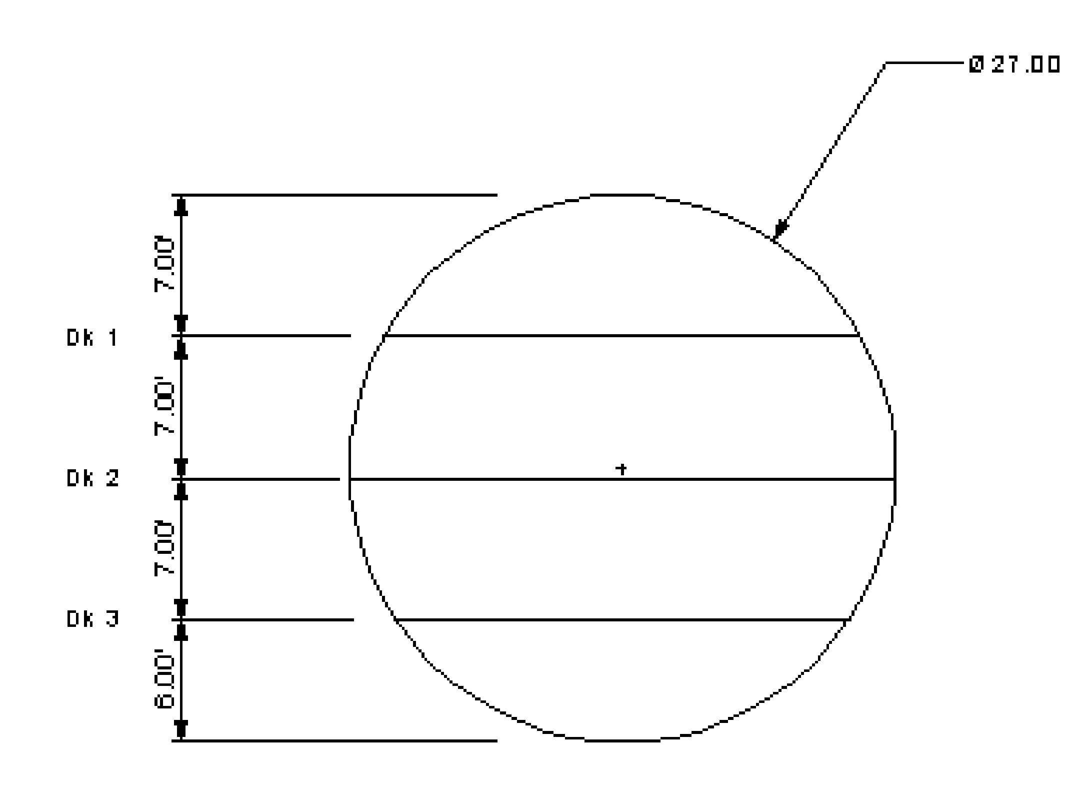


Figure 58 - Midship Section

4.5 Power and Propulsion

The SSG(X) propulsion system consists of two open-cycle CAT 3512 V12 diesel engines for use during snorkel, two 500 kW PEM fuel cells used during submerged operations, and 5820 kw-hr nickel-sodium Zebra batteries. The PEM fuel cells use hydrogen, stored in a solid hydride outboard of the pressure hull, and pure oxygen, stored in liquid form in the pressure hull. The SSG(X) houses an Integrated Power System (IPS) to divide power throughout the ship and power the RDP.

The process for determining the power and propulsion requirements begins with creating a hand calculation math model. The model calculates resistance, SHP requirements, and AIP, sprint, and snorkel endurances. The calculated values must satisfy the ORD requirements and should closely correlate to the values produced by the MOGO. After endurance calculations are determined to be consistent with the MOGO a prop optimization is run. The prop is initially optimized based on AIP, but adjusted to ensure no cavitation at other speed conditions. Prop characteristics are plugged into the math model and the endurances are checked with the ORD. Corrections must be made if the calculated endurances due not meet the ORD. .

4.5.1 Resistance and Effective Horsepower

Submerged bare hull resistance calculations are performed using a modified Gilmer and Johnson method and checked with the MIT Harry Jackson method. Figure 59 shows the VT method. The initial values used in this method correlate closely with those from the MOGO. The viscous resistance was found using a modified Gilmer and Johnson form factor and an ITTC coefficient of friction with uses a 30% correction factor for sails and appendages. The total bare hull resistance was found by adding a correlation factor. 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 60) for validation. The MIT method includes the sail directly and other appendages using a percentage. Figure 61 shows the bare hull resistance curves.

Resistance and Power

$iii := 21$

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

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

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 59 - 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_{frf}) yields:

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

Appendage drag (including sail) calculation:

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

For the remaining appendages, use the expression for $A_{other} * C_{dother}$ = $App := \frac{LOA \cdot D}{1000} \qquad App = 7.688\,ft^2$

$$EHPMIT_i := 0.5 \cdot \rho_{SW} \cdot (V_i)^3 \cdot \left[S \cdot \left(C_{F_i} \cdot C_{frf} + C_A\right) + \left[(A_s \cdot C_{Ds}) + App\right]\right] \qquad EHPMIT_1 = 66.26\,hp$$

Figure 60 - MIT Method Resistance Calculations

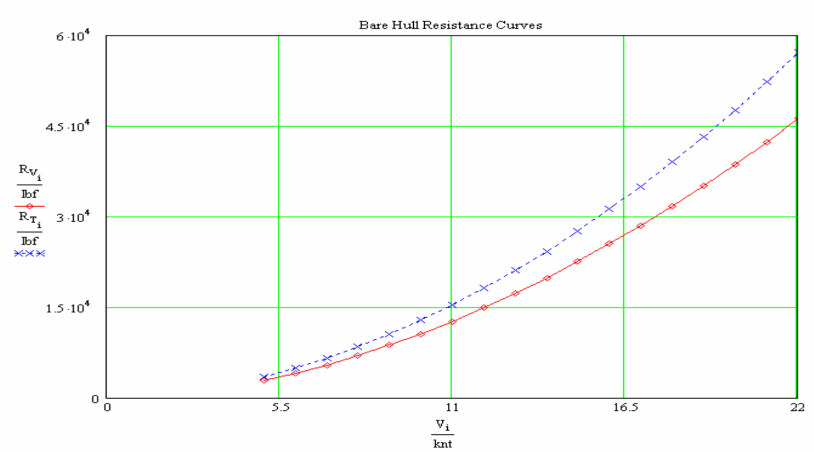


Figure 61 - Submerged Bare Hull Resistance versus Speed

Figure 62 shows a comparison of the VT and MIT methods for the EHP. There is good agreement between the methods. Figure 63 shows the ship's EHP curves.

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

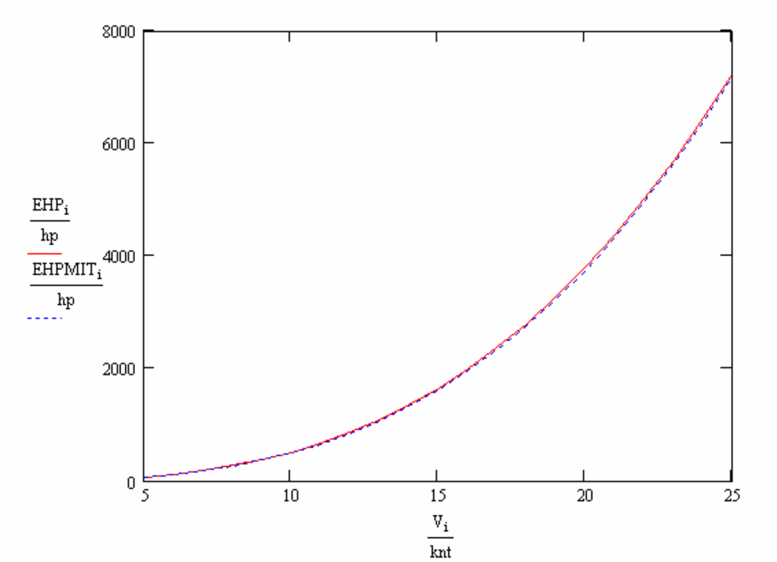


Figure 62 - Comparison of VT and MIT Methods

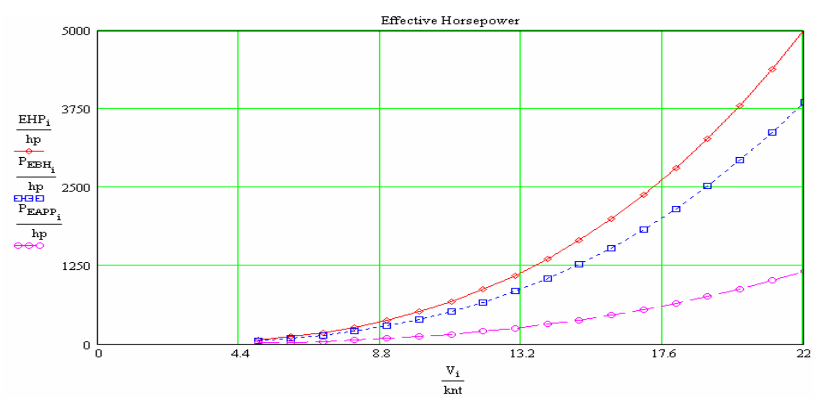


Figure 63 – Submerged Effective Horsepower versus Speed

4.5.2 Propeller Optimization

Additional calculations provided values for the wake fraction, thrust deduction factor and thrust. Figure 64 shows the calculations for these values. These values were necessary for optimization of the propeller.

$$C_{WS} := \frac{S}{\pi \cdot LOA \cdot D} \qquad C_{WS} = 0.819$$

$$w := 1 - .371 - 1.7151 \cdot \frac{\frac{D_P}{D}}{\sqrt{C_{WS} \cdot \frac{LOA}{D}}} \qquad w = 0.31$$

wake fraction

$$w := \text{if}(w > 0.2, 0.2, w) \qquad w = 0.2$$

$$t := 1 - .632 - 1.3766 \frac{\frac{D_P}{D}}{\sqrt{C_{WS} \cdot \frac{LOA}{D}}} \qquad t = 0.112$$

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

$$t := \text{if}(t < .17, .17, t) \qquad t = 0.17$$

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

speed of advance - average wake velocity seen by prop

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

$$\eta_H := \frac{1 - t}{1 - w} \qquad \eta_H = 1.037$$

hull efficiency

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

Figure 64 - Calculation of Wake Fraction, Thrust Deduction Factor and Thrust

Optimization of the propeller is performed using the Michigan POP (Propeller Optimization Program). The program is based off of the Wageningen B Series propeller curves. The propeller is optimized for AIP endurance and is then evaluated for snorkel and AIP sprint. If the propeller cavitates or is not feasible, it must be re-optimized. Table 45 shows the input values for the propeller analysis.

Table 45 - Input Values for Propeller Optimization

Description	Value
Thrust AIP endurance @ 5 knt	18.14 kN
Thrust AIP Sprint @ 22 knt	298.6 kN
Thrust Snorkel (submerged) @ 12 knt	94.71 kN
Propeller Diameter (Dp) (optimized)	4.5 m
Wake fraction (based on Prop Dia)	0.20
Depth of shaft centerline (SSGX submerged)	30 m
Depth of shaft center line (snorkel)	14 m
Number of blades	7
Burrill Percent of Back Cavitation	5%
Weight fuel AIP (Hydrogen)	621 lton
Weight fuel Diesel	160 lton

For the optimization, initial estimates were made for the 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 ORD and that the propeller does not cavitate. The POP program uses Burrill's Simple Cavitation Diagram, shown in Figure 65; this is a plot of the mean thrust loading against the local cavitation number. To keep the signatures as small as possible, a strict 5% Burrill back cavitation criteria is used. If the propeller violates the cavitation criteria, the POP program gives a warning and changes must be made. The most effective change is a decrease of P/D.

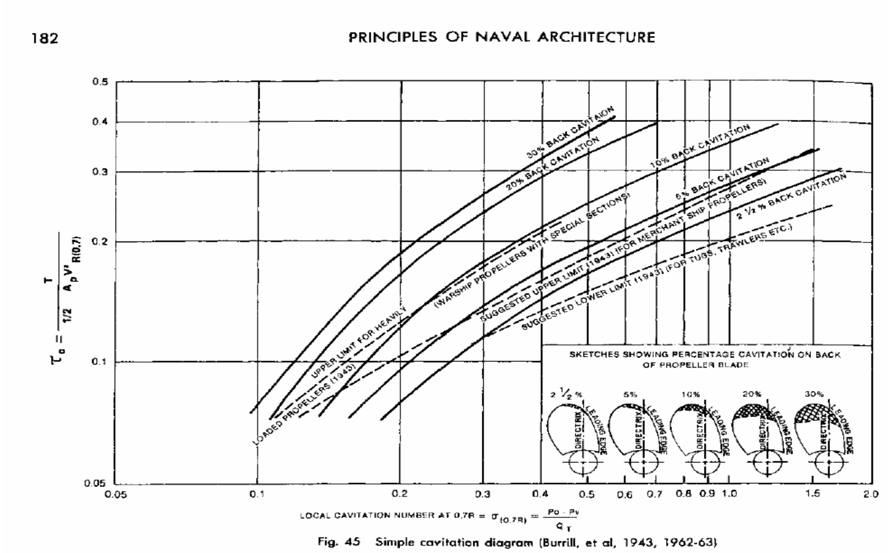


Figure 65 - Burrill's Simple Cavitation Diagram [Principles of Naval Architecture]

The iteration process is repeated until all ORD efficiencies are satisfied and the propeller does not cavitate during snorkel and sprint. The snorkel resistance calculation included a wave induced drag while snorkeling, which the original model did not include. Because of this the snorkel endurance did not satisfy the ORD requirement. To meet this requirement, 40 ltons of diesel fuel were added to the baseline design. Figure 66 and Figure 67 show the propeller curves for AIP endurance and AIP sprint respectively. Figure 68 shows the propeller curves for snorkel endurance.

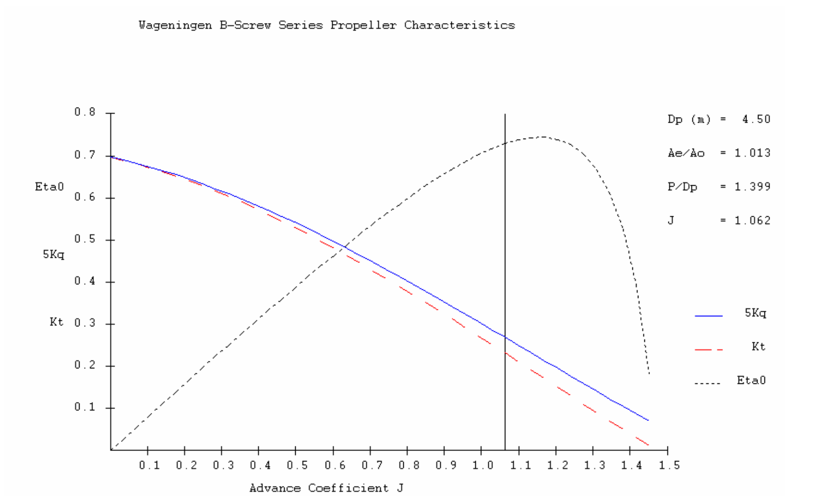


Figure 66 - Propeller Curves for AIP Endurance (5 knt)

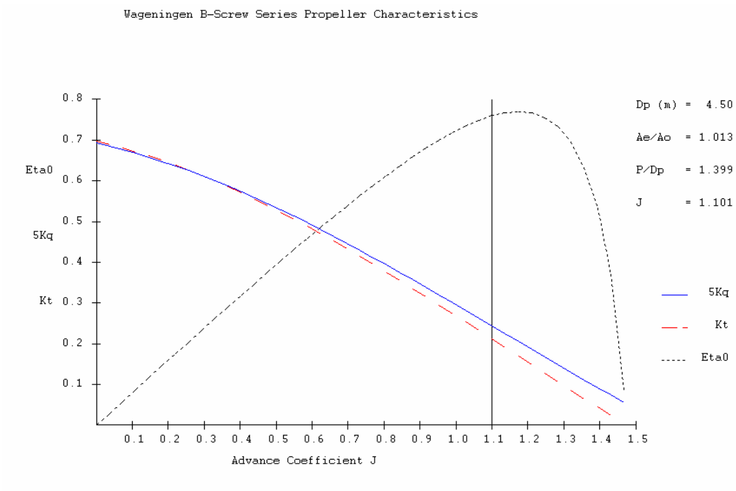


Figure 67 - Propeller Curves for AIP Sprint (22 knt)

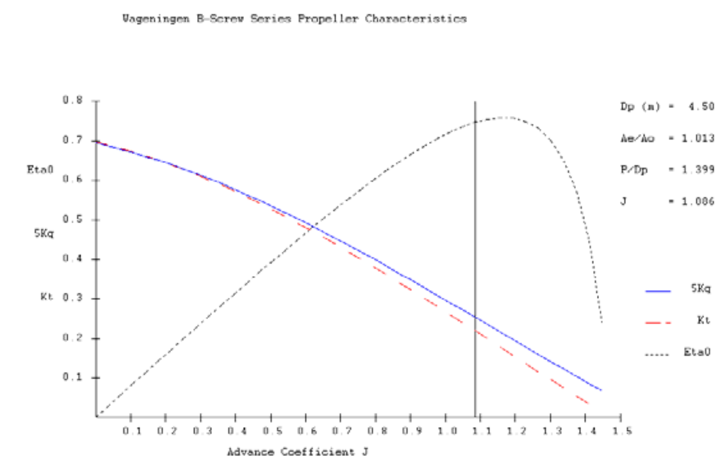


Figure 68 - Propeller Curves for Snorkel Endurance (12 knt)

The propeller characteristics after optimization are summarized in Table 46. The propeller is 7-bladed with a diameter of 4.5 m. Table 47 summarizes the propeller performance characteristics at AIP endurance, sprint and snorkel speeds.

Table 46 - Summary of Optimized Propeller Characteristics

Description	Optimization Result
P/D	1.40
Pitch (P)	6.30 m
EAR	1.01
# Blades	7
DP	4.5 m
Wake Fraction	0.20

Table 47 - Summary of Propeller Performance for Each Condition

Condition	η (Open Water Efficiency)	RPM
AIP Endurance	0.741	25.9
AIP Sprint	0.772	109.8
Snorkel	0.759	60.7

..

4.5.3 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 to ensure these values meet the ORD requirements. Table 48 summarizes the input values.

Table 48 - Summary of Input Values for Speed and Endurance Calculations

Condition	V (knt)	SFC (lbf/ ((hp*hr))	Weight Fuel (lton)	Battery Capacity (kW*hr)	PMF	η Electric	KW24Avg (kW)	SHP (kW)
AIP Endurance	5	5.74	621	5820	1.1	0.93	177.6	59
AIP Sprint	22	n/a (battery)	n/a (battery)	5820	1.25	0.93	177.6	4129
Snorkel	12	0.355	139	5820	1.1	0.93	177.6	1061

The Shaft Horsepower (SHP) and Brake Horsepower (BHP) are calculated for each condition to determine the endurance. Figure 69 shows the AIP endurance and sprint calculations respectively. It was only necessary to determine a submerged SHP for these conditions.

Endurance Range AIP:

$$P_{aipavg} := \frac{KW_{24AVG}}{\eta_{elec}} + BHP_{aipreq} \qquad P_{aipavg} = 268.074\,kW \qquad E_{faip} := Wfaip \cdot \frac{1.}{SFC_{aip}} \qquad E_{faip} = 1.807 \times 10^{5}\,kW \cdot hr$$

$$E_{aip} := \frac{E_{faip}}{\left(f_1 \cdot 1.05 \cdot P_{aipavg}\right)} \qquad E_{aip} = 25.722\,days$$

Yellow Values must be within ORD

Sprint Range :

$MaxFuncLoad := 738 \cdot kW$ From ELA Summary for Sprint Electric Loading

$$BHP_{reqsprint} := BHP_{req} + MaxFuncLoad \qquad BHP_{reqsprint} = 6.831 \times 10^{3}\,kW$$

$Sprint_{pow} := E_{battery} + 1000 \cdot kW \cdot hr$ Add a 1000 kW*hr produced by the Fuel cells during sprint

$$E_{sprint} := \frac{Sprint_{pow}}{BHP_{reqsprint}} \qquad E_{sprint} = 0.998\,hr$$

$$E_S := \left(E_{sprint}\right) \cdot V_{18} \qquad E_S = 22\,nm$$

Figure 69 - AIP Endurance and Sprint Calculations

The total SHP for the snorkel condition is the summation of the submerged SHP and the wave-induced SHP. To obtain an accurate wave induced coefficient of drag, a sixth degree polynomial is fitted to a drag curve provided by Captain Jackson's propulsion notes. The calculation of the endurance snorkel is given in Figure 70.

Snorkel Range:

$SHP_{snrkv} = 797.568 kW$

Froude # for Cdw Coef Calc:

$$Fn := \frac{V_{esnork}}{(g \cdot LOA)^{.5}} \qquad Fn = 0.227$$

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

$C_{DW} = 1.25$

$$C_W := \frac{C_{DW}}{4 \cdot \left[\left(\frac{LOA}{D}\right) - 1.3606\right]\left(\frac{LOA}{D}\right)^2} \qquad C_W = 7.355 \times 10^{-4}$$

Wave Induced:

$$SHP_W := C_W \cdot S \cdot \rho_{SW} \cdot V_{esnork}^3 \qquad SHP_W = 327.351 kW$$

SHP Snorkel:

$$SHP_{snrk} := SHP_{snrkv} + SHP_W \qquad SHP_{snrk} = 1125 kW$$

Endurance Snork Calculation:

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

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

$$P_{snkAVG} := \frac{SHP_{snrk} + KW_{24AVG}}{\eta_{elec}} \qquad P_{snkAVG} = 1878 hp$$

$$E_{snork} := \frac{(W_{fsnk} \cdot V_{esnork} \cdot TPA)}{P_{snkAVG} \cdot FR_{AVGsnk}} \qquad E_{snork} = 5612 nm$$

Figure 70 - Calculations for Snorkel

The snorkel range does not meet the ORD requirement. Including the wave-induced drag increased the power required by 300 kW. Forty long tons of fuel were added to satisfy the requirement. The last equation in Figure 70 shows the calculations performed after the fuel was added so that the range now meets the required value.

Table 49 shows a summary of the speed and endurance calculations. The range for each condition meets the ORD requirement.

Table 49 - Summary of Speed and Endurance Calculations

Condition	Thrust (kN)	Overall SHP (kW)	η_{Prop} Efficiency THP/DHP	η_{PC} (Propulsion Coefficient)	Range	ORD Requirement
AIP Endurance	18.14	58.6	0.716	0.882	25.7 days	26 days
AIP Sprint	298.6	4129	0.735	0.906	1 hr/ 22 nm	20 nm
Snorkel	94.71	1061	0.716	0.882	5610 nm	5280 nm

4.5.4 Propulsor Selection

The propulsor type in variant 44 is a Rim Driven Podded Propulsor (RDP). If feasible, a single RDP is more efficient and producible. A single RDP would also have a reduced signature. However, a double RDP configuration would have greater survivability from redundancy and may have advantages in maneuvering.

The maximum brakehorse power required with electric loads included for the SSG(X) is 6.5 MW at sprint. The information from Table 50 shows the feasibility of a single propulsor. [Blarcom, Hanhinen, and Mewis, SNAME, 2003]

Table 50 - RDP Capabilities

	ABB Azipod	EB's CRDP	SSG(X) Requirement
Nominal Power Rating	~20 MW	18.5 MW	6.5 MW
Continuous Torque Rating	~1340 kN-m (est)	1918 kN-m	1000 (est)
Length	11.40 m	3.90 m	3 m (est)
Hub Diameter	2.85 m	1.46 m	1.2 m (est)
Propeller Diameter	5.80 m	4.90 m (propeller) 5.85 m (duct)	4.5 m

Figure 71 shows the envelope hull with the single RDP. The propeller diameter is 14.75 ft and the shroud length is 12 feet.

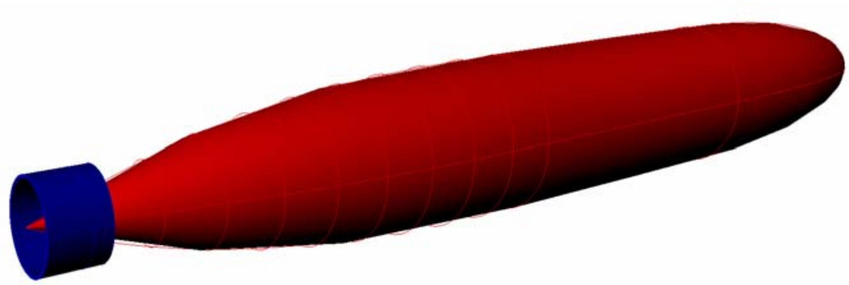


Figure 71 - SSG(X) Hull with RDP

4.5.5 Electric Load Analysis (ELA)

Table 52 shows a summary of the Electric Load Analysis (ELA). The electric load conditions analyzed are AIP, snorkel, and sprint. The ELA was created by making worksheets for each SWBS group and using data from the Machinery Equipment List shown in Table 51 (Full MEL shown in Appendix E) and combat systems to determine what equipment needed power and how much was required. Load factors were then applied for each condition. The summary table below comes from this information. Analysis of the power available from the generators available in each condition is shown in Table 52. For each condition, the electric power required is less than that available from the generators.

Table 51– Machinery Equipment List (MEL)

ITEM	QTY	DESCRIPTION	LOCATION	SWBS
		Propulsion and Electrical:		
1	2	PEM	MMR	235
2	2	CAT 3512 V12 Diesel Generator (AC)	MMR-dk 3	230
3	1	Main Machinery Control Console	MMR-dk 2	310
4	2	Main Batteries - Bank	Bat Compt	220
5	1	DC (400V) Main SWB	MMR-dk 2	320
6	1	Emergency SWB	AUX	320
7	2	Oxygen Tanks, cylindrical	MMR-dk 1	520
8	2	Power Conversion Modules (ACtoDC)	MMR-dk 3	310
9	1	Motor Control Center	MMR-dk 2	300
10	1	AC Synchronous Permanent Magnet Motor	Prop	300
11	2	Lighting Load Panel	AUX	300
12	2	Starting Air Cylinder	MMR-dk 3	250/260
13	1	Degaussing	Various	475
		Fuel Transfer and Storage:		
14	2	FO Purifier	MMR-dk 2	250/260
15	2	FO Transfer Pump	MMR-dk 2	250/260
		Lube Oil Transfer and Storage		
16	2	LO Purifier	MMR-dk 2	250/260
17	2	LO Transfer Pump	MMR-dk 2	250/260
18	2	Oily Waste Transfer Pump	MMR-dk 2	250/260
19	2	Oily Water Separator	MMR-dk 2	250/260
		Steering and Control		
20	1	Steering Hydraulics	aft	560
21	1	Aft Plane Hydraulics	aft	560
22	1	Sail Plane Hydraulics	Sail	560
		Air Systems:		
23	2	High Pressure Air Compressor	MMR-dk 2	550
24	2	High Pressure Air Dehydrator	MMR-dk 2	550
25	12	High Pressure Air Cylinders	MBT	550
26	2	Air Reducer Manifold	AUX	550
		Hydraulic Systems:		
27	2	Main Hydraulic Pump	AUX	550
28	2	Hydraulic Pressure Accumulator	AUX	550
29	1	Hydraulic vent and Supply Tank	AUX	550
		Fresh Water Systems:		
30	2	Potable Water Pump	AUX	530
31	2	Hot Water Circ Pump	AUX	530
32	2	Reverse Osmosis Distiller	AUX	530
33	2	Distiller Pump	AUX	530
		Salt Water Systems:		
34	2	Trim manifold	AUX	520
35	2	Trim pump	AUX	520
36	2	Drain and Bilge Pump	MMR-dk 3	500
37	2	Salt Water Circulating Pump	MMR-dk 3	250/260
38	2	Fire pump	MMR-dk 2	550
39	2	AFFF station	MMR-dk 2	550
40	2	Distiller Feed Pump	AUX	530
		Ventilation and Air purification:		
41	2	Main Induction Blower	Sail	500
42	2	Main Exhaust Fan	MMR-dk 2	500
43	2	Ventilation Fan	Air Pur Rm	510
44	2	CO2 Scrubber	Air Pur Rm	510
45	2	CO/H2 Burner	Air Pur Rm	510
		AC and Refrigeration		
46	2	AC Unit	AUX	510
47	2	Chilled Water Pump	AUX	530
48	2	Refrigeration Units	AUX	530
49	1	Chill/Freeze Box	Galley	500
		Environmental Systems		
50	1	Trash Disposal Unit (TDU)	Galley	593
51	2	Sewage Vacuum Sys	AUX	593
52	2	Waste Water Discharge Pump	AUX	593

Table 52 - SSG(X) Electric Load Analysis Summary

SWBS	Description	Connected (kW)	Average Load (kW)	AIP (kW)	Snorkel (kW)	Sprint (kW)		
100	**Deck**	**210**	**84**	**0.0**	**0.0**	**0.0**	EDMF=	1.05
200	**Propulsion**	**37.75**	**15.1**	**475.2**	**1447.1**	**5562.0**	EFMF=	1.05
220	Battery	2.5	1	200.0	100.0	0.0		
235	Electric Propulsion Drive	0	0	260.2	1332.0	5550.0		
250&260	Support	35.25	14.1	15.0	15.1	12.0		
300	**Electric**	**80**	**32**	**32.0**	**32.0**	**32.0**		
310	Power Generation	30	12	12.0	12.0	12.0		
330	Switch Board	10	4	4.0	4.0	4.0		
400	**Combat Systems**	**497.25**	**198.9**	**194.4**	**198.9**	**166.5**		
500	**Overall**	**579**	**231.6**	**223.6**	**218.2**	**216.2**		
500	Combat Systems	18	7.2	7.2	1.8	1.8		
500	Aux Machinery	87.5	35	33.0	33.0	33.0		
510	HVAC	170	68	68.0	68.0	68.0		
520	Seawater Systems	27.5	11	11.0	11.0	11.0		
530	Fresh Water Sys	62.5	25	25.0	25.0	25.0		
550	Air and Gas	146	58.4	52.4	52.4	52.4		
560	Ship Control	37.5	15	15.0	15.0	15.0		
593	Environmental	30	12	12.0	12.0	10.0		
700	**Payload**	**9.5**	**3.8**	**3.8**	**3.8**	**3.8**		
	Max Functional Load			929.0	1900.0	5980.5		
	MFL w/ Margins			975.5	1995.0	6279.5		
Number	**Generator**		**Rating (kW)**	**AIP**	**Snorkel**	**Sprint**		
2	Diesel Propulsion Generators		1000.0	0	2	0		
2	PEM		500.0	2	0	2		
1	Battery		5280.0	0	0	1		
	Power Available (kW)			1000.0	2000.0	6280.0		

4.6 Mechanical and Electrical Systems

Mechanical and electrical systems are selected based on mission requirements, standard naval requirements for combat ships, and expert opinion. The Machinery Equipment List (MEL) of major mechanical and electrical systems includes quantities, dimensions, weights, and locations. The complete MEL is provided in Appendix D. The major components of the mechanical and electrical systems and the methods used to size them are described in the following two subsections. The primary systems for a submarine are hydraulic, HP air, fresh water, salt water, ventilation, AC systems, and electrical power distribution. The arrangement of the system is detailed in Section 4.8.2.

4.6.1 Integrated Power System (IPS)

The SSG(X) use an IPS to distribute power throughout the ship and power the propulsor. This is represented by the One-Line Electrical Diagram (Figure 72). Diesel generators with power conversion modules (AC/DC) and PEM fuel cells connect directly to the main switchboard (SWB). The battery banks are also connected to the SWB. The system uses two DC/440V buses with multiple Power Conversion Modules (PCMs); the power generated by the diesel engines is converted to DC/440V power by PCMs 3A and 3B. The other PCMs (1A – 2B) convert the DC power to either 120 or 440 V 60 Hz AC power. The battery system is configured at 400V, 58200 kW-hr banks wired in parallel.

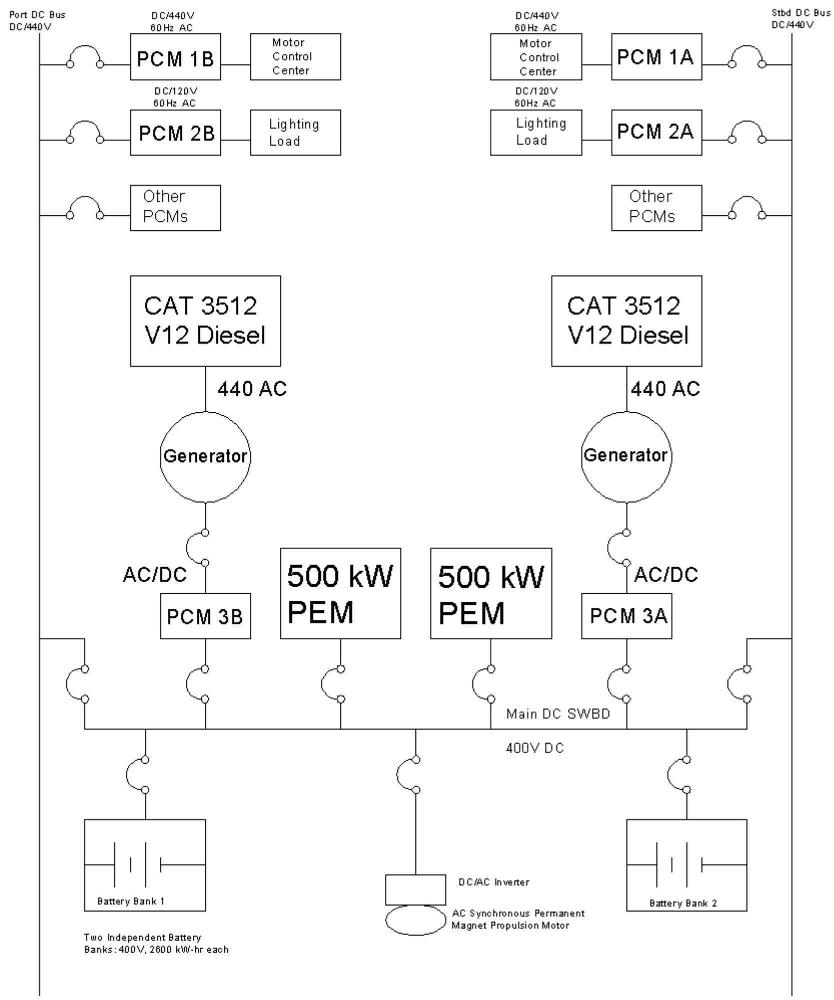


Figure 72 - SSG(X) One-Line Electrical Diagram

4.6.2 Service and Auxiliary Systems

The service and auxiliary systems were chosen to minimize cost and maintenance by emphasizing the use of Commercial-Off-The-Shelf (COTS) systems. COTS systems already in use by the Navy are most desirable. Risk and cost are minimized because these systems are already tested, proven and approved by the Navy.

Tanks for lube oil, fuel oil and waste oil are sized based on power and propulsion requirements. Equipment capacity and size are based on similar ships. A Reverse Osmosis Distiller (ROD) will produce potable water on SSG(X). These systems work by pushing heated seawater through a series of membranes that remove salt and other impurities. The resulting water is as pure as distilled water. Thermal management of all electrical equipment is an important consideration in the marine environment. Another important system is the air compressors providing pressurized air to fill the MBTs. SSG(X)'s MBT tanks are capable of blowing three times without having to be recharged. The main high pressure air tank and compressors fill smaller high pressure bottles located inside each MBT.

Environmental control equipment is located in the submarine fan room in the AMR. This includes an induction inlet which can be used to ventilate hull exhaust. This system also includes a CO2 scrubber and CO2/H2 burner.

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

4.6.3 Ship Service Electrical Distribution

The submarine's integrated power system (IPS) is used to power the propulsion system, provide ship service power, and charge the batteries. Power from the PEM fuel cell is sent to the main switchboard where it can then be distributed to any of the three areas previously described. Ship service power is first sent to the zonal buses where it is then distributed to the Power Conversion Modules (PCM) where it can be converted from DC to AC or AC to DC as needed. These PCMs provide circuit protection and automatic reconfiguration for their particular area. Power from the CAT 3512 diesel engines is converted from AC to DC in the same manor. SSG(X) will only use the CAT 3512 power while under snorkel for transiting, ship services and charging batteries as necessary.

4.7 Manning

The specific mission and smaller size of SSG(X) will require manning to have some special considerations. Through expert opinion, the number of officers was set at 8. In concept exploration, the number of enlisted personnel was calculated to be 21 with a manning automation and reduction factor of 0.54. Manning automation is focused in on areas where technology or automation can simplify a process. Motor, pump, and generator improvements over the past several years have allowed for these systems to have less maintenance and be more reliable. Damage Control (DC) requires a large number of personnel to perform the various tasks. An on-going DC Arms program is underway to reduce the required DC personnel to half. The focus is on advance detection, smart valves, zonal water and smoke control, and an intelligent Supervisory Control System (SCS).

The SSG(X) manning breakdown was created using the SSN21 manning as a guide. The total crew for the SSG(X) is 29, with 21 enlisted men and 8 officers. Manning is split into the following departments:

- Engineering
- Combat Systems
- Executive
- Navigation/Operations
- Supply

These departments were further broken down into divisions as described in Table 53 which lists the department, division, and the enlisted rate for the manning breakdown. MM is the rating for a Machinist Mate; EM is the rating for the Electrician's Mate; ET is the rating for Electronics Technician; YN, PN is the rating for Yeoman Personal Man; STS is the rating for Sonar Technician Submarine; SK is the rating for Storekeeper.

Table 53 - Manning Departments, Divisions, and Rates

Department	Division	Rate
Engineering	AUX	MM
Engineering	MM	MM
Engineering	E	EM
Combat Systems	Weps	MM
Combat Systems	ST	STS
Executive	Exec	YN, PN
Navigation/Operations	COM	ET
Navigation/Operations	NAV	ET
Supply	S	SK

Table 54 lists the manning summary for the SSG(X). Figure 73 shows the manning hierarchy.

Table 54 - SSG(X) Manning Summary

SSGX Manning

Enlisted = 21

Department	Division	Rate	E1-E3 (non-rate)	E4-E6 (Petty Officers)	E7-E8 (Chiefs)
Engineering	AUX	MM	1	1	0
	MM	MM	1	1	1
	E	EM	0	2	1
Combat Systems	Weps	MM	1	2	1
	ST	STS	0	2	0
Executive	Exec	YN,PN	0	0	1
Navigation/Operations	COM	ET	1	1	0
	Nav	ET	0	1	1
Supply	S	SK	1	1	0

Officers = 8

Department	Division	01-02 (Jr. Officers)	03-04 (Officers)	05-06 (Command)
Engineering	AUX	0	1	0
	MM	0	1	0
	E	0	0	0
Combat Systems	Weps	0	1	0
	ST	0	0	0
Executive	Exec	0	0	2
Navigation/Opperations	COM	1	0	0
	Nav	0	1	0
Supply	S	1	0	0

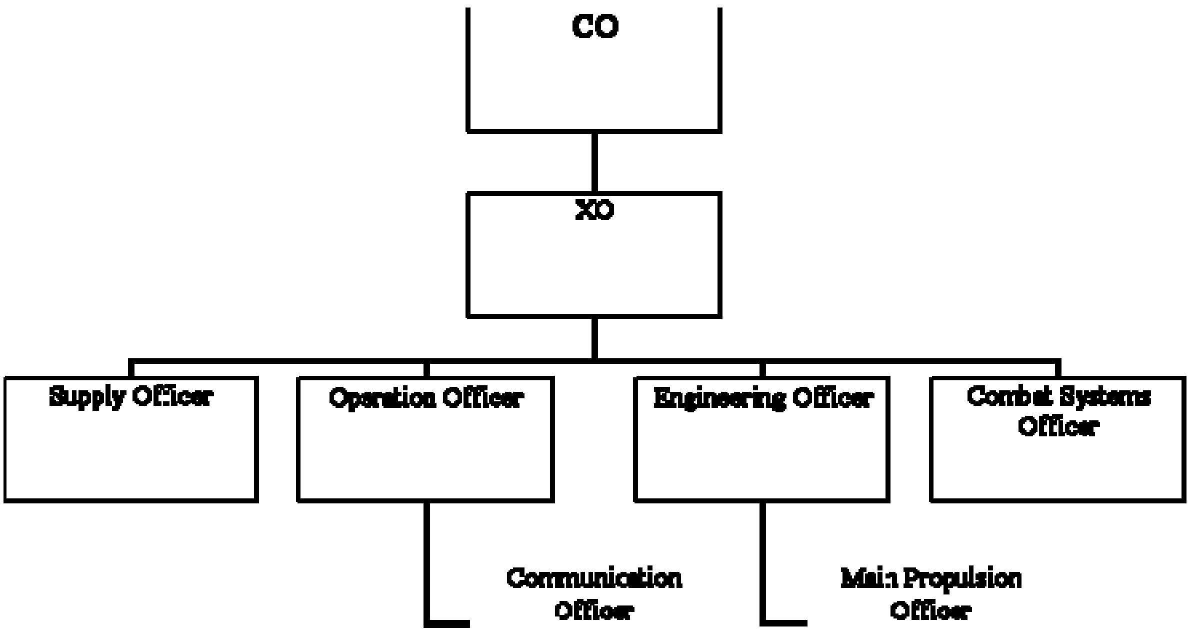


Figure 73 - SSG(X) Manning Hierarchy

4.8 Space and Arrangements

Rhino is used to generate and assess subdivision and arrangements. A profile showing the internal arrangements is shown in Figure 74.

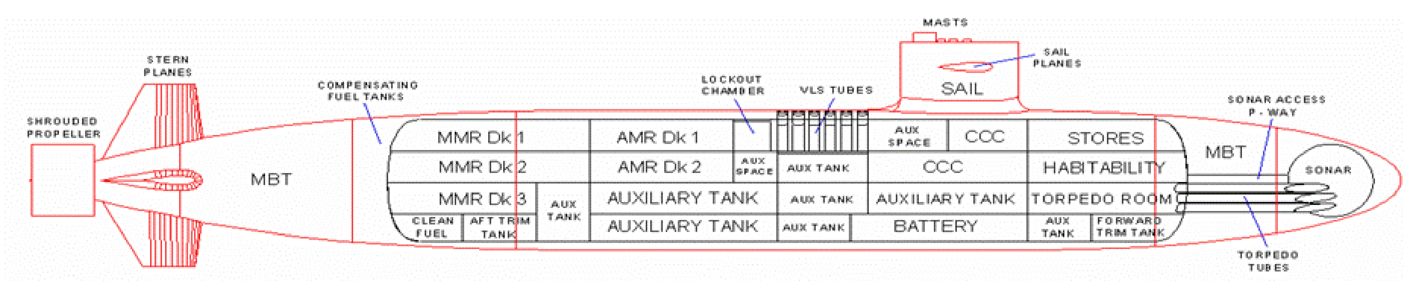


Figure 74 - Profile View Showing Arrangements

4.8.1 Volume

Initial space requirements and availability in the ship are determined in the ship synthesis model. Arrangeable area estimates and requirements are refined in concept development arrangements and discussed in Sections 4.8.2 through 4.8.4. Table 55 compares required versus actual tankage volume.

Table 55 – Required vs. Available Liquid Tankage Volume

Variable	Required (ft^3)	Final Concept Design (ft^3)
Lube Oil	42	42
Potable Water	160	160
Sewage	58	58
Clean Ballast	25156	26092
Diesel Fuel (Compensated)	5095	7948
Diesel Fuel (Clean)	1075	1086
Liquid Oxygen Tank	2839	2787

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

The pressure hull diameter is 4 ft smaller than the outer hull to provide space for piping and other outboared systems. The auxiliary tanks, main machinery room, auxiliary machinery room, trim tanks, clean fuel tank, battery, CCC, habitability, stores, and torpedo room are located in the pressure hull. The remaining space enclosed by the outer hull contains the main ballast tanks, compensating fuel tank, hydrogen tank, torpedo tubes, and the sonar dome.

4.8.2 Main and Auxiliary Machinery Spaces and Machinery Arrangement

Figure 75 shows the Main Machinery Room (MMR) and Auxiliary Machinery Room (AMR) located in the aft section of the pressure hull. The MMR spans the entire beam and 37 feet forward to aft on the first through the third deck. The AMR, just forward of the MMR, is comprised of the entire beam and 27 feet forward to aft on the second and third decks. A watertight bulkhead separates the two machinery spaces. For both the MMR and AMR each deck is accessible by a ladder system.

Figure 75 - Profile view of MMR and AMR.

The initial step in arranging the MMR and AMR is to create a machinery equipment list (MEL). The MEL is composed of the major propulsion, electrical, and auxiliary equipments with the corresponding weights and sizes. The primary systems of the SSG(X) submarine included in the MEL are the hydraulics, high pressure air, water distribution, electrical power distribution, and ventilation and air conditioning systems.

After the MEL is completed the electric load diagram is used to place and connect the PEM fuel cells and diesel engines with the submarines systems. Once this basic layout is established, secondary equipment such as pumps, small tanks, and distribution panels are arranged in the machinery spaces. Figure 76 show that the LOX oxygen tanks and a PEM fuel cell located on the first deck of the MMR.

Figure 76 - MMR Deck one equipment layout

Figure 77 shows the equipment layout on the second deck of the MMR. The machinery equipments located on this deck include a PEM fuel cell, high pressure compressor and dehydrator, inlet and exhaust for the CAT 3512 diesel engines, and main machinery control console.

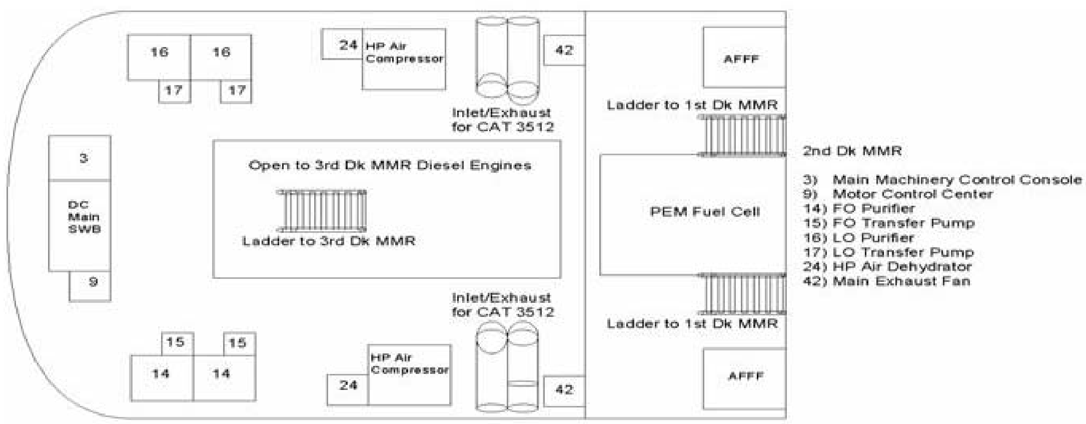


Figure 77 - MMR Deck two equipment layout

Figure 78 shows the equipment layout on deck three of the MMR. The machinery equipment located on this deck includes the CAT 3512 V12 diesel engines, power conversion module, air standard cylinder, oil water separator, generators, and pumps.

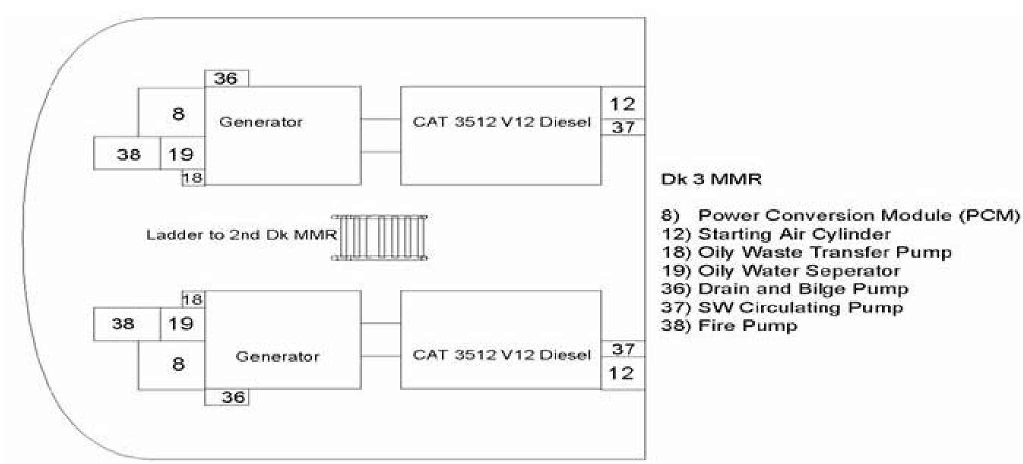


Figure 78 - MMR deck three equipment layout

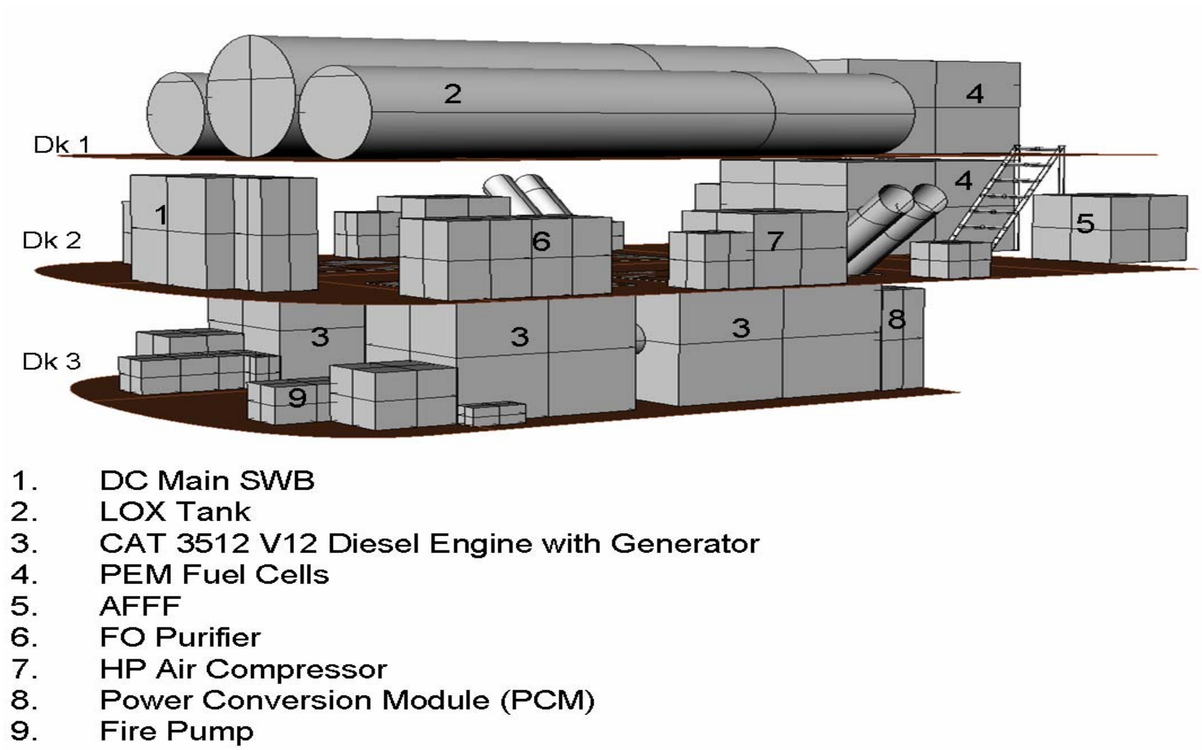


Figure 79 - MMR 3D model of arrangements

Figure 80 shows the equipment layout on deck one of the AMR. The machinery equipment located on this deck includes manifolds, pumps, hydraulic pressure accumulator, supply tanks, air conditioning units, and refrigeration units.

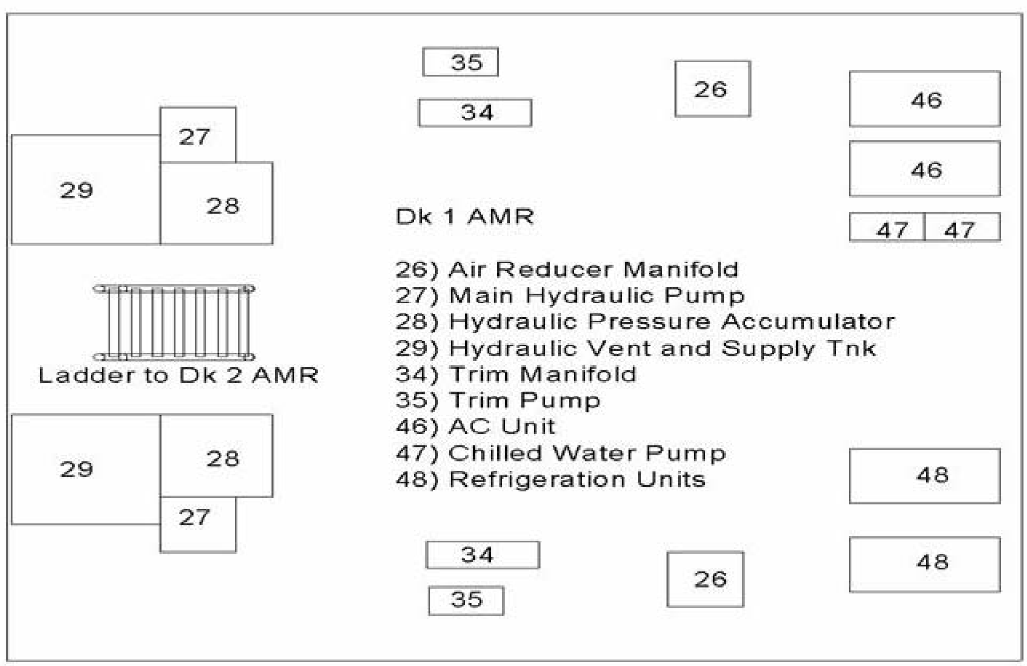


Figure 80 - AMR deck one layout

Figure 81 shows the equipment layout on deck two of the AMR. The machinery equipment included on this deck includes pumps, a distiller, ventilation fan, scrubber, burner, and waste management systems. Three separate rooms help separate the systems associated with waste discharge, air purification, or fresh water purifiers.

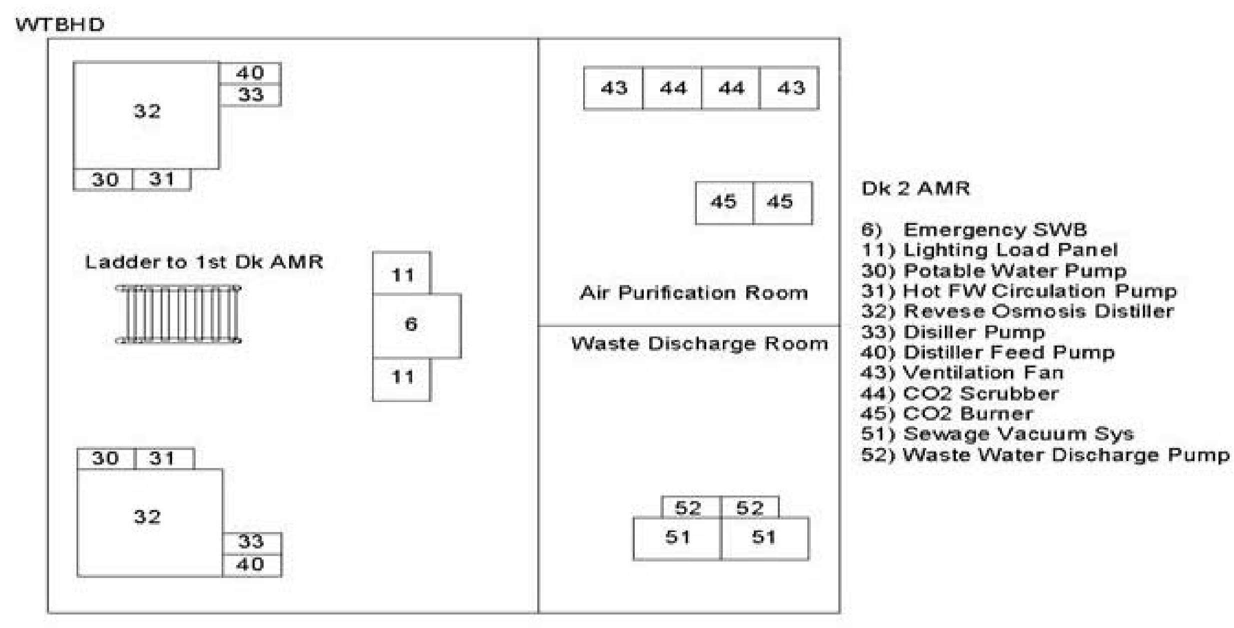


Figure 81 - AMR deck two layout

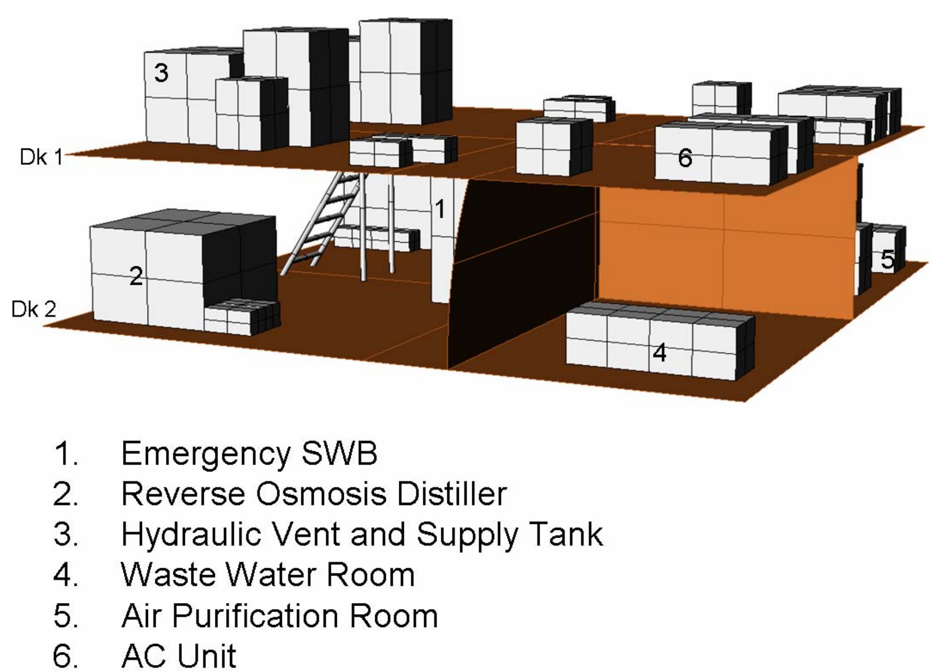


Figure 82 - AMR 3D model of arrangements

4.8.3 Internal Arrangements

The pressure hull is divided into three decks and a bilge space. The decks and bilge space are subdivided to accommodate six separate areas. The six areas are combat systems, habitability, stores, mission, machinery, and ballast. Required area and volume for these spaces was determined from regression equations and similar arrangements. Additional area and volume requirements were determined from the weight and volume balance and the equilibrium polygon. As stated before, the initial longitudinal arrangement was determined from the cartoon and flounder diagram. Figure 83 shows the internal arrangement for the SSG(X) submarine.

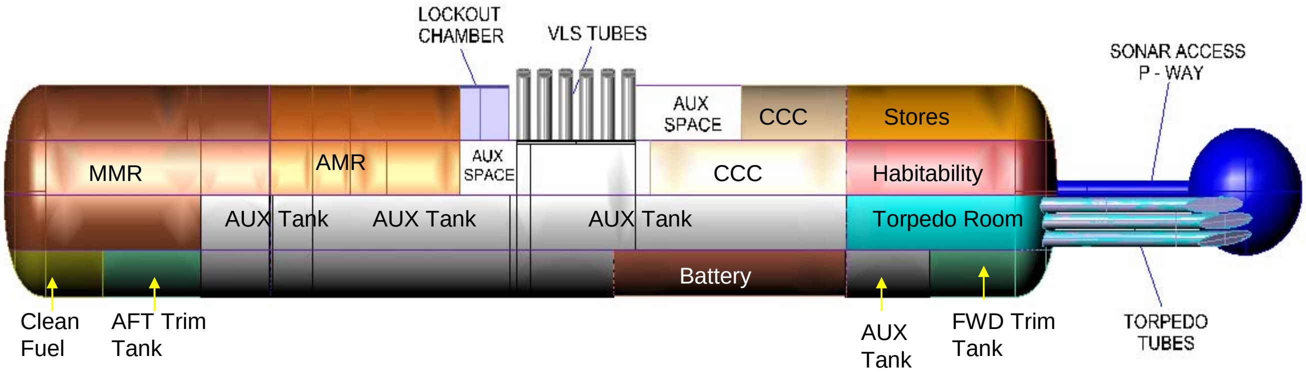


Figure 83 - Profile view of arrangement

Table 56 - Individual Tanks and Volumes

Tank Number	Tank	Capacity (ft^3)
1	Forward Main Ballast Tank	9925
2	Forward Trim Tank	1472
3	Auxiliary Tank 1 – Starboard	571.5
4	Auxiliary Tank 1 – Port	571.5
5	Auxiliary Tank 2 – Starboard	2670.5
6	Auxiliary Tank 2 – Port	2670.5
7	Auxiliary Tank 3 – Starboard	2267
8	Auxiliary Tank 3 – Port	2267
9	Auxiliary Tank 4 – Starboard	4778.5
10	Auxiliary Tank 4 – Port	4778.5
11	Auxiliary Tank 5 – Starboard	1359
12	Auxiliary Tank 5 – Port	1359
13	Aft Trim Tank	1326
14	Compensating Fuel Tank	7950
15	Aft Main Ballast Tank	10685
16	Hydrogen Fuel Tank	5654

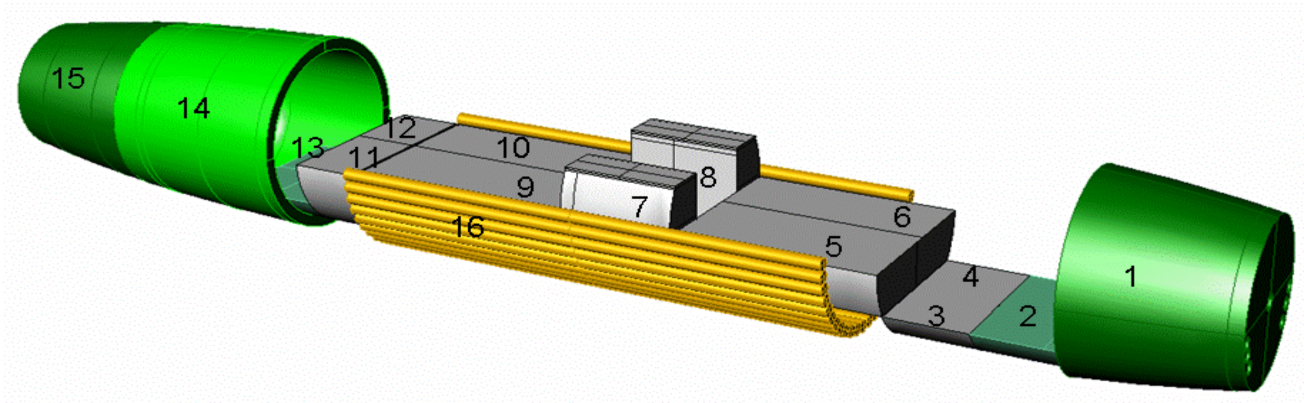


Figure 84 - Individual Tanks

4.8.4 Living Arrangements

Initial living space requirements are determined in the ship synthesis model. The model estimated the required areas and volumes for the commanding officer, officers, and crew berthing and messing spaces. Further living space requirements are determined from the Naval Sea Systems Command's Ship Board Habitability Design Criteria Manual. Figure 85 shows the location and subdivision of the habitability space. It is located on the second deck in close proximity to the command, control, and communication space, and other mission spaces to allow for easy access. The habitability space subdivisions are arranged such that the officers staterooms are separated from the enlisted by a primary passage way. There is one galley serving both the officers and enlisted personnel. The galley is located between the enlisted mess and the wardroom to allow for easy service. In addition to the chill freezer box and dry stores located in the gallery, a storage space is located on the first deck above the habitability space.

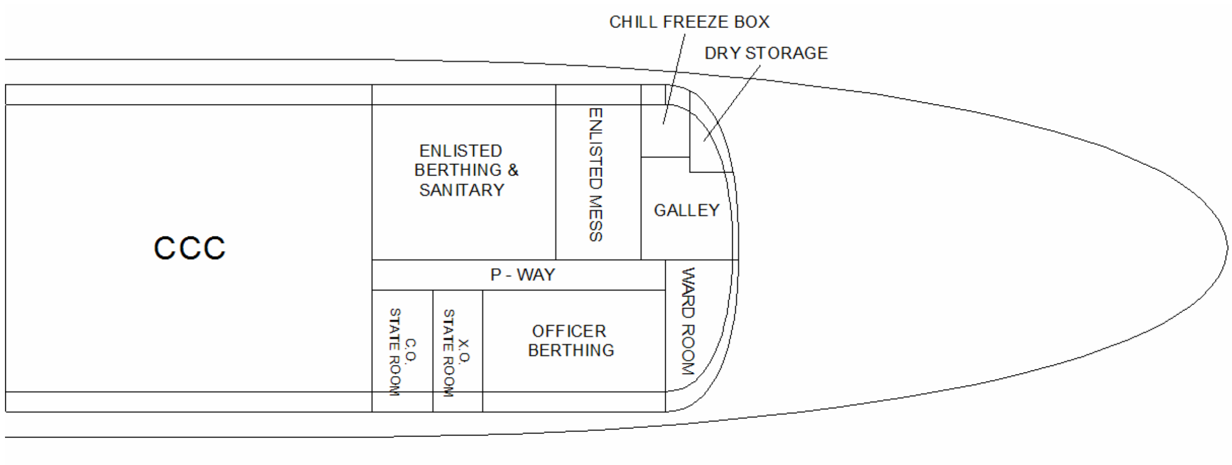


Figure 85 - Location and subdivision of habitability space

Figure 86 shows the layout of a double accommodation officer stateroom. The requirements used to develop this layout are obtained from the Ship Board Habitability Design Criteria Manual. The first step in developing this layout is determining the required outfitting and furnishings requirements and their corresponding sizes. This includes berth, wardrobe, book shelf, locker/drawer, and sanitary spaces.

Figure 86 - Figure 88 show a 2D and 3D model of the stateroom and enlisted berthing layout and the required outfitting and furnishings. The two tier officer berth provides space for a 36 inch wide by 76 inch long mattress and each wardrobe is 24 in. wide by 24 in. long and 72 in. tall and provides a tall and short hanging space and drawer space. The bookcase has two tiers and each tier is 13 in. deep by 13 in. tall and 20 in. long. A foldable table 20 in. deep by 24 in. wide and a chair is also included in the layout. The sanitary space in the state room includes a wash closet, mirror, toilet, and a 42 in. by 32 in. shower.

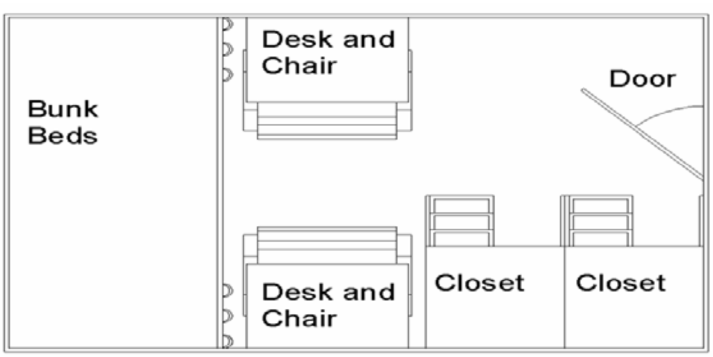


Figure 86 - Officer Stateroom layout

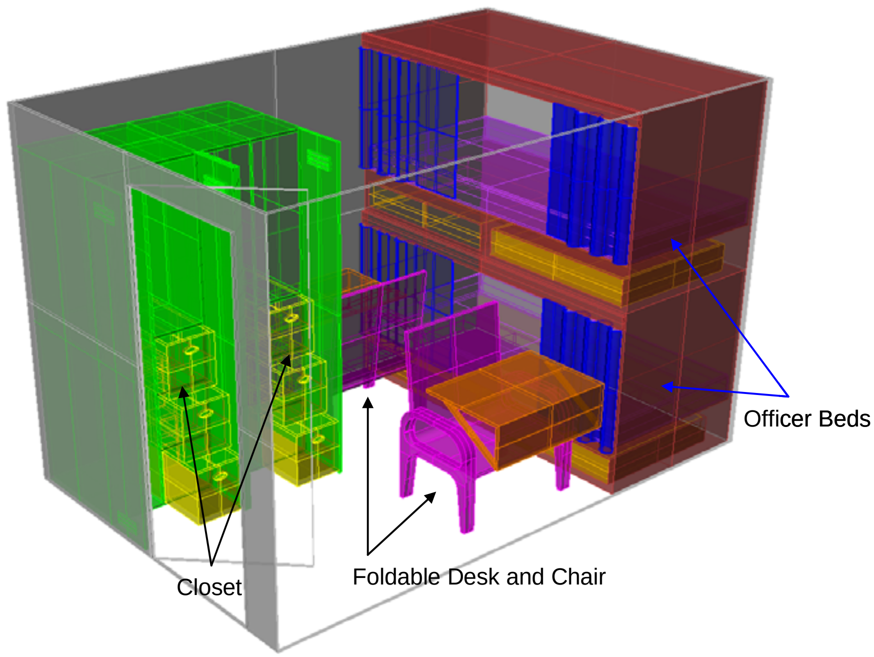


Figure 87 - 3D Rhino model w/o bulkheads - Outfitting and furnishings for officer stateroom

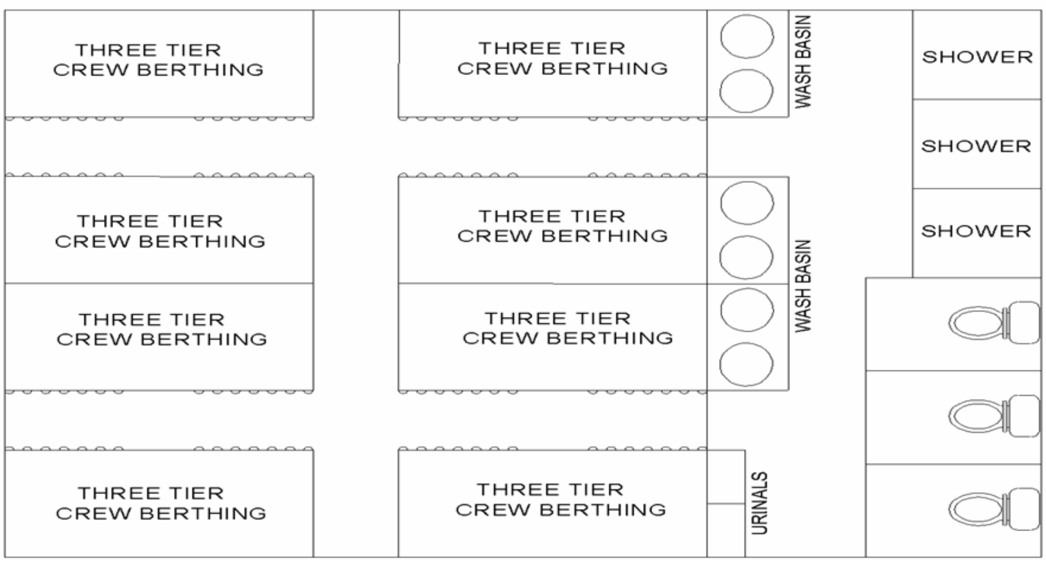


Figure 88 - Enlisted Berthing

Table 57 lists the areas and volumes of the subdivision in the habitability space. The areas and volumes are calculated based on the deck area and the head room clearance of the habitability space.

Table 57 - Accommodation Space

Item	Area (Deck)	Volume
C. O. Stateroom	50 ft^2	320.8 ft^3
X. O. Stateroom	40 ft^2	256.5 ft^3
Officer berthing and ward room	187.4 ft^2	1224.3 ft^3
Enlisted berthing, Sanitary, and mess	282.3 ft^2	2104.6 ft^3
Galley	63 ft^2	441 ft^3
Chill freezer box	24 ft^2	144.7 ft^3
Dry stores	11.9 ft^2	83.5 ft^3
P – way	60 ft^2	420 ft^3

4.8.5 Final External Arrangements

The locations of the vertical launch system (VLS) and hydrogen storage tanks are the two important criteria in developing the external arrangements see section 4.3. Figure 89 and Figure 90 show the location of the combat and mission systems. The combat system is comprised of the VLS located at amidships, torpedo and sonar systems located in the bow, and the sail and masts located forward of the VLS. The command, control, and communications space is located directly below the sail in the pressure hull. The ballast tanks, hydrogen fuel tanks, compensating fuel tank, shrouded propeller, sail and stern plans are also shown in Figure 89 and Figure 90.

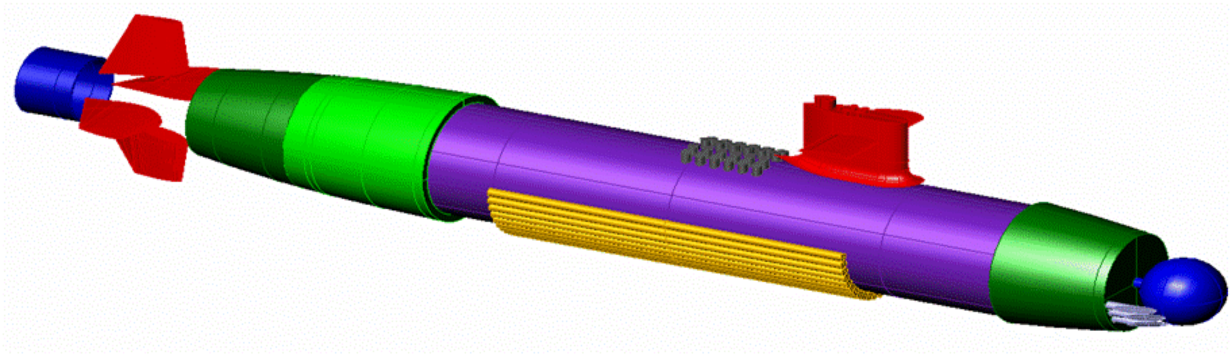


Figure 89 - External Arrangements

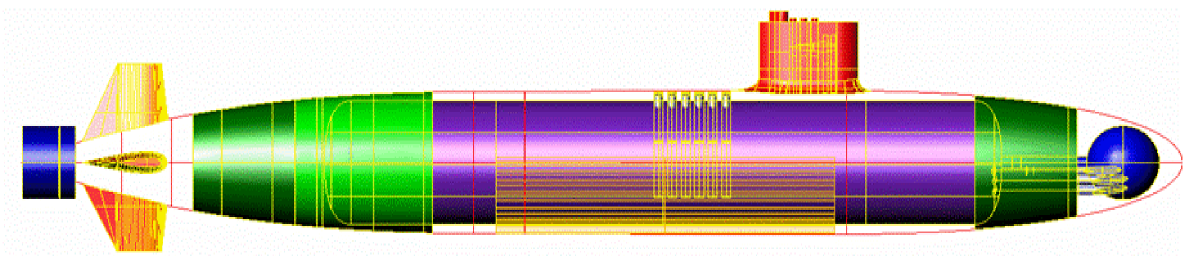


Figure 90 - External Arrangements - Profile View

4.9 Final Weights, Loading and Equilibrium

4.9.1 Summary of Concept Development Equilibrium Changes

The first step in balancing SSG(X) was to calculate its longitudinal center of buoyancy (LCB). To do this, the LCBs of each displacing volume were compiled into an Excel spreadsheet. The LCBs were estimated using the ship's arrangements drawings. The LCB and TCB of the ship were determined by summing the LCBs of the displacing volumes. The next step in balancing SSG(X) was to calculate its longitudinal center of gravity (LCG). Ship weights are grouped by SWBS. The components list was obtained from the Model Center optimization. The weight for each component was compiled into the spreadsheet. In addition to the weights, their centers of gravity (vertical and longitudinal) were entered. These centers of gravity were estimated using the ship's arrangements drawings. The weights and centers of gravity (CGs) were used to find the lightship load and the LCG of SSG(X). To make sure that SSG(X) was balanced, the LCG needed to be as close to the LCB as possible. In order to facilitate this need, the CG of every component was taken with reference to the LCB of the submarine. The variable ballast tank volumes and CGs were then added to the spreadsheet. The variable ballast tanks were used to create the boundary of the equilibrium polygon. The equilibrium polygon serves as the boundary of the operational envelope for ballast and trim for SSG(X). The submarine design is feasible if all of its loading conditions lie within the equilibrium polygon. The arrangements drawings, weights spreadsheet, and the variable loads are used in creating the extreme loading conditions in the different water densities that the submarine will encounter. The loading conditions used are the Normal Condition, Light #1, Heavy #1, Heavy #2 (mines), Heavy Forward #1, Heavy Forward #2, and Heavy Aft. Table 39 illustrates each of the loading conditions and the water density used for each loading condition. Figure 91 shows the initial equilibrium polygon with the initial loading conditions.

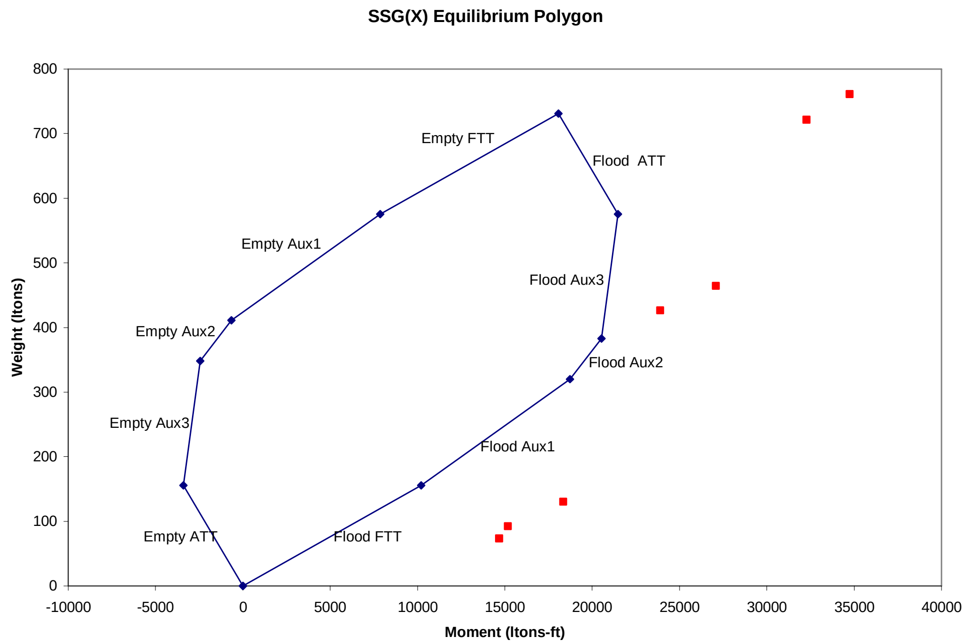


Figure 91 - Initial Equilibrium Polygon with Loading Conditions

Once the loading conditions were positioned on the plot with the polygon, the next task was to get all of the points inside of the polygon. The CGs of all of the components were moved to accomplish this task. The compensating fuel tank and the clean fuel tank were both moved so that their CGs were the same. This was done so that when all of the fuel was used, there would be no extra moment created by having salt water in the compensating diesel tank and an empty clean fuel tank. The amount and position of the lead was also altered to move all of the loading conditions inside of the equilibrium polygon. The position and size of all external tanks were also changed.

4.9.2 Final Weights

The LCB of the ship was taken to be at the volumetric center of the buoyant volumes of the submarine. The LCB is 119 ft. from the bow. A summary of the weights by SWBS code and the lightships weight are listed in Table 58. The weights spreadsheet organized by SWBS (single and multi digit codes) is provided in appendix F.

Table 58 – Final Lightship Weight Summary

SWBS Group	Weight (lton)	VCG (ft)	LCG(ft) (fwdLCB)
100	1220	-0.29	3.66
200	335	-2.55	-50.1
300	45.0	-2.40	-33.4
400	160	1.52	76.5
500	178	1.09	-0.62
600	58.0	0.73	9.52
700	50.0	0.55	32.0
8 (Lead)	315	-15.0	27.0
F10	3.11	0.00	-10.2
F20	87.0	0.28	33.8
F30	5.27	4.24	63.4
F40	841	-5.64	-13.3
F50	16.0	-20.0	-7.65
Total (LS+8)	2360	-2.34	3.80
Condition A	2360	-2.34	3.80
Condition A-1	2045	-0.39	0.23
NSC	3310	-3.18	0.28

4.9.3 Final Loading Conditions

The loading conditions used are the Normal Condition, Light #1, Heavy #1, Heavy #2 (mines), Heavy Forward #1, Heavy Forward #2, and Heavy Aft. A table of the final loading conditions can be seen in Appendix F. Figure 92 shows the final equilibrium polygon with all of the loading conditions inside of it.

4.9.4 Final Equilibrium Polygon

The final calculations for the boundaries of the equilibrium polygon are shown in Table 59. Figure 92 shows the final equilibrium polygon.

Table 59 – Construction of Polygon Boundaries

Tanks Filled	Volume (ft3)	Weight (lton)	Moment
Empty	0	0	0
Forward Trim Tank (FTT)	1472	42.06	2861.08
FTT + Aux 1 (A1)	2615	74.71	4630.39
FTT + A1 + A2	7956	227.31	9708.66
FTT + A1 + A2 + A3	12490	356.86	10910.59
FTT + A1 + A2 + A3 + A4	22047	629.91	6481.15
FTT + A1 + A2 + A3 + A4 + A5	24765	707.57	3474.13
FTT + A1 + A2 + A3 + A4 + A5 + ATT	26091	745.46	1552.50
A1 + A2 + A3 + A4 + A5 + ATT	24619	703.40	-1308.57
A2 + A3 +A4 + A5 + ATT	23476	670.74	-3077.88
A3 + A4 + A5 + ATT	18135	518.14	-8156.15
A4 + A5 + ATT	13601	388.60	-9358.09
A5 + ATT	4044	115.54	-4928.64
Aft Trim Tank (ATT)	1326	37.89	-1921.63
Empty	0	0	0

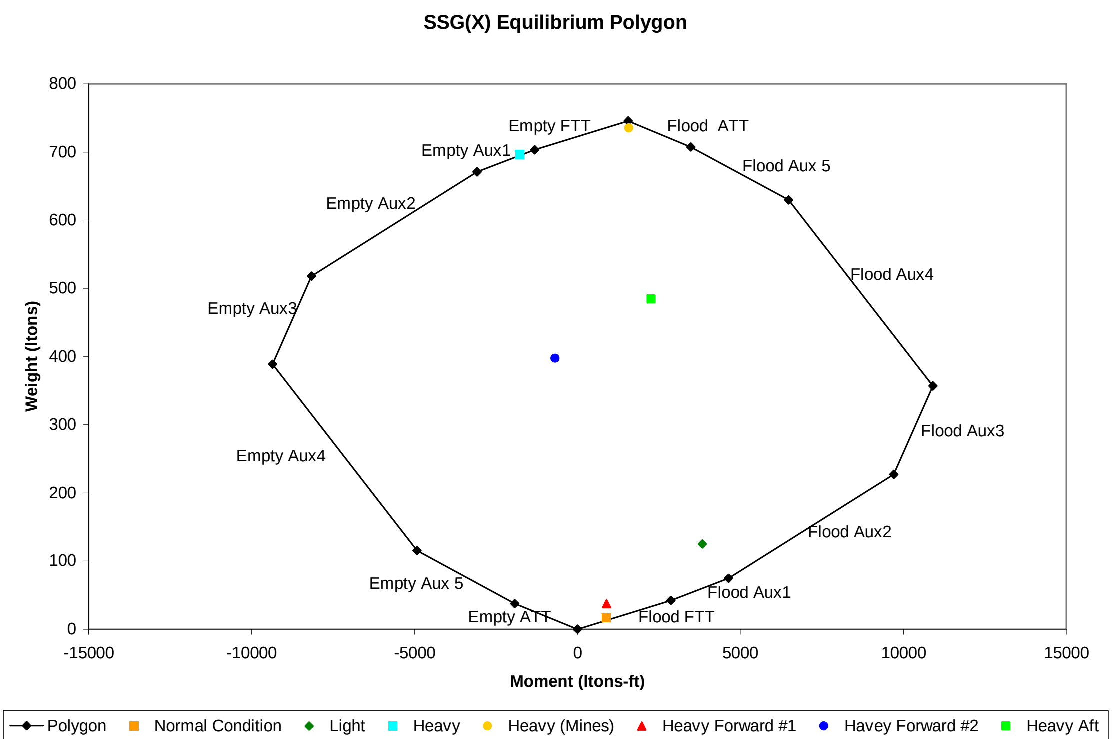


Figure 92 - SSG(X) Equilibrium Polygon

4.10 Dynamic Stability and Maneuverability

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

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

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

4.10.1 Control Surface Calculations and Response Surface Model (RSM)

Figure 93 shows the process used to determine the configuration, size, and location of the SSG(X) control surfaces. Lisa Minnick of Virginia Tech developed a control surface database by measuring the control surfaces of twelve submarines. This information was used to create a regression model that is a function of the submarine's diameter and length to diameter ratio. The regression model provided the size and location of the surfaces. A Response Surface Model (RSM) was developed using NSWC Carderock stability code calculates G_H and G_V to determine the feasibility of the calculated control surfaces. The SSG(X) is stable with sail planes and a cruciform stern which is described in Section 4.10.2.

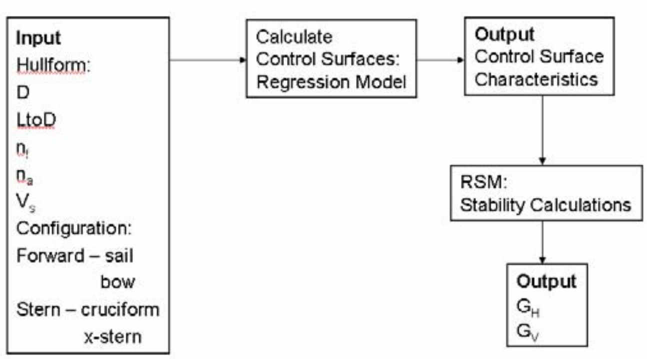


Figure 93 - Control Surface Calculation and RSM Flowchart

4.10.2 SSG(X) Control Surfaces

The size, location, and configuration of the submarine's sail and control surfaces were provided by the control surface calculations and RSM. The SSG(X) will have sail planes and a cruciform stern. Table 60 lists a summary of the sail and control surface characteristics given by the RSM. All surfaces have a NACA 0020 symmetrical airfoil cross-section. The X values in Table 60 represent the distance from the nose of the submarine to the leading edge of the control surface plane. The span (b) for the sail and sail planes is the exposed span; for the horizontal and vertical stern planes (h and v respectively), b is referenced from the centerline of the submarine. The vertical stern planes, rudders, are not symmetric; the lower plane will have a shorter span due to port restrictions. The chord (c) is the distance from the leading edge to the trailing edge of the control surface cross-section; it is given at the root (c_r) and the tip (c_t). These control surfaces provide SSG(X) with a G_H of 0.199 and a G_V of 0.539. Thus the SSG(X) will exhibit stability in the horizontal and vertical planes and will have sufficient maneuverability for strike missions in littoral regions. Figure 94 shows the SSG(X) model with sail planes and a cruciform stern.

Table 60 - SSG(X) Sail and Control Surface Characteristics

Description	Value (ft)
X_{sail}	61.75
b_{sail}	20.17
c_{rsail}	33.24
c_{tsail}	28.84
$X_{sailplane}$	36.02
$b_{sailplane}$	12.87
$c_{rsailplane}$	10.18
$c_{tsailplane}$	10.18
X_h	231.57
b_h	20.5
c_{rh}	14.35
c_{th}	9.75
X_{vtop}	231.57
b_{vtop}	21.50
c_{rvtop}	14.30
c_{tvtop}	9.65
$X_{vbottom}$	231.57
$b_{vbottom}$	19.30
$c_{rvbottom}$	14.39
$c_{tvbottom}$	9.86

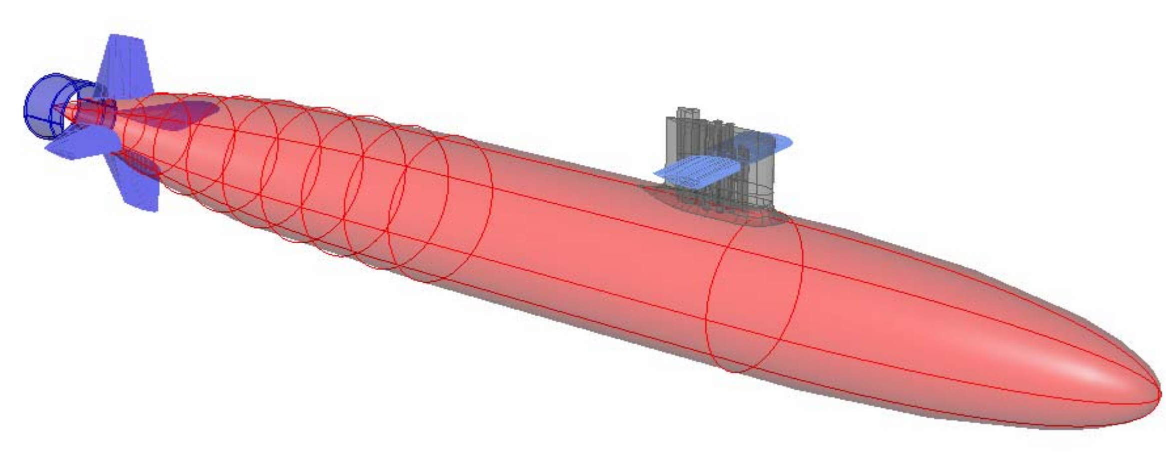


Figure 94 - SSG(X) with Sail and Control Surfaces

4.11 Cost and Risk Analysis

4.11.1 Cost and Producibility

SSG(X) is a highly producible, body of revolution design. The structure is made of HY80steel that the U.S. Navy uses on current submarines. The beam to depth ratio of unity reduces extra production costs that arise from non-uniform shapes. The design also is capable of being produced modularly for quick substitution of the fore, mid, or aft sections tailored to different mission objectives.

The cost calculation is primarily based on SWBS group weights. Multiplying a specific complexity factor for each group by the weight of the SWBS group times the man-hour rate produces the labor costs. The material costs for each group were determined by multiplying the specific complexity factor by the weight times an average inflation factor. Following these calculations the total Direct Cost (DC) is determined by adding the total Cost of Labor (C_L) and the total Cost of Material (C_M). An example of these calculations done in is shown below in Figure 95.

C. Lead Ship Shipbuilder Labor Cost :

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

Structure $K_{N1} := \frac{700 \cdot hr}{lton}$ $C_{L_1} := K_{N1} \cdot W_1 \cdot Mh$ $C_{L_1} = 64.1 Mdol$

+ Propulsion $K_{N2} := \frac{800 \cdot hr}{lton}$ $C_{L_2} := K_{N2} \cdot W_2 \cdot Mh$ $C_{L_2} = 20.1 Mdol$

D. Lead Ship Shipbuilder Material Cost :

Structure $K_{M1} := \frac{20 \cdot Kdol}{lton}$ $C_{M_1} := F_I \cdot K_{M1} \cdot W_1$ $C_{M_1} = 32.9 Mdol$

+ Propulsion $K_{M2} := \frac{150 \cdot Kdol}{lton}$ $C_{M_2} := F_I \cdot K_{M2} \cdot W_2$ $C_{M_2} = 67.5 Mdol$

3. Direct Cost:

$$DC := C_L + C_M$$

Figure 95 - Cost Calculations

The indirect costs were calculated as an overhead percentage of the direct costs, in this case 25%. For a typical U.S. nuclear submarine this percentage would be closer to 150%. The cost of the boat satisfies the threshold value specified in the ORD, $700 million for basic cost of construction and $1 billion for lead ship cost. Figure 96 below shows the SWBS cost percentage breakdown. SSG(X) is a cost efficient and producible alternative to today's nuclear powered submarines.

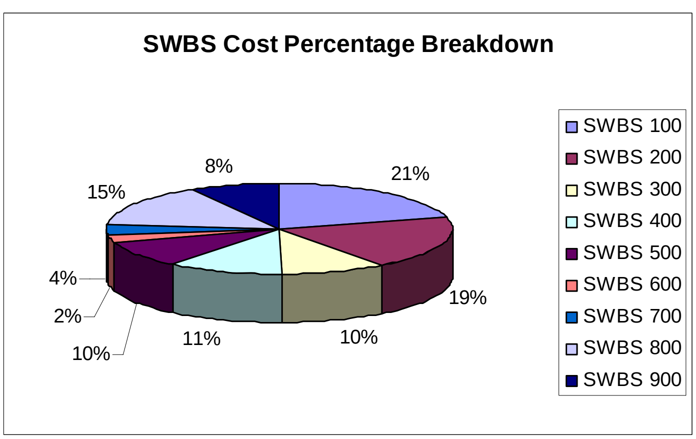


Figure 96 - SWBS Cost percentage breakdown

4.11.2 Risk Analysis

The selected baseline design for SSG(X) is a high risk alternative with an OMOR equal to 0.84. From the baseline, the high risk items are primarily the PEM fuel cell, automation manning factor and Zebra batteries performance risk. The largest concern with risk is the performance of these systems. For all of these systems the technology is currently available somewhere; therefore, the cost and schedule is less of an issue. The risk mostly comes from the United States lack of experience with these technologies. These systems will require extensive testing to determine their true performance capabilities. Specifically the PEM fuel cells are currently on German U212/214 boats and have great potential. The zebra batteries, although never used by the United States Navy, exist on Royal Navy submarines. The SSG(X) manning coefficient is 0.54 which is almost as much automation as allowable. The decrease in manning and increase in automation always increases risk.

Risk associated with each of these options is controlled by setting production for 2015. This 10 year time period allows for further testing and development of all the systems that will be onboard. The efficiency and performance of the PEM and Zebra batteries will increase in that time period and automation will be made much more effective, efficient, and reliable. A ten year period will allow a crew of non-nuclear submariners to be very highly trained and well educated to deal with the new systems.

5 Conclusions and Future Work

5.1 Assessment

Work carried out in Concept Development has shown that the baseline design was a good start for SSG(X). With the added wave induced drag calculated for snorkel, an increase in diesel fuel was necessary to meet snorkel endurance. Obtaining the high AIP endurance required a large amount of variable ballast to compensate for the heavy hydrogen-iron hydride. Compensated tanks could not be used with the hydride so internal compensating (trim and aux) tanks were required. Overall, the final concept baseline shows a close agreement with the specifications of the ORD and the original concept baseline, as seen in Table 61.

Table 61 - Compliance with Operational Requirements

Technical Performance Measure	Threshold	Goal	Concept Exploration BL/ ORD TPM	Final Concept Development BL
Mission payload	Passive/Active ranging sonar, 6 OB torpedo tubes, countermeasure launchers, 688 Class Sail masts, 12 VLS cells	Advanced Passive/Active ranging sonar, 6 IB torpedo tubes, countermeasure launchers, Virginia Class Sail masts, degaussing, 4 man lock-out trunk, 24 VLS cells	Advanced Passive/Active ranging sonar, 6 IB torpedo tubes, countermeasure launchers, Virginia Class Sail masts, degaussing, 4 man lock-out trunk, 24 VLS cells	Advanced Passive/Active ranging sonar, 6 IB torpedo tubes, countermeasure launchers, Virginia Class Sail masts, degaussing, 4 man lock-out trunk, 24 VLS cells
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)	4000	6000	5160	5610
Sprint Endurance (hr)	1	2	.95	1.00
AIP Endurance (days)	20	30	26	25.7
Snorkel Speed (knots)	12	12	12	12
Sprint Speed Vs (knots)	15	22	22	22
AIP Speed (knots)	5	5	5	5
Crew size	29	29	29	29
Diving Depth (ft)	500	1000	1000	1000

5.2 Summary of Changes Made in Concept Development

Concept Development for SSG(X) brought centered the balancing of the submarine at submerged and surfaced conditions. Main ballast tanks had to be moved forward and increased to create level trim and proper freeboard at the surfaced condition. The auxiliary ballast tanks were constantly moving and increasing to get all of the load points inside the equilibrium polygon. With the aft end of the ship predominantly heavy and creating a trim, the majority of the auxiliary tank space created was placed towards the stern to balance the weight. Change to the clean and compensating fuel tanks was on going because no moment difference had to be created when either full or empty. Internal and space arrangements were affected by the addition of two water tight bulkheads placed just forward of the MMR and just aft of the Torpedo room. The reasoning behind this addition was to isolate the hydrogen fuel and torpedoes. The MMR and AMR saw several variations to get the propulsion, hydraulic, and air systems together. Rearrangements were also made to allow for movement from one room or deck to another and for access to various pumps or equipment which may require maintenance.

5.3 Future Work

The following will be implanted on the SSG(X) the next time around the design spiral:

- Shaping of the bow to delay transition from laminar to turbulent flow until aft of the sonar dome

- Current SSG(X) design has extra free flood aft. The envelope hull can be decreased to reduce overall resistance. A reduction in resistance would increase the AIP endurance enough to meet the ORD.
- Add rubber boot to dampen the transition noise on bow
- Reshape the pressure hull caps: hemisphere with half the boat diameter followed by 30 degree cone finished with hemisphere diameter of 19 ft.
- Move the torpedo room above the water line for front loading purposes.
- Reconfigure torpedo room to allow for three torpedo lengths from the aft bulkhead of the room to the launch point of the bow.
- Angle the torpedo tubes at 7 degrees for high speed launches.
- Current VLS spacing arrangement is for outboard cells. Either increase the room around each cell or determine if it is feasible to place the VLS outboard of the pressure hull and have two pressure hulls connected by a pathway.
- Design heating device for hydride

5.4 Conclusions

The SSG(X) provides a non-nuclear platform alternative for strike missions. With the rising cost of the new Virginia Class exceeding three billion dollars, advanced fuel technology is an attractive option at a fraction of the cost. On top of cost savings, fuel cells have potential for quieter operation because they do not require the use of constant cooling pumps. In today's hostile global environment, the threat of bringing nuclear material into ports is a growing concern. Again, the use of fuel cells removes this threat.
Despite a having an overall length 100 feet less than the Virginia Class, SSG(X) houses a greater missile payload. Twenty-four VLS cells and six torpedo tubes with 24 reloads make the SSG(X) a highly effective launch platform. The addition of two torpedo tubes to the Virginia Class platform provides increased options for AUV launch in support of reconnaissance missions. The SSG(X)'s smaller diameter and length makes it ideal for operation in shallower littoral regions. This advantage is ideal for integration with Sea Power 21. In addition to impressive missile capabilities, the SSG(X) also supports an advanced sonar system. This makes it fully capable for ISR operations.

Although new to the United States, fuel cells are a maturing technology in foreign submarines. With great effectiveness at a low cost, the United States can no longer remain behind in this advancing technology. With only a few knowledge barriers to conquer, SSG(X) is highly producible and effective with minimal risk, and is the ideal solution to the new model of a cost effective covert warfare.

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Appendix A - Mission Need Statement (MNS)

MISSION NEED STATEMENT

FOR A

COVERT MISSILE-LAUNCH PLATFORM

1. DEFENSE PLANNING GUIDANCE ELEMENT.

The Department of the Navy's 1992 white paper, "From the Sea", outlines a significant change in priorities from a "Blue Water Navy fighting a traditional Super Power". The rapidly changing global political climate, and seven major theater operations conducted over the following 22 months, prompted the Department of the Navy to publish a revised white paper, "Forward from the Sea", in December 1994.

"Forward from the Sea" emphasizes the importance of action against aggression of regional powers at the farthest points on the globe. Such action requires a rapid, flexible response to emergent crises which projects decisive military power to protect vital U.S. interests (including economic interests), and defend friends and allies. It states, "...the most important mission of naval forces in situations short of war is to be *engaged* in forward areas, with the objectives of *preventing* conflicts and *controlling* crises". Naval forces have five fundamental and enduring roles in support of the National Security Strategy: projection of power from sea to land, sea control and maritime supremacy, strategic deterrence, strategic sealift, and forward naval presence.

Most recently, the Quadrennial Defense Review Report, the Department of the Navy's whitepaper, "Naval Transformational Roadmap", and CNO's "Sea Power 21" vision statement provide additional unclassified guidance and clarification on current DoD and USN defense policies and priorities.

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

The "Naval Transformational Roadmap" and "Sea Power 21" provide the US Navy's plan to support these goals including nine necessary warfighting capabilities in the areas of Sea Strike – strategic agility, maneuverability, ISR, time-sensitive strikes; Sea Shield – project defense around allies, exploit control of seas, littoral sea control, counter threats; and Sea Base – accelerated deployment & employment time, enhanced seaborne positioning of joint assets.

This Mission Need Statement specifically addresses critical components of Sea Strike and Sea Shield consistent with operational goals 1), 3), 4) and 5) of the Quadrennial Defense Review. While addressing these capabilities, there is also a need to reduce cost, minimize personnel in harms way, prevent compromise of sensitive technology, and prevent nuclear environmental incidents.

2. MISSION AND THREAT ANALYSIS.

a. Threat.

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

(a) Threats from nations with either a superior military capability, or the demonstrated interest in acquiring such a capability. Specific weapons systems that could be encountered include ballistic missiles, land and surface launched cruise missiles, significant land based air assets and submarines.

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

(2) Since many potentially unstable nations are located on or near geographically constrained bodies of water, the tactical picture will be on smaller scales relative to open ocean warfare. Threats in such an environment include: (1) technologically advanced weapons - cruise missiles like the Silkworm and

Exocet, land-launched attack aircraft, fast gunboats armed with guns and smaller missiles, and diesel electric submarines; and (2) unsophisticated and inexpensive passive weapons - mines, chemical and biological weapons. Many encounters may occur in shallow water which increases the difficulty of detecting and successfully prosecuting targets. Platforms chosen to support and replace current assets must have the capability to dominate all aspects of the littoral environment.

b. Mission

(1) 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. It must provide covert and time-sensitive strike on demand. New platforms must complement and support this force.

(2) Power Projection requires the execution and support of flexible strike missions and support of naval amphibious operations. This includes inland strike support, protection to friendly forces from enemy attack, unit self defense against littoral threats, area defense, and theater ballistic missile defense.

(3) The platforms must be able to support, maintain and conduct operations with the most technologically advanced unmanned/remotely controlled tactical and C^4/I reconnaissance vehicles.

(4) The platform must possess sufficient stealth, mobility and endurance to perform all missions on extremely short notice, at locations far removed from home port.

c. Need:

A covert missile strike platform is required to deploy on-station in sensitive and vulnerable remote littoral regions, ready to provide immediate, time sensitive anti-air, anti-surface and inland missile strikes, using TLAM, anti-air, anti-ship, and possibly Kinetic Energy Interceptor missiles, in support of the battle group, amphibious operations, ballistic missile defense, and other national objectives.

3. NON-MATERIAL ALTERNATIVES.

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

4. POTENTIAL MATERIAL ALTERNATIVES.

a. Retain and upgrade current fleet assets as necessary. Possibilities include SSN and SSBN modifications and service life extension.
b. Design and build a new class of stealthy surface ships specifically-designed to satisfy the mission need.
c. Design and build a new class of SSGNs specifically-designed to satisfy the mission need.
d. Design and build a new class of conventional SSGs specifically-designed to satisfy the mission need.

5. CONSTRAINTS.

a. The cost of the platforms must be kept to the absolute minimum, acknowledging the rapidly decreasing U.S. defense department budget.
b. The platforms must be highly producible, minimizing the time from concept to delivery to the Fleet. The design must be flexible enough to support variants if necessary.
c. The platforms must operate within current logistics support capabilities.
d. Inter-service and Allied C^4/I (inter-operability) must be considered in the development of any new platform or the upgrade of existing assets.
f. The platform must have absolute minimum manning.

Appendix B - Acquisition Decision Memorandum (ADM)

August 24, 2005

From: Virginia Tech Naval Acquisition Executive
To: SSG(X) Design Teams

Subject: ACQUISITION DECISION MEMORANDUM FOR a Conventional Guided Missile Submarine

Ref: (a) VT Mission Need Statement for a Covert Missile Launch Platform

1. This memorandum authorizes concept exploration of a single material alternative proposed in Reference (a) to the Virginia Tech Naval Acquisition Board on 24 August 2005. Additional material and non-material alternatives supporting this mission may be authorized in the future.

2. Concept exploration is authorized for a new SSG(X) Conventional Guided Missile Submarine consistent with the mission requirements and constraints specified in Reference (a), with particular emphasis on providing a covert non-nuclear platform for launching time-sensitive anti-air, anti-surface and inland missile strikes, using TLAM, anti-air, anti-ship, and possibly Kinetic Energy Interceptor missiles, in support of the battle group, amphibious operations, ballistic missile defense, and other national objectives. The submarine would deploy from the US to stations in sensitive and vulnerable remote littoral regions, ready to provide immediate time-sensitive response. Additional essential requirements include survival in a high-threat environment and operation in all warfare areas (multi-mission). The design must minimize personnel vulnerability in combat through automation, innovative concepts for minimum crew size, and signature reduction. Concepts shall include moderate to high-risk alternatives. Average follow-ship acquisition cost shall not exceed $700M (FY2010) with a lead ship acquisition cost less than $1B. It is expected that 20 ships of this type will be built with IOC in 2015.

A.J. Brown
VT Acquisition Executive

Appendix C - Operational Requirements Document (ORD)

Operational Requirements Document (ORD)

Guided Missile Submarine (SSG(X))

Virginia Tech Team 3 – Design Alternative 44-2

1. Mission Need Summary

This Guided Missile Submarine (SSG(X)) requirement is based on the Virginia Tech SSG(X) Acquisition Decision Memorandum (ADM).

SSG(X) will operate from CONUS or a Sea Base to conduct Strike and ISR operations. A small crew size will put fewer people in harm's way and low cost will facilitate a shorter production timeline. SSG(X) will support the following missions:

1. Missile Launch (AAW, ASUW, ASW, STK)
2. Intelligence, Surveillance, and Reconnaissance (ISR)

SSG(X) will be capable of conducting intelligence, surveillance, and reconnaissance missions with the aid of AUVs and special forces. It will be a covert, upgradeable, and defensive ship capable of taking the U.S. Navy into the new millennium of warfare.

2. Acquisition Decision Memorandum (ADM)

The SSG(X) ADM authorizes Concept Exploration of a material alternative for a Guided Missile Submarine, as proposed to the Virginia Tech Naval Acquisition Board. Additional material and non-material alternatives supporting this mission may be authorized in the future.

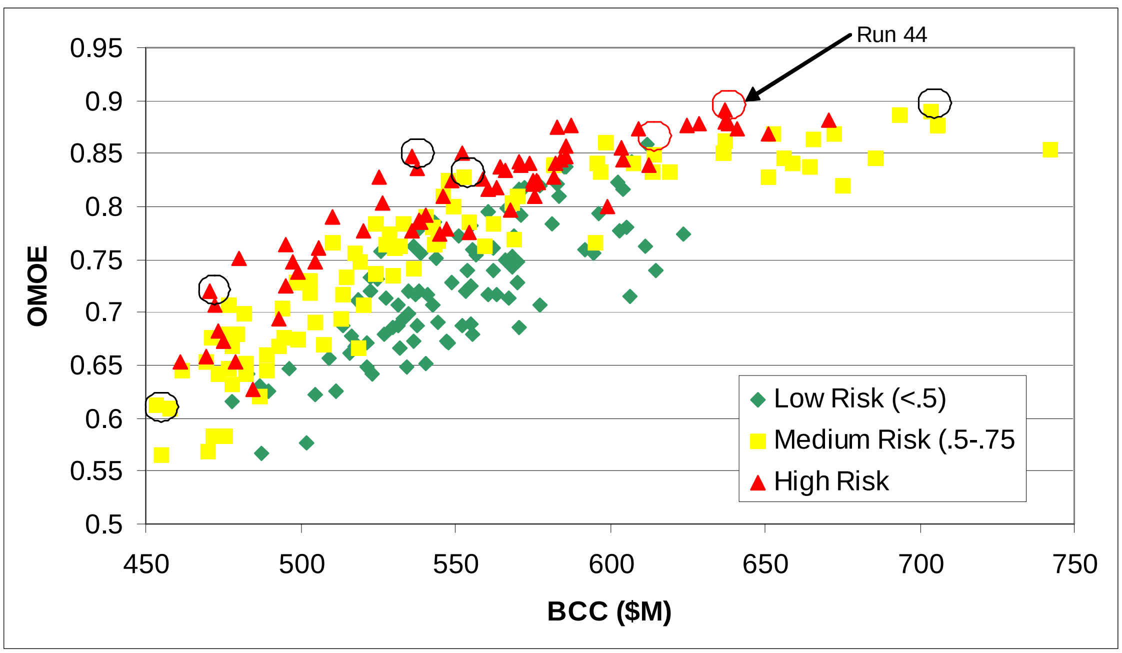

Figure 1 - SSG(X) Non-Dominated (ND) Frontier

3. Results of Concept Exploration

Concept exploration was performed using a multi-objective genetic optimization (MOGO). A broad range of non-dominated SSG(X) alternatives within the scope of the ADM were investigated based on base cost of construction, effectiveness and risk. This ORD specifies a requirement for concept development of SSG(X) Alternative 44, Variant 2. Other alternatives are specified in separate ORDs. Alternative 44, Variant 2 is a three-deck, high risk, knee-in-the-curve design on the ND frontier (Figure 1).

4. Technical Performance Measures (TPMs)

TPM	Threshold
Mission payload	Passive/Active ranging sonar, flank array sonar, integrated bow array sonar, 6 inboard torpedo tubes, countermeasure launchers, UAV mast launch, Virginia Class Sail masts, mine avoidance sonar, degaussing, 4 man lock-out trunk
Propulsion	OCD/AIP, 2xCAT 3512 V12 + 2x500KW PEM, Zebra batteries
Endurance range (nm)	5160
Sprint range (1hr)	1
Stores duration (days)	26
Sustained Speed Vs (knots)	22
Crew size	29
Diving Depth (ft)	1000

5. Program Requirements

Program Requirement	Threshold
Base Construction Cost ($ M)	700
Lead Ship Acquisition Cost ($ B)	1

1.

6. Other Design Requirements, Constraints and Margins

SSG(X) must be highly producible and able to support variants if needed. The platform must operate with current logistics support capabilities and have absolute minimum manning.

7. Special Design Considerations and Standards

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

- Hull design shall incorporate features to reduce drag and minimize structural weight.
- Propulsion plant options shall consider air independent, non-nuclear systems to satisfy the need for reduced acoustic and infrared signatures while addressing required speed and endurance.
- Reduced manning and maintenance factors shall be considered to minimize total ownership cost

The following standards shall be used as design guidance:

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

Use the following cost and life cycle assumptions:

- Ship service life = L_S = 15 years
- Base year = 2010

IOC = 2015

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

Figure 97 - MOP 1 VOP's

Figure 98 - MOP 2 VOP's

Figure 99 - MOP 3 VOP's

Figure 100 - MOP 4 VOP's

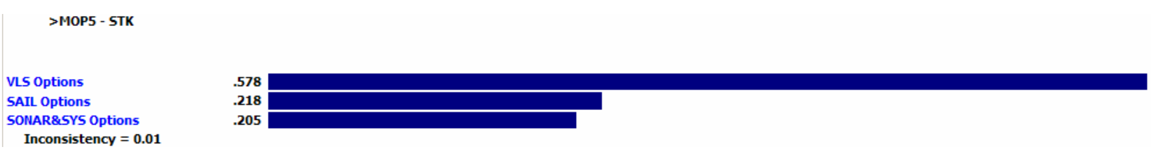

Figure 101 - MOP 5 VOP's

Figure 102 - MOP 6 VOP's

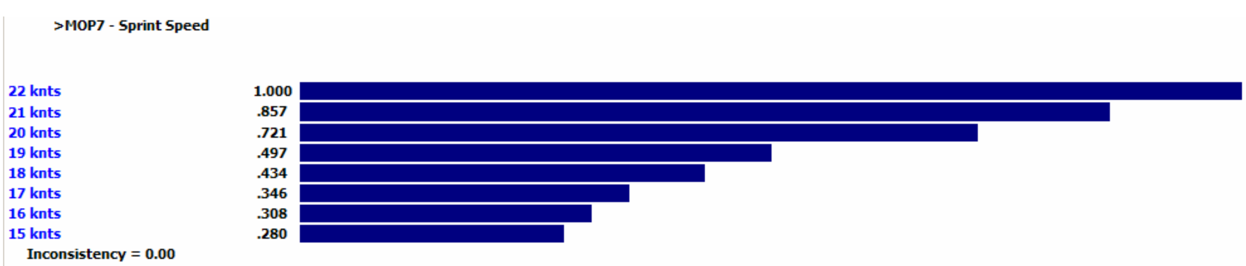

Figure 103 - MOP 7 VOP's

Figure 104 - MOP 8 VOP's

Figure 105 - MOP 9 VOP's

Figure 106 - MOP 10 VOP's

Figure 107 - MOP 11 VOP's

Figure 108 - MOP 12 VOP's

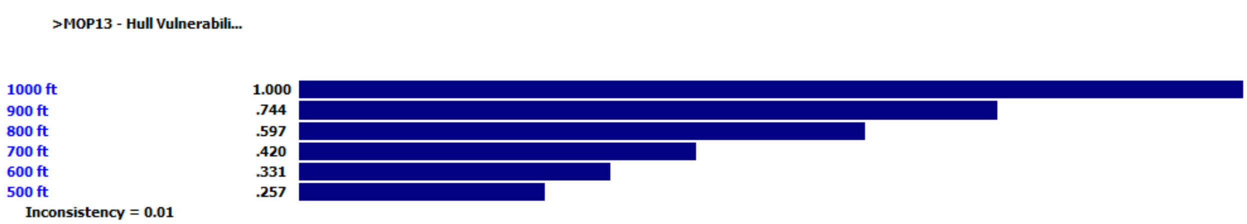

Figure 109 - MOP 13 VOP's

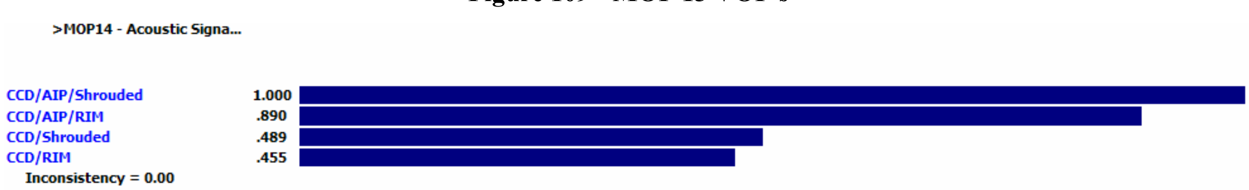

Figure 110 - MOP 14 VOP's

Figure 111 - MOP 15 VOP's

Figure 112 - MOP 16 VOP's

Figure 113 - VLS Normalized VOP's

Figure 114 - SAIL Normalized VOP's

Figure 115 - ESM Normalized VOP's

Figure 116 - SONARSYS Normalized VOP's

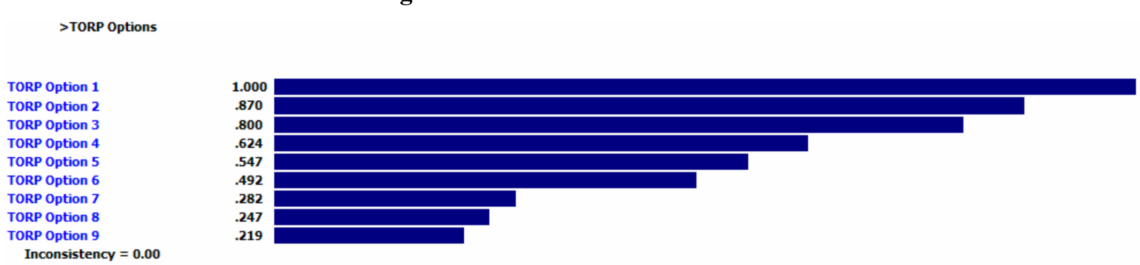

Figure 117 - TORP Normalized VOP's

Figure 118 - SPW Normalized VOP's

Appendix E – Machinery Equipment List

Table 62 - Machinery Equipment List

ITEM	QTY	DESCRIPTION	LOCATION	SWBS	UNIT WEIGHT (lton)	POWER REQD (kW)	REMARKS	DIMENSIONS (ft) LxWxH
		Propulsion and Electrical:						
1	2	PEM	MMR	235	8.5	-	500 kW PEM	8x8x7
2	2	CAT 3512 V12 Diesel Generator (AC)	MMR-dk 3	230	54	-	1752 kW	9x7x6 diesel 7x7x6 generator
3	1	Main Machinery Control Console	MMR-dk 2	310	2	6.0		3x6x3
4	2	Main Batteries - Bank	Bat Compt	220	46	1.0	5820 kWhr	35x5x5
5	1	DC (400V) Main SWB	MMR-dk 2	320	5	2.0		3x6x6
6	1	Emergency SWB	AUX	320	1	2.0		3x3x6
7	2	Oxygen Tanks, cylindrical	MMR-dk 1	520	54	1.0	1.5x size for insulation	12 ft D sphere
8	2	Power Conversion Modules (ACtoDC)	MMR-dk 3	310	7.5	6.0	3000 kW	3x3x3
9	1	Motor Control Center	MMR-dk 2	300	1	6.0		2x2x6
10	1	AC Synchronous Permanent Magnet Motor	Prop	300	3	6.0	6000 kW includes inverters	7x9x9
11	2	Lighting Load Panel	AUX	300	12.5	4.0		2x2x6
12	2	Starting Air Cylinder	MMR-dk 3	250/260	2	3.0		2x2x6
13	1	Degaussing	Various	475	8.4	8.4		panel 1x1x2
		Fuel Transfer and Storage:						
14	2	FO Purifier	MMR-dk 2	250/260	0.5	1.0		3x3x4
15	2	FO Transfer Pump	MMR-dk 2	250/260	0.5	2.0		1.5x1.5x2
		Lube Oil Transfer and Storage						
16	2	LO Purifier	MMR-dk 2	250/260	0.5	1.0		3x3x4
17	2	LO Transfer Pump	MMR-dk 2	250/260	0.5	2.0		1.5x1.5x2
18	2	Oily Waste Transfer Pump	MMR-dk 2	250/260	0.3	2.0		1x1x2
19	2	Oily Water Separator	MMR-dk 2	250/260	0.3	1.0		2x2x2
		Steering and Control						
20	1	Steering Hydraulics	aft	560	2	5.0	Operating Ram	2x2x2
21	1	Aft Plane Hydraulics	aft	560	2	5.0	Operating Ram	2x2x2
22	1	Sail Plane Hydraulics	Sail	560	2	5.0	Operating Ram	2x2x2
		Air Systems:						
23	2	High Pressure Air Compressor	MMR-dk 2	550	0.5	11.0		4x4x4
24	2	High Pressure Air Dehydrator	MMR-dk 2	550	0.5	2.0		2x2x3
25	12	High Pressure Air Cylinders	MBT	550	0.5	1.0	2% of MBT	3x2x5

26	2	Air Reducer Manifold	AUX	550	0.3	1.0		2x2x2
		Hydraulic Systems:						
27	2	Main Hydraulic Pump	AUX	550	12	25.0		2x2x3
28	2	Hydraulic Pressure Accumulator	AUX	550	5	6.0		3x3x5
29	1	Hydraulic vent and Supply Tank	AUX	550	5	4.0		4x4x4
		Fresh Water Systems:						
30	2	Potable Water Pump	AUX	530	0.7	7.0		2x1x1
31	2	Hot Water Circ Pump	AUX	530	0.3	7.0		2x1x1
32	2	Reverse Osmosis Distiller	AUX	530	0.5	1.0		5x5x4
33	2	Distiller Pump	AUX	530	2.5	2.0		2x1x1
		Salt Water Systems:						
34	2	Trim manifold	AUX	520	2	5.0		3x1x1
35	2	Trim pump	AUX	520	2	5.0		2x1x1
36	2	Drain and Bilge Pump	MMR-dk 3	500	16	12.0		2x1x1
37	2	Salt Water Circulating Pump	MMR-dk 3	250/260	1	2.0		2x1x1
38	2	Fire pump	MMR-dk 2	550	1	4.2		3x2x2
39	2	AFFF station	MMR-dk 2	550	2	4.2		4x4x4
40	2	Distiller Feed Pump	AUX	530	2	2		2x1x1
		Ventilation and Air purification:						
41	2	Main Induction Blower	Sail	500	8	8.0		2x2x2
42	2	Main Exhaust Fan	MMR-dk 2	500	8	6.0		2x2x2
43	2	Ventilation Fan	Air Pur Rm	510	8	8.0		2x2x2
44	2	CO2 Scrubber	Air Pur Rm	510	2.5	8.0		2x2x5
45	2	CO/H2 Burner	Air Pur Rm	510	2.5	8.0		2x2x3
		AC and Refrigeration						
46	2	AC Unit	AUX	510	4.9	44.0		4x2x2
47	2	Chilled Water Pump	AUX	530	1	2.0		2x1x1
48	2	Refrigeration Units	AUX	530	2	4.0		4x2x2
49	1	Chill/Freeze Box	Galley	500	2	9.0		6x4x6
		Environmental Systems						
50	1	Trash Disposal Unit (TDU)	Galley	593	0.5	2.0		2x2x2
51	2	Sewage Vacuum Sys	AUX	593	1	5.0		3x2x2
52	2	Waste Water Discharge Pump	AUX	593	1	5.0		2x1x1

Appendix F - Weights and Centers

Table 63 - Weights and Centers by SWBS Code

SWBS	COMPONENT	WT - lton	VCG - ft	LCG - ft
A	**LIGHTSHIP WEIGHT + LEAD**	**2360.08**	**-2.34**	**3.80**
8	LEAD	315.00	-15.00	26.98
A-1	**LIGHTSHIP WEIGHT SWBS 1-7**	**2045.08**	**-0.39**	**0.23**
100	**HULL STRUCTURES**	**1220.51**	**-0.29**	**3.66**
110	SHELL + SUPPORTS	779.55	0.00	2.90
111	PRESSURE HULL	720.92	0.00	3.28
112	NON-PRESSURE ENVELOPE	14.66	0.00	-1.72
118	NON-PRESSURE FRAMES	43.97	0.00	-1.72
120	PRESSURE HULL STRUCTURAL BULKHDS	194.01	-3.59	-4.21
123	TRUNKS	5.61	-10.00	-10.22
125&6	SOFT AND HARD TANKS	188.40	-3.40	-4.03
140	PRESSURE HULL PLATFORMS/FLATS	16.31	-9.50	-10.22
160	SPECIAL STRUCTURES	106.37	4.73	41.86
161	COMBAT SYS STRUCTURE SUPPORT	85.80	2.69	47.73
163	SEA CHESTS	1.82	-10.00	8.28
167	HULL CLOSURES	18.75	15.50	18.28
180	FOUNDATIONS	114.16	0.00	-10.22
190	SPECIAL PURPOSE SYSTEMS	10.10	0.00	-10.22
200	**PROPULSION PLANT**	**334.58**	**-2.55**	**-50.05**
220	MAIN PROPULSOR	72.14	-1.34	-53.11
	DIESEL GENERATOR	53.44	-4.00	-58.22
	FUEL CELL	18.70	6.25	-38.51
230	PROPULSION UNITS	104.36	0.00	-131.72
240	PROPULSION POWER TRANSMISSION	0.00	0.00	118.28
250	SUPPORT SYSTEMS	0.00	0.00	118.28
	ARGON TANKS	0.00	0.00	118.28
	OXYGEN TANKS	0.00	0.00	118.28
	HYDROGEN TANKS	156.55	-4.85	5.84
	BATTERY	0.00	0.00	118.28
256	SALTWATER CIRC	29.36	9.32	-57.58
257	FRESH WATER CIRC	15.52	-8.82	3.78
290	SPECIAL PURPOSE SYSTEMS	91.37	-9.80	30.13
298	FLUIDS	15.22	0.00	-10.22
299	PARTS	5.07	0.00	-10.22
300	**ELECTRIC PLANT, GENERAL**	**1.52**	**2.56**	**-53.61**
310	ELECTRIC POWER GENERATION	1.01	2.56	-53.61
312	EMERGENCY DIESEL GENERTOR	0.51	2.56	-53.61
314	POWER CONVERSION	44.59	-2.40	-33.40
320	ELECTRICAL DISTRIBUTION SYSTEM	17.80	-6.00	-67.22
321	POWER CABLE	0.00	0.00	118.28
324	SWITCH GEAR	17.80	-6.00	-67.22
330	LIGHTING SYSTEM	14.17	0.00	-11.54
340	POWER GENERATION SUPPORT SYS	8.83	0.00	-10.22

SWBS	COMPONENT	WT - lton	VCG - ft	LCG - ft
390	SPECIAL PURPOSE SYSTEMS	5.34	0.00	-13.72
400	**COMMAND + SURVEILLANCE**	**12.62**	**0.00**	**-10.22**
420	NAVIGATION SYSTEMS	0.00	0.00	118.28
430	INTERIOR COMMUNICATIONS	0.00	0.00	118.28
440	EXTERIOR COMMUNICATIONS	159.74	1.52	76.46
450	SURF SURVEILLANCE SYS (RADAR)	16.82	2.93	33.28
460	UNDERWATER SURVEILLANCE SYS	7.71	0.00	-10.22
475	DEGAUSSING	1.65	20.40	42.31
480	FIRE CONTROL SYSTEMS	5.90	20.40	42.31
490	SPECIAL PURPOSE SYSTEMS	105.92	0.00	104.38
500	**AUXILIARY SYSTEM, GENERAL**	**8.41**	**0.00**	**-10.22**
510	CLIMATE CONTROL	2.33	2.93	33.28
512	VENTILATION	11.00	2.93	33.28
514	AIR CONDITIONING	178.12	1.09	-0.62
515	AIR REVITALIZATION	49.34	3.29	-8.88
516	REFRIGERATION	25.38	0.50	-8.45
520	SEA WATER SYSTEMS	9.21	7.50	-9.44
524	AUXILIARY SALTWATER	4.90	1.40	-8.97
528	DRAINAGE	9.84	7.50	-9.44
530	FRESH WATER SYSTEMS	19.19	-5.79	-43.53
531	DISTILLERS	3.31	0.00	-18.67
532	FW COOLING	15.87	-7.00	-48.72
533	POTABLE WATER SYSTEM	9.09	2.10	-19.44
540	FUELS/LUBRICANTS, HANDLING+STOWAGE	2.24	8.50	-31.40
541	FUEL SERVICE TANKS	6.16	0.00	-13.72
550	AIR,GAS+MISC FLUID SYSTEM	0.69	0.00	-31.72
551	NITROGEN BOTTLES	2.78	-0.90	-66.89
554	MBT BLOW AIR	2.78	-0.90	-66.89
555	FIREFIGHTING SYSTEMS	30.33	2.29	-31.48
556	HYDRAULIC SYSTEMS	0.54	-5.00	-10.22
560	SHIP CNTL SYS	4.98	2.33	-38.33
561	STEERING	2.80	-5.66	-45.64
563	DEPTH CONTROL	22.02	3.46	-28.65
564	TRIM SYSTEMS	44.59	-0.79	48.72
566	DIVING PLANES	5.23	0.00	-10.22
569	CONTROL	2.24	0.00	-10.22
580	ANCHOR, MOORING, HANDLING+STOWAGE	4.04	-9.93	7.18
581	ANCHOR HANDLING	31.20	0.00	68.28
582	MOORING	1.88	2.69	47.73
585	MAST	6.90	11.56	66.99
590	ENVIRONMENTAL + AUX SYSTEMS	1.20	-5.00	113.28
591	MISCELANEOUS MISSION AUX SYSTEMS	1.20	-5.00	113.28
592	DIVING SYSTEMS	4.50	20.40	42.31
593	ENVIRONMENTAL SYSTEMS	15.90	0.81	-9.66
600	**OUTFIT + FURNISHING, GENERAL**	**12.60**	**0.00**	**-10.22**
610&620	HULL OUTFIT	1.30	9.94	-3.36
630-650	PERSONAL OUTFIT	2.00	0.00	-10.22

SWBS	COMPONENT	WT - lton	VCG - ft	LCG - ft
700	**ARMAMENT**	**57.65**	**0.73**	**9.52**
740	VLS	42.05	0.00	-10.22
750	TORPEDOES HANDLING	15.60	2.68	62.73
760	LOCKOUT	49.89	0.55	32.03

Table 64 - Final Loading Conditions

Group	Ship Synthesis		Normal Condition N		Light #1 (diesel)	
Density	64		64		64.3	
	Equation	Value	Weight	Moment	Weight	Moment
Condition A	Wa	2360.08	2360.08	8974.13	2360.08	8974.13
Disp sub (adjusted for density, lton)	Disp'	3880.32	3880.32	0.00	3898.51	0.00
Main Ballast Tanks (adjusted for density, lton)	Wmbt'	549.07	549.07	-1805.54	551.64	-1814.01
Weight to Submerge (lton) adjusted for density	Ws'	1520.24	1520.24	-8974.13	1538.43	-8974.13
1,2,3	WF10+ Wsew+ 0.1*WF46	4.87	4.87	-53.10	4.87	-53.10
4	Wo2	78.29	78.29	-4507.89	78.29	-4507.89
	Wh2	621.00	621.00	2346.33	621.00	2346.33
5	Wvp	88.00	88.00	2935.73	0.00	0.00
6	WF52	4.35	4.35	-137.99	2.18	-68.99
7	WF31+ WF32	5.27	5.27	334.17	3.96	250.63
8	0.9*WF46	0.90	0.90	-39.35	0.68	-29.51
9	Wfcomp	116.16	116.16	-7387.12	116.16	-7387.12
10	Wfclean	24.78	24.78	-1573.82	24.78	-1573.82
11		0.00	0.00	0.00	0.00	0.00
12		0.00	0.00	0.00	0.00	0.00
13	Wresidual	9.97	9.97	32.69	9.97	32.69
Total	WF00	952.64	953.60	-8050.34	861.88	-10990.78
Variable Ballast Required	**Wtrimbal**	**0.00**	**17.57**	**881.75**	**124.91**	**3830.65**

Table 65 - Final Loading Conditions (Continued)

Group	Heavy #1 (diesel)		Heavy #1 (diesel) (mines)		Heavy Fwd #1 (diesel)	
Density	63.6		63.6		64.3	
	Weight	Moment	Weight	Moment	Weight	Moment
Condition A	2360.08	8974.13	2360.08	8974.13	2360.08	8974.13
Disp sub (adjusted for density, lton)	3856.06	0.00	3856.06	0.00	3898.51	0.00
Main Ballast Tanks (adjusted for density, lton)	545.64	-1794.26	545.64	-1794.26	551.64	-1814.01
				-8974.13	1538.43	-8974.13

Weight to Submerge (lton) adjusted for density	1495.99	-8974.13	1495.99			
1,2,3	4.87	-53.10	4.87	-53.10	4.87	-53.10
4	0.00	0.00	0.00	0.00	78.29	-4507.89
	0.00	0.00	0.00	0.00	621.00	2346.33
5	87.00	3814.92	48.40	453.27	87.50	2940.84
6	4.35	-137.99	4.35	-137.99	2.18	-68.99
7	2.64	167.08	2.64	167.08	3.96	250.63
8	0.45	-19.67	0.45	-19.67	0.68	-29.51
9	144.66	-9199.26	144.66	-9199.26	116.16	-7387.12
10	0.00	0.00	0.00	0.00	24.78	-1573.82
11	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00
13	9.97	32.69	9.97	32.69	9.97	32.69
Total	253.94	-5395.32	215.34	-8756.97	949.38	-8049.94
Variable Ballast Required	**696.41**	**-1784.55**	**735.01**	**1577.10**	**37.41**	**889.81**

Table 66 - Final Loading Conditions (Continued)

Group	Heavy Fwd #2 (diesel)		Heavy Aft (diesel)	
Density	64.3		64.3	
	Weight	Moment	Weight	Moment
Condition A	2360.08	8974.13	2360.08	8974.13
Disp sub (adjusted for density, lton)	3898.51	0.00	3898.51	0.00
Main Ballast Tanks (adjusted for density, lton)	551.64	-1814.01	551.64	-1814.01
Weight to Submerge (lton) adjusted for density	1538.43	-8974.13	1538.43	-8974.13
1,2,3	4.87	-53.10	4.87	-53.10
4	39.15	-2253.94	39.15	-2253.94
	310.50	1173.17	310.50	1173.17
5	87.50	2940.84	0.50	-5.11
6	2.18	-68.99	2.18	-68.99
7	2.64	167.08	2.64	167.08
8	0.45	-19.67	0.45	-19.67
9	119.68	-7610.74	119.68	-7610.74
10	12.39	-786.91	12.39	-786.91
11	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00
13	9.97	32.69	9.97	32.69
Total	589.32	-6479.58	502.32	-9425.52
Variable Ballast Required	**397.47**	**-680.55**	**484.47**	**2265.40**

Appendix G - MathCAD Model

Hullform:

SS Hullform Module

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: $L_{pmb} := LOA - L_{td}$ $L_{pmb} = 96\,ft$

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

(resistance optimum)

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

B. VOLUME CALCULATIONS TO SUPPORT ARRANGEMENTS:

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

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

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:

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

$$V_{env} := \int_{0 \cdot ft}^{LOA} A(x)\,dx \qquad V_{env} = 217230\,ft^3$$

$$S := \int_{0 \cdot ft}^{LOA} p(x)\,dx \qquad S = 2.725 \times 10^4\,ft^2$$

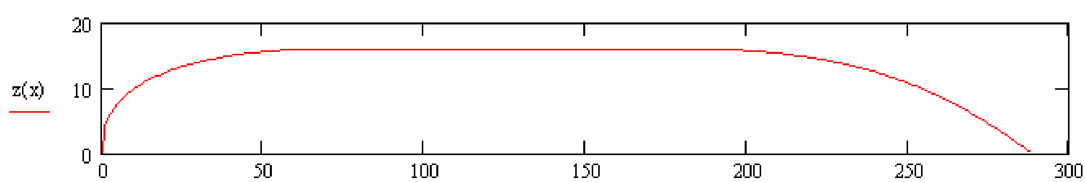

Figure 119 - MathCAD Hullform Module

$L_f = 76.8\,ft$ $L_f + L_{pmb} = 172.8\,ft$ $\frac{D}{2} = 16\,ft$ $LOA = 288\,ft$ $z(LOA) = 5.329 \times 10^{-15}\,ft$

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

x1 = (ft)	z(x1) = (ft)
0	0
7.68	8.912
15.36	11.39
23.04	12.956
30.72	14.039
38.4	14.802
46.08	15.332
53.76	15.68
61.44	15.885
69.12	15.98
76.8	16

x2 = (ft)	z(x2) = (ft)
172.8	16
184.32	15.972
195.84	15.809
207.36	15.416
218.88	14.712
230.4	13.622
241.92	12.073
253.44	10
264.96	7.338
276.48	4.025
288	$-3.908\cdot 10^{-14}$

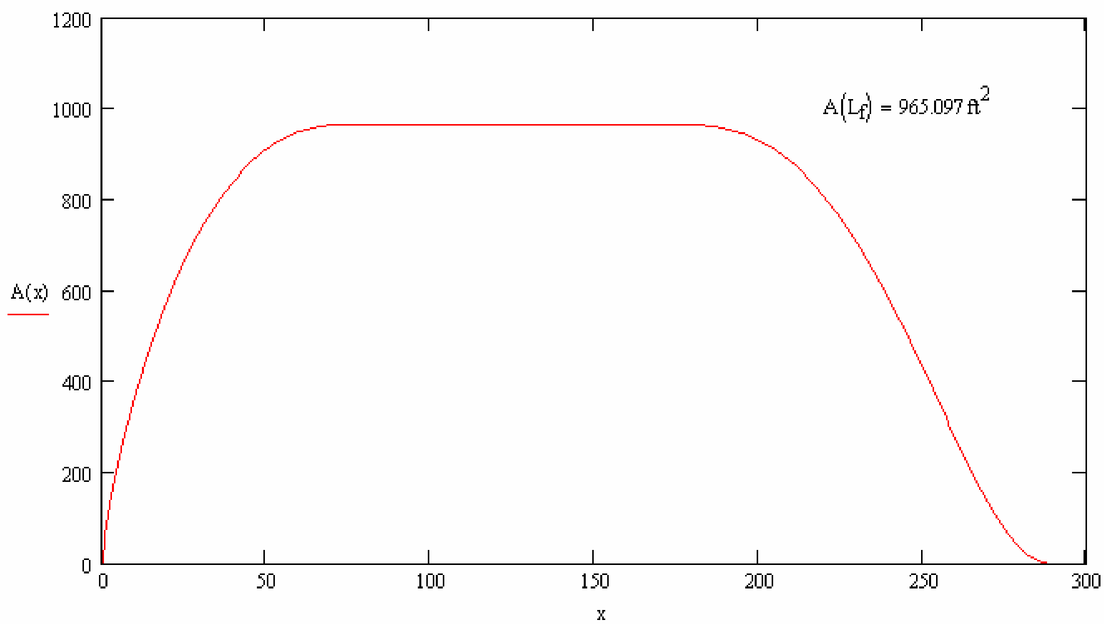

Figure 120 - MathCAD Hullform Module (cont.)

Structures:

STRUK2 - PROGRAM TO COMPUTE SUFFICIENCY OF SUBMARINE PRESSURE HULL STRUCTURAL DESIGN PARAMETERS with External Frames

Ref: "Hull Material Trade Off Study", D Fox, Jan 94; updated Mar2006 VT
PNA 1967

This programme computes the safety factors of the following criteria given hull material, scantlings and dimentions:

a. Shell Yielding;
b. Lobar Buckling;
c. General Instability;
d. Frame Yielding; and
e. Frame Instability.

Define input variables: use standard weight plate

bulkhead spacing $L_s := L_s \cdot in$ $L_s = ▮ \, in$

frame spacing $L_f := L_f \cdot in$ $L_f = ▮ \, in$

shell thickness $t_p := t_p \cdot in$ $t_p = ▮ \, in$

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

flange tickness $t_f := t_f \cdot in$ $t_f = ▮ \, in$

flange width $w_f := w_f \cdot in$ $w_f = ▮ \, in$

web thickness $t_w := t_w \cdot in$ $t_w = ▮ \, in$

web height $h_w := h_w \cdot in$ $h_w = ▮ \, in$

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

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

Compute structural efficiency (buoyancy factor):

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

$BF = ▮$ $BF \cdot 100 = ▮$

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

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

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

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

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

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

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

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

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

Figure 121 - MathCAD Structures Module for Internal Frames

Midbay shell stress is calculated:

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

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

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

Shell stress at frames is:

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

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

$$j := 1..8$$

$$\sigma_{sy} := \begin{pmatrix} \sigma_{\phi\phi so} \\ \sigma_{\phi\phi si} \\ \sigma_{xxso} \\ \sigma_{xxsi} \\ \sigma_{\phi\phi fo} \\ \sigma_{\phi\phi fi} \\ \sigma_{xxfo} \\ \sigma_{xxfi} \end{pmatrix} \qquad \sigma_{sy} = \blacksquare\ \text{psi}$$

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:

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

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

$$\sigma_{SYM} = \blacksquare\ \text{psi}$$

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

$$\sigma_{SY} = \blacksquare\ \text{psi} \qquad \gamma_{SY} := \frac{\sigma_{SY}}{\sigma_y} \qquad \gamma_{SY} = \blacksquare$$

Figure 122 - MathCAD Structures Module for Internal Frames (cont.)

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

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

Collapse pressure:

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

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

$$\gamma_{LB} := \frac{P}{P_{cLB}} \qquad \gamma_{LB} = ▮$$

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

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

Compute effective frame spacing:

$$\gamma := \frac{P}{2 \cdot E} \cdot \left(\frac{R}{t_p}\right)^2 \cdot \sqrt{3 \cdot \left(1 - \nu^2\right)} \qquad \gamma = ▮$$

Compute clear length:

$$L_c := L_f - t_w$$

$$n_1 := 0.5 \cdot \sqrt{1 - \gamma} \qquad n_1 = ▮$$

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

$t_w = ▮ in$

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

Effective plate length:

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

$L_{eff} = ▮ in$

$F_1 = ▮$ 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: $m := \pi \cdot \frac{R}{L_s}$ $m = ▮$

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

Moments of inertia for plate,flange,web:

$$I_p := \frac{L_{eff} \cdot t_p^3}{12} \qquad I_w := \frac{t_w \cdot h_w^3}{12} \qquad I_f := \frac{w_f \cdot t_f^3}{12}$$

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

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

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

Figure 123 - MathCAD Structures Module for Internal Frames (cont.)

The critical pressure is:

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

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

$P_{cGI} = ▮ \, psi$ $\quad P_{cGI} := \min(P_{cGI})$

$P_{cGI} = ▮ \, psi$ $\quad \gamma_{GI} := \frac{P}{P_{cGI}}$ $\quad \gamma_{GI} = ▮$

PART 4 FRAME YIELDING

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

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

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: $SA := 1 - \frac{\alpha_p}{\alpha_p + \beta_f + (1 - \beta_f) \cdot F_1}$ $\quad SA = ▮$

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

Compute bending stress due to eccentricity:

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

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

Figure 124 - MathCAD Structures Module for Internal Frames (cont.)

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

$\sigma_{fr} = \blacksquare\, psi$

$\gamma_{fy} := \dfrac{\sigma_{fr}}{\sigma_y}$

This must be less than one: $\gamma_{fy} = \blacksquare$

PART 5 FRAME INSTABILITY

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

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

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

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

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

Correct the individual moments from the na:

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

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

Then total plate, frame moment of inertia is:

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

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

Compute pressure limit: $P_{cFI} := \dfrac{25 \cdot E \cdot I}{D_{na}^{\,3} \cdot L_f}$ $P_{cFI} = \blacksquare\, psi$

$\gamma_{FI} := \dfrac{P}{P_{cFI}}$

This represents how much of the safety factor was actually used: $\gamma_{FI} = \blacksquare$

Global Variable Inputs:

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

Material:(HY80) $\sigma_y \equiv 80000 \cdot \dfrac{lbf}{in^2}$ $\rho_{st} \equiv 7.8 \cdot 10^3 \cdot \dfrac{kg}{m^3}$ $E \equiv 30 \cdot 10^6 \cdot \dfrac{lbf}{in^2}$ $\nu \equiv 0.3$

bulkhead spacing $D \equiv 27 \cdot ft$ $R \equiv \dfrac{D}{2}$

Geometry Variables:

Results:

$\gamma_{SY} = \blacksquare$ $BF = \blacksquare$ $g_{SY} := \gamma_{SY}$

$\gamma_{LB} = \blacksquare$ $g_{LB} := \gamma_{LB}$

$\gamma_{GI} = \blacksquare$ $g_{GI} := \gamma_{GI}$

$\gamma_{fy} = \blacksquare$ $g_{fy} := \gamma_{fy}$

$\gamma_{FI} = \blacksquare$ $g_{FI} := \gamma_{FI}$ frame instability

Figure 125 - MathCAD Structures Module for Internal Frames (cont.)

STRUK2 - PROGRAM TO COMPUTE SUFFICIENCY OF SUBMARINE PRESSURE HULL STRUCTURAL DESIGN PARAMETERS with External Frames

Ref: "Hull Material Trade Off Study", D Fox, Jan 94; updated Mar2006 VT
PNA 1967

This programme computes the safety factors of the following criteria given hull material, scantlings and dimentions:
a. Shell Yielding;
b. Lobar Buckling;
c. General Instability;
d. Frame Yielding; and
e. Frame Instability.

Define input variables: use standard weight plate

bulkhead spacing $L_s := L_s \cdot in$ $L_s = ■ \, in$

frame spacing $L_f := L_f \cdot in$ $L_f = ■ \, in$

shell thickness $t_p := t_p \cdot in$ $t_p = ■ \, in$

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

flange tickness $t_f := t_f \cdot in$ $t_f = ■ \, in$

flange width $w_f := w_f \cdot in$ $w_f = ■ \, in$

web thickness $t_w := t_w \cdot in$ $t_w = ■ \, in$

web height $h_w := h_w \cdot in$ $h_w = ■ \, in$

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

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

Compute structural efficiency (buoyancy factor):

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

$BF = ■$ $BF \cdot 100 = ■$

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

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

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

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

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

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

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

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

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

Figure 126 - MathCAD Structures Module for External Frames

Midbay shell stress is calculated:

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

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

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

Shell stress at frames is:

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

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

$$j := 1..8$$

$$\sigma_{sy} := \begin{pmatrix} \sigma_{\phi\phi so} \\ \sigma_{\phi\phi si} \\ \sigma_{xxso} \\ \sigma_{xxsi} \\ \sigma_{\phi\phi fo} \\ \sigma_{\phi\phi fi} \\ \sigma_{xxfo} \\ \sigma_{xxfi} \end{pmatrix} \qquad \sigma_{sy} = \blacksquare \, psi$$

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:

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

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

$$\sigma_{SYM} = \blacksquare \, psi$$

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

$$\sigma_{SY} = \blacksquare \, psi \qquad \gamma_{SY} := \frac{\sigma_{SY}}{\sigma_y} \qquad \gamma_{SY} = \blacksquare$$

Figure 127 - MathCAD Structures Module for External Frames (cont.)

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

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

Collapse pressure:

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

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

$$\gamma_{LB} := \frac{P}{P_{cLB}}$$ $\gamma_{LB} = \blacksquare$

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

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

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

Compute clear length:

$L_c := L_f - t_w$

$n_1 := 0.5 \cdot \sqrt{1 - \gamma}$ $n_1 = \blacksquare$

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

$t_w = \blacksquare$ 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:

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

$L_{eff} = \blacksquare$ in

$F_1 = \blacksquare$ 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: $m := \pi \cdot \frac{R}{L_s}$ $m = \blacksquare$

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: $I_p := \frac{L_{eff} \cdot t_p^3}{12}$ $I_w := \frac{t_w \cdot h_w^3}{12}$ $I_f := \frac{w_f \cdot t_f^3}{12}$

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

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

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

Figure 128 - MathCAD Structures Module for External Frames (cont.)

The critical pressure is:

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

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

$P_{cGI} = ▮\ psi$ $\qquad P_{cGI} := \min(P_{cGI})$

$P_{cGI} = ▮\ psi$ $\qquad \gamma_{GI} := \frac{P}{P_{cGI}}$ $\qquad \gamma_{GI} = ▮$

PART 4 FRAME YIELDING

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

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

Compute direct stress:

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

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

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

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

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

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

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

Compute bending stress due to eccentricity:

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

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

Figure 129 - MathCAD Structures Module for External Frames (cont.)

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

$\sigma_{fr} = \blacksquare\ psi$

$\gamma_{fy} := \dfrac{\sigma_{fr}}{\sigma_y}$

This must be less than one: $\gamma_{fy} = \blacksquare$

PART 5 FRAME INSTABILITY

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

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

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

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

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

$y_{na2} = \blacksquare\ in$

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

$I_p := \dfrac{L_f \cdot t_p^3}{12}$ $I_p = \blacksquare\ in^4$

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: $D_{na} := D + h_w + 2 \cdot y_{na2}$ $D_{na} = \blacksquare\ ft$

Compute pressure limit:

$P_{cFI} := \dfrac{25 \cdot E \cdot I}{D_{na}^3 \cdot L_f}$ $P_{cFI} = \blacksquare\ psi$

$\gamma_{FI} := \dfrac{P}{P_{cFI}}$

This represents how much of the safety factor was actually used: $\gamma_{FI} = \blacksquare$

Global Variable Inputs:

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

Material:(HY80) $\sigma_y \equiv 80000 \cdot \dfrac{lbf}{in^2}$ $\rho_{st} \equiv 7.8 \cdot 10^3 \cdot \dfrac{kg}{m^3}$ $E \equiv 30 \cdot 10^6 \cdot \dfrac{lbf}{in^2}$ $\nu \equiv 0.3$

bulkhead spacing $D \equiv 27 \cdot ft$ $R \equiv \dfrac{D}{2}$

Geometry Variables:

Results:

$\gamma_{SY} = \blacksquare$ $BF = \blacksquare$ $g_{SY} := \gamma_{SY}$

$\gamma_{LB} = \blacksquare$ $g_{LB} := \gamma_{LB}$

$\gamma_{GI} = \blacksquare$ $g_{GI} := \gamma_{GI}$

$\gamma_{fy} = \blacksquare$ $g_{fy} := \gamma_{fy}$

$\gamma_{FI} = \blacksquare$ $g_{FI} := \gamma_{FI}$ frame instability

Figure 130 - MathCAD Structures Module for External Frames (cont.)

Propulsion:

0Submarine Propulsion Calculations - SSGX 3

Units definition and Physical Parameters

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

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

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

Input Module:

Principal characteristics: $LOA := 248 \cdot ft$ $B := 31 \cdot ft$ $D := 31 \cdot ft$ $S := 19772.5 \cdot ft^2$ $C_A := .0004$

$n_f := 2.1$ $n_a := 2.71$ $V_e := 5 \cdot knt$ $V_{esnork} := 12knt$ $W_{fsnk} := 160lton$ $W_{faip} := 621lton$

$KW_{24AVG} := 177.571 \cdot kW$ $Dp := 4.5 \cdot m$ $Dp = 14.764\,ft$ $Np := 1$ $V_{env} := 137276 \cdot ft^3$

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: $SFC_{aip} := 5.74 \cdot \frac{lbf}{(hp \cdot hr)}$ DFM in diesel engine: $SFC_{snk} := .355 \cdot \frac{lbf}{hp \cdot hr}$

Battery Capacity: $E_{battery} := 5820 \cdot kW \cdot hr$

Sprint Battery Power: $P_{battery} := 11494.5 \cdot kW$

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

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

Resistance and Power

$iii := 21$

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

Correlation Allowance

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

Viscous Resistance

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

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

Coefficient of friction, ITTC: $CF_i := \frac{0.075}{\left(\log(RN_i) - 2\right)^2}$

Viscous Resistance: $Rv_i := 0.5 \cdot \rho_{SW} \cdot (V_i)^2 \cdot S \cdot CF_i \cdot formfac$

Figure 131 - MathCAD Propulsion Module

Bare Hull Resistance

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

Effective Horsepower

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

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

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

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

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

Appendage drag (including sail) calculation:

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

For the remaining appendages, use the expression for A_{other}*C_{dother} = $App := \frac{LOA \cdot D}{1000}$ $\quad App = 7.688\,ft^2$

$$EHPMIT_i := 0.5 \cdot \rho_{SW} \cdot (V_i)^3 \cdot \left[S \cdot \left(C_{F_i} \cdot C_{frf} + C_A\right) + \left[\left(A_s \cdot C_{Ds}\right) + App\right]\right] \qquad EHPMIT_1 = 66.26\,hp$$

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

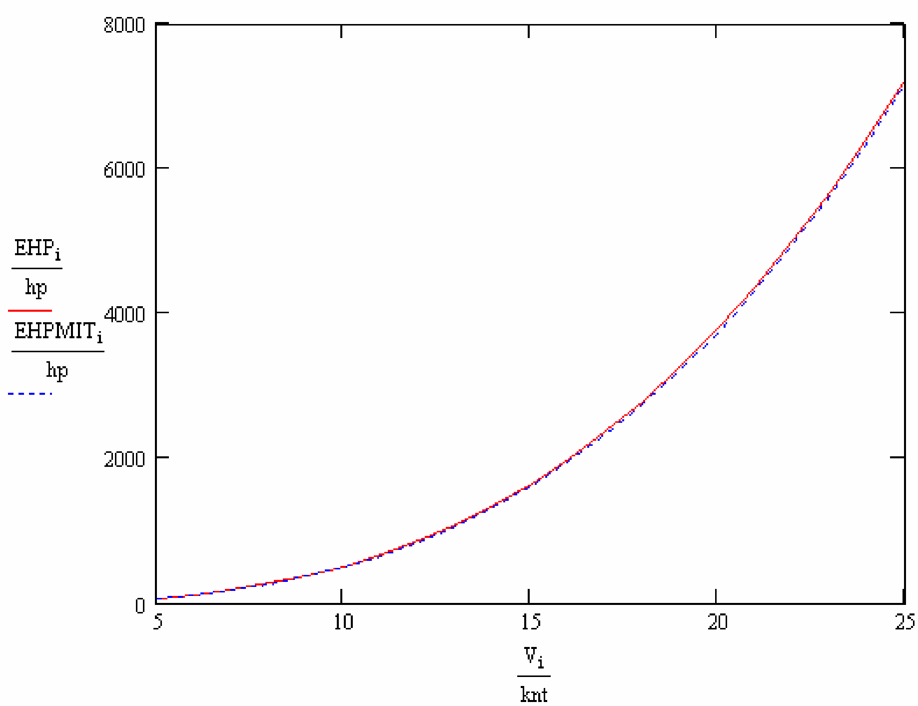

Figure 132 - MathCAD Propulsion Module (cont.)

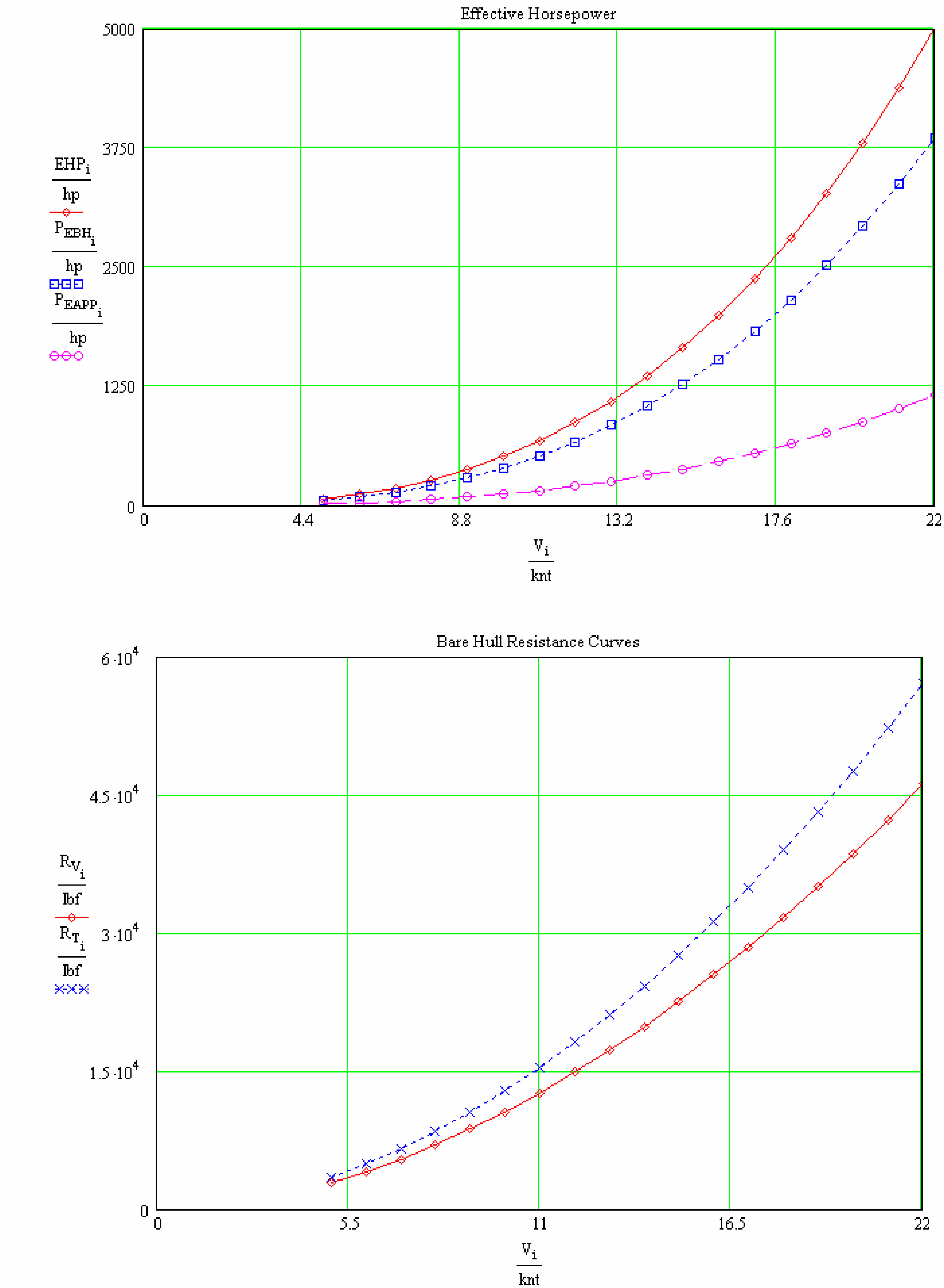

Figure 133 - MathCAD Propulsion Module (cont.)

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

$w := 1 - .371 - 1.7151 \cdot \frac{\frac{D_P}{D}}{\sqrt{C_{ws} \cdot \frac{LOA}{D}}}$ $w = 0.31$ wake fraction $w := if(w > 0.2, 0.2, w)$ $w = 0.2$

$t := 1 - .632 - 1.3766 \cdot \frac{\frac{D_P}{D}}{\sqrt{C_{ws} \cdot \frac{LOA}{D}}}$ $t = 0.112$ thrust deduction fraction - prop changes pressure distribution around hull which effectively changes the resistance of towed hull

$t := if(t < .17, .17, t)$ $t = 0.17$

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

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

$\eta_H := \frac{1 - t}{1 - w}$ $\eta_H = 1.037$ hull efficiency $THP := \frac{EHP}{\eta_H}$

	V = (knt)	THP = (hp)	T = (lbf)	V_A = (knt)
	1	1	1	1
1	5	67	$4.178 \cdot 10^3$	4
2	6	113	$5.89 \cdot 10^3$	4.8
3	7	176	$7.876 \cdot 10^3$	5.6
4	8	259	$1.013 \cdot 10^4$	6.4
5	9	364	$1.266 \cdot 10^4$	7.2
6	10	494	$1.545 \cdot 10^4$	8
7	11	650	$1.85 \cdot 10^4$	8.8
8	12	836	$2.18 \cdot 10^4$	9.6
9	13	1054	$2.537 \cdot 10^4$	10.4
10	14	1306	$2.919 \cdot 10^4$	11.2
11	15	1595	$3.326 \cdot 10^4$	12
12	16	1922	$3.759 \cdot 10^4$	12.8
13	17	2291	$4.217 \cdot 10^4$	13.6
14	18	2703	$4.699 \cdot 10^4$	14.4
15	19	3161	$5.206 \cdot 10^4$	15.2
16	20	3667	$5.738 \cdot 10^4$	16
17	21	4224	$6.295 \cdot 10^4$	16.8
18	22	4834	$6.876 \cdot 10^4$	17.6
19	23	5498	$7.481 \cdot 10^4$	18.4
20	24	6220	$8.11 \cdot 10^4$	19.2
21	25	7001	$8.764 \cdot 10^4$	20

Figure 134 - MathCAD Propulsion Module (cont.)

$T_1 = 1.858 \times 10^4 \text{newton}$ $V_1 = 5 \text{knt}$ AIP $Dp = 4.5 \text{m}$ $DEPTH_{aip} := 30 \cdot m$ $DEPTH_{snrk} := 14m$

$T_{18} = 3.058 \times 10^5 \text{newton}$ $V_{18} = 22 \text{knt}$ Sprint Thrust Endurance AIP, Sprint, Snorkel

$T_8 = 9.699 \times 10^4 \text{newton}$ $V_8 = 12 \text{knt}$ Snorkel

For B series, 7-bladed prop optimized for max open water eff at AIP speed: (EAR=1.0334, P/D=1.36, w=.2)

$\eta_{Oaip} := .741$ $n_{aipSHAFT} := 25.9 \cdot RPM$

$\eta_{Osprint} := .772$ $n_{sprintSHAFT} := 109.8 \cdot RPM$

$\eta_{Osnork} := .759$ $n_{snrkSHAFT} := 60.7 \cdot RPM$

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)... Value also optimized to prevent cavitation

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

$\eta_{Baip} := \eta_{Oaip} \cdot \eta_R$ $\eta_{Baip} = 0.763$ AIP prop efficiency behind ship = THP/DHP

$\eta_{Bsprint} := \eta_{Osprint} \cdot \eta_R$ $\eta_{Bsprint} = 0.795$ Sprint prop efficiency behind ship = THP/DHP

$\eta_{Bsnrk} := \eta_{Osnork} \cdot \eta_R$ $\eta_{Bsnrk} = 0.782$ 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

$\eta_{Daip} := \eta_H \cdot \eta_{Baip}$ $\eta_{Daip} = 0.792$

$\eta_{Dsprint} := \eta_H \cdot \eta_{Bsprint}$ $\eta_{Dsprint} = 0.825$

$\eta_{Dsnrk} := \eta_H \cdot \eta_{Bsnrk}$ $\eta_{Dsnrk} = 0.811$

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

Shaft Power - delivered at hull/stern tube

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

$SHP_{aip} = 65.216 \text{kW}$

Figure 135 - MathCAD Propulsion Module (cont.)

propulsive efficiency (Propulsive Coefficient, PC)

$\eta_{Paip} := \eta_S \cdot \eta_{Daip}$ $\eta_{Paip} = 0.792$

$\eta_{Psprint} := \eta_S \cdot \eta_{Dsprint}$ $\eta_{Psprint} = 0.825$

$\eta_{Psnrk} := \eta_S \cdot \eta_{Dsnrk}$ $\eta_{Psnrk} = 0.811$

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

Endurance Brake Power:

$BHP_{aipreq} := \frac{PMF_e \cdot SHP_{aip}}{\eta_{elec}}$ $BHP_{aipreq} = 77\,kW$ delivered by prime movers or motors

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

$V_{18} = 22\,knt$ $SHP_{sprint} = 4533\,kW$ $BHP_{req} = 6093\,kW$ $P_{IPRP} = 6570\,kW$ $n_{sprintSHAFT} = 109.8\,\frac{rev}{min}$

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

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

Specified fuel rate: $FR_{SP} := f_1 \cdot SFC_{aip}$ $FR_{SP} = 5.97\,\frac{lbf}{hp \cdot hr}$

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

$FR_{AVG} = 6.268\,\frac{lbf}{hp \cdot hr}$

Tailpipe allowance: $TPA := 0.95$

Endurance Range AIP:

$P_{aipavg} := \frac{KW_{24AVG}}{\eta_{elec}} + BHP_{aipreq}$ $P_{aipavg} = 268.074\,kW$ $E_{faip} := W_{faip} \cdot \frac{1.}{SFC_{aip}}$ $E_{faip} = 1.807 \times 10^5\,kW \cdot hr$

$E_{aip} := \frac{E_{faip}}{(f_1 \cdot 1.05 \cdot P_{aipavg})}$ $E_{aip} = 25.722\,days$ Yellow Values must be within ORD

Figure 136 - MathCAD Propulsion Module (cont.)

Sprint Range:

$MaxFuncLoad := 738 \cdot kW$ From ELA Summary for Sprint Electric Loading

$BHP_{reqsprint} := BHP_{req} + MaxFuncLoad$ $BHP_{reqsprint} = 6.831 \times 10^{3}\, kW$

$Sprint_{pow} := E_{battery} + 1000 \cdot kW \cdot hr$ Add a 1000 kW*hr produced by the Fuel cells during sprint

$E_{sprint} := \frac{Sprint_{pow}}{BHP_{reqsprint}}$ $E_{sprint} = 0.998\, hr$

$E_S := (E_{sprint}) \cdot V_{18}$ $E_S = 22\, nm$

Snorkel Range:

$SHP_{snrkv} = 797.568\, kW$

Froude # for Cdw Coef Calc:

$Fn := \frac{V_{esnork}}{(g \cdot LOA)^{.5}}$ $Fn = 0.227$

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

$C_{DW} = 1.25$

$C_W := \frac{C_{DW}}{4 \cdot \left[\left(\frac{LOA}{D}\right) - 1.3606\right] \left(\frac{LOA}{D}\right)^{2}}$ $C_W = 7.355 \times 10^{-4}$

Wave Induced:

$SHP_W := C_W \cdot S \cdot \rho_{SW} \cdot V_{esnork}^{3}$ $SHP_W = 327.351\, kW$

SHP Snorkel:

$SHP_{snrk} := SHP_{snrkv} + SHP_W$ $SHP_{snrk} = 1125\, kW$

Endurance Snork Calculation:

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

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

$P_{snkAVG} := \frac{SHP_{snrk} + KW_{24AVG}}{\eta_{elec}}$ $P_{snkAVG} = 1878\, hp$

$E_{snork} := \frac{(W_{fsnk} \cdot V_{esnork} \cdot TPA)}{P_{snkAVG} \cdot FR_{AVGsnk}}$ $E_{snork} = 5612\, nm$

Figure 137 - MathCAD Propulsion Module (cont.)

Cost:

SUBMARINE COST MODEL (Follow-Ship BCC):

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

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

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

Weight Inputs and Automation Factor:

$W_1 := 1220.51 \cdot lton$ $W_5 := 178.12 \cdot lton$

$W_2 := 334.58 \cdot lton$ $W_6 := 57.65 \cdot lton$

$W_3 := 44.59 \cdot lton$ $W_7 := 49.89 \cdot lton$

$W_4 := 159.74 \cdot lton$ $C_{man} := 0.54$

A. Additional characteristics:

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

#

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

#

B. Inflation:

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

#

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

#

C. Lead Ship Shipbuilder Labor Cost:

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

#

Structure $K_{N1} := \frac{700 \cdot hr}{lton}$ $C_{L_1} := K_{N1} \cdot W_1 \cdot Mh$ $C_{L_1} = 64.1\,Mdol$

Propulsion $K_{N2} := \frac{800 \cdot hr}{lton}$ $C_{L_2} := K_{N2} \cdot W_2 \cdot Mh$ $C_{L_2} = 20.1\,Mdol$

Electric $K_{N3} := \frac{1000 \cdot hr}{lton}$ $C_{L_3} := K_{N3} \cdot W_3 \cdot Mh$ $C_{L_3} = 3.3\,Mdol$

Command, Control, Surveillance

$K_{N4} := \frac{1500 \cdot hr}{lton}$ $C_{L_4} := K_{N4} \cdot W_4 \cdot Mh$ $C_{L_4} = 18\,Mdol$

Auxiliary $K_{N5} := \frac{1500 \cdot hr}{lton}$ $C_{L_5} := K_{N5} \cdot W_5 \cdot Mh$ $C_{L_5} = 20\,Mdol$

Figure 138 - MathCAD Cost Module

▸ **Command, Control, Surveillance**

$K_{N4} := \frac{1500 \cdot hr}{1ton}$ $C_{L_4} := K_{N4} \cdot W_4 \cdot Mh$ $C_{L_4} = 18\,Mdol$

▸ **Auxiliary** $K_{N5} := \frac{1500 \cdot hr}{1ton}$ $C_{L_5} := K_{N5} \cdot W_5 \cdot Mh$ $C_{L_5} = 20\,Mdol$

▸ **Outfit** $K_{N6} := \frac{1600 \cdot hr}{1ton}$ $C_{L_6} := K_{N6} \cdot W_6 \cdot Mh$ $C_{L_6} = 6.9\,Mdol$

▸ **Armament** $K_{N7} := \frac{1600 \cdot hr}{1ton}$ $C_{L_7} := K_{N7} \cdot W_7 \cdot Mh$ $C_{L_7} = 6\,coul$

D. Lead Ship Shipbuilder Material Cost:

Structure $K_{M1} := \frac{20 \cdot Kdol}{1ton}$ $C_{M_1} := F_I \cdot K_{M1} \cdot W_1$ $C_{M_1} = 32.9\,Mdol$

▸ **Propulsion** $K_{M2} := \frac{150 \cdot Kdol}{1ton}$ $C_{M_2} := F_I \cdot K_{M2} \cdot W_2$ $C_{M_2} = 67.5\,Mdol$

▸ **Electric** $K_{M3} := \frac{700 \cdot Kdol}{1ton}$ $C_{M_3} := F_I \cdot K_{M3} \cdot W_3$ $C_{M_3} = 42\,Mdol$

▸ **Command, Control, Surveillance**

$K_{M4} := \frac{80 \cdot Kdol}{1ton} \cdot \frac{1}{C_{man}}$ $C_{M_4} := F_I \cdot K_{M4} \cdot W_4$ $C_{M_4} = 31.9\,Mdol$

▸ **Auxiliary** $K_{M5} := \frac{100 \cdot Kdol}{1ton}$ $C_{M_5} := F_I \cdot K_{M5} \cdot W_5$ $C_{M_5} = 24\,Mdol$

▸ **Outfit** $K_{M6} := \frac{50 \cdot Kdol}{1ton}$ $C_{M_6} := F_I \cdot K_{M6} \cdot W_6$ $C_{M_6} = 3.9\,Mdol$

▸ **Armament** $K_{M7} := \frac{200 \cdot Kdol}{1ton}$ $C_{M_7} := F_I \cdot K_{M7} \cdot W_7$ $C_{M_7} = 13.4\,Mdol$

E. Integration & Assembly:

▸ **Integration (50% of labor and 0.1% of Material)**

$C_{L_8} := .50 \cdot \sum_{i=1}^{7} C_{L_i}$ $C_{L_8} = 69.2\,Mdol$

Figure 139 - MathCAD Cost Module (cont.)

$$C_{M_8} := .001 \cdot \sum_{i=1}^{7} C_{M_i} \qquad C_{M_8} = 0.2\,\text{Mdol}$$

Assembly (25% of labor and 2% of Material)

$$C_{L_9} := .25 \cdot \sum_{i=1}^{7} C_{L_i} \qquad C_{L_9} = 34.6\,\text{Mdol}$$

$$C_{M_9} := .02 \cdot \sum_{i=1}^{7} C_{M_i} \qquad C_{M_9} = 4.3\,\text{Mdol}$$

E. Direct Costs:

1. **Labor Cost:**

$$C_L := \sum_{i=1}^{9} C_{L_i} \qquad C_L = 242.2\,\text{Mdol}$$

2. **Material Cost:**

$$C_M := \sum_{i=1}^{9} C_{M_i} \qquad C_M = 220.1\,\text{Mdol}$$

3. **Direct Cost:**

$$DC := C_L + C_M \qquad DC = 462.3\,\text{Mdol}$$

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

$$IC := DC \cdot ovhd \qquad IC = 115.6\,\text{Mdol}$$

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

$$Profit := profit \cdot (IC + DC) \qquad Profit = 57.8\,\text{Mdol}$$

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

$$C_{BCC} := (1 + profit) \cdot (DC + IC) \qquad C_{BCC} = 635.6\,\text{Mdol}$$

Compare to cost constraint:

$$\frac{C_{BCC} - Cost_C}{C_{BCC}} = 5.6\,\%$$

+ Over constraint
- Under constraint

Figure 140 - MathCAD Cost Module (cont.)