Aerospace & Ocean Engineering

Design Report

Small Surface Large Combatant (SSC)

VT Total Ship Systems Engineering

SSC Large Variant
Ocean Engineering Design Project
AOE 4065/4066
AOE 5314/5904
Fall 2009 – Spring 2010
Virginia Tech Team 5

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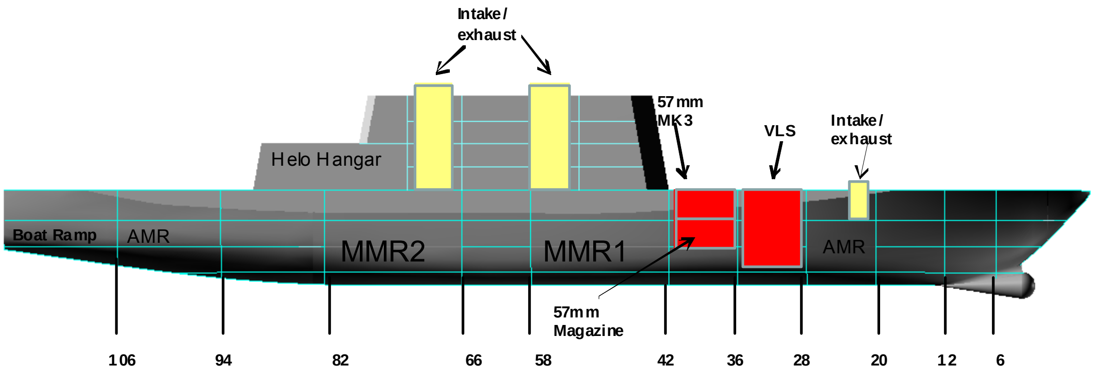
Executive Summary



This report describes the Concept Exploration and Development of a Small Surface Combatant (SSC) for the United States Navy. This concept design was completed in a two-semester ship design course at Virginia Tech.

The SSC requirement is based on the Initial Capabilities Document (ICD). The ICD is available at Appendix A.

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

The SSC design here-in is on the high end of the displacement range outlined in the ICD. This Large SSC design allows for a much more robust AAW and ASW capabilities that can significantly contribute to Carrier Strike Group defense. The trade-off for these increased capabilities is a lower sustained speed (though still within the ICD range) and increased cost, both listed in the table to the right. The SSC is more comparable to the FFG in terms of operational capability and size but with more advanced systems, increased stability, less manning, better fuel consumption at endurance speed and has the ability to conduct independent operations as outlined in the ICD. A more complete comparison between the SSC and FFG is included.

Concept Development included hull form development and analysis for intact and damage stability, structural finite element analysis, propulsion and power system development and arrangement, general arrangements, machinery arrangements, combat system definition and arrangement, seakeeping analysis, cost and producibility analysis and risk analysis. The final concept design satisfies critical operational requirements in the ORD within cost and risk constraints.

Ship Characteristic	Value
LWL	121.5 m
Beam	15.9 m
Draft	5.3 m
D10	11 m
Lightship weight	4190 MT
Full load weight	5040 MT
Sustained Speed	30.1 knots
Endurance Speed	20 knots
Endurance Range	3589 nm
Propulsion and Power	CODAG Plant 2 LM2500's & 2 CAT 3618 4 CAT 3516 SSDG's 2 CPP's
BHP	52,500 kW
Personnel	65
OMOE (Effectiveness)	0.72
OMOR (Risk)	0.26
Ship Acquisition Cost	$846 Million Lead $665 Million Follow
Life-Cycle Cost	$93 B Undiscounted $14.8 B Discounted
Combat Systems	32 Cell MK 41 VLS 57 mm Bofors Gun AN/SPY – 1E Sband Radars MK XII AIMS IFF AN/SQS 56 Sonar 2 SH-60 Helos and Hangar 1 7m RHIB w/ Boat Bay
Mission Module	1.5 X LCS

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1 Introduction, Design Process and Plan

1.1 Introduction

This report describes the concept exploration and development of a Small Surface Combatant (SSC) for the United States Navy. The SSC requirement is based on the SSC Initial Capabilities Document (ICD), and Virginia Tech SSC Acquisition Decision Memorandum (ADM), Appendix A and Appendix B. This concept design was completed in a two-semester ship design course at Virginia Tech. SSC must perform Anti-surface and subsurface warfare, Homeland Defense, ISR, Maritime Interdiction, anti-terrorism protection, provide support for special forces operations, logistics, mine warfare, and anti-air warface in Carrier Strike Groups (CSGs), Expeditionary Strike Groups (ESGs), Surface Action Groups (SAGs), and Independent Ops (IOs) It must be between 2000 and 8000 MT in displacement and must be cost effective, meaning it must cost less than $300M with an absolute ceiling of $400M. This ship will be placed to perform the missions listed above in open-ocean and littoral waters with high target densities. Therefore, SSC will function in wave heights up to SS7 and survive in SS9.

1.2 Design Philosophy, Process, and Plan

Our design project consists of two main parts: Concept and Requirements Exploration (C&RE) and Required Operational Capabilities (ROCs), or what missions the boat will be carrying out over its lifetime. C&RE provides a consistent format and methodology for making affordable multi-objective acquisition decisions and trade-offs in a non-dominated design space. It also provides practical and quantitative methods for measuring mission effectiveness and risk, as well as methods to search the design space for optimal concepts. C&RE starts with an ICD/ADM which is used to develop detailed CONOPS and Concept Development. ROCs are evaluated to create Measures of Performance (MOP) which are used to evaluate the overall effectiveness of the designs that they create. Using these MOPs, the design team identifies Design Variables (DVs), or the basic characteristics that the ship will need to accomplish all missions requirements set forth by the Navy. A Non-Dominated, design space is then created. This space (graph) allows the design team to pick the most suitable design based on the cost and the Overall Measure of Effectiveness (based on risk and the ROCs). Once the design is picked, the design team can put the details, such as mechanical systems, combat systems, electrical systems and drives, manning, and modularity.

1.3 Work Breakdown

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

Table 1 - Work Breakdown

Name	Specialization
Chaz Henderson	Mission and Mission Effectiveness
Corey Kerns	Hull, Mechanical, and Electrical, Risk
Ryan Kneifel	Combat Systems, Manning, Cost
Kevin Poole	Modularity
John Galterio	Space and Weight
Corey Kerns	Synthesis Model and Optimization

1.4 Resources

Computational and modeling tools used in this project are listed in **Error! Reference source not found.**.

Table 2 - Tools

Analysis	Software Package
Arrangement Drawings	Rhino

Hull form Development	Rhino/ASSET
Hydrostatics	HECSALV
Resistance/Power	NavCAD
Ship Motions	SWAN, SMP
Ship Synthesis Model	Model Center/ASSET
Structure Model	MAESTRO

2 Mission Definition

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

2.1 Concept of Operations

The SSC class will be able to operate as a scalable modular family of SSC ships with capabilities sufficient to satisfy the full range of specified SSC capability requirements using interchangeable, networked mission modules, and with the option of more capable AAW sensors and weapons could also be modular, but would be added in construction as a SSC variant or in a major availability using a hull plug, modular deckhouse, or modular mast(s). There variants would be able to contribute significant area AAW support for ESGs or as part of CSGs.

SSC will also be used in support of CSG/ESGs. Two to three SSC ships could be assigned to each strike group with MSCs and a carrier or amphibious ship. Their mission configuration would complement the other strike group combatants. Larger SSCs may be able to contribute to CSG and ESG area AAW defense. Tailored mission configurations could include defense against mine threats, littoral ASW threats, and small boat threats using distributed off-board systems. High speed and agility could provide tactical advantage.

SSC Surface Action Groups (SAGs) will also be utilized. They will operate as a force of networked, dispersed SSCs, providing collective flexibility, versatility and mutual support. SSC and MSC SAGs could provide defense against mine threats, littoral ASW threats, and small boat threats ahead of larger CSGs/ESGs including first-response capability to anti-access crises. High speed and agility should provide a significant tactical advantage.

During SSC Independent Operations, SSC would perform inherent (mobility) mission tasking in known threat environments including defense against mine threats, littoral ASW threats, and small boat threats. Rapid response to contingency mission tasking could provide OTH Targeting, reach-back for mission planning, insertion/extraction of USMC, Army, SOF personnel, and movement of cargo/personnel. SSC could provide ISR ahead of CSG/ESG operations and maritime interdiction/interception operations, overseas or in support of homeland defense, possibly as USCG assets.

Ship deployments could be extended with rotating crews alternately returning to CONUS. Interchangeable, networked mission modules could be changed in 2-3 days, in theater, to support force needs and changing threats. Some SSCs could be configured with more capable AAW sensors and weapons that could also be modular, but require extended availability for upgrade or change-out. Hull plugs, modular deckhouse and modular mast options should be considered for these SSC variants. They would be able to contribute significant area AAW support for ESGs or as part of CSGs.

2.2 Projected Operational Environment (POE) and Threat

SSC will be used for world-wide operation in cluttered, littoral environments or constrained bodies of water with smaller scales relative to open ocean warfare. These environments create an increased difficulty of detecting and successfully prosecuting targets. It will also be used in open ocean environments as part of CSGs and ESGs, so it must be able to withstand Sea States 1 to 9.

The threats that SSC will face are asymmetric, overlapping, and commercially available. They include threats from nations with a major military capability, or the demonstrated interest in acquiring such a capability. Major military capabilities include land, surface, and air launched cruise missiles, diesel submarines, land-attack cruise missiles, and theatre ballistic missiles. It will also face threats from smaller nations who support, promote, and perpetrate activities that cause regional instabilities detrimental to international security and/or have the potential development of nuclear weapons. These threats could be seen in small diesel/electric submarines, land-based air assets, chemical/biological/ radiological weapons, fixed and mobile SAM sites, swarming small boats, and sophisticated sea mines.

2.3 Specific Operations and Missions

The SSC will be capable of performing Underway Replenishment operations, cooperatively detect, engage, and destroy enemy aircraft with nearby AEGIS units, conduct precision missile strikes, engage and kill enemy patrol craft and small boats, perform ISR of the enemy from littoral waters, map and neutralize enemy minefields, avoid or eliminate enemy submarines using LAMPs/Sonar, conduct shore bombardment in support of amphibious assaults with ground troops, destroy incoming enemy cruise missiles, and map enemy coastlines if needed

2.4 Mission Scenarios

Mission scenarios for the primary SSC missions are provided in Table 3 through Table 6. These missions include the support of SAGs, ESGs, and CSGs as well as Independent Operations (IO).

Table 3 – SAG Mission Scenario

Day	Mission Scenario for Surface Action Group (SAG)
1-8	Transit from Home Port to forward base.
9-12	Refuel and replenish
13-20	Transit from Forward base to area of hostility
21	Avoid/Eliminate enemy submarine
22-26	Cooperatively, with Aegis unit, detect, engage and destroy enemy aircraft
26-27	Execute pre-programmed precision missile strike on inland airfield
28	Conduct precision missile strike on enemy Naval facility
29	Engage and kill enemy patrol crafts with .50-cal machine gun and harpoon missile
30-36	Receive new targeting information and conduct missile strike on update targets
37	Cooperatively, with Aegis unit, detect, engage, and destroy incoming enemy cruise missile on ARG unit
38	Detach from SAG
39-54	Perform ISR of enemy from Littoral Waters (at least 25nm from ESG).
55	Return to SAG
56-60	Receive new targeting information and conduct missile strike on update targets
58-60	Conduct precision strikes in support of ground troops

Table 4 - ESG Mission Scenario for SSC in MCM Configuration

Day	Mission Scenario for Expeditionary Strike Group (ESG) - MCM Configuration
1-8	Transit from Home Port to forward base.
9-12	Refuel and replenish
13-20	Transit from Forward base to area of hostility
21	Avoid/Eliminate enemy submarine
22-26	Map and neutralize enemy minefield to allow access to amphibious landing point
26-27	Execute pre-programmed precision missile strike on inland target
28	Conduct shore bombardment in support of amphibious landing
29	Engage and kill enemy patrol crafts with .50-cal machine gun and harpoon missile
30-36	Receive new targeting information and conduct missile strike on update targets
37	Cooperatively, with Aegis unit, detect, engage, and destroy incoming enemy cruise missile on ESG unit
38	Detach from ESG
38-48	Perform ISR of enemy from littoral waters (at least 25nm from ESG)
43-48	Search for enemy mines. Neutralize them if found.
49	Return to ESG
49-56	Map and neutralize enemy minefield to allow access to second amphibious landing point
56-60	Receive new targeting information and conduct missile strike on update targets
58-60	Conduct precision strikes in support of ground troops

Table 5 - CSG Mission Scenario for SSC in AAW Configuration

Day	Mission Scenario for Carrier Strike Group (CSG) - AAW Configuration

1-8	Transit from Home Port to forward base.
9-12	Refuel and replenish
13-20	Transit from Forward base to area of hostility
21	Search/Eliminate enemy submarine with LAMPs and Sonar
22-26	Cooperatively, with Aegis unit, detect, engage and destroy enemy aircraft
26-27	Execute pre-programmed precision TLAM missile strike on inland airfield
28	Conduct precision missile strike on enemy Naval facility
29	Perform ISR in order to facilitate the launching of aircraft from carrier
30-36	Receive new targeting information and conduct missile strike on update targets
37	Cooperatively, with Aegis unit, detect, engage, and destroy incoming enemy cruise missile on SAG unit
38	Detach from CSG
39-54	Perform ISR of enemy airfield from Littoral Waters (at least 25nm from SAG).
55	Return to CSG
56-60	Receive new targeting information and conduct missile strike on update targets
58-60	Conduct precision strikes in support of ground troops

Table 6 - IO Mission Scenario for SSC in MCM Configuration

Day	Mission Scenario for SSC Independent Operations - MCM Configuration
1-8	Transit from Home Port to forward base.
9-12	Refuel and replenish
13-20	Transit from Forward base to area of hostility
21	Search/Eliminate enemy submarine with LAMPs and Sonar
22-26	Map and neutralize enemy minefield. Conduct ISR
26-27	Execute pre-programmed precision TLAM missile strike on inland airfield
28	Conduct precision missile strike on enemy Naval facility
29	Perform ISR in order to facilitate the launching of aircraft from carrier
30-36	Receive new targeting information and conduct missile strike on update targets
37-44	Map enemy coastline. Neutralize any enemy mines that are found.
45-54	Perform ISR of enemy airfield and naval facility
56-60	Receive new targeting information and conduct missile strike on update targets
58-60	Conduct precision strikes in support of ground troops

2.5 Required Operational Capabilities

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

Table 7 - List of Required Operational Capabilities (ROCs)

ROCs	Description
AAW 1	Provide anti-air defense
AAW 1.1	Provide area anti-air defense
AAW 1.2	Support area anti-air defense
AAW 1.3	Provide unit anti-air self defense
AAW 2	Provide anti-air defense in cooperation with other forces
AAW 5	Provide passive and soft kill anti-air defense
AAW 6	Detect, identify and track air targets
AAW 9	Engage airborne threats using surface-to-air armament
AMW 6	Conduct day and night helicopter, Short/Vertical Take-off and Landing and airborne autonomous

ROCs	Description
	vehicle (AAV) operations
AMW 6.3	Conduct all-weather helo ops
AMW 6.4	Serve as a helo hangar
AMW 6.5	Serve as a helo haven
AMW 6.6	Conduct helo air refueling
AMW 12	Provide air control and coordination of air operations
AMW 14	Support/conduct Naval Surface Fire Support (NSFS) against designated targets in support of an amphibious operation
AMW 15	Provide air operations to support amphibious 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 1.3	Engage surface ships at close range (gun)
ASU 1.4	Engage surface ships with large caliber gunfire
ASU 1.5	Engage surface ships with medium caliber gunfire
ASU 1.6	Engage surface ships with minor caliber gunfire
ASU 1.9	Engage surface ships with small arms gunfire
ASU 2	Engage surface ships in cooperation with other forces
ASU 4	Detect and track a surface target
ASU 4.1	Detect and track a surface target with radar
ASU 6	Disengage, evade and avoid surface attack
ASW 1	Engage submarines
ASW 1.1	Engage submarines at long range
ASW 1.2	Engage submarines at medium range
ASW 1.3	Engage submarines at close range
ASW 4	Conduct airborne ASW/recon
ASW 5	Support airborne ASW/recon
ASW 7	Attack submarines with antisubmarine armament
ASW 7.6	Engage submarines with torpedoes
ASW 8	Disengage, evade, avoid and deceive submarines
CCC 1	Provide command and control facilities
CCC 1.6	Provide a Helicopter Direction Center (HDC)
CCC 2	Provide own unit Command and Control
CCC 3	Maintain data link capability
CCC 4	Provide communications for own unit
CCC 6	Relay communications
CCC 9	Perform cooperative engagement
CCC 21	Provide support services to other units

ROCs	Description
FSO 3	Conduct towing/search/salvage rescue operations
FSO 5	Conduct SAR operations
FSO 6	Provide explosive ordnance disposal services
FSO 7	Conduct port control functions
FSO 8	Provide routine health care
FSO 9	Provide first aid assistance
FSO 10	Provide triage of casualties/patients
FSO 11	Provide medical/surgical treatment for casualties/patients
FSO 12	Provide medical, surgical, post-operative and nursing care for casualties/ patients
FSO 13	Provide medical regulation, transport/evacuation and receipt of casualties and patients
FSO 14	Provide routine and emergency dental care
FSO 16	Support/conduct intelligence collection
INT 1	Provide intelligence
INT 2	Conduct surveillance and reconnaissance
INT 3	Process surveillance and reconnaissance information
INT 8	Disseminate surveillance and reconnaissance information
INT 9	Provide intelligence support for non-combatant evacuation operation (NEO)
INT 15	Transfer/receive cargo and personnel
LOG 2	Provide airlift of cargo and personnel
LOG 6	Conduct mine neutralization/destruction
MIW 3	Conduct mine avoidance
MIW 4	Conduct magnetic silencing (degaussing, deperming)
MIW 6	Maintain magnetic signature limits
MIW 6.7	Steam to design capacity in most fuel efficient manner
MOB 1	Support/provide aircraft for all-weather operations
MOB 2	Prevent and control damage
MOB 3	Counter and control NBC contaminants and agents
MOB 3.2	Maneuver in formation
MOB 5	Perform seamanship, airmanship and navigation tasks (navigate, anchor, mooring, scuttle, life boat/raft capacity, tow/be-towed)
MOB 7	Replenish at sea
MOB 10	Maintain health and well being of crew
MOB 12	Operate and sustain self as a forward deployed unit for an extended period of time during peace and war without shore-based support
MOB 13	Operate in day and night environments
MOB 16	Operate in heavy weather
MOB 17	Operate in full compliance of existing US and international pollution control laws and regulations
MOB 18	Provide upkeep and maintenance of own unit
NCO 3	Conduct maritime law enforcement operations
NCO 19	Conduct sensor and ECM operations
SEW 2	Conduct sensor and ECCM operations
SEW 3	Conduct coordinated SEW operations with other units
SEW 5	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

3.1.1.1 Hull Form Technology Selection Process

The Transport Factor methodology is used to identify alternative hull-form type(s). Important parameters used to calculate transport factor are payload or cargo weight, required sustained speed, endurance speed and range. Design lanes are used to specify hull-form design parameter ranges for the design space. Hull Form performance metrics are considered during the selection process. These metrics include but are not limited too available deck area, radar cross-section, cost, structural efficiency and seakeeping characteristics. Hull form modeling alternatives have also been considered. Transport Factor equations and examples are shown in Figure 1-Figure 3.

$$TF = \frac{W_{FL}V_S}{SHP_{TI}} = \frac{(W_{LS} + W_{Fuel} + W_{Cargo})V_S}{SHP_{TI}}$$

$$TF = \frac{(W_{LS} + W_{Cargo})V_S}{SHP_{TI}} + \frac{SFC_E SHP_E \frac{R}{V_E} V_S}{SHP_{TI}}$$

W_{FL} = Full load weight of the ship
W_{LS} = Light ship weight
W_{Fuel} = Ship's fuel weight
W_{Cargo} = Ship's cargo or payload weight
V_S = Sustained speed
V_E = Endurance speed
SHP_{TI} = Total installed shaft horsepower including propulsion and lift systems
R = Range at endurance speed
SFC_E = Specific fuel consumption at endurance speed

Figure 1 Transport Factor Equation

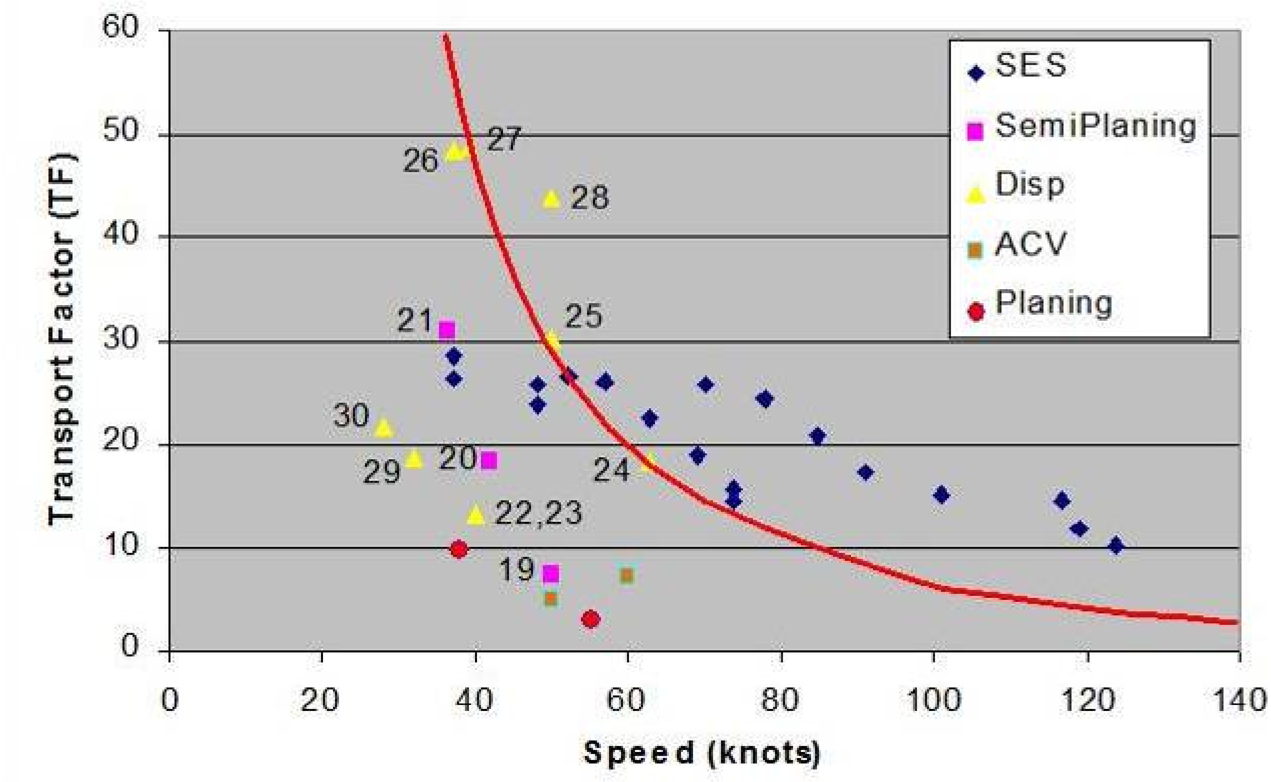


Figure 2 Transport Factor Example for Hull Type

Ship or Concept	#	Type	Speed	TF	Power	Range	Payload	Displacement
			(knots)		(SHP)	(n.mi)	(LT)	(LT)
Destriero	19	SP	50	7.32	51675	2000	260	1100
Fastship-Atlantic TG-770 (design)	20	SP (Design)	42	18.33	480000	4800	13600	30480
SOCV (Fastship-Atlantic daughter hull design)	21	SP (Design)	36.5	30.95	320000	4000	10000	39475
Aker Finnyards HSS 1500	22	Disp	40	13.02	95000	500	1300	4500
Aker Finnyards Swath 2000 (design)	23	Disp (Design)	40	13.2	125000	1000	2000	6000
INCAT 130m (design)	24	Disp (Design)	63	18.35	118008	4300	2000	5000
Sumitomo Monohull (design)	25	Disp (Design)	50	30.18	266300	5000	1000	23400
SS United States - As Built	26	Disp	37.25	48.49	240000	10000	5750	45450
SS United States 1997 (design)	27	Disp (Design)	39.5	48.85	240000	10000	5750	43178
1500' Slender Monohull (design)	28	Disp (Design)	50	43.86	525000	10000	20000	67000
DDG51	29	Disp	32	18.72	100000	4500	800	8500
FFG7	30	Disp	28	21.68	40000	6000	350	4500

Figure 3 - Transport Factor for a Selection of Hulls

3.1.1.2 Transport Factor Estimate for SSC

Transport Factor for the SSC was calculated by using the range of characteristic possibilities stated in the ICD. These ranges include a scalable modular ship from 2000-5000MT, sustained speed 30-45kts, SHP 40-70MW and an endurance range of 4000-5000nm. The resulting transport factor for the SSC ranged from 5 to 25 averaging 13.5. This Transport Factor suggests planing, semi-planing, or displacement hulls which include possibilities for monohull or multi-hull vessels. The large range for transport factor required separate analyses for a 30-35 knot ship and a 40-45 knot ship. Our team was assigned the 30-35 knot large end of the design space with displacement extended above the original range to 4000-8000MT.

3.1.1.3 Important Hullform Characteristics

There are other important hullform characteristics besides transport factor that were used to decide the final hullform. These include a hull with sufficient weight and space margin to have interchangeable modules, enough deck space for a Helo Deck area and hangar for 1-2 SH-60 and/or 1-2 VTUAV's and the ability to have stern or side launch and recovery for surface and underwater vehicles. The hullform also requires good seakeeping abilities which could include flare or hybrid hullform designs. Another consideration is the producibility of the hullform to fulfill a possible fleet of 50 SSC vessels.

Specific requirements include a moderate speed hullform for the sustained speed of 30-35 knots with a transport factor range of 13-25 which suggests a displacement monohull. Also considered is ample large object space for equipment such as VLS which also would typically require a monohull. The final requirement in large deck space to support helo or UAV operations and space for launch and recovery of other waterborne vehicles which could suggest either a multihull or monohull form**.** It was decided that a displacement monohull design best meets all of these requirements. 4000-8000 is a frigate sized ship.

3.1.1.3.1 Design Lanes (30-35kt SSC)

Typical frigate hullform design lanes are listed in Table 8. We will extend the displacement range to 8000MT and investigate the design space for 4000-8000MT listed in Table 9.

Table 8 - Frigate Design Lanes

Design Lane	Range
displacement	2000-5000 MT
TF	12 – 25.2
L/B	7.6 – 8.5
B/T	3.2 – 3.4
C_p	.54-.6
C_x	.75-.84

Table 9 - Hullform Design Space Summary (30-35kt SSC)

Design Lane	Range
Hullform Type	Monohull
Displacement	4000-8000MT
L	100-140 m
B/ T	2.9-3.2
L/B	7-10
L/D	11-14
C_p	.57-.63
C_x	.76-.85

We will generate our baseline hullforms spanning this design space using ASSET DDG-51 parent boundary curves. Hull volume, weight and performance RSMs will also be generated using ASSET.

3.1.2 Propulsion and Electrical Machinery Alternatives

We began the process of creating propulsion and electrical machinery alternatives by developing machinery general requirements and guidelines based on the IDC and ADM. We selected viable machinery alternatives based on these guidelines and developed an alternative machinery selection hierarchy. Data was gathered and developed for viable machinery alternatives by using manufacturer data, modeling each machinery alternative in an ASSET baseline design and collecting all data in a propulsion alternative data base (Excel file). This file was used to update our ship synthesis propulsion module. A machinery system trade off was performed as part of total ship synthesis and optimization.

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 design required a range of 4000-5000 nautical miles at an endurance speed of 20 knots. .Navy qualified and grade A shock certified gas turbines were considered in the alternatives as a design variable. We also considered low IR signature and possible CODAG (see Figure 4-Figure 5) options for endurance. Design for continuous operation using distillate fuel in accordance with ASTM D975, Grade 2-D; ISO 8217, F-DMA, DFM (NATO Code F-76 and JP-5 (NATO Code F-44).

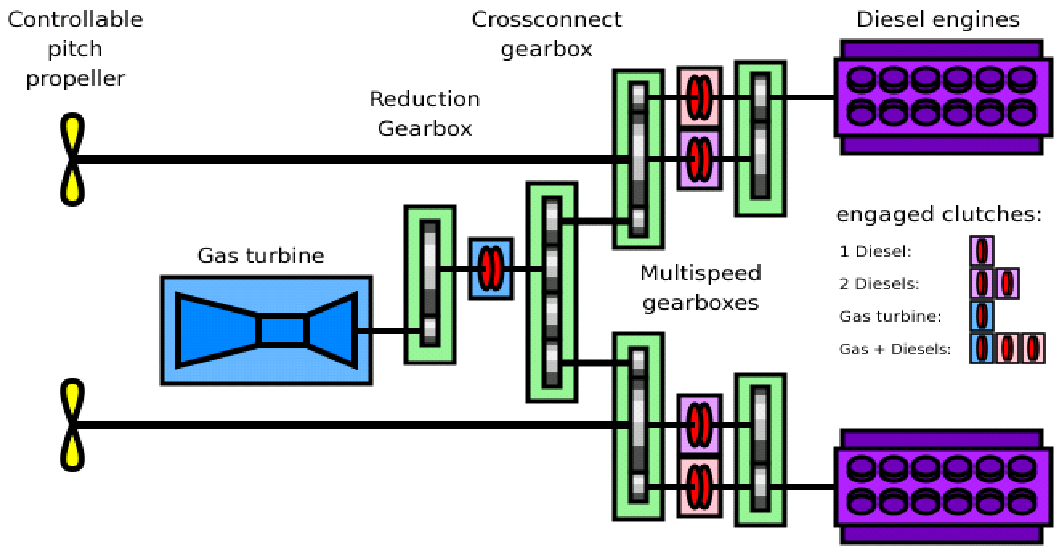


Figure 4 - CODAG sample arrangement for 2 Diesels and 1 Gas turbine connected to two shafts

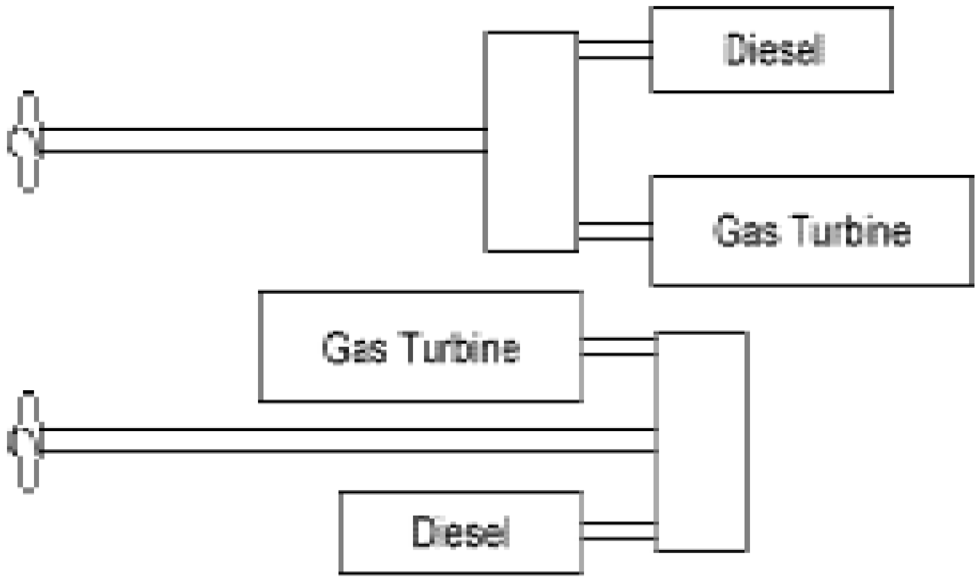


Figure 5 - CODAG sample arrangement for 1 Gas Turbine and 1 Diesel per shaft

Sustained Speed and Propulsion Power – The alternatives span a 40-70MW SHP power range. We considered only designs that met a minimum sustained speed of 30 knots in the full load condition, calm water, and clean hull using no more than 80% of the installed engine rating (MCR) of main propulsion engines or motors. The goal speed for the SSC is 35 knots.

Ship Control and Machinery Plant Automation – Control automation requirements include an integrated bridge system that encompasses integrated navigation, radio communications, interior communications, and ship maneuvering equipment and systems. This integrated bridge system must comply with the ABS Guide for One Man Bridge Operated (OMBO) Ships. Machinery plant automation must comply with ABS ACCU requirements for periodically unattended machinery spaces. Other automation requirements include continuously monitored auxiliary systems, electric plant and damage control systems monitored from the SCC, MCC and Chief Engineer's office and control systems from the MCC and local controllers.

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 may be grade A shock certified and Navy qualified by IOC.

3.1.2.2 Machinery Plant Alternatives

High speed requires high power density so we considered gas turbine engines and epicyclic (planetary) reduction gears with the possibility of CODAG for endurance. The power requirement was satisfied with 2 main engines with a power range of 20000-36000 kW each. Propulsion efficiency at 30-35 knots for displacement/semi-displacement hulls suggests standard CPP and shafting. We considered mechanical drive and IPS along with the possible combination of the two systems. With gas turbine mains we considered Diesel Gen Sets to meet the 4000-6000nm endurance range requirements.

IPS machinery plants with DC Bus, zonal distribution and permanent magnet motors were also alternatives. The IPS alternatives provide arrangement and operational flexibility, future power growth, improved fuel efficiency and survivability with moderate weight and volume penalties.

Data for Trade-Off studies was collected by creating alternative propulsion plants in a baseline ship using ASSET. Machinery plant alternatives are listed in Figure 6 with specific data in Table 10 and Table 11 with individual components displayed in Figure 7-Figure 13.

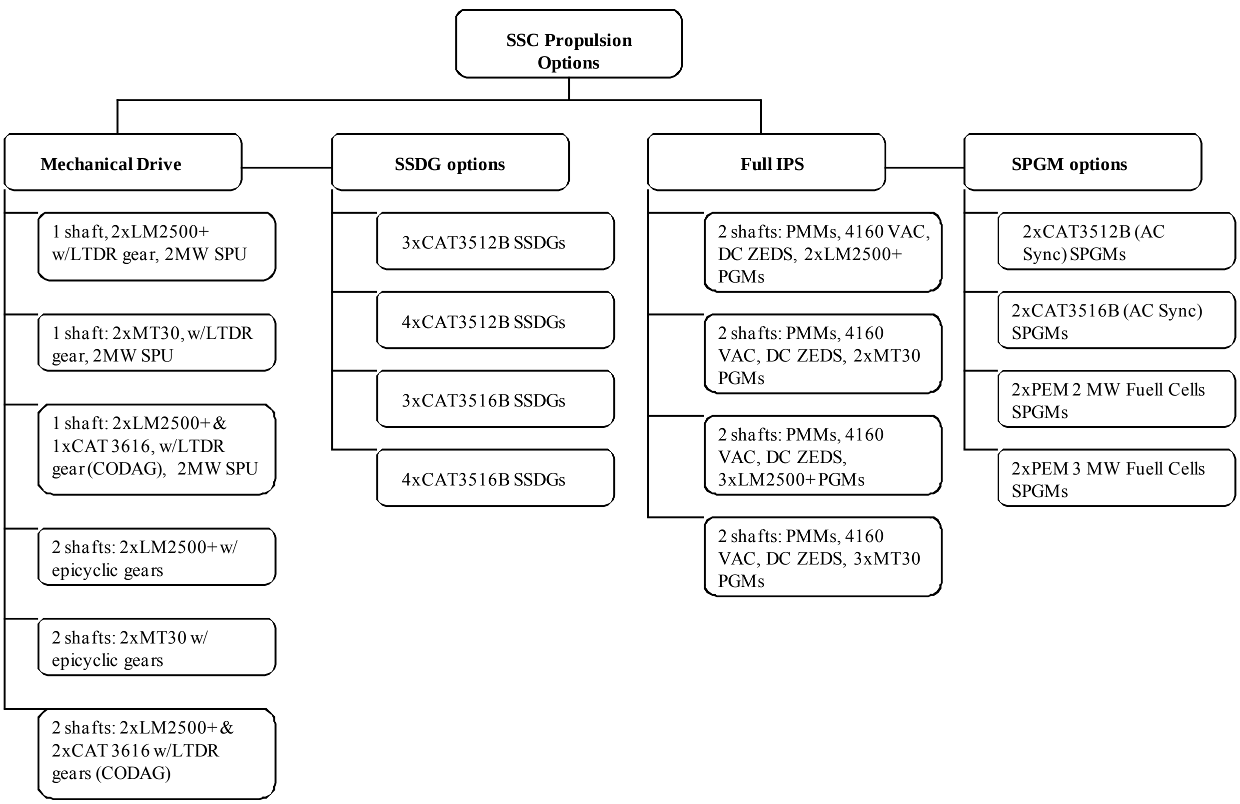


Figure 6 - Machinery Plant Alternatives

Table 10 - Propulsion Plant Data

Propulsion Option	PSYS Option	PSYStype	Nprop	Total Propulsion Engine BHP $P_{BPENGTOT}$(kw)	Endurance Brake Propulsion Power, Pbpengend (kw)	Endurance Propulsion SFC SFC_{ePE}(kg/kwhr)	Machinery Box Minimum Length L_{MB}(m)	Machinery Box Minimum Height H_{MB}(m)	Machinery Box Required Volume V_{MB}(m^3)	Basic Propulsion Machinery Weight W_{PM}(MT)	PGM Inlet and Uptake Area A_{PIE}(m^2)
2xLM2500+, LTDR, CP	1	1	1	52198	26099	0.298	14.97	6.28	1783	395.2	61.8
2xMT30, LTDR, CP	2	1	1	72000	36000	0.245	16.25	6.76	2409	515	87.0
2xLM2500+,1x CAT3616, CODAG, LTDR, CP	3	1	1	57258	31159	0.189	14.97	6.28	2117	446	67.3
2xLM2500+, Epicyclic, CP	4	1	2	52198	26099	0.298	11.74	4.00	1149	336.9	61.8
2xMT30, Epicyclic, CP	5	1	2	72000	36000	0.245	12.76	4.78	1466	433.5	87.0
2xLM2500+,2x CAT3616, CODAG, 2xLTDR, CP	6	1	2	62318	10120	0.189	14.13	6.08	1753	640.7	71.6
1xLM2500+,4160 VAC, FPP	7	2	2	26099	26099	0.298	15.89	5.80	1410	662	30.9
1xMT30,4160 VAC, FPP	8	2	2	36000	36000	0.245	15.68	5.65	1490	699	43.5
2xLM2500+,4160 VAC, FPP	9	2	2	52198	26099	0.226	15.68	5.37	2002	1047	61.8
2xMT30,4160 VAC, FPP	10	2	2	72000	36000	0.213	15.89	5.80	2969	1059	87.0

Table 11 - Electrical Plant Data

SSDG/SPGM Option	GSYS	Nssg	KWg ea	SFCssg	Machinery Box Required Volume V_{MB}(m^3) Delta	Basic Electric Machinery Weight W_{BME}(MT) or W_{PM}(MT) Delta	SSG Inlet and Exhaust Area A_{GIE}(m^2)
3xCAT3512B SSDG	1	3	1119	0.214	287	136.2	11.1
4xCAT3512B SSDG	2	4	1119	0.214	371	180.5	14.8
3xCAT3516B SSDG	3	3	1491	0.214	283	133.9	10.5
4xCAT3516B SSDG	4	4	1491	0.214	381	194.5	15.6
2xCAT3516B SPGM	5	2	1491	0.214	247	67.0	5.3
2xCAT3616 SPGM	6	2	5060	0.189	500	97.0	9.8
2x4MW PEM Fuel Cell	7	2	4000	0.154	514	99.4	16.0
2x6MW PEM Fuel Cell	8	2	6000	0.154	771	149.1	24.0

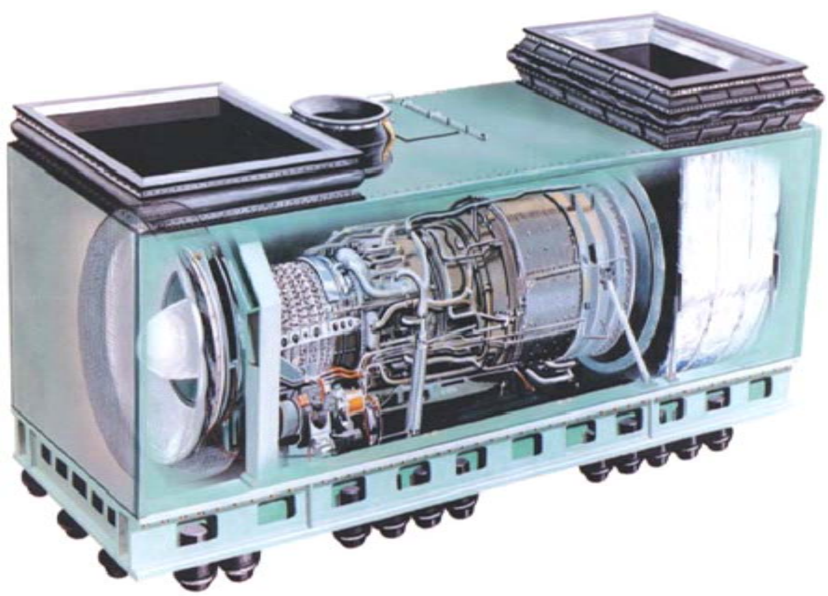


Figure 7 - LM2500+

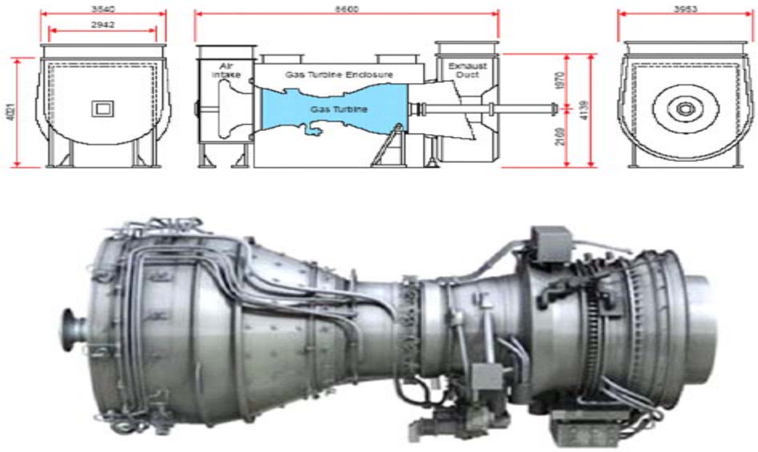


Figure 8 - MT30

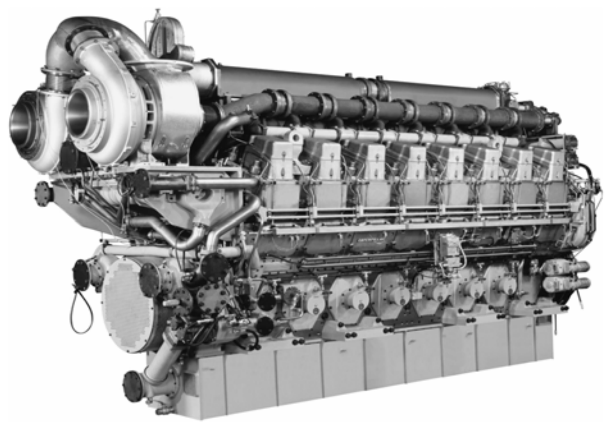


Figure 9 - CAT 3616B

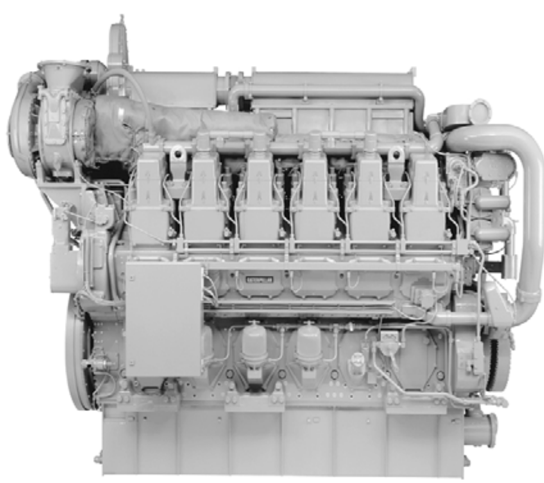


Figure 10 - CAT 3612B

Figure 11 - CAT 3516/3512B Gen Sets

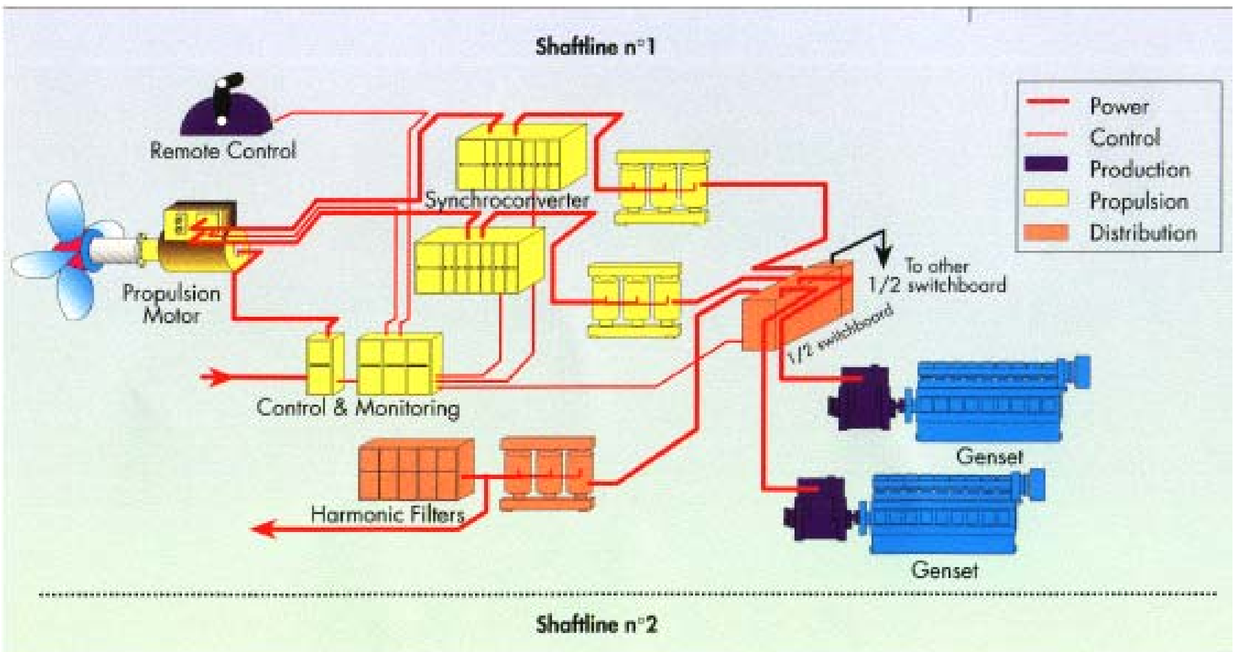


Figure 12 - Integrated Power System

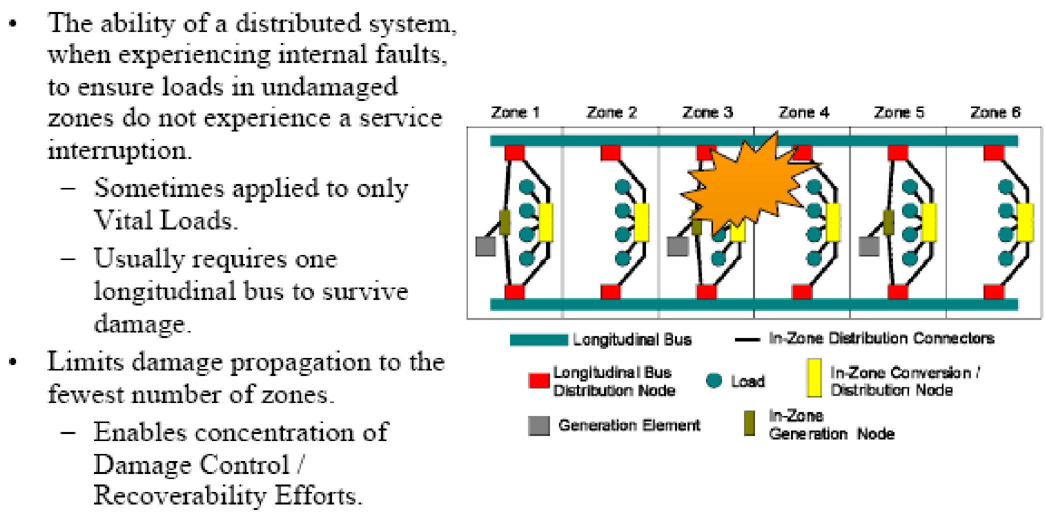


Figure 13 - Zonal Survivability

3.1.3 Automation and Manning Parameters

Manning is the greatest cost over a ships lifetime. The cost of manning is sixty percent of the Navy's budget. The largest expense incurred over a ship's lifetime is the crew. One of the issues with manning is that the manpower on a vessel can be put in harms way. Damage control and firefighting are managed by manpower with a high risk to the personnel. Job enrichment, computer literacy, and response time are all human factors that can cause the death of personnel. Another problem is the background of each sailor. Each background comes with different cultures and traditions that must be addressed in tight living spaces. The manning triad that includes watch standing, maintenance, and damage control requires a significant amount of manning. Recent developments in technology has allowed for a reduction in manpower over most areas of a ship. That said it is important in early design phases to try and reduce the number of personnel on a ship.

The use of computers or machinery in place of personnel is automation. Automation can be applied to many areas of a ship. Firefighting can be replaced by automated robot arms for fire suppression. These arms can sense heat or smoke and if used with an automated sprinkler system they can keep personnel away from harm. The response time can be reduced by using an automated system. Without the need for extra personnel during a fire manning is reduced.

Other technologies are available to help reduce manning. Watch standing technology can assist an individual with automated route planning, electronic charting, navigation, collision avoidance and electronic log keeping. Video conferencing allows for the knowledge of expert personnel without having them onboard. Computer systems can be learned on shore rather than having to have hands on experience. These tutorials can be replayed if one forgets exactly how to perform a task. Using these computer systems helps make a ship paperless. It keeps administration personnel on shore while allowing them to perform their duties electronically.

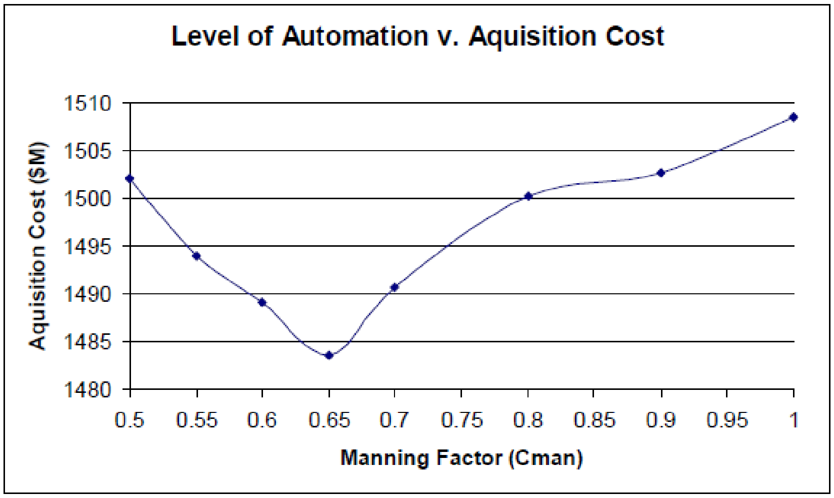


Figure 1 – Level of Automation vs. Acquisition Cost

A manning Response Surface Model (RSM) allows for the calculation of required manning. ISMAT (Integrated Simulation Manning Analysis Tool) is used to develop scenarios to test ability of the crew. It dynamically allocates each task to a crew member. A size and make up of crew is optimized for four different goals: cost, crew size, different jobs, and workload. The total crew size is calculated using the formula below:

$$NT = 374.49 + 82.06 * LevAuto - 6.09 * MAINT + 11.29 * LWLComp - 59.85 * LevAuto^2$$
$$+ 2.08 * PSYS * LWLComp - .147 * PSYS^3 + 8.52 * LevAuto^3 - .294 * ASuW * PSYS *$$
$$LevAuto + .341 * ASuw * MAINT^2 - .684 * PSYS^2 * LWLComp + .413 * PSYS * LevAuto *$$
$$CCC - .485 * MAINT * CCC * LWLComp + .210 * CCC * LWLComp^2$$

Figure 14 - “Standard” Manning Calculation

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_{AUTO}, varies from 0.5 to 1.0. It is used in the regression based manning equations shown in

Figure 15. 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. Manning calculations are shown in

Figure 15. A more detailed manning analysis is performed in concept development.

Figure 15 - “Standard” Manning Calculation

3.1.4 Combat System Alternatives

Combat systems are grouped in sections. These sections include but are not limited to: Anti-Air Warfare (AAW), Anti-Submarine Warfare (ASW), Anti-Surface Warfare (ASUW), and Light Airborne Multi-Purpose System (LAMPS).

3.1.4.1 AAW

1. **Warfighting System**	2. **Options**
3. AAW system alternatives	Option 1) AN/SPY-1E MFR – Multi Mode Radar , ICMS, AIMS IFF,AIEWS, Combat DF, 2xMK137 LCHR SRBOC/NULKA
	Option 2) SEAPAR MFR, ICMS, AIMS IFF, AIEWS, Combat DF, 2xMK137 LCHR SRBOC/NULKA
	Option 3) EADS TRS-3D C-band radar, AIMS IFF, 2xSRBOC, 2xSKWS decoy launcher, WBR 2000 ESM, COMBATSS-21, COMBAT DF

AN/SPY-1E is a multi-function phased array radar capable of search, automatic detection, transition to track, tracking of air and surface targets, and missile engagement support.

The SEAPAR is a medium to long-range, 3D multi-beam, volume search radar (VSR) which is suitable for both air surveillance, helicopter guidance, and target designation in the littoral environments. It is designed to be used with the Evolved Sea Sparrow Missiles (ESSM). It is roughly 75% smaller and lighter than Active Phased Array Radars. VSR is an S-band frequency, 3-D tracking, and long range volume search radar. It can be used for enhanced ballistic missile defense (BMD).

EADS TRS 3-D is a multimode, C-band, ship mounted, air and sea surveillance and target acquisition radar. It automatically detects and tracks both surface and airborne fast moving targets serving as stand-alone radar and can be netter with other sensors. It can also detect guided missiles, high speed patrol boats and unmanned aerial vehicles in extreme weather conditions.

Combat-SS21 is a network-enabled interoperability, with an open architectural design, and innovative capabilities proven on modern platforms. Its capabilities include anti-submarine warfare, surface warfare, anti-air warfare, mine warfare, special operations, intelligence, homeland defense, surveillance and reconnaissance.

3.1.4.2 ASUW

1. **Warfighting Systems**	2. **Options**

3. ASUW system alternatives	Option 1) MK45 5"/62 gun, AN/SPS-73, IRST, 7m RHIB, 1x30mm CIGS, MK86 GFCS, Small Arms Locker, 2x50cal Machine Guns
	Option 2) 57mm MK3 naval gun, AN/SPS-73, IRST, 7m RHIB, DORNA EOD EO/IR, Small Arms Locker, 2x50cal Machine Guns
	Option 3) 57mm MK3 naval gun, AN/SPS-73, FLIR, 7m RHIB, SEASTAR SAFIRE III E/O IR,Small Arms Locker, 2x50cal Machine Guns

AN/SPS-73 is a short-range, 2-D, surface-search/navigation radar system. At short ranges it can detect low-flying air units and provide surveillance of surface units. It provides contact range and bearing information while enabling quick and accurate determination of ownship position relative to nearby vessels and navigational hazards.

The MK 45 5IN/62 gun has a range of over 60 nautical miles with Extended Range Guided Munitions (ERGM). The gun mount is a basic Mk 45 gun mount with a 62-caliber barrel, strengthened trunnion supports, lengthened recoil stroke, an ERGM initialization interface, round identification capability, and an enhanced control system.

The MK3 Naval 57 mm Gun (Bofors) is capable of firing 2.4 kilogram shells at a rate of 220 rounds per minute at a range of more than 17 kilometres.

The Gun Fire Control System (GFCS) is used to engage surface, air, and shore targets. It can maintain a track file on up to four Surface Direct Fire (SDF) or Anti-air (AA) targets assigned by Command and Decision (C&D), and a maximum of 10 NSFS targets entered at the Gun Console (GC).

Infrared Search and Track (IRST) is a integrated sensor designed to detect and report low flying ASCMs by their heat plumes. It works by scanning the horizon +/- a few degrees but can be manually changed to search higher. It provides accurate bearing, elevation angle, and relative thermal intensity readings.

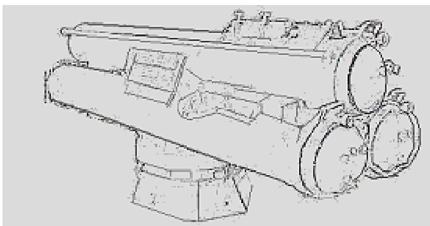
The RHIB or Rigid Hull Inflatable Boats are 7 meters longs, weigh 4400 lbs, have a beam of 9 feet 6 inches and a draft of 13 inches. Using a Cummins 6-cycle, 234 horsepower engine, it can carry up to 18 people.

3.1.4.3 ASW

4. **Warfighting Systems**	5. **Options**
6. ASW system alternatives	Option 1) SQS-56 Sonar, AN/SLQ-25 NIXIE & Tripwire, 2xMK32 SVTT, SQQ-89 UFCS, Mine Avoidance Sonar
	Option 2) AS/SLQ-25 NIXIE & Tripwire, MK32 SVTT, SQQ-89 UFCS, Mine Avoidance Sonar
	Option 3) AN/SLQ-25 NIXIE & Tripwire, Mine Avoidance Sonar

The SQS-56 is a hull mounted sonar with digital implementation, system control by a built in minicomputer, and an advanced display system. It is extremely flexible and easy to operate. It also incorporates active/passive operating capability, as well as preformed beam, digital sonar providing panoramic echo ranging and panoramic (DIMUS) passive surveillance. A single operator can search, track, classify and designate multiple targets from the active system while simultaneously maintaining anti-torpedo surveillance on the passive display.

The MK 32 Surface Vessel Torpedo Tube (SVTT) is a ASW launching system which pneumatically launches torpedoes over the side. It can handle the MK-46 and MK-50 torpedoes and stow up to three torpedoes. The torpedo tube launches torpedoes under local control or remote control from an ASW fire control system.



Nixie is a tow-behind decoy that employs an underwater acoustic projector which is towed behind the ship. It provides deceptive countermeasures against acoustic homing torpedoes and can be used in pairs or as singles.

3.1.4.4 LAMPS

Warfighting Systems	**Options**
LAMPS/helo system alternatives	Option 1) Dual SH-60, hangar

	Option 2) 1 x SH-60, hangar
	Option 3) Flight Deck

A SH-60 Seahawk is capable of ASW, search and rescue, ASUW, special operations, cargo lift, and deploying sonobuoys. It extends the ships radar capabilities. The Seahawk carries either Mk46 or Mk50 torpedoes, two 7.62mm machine guns, and AGM-119 penguin missiles.

Having a flight deck also allows for Vertical Takeoff Unmanned Aircraft Vehicle (VTUAV). It provides an extension of the ships sensors and is suited for high risk missions. It is small in size and stored easily onboard.

3.1.4.5 GMLS

Warfighting Systems	**Options**
Guided Missile Launcher	Option 1) 32xMK41 VLS
	Option 2) 16xMK48VLS
	Option 3) RAM/SEARAM 11 cell GMLS

The MK 41 VLS is a fixed vertical, multi-canister storage, firing system. It allows fast reaction to multiple threats with concentrated and continuous firepower. Each MK 41 VLS launcher has 16 cells that can be loaded with Tomahawk and Standard Missiles and vertically launched ASROC torpedos.

The SEARAM is an evolved close-in weapons system. It is designed to effectively engage future high-performance supersonic threats in the littoral environments. It has an 11 cell launcher and combines Rolling Airframe Missile (RAM) maneuverability, accuracy and extended range with the Phalanx search and track radar and IR systems and quick response capability.

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 12 are included in the ship synthesis model data base.

Table 12 - Combat System Ship Synthesis Characteristics

ROCs	Description
AAW 1	Provide anti-air defense
AAW 1.1	Provide area anti-air defense
AAW 1.2	Support area anti-air defense
AAW 1.3	Provide unit anti-air self defense
AAW 2	Provide anti-air defense in cooperation with other forces
AAW 5	Provide passive and soft kill anti-air defense
AAW 6	Detect, identify and track air targets
AAW 9	Engage airborne threats using surface-to-air armament
AMW 6	Conduct day and night helicopter, Short/Vertical Take-off and Landing and airborne autonomous vehicle (AAV) operations
AMW 6.3	Conduct all-weather helo ops
AMW 6.4	Serve as a helo hangar
AMW 6.5	Serve as a helo haven
AMW 6.6	Conduct helo air refueling
AMW 12	Provide air control and coordination of air operations
AMW 14	Support/conduct Naval Surface Fire Support (NSFS) against designated targets in support of an amphibious operation
AMW 15	Provide air operations to support amphibious 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 1.3	Engage surface ships at close range (gun)
ASU 1.4	Engage surface ships with large caliber gunfire
ASU 1.5	Engage surface ships with medium caliber gunfire
ASU 1.6	Engage surface ships with minor caliber gunfire
ASU 1.9	Engage surface ships with small arms gunfire
ASU 2	Engage surface ships in cooperation with other forces
ASU 4	Detect and track a surface target
ASU 4.1	Detect and track a surface target with radar
ASU 6	Disengage, evade and avoid surface attack
ASW 1	Engage submarines
ASW 1.1	Engage submarines at long range
ASW 1.2	Engage submarines at medium range
ASW 1.3	Engage submarines at close range
ASW 4	Conduct airborne ASW/recon

ROCs	Description
ASW 5	Support airborne ASW/recon
ASW 7	Attack submarines with antisubmarine armament
ASW 7.6	Engage submarines with torpedoes
ASW 8	Disengage, evade, avoid and deceive submarines
CCC 1	Provide command and control facilities
CCC 1.6	Provide a Helicopter Direction Center (HDC)
CCC 2	Coordinate and control the operations of the task organization or functional force to carry out assigned missions
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 8	Conduct port control functions
FSO 9	Provide routine health care
FSO 10	Provide first aid assistance
FSO 11	Provide triage of casualties/patients
FSO 12	Provide medical/surgical treatment for casualties/patients
FSO 13	Provide medical, surgical, post-operative and nursing care for casualties/ patients
FSO 14	Provide medical regulation, transport/evacuation and receipt of casualties and patients
FSO 16	Provide routine and emergency dental care
INT 1	Support/conduct intelligence collection
INT 2	Provide intelligence
INT 3	Conduct surveillance and reconnaissance
INT 8	Process surveillance and reconnaissance information
INT 9	Disseminate surveillance and reconnaissance information
INT 15	Provide intelligence support for non-combatant evacuation operation (NEO)
LOG 2	Transfer/receive cargo and personnel
LOG 6	Provide airlift of cargo and personnel
MIW 3	Conduct mine neutralization/destruction
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 2	Support/provide aircraft for all-weather operations
MOB 3	Prevent and control damage
MOB 3.2	Counter and control NBC contaminants and agents
MOB 5	Maneuver in formation
MOB 7	Perform seamanship, airmanship and navigation tasks (navigate, anchor, mooring, scuttle, life boat/raft capacity, tow/be-towed)
MOB 10	Replenish at sea
MOB 12	Maintain health and well being of crew
MOB 13	Operate and sustain self as a forward deployed unit for an extended period of time during peace and war without shore-based support

ROCs	Description
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
NCO 3	Provide upkeep and maintenance of own unit
NCO 19	Conduct maritime law enforcement operations
SEW 2	Conduct sensor and ECM operations
SEW 3	Conduct sensor and ECCM operations
SEW 5	Conduct coordinated SEW operations with other units
STW 3	Support/conduct multiple cruise missile strikes

3.1.5 Modularity Alternatives

In order to explain how modularity is going to be implemented into the ship it is necessary to define modularity and other module type terms that will be used.

Module: A module is a structurally independent building block of a larger system with well-defined interfaces. A module is connected to the rest of the system in a manner that allows independent development of the module as long as the interconnections at the interfaces meet the established standards.

Modularity: A design approach in which a system component acts as an independently operable unit, subject to periodic change. The system is designed with standardized interfaces, dimensions, and performance parameters for easy assembly and repair or flexible arrangement and use.

The concepts of Open Systems and the Modular Open Systems Approach (MOSA) are closely related to modularity. These terms are defined below:

Open System – A system that employs modular design and uses consensus-based standards for key interfaces. The system is partitioned into functional elements such that the elements within them represent the technical and functional building blocks of the system. Modular components may be replaced by other modules of similar function and capacity without requiring significant changes to the system.

Modular Open Systems Approach (MOSA) – Integrated business and technical strategy that employs a modular design and, where appropriate, defines key interfaces using widely supported, consensus-based standards that are published and maintained by a recognized industry standards organization.

There are 3 components that should be considered for designing the modularity options of the vessel. This includes the modules, the interfaces and the platforms the modules will be placed into. The modules themselves can be broken down into a number of different sizes. During the construction stages of the ship modularity can have an impact on how and when certain areas are built. The vessels hull can be broken down into different segments. The traverse structural barriers ranging from the bow of the ship to the stern would be an appropriate place to segment the hull for different packages to be placed in. Also major sub-assemblies with-in these segments can be implemented to speed up the construction process. Foreign ship building yards have now become assembly sites for modules that are built by other companies. A module’s building-block design allows it to be used almost anywhere on the ship. Weapons can be prepackaged into different containers. Radar arrays and masts for radar components can be switched depending on the type of target and proximity of the target to the ship. Habitual places for the crew can have different configurations based on the amount of manning and systems have will have to utilize. Modularity can also be adapted and configured from other ships. The capabilities of the ship can be enhanced through exchange of a module. Most modules that will be used for the vessel are standardized for all ships in the fleet. These pre-built containers can contain anything from off board vehicles to stations containing components for C4I. As long as the interface between the module and the platform is common amongst the modules they can be changed out. It also allows modernization and conversion at the component level. Changing the modules of the system would need to be done because of advancing technology, changes in the threat the vessel faces on its missions and finally modules allows this to easily be done without any major structural changes.

The Small Surface Combatant will take advantage of the newest generation hull form and will have modularity and scalability built in. It focuses on mission capabilities, affordability, and life cycle costs. The SSC is an entirely new breed of U.S. Navy warship. A fast, agile, and networked surface combatant, SSC's modular, focused-mission design will provide Combatant Commanders the required warfighting capabilities and operational flexibility to ensure maritime dominance and access for the joint force. SSC will operate with focused-mission packages that deploy manned and unmanned vehicles to execute missions as assigned by Combatant Commanders. SSC will also perform Special Operations Forces (SOF) support, high-speed transit, Maritime Interdiction Operations (MIO), Intelligence, Surveillance and Reconnaissance (ISR), and Anti-Terrorism/Force Protection

(AT/FP). While complementing capabilities of the Navy's larger multi-mission surface combatants, SSC will also be networked to share tactical information with other Navy aircraft, ships, submarines, and joint units.

SSC will transform naval operations in the littorals: The littoral battle space requires focused capabilities in greater numbers to assure access against asymmetrical threats. The SSC is envisioned to be a networked, agile, stealthy surface combatant capable of defeating anti-access and asymmetric threats in the littorals. This relatively small, high-speed combatant will complement the U.S. Navy's Aegis Fleet, DD(X) and CG(X) by operating in environments where it is less desirable to employ larger, multi-mission ships. It will have the capability to deploy independently to overseas littoral regions, remain on station for extended periods of time either with a battle group or through a forward-basing arrangement and will be capable of underway replenishment. It will operate with Carrier Strike Groups, Surface Action Groups, in groups of other similar ships, or independently for diplomatic and presence missions. Additionally, it will have the capability to operate cooperatively with the U.S. Coast Guard and Allies.

SSC will be a Modular Ship. The platform will support mine warfare, anti-submarine warfare and anti-surface boat modules. The SSC concept is presently being defined and is envisioned to be an advanced hullform employing open systems architecture modules to undertake a number of missions and to reconfigure in response to changes in mission, threat, and technology. Primary missions are those that ensure and enhance friendly force access to littoral areas. Access-focused missions include the following primary missions:

- Anti-surface warfare (ASuW) against hostile small boats
- Mine Counter Measures (MCM)
- Littoral Anti-Submarine Warfare (ASW), and may include the following secondary missions
- Intelligence, Surveillance and Reconnaissance (ISR)
- Homeland Defense / Maritime Intercept
- Special Operation Forces support
- Logistic support for movement of personnel and supplies.

The mission packages are not included in the basic SSC ship cost, but are paid for separately. The ships were projected in early 2007 to cost between $300 million and $400 million. One of the primary, focused missions of the Small Surface Combatant (SSC) will be littoral ASW. The SSC will be capable of carrying unmanned air, surface and undersea vehicles and other sensors that complement the substantial ASW capabilities planned for DD(X) and the follow on Advanced Cruiser (CG(X)). Revolutionary advances in propulsion, materials, and hull forms are being incorporated into transformational design concepts for the SSC.

SSC is significantly different from other classes of warships in a number of ways. The two most noteworthy are an aggressive spiral development acquisition process that begins deploying and employing SSC while still working out major operational and ship design details, and the design of mission modules that allows each SSC to have the flexibility and adaptability to quickly reconfigure from one warfare specialty to another.

The SSC seaframe without any mission module is a warship with warfare capabilities. It has sensors and weapons, is capable of safe navigation, receives and contributes to the Common Tactical Picture (CTP) and performs limited operational tasking consistent with its capabilities. When a mission module with support personnel is embarked, the now mission focused SSC presents considerably more capabilities than the seaframe, to include defensive capabilities.

The modular Mission Packages are a central feature of the SSC design and will provide the main war fighting capability and functionality for specific mission areas. A Mission Package may consist of a combination of modules, manned and unmanned off-board vehicles, deployable sensors, and mission manning detachments. The modules will be integrated in the ships' module stations or zones. The ship's module stations will have defined volumes, structures, and support service connections. The SSC design must meet the critical performance parameter requirements for mission reconfigurability. The ship's open system architecture will affordably maximize lifecycle flexibility for use of future systems upgrades and required mission systems change-out. This will facilitate the separate production and platform integration of modular mission systems. The major elements of the open systems architecture, module stations, functional element zones, standard interfaces, links, controls etc., will be designed to accommodate future Mission Packages, future ship flights, and technology refresh. Mission packages, to the greatest extent possible, should integrate into the Seaframe's core command and control architecture to minimize the use of unique equipment.

In all mission configurations the SSC shall have core systems that provide the capability to conduct precise navigation to avoid previously identified minefields, and enable the employment of off-board or onboard sensors to perform mine avoidance along the SSC's intended track. When equipped with the appropriate Mission Package, the SSC will conduct mine warfare missions along its intended track and in operational areas as assigned with on-board and off-board systems from deep water through the beach. Mission requirements may dictate employing different package configurations on multiple SSC's.

Mine & Inshore Warfare [MIW]

The SSC will make use of MIW environmental models and databases. The Mission Package will enable SSC to:

- Detect classify and identify surface, moored and bottom mines to permit maneuver or use of selected sea areas.
- Coordinate/support mission planning and execution with Joint and Combined assets in the absence of dedicated MIW command and control platforms. MIW mission planning will include the use of organic and remotely operated sensors. The SSC will exchange MIW tactical information including Mine Danger Areas (MDA), mine locations, mine types, environmental data, bottom maps, off-board system locations, planned search areas and confidence factors.
- Conduct mine reconnaissance.
- Perform bottom mapping.
- Perform minefield break through/punch through operations using off-board systems.
- Perform minesweeping using off-board mission system.
- Conduct precise location and reporting of a full range of MCM contact data. For example: identified mines and non-mine bottom objects.
- Perform mine neutralization.
- Employ, reconfigure, and support SH-60S for MIW operations.
- Embark an EOD detachment.
- Deploy, control, and recover off-board systems, and process data from off-board systems.

Surface Warfare

In all mission configurations the SSC shall have core systems that provide the capability to conduct multi-sensor search, detection, classification, localization and tracking of surface contacts in its assigned area of responsibility. The SSC will also have the core capability to protect itself against small boat attacks, including the use of speed and maneuverability, and have the core capability to conduct warning and disabling fire. When equipped with the appropriate Mission Package, the SSC will have the capability to engage surface threats, particularly small fast boats, to minimize threats to friendly units. The Mission Package will enable SSC to:

- Conduct integrated surface surveillance using onboard and off board sensors.
- Discriminate and identify friendly and neutral surface vessels from surface threats in high-density shipping environments.
- Conduct coordinated SUW mission planning, contribute to and receive the Common Tactical Picture, and initiate engagement of surface threats. Maintain and share situational awareness and tactical control in a coordinated SUW environment. When operating in company with other SUW assets, such as fixed-wing/rotary wing attack aircraft and maritime patrol aircraft, the SSC must be capable of planning and coordinating the SUW mission.
- Engage surface threats independently, as part of a SSC group, and in coordination with other friendly forces. This includes threats in the line-of-sight and over-the horizon. In addition to hard kill capabilities, the SSC will use agility and speed, signature management and soft kill measures to disrupt the threat's detect-to-engage sequence and conduct offensive operations against surface threats.
- Deploy, control, and recover off-board systems, and process data from off-board systems.
- Employ, reconfigure, and support SH-60 series helicopters and smaller rotary wing aircraft for SUW operations.
- Conduct SUW Battle Damage Assessment after engagements against surface threats.

The Navy is moving forward with development of the Surface Warfare (SUW) Mission Package -— a self-contained set of remote sensors and precision attack weapons designed to combat small, fast boat terrorist threats to the fleet. The SUW package is one of three “plug and fight” packages being built for the Small Surface Combatant (SSC), an advanced seaframe that uses modularity and open architecture concepts to provide the Navy with a fast, affordable, and rapidly reconfigurable ship tailored for operations in littoral waters.

When integrated into the SSC, the SUW package augments the ship’s capability to conduct surface surveillance using off-board sensors, and to engage surface threats both in the line of sight and over the horizon. The other two packages under simultaneous development for the SSC are the mine countermeasures and antisubmarine warfare packages.

The Program Executive Officer Littoral and Mine Warfare's SSC Mission Modules Program Office manages the development and acquisition of SSC mission packages. The Navy’s surface warfare package will enable the SSC to protect high-value naval assets and friendly surface vessels, both military and non-military, while conducting maritime security operations in high-density shipping environments.

The SUW mission package contains several sensor, weapon, and software components packaged in a modular fashion that easily and quickly swaps in and out of the SSC. These components include electro-optical/infrared sensors mounted on a vertical takeoff unmanned air vehicle to provide over-the-horizon detection; 30mm guns to kill close-in targets; four non-line-of-sight launching system (NLOS-LS) container launch units or “missile-in-a-box” systems, with each system containing 15 offensive missiles; and the SH-60R armed helicopter for surveillance and attack missions.

The SUW mission package has software that interfaces with the SSC command and control system to maintain and share situational awareness and tactical control in a coordinated SUW environment. The software supports SUW mission planning, receives and processes the common tactical picture, runs surveillance operations and, if required, initiates offensive actions against surface threats.

Anti-Submarine Warfare

In all mission configurations the SSC shall have core systems that provide the capability to detect threat torpedoes at sufficient range to permit initiation of effective countermeasure and/or maneuver action to defeat the threat.

When equipped with the appropriate ASW Mission Package, the SSC will conduct multi-sensor ASW detection, classification, localization, tracking and engagement of submarines throughout the water column in the littoral operating environment. The SSC will have the capability to embark ASW/multi-mission helicopters and unmanned vehicles, and will utilize Undersea Surveillance Systems, environmental models and databases. The Mission Package will enable SSC to:

- Conduct offensive ASW operations. The SSC must achieve a mission abort or sink a threat submarine, if the submarine target of interest is transiting through a designated key choke point or operating (e.g., patrolling) in a designated search/surveillance area.
- Conduct defensive ASW operations. The SSC must defeat threat submarine attacks against units operating in company with CSGs, ESGs, or SSC squadrons. The SSC must achieve a mission abort or sink a threat submarine that poses a threat to any friendly units.
- Conduct coordinated ASW, contribute to the Common Undersea Picture, maintain and share situational awareness and tactical control in a coordinated ASW environment.
- Maintain the surface picture while conducting ASW in a high-density shipping environment.
- Detect, classify, localize, track and attack diesel submarines operating on batteries in a shallow water environment to include submarines resting on the sea floor.
- Perform acoustic range prediction and ASW search planning.
- Conduct integrated undersea surveillance employing on-board and off-board systems.
- Achieve a mission kill of ASW threats through engagement with hard kill weapons from on-board and off-board systems.
- Employ signature management and soft kill systems to counter and disrupt the threat's detect-to-engage sequence in the littoral environment.
- Deploy, control, recover, and conduct day and night operations with towed and offboard systems, and process data from off-board systems.
- Employ, reconfigure, and support SH-60R in ASW operations.
- Conduct ASW Battle Damage Assessment after engagements against undersea threats.

Special Operations Forces

The SSC will have an array of inherent capabilities including Joint Littoral Mobility, Intelligence, Surveillance and Reconnaissance, Special Operations Forces support, Maritime Interdiction Operations, Homeland Defense, and Anti-Terrorism/Force Protection.

The SSC' speed, agility, and shallow draft will give it the inherent capability to provide rapid movement of small groups of personnel and material. When equipped with the appropriate Mission Package, the SSC will provide transport and limited lift capability to move personnel, supplies and equipment within the littoral operating environment. The Mission Package will enable SSC to:

- Provide facilities for secure stowage of transported materials and equipment.
- Provide habitability support for transported personnel.

- Replenishment and refueling at sea of SH-60 sized non-organic helicopters and SOF craft/boats.

Intelligence, Surveillance and Reconnaissance

In all mission configurations the SSC shall have core systems that provide that level of persistent ISR consistent with the use of installed apertures, automated data collection, storage and processing: emphasizing SSC as an information node for through-put. ISR coverage will include surface, overland and electronic domains, When equipped with the appropriate Mission Package, the SSC will provide enhanced collection and onboard processing capabilities using onboard systems and off-board vehicles and sensors and in some cases embarked detachments that include the capability to conduct Information Operations (TO), Electronic Warfare (EW), Military Deception (MILDEC), Operational Security (OPSEC), Computer Network Defense/Attack (CND/CNA), and Psychological Operations (PSYOP). The SSC will have the command and control architecture and systems to conduct ISR planning and coordination, make near-real-time input to enhance decision making, and facilitate order generation, weapons direction and ship system monitoring and control. The Mission Package will enable SSC to:

- Use organic and non-organic resources to conduct surveillance and reconnaissance operations with onboard and off board equipment.
- Use organic and non-organic resources to collect, process and disseminate strategic, operational and tactical information.
- Use ISR planning, coordination and execution tools.

Naval Special Warfare

The SSC will have the inherent core capability to provide rapid movement of small groups of SOF personnel and material due to the SSC' speed, agility, and shallow draft. When equipped with the appropriate Mission Package, the SSC will have the following SOF capabilities:

- Support Naval Special Warfare (NSW) Task Unit and surface/subsurface combatant craft and mobility platforms, or their JSOF equivalent including weapons and equipment stowage, berthing, C4ISR connectivity and space within the hull for mission planning and rehearsal.
- Launch, recover, and conduct organic maintenance on multiple embarked and organic craft specified in section 3.1.
- Support Marine Expeditionary Unit (Special Operations Capable) [MEU(SOC)] and JSOF hostage rescue operations, aircraft operations for helicopters such as the SH-60S.
- Support maritime Special Operations with the capability to refuel MK V Special Operations Craft (SOC) and follow-on (Special Operations Forces) Medium Range Insertion Craft (MRTC).
- Support SOF in Noncombatant Evacuation Operations (NEO).
- Provide compressed air (diver quality) for the SEAL Delivery Vehicle (SDV).
- Embark a Fly Away Recompression Chamber (FARC).
- Support and conduct Combat Search and Rescue (CSAR) operations.
- Support a Tactical Sensitive Compartmented Information Facility (TSCIF).

Maritime Intercept Operations

The SSC will have the inherent core capability to support MIO due to the SSC' speed, agility, and shallow draft, and have the core capability to conduct warning and disabling fire, When equipped with the proper Mission Package, the SSC will have the capability to:

- Perform maritime interception and interdiction operations.
- Provide staging areas for MIO teams.
- Provide a secure holding area for detainees.
- Employ, reconfigure, and support SH-60 and smaller rotary wing aircraft for MIO.

Homeland Defense (HLD)

The SSC will have the inherent core capability to support the HLD by providing rapid movement of small groups of personnel and material due to the SSC' speed, agility, and shallow draft. When equipped with the proper Mission Package, the SSC will perform operations to support national and coalition policy. In support of national security and HLD objectives, the ship will be capable of supporting and conducting missions in coordination with the U.S. Coast Guard (USCG). The Mission Package will enable SSC to:

- Perform maritime interception, interdiction and law enforcement operations.
- Provide staging areas for boarding teams.
- Conduct maritime Law Enforcement Operations (LEO) including counter-narcotic operations with embarked law enforcement detachment.
- Provide emergency, humanitarian, and disaster assistance.
- Support JSOF hostage rescue operations.
- Conduct marine environmental protection.
- Perform naval diplomatic presence operations.
- Employ, reconfigure, and support SH-60 and smaller rotary wing aircraft for HLD, and AT/FP operations.

Antiterrorism/Force Protection (AT/FP)

The SSC will have the inherent core capability to conduct AT/FP through its speed, agility, and shallow draft. When equipped with the proper Mission Package will:

- Perform maritime interception, interdiction and law enforcement operations.
- Provide staging areas for boarding teams.
- Conduct maritime Law Enforcement Operations (LEO) including counter-narcotic operations with embarked law enforcement detachment.
- Provide AT/FP to U.S. and friendly forces against attack in port, at anchorage, and during period of restricted maneuvering. Defensive capability will incorporate both passive design and active weapon measures, including non-lethal mechanisms, that can deter, delay, and defend against attack by terrorist and unconventional threats,

- Employ, reconfigure, and support SH-60 and smaller rotary wing aircraft for HLD, and AT/FP operations.

3.2 Design Space

The Design Variables (DVs) are variables that are changed from design to design in order to find the optimal design for the necessary capabilities for a given mission or mission package. They include the general characteristics of the ship, propulsion systems, manning and sustainability considerations, as well as the necessary war-fighting packages. They are used to develop the Measures of Performance (MOPs) and the Values of Performance (VOPs).

Table 13 - Design Variables (DVs)

DV #	DV Name	Description	Design Space
1	LWL	Length Waterline	100-140m
2	LtoB	Length to Beam ratio	7-10
3	LtoD	Length to Depth ratio	11 - 14
4	BtoT	Beam to Draft ratio	2.9-3.2
5	Cp	Prismatic Coeficient	.57-.63
6	Cx	Max Section Coef	.76-.85
7	Crd	Raised Deck Coef	.6-.8
8	VD	Deckhouse volume	5000-10000m3
9	Cdmat	Deckhouse Material	1 = Steel, 2 = Aluminum, 3 = Advanced Composite
10	PSYS	Propulsion system alternative	Option 1 – mechanical drive, 1 shaft: 2xLM2500+ w/LTDR gear, 2MW SPU (Secondary Propulsion Unit)
			Option 2 – mechanical drive, 1 shaft: 2xMT30 w/LTDR gear, 2MW SPU
			Option 3 – mechanical drive, 1 shaft: 2xLM2500+ and 1xCAT 3616 w/LTDR gear (CODAG), 2MW SPU
			Option 4 – mechanical drive, 2 shafts: 2xLM2500+ w/epicyclic gears
			Option 5 – mechanical drive, 2 shafts: 2xMT30 w/epicyclic gears
			Option 6 – mechanical drive, 2 shafts: 2xLM2500+ and 2xCAT 3616 w/LTDR gears (CODAG)
			Option 7 – IPS, 2 shafts, 2xPMMs, 4160 VAC, DC ZEDS, 1xLM2500+, 2xCAT 3616 PGMs (Power Generation Modules)
			Option 8 – IPS, 2 shafts, 2xPMMs, 4160 VAC, DC ZEDS, 1xMT30, 2xCAT 3616 PGMs
			Option 9 – IPS, 2 shafts, 2xPMMs, 4160 VAC, DC ZEDS, 3xLM2500+ PGMs
			Option 10 – IPS, 2 shafts, 2xPMMs, 4160 VAC, DC ZEDS, 3xMT30 PGMs
11	SSDG/SPGM	Ship Service Diesel Generator or Secondary Power Generation Module	Option 1 - 3xCAT3512B SSDGs (PSYStype=mech drive) or 2xCAT3512B SPGMs (PSYStype=IPS)
			Option 2 - 4xCAT3512B SSDGs (PSYStype=mech drive) or 2xCAT3516B SPGMs (PSYStype=IPS)
			Option 3 - 3xCAT3516B SSDGs (PSYStype=mech drive) or 2x2MW PEM Fuel Cell SPGMs (PSYStype=IPS)
			Option 4 - 4xCAT3516B SSDGs (PSYStype=mech drive) or 2x3MW PEM Fuel Cell SPGMs (PSYStype=IPS)
12	Ts	Stores and Provisions	30-60 days
13	CPS	Collective Protection System	0 = none, 1 = partial, 2 = full
14	Ndegaus	Degaussing system	0 = none, 1 = degaussing system
15	Cman	Manning reduction and automation factor	0.5 – 0.1
16	AAW	AAW/SEW system Alternative	Option 1) AN/SPY-1E MFR - MULTI MODE RADAR, ICMS, AIMS IFF,AIEWS, COMBAT DF, 2xMK137 LCHR SRBOC/NULKA
			Option 2) SEAPAR MFR, ICMS, AIMS IFF, AIEWS, COMBAT DF, 2xMK137 LCHR SRBOC/NULKA
			Option 3) EADS TRS-3D C-band radar, AIMS IFF, 2xSRBOC, 2xSKWS decoy launcher, WBR 2000 ESM, COMBATSS-21, COMBAT DF
17	ASUW	ASUW system alternative	Option 1) MK45 5"/62 gun, AN/SPS-73, IRST, 7m RHIB, 1x30mm CIGS, MK86 GFCS, Small Arms Locker, 2x50cal Machine Guns
			Option 2) 57mm MK3 naval gun, AN/SPS-73, IRST, 7m RHIB, DORNA EOD EO/IR, Small Arms Locker, 2x50cal Machine Guns
			Option 3) 57mm MK3 naval gun, AN/SPS-73, FLIR, 7m RHIB, SEASTAR SAFIRE III E/O IR,Small Arms Locker, 2x50cal Machine Guns
18	ASW	ASW/MCM system alternative	Option 1) SQS-56 Sonar, AN/SLQ-25 NIXIE & Tripwire, 2xMK32 SVTT, SQQ-89 UFCS, Mine Avoidance Sonar
			Option 2) AS/SLQ-25 NIXIE & Tripwire, MK32 SVTT, SQQ-89 UFCS, Mine Avoidance Sonar
			Option 3) AN/SLQ-25 NIXIE & Tripwire, Mine Avoidance Sonar
19	CCC	C4ISR system alternatives	Option 1) Comm Suite Level A, CTSCE, Cooperative Engagement
			Option 2) Comm Suite Level B, CTSCE, Cooperative Engagement
20	LAMPS	LAMPS system alternatives	Option 1) 2x Embarked LAMPS w/Hangar
			Option 2) 1x Embarked LAMPS w/Hangar
			Option 3) LAMPS haven (flight deck)
21	GMLS	Guided Missile Launcher Alternatives	Option 1) 32xMK41 VLS
			Option 2) 16xMK48VLS
			Option 3) RAM/SEARAM 11 cell GMLS
22	MISMOD	Mission Modular Space and Weight	Option 1) 1.5xLCS
			Option 2) 1xLCS
			Option 3) 0.5xLCS
23	C4IMOD	Computer and Informations Systems Compartment Modularity	Option 1) C4I Raft System
			Option 2) C4I Track System
			Option 3) Conventional Install
24	HMEMOD	Hull and Mechanical Spaces Modularity	Option 1) Mechanical Room Deck Racks
			Option 2) HM&E Palletized
			Option 3) HM&E Component Modules
			Option 4) Conventional Install
25	HABMOD	Habitat/Living Quarters Modularity	Option 1) Habitat Track System
			Option 2) Modular Habitat Spaces
			Option 3) Conventional Install
26	WEAPMOD	Weapons Modularity	Option 1) Maximum Margin and Interface Connectivity
			Option 2) Minimum Margin and Interface Connection
			Option 3) Same/Similar Weapon-Only Modularity
			Option 4) Conventional Install
27	SENSMOD	Sensor Systems Modularity	Option 1) Modular Sensors
			Option 2) Modular Mast
			Option 3) Conventional Install

3.3 Ship Synthesis Model

The primary functions of a synthesis model are to ensure balance and feasibility while providing a means for engineering analysis of the design. By ensuring balance, or a balanced design, we mean to ensure that basic principles are met, such as; displacement equals weight, the design has sufficient space, sufficient volume and has adequate stability. For feasibility we mean to ensure that the cost and risk associated with the design are acceptable. The ability to conduct an engineering analysis on a design is what gives us the ability to determine the cost, risk, stability, volume, etc. and hence the balance and feasibility of the design.

The ship synthesis model for the SSC large is shown in Figure 16. The model in includes both fortran modules and response surface models linked together in the Model Center environment. Response Surface Model (RSM) are parametric (regression) models to inexpensively ``mimic'' the more complex workings of a simulation or experimental data. The RSM's in this model were developed by running ASSET with Model Center. The RSM's are then linked to specific modules and take the place of more complex calculations that would normally take place in that module.

The Input module is the first module and it does not conduct calculations but acts as a single point of input for data to the rest of the module. This data can be entered by hand or can take new data from a Multi-Objective Genetic Optimizer, which is linked at the end of the model, to rerun an optimized design.

The Combat Systems and Propulsion modules use data tables developed in ASSET using a baseline design and varying combat system components or machinery components respectively. These modules pull specific systems into the synthesis module where they can be analyzed for balance and feasibility within an optimized ship design.

The Hull module conducts simple naval architecture calculations that are provided to other modules. These calculations include surface area, full load displacement and block coefficient. Linked to the Hull module are RSM's for hull volume and bare hull structural weight.

The Space Available module calculates the volume of the hull, total ship volume, height and volume of the machinery box, depth at station 10, and the average depth for the ship.

The Electric module calculates power requirements for the ship with the exception of the combat systems power requirements. This module also conducts the ship manning calculation. This module is preceded by RSM's for effective horsepower, kilowatts, and propulsive coefficient. These RSM's take the place of what would be a Resistance module.

The Weight module requires the most inputs and provides the most outputs. Some of the inputs this module requires are the payload weights and vertical centers of gravity for the combat systems. Among the outputs are KG, KB, VCG, and GM which are all critical to establishing the design ship's initial stability. It also calculates the weights of the single digit weight groups and the loads, such as; fuel, water, etc. The Weight module is linked to RSM's for W320, W330, W4NP, W5, W6 and RSM's for weights for internal communications (1150), human support (2000), ship support (3000) and auxiliaries (4300).

The Tankage module takes the weight of the fuel from the Weight module and calculates the total tank volume, fuel volume, endurance range, gallons of fuel burned a year, and the average brake horsepower.

The Space Required module compares deck house area available versus area required along with total area available versus area required.

The Feasibility module brings together balance related parameters from previous modules that include space, weight, and performance threshold requirements. The modules outputs are error fractions. These fractions need to be greater than or equal to zero for the ship to be feasible/balanced.

The OMOE and Risk modules calculate the overall measure of effectiveness and risk respectively. The final module before the optimizer is the Cost module. This module calculates the cost of the ship, total life cycle costs, cost of manning and the cost of follow on ships

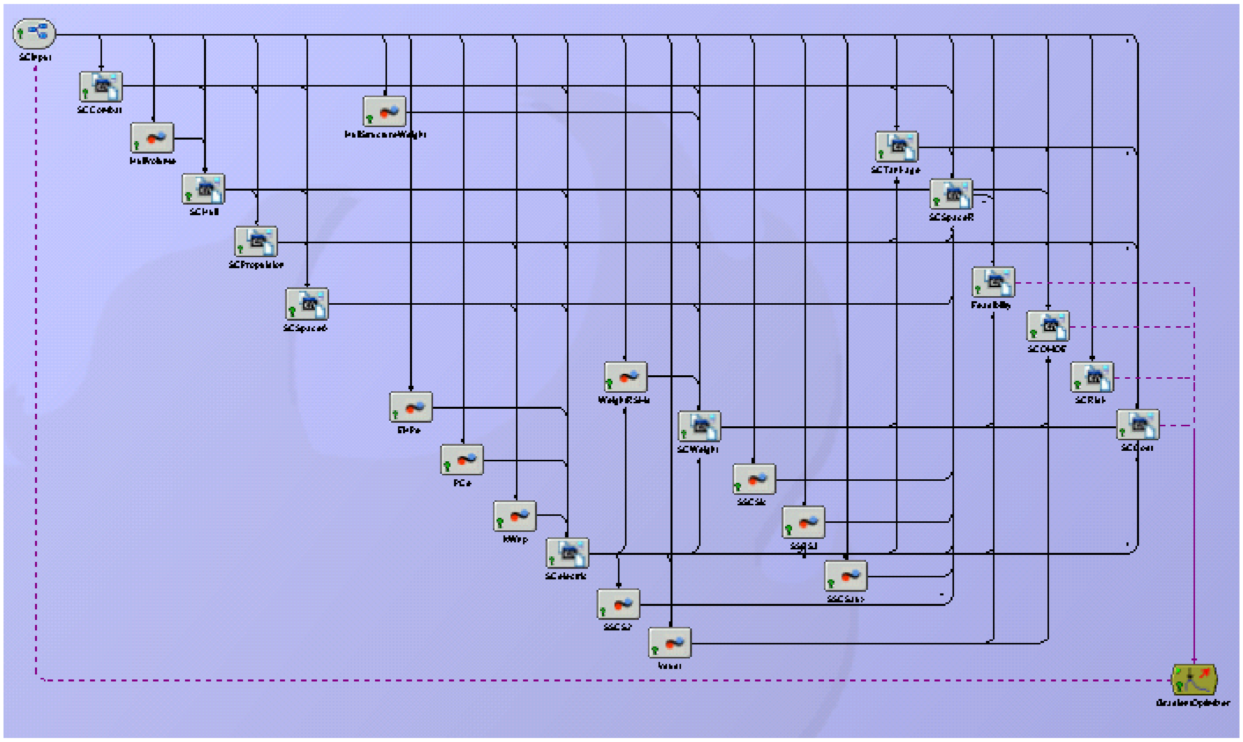


Figure 16 - Ship Synthesis Model in Model Center (MC)

3.4 Objective Attributes

3.4.1 Overall Measure of Effectiveness (OMOE)

The Overall Measure of Effectiveness (OMOE) is a single overall figure of merit index (0-1.0) describing ship effectiveness for specified missions. In order to calculate the OMOE, we take our Measures of Performance (MOPs), which are ship or system performance metrics in required capabilities that are independent of the mission (speed, range, number of missiles), and our Values of Performance (VOP), which are figure of merit indices (0-1.0) specifying the value of a specific MOP to a specific mission area for a specific mission type, and insert these values into the following equation:

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

Ideally, war-gaming simulations would be used to predict measures of effectiveness for the matrix of ship performance inputs (DOE) in a series of probabilistic scenarios. A regression analysis (RSM) would then be applied to the results in order to define the mathematical relationship between the input ship MOPs and output effectiveness. However, due to constraints, we used expert opinion to integrate these diverse inputs and assess the value or utility of ship MOPs for a given mission, force, and threat. These values are detailed in Tables 5 and 6.

Table 14 - ROC/MOP/DV Summary

ROC	Description	MOP	Related DV	Goal	Threshold
MOB 1	Steam to design capacity in most fuel efficient manner	MOP 15 - Es	LtoB	LtoB=10	LtoB=7
		MOP 15 - Es	LtoD	LtoD=17.8	LtoD=10.75
		MOP 15 - Es	BtoT	BtoT=3.2	BtoT=2.8
		MOP 15 - Es	PSYS	PSYS=1	PSYS=6

MOB 2	Support/provide aircraft for all-weather operations	MOP 8 - Magnetic	LAMPS	LAMPS=1	LAMPS=3
MOB 3	Prevent and control damage	MOP 11 - Seakeeping and Stability	LtoB	LtoB=7	LtoB=10
		MOP 11 - Seakeeping and Stability	LtoD	LtoD=10.75	LtoD=17.8
		MOP 11 - Seakeeping and Stability	BtoT	BtoT=2.8	BtoT=3.2
		MOP 10 - RCS	VD	VD=200,000ft3	VD=140,000ft3
		MOP 12 - VUL	Cdmat	Cdmat=1	Cdmat=2 or 3
		MOP 7 - IR	PSYS	PSYS=1	PSYS=6
		MOP 12 - VUL	Ndegaus	Ndegaus=1	Ndegaus=0
		MOP 12 - VUL	Cman	Cman=0.1	Cman=0.5
MOB 3.2	Counter and control NBC contaminants and agents	MOP 9 - NBC	CPS	Ncps=2	Ncps=0
MOB 5	Maneuver in formation	Required in All Designs			
MOB 7	Perform seamanship, airmanship and navigation tasks (navigate, anchor, mooring, scuttle, life boat/raft capacity, tow/be-towed)	Required in All Designs			
MOB 12	Maintain health and well being of crew	Required in All Designs			
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	MOP 15 - Es	LtoB	LtoB=10	LtoB=7
		MOP 15 - Es	LtoD	LtoD=17.8	LtoD=10.75
		MOP 15 - Es	BtoT	BtoT=3.2	BtoT=2.8
		MOP 15 - Es	PSYS	PSYS=1	PSYS=6
		MOP 14 - Ts	Ts	Ts=21 days	Ts=14 days
MOB 16	Operate in day and night environments	Required in All Designs			
MOB 17	Operate in heavy weather	MOP 11 - Seakeeping and Stability	LtoB	LtoB=7	LtoB=10
		MOP 11 - Seakeeping and Stability	LtoD	LtoD=10.75	LtoD=17.8

		MOP 11 - Seakeeping and Stability	BtoT	BtoT=2.8	BtoT=3.2
MOB 18	Operate in full compliance of existing US and international pollution control laws and regulations	Required in All Designs			
AAW 1.3	Provide unit anti-air self defense	MOP 1 - AAW	AAW/SEW	AAW/SEW=1	AAW/SEW=4
AAW 2	Provide anti-air defense in cooperation with other forces	MOP 1 - AAW MOP 1 - AAW	AAW/SEW C4ISR	AAW/SEW=1 C4I=1	AAW/SEW=4 C4I=2
AAW 5	Provide passive and soft kill anti-air defense	MOP 1 - AAW	AAW/SEW	AAW/SEW=1	AAW/SEW=4
AAW 6	Detect, identify and track air targets	MOP 1 - AAW	AAW/SEW	AAW/SEW=1	AAW/SEW=4
AAW 9	Engage airborne threats using surface-to-air armament	MOP 1 - AAW	AAW/SEW	AAW/SEW=1	AAW/SEW=4
ASU 1	Engage surface threats with anti-surface armaments	MOP 2 - ASUW MOP 2 - ASUW	ASUW LAMPS	ASUW=1 LAMPS=1	ASUW=3 LAMPS=3
ASU 1.3	Engage surface ships at close range (gun)	MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3
ASU 1.5	Engage surface ships with medium caliber gunfire	MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3
ASU 1.6	Engage surface ships with minor caliber gunfire	MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3
ASU 1.9	Engage surface ships with small arms gunfire	MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3
ASU 2	Engage surface ships in cooperation with other forces	MOP 2 - ASUW MOP 4 - C4ISR	ASUW C4ISR	ASUW=1 C4ISR=1	ASUW=3 C4ISR=2
ASU 4.1	Detect and track a surface target with radar	MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3

		MOP 2 - ASUW	LAMPS	LAMPS=1	LAMPS=3
ASU 6	Disengage, evade and avoid surface attack	MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3
ASW 1.3	Engage submarines at close range	MOP 3 - ASW	LAMPS	LAMPS=1	LAMPS=3
ASW 4	Conduct airborne ASW/recon	MOP 3 - ASW MOP 3 - ASW MOP 3 - ASW	LAMPS ASW/MCM C4ISR	LAMPS=1 ASW/MCM=1 C4ISR=1	LAMPS=3 ASW/MCM=4 C4ISR=2
ASW 5	Support airborne ASW/recon	MOP 3 - ASW MOP 3 - ASW	LAMPS C4ISR	LAMPS=1 C4ISR=1	LAMPS=3 C4ISR=2
ASW 8	Disengage, evade, avoid and deceive submarines	MOP 13 - Vs MOP 13 - Vs MOP 13 - Vs MOP 13 - Vs MOP 3 - ASW	LtoB LtoD BtoT PSYS ASW/MCM	LtoB=10 LtoD=17.8 BtoT=3.2 PSYS=1 ASW/MCM=1	LtoB=7 LtoD=10.75 BtoT=2.8 PSYS=6 ASW/MCM=4
MIW 4	Conduct mine avoidance	MOP 3 - ASW	ASW/MCM	ASW/MCM=1	ASW/MCM=4
MIW 6.7	Maintain magnetic signature limits	MOP 12 - VUL MOP 12 - VUL	Cdmat Ndegaus	Cdmat=2 or 3 Ndegaus=1	Cdmat=1 Ndegaus=0
CCC 1	Provide command and control facilities	MOP 4 - C4ISR	C4ISR	C4ISR=1	C4ISR=2
CCC 3	Provide own unit Command and Control	MOP 4 - C4ISR	C4ISR	C4ISR=1	C4ISR=2
CCC 4	Maintain data link capability	MOP 4 - C4ISR	C4ISR	C4ISR=1	C4ISR=2
CCC 6	Provide communications for own unit	MOP 4 - C4ISR	C4ISR	C4ISR=1	C4ISR=2
CCC 9	Relay communications	MOP 4 - C4ISR	C4ISR	C4ISR=1	C4ISR=2
CCC 21	Perform cooperative engagement	MOP 4 - C4ISR	C4ISR	C4ISR=1	C4ISR=2
SEW 2	Conduct sensor and ECM operations	MOP 1 - AAW	AAW/SEW	AAW/SEW=1	AAW/SEW=4
SEW 3	Conduct sensor and ECCM operations	MOP 1 - AAW	AAW/SEW	AAW/SEW=1	AAW/SEW=4
FSO 6	Conduct SAR operations	MOP 5 - FSO/NCO	LAMPS	LAMPS=1	LAMPS=3
FSO 8	Conduct port control functions	MOP 5 - FSO/NCO	C4ISR	C4ISR=1	C4ISR=2

		MOP 13 - Vs MOP 13 - Vs MOP 13 - Vs MOP 13 - Vs MOP 2 - ASUW MOP 5 - FSO/NCO	LtoB LtoD BtoT PSYS ASUW LAMPS	LtoB=10 LtoD=17.8 BtoT=3.2 PSYS=1 ASUW=1 LAMPS=1	LtoB=7 LtoD=10.75 BtoT=2.8 PSYS=6 ASUW=3 LAMPS=1
INT 1	Support/conduct intelligence collection	MOP 6 - MCM MOP 6 - MCM	LAMPS C4ISR	LAMPS=1 C4ISR=1	LAMPS=3 C4ISR=2
INT 2	Provide intelligence	MOP 6 - MCM MOP 6 - MCM	LAMPS C4ISR	LAMPS=1 C4ISR=1	LAMPS=3 C4ISR=2
INT 3	Conduct surveillance and reconnaissance	MOP 6 - MCM MOP 6 - MCM	LAMPS C4ISR	LAMPS=1 C4ISR=1	LAMPS=3 C4ISR=2
LOG 1	Conduct underway replenishment	Required in All Designs			
LOG 2	Transfer/receive cargo and personnel (CONREP)	Required in All Designs			
LOG 6	Provide airlift of cargo and personnel (VERTREP)	MOP 8 - Magnetic	LAMPS	LAMPS=1	LAMPS=3
NCO 3	Provide upkeep and maintenance of own unit	Required in All Designs			
NCO 19	Conduct maritime law enforcement operations	MOP 2 - ASUW MOP 13 - Vs MOP 13 - Vs MOP 13 - Vs MOP 13 - Vs	ASUW LtoB LtoD BtoT PSYS	ASUW=1 LtoB=10 LtoD=17.8 BtoT=3.2 PSYS=1	ASUW=3 LtoB=7 LtoD=10.75 BtoT=2.8 PSYS=6

Table 15 - MOP Table

MOP#	MOP	Goal	Threshold	Related DV
1	AAW	AAW/SEW=1 C4I=1	AAW/SEW=3 C4I=2	AAW/SEW option C4I option
2	ASUW/NSFS	ASUW=1 Mod SUW=1 LAMPS=1 C4I=1	ASUW=1 Mod SUW=5 LAMPS=2 C4I=2	ASUW option Mod SUW option LAMPS option C4I option
3	ASW/MCM	ASW/MCM=1 Mod MIW/MCM=1	ASW/MCM=2 Mod MIW/MCM=6	ASW/MCM option Mod MIW/MCM option

		Mod ASW=1 LAMPS=1 C4I=1	Mod ASW=4 LAMPS=2 C4I=2	Mod ASW option LAMPS option C4I option
4	C4ISR	C4I=1	C4I=2	C4I option
5	MISMOD	LAMPS=1	LAMPS=2	LAMPS option
6	MCM	LAMPS=1 C4I=1	LAMPS=2 C4I=2	LAMPS option C4I option
7	IR	SPGM=1	SPGM=0	SPGM Option
8	Magnetic	Ndegaus=1	Ndegaus = 0	Degaussing Option
9	NBC	Ncps=2	Ncps=0	CPS option
10	RCS	VD=4000	VD=8000	Deckhouse volume, m^3
11	Seakeeping and Stability	LtoB=8 LtoD=12 BtoD=3.4	LtoB=6.5 LtoD=8.5 BtoD=3	LtoB LtoD BtoD
12	VUL (Vulnerability)	Cdmat=1	Cdmat=3	Ship material
13	Vs (Sprint Speed)	50	40	knots
14	Ts (Provisions)	28	14	days
15	Es (Endurance range at 18 kt)	6000	3000	nm
16	Draft	3	5	m
17	Acoustic signature	PSYS=3,4	PSYS=1,2,5,6	PSYS Option

OMOE Hierarchy

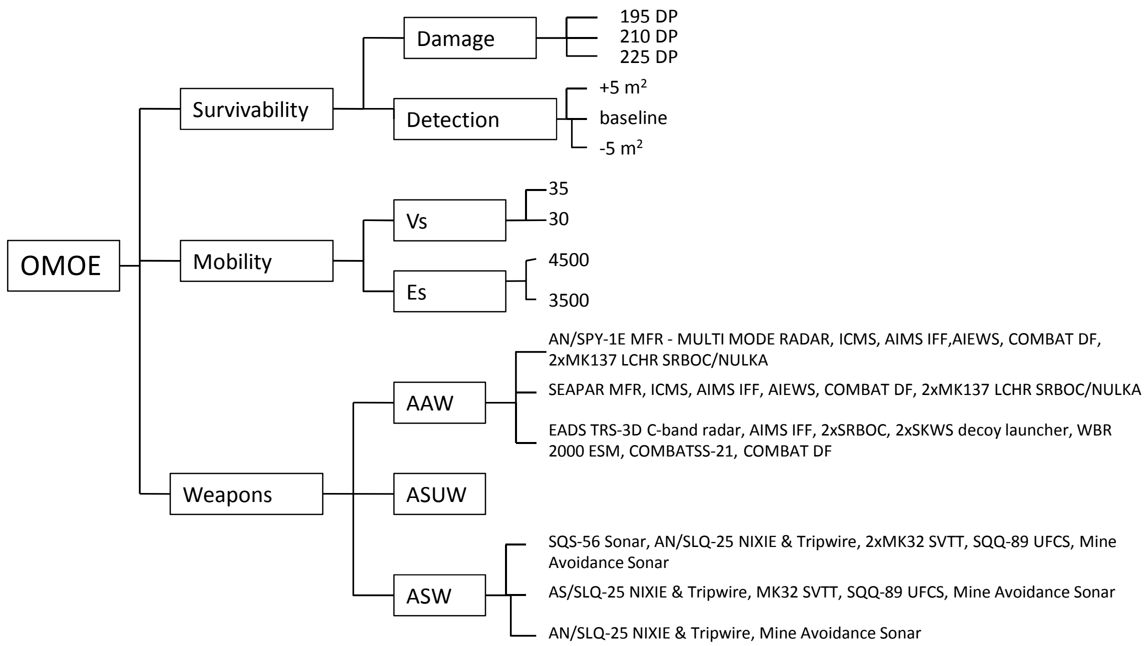
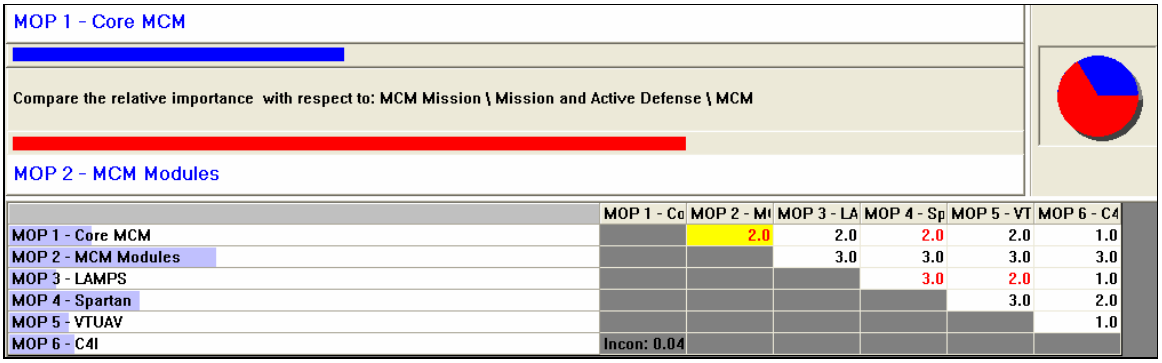


Figure 17 - OMOE Hierarchy

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



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

Figure 18 - AHP Pairwise Comparison

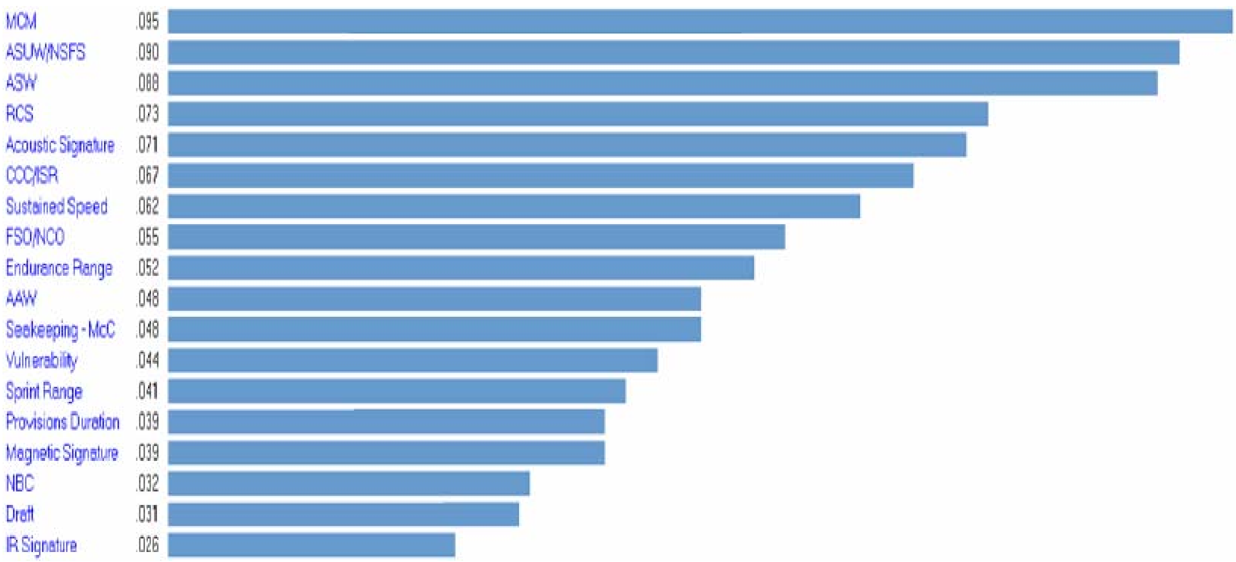


Figure 19 – Bar Chart Showing MOP Weights

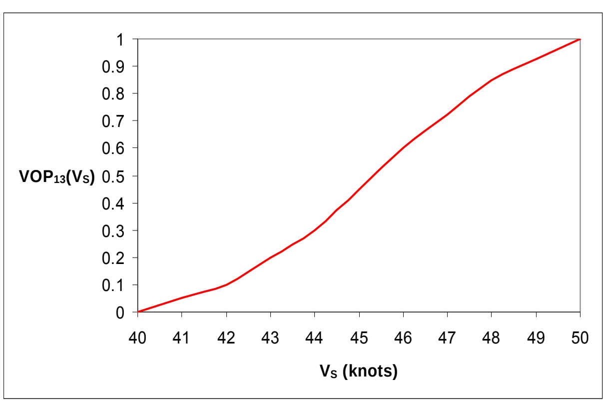


Figure 20 - Value of Performance Function for Sprint (Sustained) Speed

3.4.2 Overall Measure of Risk (OMOR)

The purpose of OMOR is to calculate a quantitative overall measure of risk (OMOR) for a specific design based on the selection of technologies defined in the design variable table. The three types of risk we measured were performance, cost and consequence. We identified risk events associated with specific design variables, required capabilities, schedule and cost. A Pi and Ci were estimated for each risk event using

Table **17** and

Table **18** to define the metric for each variable. Pi is the probability of occurrence of a major impact on performance, cost or schedule. Ci is the consequence of occurrence of a major impact on performance, cost or schedule. The product of Pi and Ci is the calculated risk for that specific event. After the risk is calculated for each event it is recorded in a risk register shown in Table 16. The calculated risk associated with each type of risk is summed and multiplied by a weight given to the risk of performance, cost and schedule all designated by *W* in the OMOR equation below. We used pair-wise comparison to calculate OMOR hierarchy weights.

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

Table 16 - Risk Register

SWBS	Risk Type	Related DV #	DV Options	DV Description	Risk Event Ei	Event #	Pi	Ci	Ri
1	Performance	DV6	2,3	Hull Material	implementation problems	1	0.5	0.7	0.35
1	Cost	DV6	2,3	Hull Material	Lack of industrial base for working with non-steel materials	2	0.3	0.3	0.09
2	Performance	DV7	7,8,9,10	Integrated power system	Development and use of new IPS system	3	0.4	0.4	0.16
2	Cost	DV7	7,8,9,10	Integrated power system	Development and use of new IPS system will incur cost	4	0.3	0.6	0.18
2	Schedule	DV7	7,8,9,10	Integrated power system	Development and use of new IPS system will be behind schedule	5	0.3	0.3	0.09
4	Performance	DV12	0.5-1.0	Manning & automation factor	Development and integration of automation systems	6	0.3	0.7	0.21
4	Cost	DV12	0.5-1.0	Manning & automation factor	Development and integration of automation systems will have cost overruns	7	0.4	0.4	0.16
4	Schedule	DV12	0.5-1.0	Manning & automation factor	Development and acquisition cost overruns will be behind schedule	8	0.4	0.4	0.16
4	Performance	DV13	1	SPY-1E MFR	Does not meet performance TLRs	9	0.4	0.5	0.2
4	Schedule	DV13	1	SPY-1E MFR	Schedule delays impact program	10	0.3	0.35	0.105
4	Cost	DV13	1	SPY-1E MFR	Development and acquisition cost overruns	11	0.3	0.65	0.195
4	Performance	DV13	2	SEAPAR MFR	Does not meet performance TLRs	12	0.4	0.5	0.2
4	Schedule	DV13	2	SEAPAR MFR	Schedule delays impact program	13	0.3	0.35	0.105
4	Cost	DV13	2	SEAPAR MFR	Development and acquisition cost overruns	14	0.3	0.65	0.195
4	Performance	DV13	3	EADS TRS-3D C-band radar	Does not meet performance TLRs	15	0.4	0.5	0.2
4	Schedule	DV13	3	EADS TRS-3D C-band radar	Schedule delays impact program	16	0.3	0.35	0.105
4	Cost	DV13	3	EADS TRS-3D C-band radar	Development and acquisition cost overruns	17	0.3	0.65	0.195

Table 17 - 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 18 - 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

There are many things to consider in the cost of a ship. The life cycle cost of a ship is significantly different from the acquisition cost because it also includes the ownership of the ship over its useful life span. The life cycle cost of the ship includes but is not limited to development, acquisition, operations, support, logistics, and disposal costs. A parametric method is used in calculating cost. It is a statistical method using "like" elements to relate weight and other parameters to cost. In a cost model the following inputs are used: power and propulsion system, deck house material, speed and endurance range, fuel volume, SWBS weight groups 100-700, number of personnel, profit margin, inflation rate, number of ships to be built, and base year for cost calculations. Using the inflation factor the cost for each SWBS group 100-700 is calculated. The weight of each group is multiplied by complexity factors. This total is then multiplied by margin weight and added to SWBS 800,900 costs to end up with a lead ship basic construction cost. Adding change order costs, government costs, and delivery costs produces a final acquisition cost for the lead ship. The quality of the cost estimate is important but usually a class D estimate of within 20% is adequate. Building more ships is cost effective because the lead ship is more expensive due to design costs. It also requires more effort from the shipyard because each time they build a new ship they "learn" how to put it together. When building multiple ships the shipyard will learn to build each ship more efficiently. A learning factor helps estimate the cost of the follow ships.

Cost of Lead ship

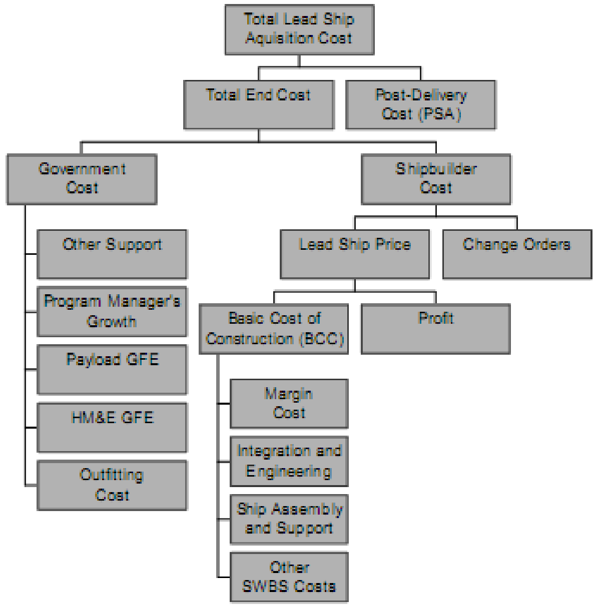
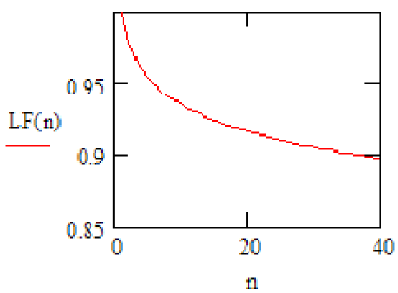


Figure 21 - Naval Ship Acquisition Cost Components

Learning Factor

Learning Rate: $R_L := .98$ (for every doubling of number of units) $LF(n) := R_L^{\frac{\ln(n)}{\ln(2)}}$ $n := 1..N_S$



Average Follow Ship Learning Cost Factor:

$$F_{LAV} := \frac{\sum_{n=2}^{N_S} LF(n)}{N_S - 1} \qquad F_{LAV} = 0.921$$

Ship $N_S/2$ Learning Cost Factor: $F_I := LF\left(\frac{N_S}{2}\right)$ $F_I = 0.916$

Figure 22 - Naval Ship Acquisition Cost Components

3.5 Multi-Objective Optimization

3.6 Optimization Results and Initial Baseline Design (Variant 137)

The non-dominated frontier presented in Figure 10 show the relationship between cost, effectiveness, and risk. Figures 10 and 11 show that the most effective designs are some of the cheapest; however, those designs are high risk. For the purposes of this design, high risk designs are more likely to be looked at. It is interesting to note that as cost increases, the overall effectiveness and risk decreases. The designs that will be used in this report will be those that fall in the range of high risk, high effectiveness, and low cost.

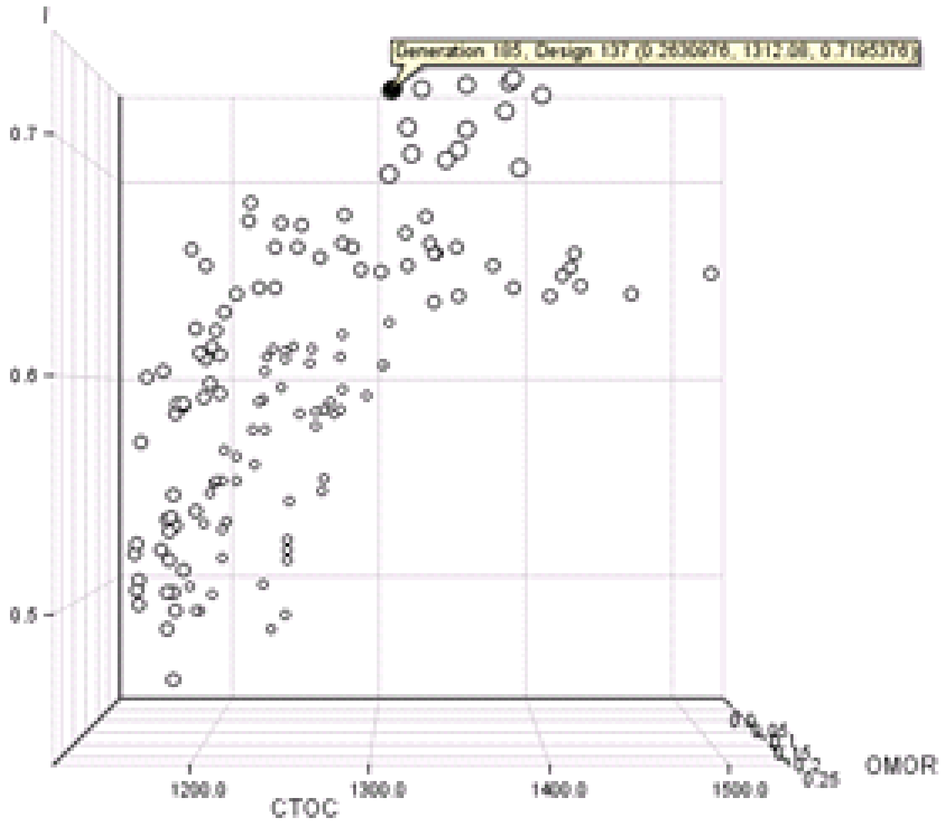


Figure 23 – 3D Non-Dominated Frontier

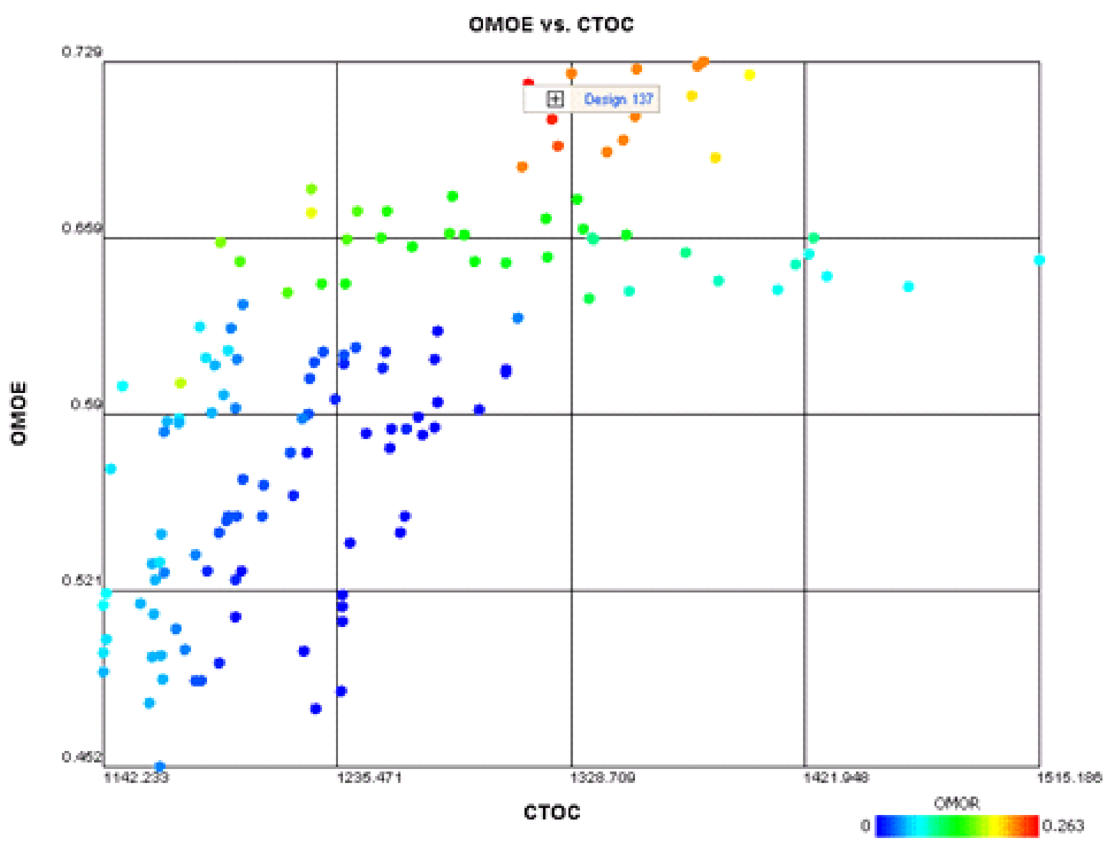


Figure 24 – 2D Non-Dominated Frontier

3.7 Improved Baseline Design – Single Objective Optimization

Design 137 was chosen to be further optimized using Model Center's gradient optimizer tool. This tool allows the fine tuning of continuous design variables in order to maximize or minimize a certain characteristic, usually cost, or OMOE. In our single objective optimization, cost was chosen two be minimized, while putting constraints on other variables in order to keep them within required values. This optimization allows the best design from the 3 dimensional design spaced to be further optimized for cost. The design variable output results from Design 137 were only allowed to be varied in a very small range about their value from Design 137.

The results of the single objective optimization are shown in Table 16 and compared to the Design 137 values.

Table 19 - Design Variables Summary

Design Variable	Description	Trade-off Range	Initial Baseline (Variant 137)	Improved Baseline
LWL	Length Waterline	115 -130	128.5	121.8
L to B	Length to Beam ratio	7.5 – 8.1	8.4	8
L to D	Length to Depth ratio	13 – 13.5	13.26	13.02
B to T	Beam to Draft ratio	2.9 – 3	2.93	3
Cp	Prismatic Coefficient	.6 - .63	.61	.621
Cx	Midship section Coefficient	.79 - .85	.79	.831
Crd		.7 - .8	.73	.8
VD	Volume Displacement	5000 – 7500	5561	5522
Cman	Manning Factor	.5 - .7	.5088	.7

Table 20 – Improved Baseline Weights and Vertical Center of Gravity Summary

Group	Weight	VCG
SWBS 100	1484.64	5.94
SWBS 200	748.59	3.24
SWBS 300	311.79	7.31
SWBS 400	149.28	7.90
SWBS 500	768.97	7.51
SWBS 600	395.12	3.89
SWBS 700	107.87	6.07
Lightship	4362.88	5.71
Lightship w/Margin	4680	6.19
Full Load w/Margin	5204.45	5.76

Table 21 – Improved Baseline Area Summary

Area	Required	Available
Total-Arrangeable	4727	4699
Deck House	2301	3088

Table 22 – Improved Baseline Electric Power Summary

Group	Description	Power
SWBS 200	Propulsion	
SWBS 300	Electric Plant, Lighting	
SWBS 430, 475	Miscellaneous	
SWBS 521	Firemain	
SWBS 540	Fuel Handling	
SWBS 530, 550	Miscellaneous Auxiliary	
SWBS 561	Steering	
SWBS 600	Services	
CPS	CPS	
KW_{NP}	Non-Payload Functional Load	
KW_{MFLM}	Max. Functional Load w/Margins	
KW_{24}	24 Hour Electrical Load	

Table 20 – Improved Baseline / ASSET Design Principal Characteristics

Characteristic	SSSM	ASSET	FFG
Displ, Full Load	5204	5481	4453
L	121.8	121.8	124.4
B	15.1	15.1	13.7
T	5.03	5.3	5.1
D10	9.35	9.3	9.1
KG	5.2	5.8	5.7
KB	2.95	3.19	3.16
Vol Total	17535	20139	15028
Vol Deckhs	5521	8536	4350
Power System	CODAG 2xLM2500+ 2xCAT3616	CODAG 2xLM2500+ 2xCAT3616	2x LM2500-21
Prop	2	2	1
Total Power Reqd	55000	NA	NA
Total Power Inst	70199	70199	36064
SS Generators	4 x CAT3516B	4 x CAT3516B	4xDD 16v149TI
SS Power Total	10000	10000	4000
Sustained Speed	31.7	30.1	27.5
Endurance Speed	20	20	20
Range at Endr	4621	3560	3469.2
Provisions	70	70	NA
Fuel Capacity	497.8	497.8	557
Officers	19	19	13
Enlisted	46	46	180
Total Crew (Berthing Allowance)	65 (90)	65 (90)	193
Lead ship acquisition cost	$912.60	NA	NA
Follow ship acq cost	$658.55	NA	NA
Follow ship total owner cost	$1.31	NA	NA
Sustained Speed (knts)	31.7	30.1	27.5
Endurance Range (nm)	4621	3560	3469
Total Required Area	4727	3835	2801
Total Available Area	4699	2194	2332
Available Hull Volume	12899	11602	10678
Maximum Functional Load with Margins	3567	4313.3	3385
Average 24 Hour Electric Load	1629	1893	1373
Full Load Displacement	5204	5481	4453
Usable Fuel Weight	498	498	557
KG	5.19	5.8	5.7
GM	0.133	0.085	0.071
SWBS 100	1484.64	1695	1551.9
SWBS 200	748.59	840.8	307.2
SWBS 300	311.79	366.8	245.1
SWBS 400	149.28	168	143.5
SWBS 500	768.97	607.3	523.4
SWBS 600	395.12	376	349.1
SWBS 700	107.87	111.9	99
Wm24	396.62	428.3	389.5
Lightship	4362.88	4594.2	3608.7
SWBS F10	8.88	9.1	21.8
SWBS F31	11.66	16.5	28.7
SWBS F32	3.71	3.2	14.9
SWBS F41	497.78	524	586.3
SWBS F46	17.88	29.2	14.5
SWBS F52	9.9	12.4	32.3
Variable Payload	287.89	NA	402.9
Full Load	5204.45	5481.1	4453.9

3.8 ASSET Feasibility Study

The improved baseline is the model that will be developed into a full ship design in the Concept Development stage. The improved baseline design variable values were entered into ASSET for the purposes of a feasibility study of the Synthesis Model (SSSM) method. The improved baseline and the ASSET model using the improved baseline variables are listed in Table 20.

The SSSM and ASSET models compare favorably in most categories. There are some discrepancies in the individual SWBS weight groups and a large difference in the endurance range. While these differences require some investigation, the relatively close results of the two models should validate the method of the MOGO optimization of ship design during the concept exploration stage. The ASSET model based on the improved baseline will be used during several design steps during Concept Development. Specifically it will be used to assist with preliminary arrangements and weight calculations. Below in Figure 25 is the ASSET machinery arrangements output that will be used to assist in machinery placement during concept development.

In Table 20 the improved baseline and the improved ASSET model are compared to the Navy's legacy FFG7. This comparison is made due to the relative size and capabilities the improved baseline resulted in. Designing the SSC to the lower sustained speed of between 30 – 35 knots has resulted in a larger vessel with more area defense capabilities than if the SSC were designed to the higher speed threshold. Because the improved baseline in significant missile, radar, and sonar technologies, the SSC will be able to contribute to area AAW and ASW defense of a CSG/ESG. These capabilities along with its size and speed would mean the SSC would be able to fill the role of the FFG in the CSG/ESG while still being able to meet the littoral defense requirements of the SSC.

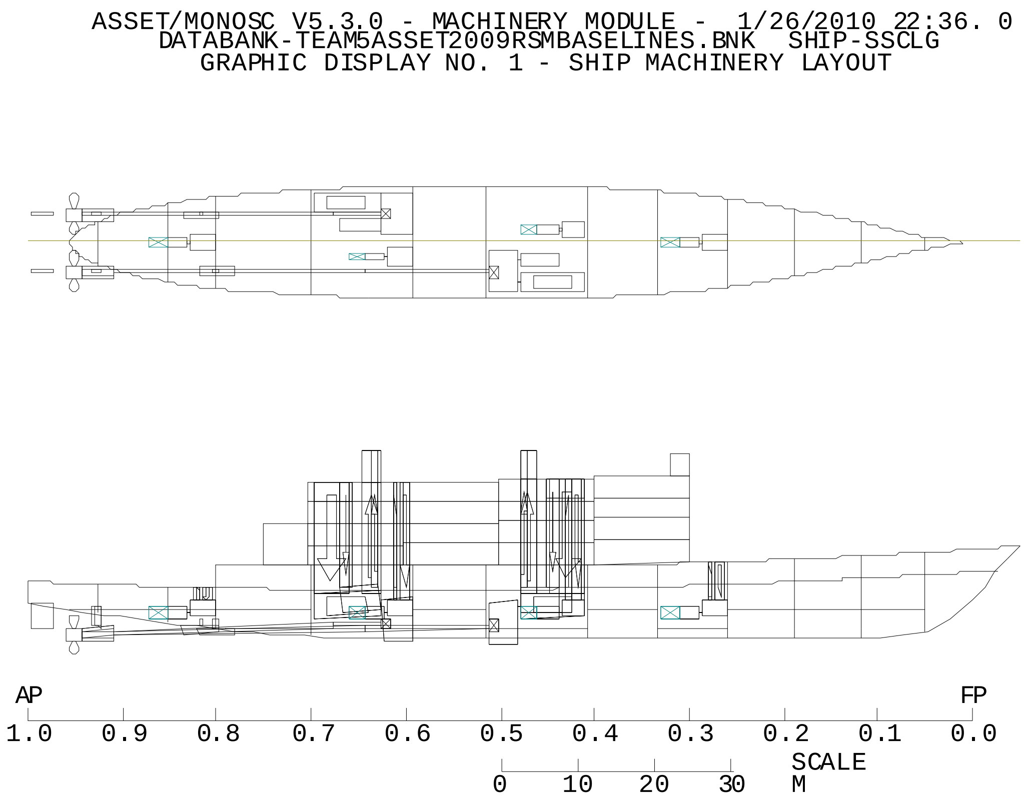


Figure 25 - ASSET Improved Baseline Machinery Arrangements

4 Concept Development (Feasibility Study)

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

4.1 Hull Form and Deck House

4.1.1 Hullform

Hullform development was the first phase of the concept development process. A 3D model of the hullform and deckhouse were created in Rhino based on the principal characteristics of the improved baseline. An iges file from the ASSET improved baseline hull was imported into Rhino where curves were lofted, and faired hull surfaces were created. At this stage, an AN/SQS-56 sonar dome was added to the hullform.

During the hullform development phase, emphasis was placed on minimizing drag, providing good maneuvering and seakeeping characteristics, and maximizing developable surfaces to reduce acquisition costs. The faired hull lines and a table of principal particulars is presented in Figure 26.

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Figure 26: SSC Large Lines Drawing

Once the hullform had been finalized in Rhino, preliminary hydrostatics were created using ORCA 3D. The intact heeling arm curve for the vessel at varying drafts is presented in Figure 27. Curves of form for vessel are presented in Figure 27 through Figure 32.

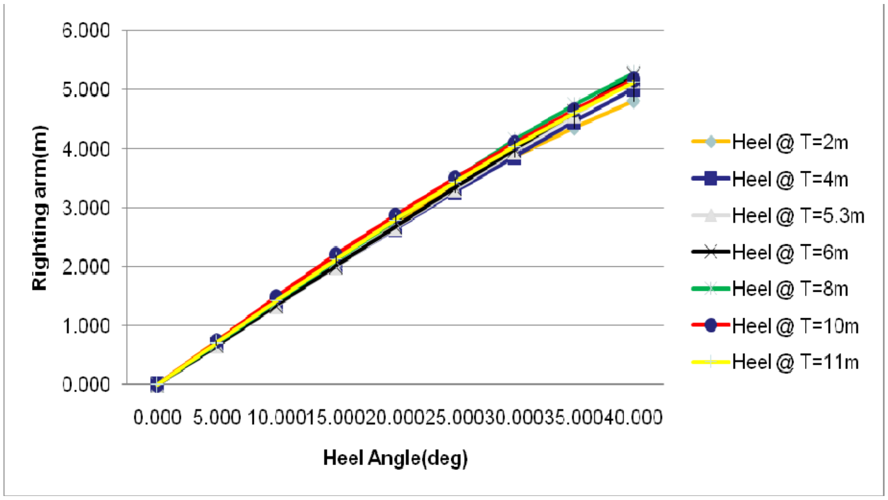


Figure 27: Intact Righting Arm Curves

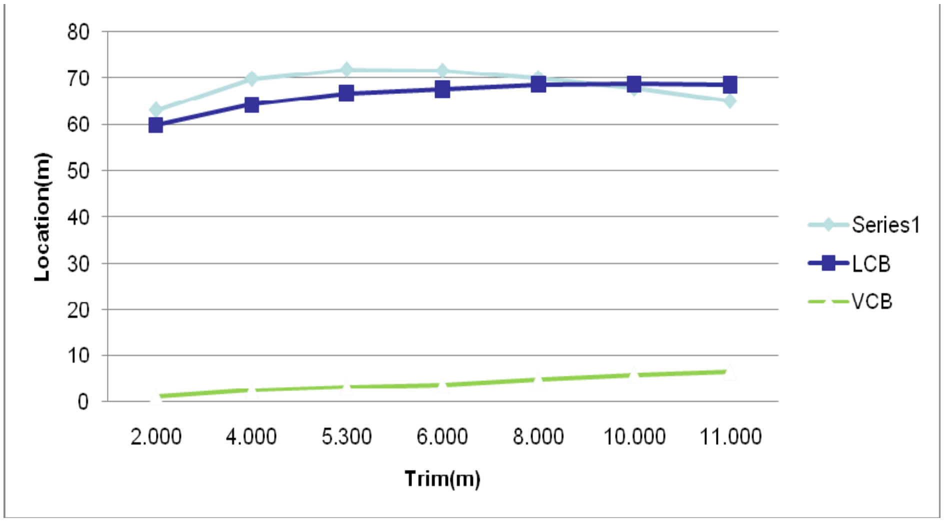


Figure 28: Buoyancy Centers

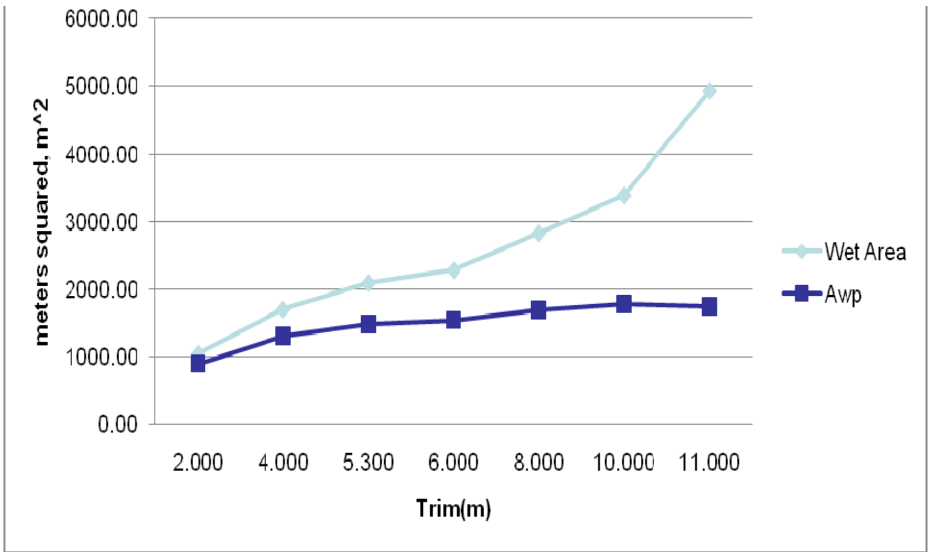


Figure 29: Wetted Area and Waterplane Area

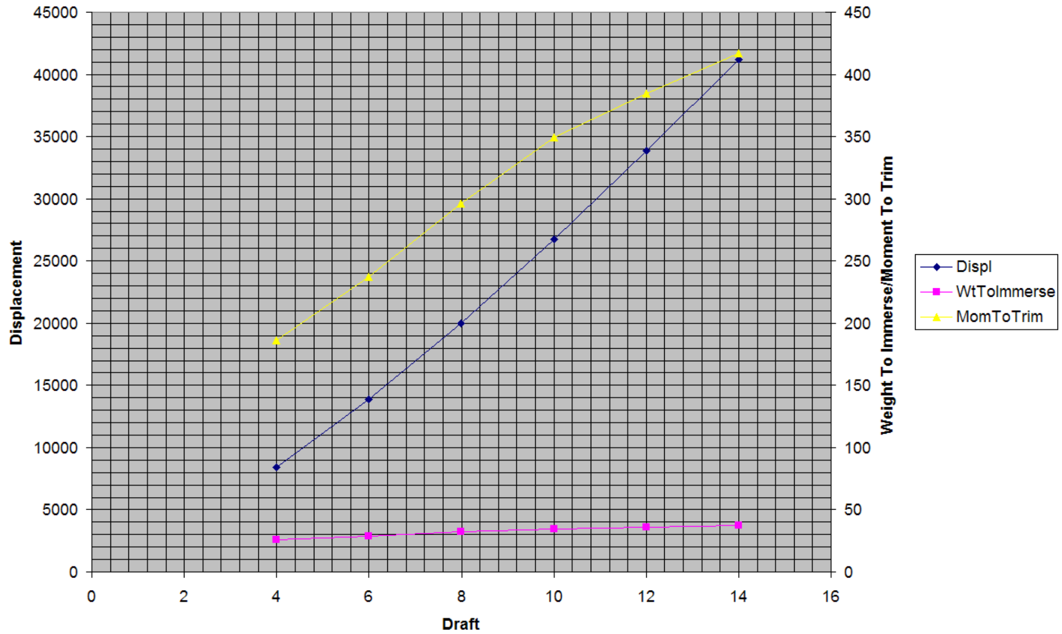


Figure 30: Displacement, TPC Immersion, and Moment to Trim Curves

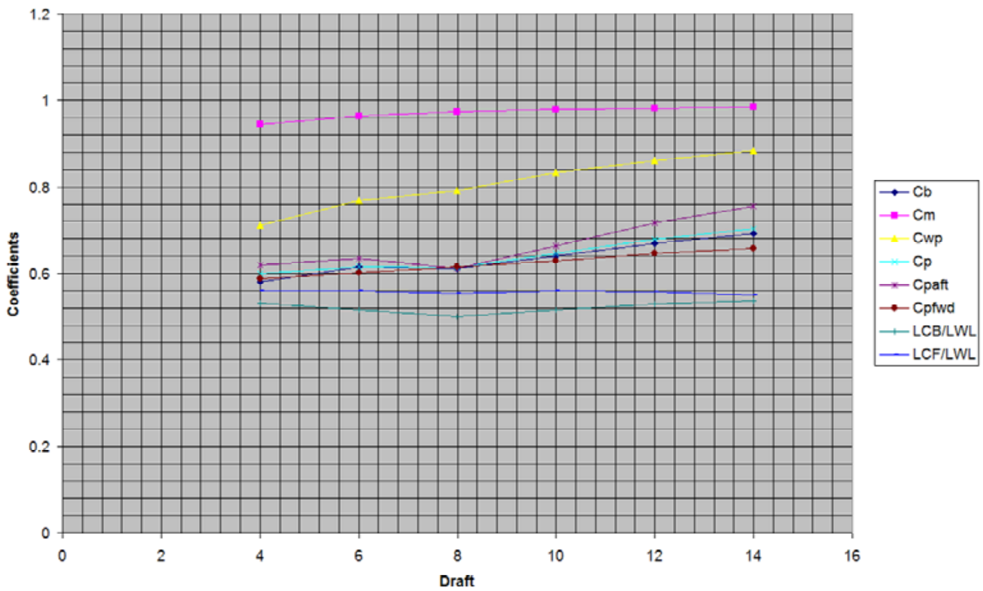


Figure 31: Hullform Coefficients

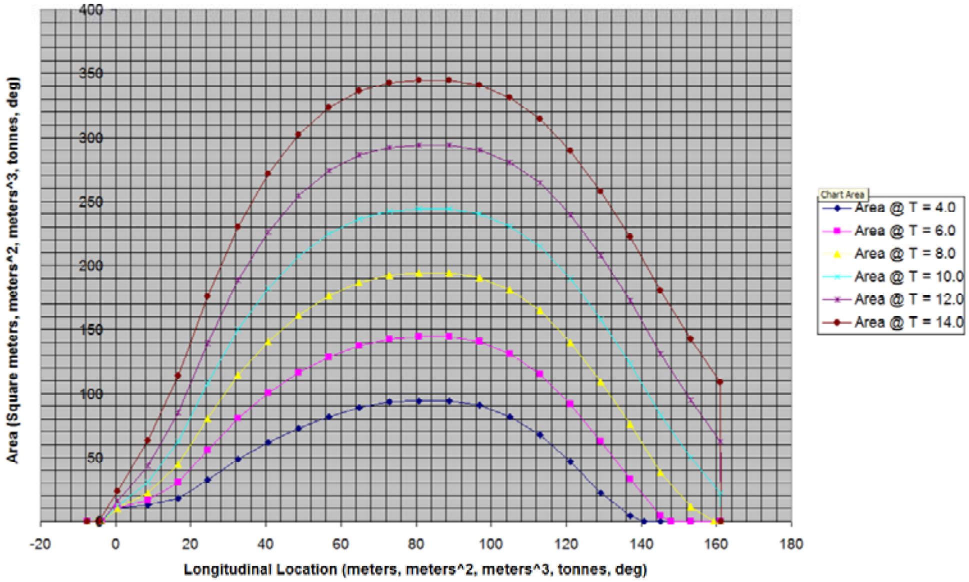


Figure 32: Sectional Area Curves

4.1.2 Deck House

The deckhouse was shaped and positioned in Rhino to support mission systems, provide an efficient means for routing the intakes and exhausts, and to provide volume and surface area to support weapons sensors, the AN/SPY 1E X Band arrays, and the other combat system antennas. The position of the deckhouse was also modified from the improved ASSET baseline in order to align the deckhouse transverse subdivision with the hull transverse subdivision. The Rhino 3D model of the hull and deckhouse are shown in Figure 33

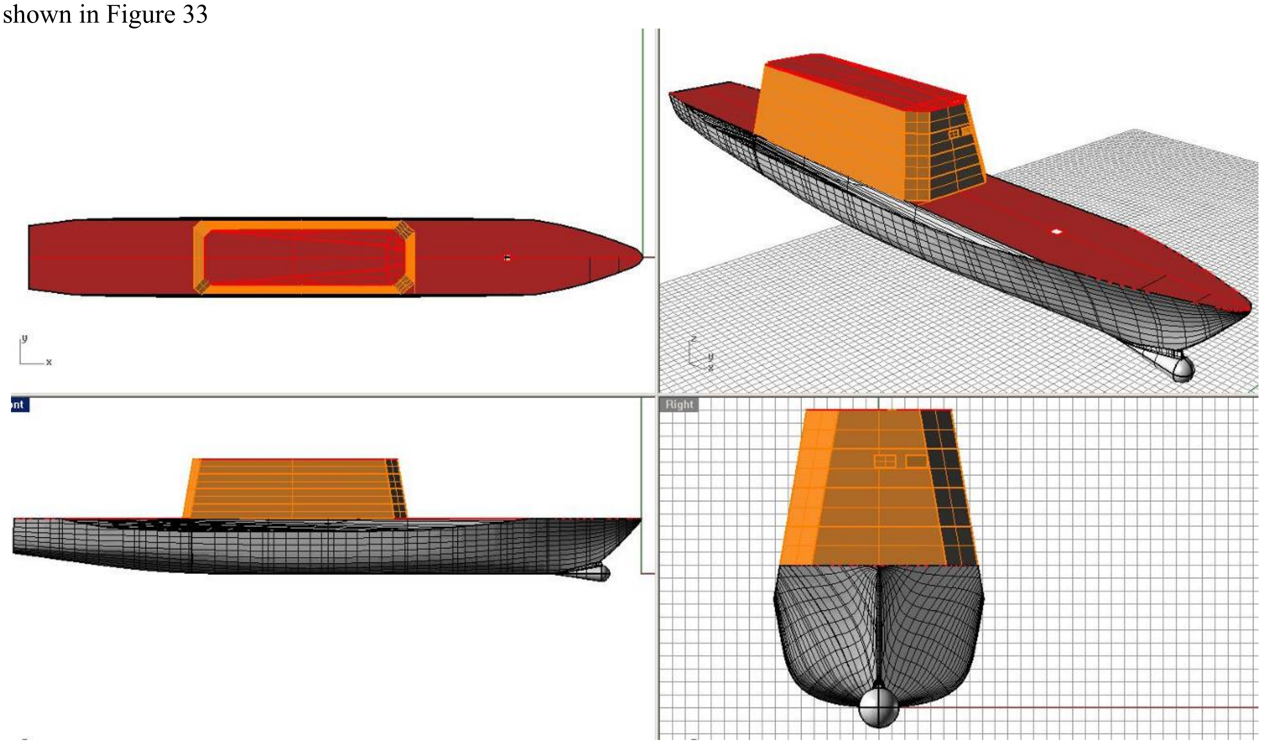


Figure 33: Refined Hullform and Deckhouse

4.2 Preliminary Arrangement (Cartoon)

The cartoon of the large SSC is created as part of concept development in order to ensure that the vessel has the required area and volume, and to ensure that all large objects fit into the hull. The preliminary arrangement defines the primary hull and deckhouse subdivision by placing decks and bulkheads in order to locate tanks, large machinery spaces, and other large object spaces.

In establishing a preliminary general arrangement, static and damaged stability, trim, machinery arrangements and propulsion train alignment, signatures, large object arrangement, engine intakes and uptake routing, structural efficiency, survivability, producibility, and mission requirements must be considered. Preliminary arrangements will guide more detailed general arrangements later on in concept development.

The preliminary arrangement was created by using the hull and deckhouse profile and deck plan views from the Rhino model and the required area and volume reports from the ASSET improved baseline model to establish the hull subdivision. The Rhino model with the hullform and deckhouse built from the improved ASSET improved baseline ship synthesis model is shown below in Figure 34.

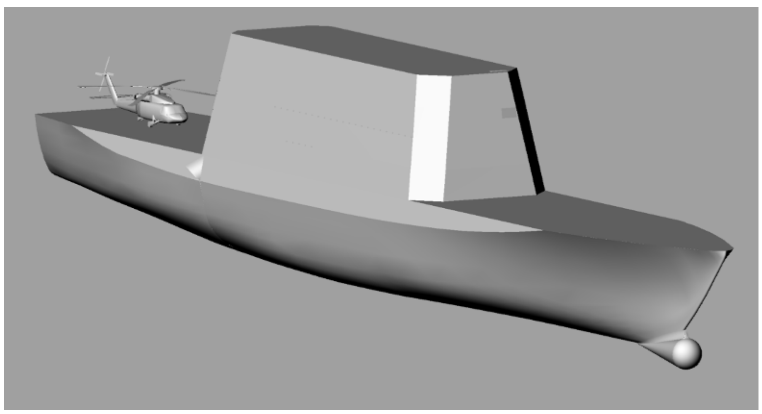


Figure 34: Rhino Hullform and Deckhouse Model

The required area and volumes and manning profile used to establish the preliminary hull subdivision is given in Table 23.

Table 23: Required Areas and Volumes

REQUIRED AREAS AND VOLUMES		
VD	5221.89 m^3	deckhouse volume
Vtk	929.2 m^3	total tankage volume
Vaux	834.153 m^3	auxillary machinery space volume
Vht	12012.6 m^3	total hull volume
Vmb	1853 m^3	propulsion machinery box volume
ADPR	971.82 m^2	required deckhouse payload area
AHPR	682.418 m^2	required hull or deckhouse payload area
Ahie	147 m^2	required hull propulsion inlet and exhause area
Adie	510 m^2	required deckhouse propulsion inlet and exhaust area
Ts	70	endurance days
Cn	5.6638	hull cubic number
NT	65	total crew
NO	19	number of officers
NA	16	number of additional accomodations
Adr	2350 m^2	total deckhouse required area
Ada	3088 m^2	available deckhouse area
Atr	4727 m^2	total required arrangeable area
Ata	4699.7 m^2	total available arrangeable area

These required areas and volumes from the improved baseline model were used to place transverse watertight bulkheads and decks, and create an initial topsides arrangement. The cartoon for the large SSC is shown below in Figure 35. This cartoon shows the location of transverse bulkheads, decks and platforms, machinery spaces, engine intakes and exhausts, large object spaces, and mission module spaces. This cartoon also shows an initial tankage arrangement to meet the required tankage volumes and meet intact and damaged stability requirements.

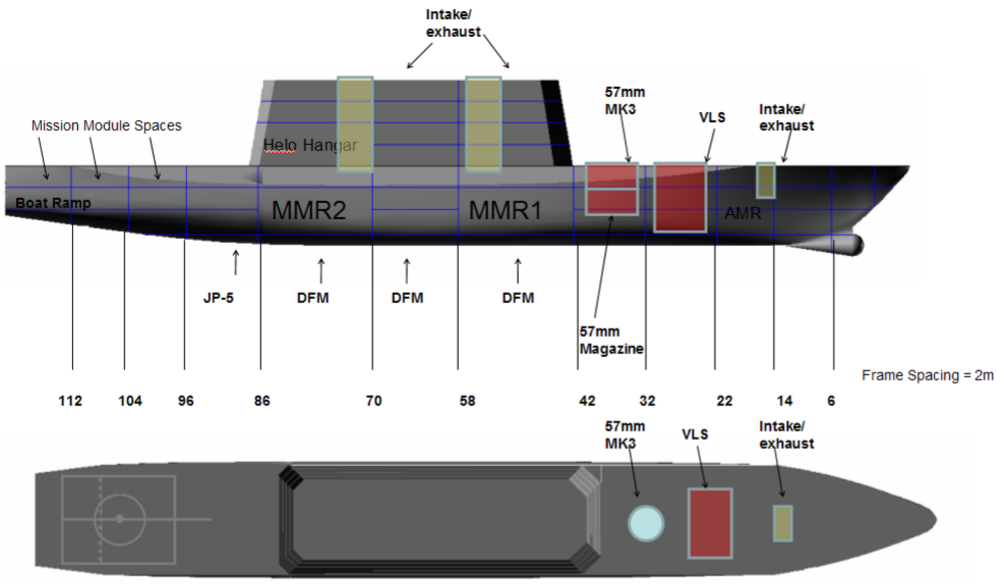


Figure 35: Large SSC Preliminary Arrangement (Cartoon)

The following cartoon shows an initial topside arrangement large SSC with placement of the improved baseline X band arrays and hull features to meet the required mission profile.

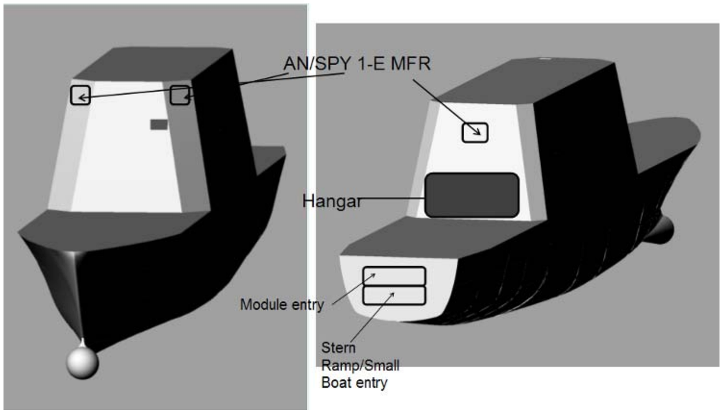


Figure 36: Mission Profile Features

4.3 Design for Production

In the concept and requirements exploration phase, design for production is one of the major inputs into the cost model. The decisions that are made at an early stage in concept design and preliminary design will have a large impact upon the cost and schedule of the ship.

A generic build strategy was first established for the large SSC. The generic build strategy includes producibility features as described below:

1). Design a producible hull form with modular construction techniques (avoid complex curvature of panels)

2). Create a zonal classification as shown with the following numbering scheme
- Bow/stern - 1000/3000- more curvature and transition to transverse stiffening
- Machinery - 2000- difficult distributed systems and outfitting
- Deckhouse – 4000 – reduced curvature and lighter zones
- On-board - 5000 - actually defines construction stage - electrical wiring, etc.
- Special - 6000 - high skill - electronics, CS, accommodations

3). Follow the unit break criteria outlined below to allow for improved handling and erection of units
- Above deck (10cm) and aft of TBHD (25cm)
- Stiffeners on FWD side of TBHD (except in Machinery spaces)
- Blocks extend between TBHD - attempt to keep TBHD spacing less than plate length (50’)
- Max unit width - 10m
- Units one deck high except wing tanks/spaces and in bow
- Max structural assembly weight of 200 MT

4). Use the following guidelines when creating the general arrangements
- Air locks on fwd side of TBHD
- Standard openings / closures
- Escape trunks on fwd side of TBHD
- Standard space arrangements, avoid mirror image (Troop Living, Crew Living, etc)
- Use modular living quarters where possible
- Transverse passageways on aft side of TBHD
- Locate habitability spaces away from machinery spaces and intake/uptakes to avoid acoustic insulation

5). Use a zonal distribution for electrical, HVAC, and the firemain for zonal outfitting

6). Use service tunnels to minimize bends in piping and cable

7). Use the following techniques in detailed design to minimize unnecessary production costs
- Permit wire brushing in lieu of blasting of erection butts and seams

- Permit one-sided welding with ceramic backing tape when joining units
- Use sleeve couplings to join piping
- Use pre-fab plate with piping welded to it for bulkhead penetrations.
- Maximize retention of CFE and GFE paint
- Permit use of weld-through primer
- Minimize use of HY and HSLA materials to reduce pre-heating requirements.
- Use standard shapes/plates. Avoid using built up sections (require more welding and straightening than rolled shaped
- Minimize complex curvature in plates above the waterline

If these guidelines in the generic build strategy are followed throughout preliminary and detailed design, significant cost and time savings will be seen in the shipyard. Given the cost cap of $400 million for follow ship acquisition, it is essential that these guidelines be followed.

Refinements were made to the ASSET improved baseline design for producibility. Unnecessary deck shear was eliminated from the forward and aft ends of the ship. This eliminated curvature from the decks in these regions of the ship, and will allow for the deck panels to be effectively built in the panel line without heating and rolling the plates and stiffeners. This change is shown in Figure 37.

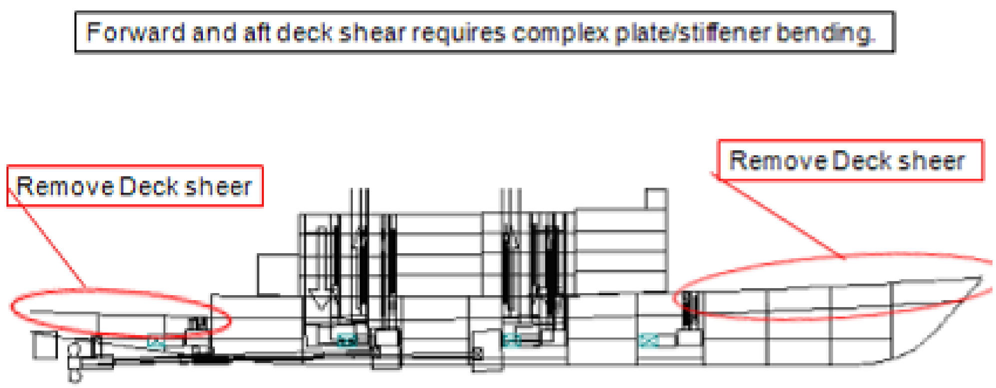


Figure 37: Producibility Improvements – Shear Removed

Another producibility improvement that was made to the large SSC from the improved baseline was that the locations of the transverse bulkheads in the deckhouse were shifted al align with the transverse bulkheads in the hull. This will help to improve the structural efficiency of the design. The deckhouse was also shortened because the volume contained in the deckhouse of the improved baseline was greater than required. The structural continuity improvement is detailed in Figure 38.

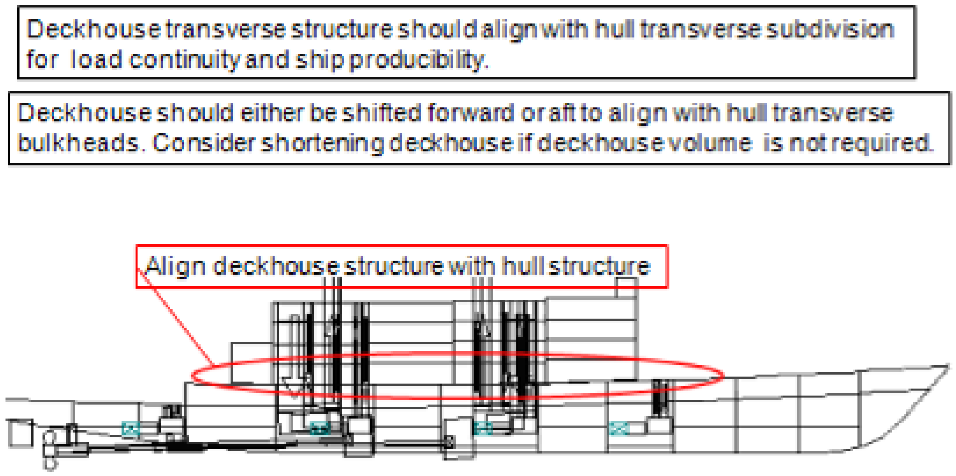


Figure 38: Producibility Improvements - Structural Continuity

The ship service diesel generator in AMR 2 was also relocated to MMR 2 in order to avoid complex routing of the intakes and uptakes through the deckhouse. The improved baseline design placed the second ship service diesel generator below the flight deck. This would have been problematic because the intakes and uptakes would have to have been routed away from the flight deck, and through the deckhouse. Relocating the generator to a main machinery space below the deckhouse provides an improved intake and uptake arrangement. This improvement to the improved baseline design is shown in Figure 39.

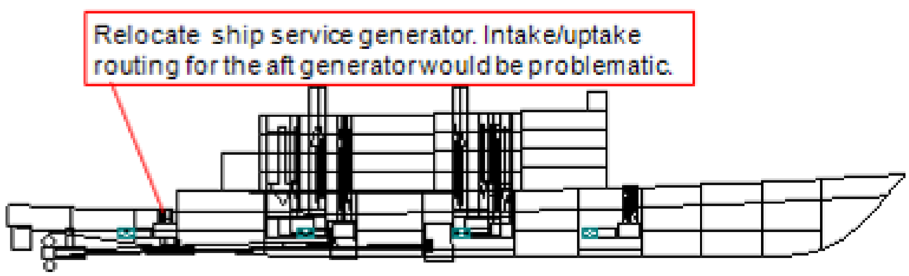


Figure 39: Producibility Improvements – Machinery Arrangement

Hull sections from the improved baseline design were also examined from a producibility point of view. The objective was to re-shape the hull above the design waterline where possible to straighten the sections. This helped to reduce complex curvature and avoid having to heat and roll the shell and shell stiffeners in the shipyard. The body plan of the large SSC from the ASSET improved baseline is shown in Figure 40.

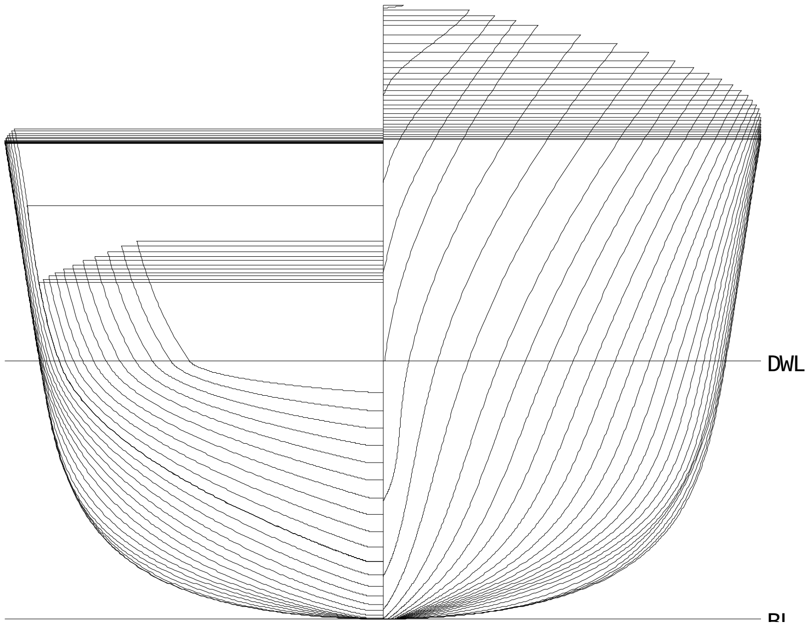


Figure 40: Improved Baseline Sections

These sections had relatively minor curvature above the design waterline to begin with, but the hullform was refined and the sections were straightened. The Gaussian curvature for the refined hull form was examined in Rhino and is shown in Figure 41. The Gaussian curvature is a measure of complex curvature, and is a helpful visual aid to show whether the surfaces can be developed from a flat panel. A smooth surface has two principal curvatures. The Gaussian curvature is a product of the principal curvatures. The SSC hullform Gaussian Curvature close to zero almost everywhere.

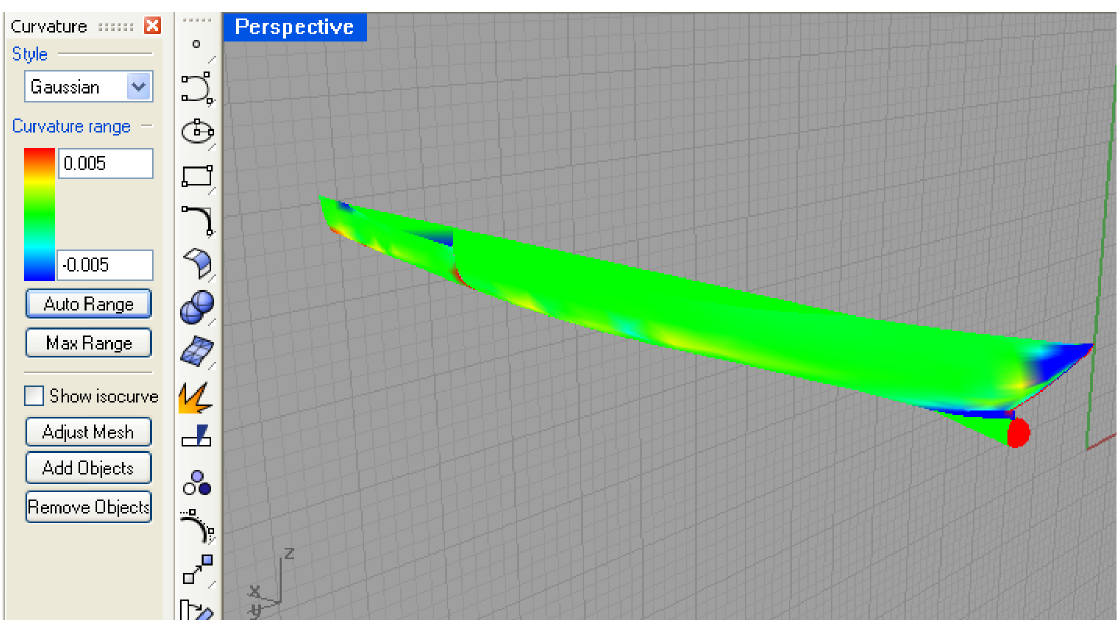


Figure 41: Refined Hullform Gaussian Curvature

The guidelines listed in the generic build strategy are to be followed regardless of which shipyards are selected for lead and follow ship acquisition. These are strategies that will be built into the design that will help to lower cost and increase shipbuilding efficiency. The choice of shipbuilder also impacts the acquisition cost and schedule for the large SSC, but early in the concept and preliminary design, the lead and follow yards have typically not been selected.

The major US shipyards specializing in the construction of naval surface combatants have improved their efficiency in the past decade. This is due to improvements and advancements in the shipbuilding methodology. These shipyards are moving away from "stick building" ships on a set of inclined building ways, and are moving towards building progressively larger units under cover. Shipyards like Bath Iron Works have built large assembly buildings to move the ship construction under cover to the greatest extend possible. Ship structural units are stacked vertically into a grand block, and multiple grand blocks are then joined together into an ultra unit under the cover of climate controlled buildings. The structural units that make up the large SSC are presented in Figure 42 through Figure 45.

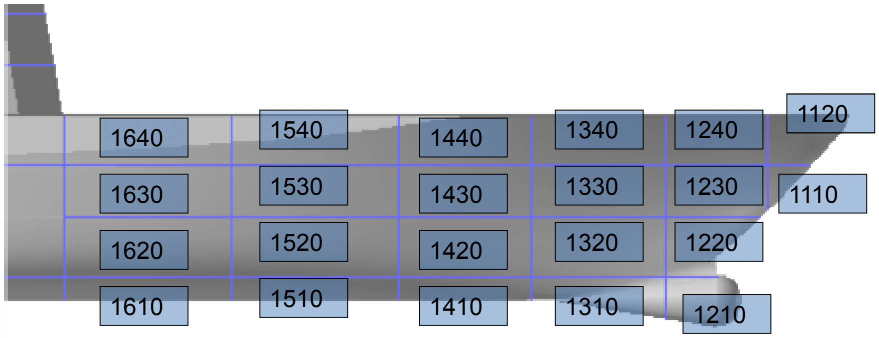


Figure 42: 1000 Grand Block Units

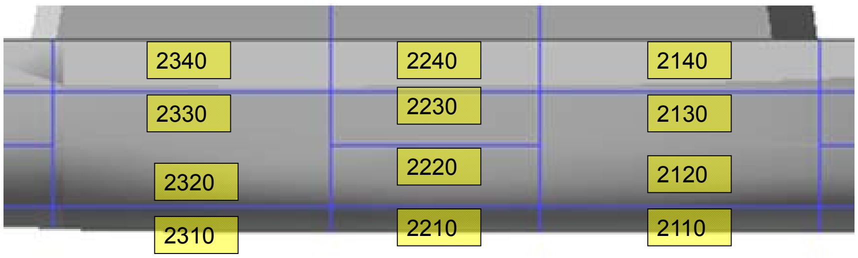


Figure 43: 2000 Grand Block Units

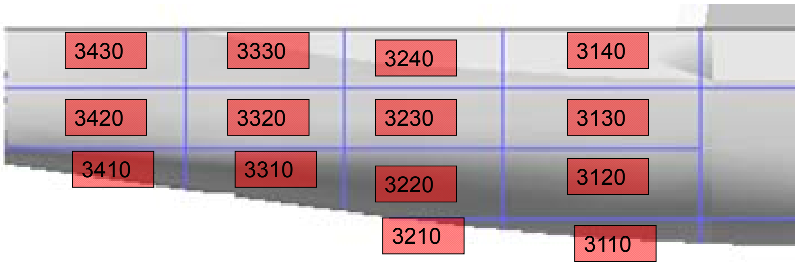


Figure 44: 3000 Grand Block Units

Figure 45: 4000 Grand Block Units

These structural units are then stacked vertically in an assembly building prior to blast and paint to form grand blocks. The grand blocks for the ship are given in Figure 46 through Figure 49.

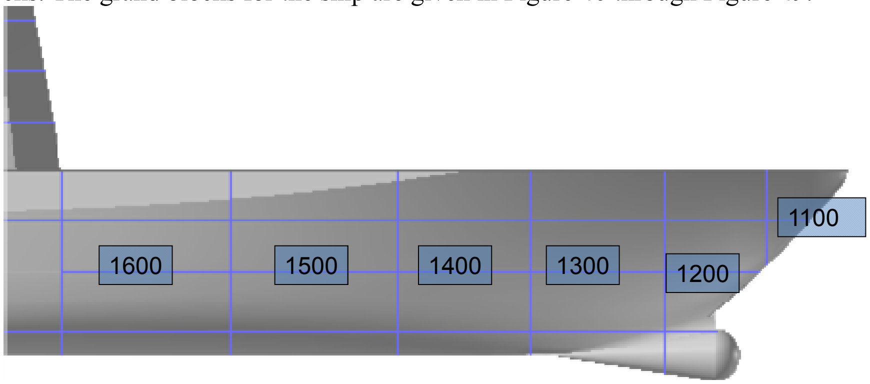


Figure 46: 1000 Grand Blocks

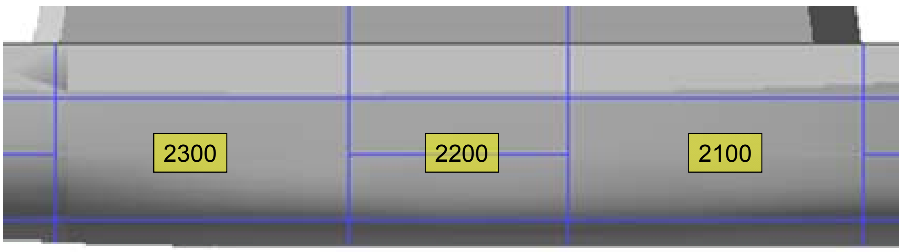


Figure 47: 2000 Grand Blocks

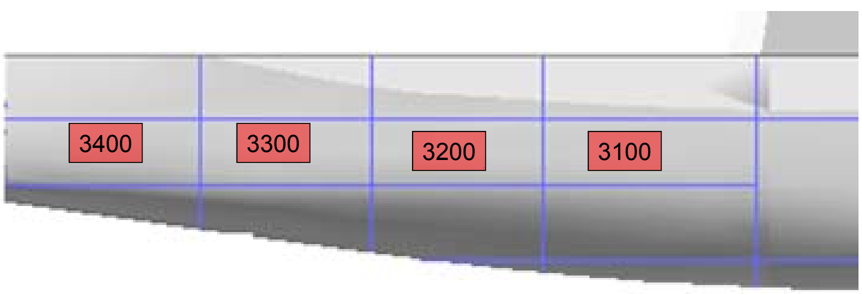


Figure 48: 3000 Grand Blocks

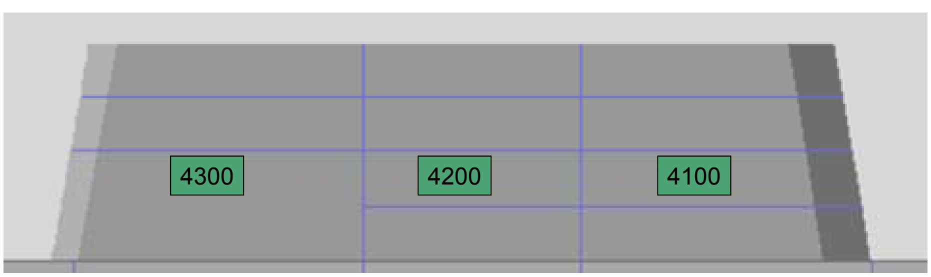


Figure 49: 4000 Grand Blocks

In addition to moving much of the ship construction process out of the elements, much of the ships outfitting is also brought under cover. Ultra units similar the one shown in Figure 50 are currently being constructed in specialized assembly buildings. These units can be several thousand tons, and have a high degree of zonal outfitting accomplished prior to erection with other ultra units on the land level transfer facility (LLTF). The 4 ultra units that will form the hull and deckhouse of the large SSC are shown in Figure 51.

Figure 50: Modern Ultra Unit

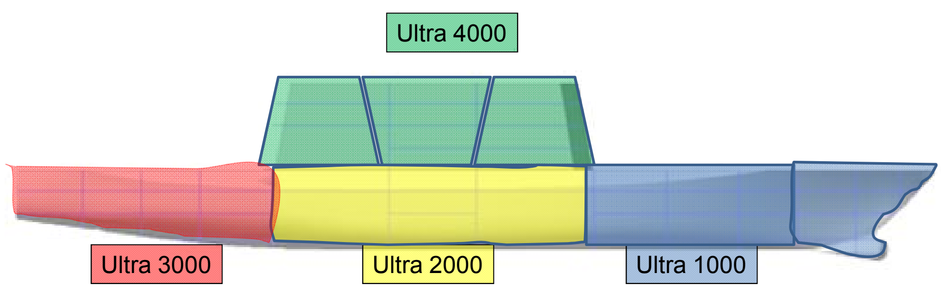


Figure 51: Large SSC Ultra Units

In order to establish a preliminary schedule of principal events for the construction of the large SSC, a claw chart was established to show the unit erection schedule for a modern shipyard like Bath Iron Works. This claw chart was built with the assumption that serial production of multiple large SSC would be underway at any given time. It is important to establish a unit erection schedule and schedule of principal events for a ship being built in modern shipyard, because numerous ships are under construction simultaneously, and the ship construction schedule as defined in the build contract must be closely adhered to. The claw chart presented in Figure 52 shows how the individual units will be stacked vertically to create grand blocks. The grand blocks will then be joined with other grand blocks to form ultra units. The entire ship will be constructed in 4 ultra units that will be completed under cover, and moved to the Land Level Transfer Facility (LLTF) for erection with other ultra units.

Week	4300	4200	4100	3400	3300	3200	3100	2300	2200	2100	1600	1500	1400	1300	1200	1100
1									2210							
2								2310	2220							
3								2320	2230	2110						
4								2330	2240	2120						
5								2340	PO1	2130						
6					3310			PO1		2140						
7				3410	3320				B&P	PO1						
8				3420	3330	3210		B&P	P02							
9				3430	PO1	3220	3110	PO2		B&P						
10				PO1		3230	3120			PO2						
11					B&P	3240	3130			MTG Loadout						
12				B&P	PO2	PO1	3140									
13				PO2			PO1							1310		
14						B&P		MTG Loadout					1410	1320		
15						P02	B&P						1420	1330	1210	
16							PO2						1430	1340	1220	1110
17								ULTRA 2000 Erection				1510	1440	PO1	1230	1120
18				ULTRA 3000 Erection							1610	1520	PO1		1240	PO1
19								ULTRA 2000 to LLTF			1620	1530		B&P	PO1	
20		4210									1630	1540	B&P	PO2		B&P
21	4310	4220		ULTRA 3000 to LLTF							1640		PO2		B&P	PO2
22	4320	4230										B&P	ATG Loadout		P02	
23	4330	4240	4110								B&P	PO2				
24	4340	PO1	4120								PO2					
25	PO1		4130													
26		B&P	4140									ULTRA 1000 ERECTION				
27	B&P	P02	PO1													
28	PO2															
29			B&P									ULTRA 1000 to LLTF				
30			PO2													
31																
32	ULTRA 4000 Erection															
33																
34	Ultra 4000 to LLTF															

Figure 52: Claw Chart Unit Construction Schedule

The claw chart is driven mainly by the schedule of principal events that is established by shipyard production planning and upper management. This master design schedule shows all of the major milestones in the design and construction of the vessel. In order to meet the deadlines listed in the schedule of principal events and balance the total workload within the shipyard, the claw chart must be created and followed.The schedule of principal events shown in Figure 53 shows the sequencing and duration of major design and construction activities.

Event	Description	Duration (months)	MBD
1	Contract Award	0	66
2	Detail Design	36	64
3	Material Procurement	45	60
4	MFG/Production Planning	64	64
5	2D Drawing Extraction	20	57
6	Material Lofting	20	57
7	Start Fab	39	48
8	Start Compartment Testing	38	44
9	Start Pre-Outfit (1st Unit)	24	44
10	Grand Block Erection	18	40
11	Ultra Unit Erection and Outfit	20	32
12	Combat/AEGIS Weapon Systems Loadout	17	30
13	Lay Keel	0	24
14	Ultra Unit Assembly (distributed systems integration)	6	24
15	Complete Hull Assembly	0	18
16	Electrical Cable Pull	12	18
17	Distributed Systems Testing	13	17
18	Prop Shaft Loadout/Alignment	3	18
19	Light Off SSGTGs	0	13
20	Aegis Combat System Light Off	9	13
21	Ship Translation/Launch	0	12
22	Compartment Inspections (GI's)	8	9
23	Complete Compartment Testing	0	6
24	Main Engine Light Offf	0	6
25	Start Dock Trials	0	5
26	Start Builders Trials	2	5
27	Start Acceptance Trials	0	3
28	Delivery	0	0

Figure 53: Schedule of Principal Events

4.4 Subdivision

The primary subdivision and tankage arrangement was established in order to define large object spaces with sufficient maintenance envelopes and arrangeable space and volume, establish a tankage arrangement, and ensure that the vessel meets the intact and damaged stability criteria given in the US Navy DDS 079. After an initial primary subdivision was defined to meet tankage and large object space requirements, a floodable length curve was generated in HECSALV to ensure that the ship can survive damage along at lease 15% of the DWL.

4.4.1 Hullform in HECSALV

The rhino hull file was imported into HECSALV using the ship project editor. The general process used to define the primary subdivision in HECSALV is given below:

1. Start new project – enter particulars
2. Import Rhino file (if applicable)
3. Select coordinate system and adjust model
4. Finish particulars
5. Input or refine offsets
6. Define References (Decks and TBHDs)
7. Complete margin line and floodable length analysis if applicable
8. Update TBHDs as required
9. Export hull.dxf back to Rhino
10. Define tanks and compartments (Generation Table)
11. Generate compartments
12. Generate tanks from compartments
13. Generate Tank Tables and Hydrostatic Tables
14. Enter lightship characteristics and weight curve
15. Validate
16. Export .dxf back to Rhino or subdivision to Rhino model by hand.

Rhino was used initially to generate a hullform from the ASSET improved baseline offsets, and that hullform was modified to include a number of producibility improvements. The Rhino hullform is shown in Figure 54.

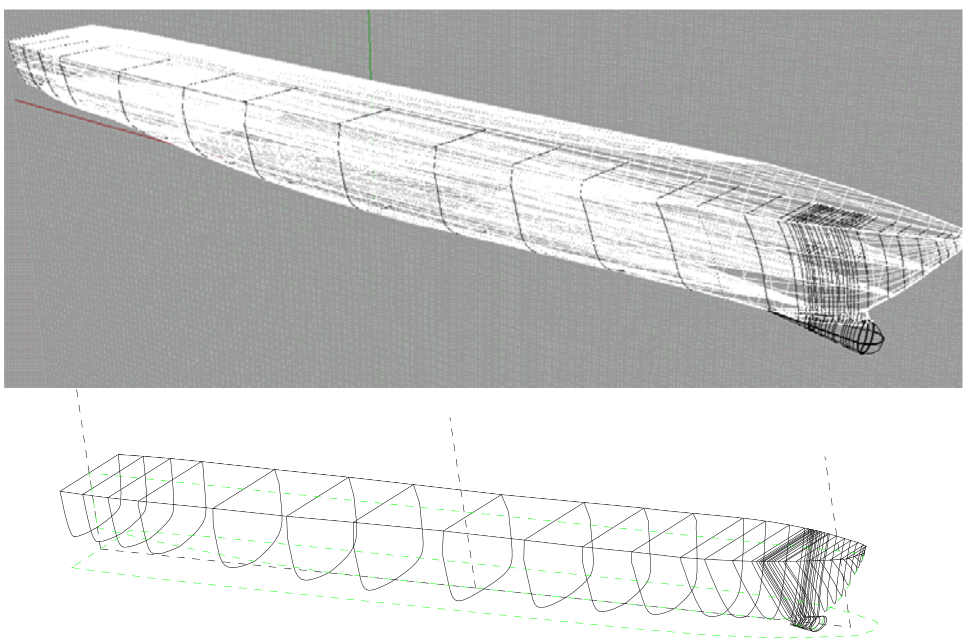


Figure 54: Improved Rhino Hullform

These sections were imported into HECSALV, and the sections were faired and cleaned up where required. Once the Rhino hull file was input into HECSALV, the hull principal particulars were input into HECSALV from the improved baseline. The hullform in HECSALV with the hull form parameters defined is shown in Figure 55.

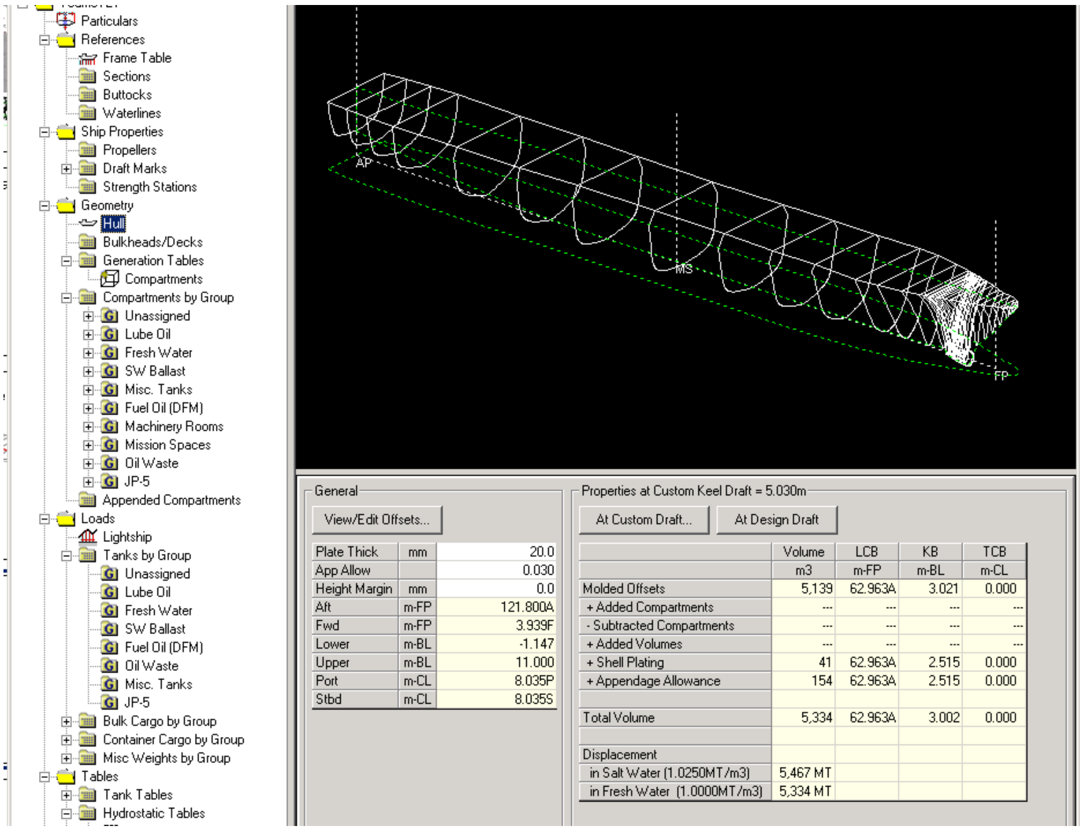


Figure 55: Hullform in HECSALV

4.4.2 Transverse Subdivision, Floodable Length and Preliminary Tankage

A number of criteria and constraints were taken into consideration when defining the primary hull subdivision. Some of these criteria and constraints include:

- Damage stability and floodable length
- Other survivability considerations – separation
- Tankage
- Propulsion
- Other function accessibility, stowage, machinery stack-up length
- Trim
- Structural design
- Producibility
- Hull form
- Tank volume requirements
- Deck height
- Continuous deck requirement
- Machinery room volume, dimension requirements, shaft alignment
- Large object spaces and stack-up length
- Structural design including preliminary estimate of frame spacing
- Mission requirements

Guidance was initially taken from the ASSET improved baseline and Rhino preliminary arrangement. Improvements and refinements to the preliminary arrangement were then made to the hull subdivision by considering the constraints and guiding criteria listed above.

The primary hull subdivisions were altered in an iterative manner until tankage, intact and damaged stability, large object stack up length, machinery space and volume, and the other requirements listed above were met. The finalized locations of decks and transverse watertight bulkheads are shown below in Figure 56 and Figure 57.

*	Name	Vert
		m-BL
	BL	0.00
	Keel	0.00
	Inner Bottc	1.50
	3rd Deck	5.00
	2nd Deck	8.00
	1st Deck (I	11.00
	waterline	5.30

Figure 56: Deck Locations

		m-FP
	AP	121.800A
	MS	60.900A
	FP	0.000
	TBHD1	0.900A
	TBHD2	6.900A
	TBHD3	14.900A
	TBHD4	22.900A
	TBHD5	32.900A
	TBHD6	42.900A
	TBHD7	58.900A
	TBHD8	70.900A
	TBHD9	86.900A
	TBHD10	96.900A
	TBHD11	104.900A
	TBHD12	112.900A
	bow	3.939F

Figure 57: Transverse Bulkhead Locations

The profile and plan views of the primary hull subdivision with the decks and bulkheads and bulkheads modeled are shown in Figure 58. In these views, orange spaces are unassigned spaces (available for berthing, operations, mission spaces, etc), lube oil tanks are purple, potable water tanks are light blue, seawater ballast tanks are dark blue, fuel oil tanks are red, JP-5 tanks are black, machinery spaces are light green, mission spaces are dark green, and oily waste tanks are maroon.

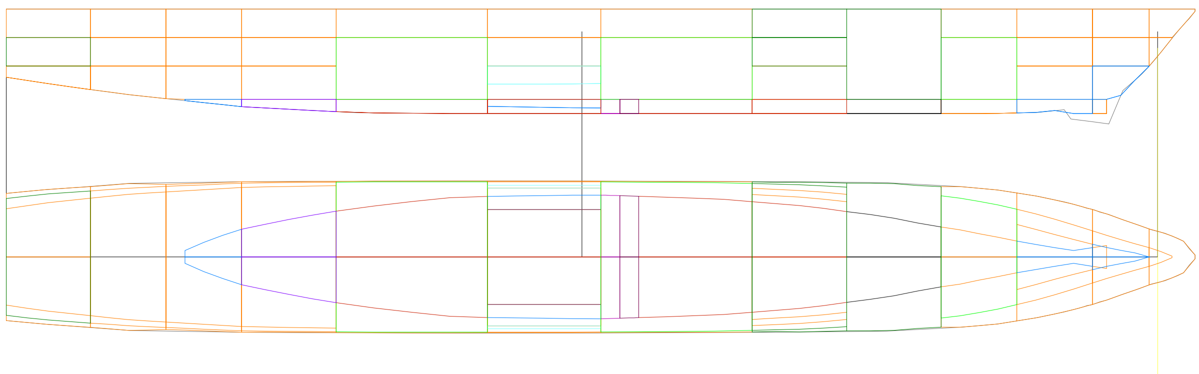


Figure 58: Hull Primary Subdivision

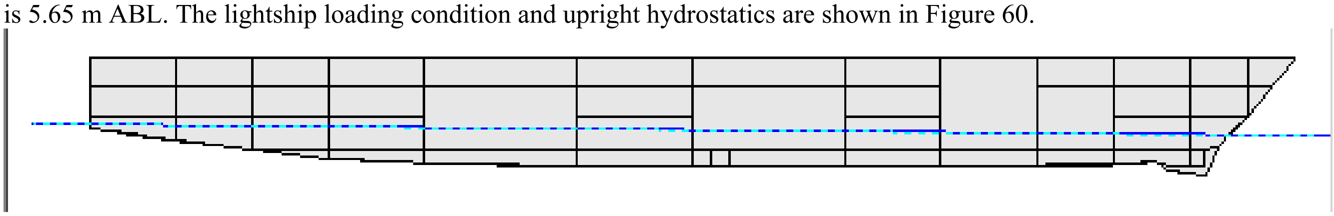
A summary of the volumes and centers for the fuel groups, machinery spaces, mission spaces, and other spaces as calculated by HECSALV is given in Figure 59.

*	Name	Color	Perm	LCG	VCG	TCG	Slack
			m3	m-FP	m-BL	m-CL	m4
G	Unassigned		8,152	73.158A	7.067	0.000P	50,660
G	Lube Oil		29	57.904A	0.872	0.000P	85
G	Fresh Water		8	64.952A	4.332	0.000P	0
G	SW Ballast		55	36.554A	1.838	0.000P	17
G	Misc. Tanks		72	28.274A	0.944	0.000	105
G	Fuel Oil (DFM)		574	59.950A	0.903	0.000P	1,400
G	Machinery Rooms		3,013	58.513A	4.898	0.000P	11,031
G	Mission Spaces		2,300	43.934A	7.147	0.000S	10,372
G	Oil Waste		28	55.905A	0.879	0.000S	82
G	JP-5		46	91.029A	1.109	0.000	91

Figure 59: HECSALV Tankage Summary

4.4.3 Loading Conditions and Preliminary Stability Analysis

Loading conditions were defined in HECSALV for the lightship, full load, and minimum operating conditions. The lightship condition was first defined, and then the other loading conditions were defined. The lightship condition was taken from the ASSET improved baseline with design development. This condition is a theoretical condition that would be approached as the ship went into a dry-docking period. It does not contain any liquid loads, or expendable loads such as munitions, personnel and their effects, or stores. The preliminary lightship weight for the large SSC is 4166 MT, and the preliminary lightship VCG is 5.65 m ABL. The lightship loading condition and upright hydrostatics are shown in Figure 60.



lan for Team5T21 - [Intact Trim and Stability Summary]

Results Tools Window Help

light stillwater

Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT
Light Ship	4,166	5.650	65.000A	0.000	----
Constant	0	0.000	60.900A	0.000	0
Lube Oil	0	----	----	----	----
Fresh Water	0	----	----	----	----
SW Ballast	0	----	----	----	----
Fuel Oil (DFM)	0	----	----	----	----
Oil Waste	0	----	----	----	----
JP-5	0	----	----	----	----
Misc. Weights	0	----	----	----	----
Displacement	4,166	5.650	65.000A	0.000	0

Stability Calculation			Trim Calculation		
KMt	8.047	m	LCF Draft	4.072	m
VCG	5.650	m	LCB	65.080A	m-FP
GMt (Solid)	2.397	m	LCF	68.569A	m-FP
FSc	0.000	m	MT1cm	107	m-MT/cm
GMt (Corrected)	2.397	m	Trim	1.355	m-A
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		

Drafts			Strength Calculations		
Draft at F.P.	3.309	m	Shear	173	MT at 102.900A m-FP
Draft at M.S.	3.987	m	Bending Moment	4,822H	m-MT at 82.123A m-FP
Draft at A.P.	4.664	m			
Draft at FwdMarks	3.343	m			
Draft at Mid Marks	4.020	m			
Draft at AftMarks	4.698	m			

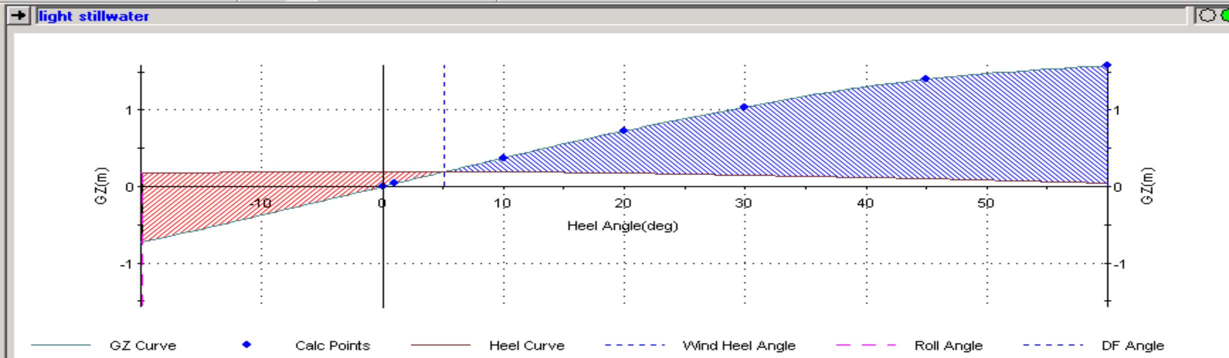
Figure 60: Lightship Condition

Intact stability was assessed for the lightship condition against the criteria contained in DDS 079. A plot of the GZ curve for the lightship intact condition can be found in Figure 61.

lan for Team5T21 - [Righting Arm Summary Intact From Offsets - U.S. Navy DDS079-1: Beam Wind and Rolling]

Results Tools Window Help

light stillwater



Parameter	Units	Value	Required
Wind Heel	deg	5.1	---
Wind Heeling Arm Lw	m	0.194	---
Maximum Righting Arm Ratio		0.12	0.6
Capsizing Area A2	m-rad	0.20	---
Righting Area A1	m-rad	0.87	0.29
Angle Limiting Area	deg	60.0	---
Maximum Righting Arm	m	1.582	---
Angle at Max. GZ	deg	60.0	---
Projected Sail Area	m2	862.48	---
Vertical Arm ABL	m	7.521	---
Heeling Arm at 0 deg.	m	0.196	---
Wind Pressure	bar	0.02	---
Input Parameters			
Wind Speed		100.0	
Reference Draft	m	0.000	
Projected Sail Area	m2	0.00	
Vertical Center of Sail Area -BL	m	0.000	
Factor f where p = f*V^2 (lb/ft^2)		0.0035	
Roll Angle	deg	25.0	

Figure 61: Lightship Intact Stability

This plot shows that the large SSC does meet the DDS 079 intact stability criteria in the lightship condition. The ratio of maximum heeling arm to maximum righting arm for a 100 kt wind does not exceed

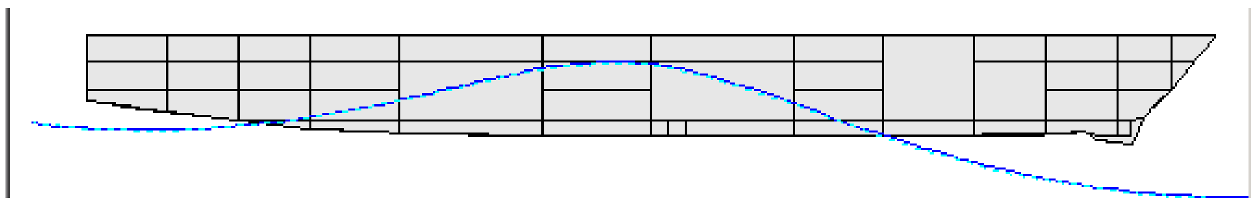
0.6. Also, the area under the righting arm curve (A1) is greater than the required value, and the static wind heel angle does not exceed 15 degrees.

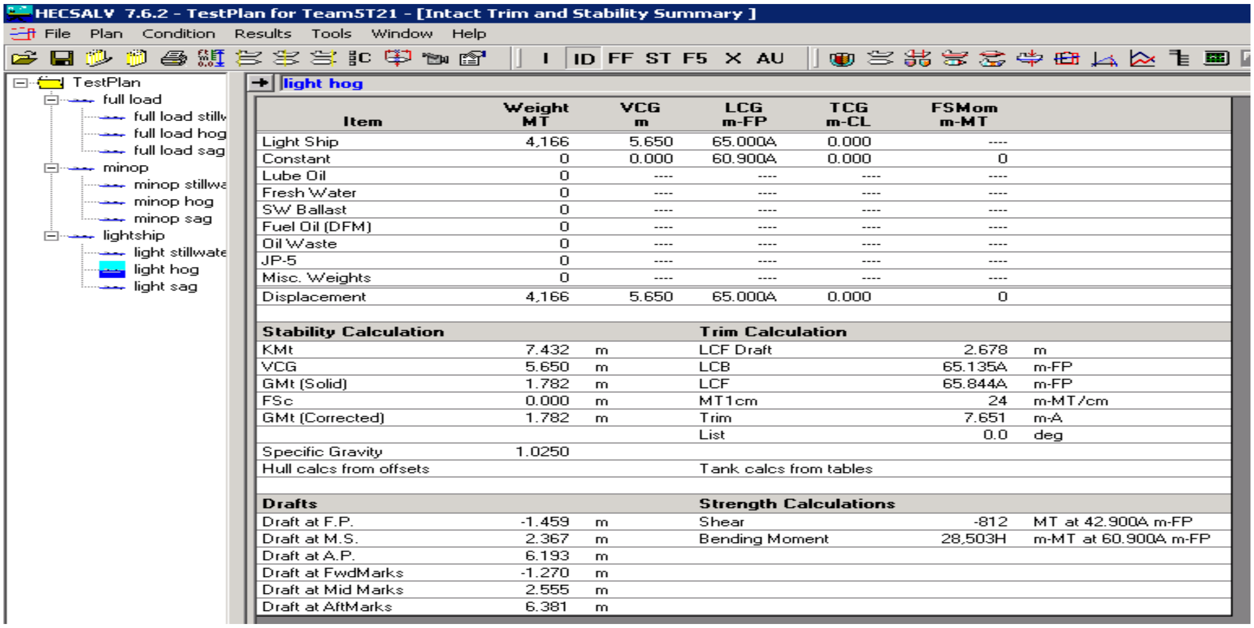
The still water shear force and bending moment diagrams for the lightship condition are given in Figure 62. This bending moment distribution shows that the vessel is hogging in the lightship condition. This is typical of a naval surface combatant because the largest volume spaces are near amidships and these spaces contain the machinery rooms. There is more open volume in machinery spaces, so the buoyancy is greater than the live load in these spaces.

Figure 62: Lightship Stillwater Shear force and Bending Moment Diagram

Hydrostatics, intact stability, and hull loading were also checked in the lightship condition with the ship balanced on a design hogging and design sagging wave. The equilibrium hydrostatics for the lightship condition on a hogging and sagging wave are given in Figure 63 and Figure 64. In the case of waves, both the hogging and sagging conditions were evaluated using a trochoidal wave, with the wave height (h) given by:

$$H = \sqrt{0.6 * LBP} \text{ (m)}$$



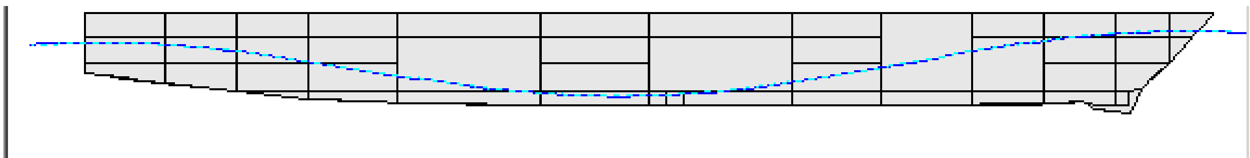


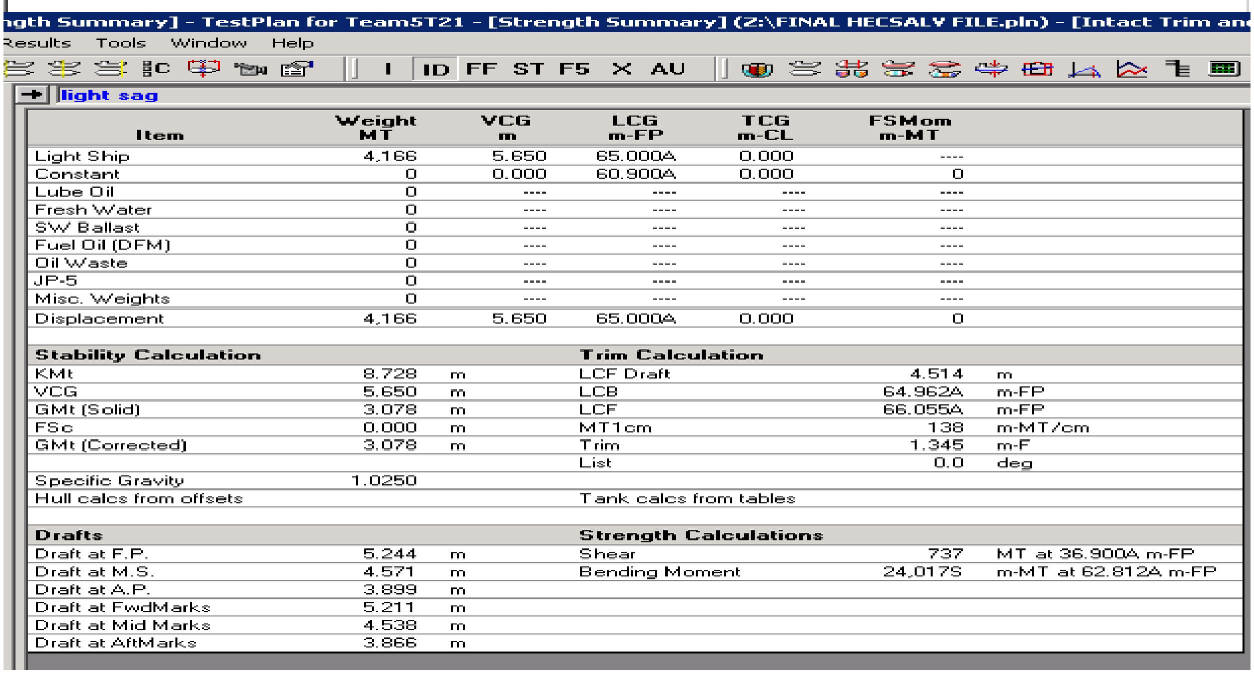
Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT
Light Ship	4,166	5.650	65.000A	0.000	----
Constant	0	0.000	60.900A	0.000	0
Lube Oil	0	----	----	----	----
Fresh Water	0	----	----	----	----
SW Ballast	0	----	----	----	----
Fuel Oil (DFM)	0	----	----	----	----
Oil Waste	0	----	----	----	----
JP-5	0	----	----	----	----
Misc. Weights	0	----	----	----	----
Displacement	4,166	5.650	65.000A	0.000	0

Stability Calculation			Trim Calculation		
KMt	7.432	m	LCF Draft	2.678	m
VCG	5.650	m	LCB	65.135A	m-FP
GMt (Solid)	1.782	m	LCF	65.844A	m-FP
FSc	0.000	m	MT1cm	24	m-MT/cm
GMt (Corrected)	1.782	m	Trim	7.651	m-A
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		

Drafts			Strength Calculations		
Draft at F.P.	-1.459	m	Shear	-812	MT at 42.900A m-FP
Draft at M.S.	2.367	m	Bending Moment	28,503H	m-MT at 60.900A m-FP
Draft at A.P.	6.193	m			
Draft at FwdMarks	-1.270	m			
Draft at Mid Marks	2.555	m			
Draft at AftMarks	6.381	m			

Figure 63: Lighship Hogging Wave Equilibrium Condition





Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT
Light Ship	4,166	5.650	65.000A	0.000	----
Constant	0	0.000	60.900A	0.000	0
Lube Oil	0	----	----	----	----
Fresh Water	0	----	----	----	----
SW Ballast	0	----	----	----	----
Fuel Oil (DFM)	0	----	----	----	----
Oil Waste	0	----	----	----	----
JP-5	0	----	----	----	----
Misc. Weights	0	----	----	----	----
Displacement	4,166	5.650	65.000A	0.000	0

Stability Calculation			Trim Calculation		
KMt	8.728	m	LCF Draft	4.514	m
VCG	5.650	m	LCB	64.962A	m-FP
GMt (Solid)	3.078	m	LCF	66.055A	m-FP
FSc	0.000	m	MT1cm	138	m-MT/cm
GMt (Corrected)	3.078	m	Trim	1.345	m-F
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		

Drafts			Strength Calculations		
Draft at F.P.	5.244	m	Shear	737	MT at 36.900A m-FP
Draft at M.S.	4.571	m	Bending Moment	24,017S	m-MT at 62.812A m-FP
Draft at A.P.	3.899	m			
Draft at FwdMarks	5.211	m			
Draft at Mid Marks	4.538	m			
Draft at AftMarks	3.866	m			

Figure 64: Lighship Sagging Wave Equilibrium Condition

The shear force and bending moment diagram for the hogging and sagging conditions were calculated for lightship and are shown in Figure 65 and Figure 66.

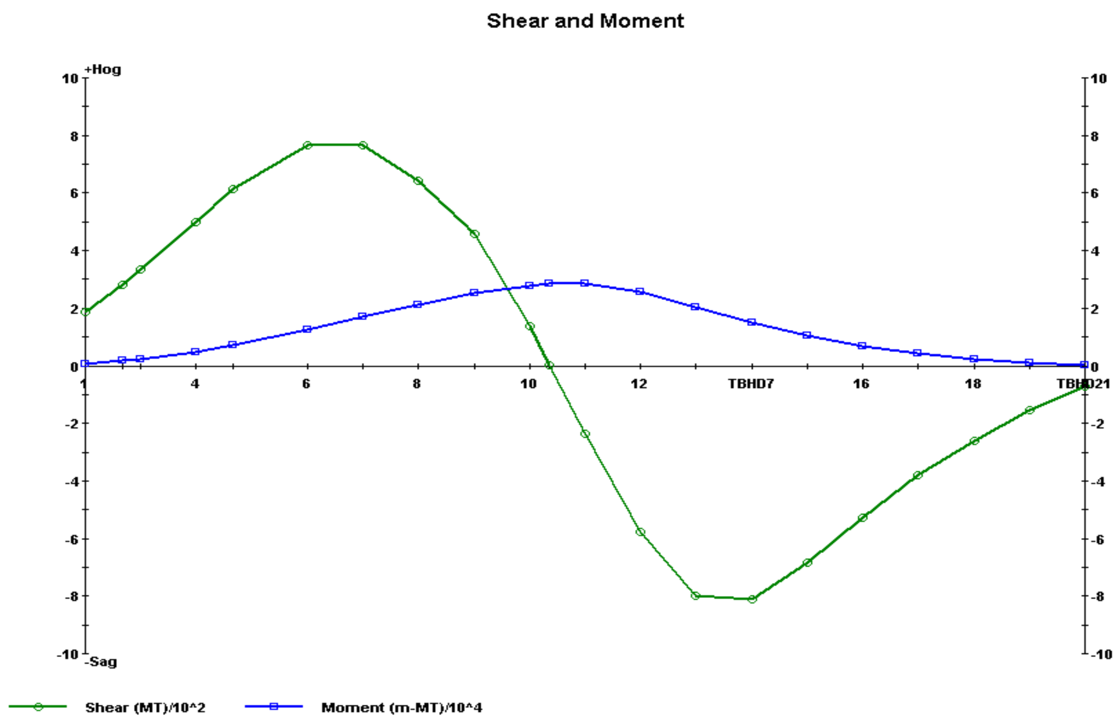


Figure 65: Lightship Hogging Design Wave Shear force and Bending Moment Diagram

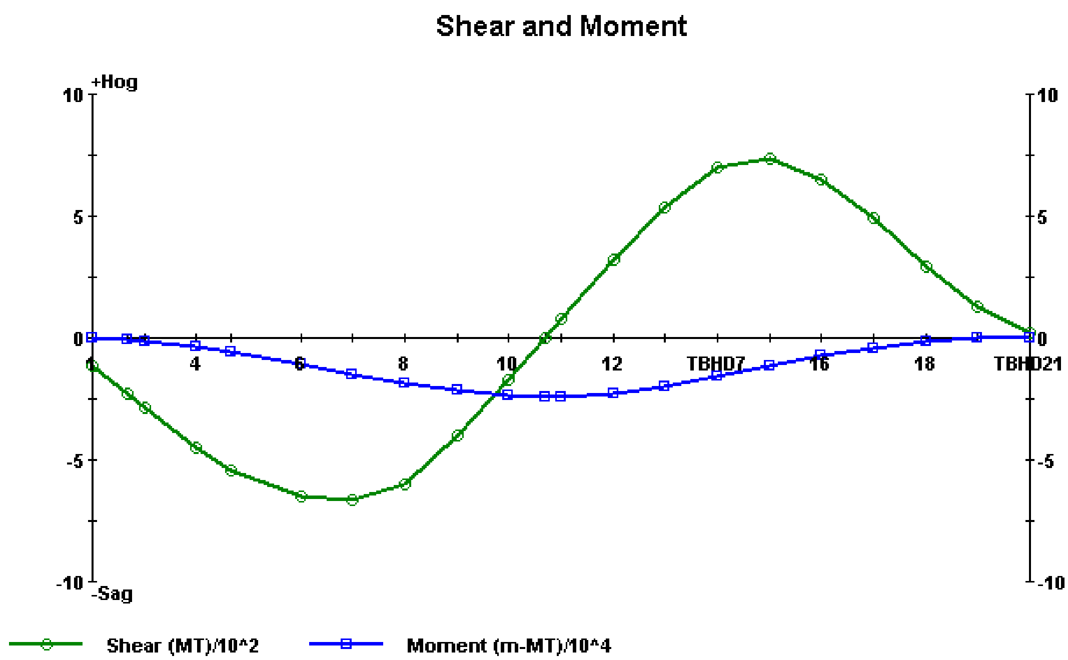
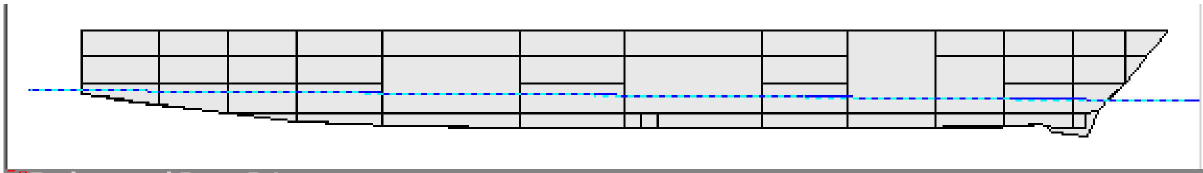


Figure 66: Lightship Sagging Design Wave Shear force and Bending Moment Diagram

The minimum operating condition was taken from the the ASSET improved baseline with design development. This condition is a theoretical condition that would be approached as the ship went into a dry-docking period. It reduces the fuel oil, lube oil, fresh water, and stores to 1/3 of the full load values. The preliminary minimum operating condition displacement for the large SSC is 4443 MT, and the preliminary VCG is 5.337. The lightship loading condition and upright hydrostatics are shown in Figure 67.



Intact Trim and Stability Summary

minop stillwater

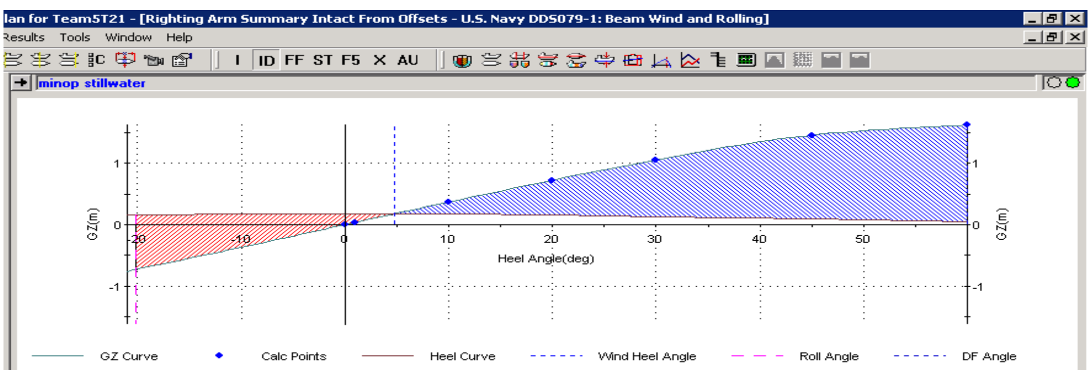
Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT
Light Ship	4,166	5.650	65.000A	0.000	----
Constant	0	0.000	60.900A	0.000	0
Lube Oil	13	0.536	57.907A	0.000S	64
Fresh Water	4	3.950	64.987A	0.000P	0
SW Ballast	0	----	----	----	----
Fuel Oil (DFM)	241	0.581	59.875A	0.000S	948
Oil Waste	0	----	----	----	----
JP-5	19	0.881	90.657A	0.000	55
Misc. Weights	0	----	----	----	----
Displacement	4,443	5.337	64.813A	0.000P	1,068

Stability Calculation			Trim Calculation		
KMt	7.914	m	LCF Draft	4.252	m
VCG	5.337	m	LCB	64.879A	m-FP
GMt (Solid)	2.576	m	LCF	68.481A	m-FP
FSc	0.240	m	MT1cm	109	m-MT/cm
GMt (Corrected)	2.336	m	Trim	1.189	m-A
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		

Drafts			Strength Calculations		
Draft at F.P.	3.584	m	Shear	145	MT at 108.900A m-FP
Draft at M.S.	4.178	m	Bending Moment	3,743H	m-MT at 85.453A m-FP
Draft at A.P.	4.772	m			
Draft at FwdMarks	3.613	m			
Draft at Mid Marks	4.207	m			
Draft at AftMarks	4.802	m			

Figure 67: Minimum Operating Condition

Intact stability was assessed for the min op condition against the criteria contained in DDS 079. A plot of the GZ curve for the intact condition is shown in Figure 68.



Parameter	Units	Value	Required
Wind Heel	deg	4.8	---
Wind Heeling Arm Lw	m	0.177	---
Maximum Righting Arm Ratio		0.11	0.6
Capsizing Area A2	m-rad	0.20	---
Righting Area A1	m-rad	0.90	0.27
Angle Limiting Area	deg	60.0	---
Maximum Righting Arm	m	1.631	---
Angle at Max. GZ	deg	60.0	---
Projected Sail Area	m2	839.49	---
Vertical Arm ABL	m	7.615	---
Heeling Arm at 0 deg.	m	0.178	---
Wind Pressure	bar	0.02	---
Input Parameters			
Wind Speed		100.0	
Reference Draft	m	0.000	
Projected Sail Area	m2	0.00	
Vertical Center of Sail Area -BL	m	0.000	
Factor f where p = f*V^2 (lb/ft^2)		0.0035	
Roll Angle	deg	25.0	

Figure 68: MinOp Intact Stability

This plot shows that the large SSC does meet the DDS 079intact stability criteria in the MinOp condition. The ratio of maximum heeling arm to maximum righting arm for a 100 kt wind does not exceed

0.6. Also, the area under the righting arm curve (A1) is greater than the required value, and the static wind heel angle does not exceed 15 degrees.

The still water shear force and bending moment diagrams for the MinOp condition are given in Figure 69. This bending moment distribution shows that the vessel is hogging in the MinOp condition.

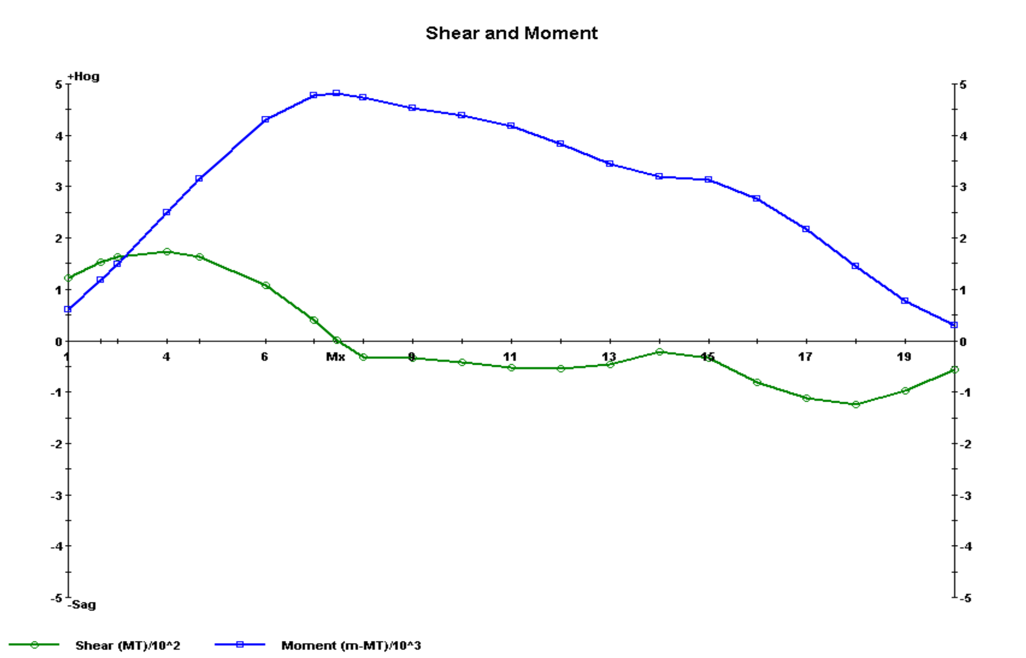
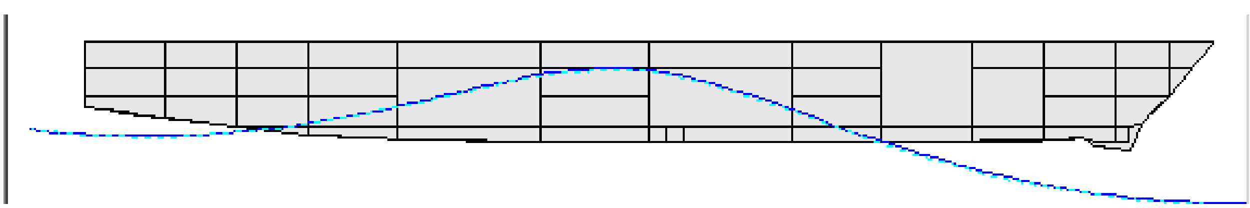


Figure 69: MinOp Stillwater Shear force and Bending Moment Diagram

Hydrostatics, intact stability, and hull loading were also checked in the MinOp condition with the ship balanced on a design hogging and design sagging wave. The equilibrium hydrostatics for the MinOp condition on a hogging and sagging wave are given in Figure 70 and Figure 71. In the case of waves, both the hogging and sagging conditions were evaluated using a trochoidal wave, with the wave height (h) given by:

$$H = \sqrt{0.6*LBP} \text{ (m)}$$



lan for Team5T21 (Z:\FINAL HECSALV FILE.pln) - [Intact Trim and Stability Summary]

Results Tools Window Help

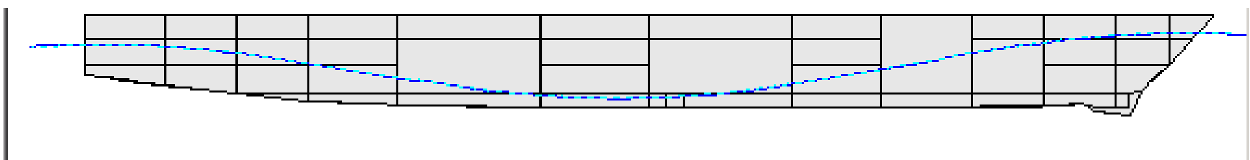
minop hog

Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT
Light Ship	4,166	5.650	65.000A	0.000	----
Constant	0	0.000	60.900A	0.000	0
Lube Oil	13	0.536	57.907A	0.000S	64
Fresh Water	4	3.950	64.987A	0.000P	0
SW Ballast	0	----	----	----	----
Fuel Oil (DFM)	241	0.581	59.875A	0.000S	948
Oil Waste	0	----	----	----	----
JP-5	19	0.881	90.657A	0.000	55
Misc. Weights	0	----	----	----	----
Displacement	4,443	5.337	64.813A	0.000P	1,068

Stability Calculation			Trim Calculation		
KMt	7.464	m	LCF Draft	2.954	m
VCG	5.337	m	LCB	64.908A	m-FP
GMt (Solid)	2.127	m	LCF	65.756A	m-FP
FSc	0.240	m	MT1cm	26	m-MT/cm
GMt (Corrected)	1.886	m	Trim	7.133	m-A
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		

Drafts			Strength Calculations		
Draft at F.P.	-0.897	m	Shear	-810	MT at 42.900A m-FP
Draft at M.S.	2.670	m	Bending Moment	28,322H	m-MT at 60.900A m-FP
Draft at A.P.	6.236	m			
Draft at FwdMarks	-0.721	m			
Draft at Mid Marks	2.846	m			
Draft at AftMarks	6.412	m			

Figure 70: MinOp Hogging Wave Equilibrium Condition



lan for Team5T21 (Z:\FINAL HECSALV FILE.pln) - [Intact Trim and Stability Summary]

Results Tools Window Help

minop sag

Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT
Light Ship	4,166	5.650	65.000A	0.000	----
Constant	0	0.000	60.900A	0.000	0
Lube Oil	13	0.536	57.907A	0.000S	64
Fresh Water	4	3.950	64.987A	0.000P	0
SW Ballast	0	----	----	----	----
Fuel Oil (DFM)	241	0.581	59.875A	0.000S	948
Oil Waste	0	----	----	----	----
JP-5	19	0.881	90.657A	0.000	55
Misc. Weights	0	----	----	----	----
Displacement	4,443	5.337	64.813A	0.000P	1,068

Stability Calculation			Trim Calculation		
KMt	8.675	m	LCF Draft	4.691	m
VCG	5.337	m	LCB	64.784A	m-FP
GMt (Solid)	3.338	m	LCF	65.805A	m-FP
FSc	0.240	m	MT1cm	141	m-MT/cm
GMt (Corrected)	3.097	m	Trim	1.419	m-F
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		

Drafts			Strength Calculations		
Draft at F.P.	5.458	m	Shear	800	MT at 36.900A m-FP
Draft at M.S.	4.749	m	Bending Moment	26,112S	m-MT at 62.834A m-FP
Draft at A.P.	4.039	m			
Draft at FwdMarks	5.423	m			
Draft at Mid Marks	4.714	m			
Draft at AftMarks	4.004	m			

Figure 71: MinOp Sagging Wave Equilibrium Condition

The shear force and bending moment diagram for the hogging and sagging conditions were calculated for MinOp and are shown in Figure 72.

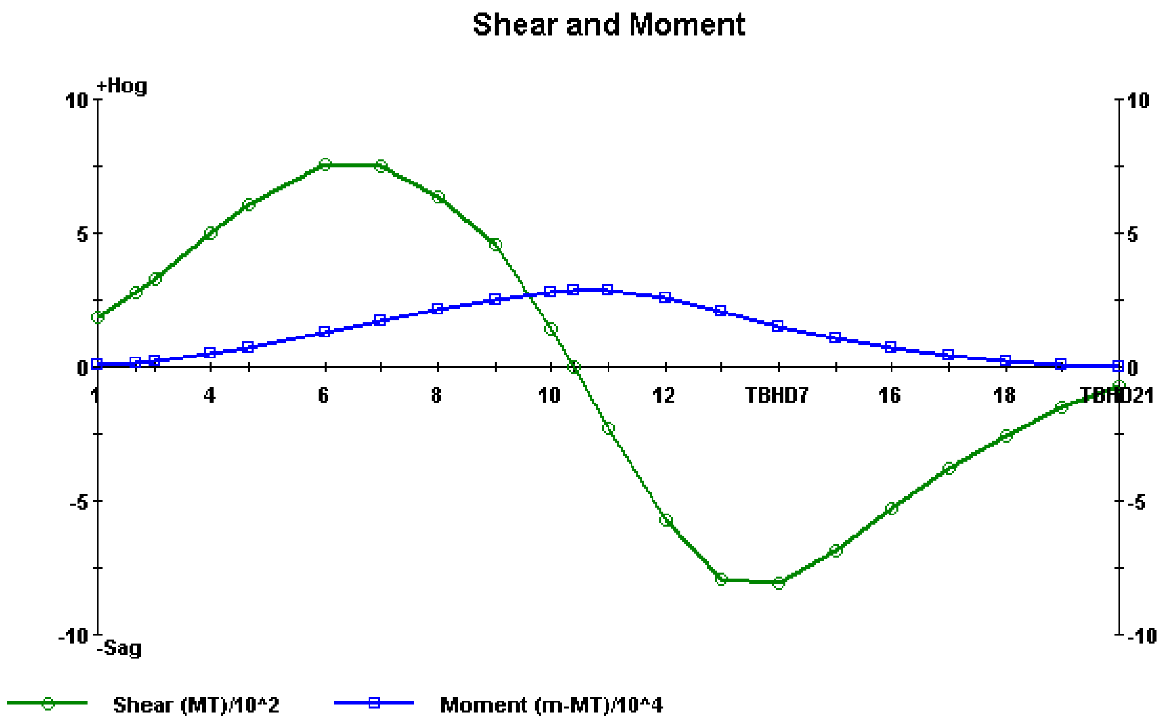


Figure 72: MinOp Hogging Design Wave Shear force and Bending Moment Diagram

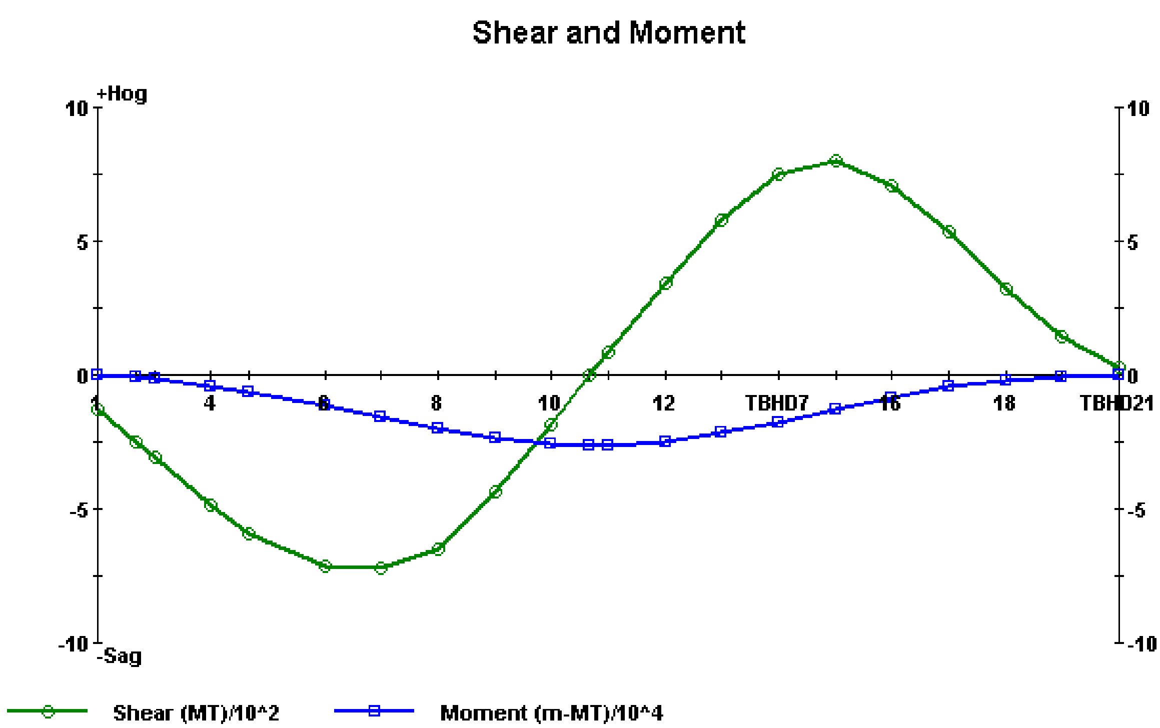
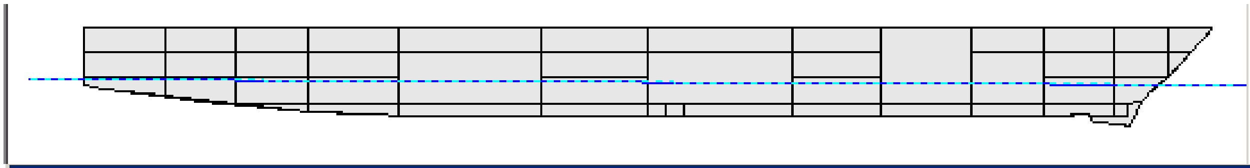


Figure 73: MinOp Sagging Design Wave Shear force and Bending Moment Diagram

The Full Load condition was taken from the ASSET improved baseline with design development. In this condition, the lube oil, fuel oil, potable water and stores all at their maximum service load. The preliminary Full Load displacement for the large SSC is 5224 MT, and the preliminary lightship VCG is 4.601 m ABL. The full load loading condition and upright hydrostatics are shown in Figure 74.



Intact Trim and Stability Summary

full load stillwater

Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT
Light Ship	4,166	5.650	65.000A	0.000	----
Constant	0	0.000	60.900A	0.000	0
Lube Oil	25	0.841	57.905A	0.000P	34
Fresh Water	8	4.332	64.952A	0.000P	0
SW Ballast	0	----	----	----	----
Fuel Oil (DFM)	458	0.873	59.945A	0.000P	517
Oil Waste	0	----	----	----	----
JP-5	37	1.089	91.004A	0.000	30
Misc. Weights	530	0.000	60.900A	0.000	0
Displacement	5,224	4.601	64.290A	0.000P	580

Stability Calculation			Trim Calculation		
KMt	7.634	m	LCF Draft	4.749	m
VCG	4.601	m	LCB	64.332A	m-FP
GMt (Solid)	3.034	m	LCF	68.129A	m-FP
FSc	0.111	m	MT1cm	114	m-MT/cm
GMt (Corrected)	2.923	m	Trim	0.707	m-A
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		

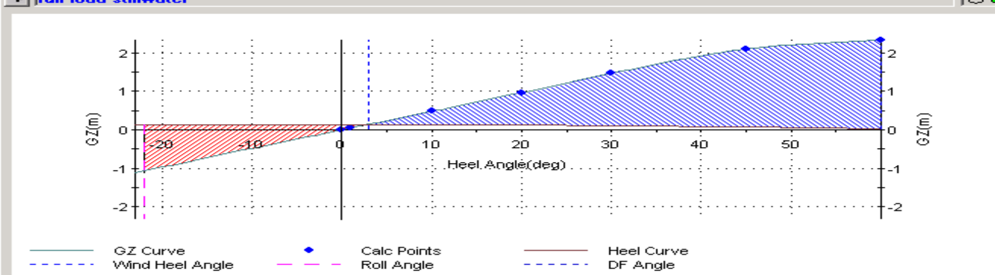
Drafts			Strength Calculations		
Draft at F.P.	4.354	m	Shear	-274	MT at 66.900A m-FP
Draft at M.S.	4.707	m	Bending Moment	4,734S	m-MT at 60.494A m-FP
Draft at A.P.	5.061	m			
Draft at FwdMarks	4.371	m			
Draft at Mid Marks	4.725	m			
Draft at AftMarks	5.079	m			

Figure 74: Full Load Stillwater Condition

Intact stability was assessed for the full load condition against the criteria contained in DDS 079. A plot of the GZ curve for the intact condition is shown in Figure 75.

Righting Arm Summary Intact From Offsets - U.S. Navy DDS079-1: Beam Wind and Rolling

full load stillwater



Parameter	Units	Value	Required
Wind Heel	deg	2.9	---
Wind Heeling Arm Lw	m	0.140	---
Maximum Righting Arm Ratio		0.06	0.6
Capsizing Area A2	m-rad	0.26	---
Righting Area A1	m-rad	1.34	0.36
Angle Limiting Area	deg	60.0	---
Maximum Righting Arm	m	2.330	---
Angle at Max. GZ	deg	60.0	---
Projected Sail Area	m2	775.79	---
Vertical Arm ABL	m	7.876	---
Heeling Arm at 0 deg.	m	0.140	---
Wind Pressure	bar	0.02	---
Input Parameters			
Wind Speed		100.0	
Reference Draft	m	0.000	
Projected Sail Area	m2	0.00	
Vertical Center of Sail Area -BL	m	0.000	
Factor f where p = f*V^2 (lb/ft^2)		0.0035	
Roll Angle	deg	25.0	

Figure 75: Full Load Intact Stability

This plot shows that the large SSC does meet the DDS 079 intact stability criteria in the full load condition. The ratio of maximum heeling arm to maximum righting arm for a 100 kt wind does not exceed 0.6. Also, the area under the righting arm curve (A1) is greater than the required value, and the static wind heel angle does not exceed 15 degrees and A1/A2 > 1.4.

The still water shear force and bending moment diagrams for the full load condition are given in Figure 76. This bending moment distribution shows that the vessel is sagging in the full load condition.

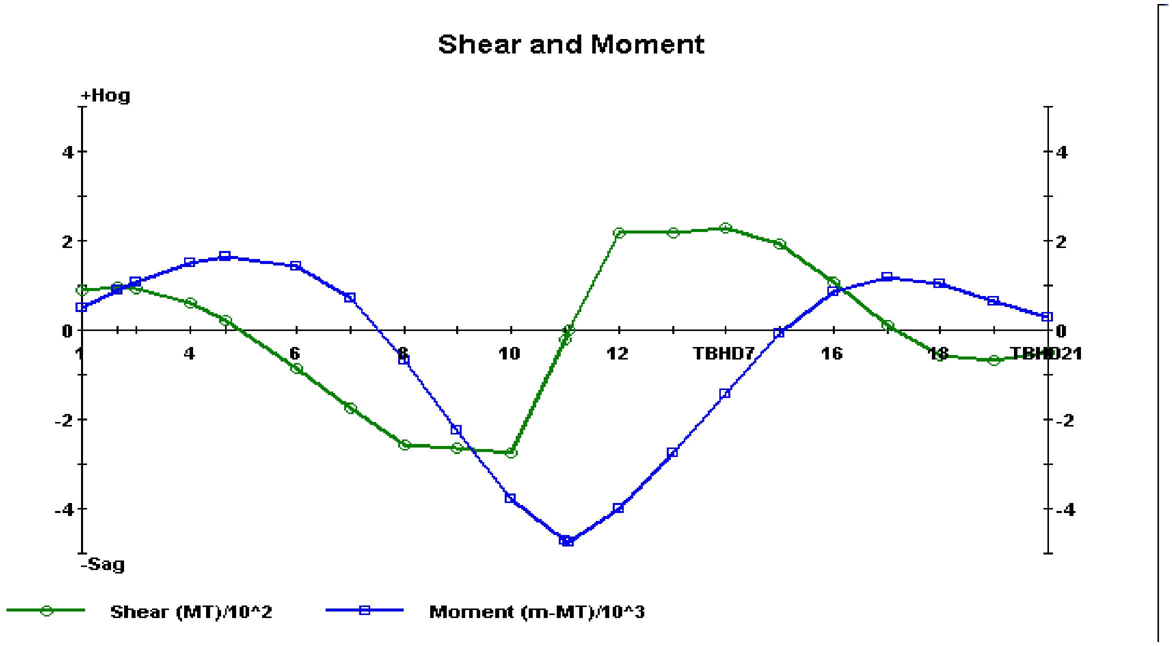
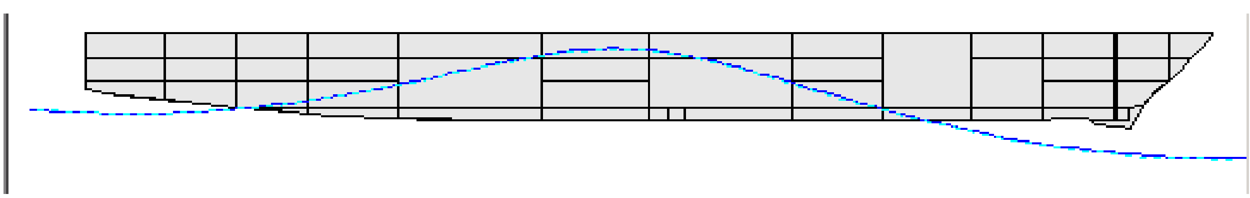


Figure 76: Full Load Stillwater Shear force and Bending Moment Diagram

Hydrostatics, intact stability, and hull loading were also checked in the full load condition with the ship balanced on a design hogging and design sagging wave. The equilibrium hydrostatics for the lightship condition on a hogging and sagging wave are given in Figure 77 and Figure 78. In the case of waves, both the hogging and sagging conditions were evaluated using a trochoidal wave, with the wave height (h) given by:

$$H = \sqrt{0.6 * LBP} \text{ (m)}$$



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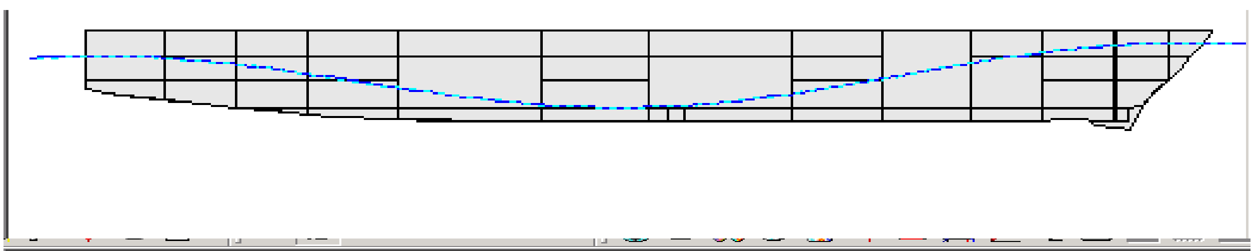
Tools Window Help

full load hog

Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT
Light Ship	4,166	5.650	65.000A	0.000	----
Constant	0	0.000	60.900A	0.000	0
Lube Oil	25	0.841	57.905A	0.000P	34
Fresh Water	8	4.332	64.952A	0.000P	0
SW Ballast	0	----	----	----	----
Fuel Oil (DFM)	458	0.873	59.945A	0.000P	517
Oil Waste	0	----	----	----	----
JP-5	37	1.089	91.004A	0.000	30
Misc. Weights	530	0.000	60.900A	0.000	0
Displacement	5,224	4.601	64.290A	0.000P	580

Stability Calculation			Trim Calculation		
KMt	7.470	m	LCF Draft	3.690	m
VCG	4.601	m	LCB	64.311A	m-FP
GMt (Solid)	2.869	m	LCF	65.577A	m-FP
FSc	0.111	m	MT1cm	30	m-MT/cm
GMt (Corrected)	2.758	m	Trim	5.856	m-A
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		
Drafts			**Strength Calculations**		
Draft at F.P.	0.537	m	Shear	701	MT at 90.900A m-FP
Draft at M.S.	3.465	m	Bending Moment	24,471H	m-MT at 60.900A m-FP
Draft at A.P.	6.393	m			
Draft at FwdMarks	0.681	m			
Draft at Mid Marks	3.609	m			
Draft at AftMarks	6.537	m			

Figure 77: Full Load Hogging Wave Equilibrium Condition



Intact Trim and Stability Summary

full load sag

Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT
Light Ship	4,166	5.650	65.000A	0.000	----
Constant	0	0.000	60.900A	0.000	0
Lube Oil	25	0.841	57.905A	0.000P	34
Fresh Water	8	4.332	64.952A	0.000P	0
SW Ballast	0	----	----	----	----
Fuel Oil (DFM)	458	0.873	59.945A	0.000P	517
Oil Waste	0	----	----	----	----
JP-5	37	1.089	91.004A	0.000	30
Misc. Weights	530	0.000	60.900A	0.000	0
Displacement	5,224	4.601	64.290A	0.000P	580

Stability Calculation			Trim Calculation		
KMt	8.513	m	LCF Draft	5.176	m
VCG	4.601	m	LCB	64.271A	m-FP
GMt (Solid)	3.913	m	LCF	65.148A	m-FP
FSc	0.111	m	MT1cm	147	m-MT/cm
GMt (Corrected)	3.802	m	Trim	1.635	m-F
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		
Drafts			**Strength Calculations**		
Draft at F.P.	6.050	m	Shear	1,008	MT at 36.900A m-FP
Draft at M.S.	5.233	m	Bending Moment	34,915S	m-MT at 61.921A m-FP
Draft at A.P.	4.415	m			
Draft at FwdMarks	6.010	m			
Draft at Mid Marks	5.193	m			
Draft at AftMarks	4.375	m			

Figure 78: Full Load Sagging Wave Equilibrium Condition

The shear force and bending moment diagram for the hogging and sagging conditions were calculated for full load and are shown in Figure 79and Figure 80.

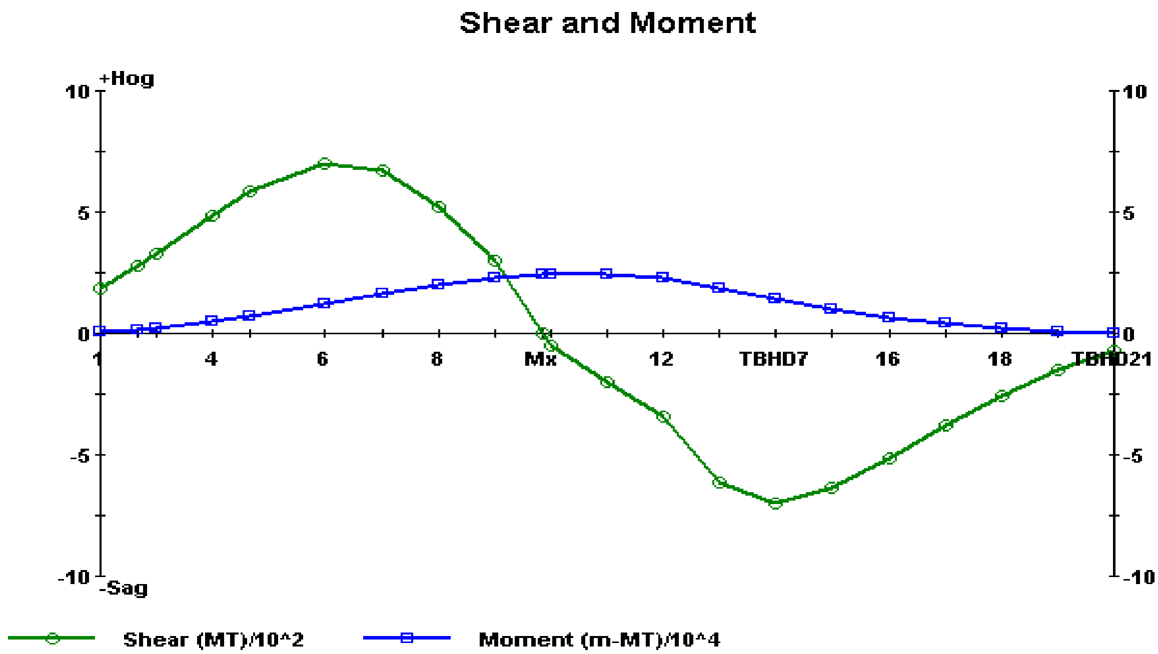


Figure 79: Full Load Hogging Design Wave Shear force and Bending Moment Diagram

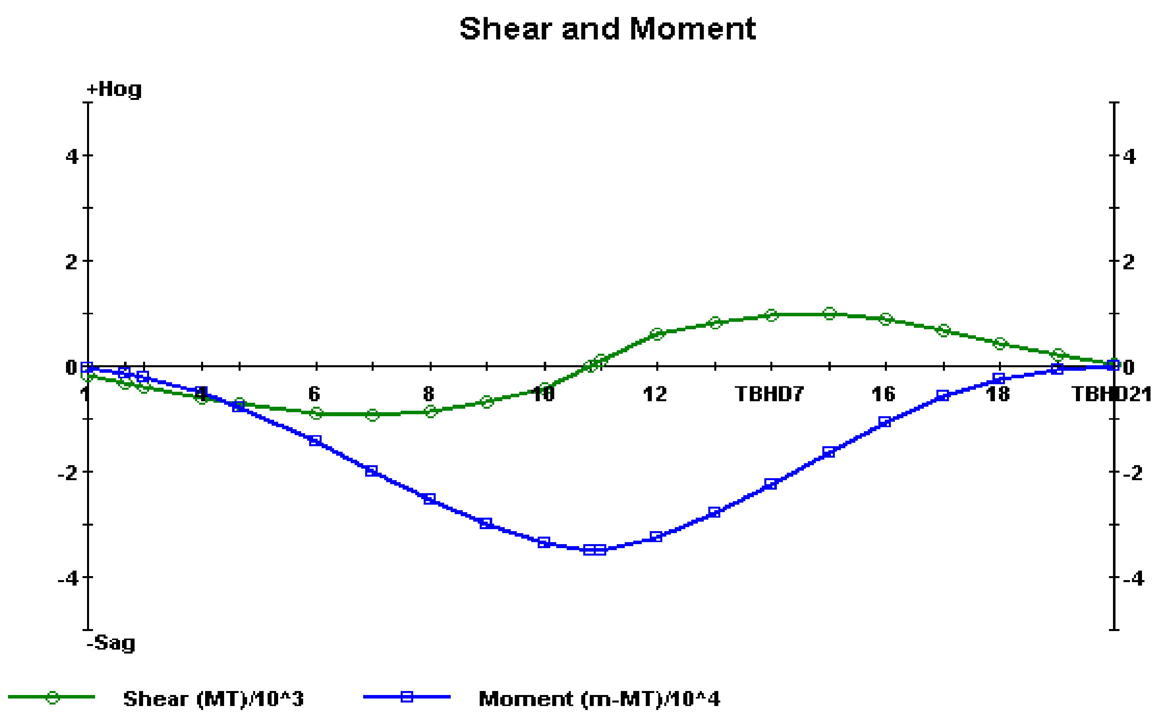


Figure 80: Full Load Sagging Design Wave Shear force and Bending Moment Diagram

4.5 Structural Design and Analysis

A full structural model of the SSC was created in MAESTRO in order to fully simulate the loading on the ship using US Navy structural load criteria. Structural inputs were taken from ASSET in order to determine the main scantlings and the 3D Rhino model was used to input the faired geometry of the SSC.

4.5.1 Geometry, Components and Materials

The geometry of the structural model was initially created by using buttock lines and waterlines to create the endpoints in MAESTRO. The lines were output from the 3D Rhino model and provided the geometry of the outer hull at each station. The Buttock heights are provided in Table 24, and the Waterline half-breadths are provided in Table 25.

Table 24: Buttock Heights from the 3D Rhino Model

		BUTTOCK HEIGHTS					
		Buttock	Buttock	Buttock	Buttock		
FP	Station	0.000	2.000	4.000	6.000	Station	
1	0.900	9.436				0.900	1.000
2	6.900	3.425	8.544			6.900	2.000
3	14.900	-0.460	4.460	8.191	10.789	14.900	3.000
4	22.900	0.007	1.270	4.924	8.554	22.900	4.000
5	32.900	0.002	0.568	1.776	5.447	32.900	5.000
6	42.900	0.000	0.373	1.070	2.661	42.900	6.000
7	58.900	0.000	0.100	0.491	1.661	58.900	7.000
8	70.900	0.000	0.105	0.481	1.511	70.900	8.000
9	86.900	0.043	0.437	1.182	2.489	86.900	9.000
10	98.900	0.673	1.235	2.111	3.388	98.900	10.000
11	110.900	2.049	2.551	3.225	4.384	110.900	11.000
AP	121.800	3.560	3.865	4.383	6.475	121.800	aft

Table 25: Waterline Half-Breadths from the 3D Rhino Model

	WATERLINE HALF-BREADTHS						
		Waterline	Waterline	Waterline	Waterline	Waterline	
	Station	1.500	5.000	5.300	8.000	11.000	Station
FP	0.900					-1.361	0.900
1	6.900		-0.465	-0.536	-1.675	-3.811	6.900
2	10.809	-0.362	-1.276	-1.384	-2.776	-5.075	10.809
3	14.900	-0.900	-2.221	-2.353	-3.871	-6.182	14.900
4	22.900	-2.201	-4.036	-4.181	-5.657	-7.663	22.900
5	32.900	-3.674	-5.820	-5.941	-7.078	-7.663	32.900
6	42.900	-4.791	-6.890	-6.973	-7.731	-7.663	42.900
7	58.900	-5.833	-7.485	-7.543	-8.032	-7.663	58.900
8	70.900	-5.988	-7.531	-7.589	-8.060	-7.663	70.900
9	86.900	-4.619	-7.493	-7.566	-8.055	-7.663	86.900
10	98.900	-2.684	-7.273	-7.386	-7.933	-7.663	98.900
11	110.900		-6.490	-6.644	-7.398	-7.663	110.900
AP	121.800		-5.179	-5.418	-6.452	-7.010	121.800

The remaining geometrical inputs were taken from the output of the ASSET hull structures module. ASSET produced the frame spacing for the model, which was set as a standard 2.0 m, as well as the location of the design waterline, the deck locations, and the transition points for changes in material properties. The location of the structural transitions, as generated by ASSET, can be seen in Figure 81 and Figure 82.

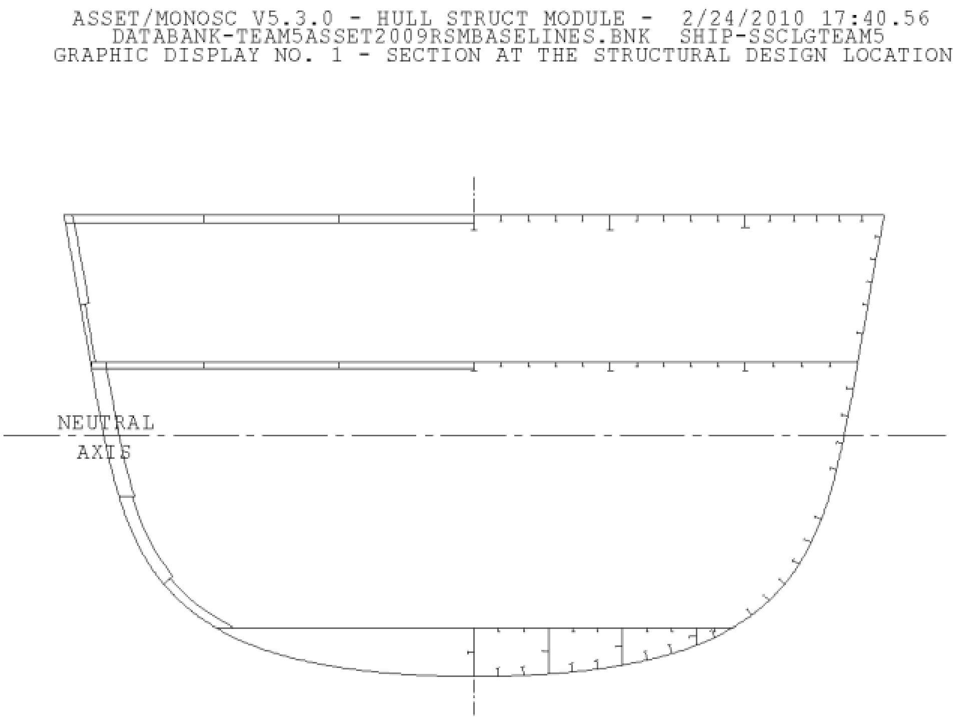


Figure 81: Structural View of the ASSET Improved Baseline Model

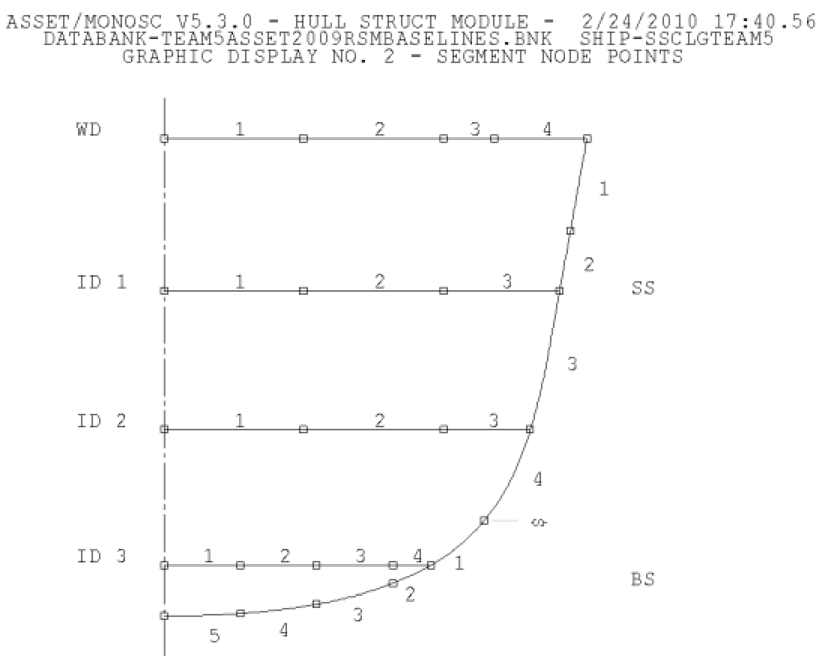


Figure 82: ASSET Output of the Node Locations and Strake Numbers

Using all of the geometric inputs, the next step in the process of building the structural model in MAESTRO is entering the endpoints for each compartment of the ship. This particular ship has 11 compartments, each separated by a transverse bulkhead. The compartments are first modeled as a wireframe of endpoints one compartment at a time, as seen in Figure 83. MAESTRO considers each compartment a separate MAESTRO module, and each module is built independently. MAESTRO also allows for port/starboard symmetry when creating the model, so only half of the ship is required to be built.

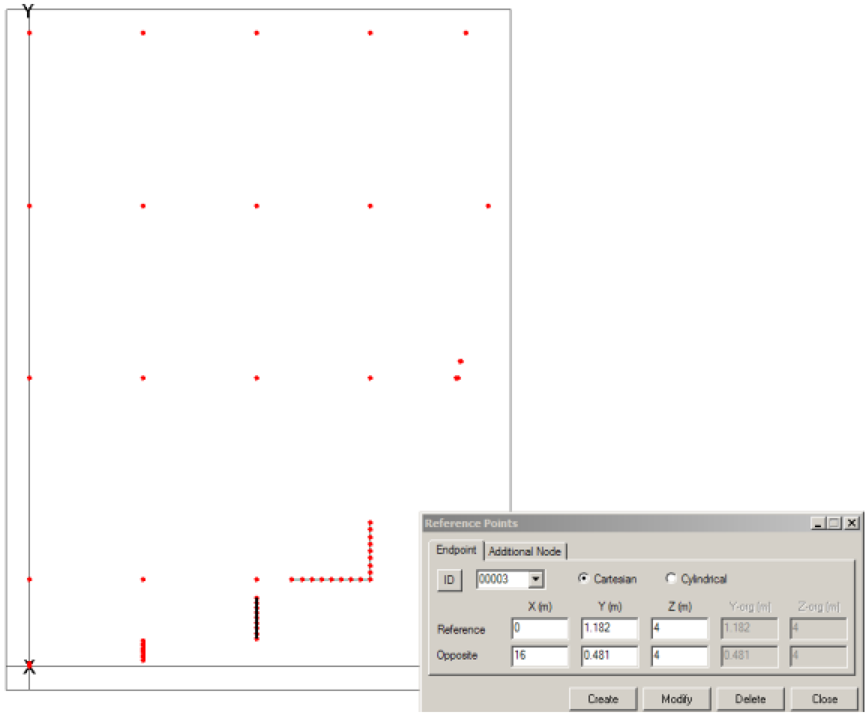


Figure 83: MAESTRO Screenshot showing the Endpoints for Compartment 9

Once the geometry is outlined, the materials and the structural scantlings are input from ASSET. HSS was used for the plating throughout the ship in its initial design and HY-80 was used for the frames, stiffeners, girders, and beams. This design choice would be reconsidered in the second round of the design spiral, due to the low stresses seen in the analysis of the structural model. HSS could be used for the structural members in order to lower cost and construction time, and HY-80 could be used at strategic locations where the additional strength could prove beneficial. The crack arrestor strake and bilge strake are typical areas where naval surface combatants have HY-80 structural members and plating.

ASSET provided all of the scantling geometry provided for the bottom shell, side shell, weather deck, the internal decks, the transverse bulkheads, the girders, the frames, and the stiffeners. The structural scantlings are shown in the amidships line drawing, shown in Figure 84.

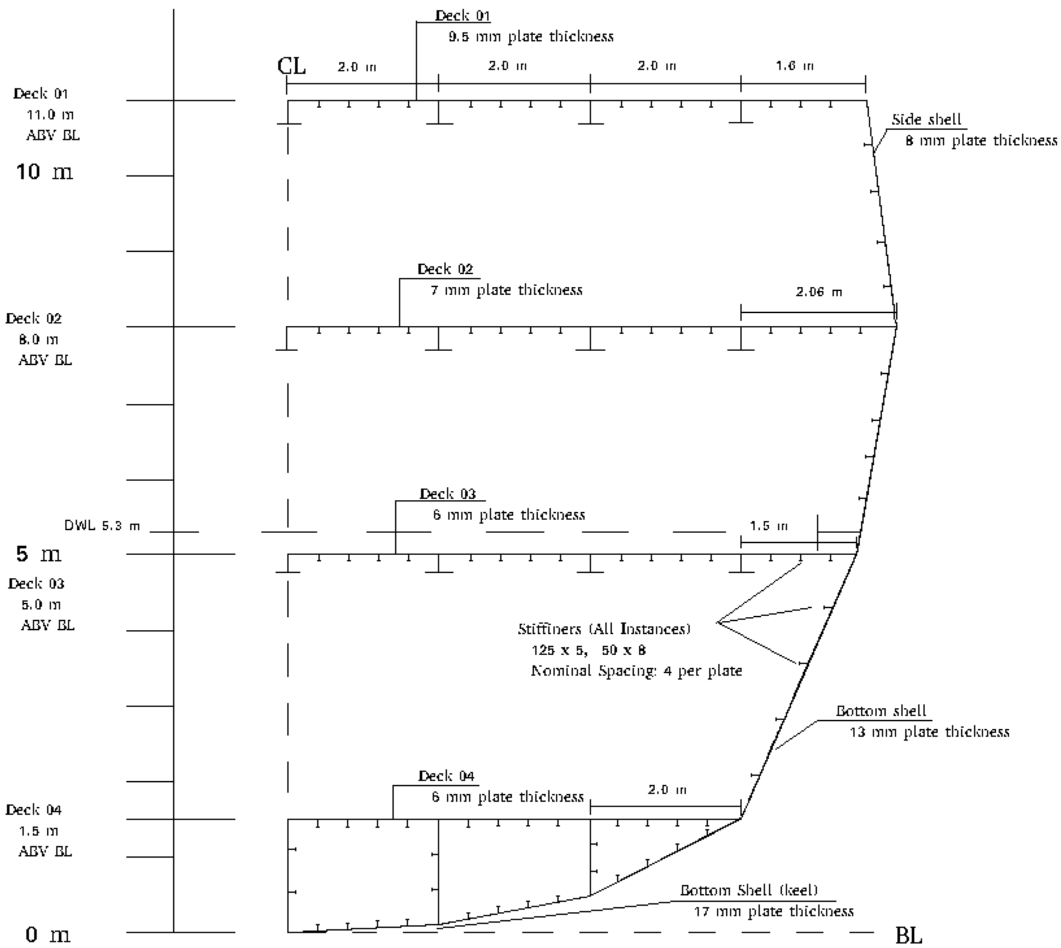


Figure 84: Amidships Structural Scantlings

Once all the material and scantling information is input into MAESTRO, the structural model can be built. First, the strakes are created between sets of endpoints. Strakes create stiffened panels which make up the outer hull and the decks. Each strake can contain a series of plates, set of frames, stiffeners, and a girder. Any of these components can be removed if necessary for creating the model. A MAESTRO screen shot of a strake and the MAESTRO dialog box can be viewed in Figure 85.

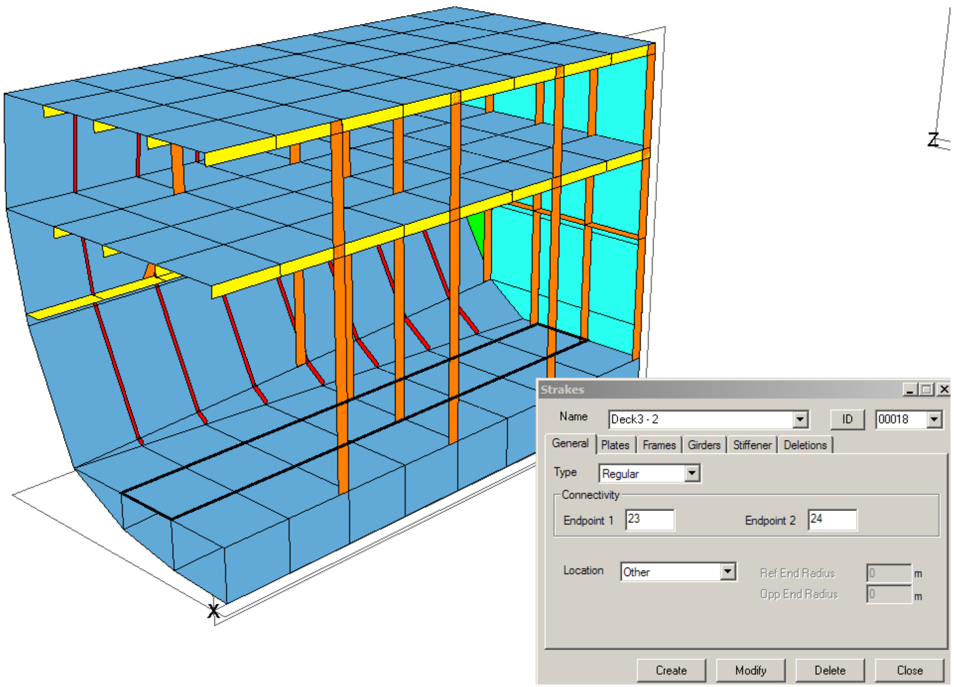


Figure 85: MAESTRO Strakes

Once the outer hull plate and the decks have been created, the other finite elements can be added in order to create transverse bulkheads, and beam supports. MAESTRO supports seven types of finite elements; however this model only used quads and triangle elements to create the transverse bulkheads and rods to create stanchions, which add structural support in the absence of a deck. Figure 86 shows a MAESTRO screen shot where the quads and triangle elements which were used to create a transverse bulkhead.

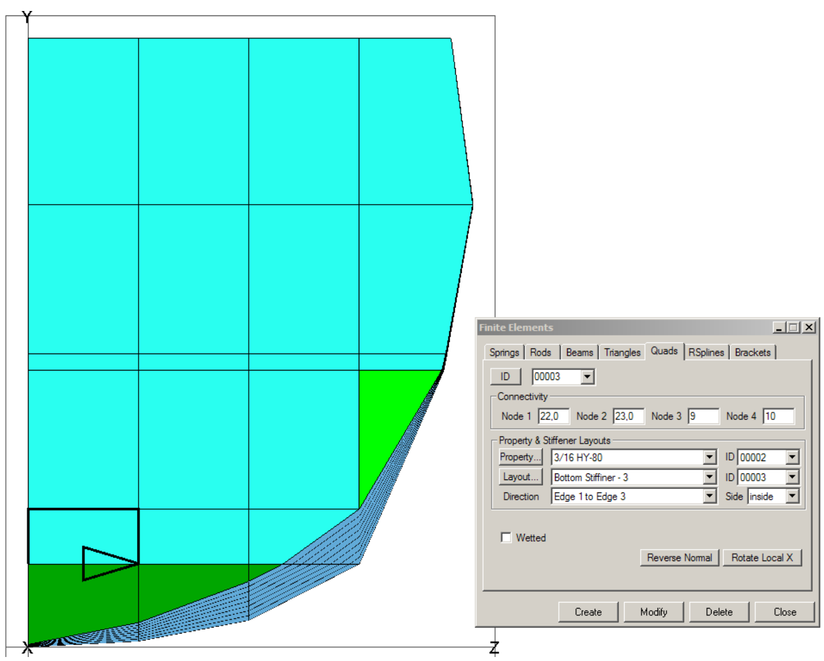


Figure 86: MAESTRO Quad and Tri Finite Elements Creating a Transverse Bulkhead

Once the transverse bulkheads have been created for each compartment, compound finite elements are used to create tanks in the inner bottom. Compounds are simply a series of repeated finite elements, such as quads or triangle elements that can be created across an entire module. In this model, the compounds will be used for the inner structure of the tanks, as seen in Figure 87. Once the tanks are created, the boundary of the tank, which will be made up of strakes, finite elements, and compounds is defined in MAESTRO. Designating this boundary is accomplished by creating a volume group in MAESTRO. This group entity allows the user to select the boundary of the tank and isolate this structure from surrounding structure. In the case of this model, these volume groups will be used to load the tanks with liquids which will accurately model the load conditions of the liquid inside the tank.

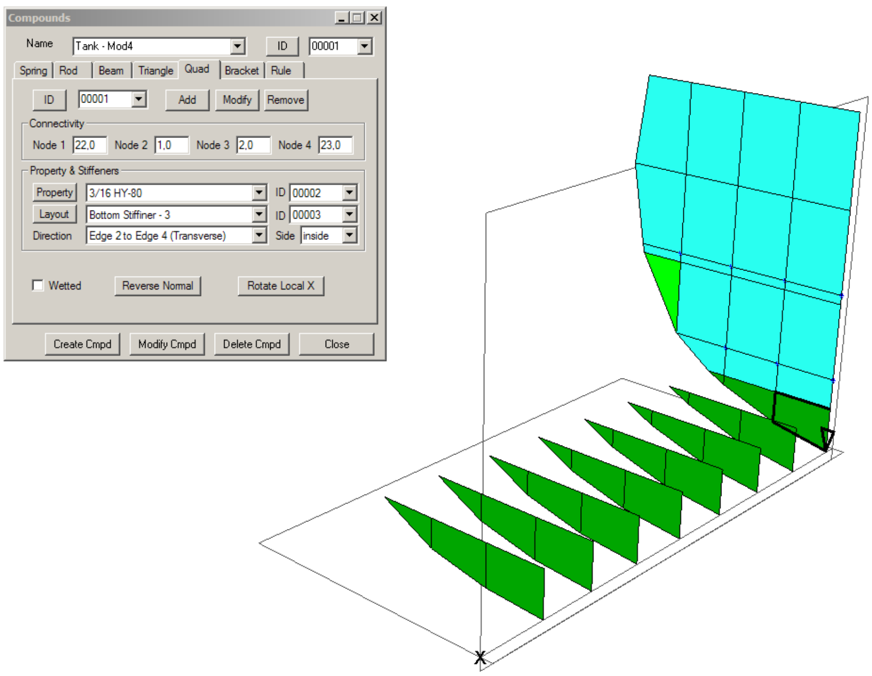


Figure 87: MAESTRO Tank Boundaries

Once the model is built and the groups are defined, a thorough check of the model must be performed in order to ensure the final structural calculations will be reliable. These checks include working through the endpoints to ensure everything remains in alignment, looking for free edges where finite elements are not properly connected, looking for duplicate elements, checking the pressure/non-pressure side of the plating, checking the side which the stiffeners are mounted on the stiffened panel, and even checking the aspect ratio, warp, and the internal angle of finite elements. A myriad of problems can be introduced into the structural model during its construction, and these checks are an integral part of creating a viable structural model. Once the final structural model passes its integrity checks, it can it be loaded and tested. The final structural model for the SSC can be seen in Figure 88, and an amidships section view can be seen in Figure 89.

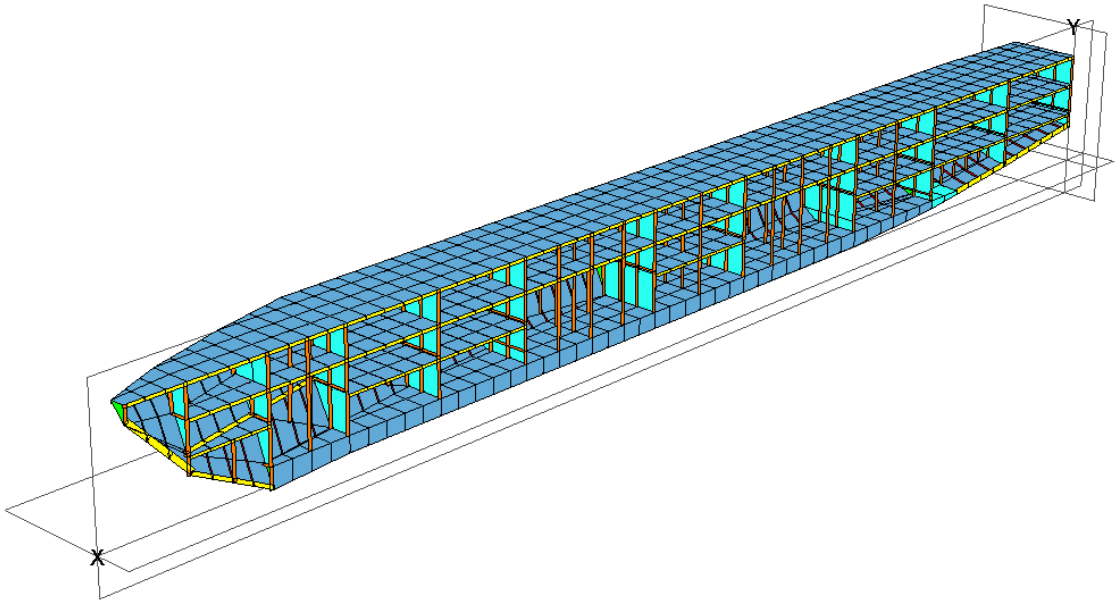


Figure 88: MAESTRO Full Ship Structural Model

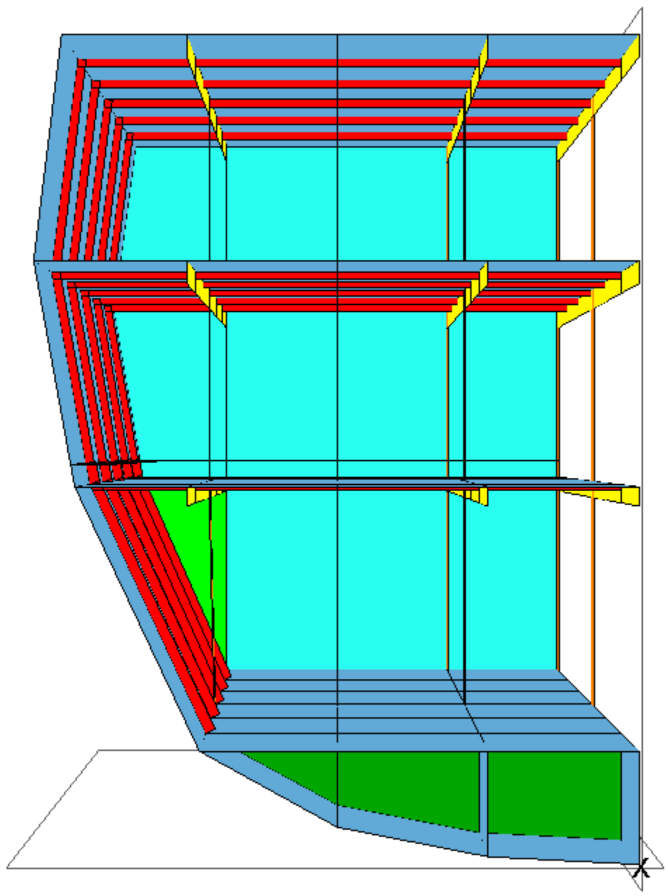


Figure 89: Amidships Section View of the MAESTRO Structural Model

4.5.2 Loads

The structural model required two primary loads that are assigned to the structural modules. These loads will be consistent for all of the loading conditions that test the adequacy of the structural model. These loads are the tank loads and the lightship loads associated with the weight of each module. The loads are separated into these two categories in order to allow MAESTRO to account for the differences in analysis of the liquid loads within the tanks versus the structural load and the permanent weight of the outfitting of the ship. Table 26 shows the necessary volume of tankage as required by the HECSALV model against the calculated volume available in the tanks that were modeled in the structural model; and Figure 90 shows a sample tank in MAESTRO along with its loading dialog box. As seen in this figure, the volume of the tank can be filled with the desired density of liquid, i.e. 840 kg/m^3 for JP5 and DFM, as well as to the desired tank level. This model assumes the tanks are filled to 98% capacity.

Table 26: Comparison Between MAESTRO and HECSALV Tankage Volumes

From HECSALV			
	1/2 Ship	Capacity	
Name	Volume	Density	Weight
	m3	MT/m3	MT
Lube Oil	15	0.92	13
Fresh Water	4	1.00	4
SW Ballast	28	1.01	28
Fuel Oil (DFM)	287	0.84	241
Oil Waste	14	0.92	13
JP-5	23	0.84	19
Total	370		318

From MAESTRO			
Volume Group Name	Volume (m^3)	Weight (kg)	Weight (MT)
tank - mod2	3	2795	3
tank - mod3	29	24266	24
tank - mod4	82	67128	67
tank - mod5	75	62067	62
tank - mod6	84	69220	69
tank - mod7	37	30760	31
tank - mod8	24	19854	20
tank - mod9	10	10088	10
Summary	345	286178	286

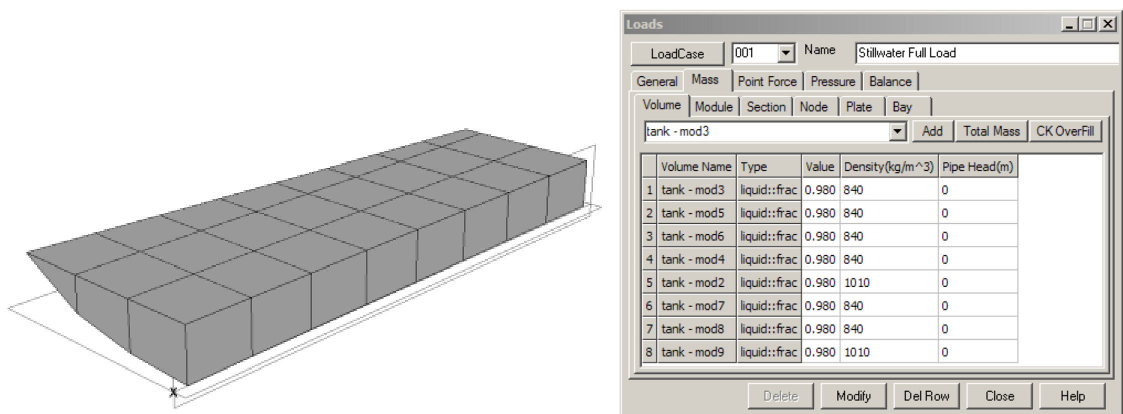


Figure 90: MAESTRO Sample Tank

Following the loading of the tanks, the lightship weight of each module is provided to MAESTRO. This allows the appropriate weight distribution to be simulated in the structural model for each compartment. Having an accurate weight distribution of each module is critical for the structural simulations. Careful calculation of the equipment and outfitting of each compartment will ensure the structure accurately responds to the loads that are placed upon it. The first round of preliminary design does not always allow for an accurate calculation of the weight distribution, so adjustments are made to match the sum of the module weights to the full load displacement, as seen in Table 27. The final ship weight distribution can be seen in Figure 91.

Table 27: Weight of MAESTRO Modules with Modifications for Full Load

	1/2 Weight	Tank Weight	Adjusted Weight	Total Weight
mod11	44000		44000	44000
mod10	57500		57500	57500
mod9	63000	10088	63000	73088
mod8	76500	19854	76500	96354
mod7	208000	30760	233000	263760
mod6	407333	69220	507333	576553
mod5	362667	62067	462667	524733
mod4	268500	67128	343500	410628
mod3	231500	24266	231500	255766
mod2	175000	2795	175000	177795
mod1	148000		148000	148000
Total (kg)	2042000	286178	2342000	2628178
Total (mtons)	2042	286	4684	4970

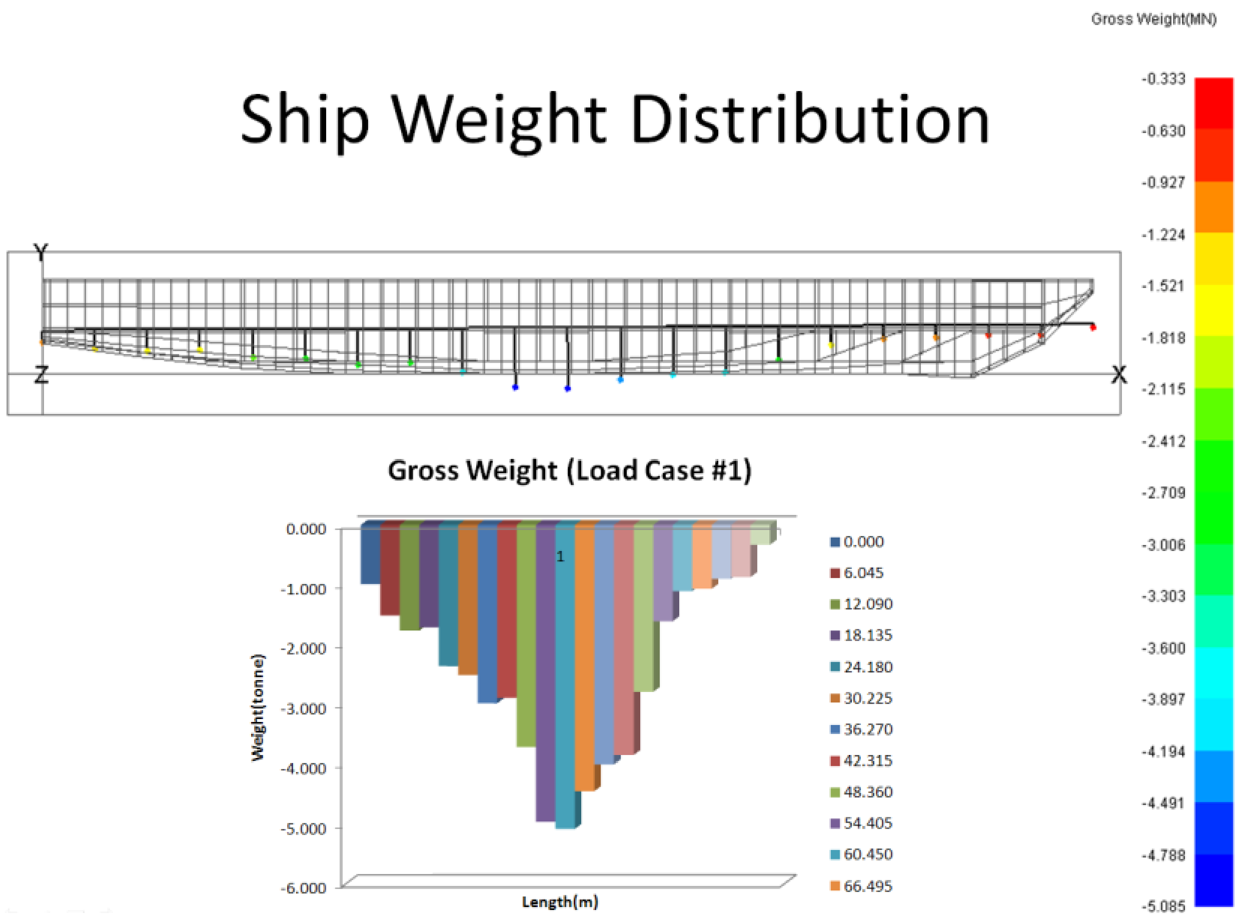


Figure 91: Weight Distribution in MAESTRO

Once the tank and module weights were input into the MAESTRO model, the loading conditions were defined. For this model, the following three primary loading conditions were considered: the standard still water case, a hogging wave, and a sagging wave. A graphical depiction of these three loading cases can be seen in Figure 92. For the hogging and sagging cases, the ship was set upon a trochoidal wave which has a wavelength equal to the LOA of the ship, and a wave height of 0.6 × √ (LBP). In addition to the three standard cases, the green water on the weather deck loading case was also considered. This load case is defined by the US Navy standard for structural loads, which requires a head pressure equal to 3.7 m of water above the weather deck at the forward perpendicular, with the head decreasing linearly to 1.2 m above the weather deck in a line to the design waterline at amidships. This can be seen graphically in Figure 93. A summary of all the loading conditions can be seen in Table 28.

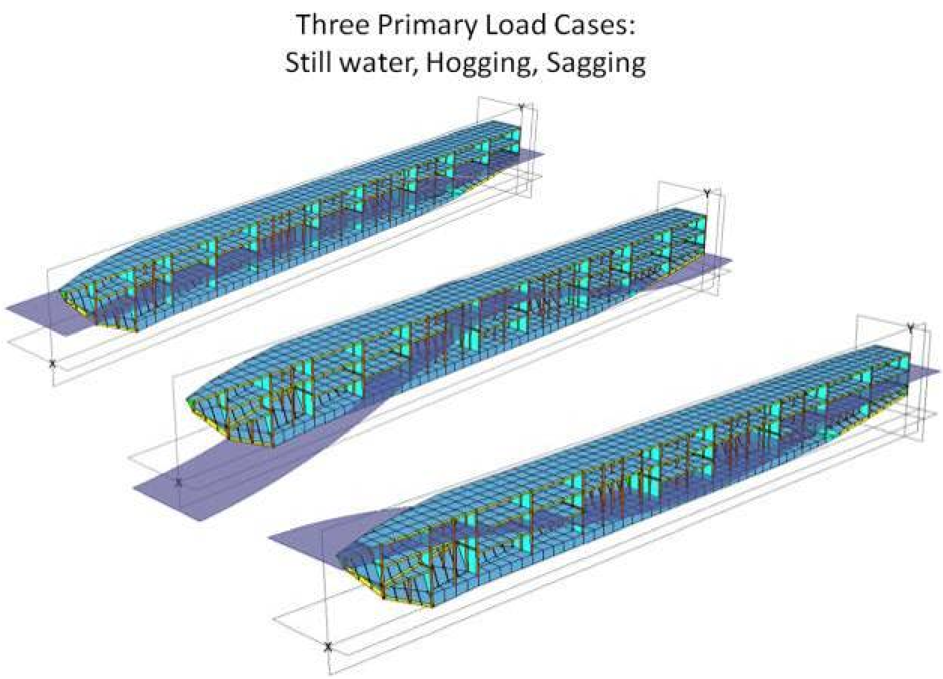


Figure 92: Three Primary Load Cases

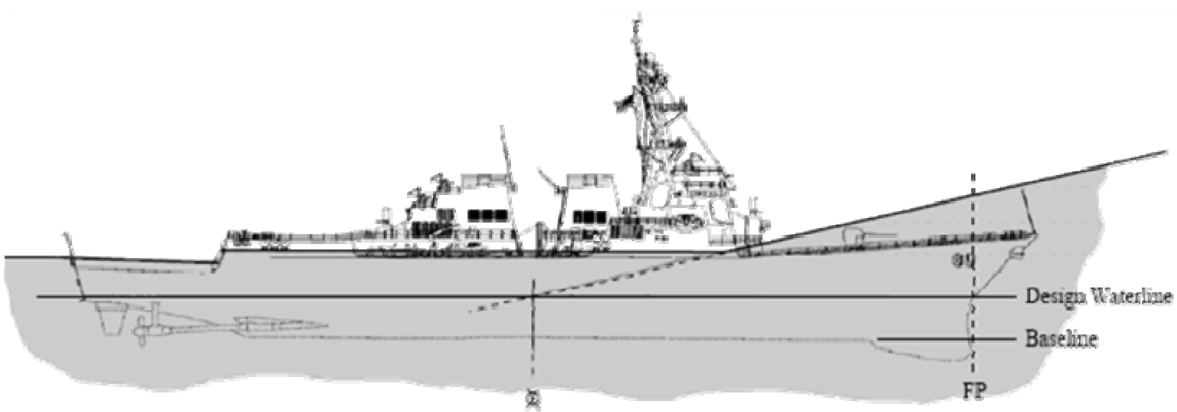


Figure 93: Green Seas Loading Condition as Defined by DDS 100

Table 28: Four Loading Conditions Tested in the Structural Model

	Still water	Hogging	Sagging	Green water on weather deck
Wavelength	--	121.8 m	121.8 m	--
Wave Height	--	6.62 m	6.62 m	--
Amplitude	--	3.31 m	3.31 m	--
Crest Location	--	60.9 m	0 m / 121.8 m	--
Type of Wave	--	Trochoidal	Trochoidal	--
Design WL	5.3 m	5.3 m	5.3 m	5.3 m

Once the ship is loaded, and the loading conditions have been set for analysis, restraints must be placed upon the ship to provide MAESTRO with certain boundary conditions for loading and testing the structure. These restraints are simple limitations in the movement of the ship for the purpose of the analysis. For this model, the ship was restrained in the vertical direction at both the bow and the stern, and was restrained from movement in the longitudinal direction in the bow. This can be seen graphically in Figure 94.

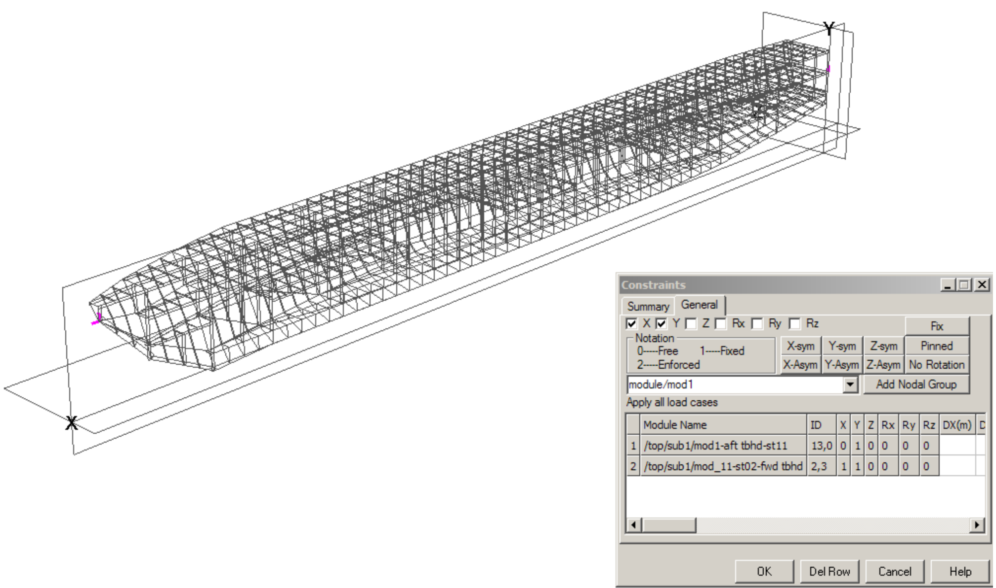


Figure 94: Constraints on the Structural Model

4.5.3 Adequacy

Once the Finite Element Analysis is run in MAESTRO, the stresses are calculated across the ship. The X Normal, Y Normal, and VonMises stresses are recovered at the neutral axis of the stiffener and plate structure. The shear stress reported for Mid is the Plate Shear stress from the mid-plane of the plate. MAESTRO can recover stresses for a stiffened panel at the mid-plane of the plate (Top), the neutral axis of the plate and stiffener combination (Mid) and the axial stress at the mid-plane of the stiffener flange (Bottom/Stiffener Flange). Graphically this can be seen in Figure 95. These details as well as further descriptions on the calculation of the calculation of the stresses can be found in the MAESTRO help file.

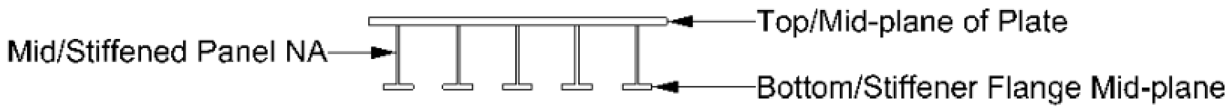


Figure 95: Graphical Depiction of how the Stresses are Calculated in MAESTRO

MAESTRO also calculates various adequacy parameters of the structural model. These adequacy parameters are limit states that define where the structure fails to meet its requirements. There are eleven limit states that examine the panel, seven limit states that examine the girder, and five limit states that examine the frame. These limit states are further categorized by the type of failure that occurs within the structure. The collapse limit states are defined when the structure has failed in its primary, load carrying role. The serviceability limit states are defined when the deterioration of loss of other, less vital functions occurred. The adequacy value is provided in a range from -1 to 1, with 0 being the value of collapse, yield, or failure.

Examining the structural analysis results of the SSC determined that the structural model was over designed in most areas of the design. By examining the output file and the graphical reports, it was determined that the sagging case represented the worst load case for this vessel. Looking closely at the vonMises stress criteria, it can easily be determined that none of the stresses come close to approaching the yield stress of the material. The maximum stresses recorded are around 100 MPa, which can be seen graphically in Figure 96. The maximum yield stress for HSS is 360 MPa, indicating that this design is overly adequate to withstand the stresses simulated.

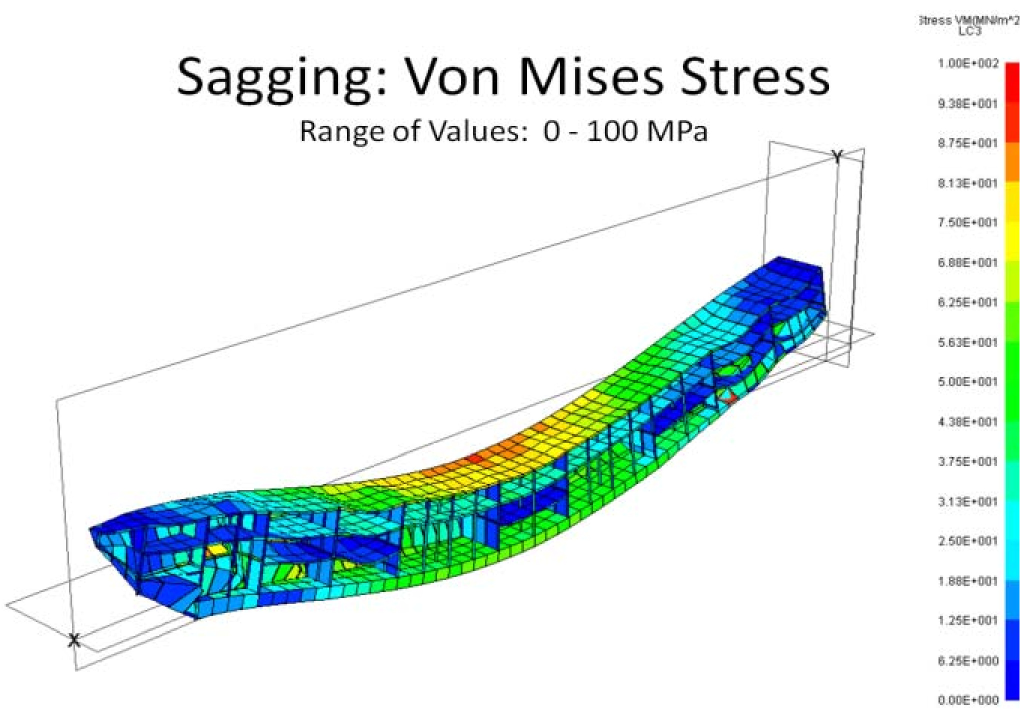


Figure 96: vonMises Stress Criteria for the Sagging Condition

Further examining the adequacy parameters for this load case, the minimum panel adequacy parameter showed a few local areas in the bow with inadequate values, however, due to the course mesh of the model and the tightly confined geometry in the bow region, these areas of inadequacy may not be accurate. Fine mesh modeling of this area could resolve any question regarding the adequacy of the panels in this area. The graphical report of this adequacy parameter can be seen in Figure 97.

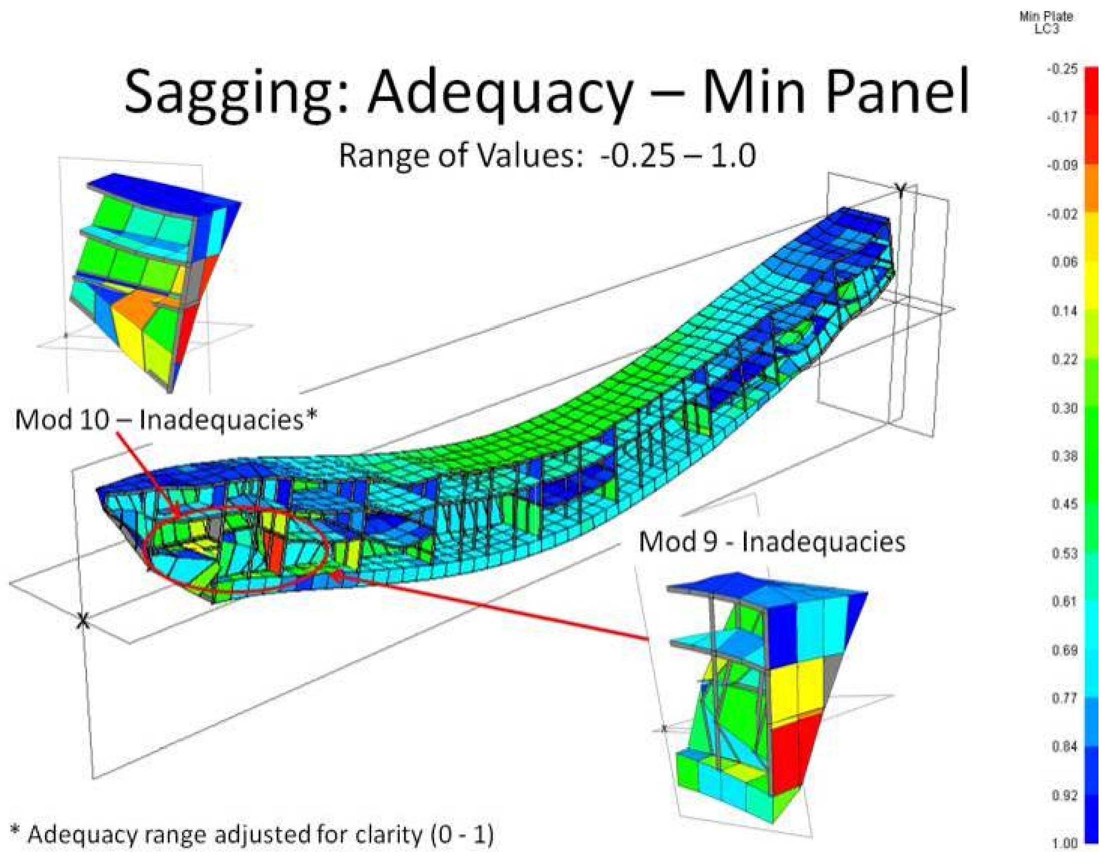


Figure 97: Minimum Panel Adequacy of the Sagging Condition

Looking further into the analysis of how the panels fail, certain panels in the structural model appear to be susceptible to local buckling, as seen in Figure 98. This frequently occurs at the bilge and the corner of where the side shell meets the weather deck. While the parameter shows that the structure is 25% above minimum adequacy, this may become an area of concern if the structural module is redesigned to reduce some of the excess structural weight.

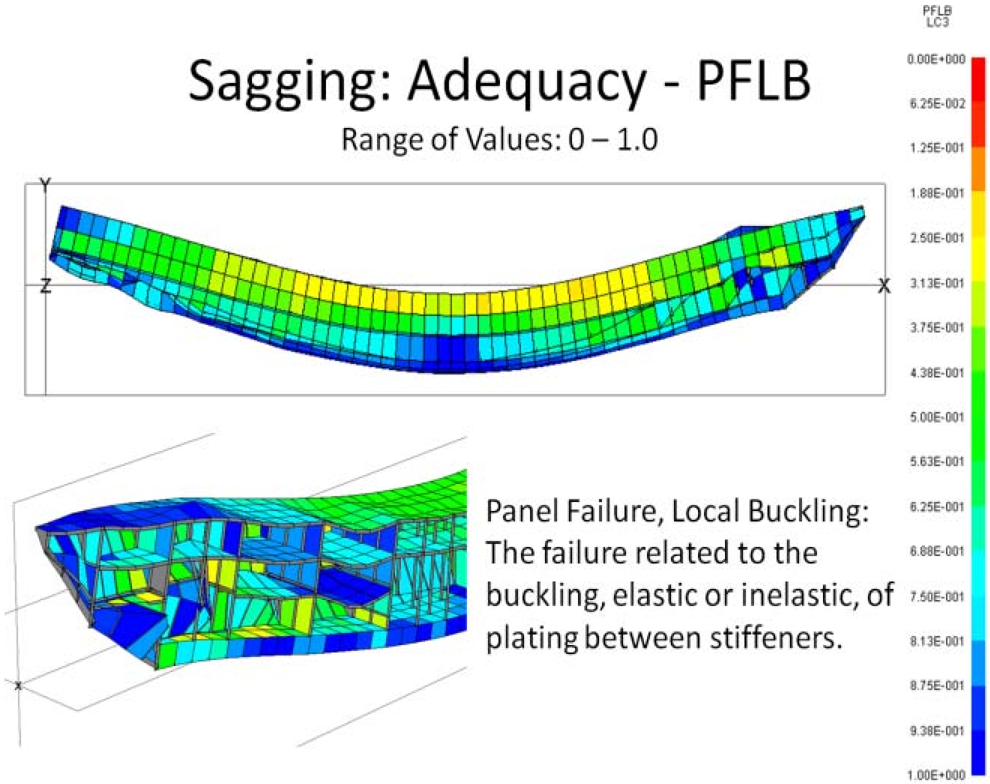


Figure 98: Panel Failure, Local Buckling Adequacy Parameter for the Sagging Condition

The beams of the model can also be examined for adequacy, and in the sagging case, there appeared to be some areas of inadequacy in the girder collapse - tripping condition, as seen in Figure 99. This failure occurs when the stiffeners of a panel collapse inward when the panel is compressed. This is shown in a laboratory experiment in Figure 100. While tripping appears to be a problem in the bow area, additional fine mesh modeling would be required to determine the extent of the tripping.

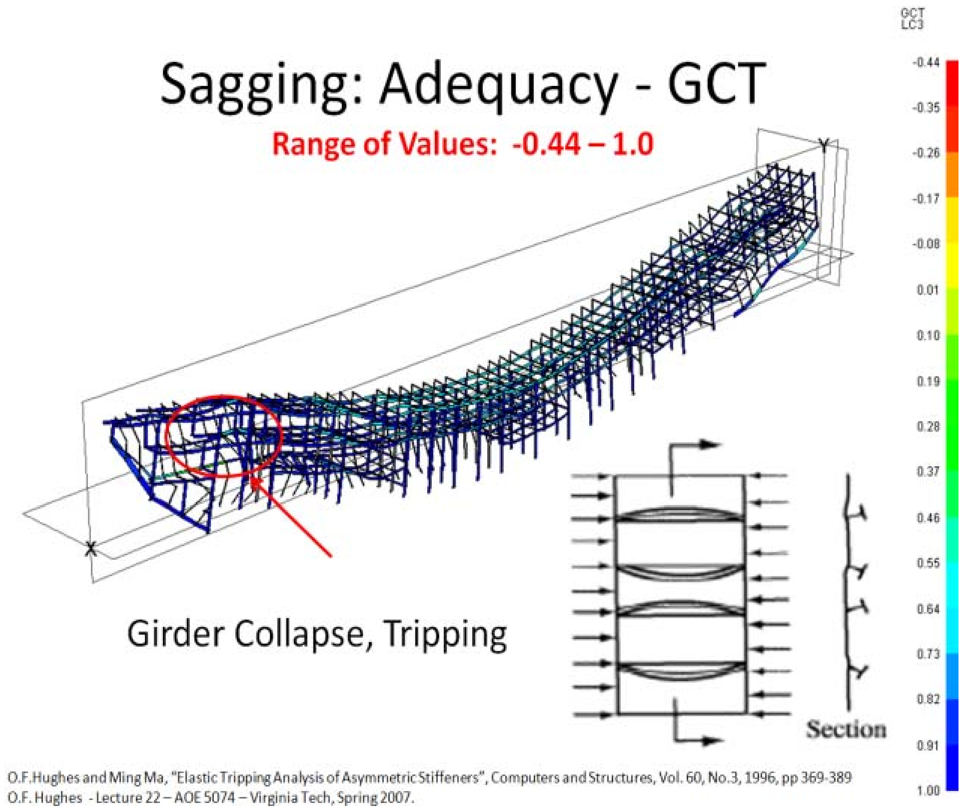


Figure 99: Girder Collapse, Tripping Adequacy Parameter

O.F. Hughes - Lecture 22 – AOE 5074 – Virginia Tech, Spring 2007.

Figure 100: Photograph of the Tripping Phenomena

4.5.4 Revisions and Final Structural Design

Creating structural model and studying the results offer several lessons learned for the next round through the design spiral. First of all, as determined by the low stresses simulated in the structural model, the ship appears to be grossly over designed. There stands to be considerable weight and cost savings by reducing the size and strength of the scantlings used in the structure. Also, by using HSS in the structural members, this will greatly increase the ease of production. HY-80 should only be used in key locations where the higher yield strength would be required such as at the bilge or the corner of the side shell and the weather deck. This, combined with appropriately sized scantlings, will help prevent a local buckling problem. By creating a fine mesh model of the design, a more accurate analysis will be able to be performed and eliminate false areas of inadequacy due to problems with the mesh and the tight geometry.

Also of note, this structural analysis did not take into account the survivability requirements and additional structure that will be required to withstand weapons effects. Those simulations would be required prior to further modification of the structural design.

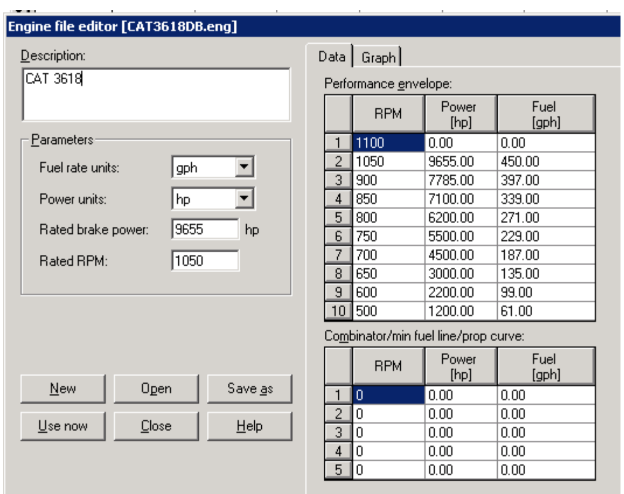
4.6 Power and Propulsion

In concept development, a more detailed analysis of the total ship resistance at various speeds is conducted. The improved ship resistance profile is used to determine the sustained speed and endurance range of the vessel given the machinery arrangement.

The coupled performance between the main propulsion engines, reduction gears, propulsors, and hull for the improved baseline model are also investigated in the concept development phase. The power and propulsion analysis for the improved baseline model is conducted in Navcad, and the outputs from Navcad are used to calculate the endurance fuel calculations in Mathcad.

The variables used in the propulsion analysis are the propeller and shaft line arrangement, main machinery room locations, propeller shaft angles, propeller diameters, propeller selection, engine speeds and SFC's, reduction gear ratios, transmission efficiencies, and hull resistance and EHP at the endurance and sustained speeds. The propulsion system modeled and analyzed in Navcad is a 2 shaft CODAG plant. This plant includes 2 LM2500 main gas turbines, 2 CAT3618 secondary propulsion diesel generators, and 4 CAT 3516B ship service diesel generator sets.

The endurance condition performance map is input into Navcad and shown below in Figure 101 for the CAT3618 secondary propulsion diesels. The propulsions diesels are large enough to power the ship alone at the endurance speed of 20 kts.



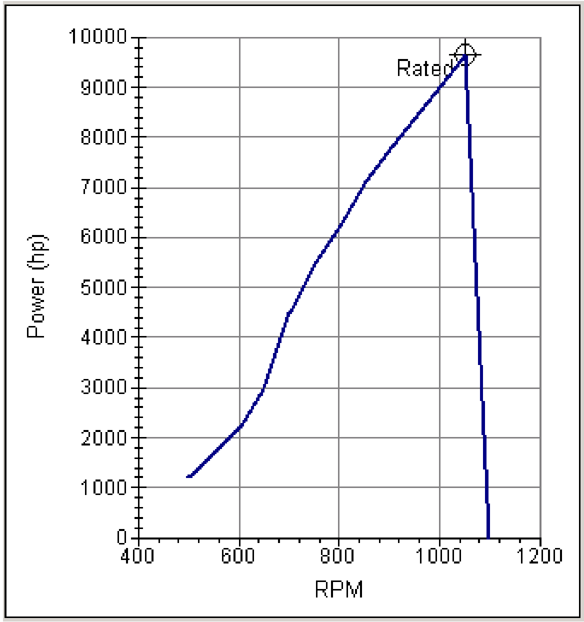
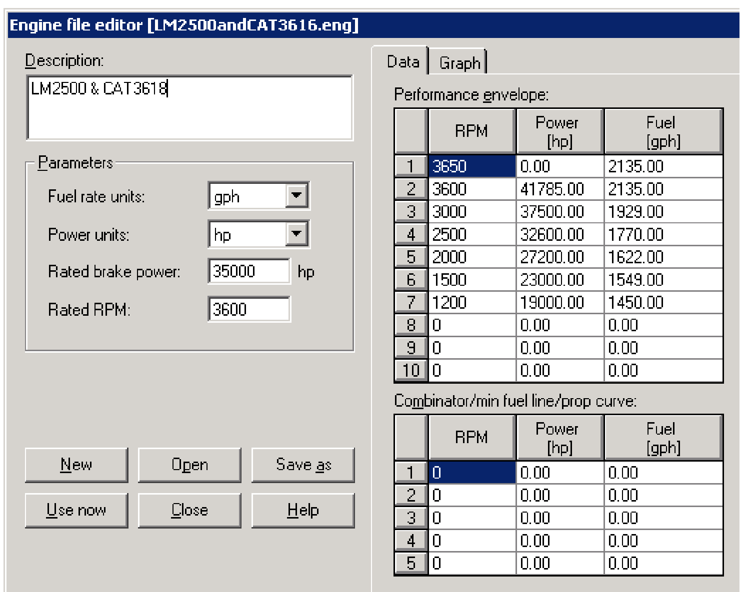


Figure 101: Endurance Condition Performance Map

The sustained speed condition performance map is input into Navcad and shown below for the LM2500 primary gas turbines and the CAT3618 secondary propulsion diesels. In order to get the power required to power the ship through the sustained speed regime, all propulsion diesels and gas turbines are online. The combined performance of the CODAG plant with the gas turbines and diesel propulsion engines online is given in Figure 102.



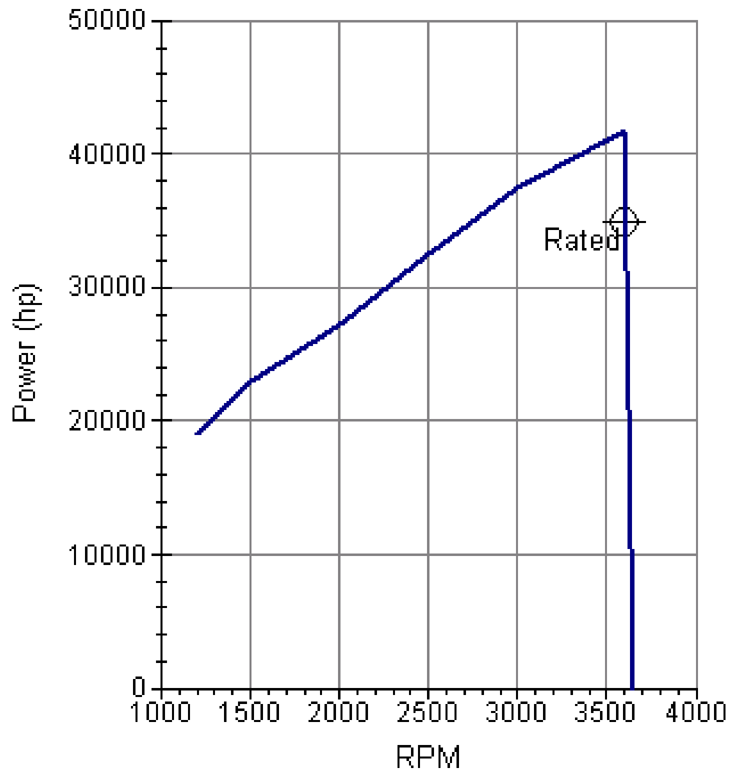


Figure 102: Sustained Condition Performance Map

4.6.1 Resistance

In order to complete the power and propulsion analysis, the hull resistance was computed for the improved baseline hullform by using the Holtrop and Mennen resistance prediction method for the selected hullform at the endurance and sustained speed regimes. The location, size, and characteristics of the propellers were obtained from the improved ASSET baseline model along with the engine characteristics, and input into Navcad. The propulsion analysis was then performed in Navcad at the endurance and sustained speeds. Finally, the output from the Navcad propulsion analysis is used to perform the endurance range calculation in Mathcad.

The inputs that Navcad requires are the endurance speed conditions, sustained speed conditions, hullform principle particulars from the finalized hullform, appendage wetted areas from the ASSET improved baseline model, environmental resistance information (wind profile, sail area, seaway definition, etc), and endurance and sustained speed design margins (10% on endurance and 25% on sustained speed).

The total ship resistance calculation in Navcad uses the Holtrop and Mennen resistance prediction method (1984) at the endurance and sustained speeds. This method approximates the bare hull viscous skin friction drag and the wave making drag.

The total ship resistance is a summation of the viscous drag using the ITTC friction line, wave making drag from the force required to move the water around the hull, appendage drag of the propellers and other underwater appendages, sonar dome drag, air drag, and transom drag.

The total ship resistance is calculated at the endurance and sustained speeds, and the effective powers are calculated. The calculated effective powers include a 10% design margin for endurance, and a 25% design margin for the sustained speed. The Navcad calculated total ship resistance for the large SSC for the endurance speed of 20 kts is given in Figure 103 and the endurance speed calculated effective power is shown in Figure 104.

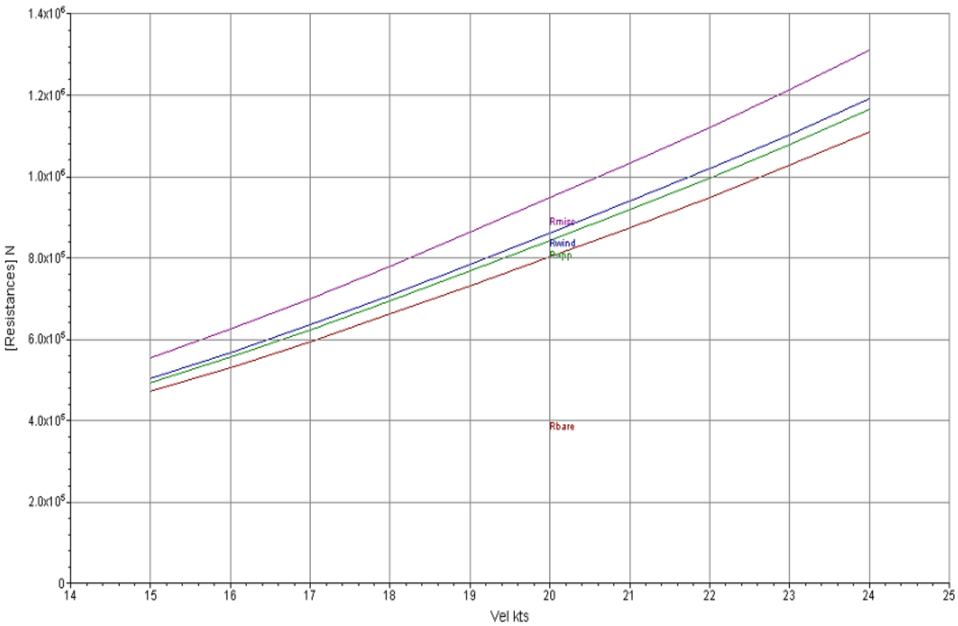


Figure 103: Navcad Endurance Resistance

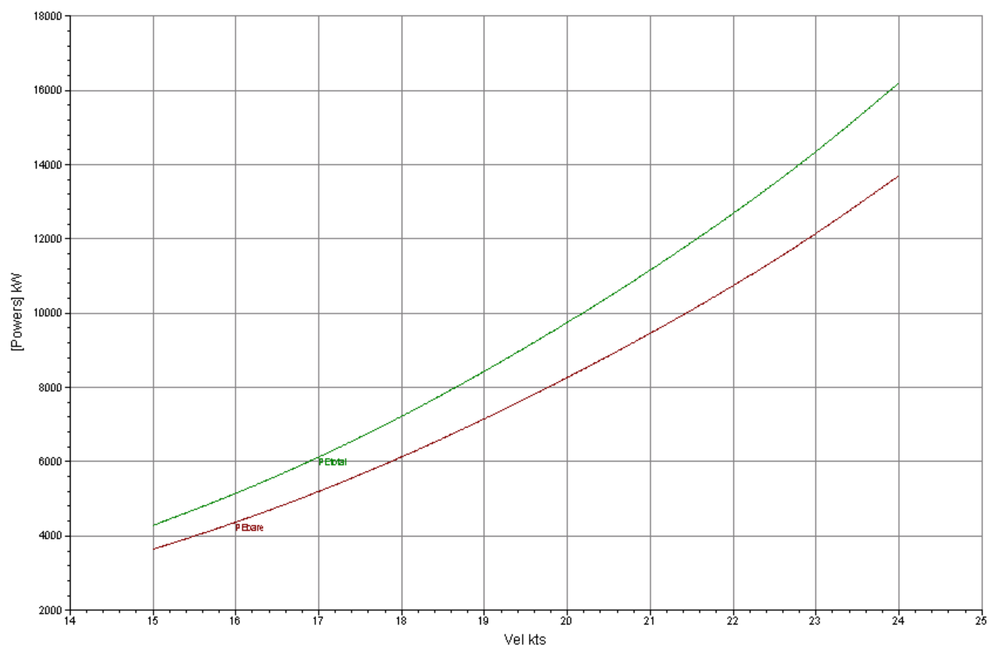


Figure 104: Navcad Endurance Speed EHP

The Navcad calculated total ship resistance for the sustained speed is shown in Figure 105 and the sustained speed effective power is shown in Figure 106.

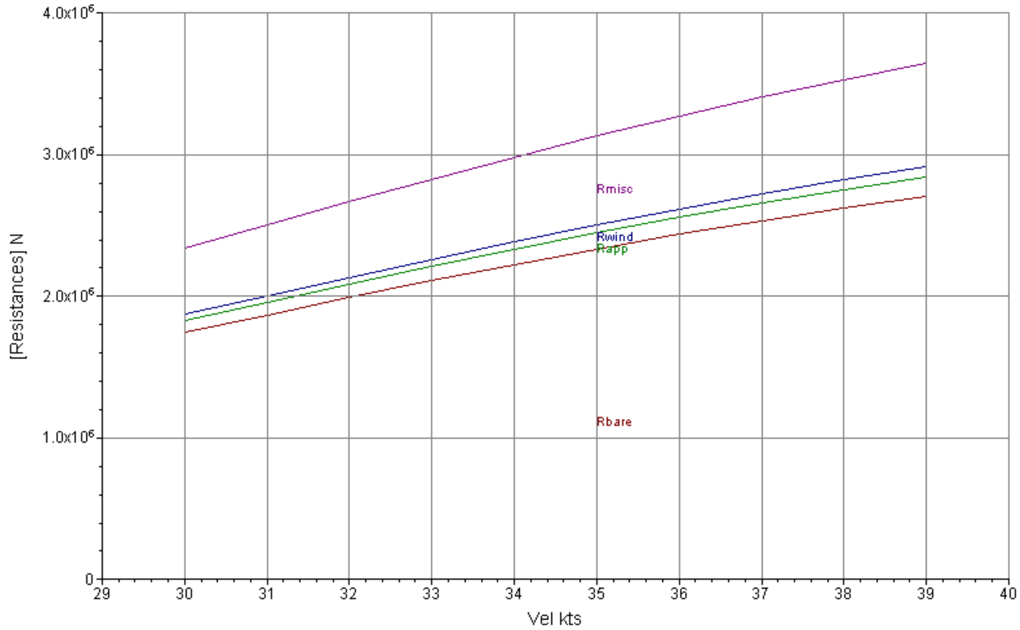


Figure 105: Navcad Sustained Speed Resistance

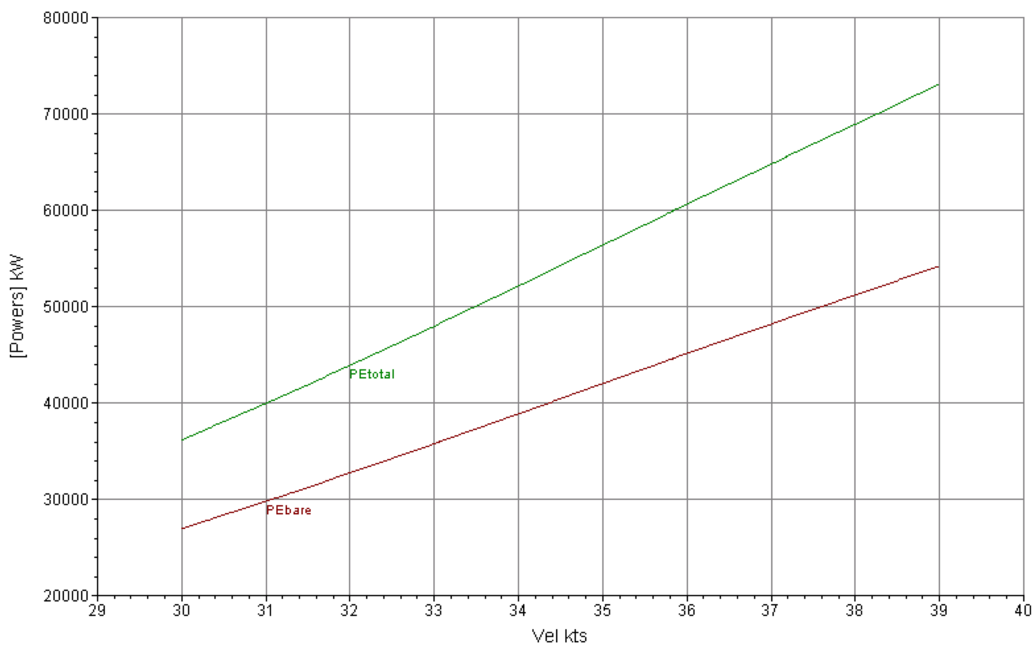


Figure 106: Navcad Sustained Speed EHP

4.6.2 Propulsion Analysis – Endurance Range and Sustained Speed

Propeller data from the improved ASSET baseline model was also input into Navcad for the endurance and sustained speed analysis. The large SSC propulsor information is shown in Figure 107 for the endurance condition.

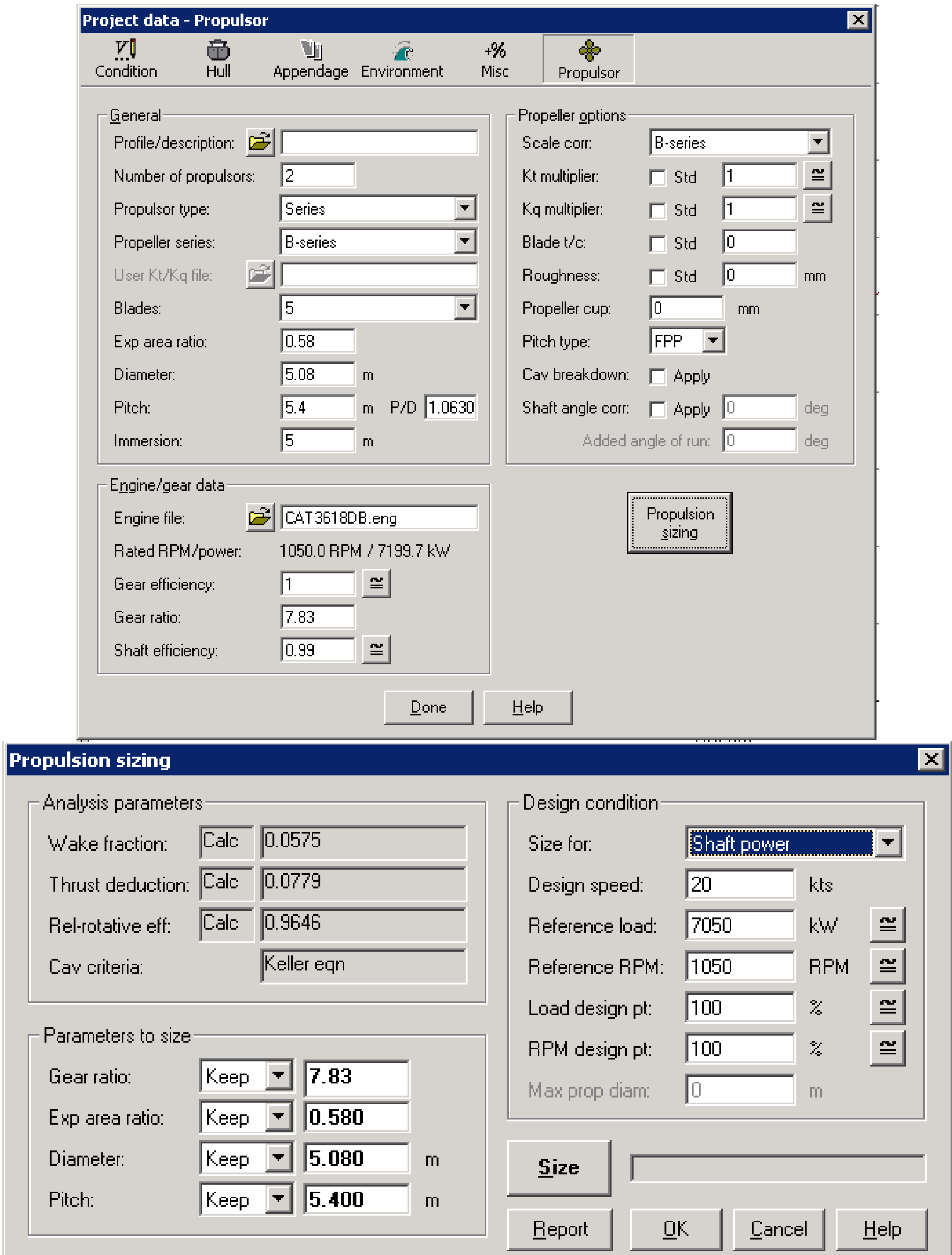


Figure 107: Endurance Range Propulsor Sizing

The Navcad calculated endurance shaft power per shaft for the endurance speed of 20 kts is shown in Figure 108.

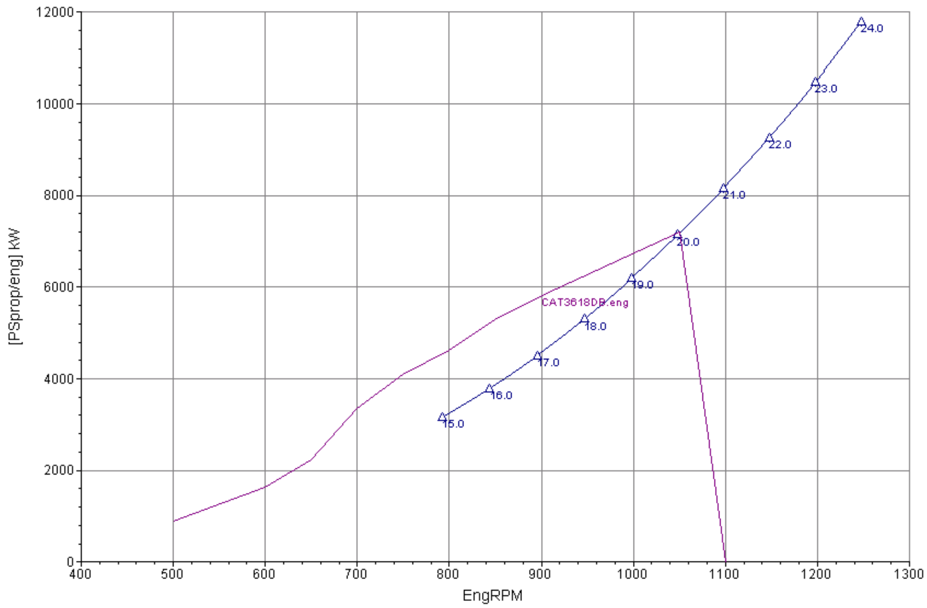


Figure 108: Endurance Condition Propulsion Shaft Power

The Navcad calculated overall propulsive coefficient (OPC) for the endurance condition is presented in Figure 109.

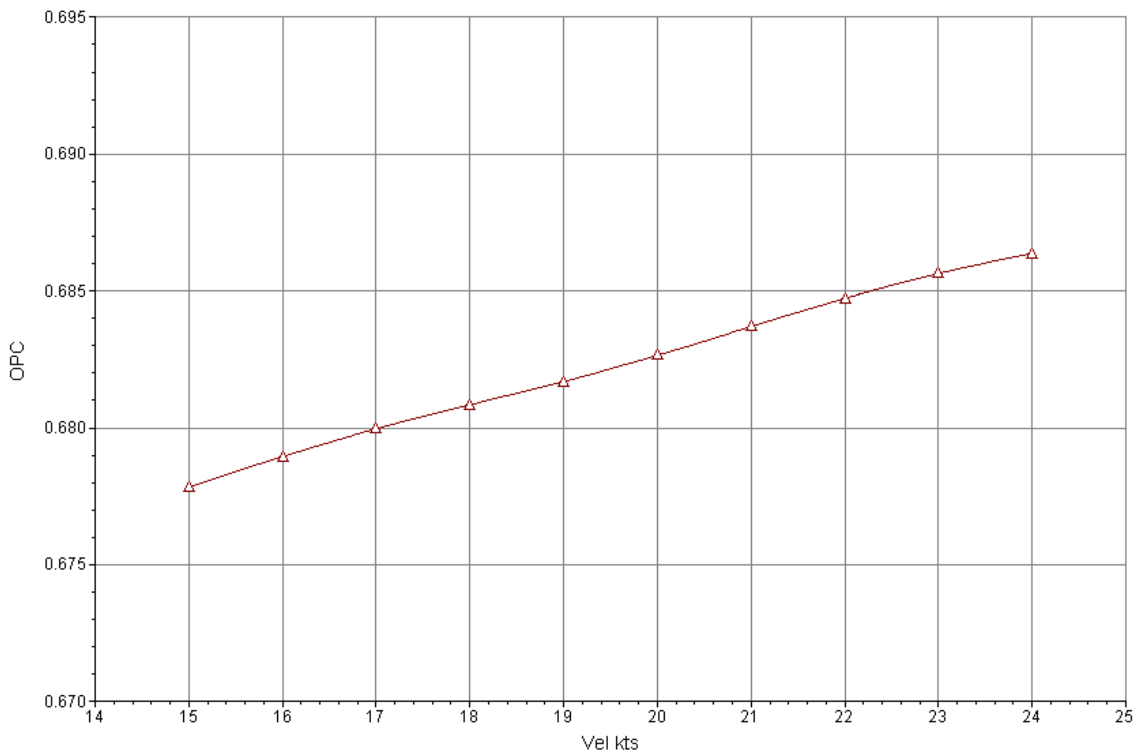


Figure 109: Endurance Condition OPC

The shaft power is then used to calculate the total brake power required per shaft in the endurance condition by dividing the assumed shaft and line shaft bearing efficiencies. The plot of the required brake power required per shaft is given in Figure 110.

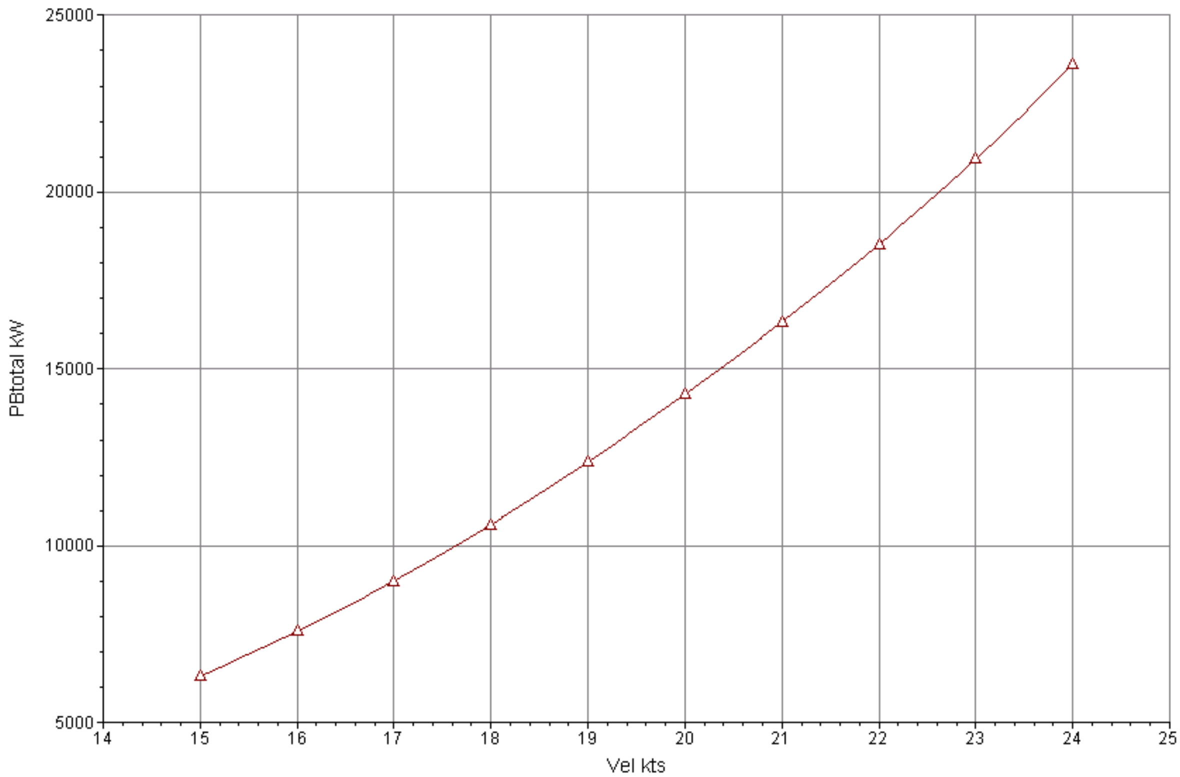
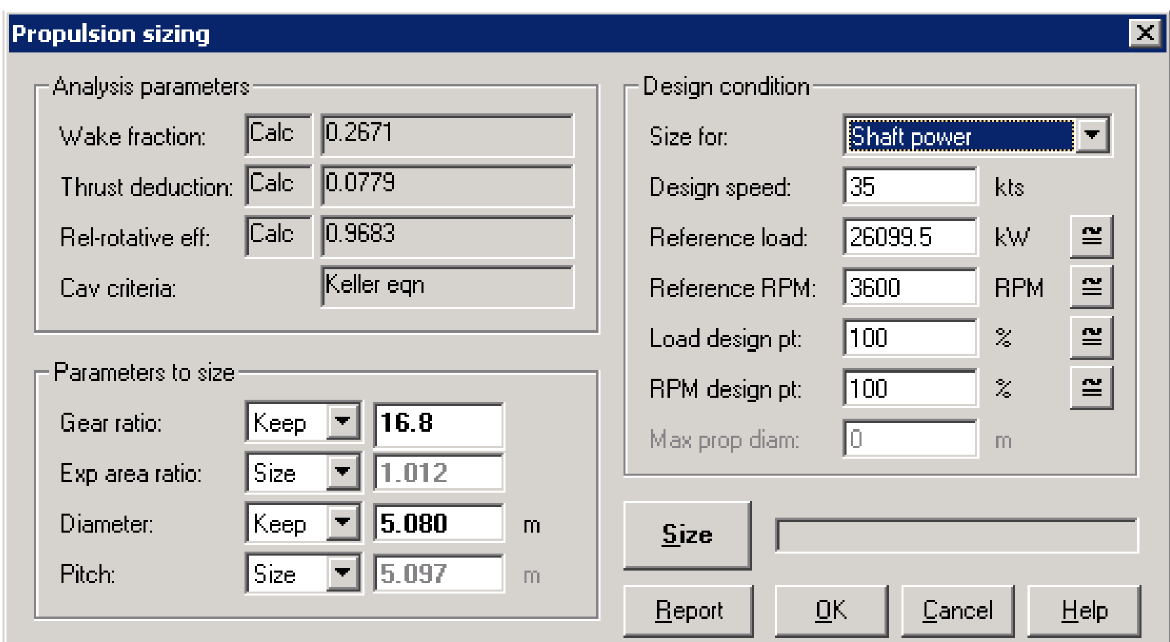


Figure 110: Endurance Condition Required Brake Power

The propulsors were sized for the sustained speed condition in Navcad, and that information is given in Figure 111.



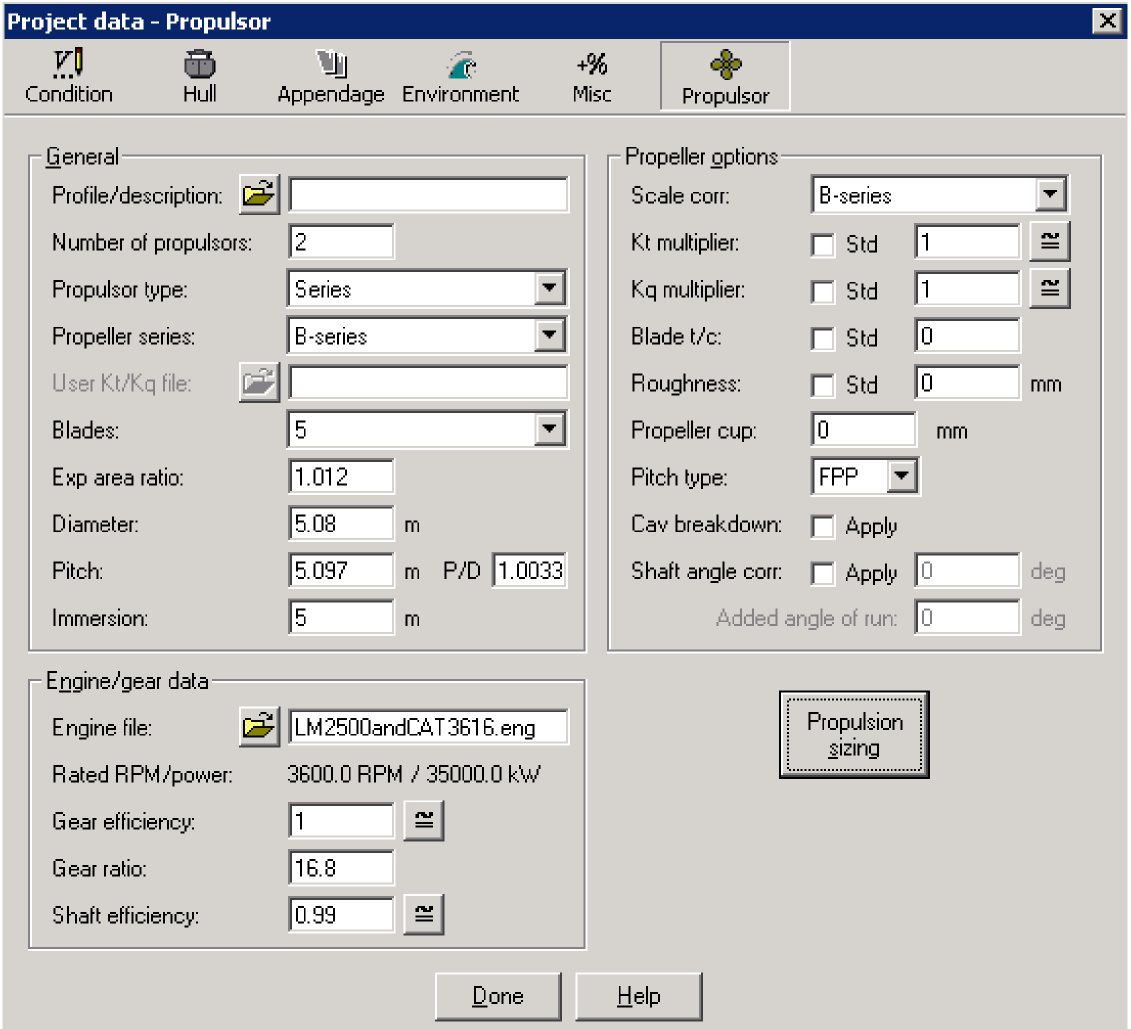


Figure 111: Sustained Speed Propulsor Sizing

The Navcad calculated propulsion shaft power per shaft is presented in Figure 112.

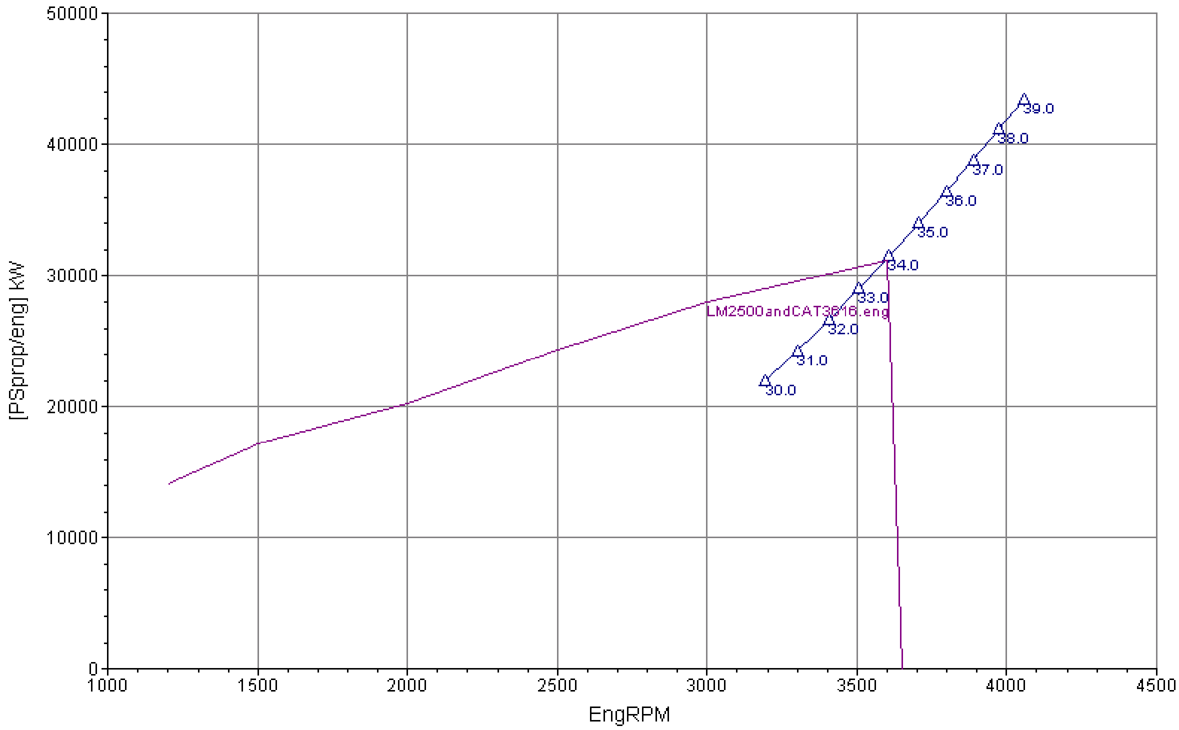


Figure 112: Sustained Speed Condition Propulsion Shaft Power

The Navcad calculated OPC in the sustained speed condition is shown in Figure 113. It is worthwhile to note that the OPC calculated by Navcad for the sustained speed is unrealistically high. The typical range of OPC's for surface ships is 0.4-0.7. The reason for the unrealistically high OPC's in the sustained speed regime is not readily apparent. It is recommended that the Navcad OPC calculation be investigated in more detail in the future.

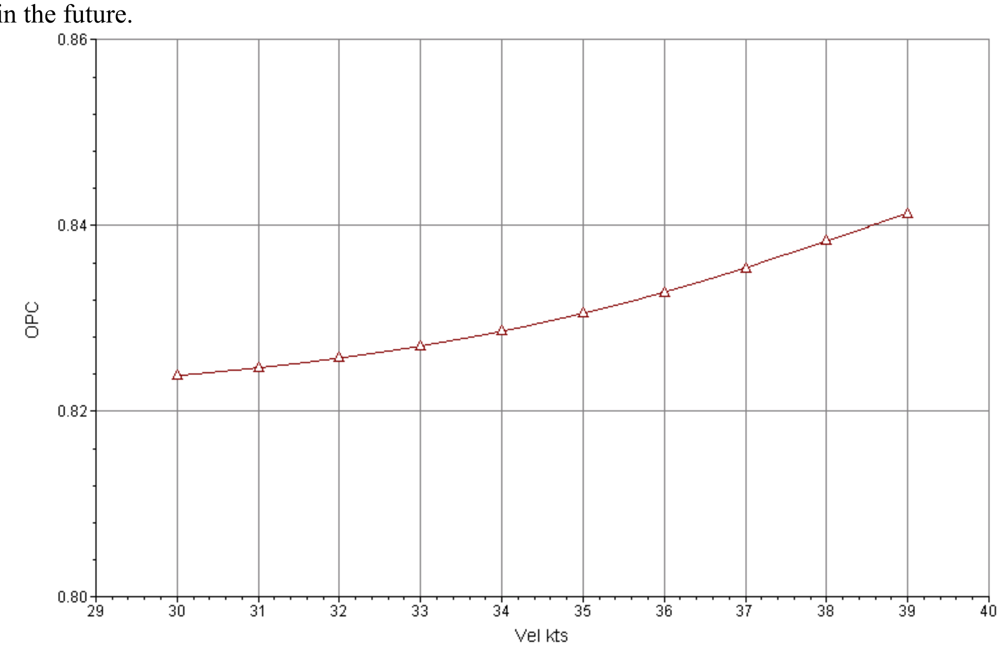


Figure 113: Sustained Speed Condition OPC

The shaft power is then used to calculate the total brake power required per shaft in the sustained speed condition by dividing the assumed shaft and line shaft bearing efficiencies. The plot of the required brake power required per shaft is given in Figure 114.

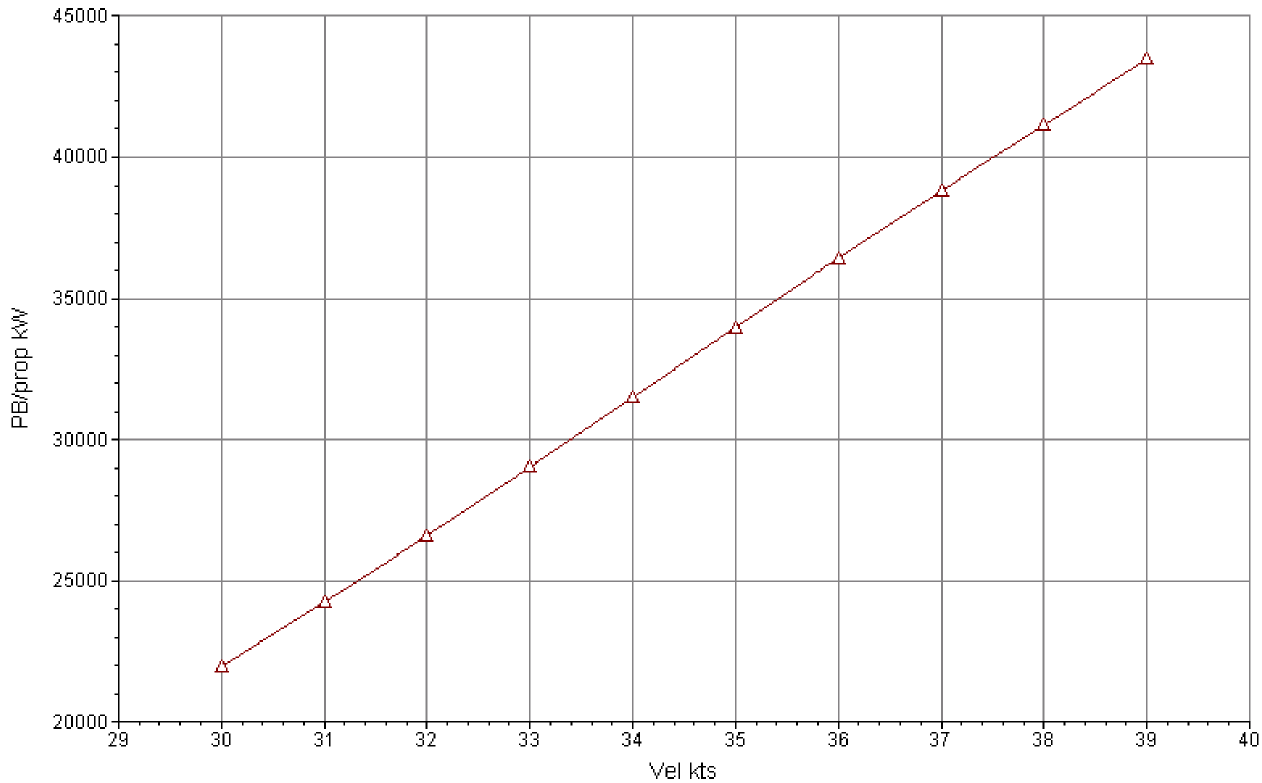


Figure 114: Sustained Speed Condition Required Brake Power

The total required brake power is used with the specific fuel consumption of the CAT 3618 propulsion diesels in the endurance condition to calculate the total fuel consumption. The endurance speed fuel calculation is given in Table 29 and Figure 115.

Table 29: Endurance Condition Fuel Consumption

Vel [kts]	Fn	Fv	Kt/J2	Kq/J3	Cth	Cp	Fuel/eng [gph]	TransEff	EngLoad%
15	0.223	0.589	0.2151	0.04720	0.5476	0.001423	184.0	65.664	52
16	0.238	0.629	0.2130	0.04666	0.5424	0.001407	240.6	58.357	54
17	0.253	0.668	0.2112	0.04620	0.5378	0.001393	306.2	52.205	58
18	0.268	0.707	0.2098	0.04582	0.5341	0.001382	351.5	46.937	63
19	0.283	0.747	0.2083	0.04545	0.5305	0.001371	397.7	42.459	69
20	0.298	0.786	0.2064	0.04497	0.5257	0.001356	446.8	38.72	74
21	0.313	0.825	0.2041	0.04439	0.5197	0.001339	---	35.575	2376
22	0.327	0.864	0.2017	0.04380	0.5137	0.001321	---	32.841	0
23	0.342	0.904	0.1997	0.04331	0.5086	0.001306	---	30.383	0
24	0.357	0.943	0.1983	0.04296	0.5051	0.001296	---	28.126	0

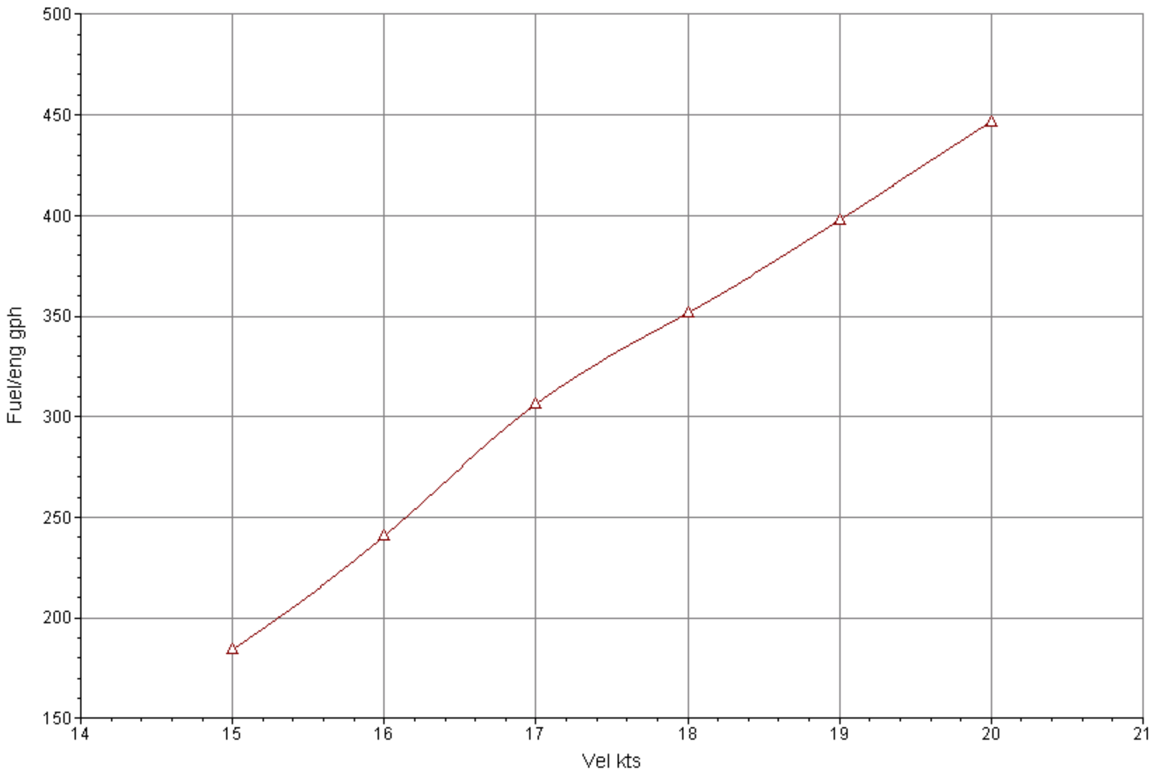


Figure 115: Endurance Condition Fuel Consumption

The output from the Navcad propulsion analysis was used to calculate the endurance range for the large SSC at 20 kts in Mathcad. The inputs needed for the endurance range calculation are given below:

1). Endurance speed
2). Brake power installed at endurance
3). Brake power required at endurance
4). Number of propulsion diesels required at endurance
5). Propulsion diesel fuel consumption at endurance
6). Number of ship service diesels at endurance
7). Total ship service KW installed
8). 24 Hr cruise electric load
9). Ship service generator SFC in cruise condition
10). Total fuel oil volume

These inputs are used to calculate the range of the ship in the endurance condition. The calculation below shows that the large SSC has an endurance range of 3589 nm. This assumes a tailpipe allowance of 5% to account for unburnable fuel, a 5 % volume allowance for fuel expansion in the tanks, a 2% volume allowance for the internal structure within the tanks, a 5% plant deterioration factor, and instrumentation inaccuracy and machinery design changes for the ship service and propulsion power. The full Mathcad calculation for endurance range is given in Appendix G.

$$E := \frac{W_{F41} \cdot V_e \cdot TPA}{BHP_{eSPGM} \cdot FR_{AVGp} + KW_{24AVG} \cdot FR_{AVGg}} \qquad E = 3589 \cdot nm$$

4.6.3 Electric Load Analysis (ELA)

An electric load analysis (ELA) was conducted in order to determine the total ship service electric load in the battle, cruise, in port, and emergency conditions. The total electric load for each of these conditions was broken down into the total electric load required for each 3 digit SWBS group. The ELA was completed by using data from the ASSET improved baseline model and the SSSM. The breakdown of the ship service electric loads required in each of the operational conditions is given in Table 30. The maximum electric load is in the battle condition, and is 3897 kW. The US Navy has an N-1 criterion that states that the highest ship service electric load must be met with one generator down for maintenance or repair. The SSC satisfies this criterion because it can supply the highest ship service load with 3 CAT 3516B diesel generators online, and one generator down for maintenance or repair.

Table 30 - Electric Load Analysis Summary

			Connected Load	Battle		Cruise	
	SWBS	Description	(kW)	Power Factor	(kW)	Power Factor	(kW)
	100	Deck Machinery	790	0.00	790	0.00	790
	200	Propulsion	469	1.00	399	1.00	246
		Propulsion Direct	29	1.00	29	0.15	11
		Propulsion support	440	0.84	370	0.16	235
	300	Electric	443	0.67	297	0.24	224
	400	CCC	1629		617		475
		Combat Systems	1599	0.37	588	0.28	450
		Miscellaneous	29	0.63	29	0.29	25
	500	Auxiliary	5172		1704		1614
	510	CPS/HVAC	2322	0.36	696	0.39	904
	520	Sea Water Systems	312	0.34	106	0.29	91
	530	Fresh Water System	244	0.56	49	0.60	147
	540	Fuel Handling	600	0.34	204	0.17	102
	550	Air System	1693	0.95	589	0.18	308
	560	Ship Central Sys	59	0.95	56	0.95	56
	590	Special Purpose	50	0.10	5	0.10	5
	600	Services	224	0.10	50	0.40	90
	700	Weapons	122	0.34	41	0.33	35
		Total Required	8848		3897		3472
		24 Hour Average	1895		1976		1671
Number	Generator	Rating (kW)	Average Connected (kW)	Online	(kW)	Online	(kW)
4	CAT 3516B	1491.0	5964	3	4473	3	4473
	Total		5964		4473		4473
			Available Power		576		1001

SWBS	Description	Connected Load (kW)	Anchor Power Factor	Anchor (kW)	In Port Power Factor	In Port (kW)	Emergency Power Factor	Emergency (KW)
100	Deck Machinery	790	1.00	790	0.5	395	0.0	790
200	Propulsion	469		71		0		69
	Propulsion Direct	29	0.02	20	0.0	0	0.0	18
	Propulsion support	440	0.03	51	0.0	0	0.0	52
300	Electric	443	0.15	213	0.4	212	0.1	85
400	CCC	1629		233		3		252
	Combat Systems	1599	0.10	221	0.0	0	0.1	243
	Miscellaneous	29	0.10	13	0.1	3	0.1	10
500	Auxiliary	5172		1433		977		438
510	CPS/HVAC	2322	0.40	860	0.0	860	0.1	249
520	Sea Water Systems	312	0.30	91	0.4	91	0.3	106
530	Fresh Water System	244	0.60	147	0.0	0	0.3	22
540	Fuel Handling	600	0.25	20	0.1	20	0.0	0
550	Air System	1693	0.20	308	0.0	0	0.0	0
560	Ship Central Sys	59		0		0		56
590	Special Purpose	50	0.15	6	0.2	6	0.2	6
600	Services	224	0.40	70	0.4	70	0.0	1
700	Weapons	122	0.30	33	0.0	0	0.0	10
	Total Required	8848		2842		1657		1646
	24 Hour Average	1895		1307		790		751

Number	Generator	Rating (kW)	Average Connected (kW)	Anchor Online	Anchor (kW)	In Port Online	In Port (kW)	Emergency Online	Emergency (KW)
4	CAT 3516B	1491.0	5964	2	2982	2	2982	2	2982
	Total		5964		2982		2982		2982
			Available Power		140		1325		1336

4.7 Mechanical and Electrical Systems and Machinery Arrangements

Mechanical and electrical systems are selected based on mission requirements, standard naval requirements for combat ships, and expert opinion. A Machinery Equipment List (MEL), was created using inputs from the ASSET improved baseline model and SSSM, with modifications due to design refinement. The MEL of major mechanical and electrical systems includes quantities, dimensions, weights, and location is provided in Appendix D.

The physical dimensions of all the major propulsion and auxiliary equipment were taken from the MEL, and modeled in 3D in the hull subdivision Rhino model. The main propulsion gas turbines and diesels were first modeled with their required maintenance envelopes, and then their respected intakes and uptakes were modeled. The propulsion shaft lines were then modeled in Rhino in order to arrange the reduction gears, thrust bearings, line shaft bearings, propeller shafts, and propellers. Then, the ship service diesel generators and their intakes and uptakes were added. The propulsion related auxiliaries were then added to the main machinery spaces, and the non-propulsion related auxiliaries were added to the AMR's. By modeling all of the machinery contained in the MEL in 3D, potential interferences were avoided, and it was proven that the machinery will fit within the main and auxiliary machinery rooms. The modeled 3D machinery arrangements can be found in Figure 116 through Figure 120.

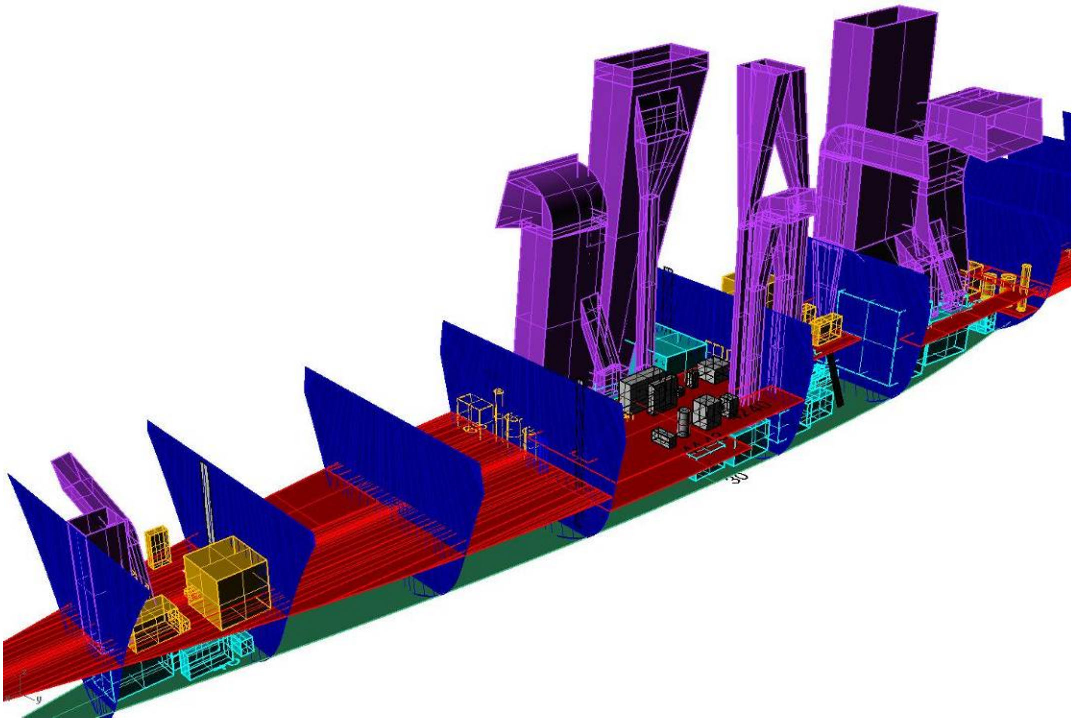


Figure 116: Machinery Space Arrangements with Intakes and Uptakes

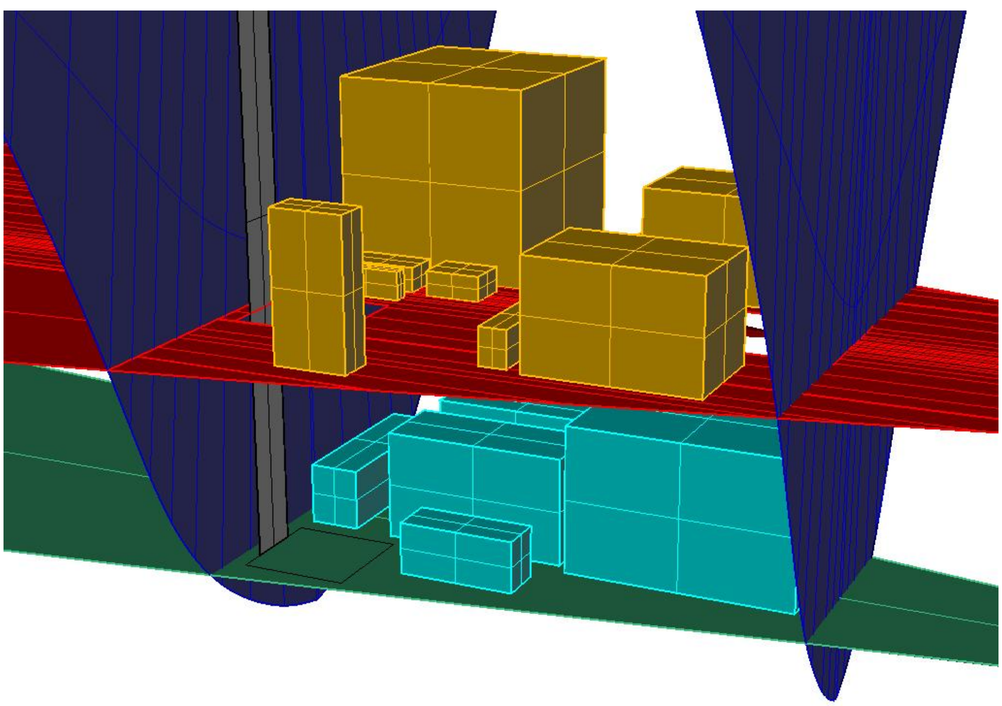


Figure 117: AMR 1 Machinery Arrangement

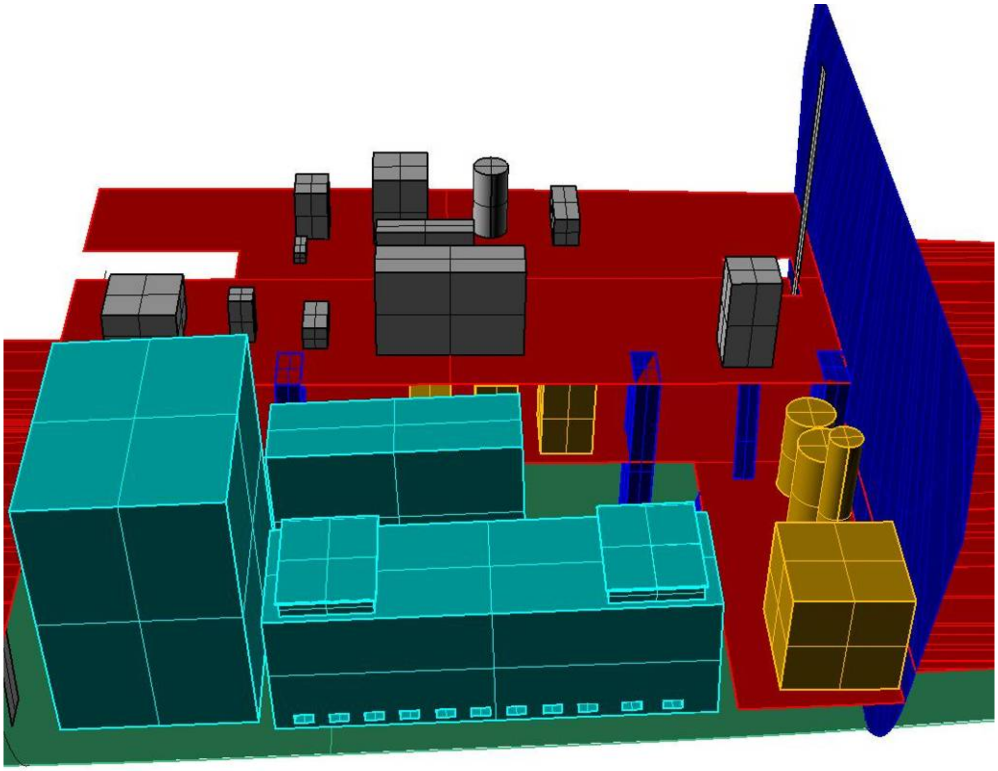


Figure 118: MMR 1 Machinery Arrangement

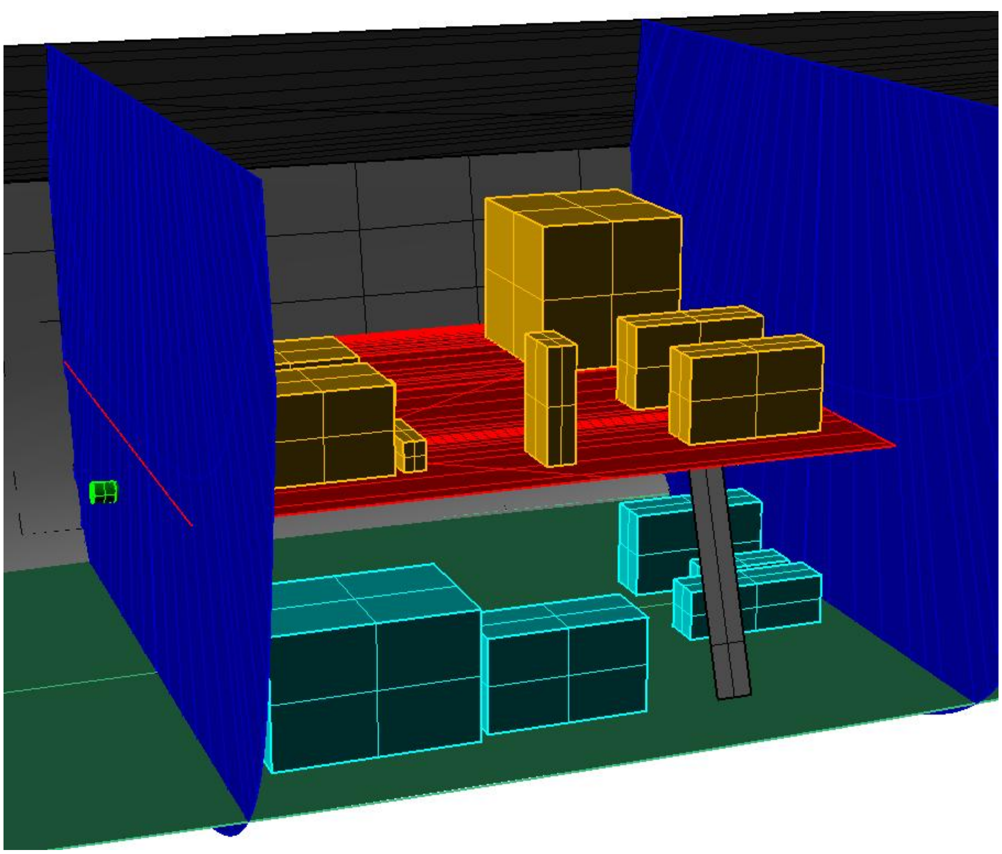


Figure 119: AMR 2 Machinery Arrangement

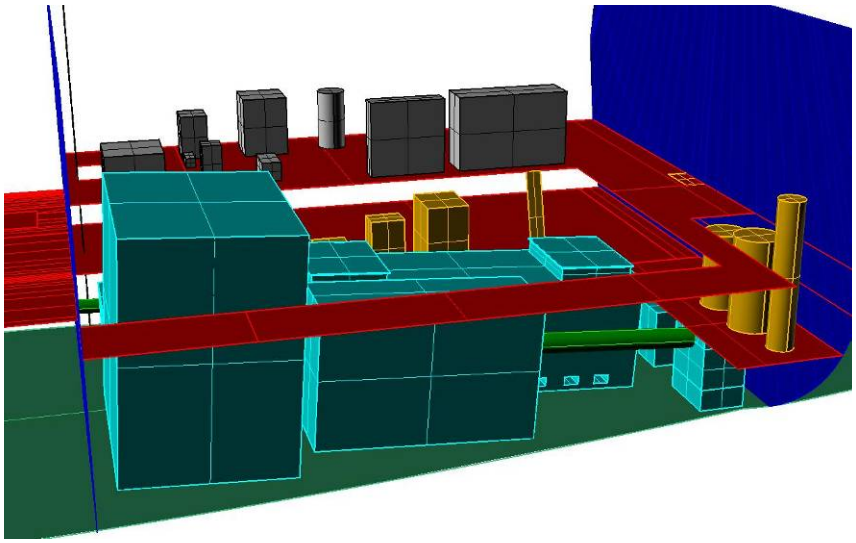


Figure 120: MMR 2 Arrangement

4.7.1 Ship Service Power and Electrical Distribution

The ship service power distribution system for the large SSC can be summarized by the one line diagram contained in Figure 121. There are 4, CAT 3516B diesel generator sets that generate ship service power adequate to power the maximum ship service electric load contained in Table 30 with one generator down for maintenance or repair.

These generators will power a 400 VAC zonal electric distribution system. This is a redundant system, and has good survivability characteristics. Each of the 4 ship service diesel generators will power a switchboard that will power the port BUS and starboard BUS. Within each zone, there are load centers for each BUS that will transform and power the ship service electric loads.

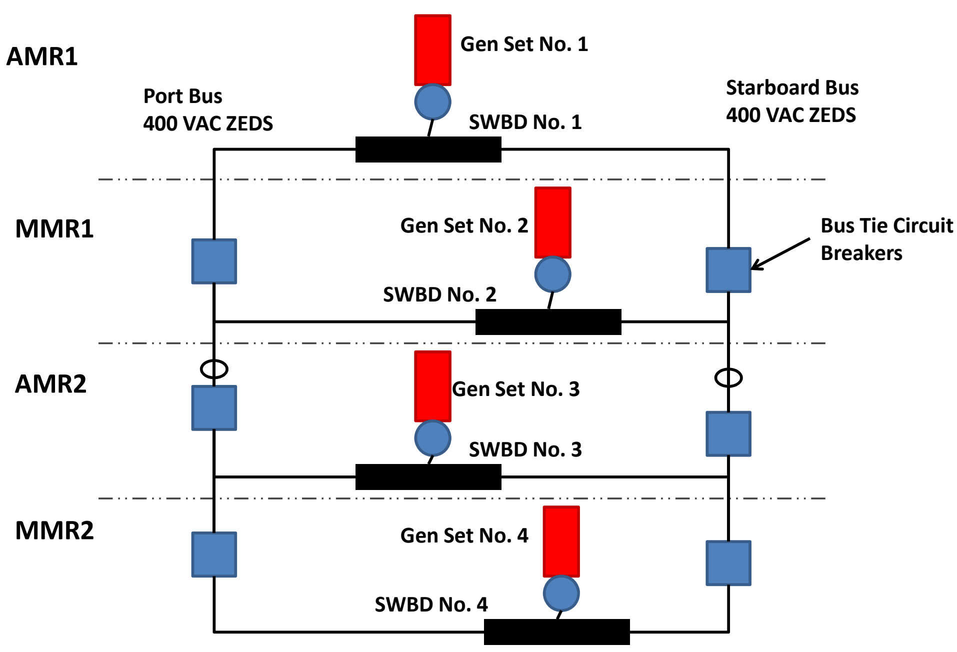


Figure 121 - One-Line Electrical Diagram

Future work should include a more detailed electric load analysis and one-line diagram. Switchboards, BUS cables, BUS transfers, load centers, and PCM's would need to selected in a future design refinement.

4.7.2 Main and Auxiliary Machinery Spaces and Machinery Arrangement

After the 3D machinery arrangements were modeled in Rhino, a series of 2D plan view drawings were created for each level of the main and auxiliary machinery spaces. In these drawings, the machinery is labeled with a find number so that it can be identified with the MEL found in Appendix D. The 2D machinery arrangement drawings are located in Figure 122 .

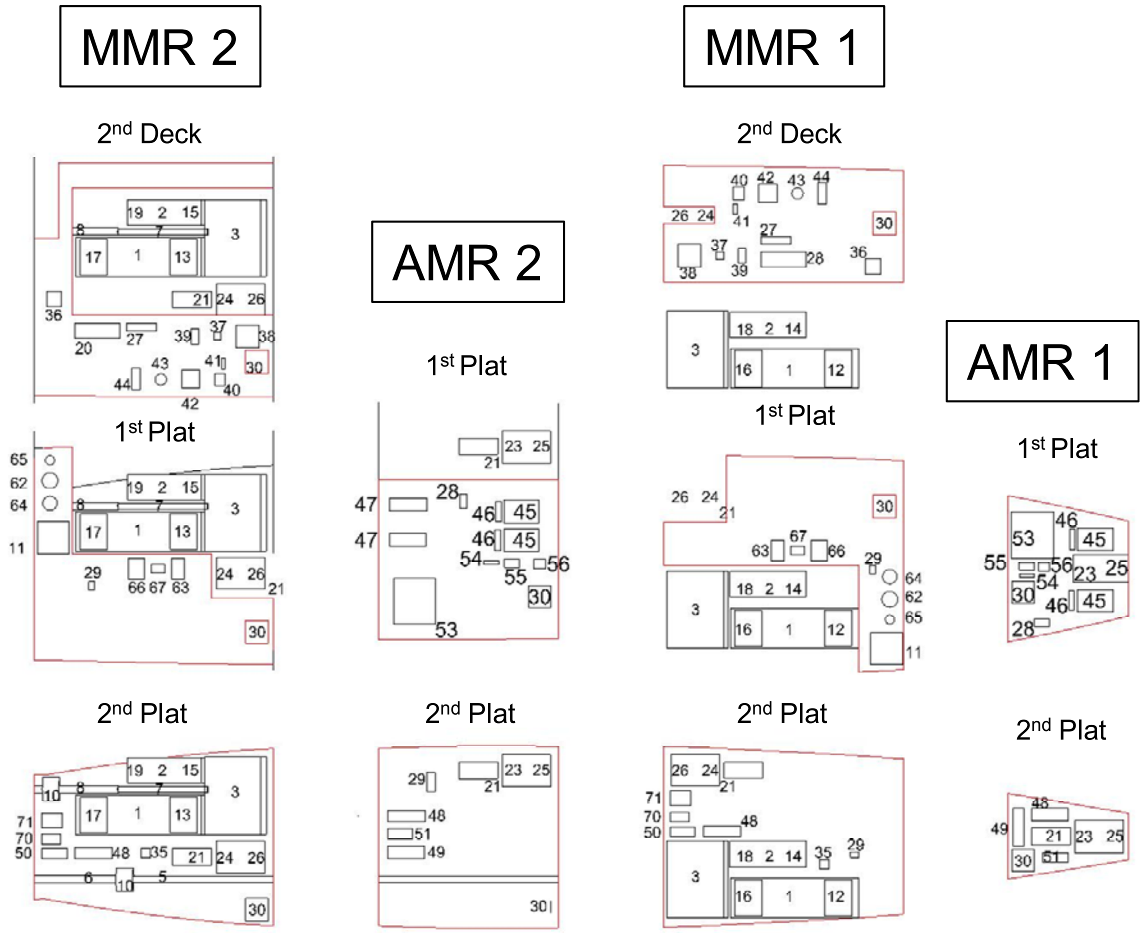


Figure 122: 2D Arrangement Drawings

4.8 Manning

In order to establish a manning estimate and profile for the large SSC, a hierarchy chart and table to assign personnel to the divisions and departments. The manning estimate from the concept exploration phase was used as a starting point with the goal of minimizing manning, and the feasibility of the manning profile was examined.

First, the hierarchy chart was developed to determine where personnel will be assigned. A typical manning breakdown for a naval surface combatant is given in Figure 123.

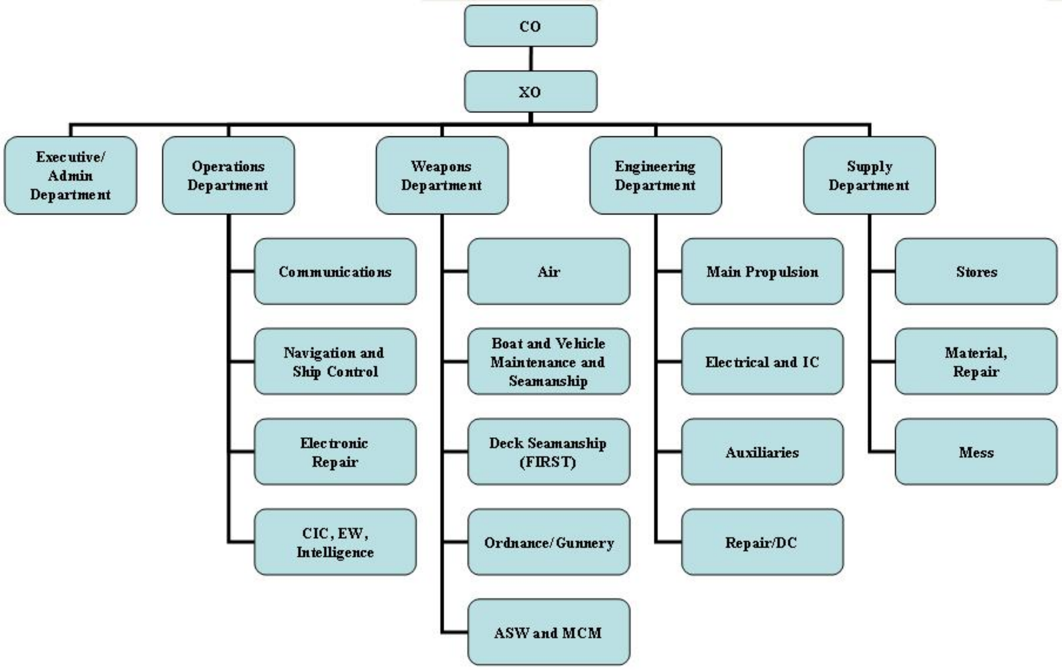


Figure 123: Naval Ship Departments and Divisions

The large SSC surface combatant manning estimate was established by determining the minimum number of personnel required to perform the missions outlined in the ADM, and fill the departments listed above. These personnel are distributed among the executive, operations, weapons, engineering, and supply departments. The manning profile for the large SSC is given in Table 31. This manning profile assumes condition III (3 watch sections), with an automated bridge, and an engineering control station for primary propulsion control on the bridge. The manning triad was also considered when determining the minimum crew for the large SSC. The functions contained in the manning triad are watch standing, maintenance, and damage control.

Table 31: Manning Profile

Departments	Division	Officers	CPO	Enlisted	Total Department	Rationale
	CO/XO	2			2	required
	Department Heads	4			4	minimum
Executive/Admin	Executive/Admin		1	1	2	
Operations	Communications	1	1	1	12	
	Navigation & Control	1	1			automated bridge
	Electronic Repair		1	2		
	CIC, EW, Intelligence	1	1	1		
Weapons	Air	3	1	1	19	
	Boat & Vehicle	1	1	2		
	Deck	1	1	1		
	Ordinance/Gunnery	1	1	2		
	ASW/MCM	2	1	1		
Engineering	Main Propulsion	1	1	2	18	
	Electrical/IC		2	3		no officer- extra CPO and enlisted
	Auxilaries		2	3		no officer- extra CPO and enlisted
	Repair/DC	1	1	2		
Supply	Stores		1	1	8	automation- no officers other than department head
	Material/Repair		1	1		
	Mess		1	3		
	Total	19	19	27	65	
	Accomodations	25	25	35	85	

The manning profile outlined in Table 31 is an optimized manning profile that is just meets the requirements of the manning triad. The following technologies will be designed into the large SSC in order to enable the minimum crew to perform and all of the required missions for the ship some of these technologies are listed below:

- Computers / CD-ROM / software
- GUI’s

- Large flat panel displays
- Expert systems
- Reliable sensors
- Fiber optics
- Corrosion and wear-resistant coatings
- Watch-standing technology
  - GPS
  - Automated route planning
  - Electronic charting and navigation (ECDIS)
  - Collision avoidance
  - Electronic log keeping
- Video teleconferencing - provides shipboard experts
- Personal Access Display Devices (PADDs)
- Condition-based maintenance
  - ICAS - Integrated Condition Assessment System
  - Trend-analysis
  - Expert assistance
  - Link to Interactive Electronic Tech Manuals (IETMs) / Gold Discs (automated troubleshooting)
- Integrated Survivability Management System (ISMS)
- Preservation - coatings costly, but cost-effective
  - Unicoat - 300% improvement in life expectancy, self-priming, 50% reduction in paint time, 50% reduction in VOC's
- Training - multimedia; embedded
- Paperless ship - Most Admin / personnel ashore
- Standard consoles/ integrated networks
- Personnel locators / active badges
- Automated mess

Future - Autonomic Ship (parts function automatically below level of consciousness) – not ready yet!

- Bridge in CIC - Command Center
- Large screen displays, 360 degree coverage, multiple magnifications and spectra
- Main control - Command Center II
- Unmanned machinery spaces; no sound & security
- virtual presence
- IR imaging (through smoke)
- robot arms for fire suppression, rigging, DC
- DC robots / virtual reality display

4.9 Space and General Arrangements

Space and General Arrangements were completed in Rhino to ensure that there is adequate arrangeable area and volume within the hull envelope to meet the requirements of the improved baseline SSCS. To do this required coordination between the subdivisions created in HECSALV, general arrangements, machinery arrangements and topside arrangements. The deliverables from these objectives are complete General Arrangements drawings which include inboard and outboard profiles and deck plans (weather deck, deckhouse decks) and arrangements for typical officer and crew berthing, messing and sanitary spaces

HECSALV and Rhino are used to generate and assess subdivision and arrangements. HECSALV is used for primary subdivision, tank arrangements and loading. Rhino is used for the 3-D geometry and to construct 2-D drawings of the inboard and outboard profiles, deck and platform plans, detailed drawings of berthing, sanitary, and messing spaces.

4.9.1 Internal Arrangements

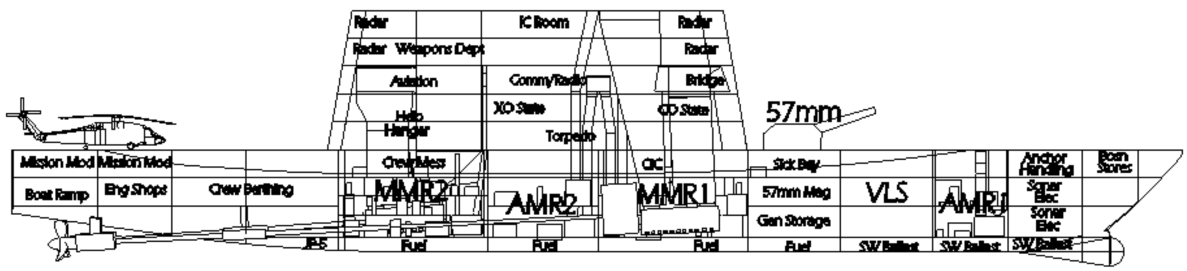


Figure 124: Inboard Profile

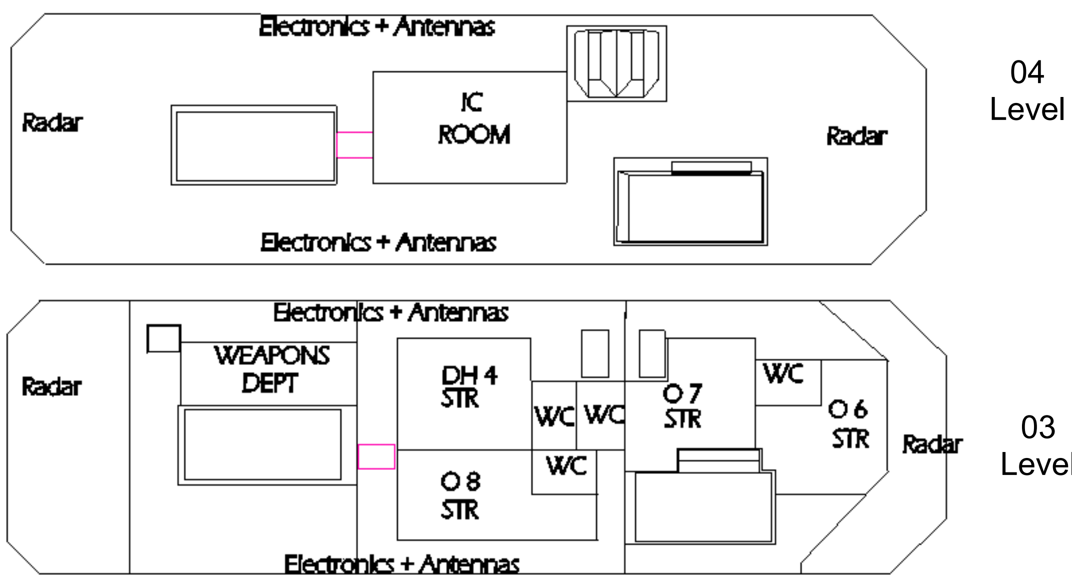


Figure 125: Internal Arrangements – Deckhouse 04 and 03

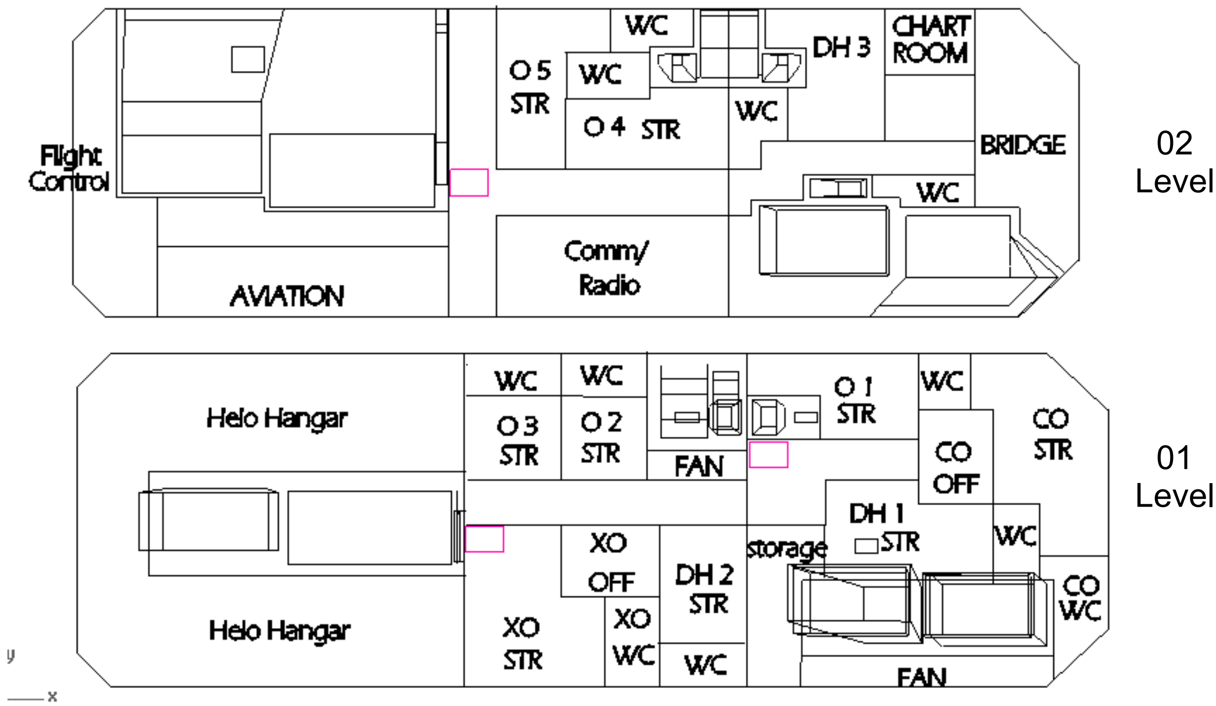


Figure 126: Internal Arrangements – Deckhouse 02 and 01

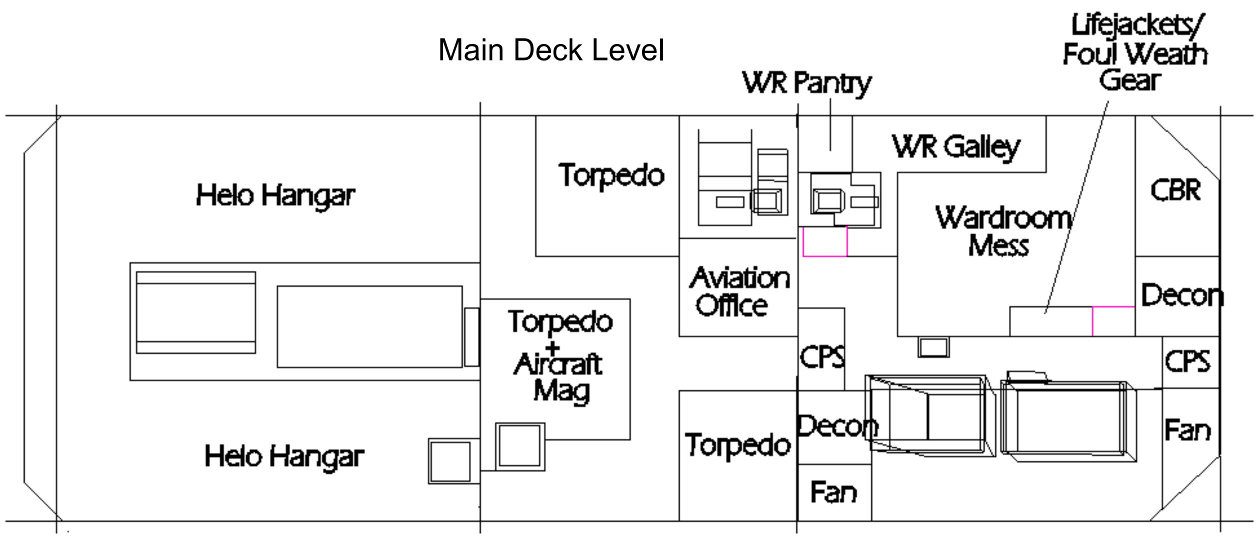


Figure 127: Internal Arrangements – Main Deck Deckhouse

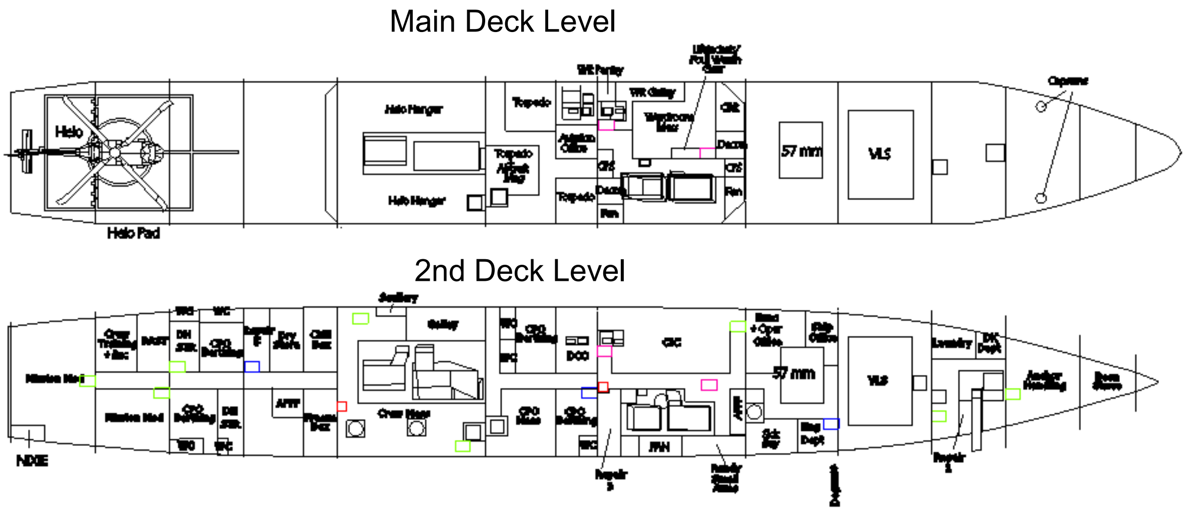


Figure 128: Internal Arrangements – Main Deck and 2nd Deck Plan View

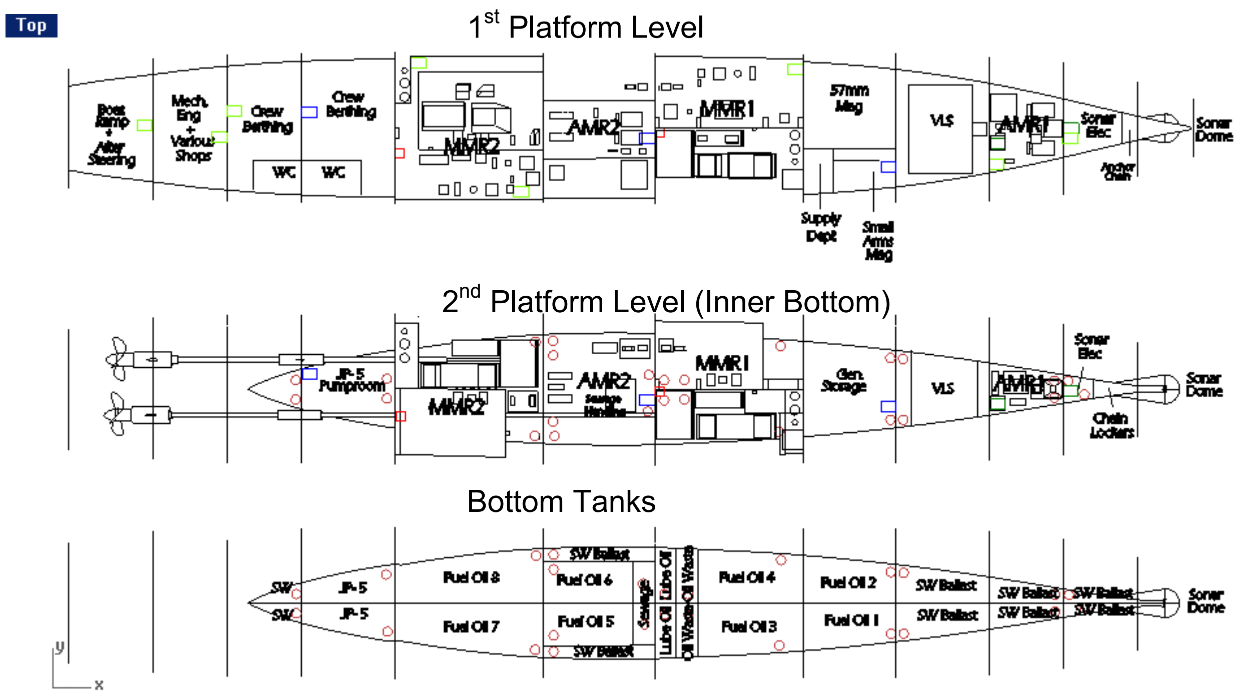


Figure 129: Internal Arrangements – 1st Platform, 2nd Platform, Bottom Tanks Plan View

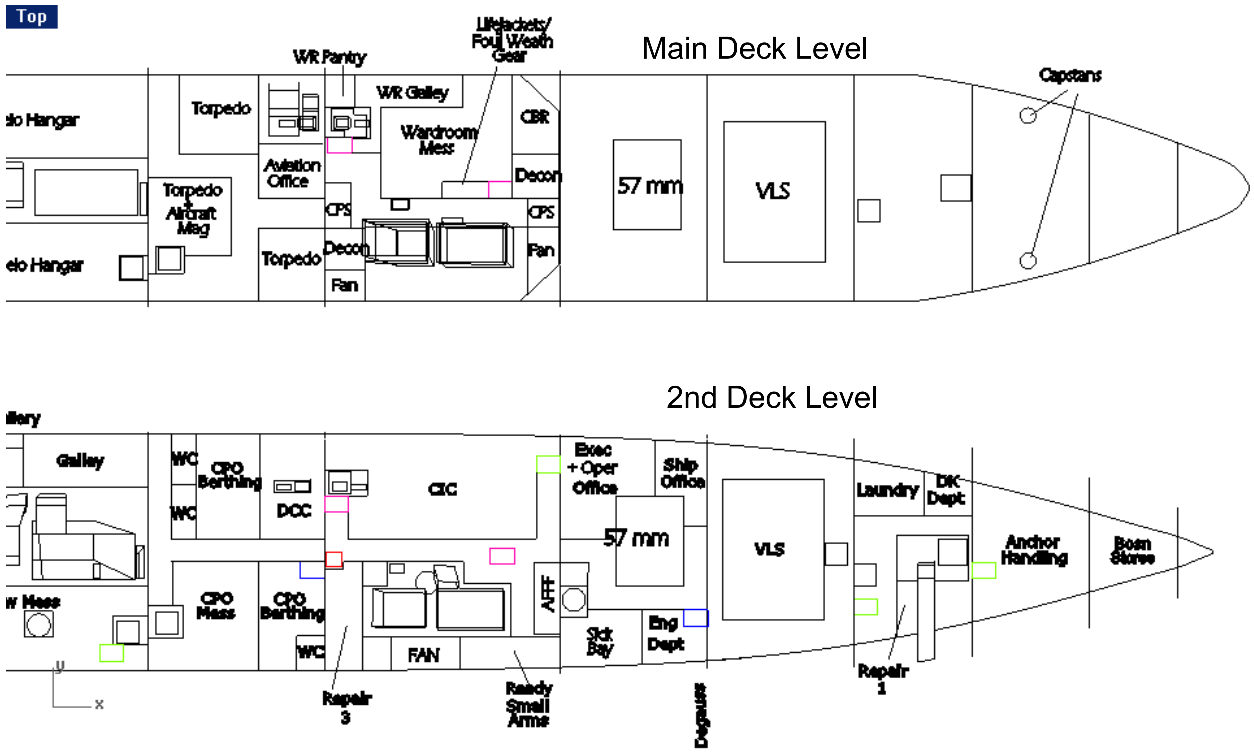


Figure 130: Internal Arrangements – Main Deck, 2nd Deck Plan View (foreword)

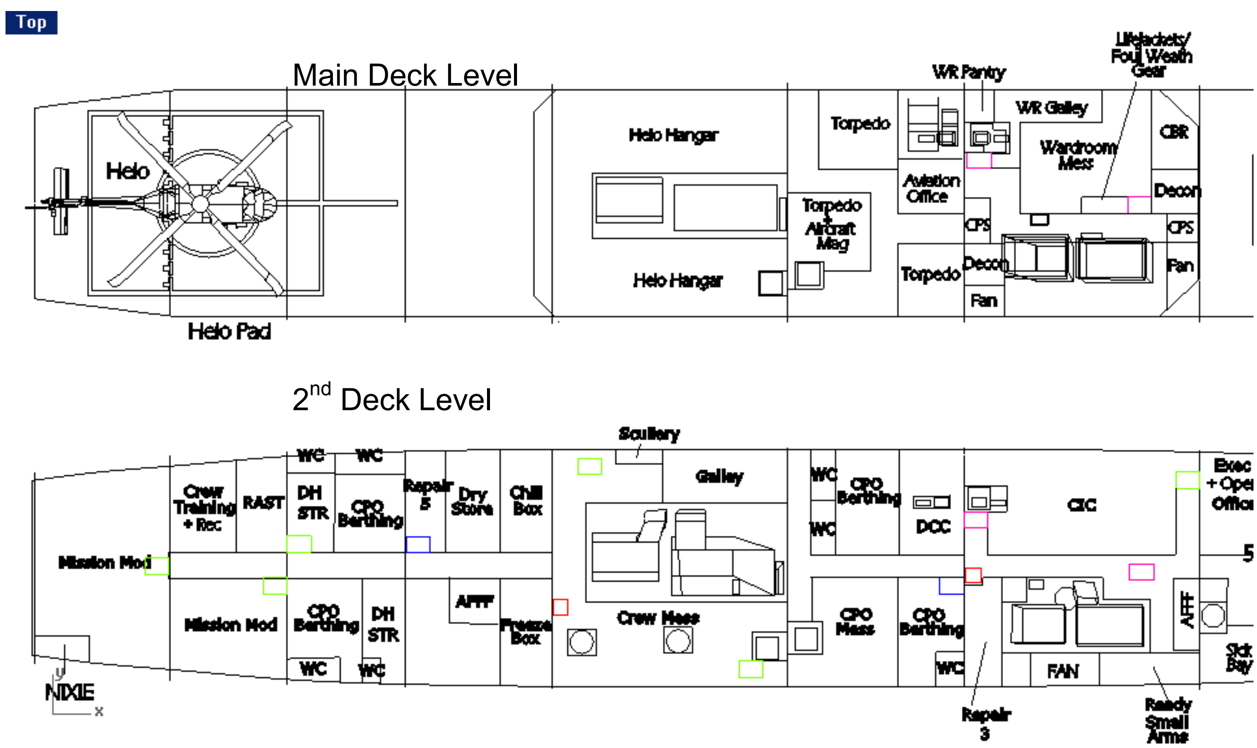


Figure 131: Internal Arrangements – Main Deck, 2nd Deck Plan View (aft)

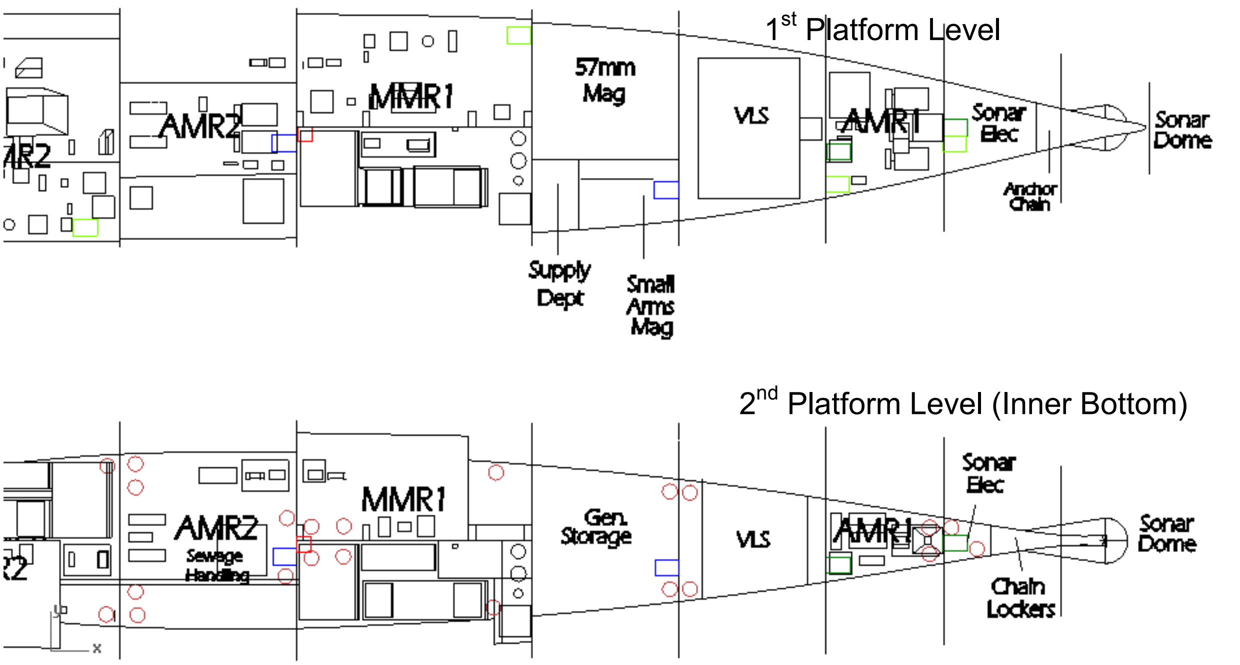


Figure 132: Internal Arrangements – 1st and 2nd Platform Plan View (foreword)

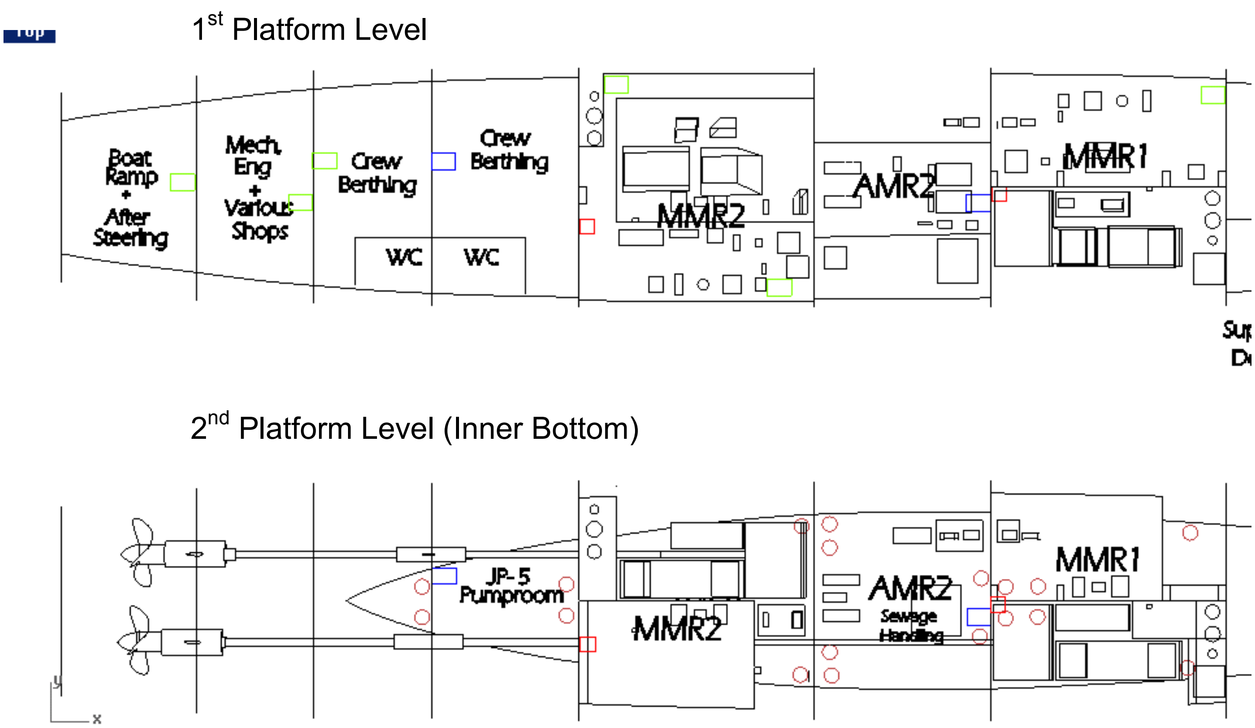


Figure 133: Internal Arrangements – 1st and 2nd Platform Plan View (aft)

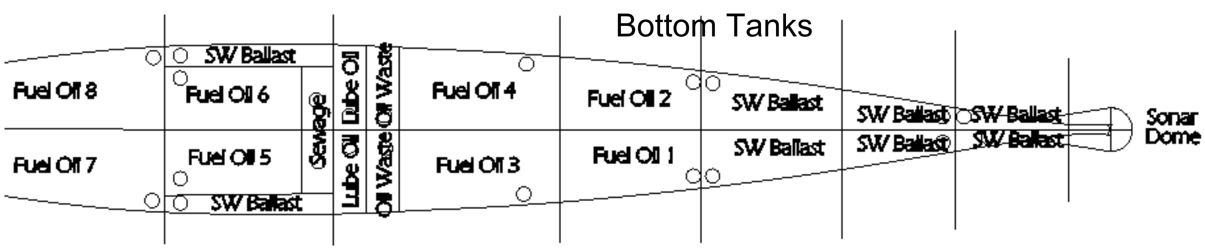


Figure 134: Internal Arrangements – Bottom Tanks Plan View (foreword)

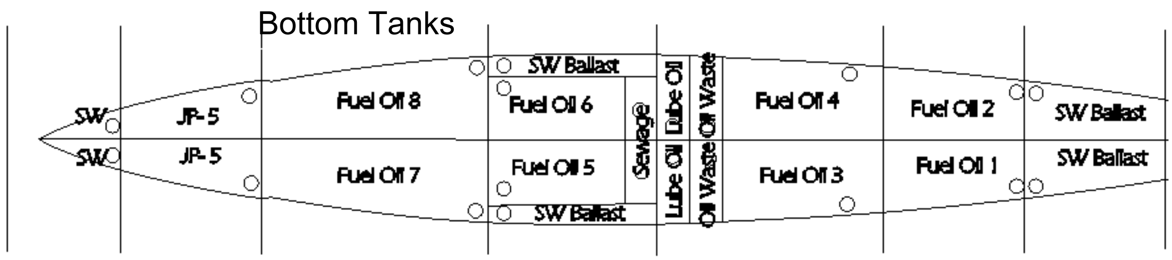


Figure 135: Internal Arrangements – Bottom Tanks Plan View (aft)

4.9.2 Living Arrangements

The SSC has accommodations for 65 personnel. These personnel include 1 Executive Officer, 1 Commanding Officer, 19 Officers, 19 Chief Petty Officers, and 25 enlisted members. The SSC can accommodate up to 20 extra crew members which allows for members of mission modularity crews. This brings the maximum available accommodations to 85 people. Space allocated for the crew was determined by following US Navy habitability standards. The accommodation space required for the ships force is listed in Table 32.

Table 32: Crew Berthing Space Allocation

Item	Accomodation Quantity	Per Space	Number of Spaces	Area Each (m2)	Total Area (m2)
CO	1	1	1	37.3	37.3
XO	1	1	1	13.9	13.9
Flag Officer	1	1	1	15	15
Department Head	4	1	4	11.6	46.4
Other Officer	18	2	9	12.5	112.5
CPO	25	5	5	13.64	68.2
Enlisted	35	18	2	40	80
Officer Sanitary	25	5	5	4	20
CPO Sanitary	25	5	5	4	20
Enlisted Sanitary	35	18	2	7	14
Total			35		427.3

A total of 35 crew berthing and sanitary spaces were added to the general arrangement. These berthing spaces are sufficient for a crew of 85. The planned minimum crew for the SSC is only 65 personnel, but berthing spaces for mission detachments was provided in the general arrangements.

The enlisted berthing spaces were concentrated on the 1st platform just aft of MMR 2. The officer berthing spaces are separated from the enlisted quarters, and are contained within the deckhouse. Officer and CPO berthing spaces contain fewer berths then enlisted spaces. The berthing spaces were located away from machinery spaces where possible to reduce airborne noise in the berthing spaces. This will reduce the amount of acoustic insulation required. The following figures show a typical arrangement for officer and crew berthing, officer and crew sanitary spaces, as well as officer and crew mess rooms.

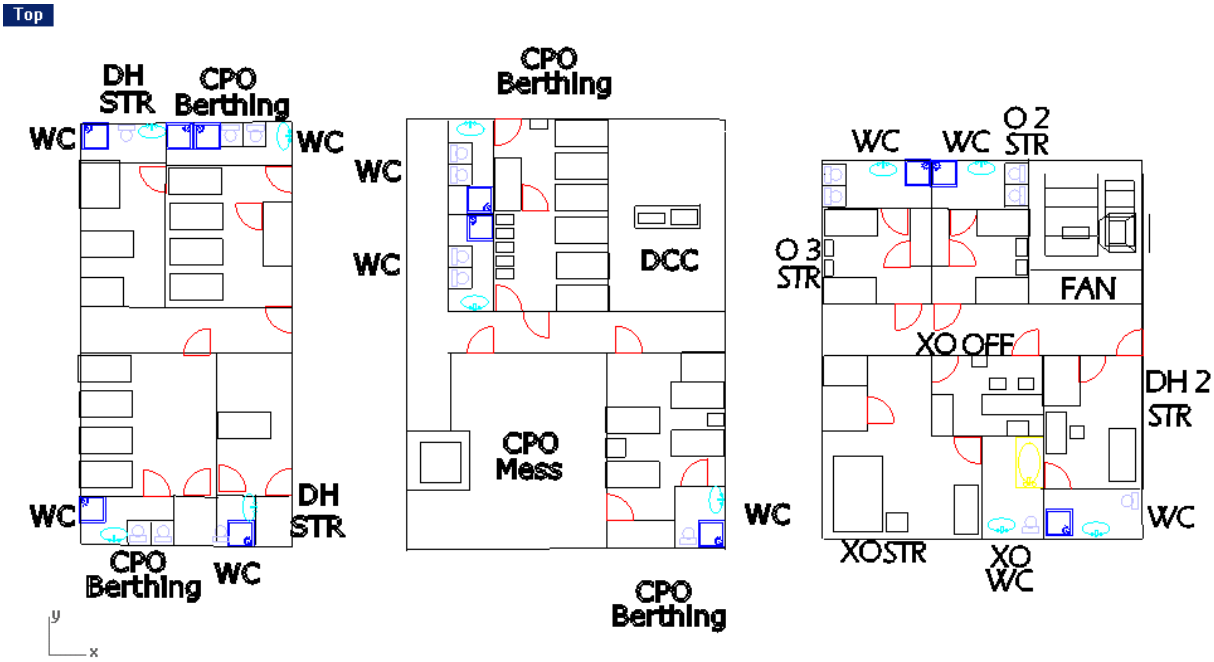


Figure 136: Living Arrangements – Typical Officer Berthing

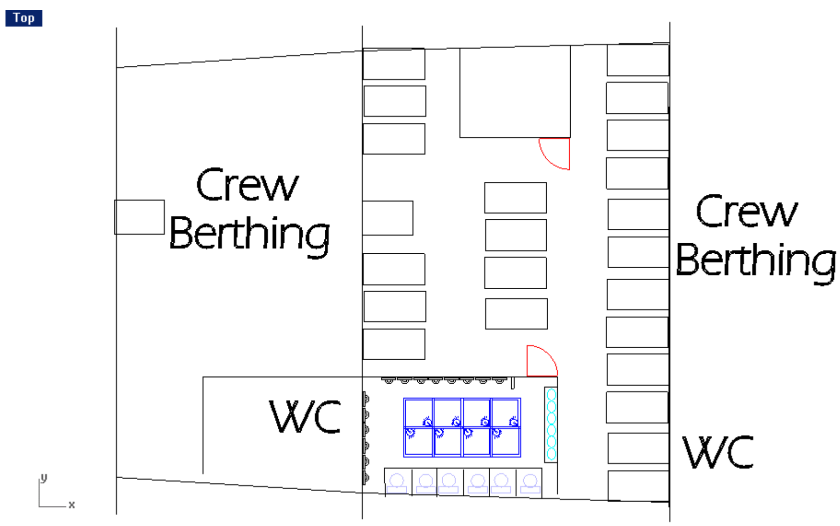


Figure 137: Living Arrangements – Typical Crew Berthing

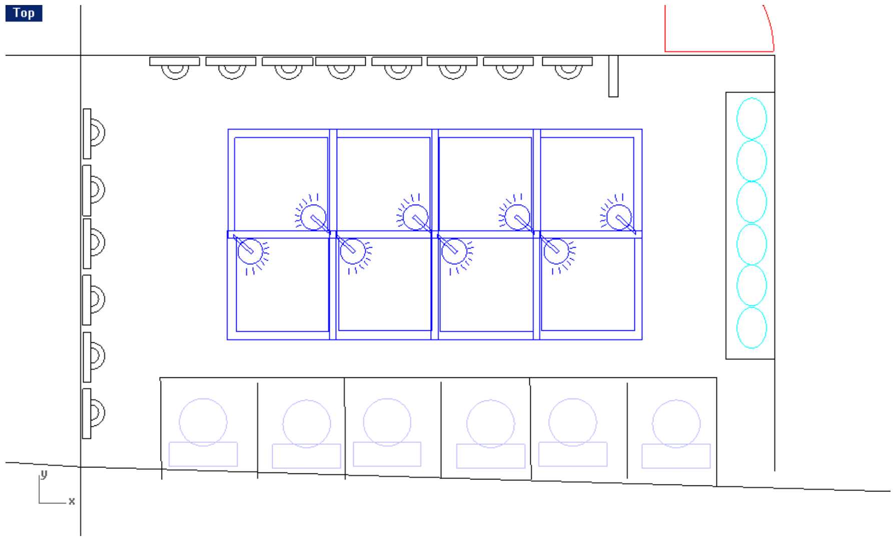


Figure 138: Living Arrangements – Typical Crew Sanitary Space

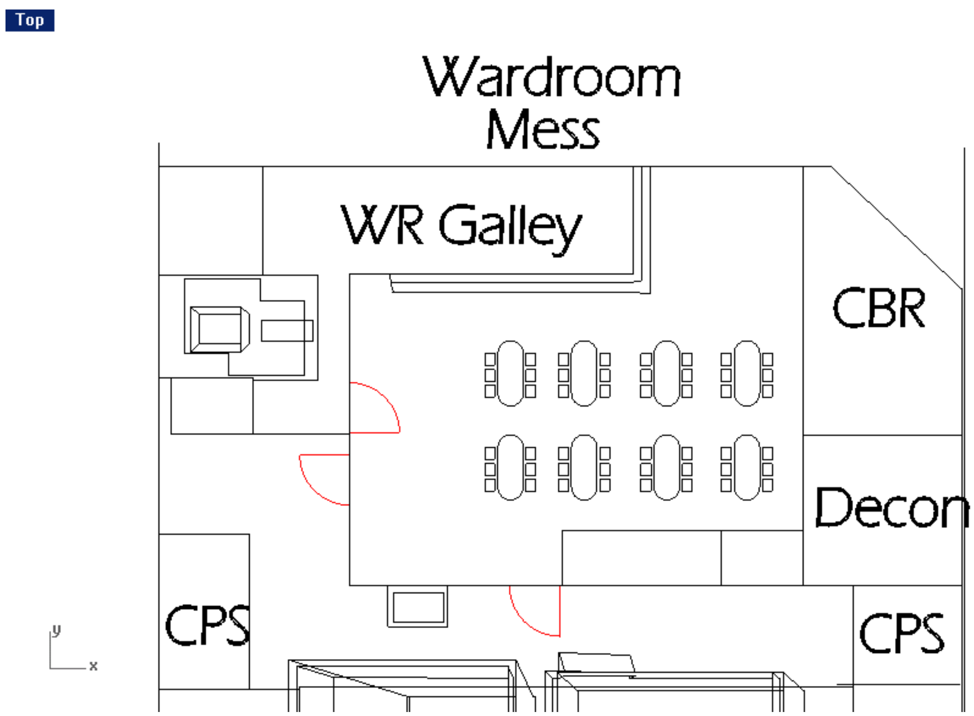


Figure 139: Living Arrangements – Typical Officer Mess Room

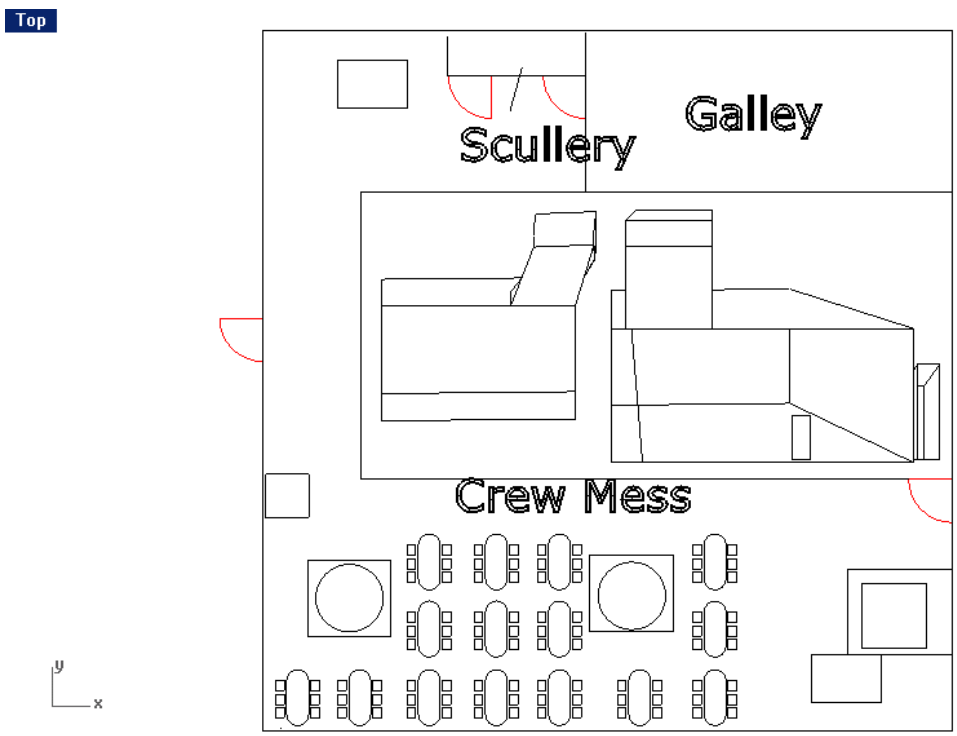


Figure 140: Living Arrangements – Typical Crew Mess Room

4.9.3 External Arrangements

Figure 108 shows that the SSC is equipped with a 57 mm deck gun and a 32 cell MK 41 VLS System. There is also a helicopter landing pad, as well as a helicopter hanger that can accommodate up to 2 SH-60 helicopters. All of the intakes and exhausts, as well as the radar and communication antennas, are stealthily hidden within the confinements of the deckhouse. This gives the ship a much reduced radar cross section.

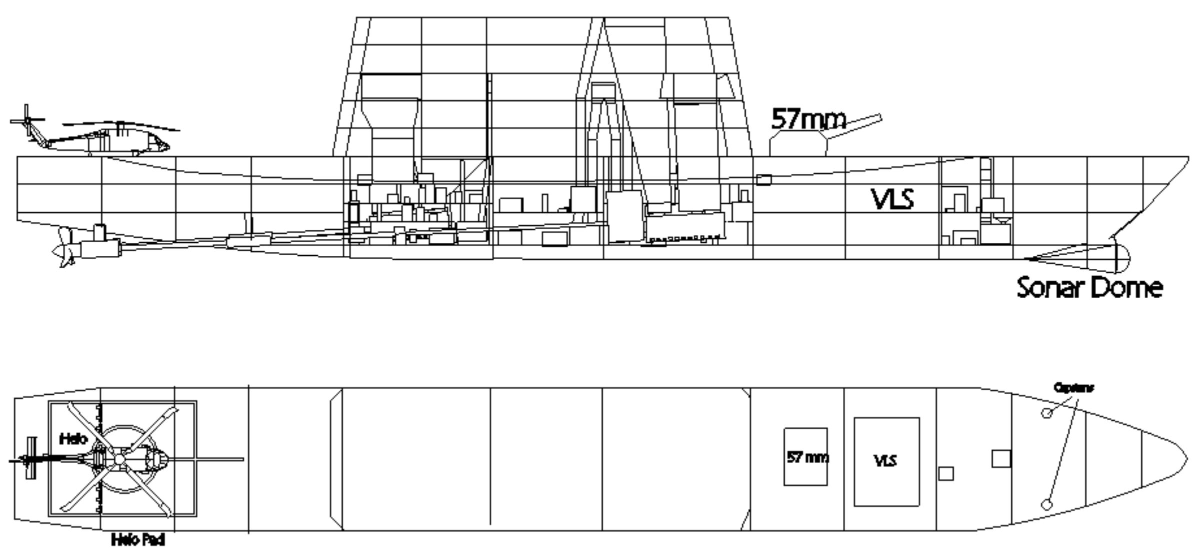


Figure 141: External Arrangements

4.9.4 Area and Volume

Throughout the General Arrangement process, it was important that enough space was used for each of the compartments within the ship. The area and/or volume of each compartment has been calculated and checked against the asset baseline numbers generated for the ship. Most of the compartments exceed the baseline ASSET numbers. A comparison between the ASSET required areas and volumes and the actual areas and volumes can be found in Appendix F.

4.10 Weights, Loading and Stability

4.10.1 Lightship Weights

The 3 digit weight breakdown from the ASSET improved baseline was modified throughout the concept development phase to include deviations from the baseline design. A summary of the lightship weights and centers for the SSC can be found in Table 33. A full 3 digit breakdown of the lightship weights and centers can be found in Appendix E.

Table 33 - Lightship Weight Summary

SWBS Group	Weight (MT)	VCG (m-Abv BL)	LCG (m-Aft FP)
100	1695.1	6.0	63.5
200	840.8	3.2	77.1
300	366.8	7.3	64.8
400	168.0	8.0	46.5
500	600.6	7.7	66.0
600	33.2	2.7	75.2
700	104.7	6.3	38.7
Margin	380.9	6.35	78.3
Total (LS)	4190.1	6.35	78.3

4.10.2 Loads and Loading Conditions

Full Load and Minimum Operating loading conditions were determined for the SSC by using the guidance contained in the US Navy Design Data Sheet 079-1. DDS 079-1 describes the Full Load condition by the summary given in Table 34, and the DDS 079-1 MinOp Condition definition is given in Table 35.

Table 34: DDS 079-1 Full Load Condition Definition

Crew and Effects	Wartime Complement
Stores	Full Design Complement
Ammunition	Full Allowance
Lube Oil	Storage 95%, Settling empty
Fresh Water	All tanks 100% full
Aviation Fuel	All tanks 95% full
Propulsion Fuel	All tanks 95% full
Water Ballast	Empty

Table 35: DDS 079-1 MinOp Condition Definition

Crew and Effects	Same as Full Load
Stores	One-third of Full Load
Ammunition	One-third of Full Load
Lube Oil	One-third Full Load
Fresh Water	Two-thirds Full Load
Aviation Fuel	One-third Full Load
Propulsion Fuel	One-third Full Load
Water Ballast	Empty*

A summary of the lightship, Full Load, and MinOp Conditions is presented in Table 36. A detailed summary of the loads that make up the MinOp and Full Load Condition is presented in Appendix E.

Table 36: SSC Large Loading Conditions

COMPONENT	WT-MT	VCG-m	Moment	LCG-m	Moment
FULL LOAD WEIGHT + MARGIN	5039.58	5.78	29145.50	75.43	380159.63
MINOP WEIGHT AND MARGIN	4509.87	6.11	27541.78	76.83	346501.11
LIGHTSHIP WEIGHT + MARGIN	4190.12	6.35	26600.27	78.30	328076.92
LIGHTSHIP WEIGHT	3809.20	6.35	24182.06	78.30	298251.75
MARGIN	380.92	6.35	2418.21	78.30	29825.17

4.10.3 Final Hydrostatics and Intact Stability

Due to time constraints, the finalized loading conditions were not input into HECSALV for the final hydrostatics and intact stability. A comparison between the finalized calculated weights as well as the loading conditions that were used for the HECSALV intact and damaged stability analyses are shown in Table 37. The weights in the finalized loading conditions are relatively similar in value to what was modeled in HECSALV for the finalized intact and damaged stability analyses, but the LCG and VCG are significantly different. The finalized calculated weights and centers for each loading condition should be modeled in the future to get more accurate equilibrium hydrostatics and righting arm curves.

Table 37: Comparison of Finalized and HECSALV Loading Conditions

		Calculated Values			HECSALV Values	
Component	WT - MT	VCG - m	LCG - m	WT - MT	VCG - m	LCG - m
Full Load Weight + Margin	5039.58	5.78	75.43	5,224	4.601	64.29
MINOP Weight + Margin	4509.87	6.11	76.83	4,443	5.337	64.81
Lightship Weight +Margin	4190.12	6.35	78.3	4,166	5.65	65

A summary of the equilibrium hydrostatics for the vessel in the full load condition is shown in Figure 142, and the intact stability analysis for the full load condition is shown in Figure 143. The DDS 079-1 intact stability criteria that the vessel is evaluated against is that the wind heeling arm at the intersection of the righting arm and 100 knot wind heeling arm curves must not be six tenths of the maximum righting arm; and the area under the righting arm curve (A1) must be at least 1.4 times the area under the wind heeling curve (A2). Figure 143 shows that the vessel meets the intact stability criteria of DDS 079-1 by a large margin. It is unlikely that the change in the weight and centers for the finalized calculated condition would cause the vessel to fail the intact stability criteria.

Intact Trim and Stability Summary

full load stillwater

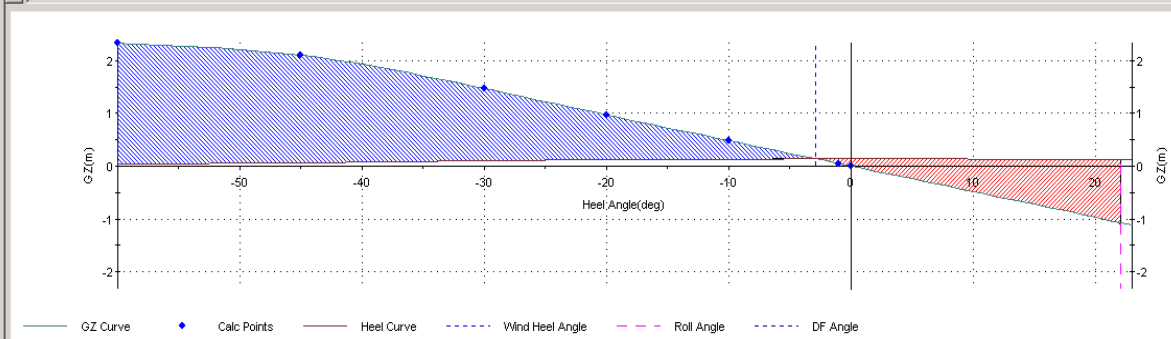
Item	Weight MT	VCG m	LCG m-MS	TCG m-CL	FSMom m-MT
Light Ship	4,166	5.650	4.100A	0.000	----
Constant	0	0.000	0.000	0.000	0
Lube Oil	25	0.841	2.995F	0.000P	34
Fresh Water	8	4.332	4.052A	0.000P	0
SW Ballast	0	----	----	----	----
Fuel Oil (DFM)	458	0.873	0.955F	0.000P	517
Oil Waste	0	----	----	----	----
JP-5	37	1.089	30.104A	0.000	30
Misc. Weights	530	0.000	0.000	0.000	0
Displacement	5,224	4.601	3.390A	0.000P	580

Stability Calculation			Trim Calculation		
KMt	7.634	m	LCF Draft	4.749	m
VCG	4.601	m	LCB	3.432A	m-MS
GMt (Solid)	3.034	m	LCF	7.229A	m-MS
FSc	0.111	m	MT1cm	114	m-MT/cm
GMt (Corrected)	2.923	m	Trim	0.707	m-A
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		

Drafts			Strength Calculations		
Draft at A.P.	5.061	m	Shear	-274	MT at 6.000A m-MS
Draft at M.S.	4.707	m	Bending Moment	4,734S	m-MT at 0.406F m-MS
Draft at F.P.	4.354	m			
Draft at Aft Marks	5.079	m			
Draft at Mid Marks	4.725	m			
Draft at Fwd Marks	4.371	m			

Figure 142: Full Load Equilibrium Condition

full load stillwater



Parameter	Units	Value	Required
Wind Heel	deg	2.9	---
Wind Heeling Arm Lw	m	0.140	---
Maximum Righting Arm Ratio		0.06	0.6
Capsizing Area A2	m-rad	0.26	---
Righting Area A1	m-rad	1.34	0.36
Angle Limiting Area	deg	60.0	---
Maximum Righting Arm	m	2.330	---
Angle at Max. GZ	deg	60.0	---
Projected Sail Area	m2	775.79	---
Vertical Arm ABL	m	7.876	---
Heeling Arm at 0 deg.	m	0.140	---
Wind Pressure	bar	0.02	---
Input Parameters			
Wind Speed		100.0	
Reference Draft	m	0.000	
Projected Sail Area	m2	0.00	
Vertical Center of Sail Area -BL	m	0.000	
Factor f where p = f*V^2 (lb/ft^2)		0.0035	
Roll Angle	deg	25.0	

Figure 143: Full Load Condition Intact Stability

A summary of the equilibrium hydrostatics for the vessel in the MinOp condition is shown in Figure 142, and the intact stability analysis for the full load condition is shown in Figure 144. The DDS 079-1 intact stability criteria that the vessel is evaluated against is that the wind heeling arm at the intersection of the righting arm and 100 knot wind heeling arm curves must not be six tenths of the maximum righting arm; and the area under the righting arm curve (A1) must be at least 1.4 times the area under the wind heeling curve (A2). Figure 145 shows that the vessel meets the intact stability criteria of DDS 079-1 by a large margin. It is unlikely that the change in the weight and centers for the finalized calculated condition would cause the vessel to fail the criteria.

minop stillwater

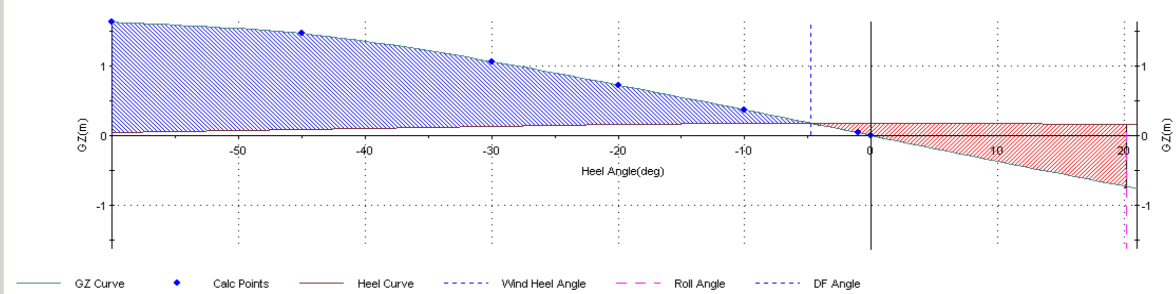
Item	Weight MT	VCG m	LCG m-MS	TCG m-CL	FSMom m-MT
Light Ship	4,166	5.650	4.100A	0.000	----
Constant	0	0.000	0.000	0.000	0
Lube Oil	13	0.536	2.993F	0.000S	64
Fresh Water	4	3.950	4.087A	0.000P	0
SW Ballast	0	----	----	----	----
Fuel Oil (DFM)	241	0.581	1.025F	0.000S	948
Oil Waste	0	----	----	----	----
JP-5	19	0.881	29.757A	0.000	55
Misc. Weights	0	----	----	----	----
Displacement	4,443	5.337	3.913A	0.000P	1,068

Stability Calculation			Trim Calculation		
KMt	7.914	m	LCF Draft	4.252	m
VCG	5.337	m	LCB	3.979A	m-MS
GMt (Solid)	2.576	m	LCF	7.581A	m-MS
FSc	0.240	m	MT1cm	109	m-MT/cm
GMt (Corrected)	2.336	m	Trim	1.189	m-A
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		

Drafts			Strength Calculations		
Draft at A.P.	4.772	m	Shear	145	MT at 48.000A m-MS
Draft at M.S.	4.178	m	Bending Moment	3,743H	m-MT at 24.553A m-MS
Draft at F.P.	3.584	m			
Draft at Aft Marks	4.802	m			
Draft at Mid Marks	4.207	m			
Draft at Fwd Marks	3.613	m			

Figure 144: MinOp Equilibrium Condition

minop stillwater



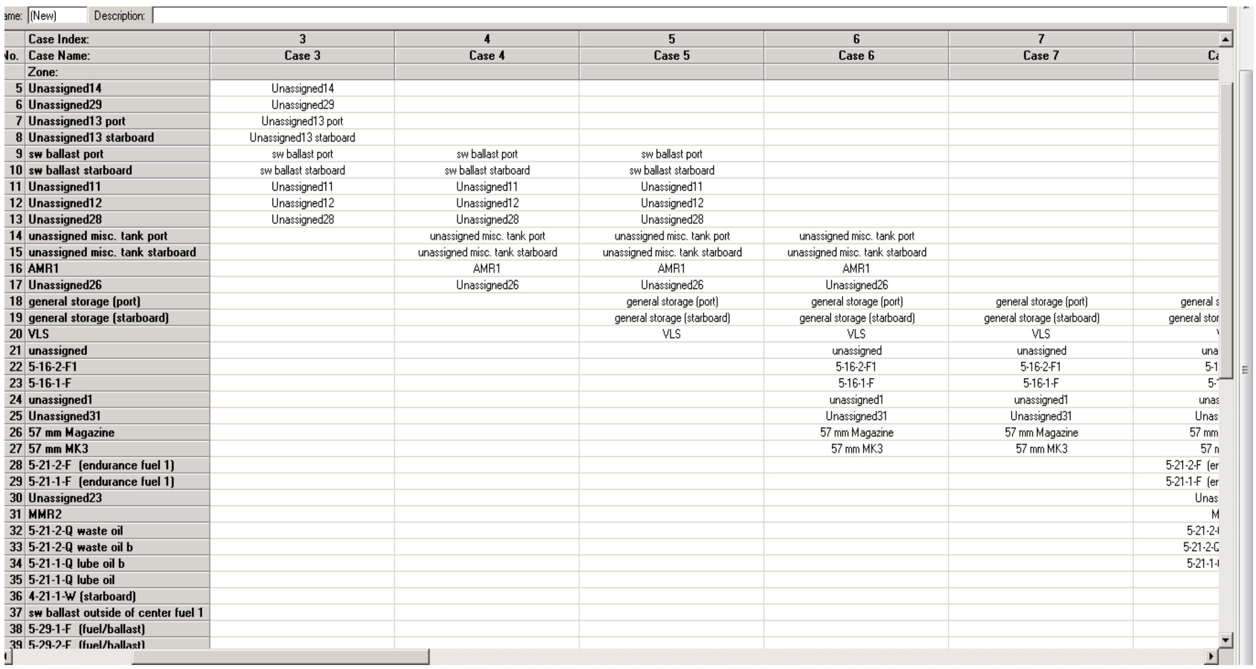
Parameter	Units	Value	Required
Wind Heel	deg	4.8	---
Wind Heeling Arm Lw	m	0.177	---
Maximum Righting Arm Ratio		0.11	0.6
Capsizing Area A2	m-rad	0.20	---
Righting Area A1	m-rad	0.90	0.27
Angle Limiting Area	deg	60.0	---
Maximum Righting Arm	m	1.631	---
Angle at Max. GZ	deg	60.0	---
Projected Sail Area	m2	839.49	---
Vertical Arm ABL	m	7.615	---
Heeling Arm at 0 deg.	m	0.178	---
Wind Pressure	bar	0.02	---
Input Parameters			
Wind Speed		100.0	
Reference Draft	m	0.000	
Projected Sail Area	m2	0.00	
Vertical Center of Sail Area -BL	m	0.000	
Factor f where p = f*V^2 (lb/ft^2)		0.0035	
Roll Angle	deg	25.0	

Figure 145: MinOp Condition Intact Stability

4.10.4 Damage Stability

The damaged stability of the vessel was evaluated for each of the loading conditions contained in Table 37. Again, these loading conditions as defined for the HECSALV damaged stability analysis are somewhat dated because the finalized calculated weights and centers for the three loading conditions are somewhat different than what was modeled in HECSALV. It is recommended that future work be completed to update the HECSALV loading conditions, and then re-run the intact and damaged stability analyses.

Transverse watertight bulkheads were previously spaced to ensure that the floodable length requirements were met. This subdivision resulted in a total of 11 watertight hull segments. The Full Load and MinOp conditions were evaluated against the damaged stability criteria contained in DDS 079-1 using a 15% damaged length along the hull. A total of 38 damaged cases (19 per load case) were developed within HECSALV, and a damaged stability analysis was run for each damaged case. Damage was assumed to extend past centerline and from the keel to the weather deck. Some of the damaged cases that were calculated in HECSALV are shown in Figure 146.


ame: (New) Description:

	Case Index:	3	4	5	6	7	
No.	Case Name:	Case 3	Case 4	Case 5	Case 6	Case 7	Ca
	Zone:						
5	Unassigned14	Unassigned14					
6	Unassigned29	Unassigned29					
7	Unassigned13 port	Unassigned13 port					
8	Unassigned13 starboard	Unassigned13 starboard					
9	sw ballast port	sw ballast port	sw ballast port	sw ballast port			
10	sw ballast starboard	sw ballast starboard	sw ballast starboard	sw ballast starboard			
11	Unassigned11	Unassigned11	Unassigned11	Unassigned11			
12	Unassigned12	Unassigned12	Unassigned12	Unassigned12			
13	Unassigned28	Unassigned28	Unassigned28	Unassigned28			
14	unassigned misc. tank port		unassigned misc. tank port	unassigned misc. tank port	unassigned misc. tank port		
15	unassigned misc. tank starboard		unassigned misc. tank starboard	unassigned misc. tank starboard	unassigned misc. tank starboard		
16	AMR1		AMR1	AMR1	AMR1		
17	Unassigned26		Unassigned26	Unassigned26	Unassigned26		
18	general storage (port)			general storage (port)	general storage (port)	general storage (port)	general s
19	general storage (starboard)			general storage (starboard)	general storage (starboard)	general storage (starboard)	general stor
20	VLS			VLS	VLS	VLS	V
21	unassigned				unassigned	unassigned	una
22	5-16-2-F1				5-16-2-F1	5-16-2-F1	5-1
23	5-16-1-F				5-16-1-F	5-16-1-F	5-
24	unassigned1				unassigned1	unassigned1	unas
25	Unassigned31				Unassigned31	Unassigned31	Unas
26	57 mm Magazine				57 mm Magazine	57 mm Magazine	57 mm
27	57 mm MK3				57 mm MK3	57 mm MK3	57 n
28	5-21-2-F (endurance fuel 1)						5-21-2-F (er
29	5-21-1-F (endurance fuel 1)						5-21-1-F (er
30	Unassigned23						Unas
31	MMR2						M
32	5-21-2-Q waste oil						5-21-2-
33	5-21-2-Q waste oil b						5-21-2-C
34	5-21-1-Q lube oil b						5-21-1-
35	5-21-1-Q lube oil						
36	4-21-1-W (starboard)						
37	sw ballast outside of center fuel 1						
38	5-29-1-F (fuel/ballast)						
39	5-29-2-F (fuel/ballast)						

Figure 146: HECSALV Damaged Cases

The DDS 079-1 damaged stability criteria that were used to evaluate the vessel were that the static heel after damage must not exceed 15 degrees, the margin line must not be submerged, and the remaining dynamic stability after damage must be adequate (A1 > 1.4 A2).

The worst case analyzed is for forward damage between FR 22.9 and FR 58.9 in the Full Load Condition. This damage case causes a trim by the bow that greatly reduced the waterplane area and transverse moment of inertia of the waterplane. The equilibrium condition for this damage case is presented in Figure 147. The corresponding righting arm curve for this damaged case with a 33 knot heeling wind is shown in Figure 148. This figure shows that the vessel meets the damaged stability criteria of DDS 079-1 by a large margin for the worst case damage scenario. It is unlikely that the change in the weight and centers for the finalized calculated condition would cause the vessel to fail the criteria.

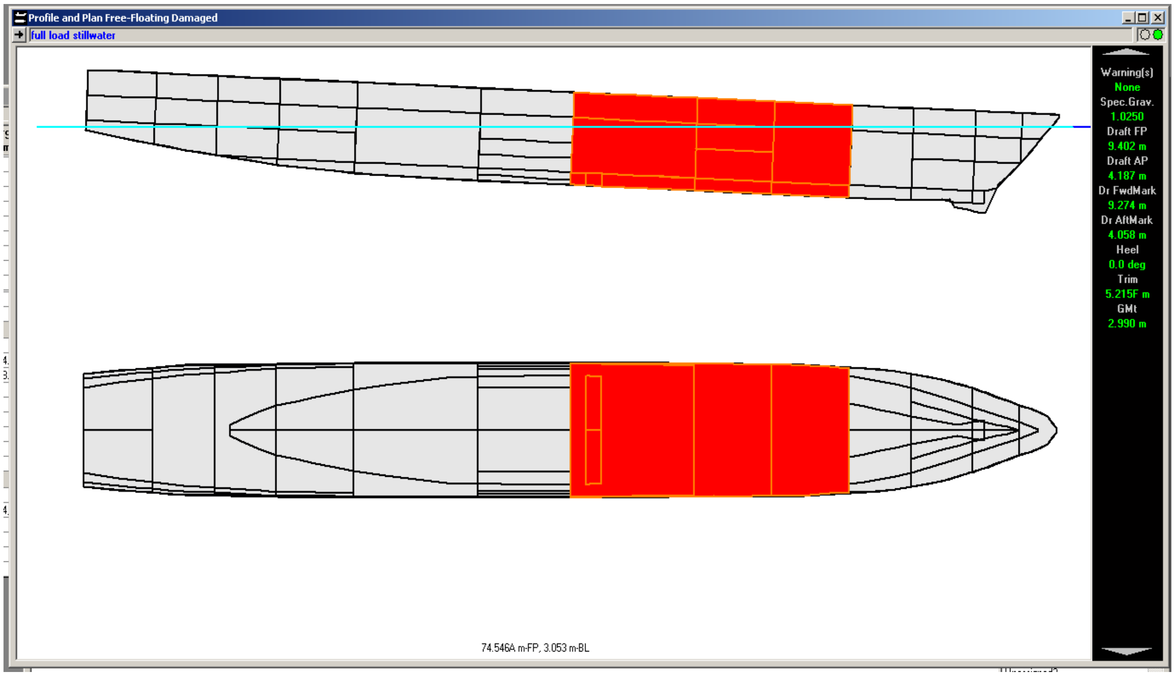
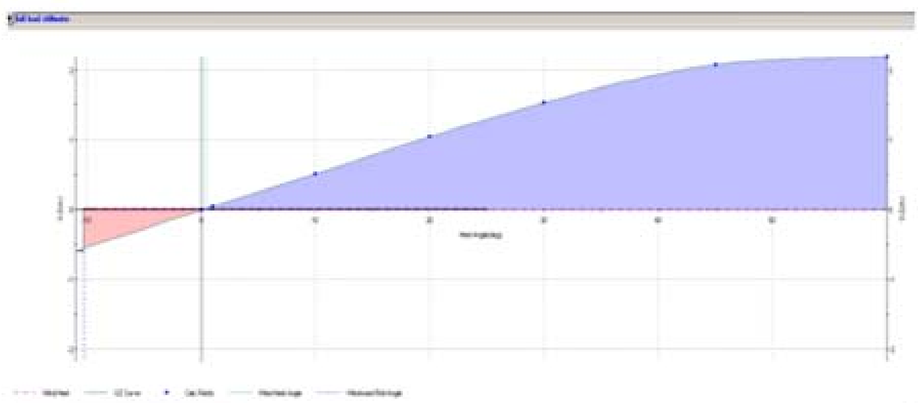


Figure 147: Worst Damaged Case Equilibrium Condition



USN DDS079-1 W/R Modified	Units	Available	Required
Wind Speed	knots	33.80	33.80
Windward Roll Angle	deg	10.7	10.7
Angle of List or Loll	deg	0.3	15.0
Wind Heel	deg	0.4	—
GZMax Margin	m	2.187	0.079
Area A1 (User defined)	m-rad	0.88	0.02
Area Ratio A1/A2		16.84	1.40
Freeboard to Margin Line	m	1.350	0.000
Freeboard to Downflooding	m	—	—
Longitudinal GM	m	157.975	—
Angle to Downflooding (Unprotected)	deg	—	—
Calculation Parameters:			
Wind Heeling Arm Lw (Press Grad)	m	0.006	—
Angle at Max. GZ	deg	60.0	—
Capsizing Area A2	m-rad	0.05	—
Righting Area A1	m-rad	0.88	—
Angle limiting Area A1	deg	45.0	—
Projected Sail Area	m2	517.58	—
Vertical Arm ABL	m	8.545	—
Heeling Arm at 0 deg	m	0.006	—
Factor f where p = f*V^2 (lb/ft^2)		0.0040	—
Wind Pressure	bar	0.00	—

Figure 148: Worst Damaged Case Damaged Stability

4.11 Seakeeping, Maneuvering and Control

Follow Assignment T26. Use everything – convert bulleted slides to text and include all Figures and Tables.

4.12 Cost and Risk Analysis

The Capability Development Document for the large SSC established a cost cap of $300 million for follow ship acquisition with an absolute cost cap of $400 Million. It is expected that 50 ships will be built in this class. The cost model predicts a lead ship cost of $845 million for the lead ship and $665 million for follow ship acquisition.

The total cost to the Navy for acquisition and ownership of the ship throughout the useful life of the ship is known as the Life Cycle Costs (LCC). The LCC is composed of research and development costs, ship acquisition, operations and support costs, and the cost of disposal. The operational costs associated with operating a ship are generally the highest, and that is why there has been an increased effort made in recent years to reduce manning on naval surface combatants.

The total lead ship cost for a vessel can be decomposed into the following sub categories. These costs can be broken down into constructions costs incurred in the shipyard, and post delivery costs (IPDA) incurred during a post shakedown availability (PSA) period.

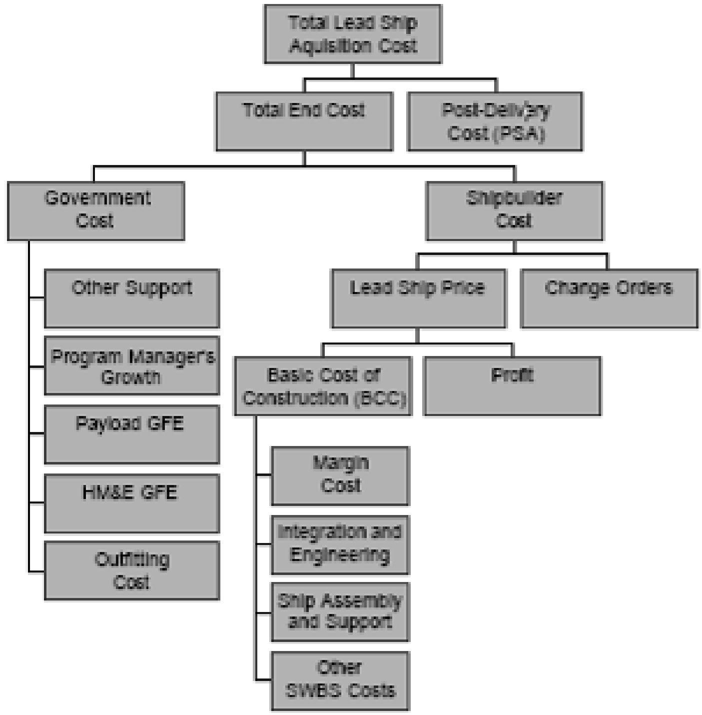


Figure 149: Total Lead Ship Acquisition Costs

The cost model for lead and follow ship acquisition were based primarily on the SWBS weight group weights. A labor cost is calculated for each SWBS by multiplying the weight of the three digit SWBS group by a labor rate and work complexity factor. Labor costs for each three digit SWBS group were then added to a material cost for each SWBS group. The material costs were determined by taking the weight of the three digit SWBS group and multiplying it by another complexity factor and an average inflation factor. The direct cost for each three digit SWBS group was then calculated by adding together the total labor and material costs for each group. A summary of the direct SWBS costs versus weight is given in Table 38.

Table 38: SWBS Weight vs. Cost

SWBS	Total Weight (LTons)	Total Weight %	Cost ($Millions)
100	1668.20	36.88	18.19
200	829.50	18.34	48.80
300	361.00	7.98	38.72
400	165.30	3.65	11.98
500	597.70	13.21	60.98
600	370.00	8.18	28.79
700	110.10	2.43	1.49
Margin	421.60	9.32	21.48
Total	4523.40	100.00	230.43

This table shows that the summation of the total shipyard construction costs for all of the SWBS weight groups is $230 million. The other costs that are included as shipbuilder costs that the Navy will pay in a fixed price contract are the costs listed above in addition to Integration and Engineering Costs (SWBS 800), Ship Assembly and Support (SWBS 900), costs associated with changing the detailed design, and a 10% profit on the lightship construction costs. The total costs incurred by the shipyard for lead ship acquisition are detailed in Table 39. The total costs incurred by the shipyard for lead ship construction is $406 million.

Table 39: Lead Ship Shipyard Costs

Items	Cost ($Millions)
SWBS Total	230.43
800	78.34
900	20.96
Total LS	329.71
Profit	32.97
Shipbuilder Price	362.68
Change Orders	43.52
Total Shipbuilder Portion	406.20

There are other costs associated with lead ship acquisition that the government will pay. These costs include construction support, Program Manager's growth, Government Furnished Equipment (GFE) for payload and H, M, & E, and other miscellaneous outfitting costs. Costs incurred by the government for lead ship acquisition are detailed in Table 40.

Table 40: Lead Ship Government Costs

Items	Cost ($Millions)
Other Support	9.07
Program Managers Growth	32.40
Payload GFE	354.17
HM&E GFE	7.25
Outfitting	14.51
Total Government Portion	421.27

The total lead ship cost is a summation of the shipyard construction costs, government construction costs, and IPDA costs associated with work completed during the PSA period. The total lead ship cost of $846 million is broken down in Table 41.

Table 41: Total Lead Ship Acquisition Cost

Items	Cost ($Millions)
Total Shipbuilder Portion	406.20
Total Government Portion	421.27
Total Lead Ship End Cost	827.47
Post Delivery Cost	18.13
Total Lead Ship Acquisition Cost	845.61

The follow ships in the class will be lower than the lead ship acquisition cost because there will be less non-recurring engineering, reduced change orders, and production efficiencies will be improved due to a reduced learning curve in the shipyard. Lead versus follow ship acquisition costs for the shipyard are detailed in Table 42. A summary of lead versus follow ship acquisition costs for the government is shown in Table 43.

Table 42: Lead vs. Follow Ship Shipyard Acquisition Costs

	Follow Ship Cost ($M)	Lead Ship Cost ($M)
SWBS	216.59	230.43
800	23.96	78.34
900	19.70	20.96
Total FS Construction	260.25	329.71
Profit	26.03	32.97
Shipbuilder Price	286.28	362.68
Change Orders	29.01	43.52
Total Shipbuilder Portion	315.29	406.20

Table 43: Lead vs. Follow Ship Government Acquisition Costs

	Follow Ship Cost ($M)	Lead Ship Cost ($M)
Other Support	7.16	9.07
Program Managers Growth	14.31	32.40
Payload GFE	331.40	354.17
HM&E GFE	5.73	7.25
Outfitting	11.45	14.51
Total Government Portion	370.05	421.27

The total direct acquisition cost for follow ship acquisition is $665 million as detailed in Table 44.

Table 44: Total Direct Acquisition Cost

	Follow Ship Cost ($Mil)	Lead Ship Cost ($Mil)
Total Shipbuilder Portion	315.29	406.2
Total Government Portion	370.05	421.27
Total Lead Ship End Cost	685.34	827.47
Post Delivery Cost	14.31	18.13
Total Ship Acquisition Cost	699.65	845.61
Average Ship Acquisition Cost	665.29	

The Life Cycle Cost (LCC) for the ship is the total discounted cost of owning, operating, maintaining, and disposing of the ship. Once all of the pertinent costs have been determined and calculated, they are discounted to their present value to generate the total LCC costs of the proposed ship. The undiscounted and discounted life cycle costs include R&D, investment, operations and support, and the residual value. These undiscounted and discounted costs are detailed in Table 45. Undiscounted LCC for a large SSC will total $93 billion, and discounted LCC will total $14.8 billion. This is a discount rate of 0.16.

Table 45: Undiscounted Life Cycle Costs

	Undiscounted ($Mil)	Discounted ($Mil)
R&D	714.55	836.94
Investment	41,579.00	11,948.00
Operations & Support	52,843.00	2,040.00
Residual Value	2,099.00	13.01
Total	93,037.00	14,811.00

5 Conclusions and Future Work

5.1 Assessment

Table 46 compares the CDD KPP's with the performance of the finalized design.

Table 46 - Compliance with Operational Requirements

Technical Performance Measure	CCD KPP (Threshold)	Original Goal	Improved Baseline	Final Baseline
AAW	ICMS, MK XII AIMS IFF, COMBAT DF, 2X-MK 137 LCHRs, AIEWS ADVANCED SEW SYSTEM, AN/SPY-1E MFR, GLYCOL WATER COOLING SYSTEM FOR SPY	AAW Self Defense Only	ICMS, MK XII AIMS IFF, COMBAT DF, 2X-MK 137 LCHRs, AIEWS ADVANCED SEW SYSTEM, AN/SPY-1E MFR, GLYCOL WATER COOLING SYSTEM FOR SPY	ICMS, MK XII AIMS IFF, COMBAT DF, 2X-MK 137 LCHRs, AIEWS ADVANCED SEW SYSTEM, AN/SPY-1E MFR, GLYCOL WATER COOLING SYSTEM FOR SPY
ASUW	IRST, AN/SPS-73, Small Arms Ammo, 2x50-cal MGs, Small Arms Locker, DORNA EO/IR Fire Control, 57 mm MK 3, 57mm stowage, 57mm ammo in gun mount(120), 57mm ammo magazie (880), 1x7m RHIB	SSC SAGs could provide defense against mine threats, littoral ASW threats	IRST, Small Arms Ammo, 2x50-cal MGs, Small Arms Locker, DORNA EO/IR Fire Control, 57 mm MK 3, 57mm stowage, 57mm ammo in gun mount(120), 57mm ammo magazie (880), 1x7m RHIB	IRST, Small Arms Ammo, 2x50-cal MGs, Small Arms Locker, DORNA EO/IR Fire Control, 57 mm MK 3, 57mm stowage, 57mm ammo in gun mount(120), 57mm ammo magazie (880), 1x7m RHIB
ASW	SQQ-89 Underwater Fire Control, AN/SLQ-25A (NIXIE) and AN/SLR-24I (TRIPWIRE), 2x Mk 32 SVTT on deck, NDS 3070 Vanguard mine sonar, SQS-56 sonar and dome	SSC SAGs to provide defense against mine threats, littoral ASW threats	SQQ-89 Underwater Fire Control, AN/SLQ-25A (NIXIE) and AN/SLR-24I (TRIPWIRE), 2x Mk 32 SVTT on deck, NDS 3070 Vanguard mine sonar, SQS-56 sonar and dome	SQQ-89 Underwater Fire Control, AN/SLQ-25A (NIXIE) and AN/SLR-24I (TRIPWIRE), 2x Mk 32 SVTT on deck, NDS 3070 Vanguard mine sonar, SQS-56 sonar and dome
LAMPS	Dual SH-60 helo and hangar, fuel, support LAMPS (modules, RAST, Aviation Magz	Dual SH-60 helo and hangar, fuel, support LAMPS (modules, RAST, Aviation Magz	Dual SH-60 helo and hangar, fuel, support LAMPS (modules, RAST, Aviation Magz	Dual SH-60 helo and hangar, fuel, support LAMPS, Aviation Magz
GMLS	2x MK41 VLS 16-cell W/3 Tomahawk + 10 SM-2 + 3 VLASROC, MK 41 control System, VLS armor, VLS magazine dewatering system	2x MK41 VLS 16-cell W/3 Tomahawk + 10 SM-2 + 3 VLASROC, MK 41 control System, VLS armor, VLS magazine dewatering system	2x MK41 VLS 16-cell W/3 Tomahawk + 10 SM-2 + 3 VLASROC, MK 41 control System, VLS armor, VLS magazine dewatering system	2x MK41 VLS 16-cell W/3 Tomahawk + 10 SM-2 + 3 VLASROC, MK 41 control System, VLS armor, VLS magazine dewatering system
LCS Modules	1.5 times LCS mission package not including LAMPS	2 times LCS mission package	1.5 times LCS mission package not including LAMPS	1.5 times LCS mission package not including LAMPS
Power and Propulsion	2 shaft CODAG, 2xLM2500+ 2xCAT3616	2 shaft CODAG, 2xLM2500+ 2xCAT3618	2 shaft CODAG, 2xLM2500+ 2xCAT3618	2 shaft CODAG, 2xLM2500+ 2xCAT3618
Endurance Range (nm)	4500 nm	4000-5000 nm	3560	3589 nm
Sustained Speed (knots)	32 kts	30-35 kts	30.1 kts	30 kts
Endurance Speed (knots)	20 knots	20 kts	20 kts	20 kts
Stores Duration (days)	70 days	70 days	70 days	70 days

Collective Protection System	Full	Full	Full	Full
Crew Size	65	65	65	65
Full Load Delivery Displacement (MT)	5200 MT	2000-5000 MT	5224 MT	5040 MT
Vulnerability (Hull Material)	Steel		Steel	Steel
Ballast/fuel system	Clean, separate ballast tanks	Clean, separate ballast tanks	Clean, separate ballast tanks	Clean, separate ballast tanks
Degaussing System	Yes	Yes	Yes	Yes

5.2 Future Work

Concept Development of SSC large followed the design spiral in sequence after Concept Exploration. In Concept Development the general concepts for the hull, systems and arrangements were 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. During the Concept Development phase, the improved baseline design was refined through stepping through the various steps in the design spiral. There are many areas of the design that would benefit from another step through the design spiral.

One of the major aspects of the design that needs more refinement is the machinery arrangement. The machinery rooms and deckhouse were positioned in a manner that would reduce the curvature in the intake and uptake trunks. However, the design currently has a ship service diesel generator forward of the VLS modules, and the exhaust for this generator terminates on the weather deck forward of the gun. This represents a potential hazard because the exhaust gasses are typically extremely hot. Having personnel on the weather deck while the generator is online could represent a hazard to personnel assisting with mooring operations. One potential solution would be to remove the generator from AMR 1, and upsize the remaining generators.

Also, a more detailed topside arrangement should be completed in the future. The current topsides arrangement shows the rough layout of the AN/SPY 1-E S-Band Arrays. However, there are numberous other combat systems weapons, sensors, and arrays that are also to be included in the topside arrangement. The topside needs to be modeled in detail in ensure that sufficient area and volume exist within the deckhouse to support the combat systems that would be detailed in the Combat Systems Equiptment List (CSEL).

The weight estimate will also need to be updated in future design spiral iterations. Changes were made to the improved baseline design throughout the concept development phase, and these changes all have an impact on the weight estimate of the ship. Resistance and propulsion, intact stability, damaged stability, the structural analysis, and the endurance range calculations all depend on an accurate and weight estimate. A design margin was incorporated into the 3 digit weight estimate, but more detailed weight calculations need to be made with future iterations.

A more detailed one-line diagram also needs to be completed for the vessel. The one-line diagram developed during the concept exploration phase shows the general architecture of the AC ZEDS system, but a more in depth analysis should be completed in the future, and one-line diagram should include more details.

Finally, the structural analysis of the ship should be re-analyzed with AH-36 (HSS) rolled shaped instead of HY80 sections. The structural analysis in MAESTRO shows that the modeled structure is more than adequate to react extreme design loads, and the scantlings should be changed. Changing the stiffeners to HSS will help to reduce the construction costs and schedule as well because HY80 is very difficult and expensive to manufacture.

5.3 Conclusions

The finalized SSC large design meets all of the major KPP's contained in Table 46, and would prove to be a effective from a cost and operational perspective. This design is based on the proven FFG 7 class parent hull form, and the various systems installed on the ship provide a low risk solution to the US Navy. The mechanical CODAG plant is a proven design that has been used in the past on future surface combatants. It enables the vessel to operate in the endurance speed regime with only the efficient propulsion diesel generators online, but has the ability to achieve relatively high sustained speeds with the diesels and gas turbines online.

The vessel also includes many features that will help improve producibility and keep initial acquisition costs down. This will allow the ship to be purchased in sufficient numbers to meet the demands of the fleet.

Through the use of the sophistocated combat systems installed on the ship in conjunction with the ability to carry deployable mission modules will enable the SSC Large to meet the complex operational mission requirements outlined in the ICD.

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Appendix A – Initial Capabilities Document (ICD)

INITIAL CAPABILITIES DOCUMENT

FOR A

SSC (SSC)

1 PRIMARY JOINT FUNCTIONAL AREAS

- Force and Homeland Protection - The range of military application for this function includes: force protection and awareness at sea; and protection of homeland and critical bases from the sea.
- Intelligence, Surveillance and Reconnaissance (ISR) - The range of military application for this function includes: onboard sensors; special operations forces; and support of manned and unmanned air, surface and subsurface vehicles.
- Power Projection - The range of military application for this function includes special operations forces.

Operational timeframe considered: 2016-2060. This extended timeframe demands flexibility in upgrade and capability over time.

2 REQUIRED FORCE CAPABILITY(S)

- Provide surface and subsurface defense around friends, joint forces and critical bases of operations at sea (ASUW, ASW)
- Provide a sea-based layer of surface and subsurface homeland defense (HLD)
- Provide persistent intelligence, surveillance and reconnaissance (ISR)
- Provide maritime interdiction/interception operations (MIO)
- Provide anti-terrorism protection (AT)
- Provide special operations forces (SOF) support
- Provide logistics support
- Support distributed off-board systems
- Support mine warfare operations
- Support area AAW defense (larger SSCs)

Provide these capabilities through the use of interchangeable, networked, tailored mission modules in combination with inherent systems. Consider a broad range of SSC size, 2000-5000 MT.

3 CONCEPT OF OPERATIONS SUMMARY

Support CSG/ESGs - 2 to 3 SSC ships could be assigned to each strike group. Their mission configuration would complement the other strike group combatants. Larger SSCs may be able to contribute to CSG and ESG area AAW defense. Tailored mission configurations could include defense against mine threats, littoral ASW threats, and small boat threats using distributed off-board systems. High speed and agility could provide tactical advantage.

SSC Surface Action Groups (SAGs) – Operate as a force of networked, dispersed SSCs, providing collective flexibility, versatility and mutual support. SSC SAGs could provide defense against mine threats, littoral ASW threats, and small boat threats ahead of larger CSGs/ESGs including first-response capability to anti-access crises. High speed and agility should provide significant tactical advantage.

SSC Independent Operations - SSC would perform inherent (mobility) mission tasking in known threat environments including defense against mine threats, littoral ASW threats, and small boat threats. Rapid response to contingency mission tasking could provide OTH Targeting, reach-back for mission planning, insertion/extraction of USMC, Army, SOF personnel, and movement of cargo/personnel. SSC could provide ISR ahead of CSG/ESG operations and maritime interdiction/interception operations, overseas or in support of homeland defense, possibly as USCG assets.

Ship deployments could be extended with rotating crews alternately returning to CONUS. Interchangeable, networked mission modules could be changed in 2-3 days, in theater, to support force needs and changing threats.

Some MSCs could be configured with more capable AAW sensors and weapons that could also be modular, but require extended availability for upgrade or change-out. Hull plugs, modular deckhouse and modular mast options should be considered for these MSC variants. They would be able to contribute significant area AAW support for ESGs or as part of CSGs.

4 CAPABILITY GAP(S)

The overarching capability gap addressed by this ICD is to provide affordable SSC capabilities in sufficient numbers for worldwide coverage of strike group and independent platform requirements. Specific capability gaps and requirements include:

Priority	Capability Description	Threshold Systems or metric	Goal Systems or metric
1	Support of distributed off-board systems including MH-60 and MH-53 aircraft	Hangar and flight deck for 1xMH-60 and 2xVTUAV; side launch and recovery of surface and underwater vehicles	Hangar and flight deck for 2xMH-60 and 2xVTUAV; side and stern launch and recovery of surface and underwater vehicles
2	Agility (speed, maneuverability, shallow draft)	Sustained speed of 30 knots, 5 meter draft	Sustained speed of 45 knots, 3 meter draft.
3	Mission flexibility and capacity	1xLCS capacity for interchangeable modules	2xLCS capacity for interchangeable modules
4	Area AAW support as part of CSG/ESG	AAW self-defense only	
5	Platform Passive Susceptibility	DDG-51 signatures	DDG1000 signatures

5 THREAT AND OPERATIONAL ENVIRONMENT

Since many potentially unstable nations are located on or near geographically constrained (littoral) bodies of water, the tactical picture may be at smaller scales relative to open ocean warfare. Threats in such an environment include: (1) technologically advanced weapons - cruise missiles like the Silkworm and Exocet, land-launched attack aircraft, fast gunboats armed with guns and smaller missiles, and diesel-electric submarines; and (2) unsophisticated and inexpensive passive weapons – mines (surface, moored and bottom), chemical and biological weapons. Encounters may occur in shallow water which increases the difficulty of detecting and successfully prosecuting targets.The sea-based environment includes:

- Open ocean (sea states 0 through 8) and littoral
- Shallow and deep water
- Noisy and reverberation-limited
- Degraded radar picture
- Crowded shipping
- Dense contacts and threats with complicated targeting
- Biological, chemical and nuclear weapons
- All-Weather

6 FUNCTIONAL SOLUTION ANALYSIS SUMMARY

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

- Increased reliance on foreign SSC support (Japan, NATO, etc.) to meet the interests of the U.S.

*b. **Ideas for Materiel Approaches***

- Design and build small, high speed surface combatants (LCS) with limited capability for dedicated CSG operations, no significant area AAW contribution beyond self defense, and very limited multi-mission capability.

 Do not consider building surface combatants smaller than 5000 MT. Satisfy all surface combatant requirements with MSCs.
 Design and build a scalable modular family of new SSC ships, 2000-5000 MT, with capabilities sufficient to satisfy the full range of specified SSC capability gaps using interchangeable, networked mission modules, and with the option of more capable AAW sensors and weapons that could also be modular, but added in construction or in a major availability using a hull plug, modular deckhouse, or modular mast(s). These variants would be able to contribute significant area AAW support for ESGs or as part of CSGs.

7 FINAL RECOMMENDATIONS

a. Non-material solutions are not consistent with national policy.

b. LCS-1 and 2 as designed may not be affordable in required force numbers. Reconfiguration for area AAW capability would be difficult. They may be too small and not sufficiently robust for required open ocean transits and CSG operations. Their service life may also be inadequate.

c. Satisfying the SSC requirement with all MSCs in necessary force numbers is not affordable.

d. The option of a scalable modular family of new SSC ships, 2000-5000 MT, with capabilities sufficient to satisfy the full range of specified SSC capability gaps using interchangeable, networked mission modules, and with the option of more capable AAW sensors and weapons should be explored. The feasibility of limiting follow-ship acquisition cost to $300M ($FY2013) must be investigated with an absolute constraint of $400M. Compromises in speed and inherent multi-mission capabilities may have to be considered. Trade-offs should be made based on total ownership cost (including cost of upgrade), effectiveness (including flexibility) and risk. It is anticipated that 50 of these ships may be built with a required service life of 30 years.

Appendix B– Acquisition Decision Memorandum (ADM)

August 24, 2009
From: Virginia Tech Naval Acquisition Executive
To: SSC Design Teams

Subject: ACQUISITION DECISION MEMORANDUM FOR a SSC
Ref: (a) Virginia Tech SSC Initial Capabilities Document (ICD), 14 August 2009

1. This memorandum authorizes concept exploration of a single material alternative proposed in Reference (a) to the Virginia Tech Naval Acquisition Board on 14 August 2007. Additional material and non-material alternatives supporting this mission may be authorized in the future.

2. Concept exploration is authorized for a scalable modular family of new SSC ships, 2000-5000 MT, with capabilities sufficient to satisfy the full range of specified SSC capability gaps using interchangeable, networked mission modules, and with the option of more capable AAW sensors and weapons. AAW sensors and weapons could also be modular, but would be added in construction as a SSC variant or in a major availability using a hull plug, modular deckhouse, or modular mast(s). These variants would be able to contribute significant area AAW support for ESGs or as part of CSGs. A full range of affordable options satisfying identified capability gaps from threshold to goal should be considered. Affordability is a critical issue in order to enable sufficient force numbers to satisfy world-wide commitments consistent with national defense policy. Rising acquisition, manning, logistics support, maintenance and energy costs must be addressed with a comprehensive plan including the application of new technologies, automation, modularity, and a necessary rational compromise of inherent multi-mission capabilities.

3. The feasibility of limiting follow-ship acquisition cost to $300M ($FY2013) must be investigated with an absolute constraint of $400M. Compromises in speed and inherent multi-mission capabilities may have to be considered to achieve these cost goals and constraints. Trade-offs should be made based on total ownership cost (including cost of upgrade), effectiveness (including flexibility) and risk. It is anticipated that 50 of these ships may be built with IOC in 2016, and with a required service life of 30 years.

A.J. Brown
VT Acquisition Executive

Appendix C– Capabilities Development Document (CDD)

UNCLASSIFIED

CAPABILITY DEVELOPMENT DOCUMENT

FOR

Large - SSC (SSC Large)
VT Team 5

1 Capability Discussion

The Initial Capabilities Document (ICD) for this CDD was issued by the Virginia Tech Acquisition Authority on 14 August 2009. The overarching capability gap addressed by this ICD is to provide affordable, SSC capabilities in large numbers in order to accomplish worldwide coverage of strike group and independent platform requirements. To meet this overarching capability gap, the SSC must be capable of providing the following force capabilities:

1. Provide surface and subsurface defense around allies, joint forces, and critical bases of operation at sea (ASW, ASUW)
2. Provide a sea-based layer of surface and subsurface homeland defense (HLD)
3. Provide persistent intelligence, surveillance, and reconnaissance (ISR)
4. Provide maritime interdiction/interception operations (MIO)
5. Provide anti-terrorism protection (AT)
6. Provide special operations forces (SOF) support
7. Provide logistics support
8. Provide distributed off-board systems
9. Provide mine warfare operations
10. Support area AAW defense

Specific capability gaps and requirements as outlined in the ICD are listed below:

Priority	Capability Description	Threshold Systems or metric	Goal Systems or metric
1	Support of distributed off-board systems including MH-60 and MH-53 aircraft	Hangar and flight deck for 1xMH-60 and 2xVTUAV; side launch and recovery of surface and underwater vehicles	Hangar and flight deck for 2xMH-60 and 2xVTUAV; side and stern launch and recovery of surface and underwater vehicles
2	Agility (speed, maneuverability, shallow draft)	Sustained speed of 30 knots, 5 meter draft	Sustained speed of 45 knots, 3 meter draft.
3	Mission flexibility and capacity	1xLCS capacity for interchangeable modules	2xLCS capacity for interchangeable modules
4	Area AAW support as part of CSG/ESG	AAW self-defense only	
5	Platform Passive Susceptibility	DDG-51 signatures	DDG1000 signatures

In order to fill all of the capability gaps in the ICD, the SSC is designed to accommodate interchangeable, networked mission modules. In order to satisfy requirements for AAW area defense in support of CSG's and ESG's, the large SSC must have more capable AAW sensors and weapons. According the the Acquisition Decision Memorandum (ADM) published on 24 August 2009, the AAW sensors and weapons on the large SSC could be modular, but would be added during construction or during a major availability using a hull plug, modular deckhouse, or modular mast.

2 Analysis Summary

An Acquisition Decision Memorandum issued on 24 August 2009 by the Virginia Tech Acquisition Authority directed Concept Exploration and Analysis of Alternatives (AoA) for a scalable, modular family of new SSC ships with an emphasis on providing a full range of affordable options to meet sufficient force numbers to satisfy worldwide commitments. Required core capabilities are AAW (SSC Large), force and homeland protection, intelligence, ISR, and power projection. Affordability is critical, and to provide sufficient numbers of SSC to meet worldwide commitments, the SSC must have the following attributes:

1. The platforms must be highly producible, maintainable and upgradable through significant modularization.
2. The time from concept to delivery must be minimized and systems must have commonality with other platforms within the fleet.
3. New technologies and automation must be implemented.
4. The new ship must have minimum manning.

In addition, the concept exploration had to include a necessary rational compromise of inherent multi-mission capabilities.

Concept Exploration was conducted from 1 September 2009 through 11 December 2009. A Concept Design and Requirements Review was conducted on 04 February 2009. This CDD presents the baseline requirements approved in the review.

Available technologies and concepts necessary to provide required functional capabilities were identified and defined in terms of performance, cost, risk and ship impact (weight, area, volume, power). Trade-off studies were performed using technology and concept design parameters to select trade-off options in a multi-objective genetic optimization (MOGO) for the total ship design. The result of this MOGO was a non-dominated frontier, Figure 1. This frontier includes designs with a wide range of risk and cost, each having the highest effectiveness for a given risk and cost. Preferred designs are often "knee in the curve" designs at the top of a large increase in effectiveness for a given cost and risk, or designs at high and low extremes. The design selected for Virginia Tech Team 5, and specified in this CDD, is a low-cost and low-risk design chosen from Figure 1. Selection of a point on the non-dominated frontier specifies requirements, technologies and the baseline design.

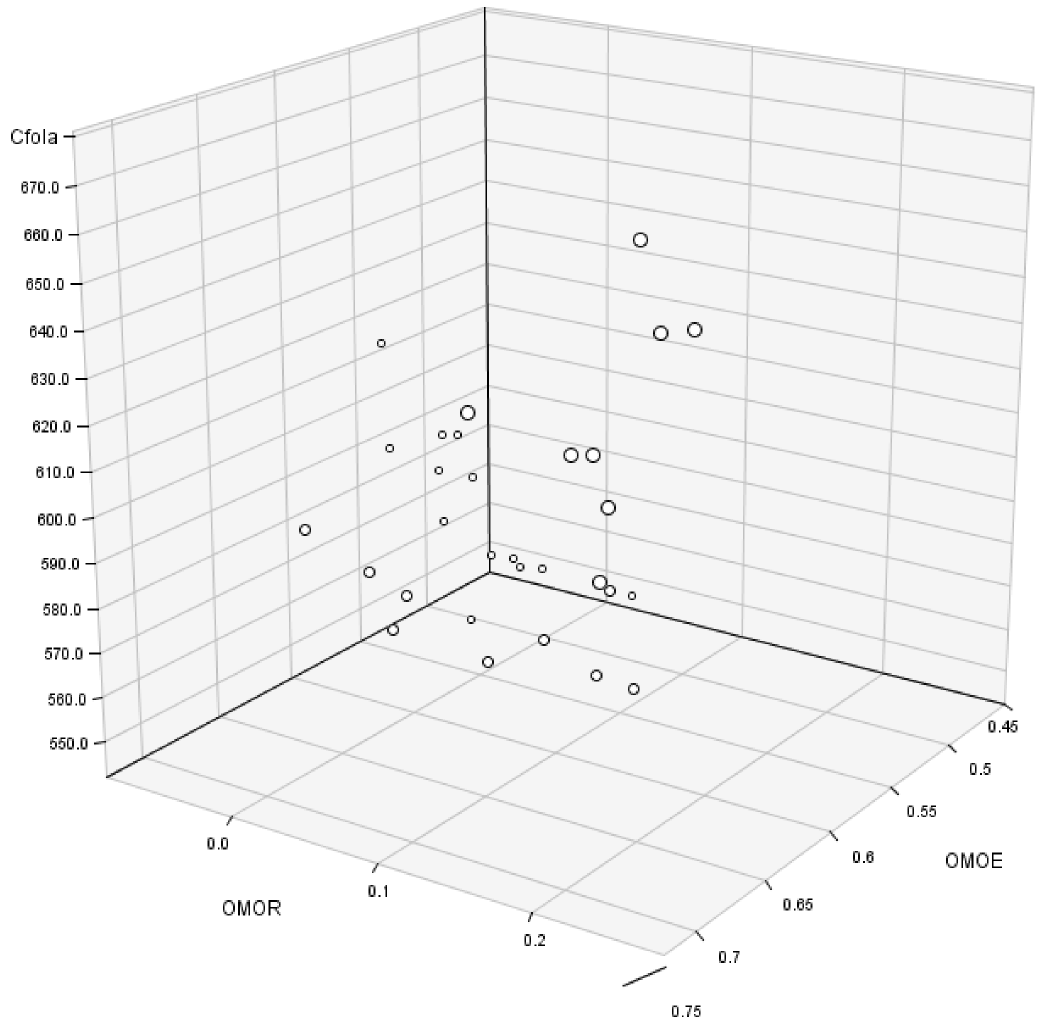

Figure 1 – SSC Non-Dominated Frontier

3 Concept of Operations Summary

The range of military operations that the large SSC is expected to perform include:

1. Support CSG/ESG for defense against mine threats, littoral ASW threats, small boat threats using distributed off-board systems and high speed and agility.
2. Support CSG/ESG with AAW defense through AAW sensors and weapons.
3. Support SAG's by operating within a force of networked, dispersed SSC's providing collective flexibility, versatility, and mutual support. SSC SAG's would provide defense against mine threats, littoral ASW threats, and small boat threats ahead of larger CSGs and ESGs. High Speed and agility should provide a tactical advantage.
4. Provide independent operations in known threat environments including defense against mine threats, littoral ASW threats, and small boat threats. The SSC could also provide ISR support ahead of CSG/ESG operations and maritime interdiction/interception operations.

SSC deployments could be extended with rotating crews, and this will result in longer periods between availabilities. In order to support the various capability gaps outlined in the ICD, the SSC will need to be equipped to handle interchangeable, networked mission modules. These modules could be changed in 2-3 days in theater.

The large SSC will be equipped with modular AAW capable sensors and weapons. These will be modular due to the extended operational timeframe considered (2016-2060). This extended time frame requires the flexibility to upgrade weapons and sensors over time. AAW capable sensor and weapons upgrades will require extended availability periods.

The range of military operations outlined above must be achieved with sufficient numbers of ships for worldwide and persistent coverage of all potential areas of conflict, vulnerability or interest.

Potential strengths of the large SSC are that it has the flexibility to satisfy a full range of specified capability gaps outlined in the ICD using interchangeable, networked modular mission modules. Most of these mission modules can be interchanged within 2-3 in theater, and this ability enables the SSC to provide a large range of military operations.

Potential limitations of a large SSC is that it not a true multi-mission ship. Individual SSCs carry a different module that enables it to perform specific missions, but it is not a large enough platform to enable it to fulfill all of the capability gaps outlined in the ICD at any given moment. The SSC has to have its mission modules swapped in theater or during an availability, and might not be capable meeting a given operational capability gap at any given time. Multiple SSCs with varying mission modules would be needed to support an ESG or CSG and provide the range of functions and capabilities outlined above. The SSC also does not have Ballistic Missile Defense (BMD) capability. Independent ballistic missile defense capability is an important operational capability outlined in the 2010 Quadrennial Defense Review (QDR), and the SSC is not a large enough platform to support large S-Band Radars.

Naval forces must also be able to support non-combatant and maritime interdiction operations in conjunction with national directives. They must be flexible enough to support peacetime missions yet be able to provide instant wartime response should a crisis escalate. The large SSC will provide an affordable solution that will meet many of the capability gaps outlined in the ICD.

4 Threat Summary

Because many unstable nations are located near geographically constrained bodies of water, the SSC must have the capability to engage an adversary in the littoral combat space. It must be small, fast, and agile enough to operate where large surface combatants cannot. The expected threats in a littoral environment include:

1. Technologically advanced weapons like the Silkworm and Exocet missiles, land-launched attack aircraft, small fast attack boats with guns and smaller missiles, and diesel-electric submarines.
2. Unsophisticated and inexpensive weapons like underwater mines (surface, moored, and bottom), and chemical and biological weapons.

The SSC will experience the following sea-based environments:

1. Open Water seaways (sea state 0 -8), and shallow water (littoral) maneuvering.

2. A degraded radar picture
3. Noise and reverberation
4. Crowded Shipping
5. Underwater explosions
6. Chemical, Biological, and Radiological (CBR) Environments
7. Dense contacts and threats with complicated targeting

5 System Capabilities and Characteristics Required for the Current Development Increment

Key Performance Parameter (KPP)	Development Threshold or Requirement
AAW	ICMS, MK XII AIMS IFF, COMBAT DF, 2X-MK 137 LCHRs, AIEWS ADVANCED SEW SYSTEM, AN/SPY-1E MFR, GLYCOL WATER COOLING SYSTEM FOR SPY
ASUW	IRST, AN/SPS-73, Small Arms Ammo, 2x50-cal MGs, Small Arms Locker, DORNA EO/IR Fire Control, 57 mm MK 3, 57mm stowage, 57mm ammo in gun mount(120), 57mm ammo magazie (880), 1x7m RHIB,
ASW	SQQ-89 Underwater Fire Control, AN/SLQ-25A (NIXIE) and AN/SLR-24I (TRIPWIRE), 2x Mk 32 SVTT on deck, NDS 3070 Vanguard mine sonar, SQS-56 sonar and dome
CCCC	CTSCE, Comms Suite Level A, Cooperative Engagement Capability
LAMPS	Dual SH-60 helo and hangar, fuel, support LAMPS (modules, RAST, Aviation Magz,
GMLS	2x MK41 VLS 16-cell W/3 Tomahawk + 10 SM-2 + 3 VLASROC, MK 41 control System, VLS armor, VLS magazine dewatering system
LCS Modules	1.5 times LCS mission package not including LAMPS
Hull	Steel, Flared Monohull
Power and Propulsion	2 shaft CODAG, 2xLM2500+ 2xCAT3616
SS Power	4 x CAT3508B
Endurance Range (nm)	4621 nm
Sustained Speed (knots)	32 knots
Endurance Speed (knots)	20 knots
Stores Duration (days)	70 days
Collective Protection System	Full
Crew Size	65
Length (m)	121.8 m
Beam (m)	15.1 m
Design Draft (m)	5 m
Full Load Delivery KG (m)	5.3
Full Load Delivery Displacement (MT)	5200 MT
Vulnerability (Hull Material)	Steel
Ballast/fuel system	Clean, separate ballast tanks
Degaussing System	Yes
McCreight Seakeeping Index	15.5

KG margin (m)	5.5 m
Propulsion power margin (design)	10%
Propulsion power margin (fouling and seastate)	25% (0.8 MCR)
Electrical margins	5%
Net Weight margin (design and service)	10%

6 Program Affordability

According to the ADM the average follow-ship acquisition cost shall not exceed $300 M ($FY2013) with an absolute constraint of $400 M. It is expected that 50 ships of this type will be built with IOC in 2016 with a required service life of 30 years.

Appendix D – Machinery Equipment List (MEL)

ITEM	QTY	NOMENCLATURE	DESCRIPTION	CAPACITY RATING	LOCATION	SWBS #	DIMENSIONS LxWxH (m)
System: Main Engines and Transmission							
1	2	Gas Turbine, Main	GE LM2500+ Marine Turbine	26MW	MMR	234	8.4x2.65x3.00
2	2	Diesel Engine, Secondary	CAT 3618	5MW	MMR		
3	2	Gear, Propulsion Reduction	Double Stage, 2.52:8.40:1 Gear Ratio (epicyclic)	50MW	MMR	241	3.79 x 5.10 x 5.41
4	1	Shaft, Line	400 mm (OD), 270 mm (ID)	-	various	243	22 m long
5	1	Shaft, Line	500 mm (OD), 335 mm (ID)	-	various	243	30 m long
6	1	Shaft, Line	750 mm (OD), 400 mm (ID)	-	various	243	4.32 m long
7	1	Shaft, Line	400 mm (OD), 270 mm (ID)	-	various	243	
8	1	Shaft, Line	500 mm (OD), 335 mm (ID)	-	various	243	
9	1	Shaft, Line	750 mm (OD), 400 mm (ID)	-	various	243	
10	2	Bearing, Line Shaft	Journal	575 mm Line Shaft	various	244	1 x .125 x .125
11	2	Unit, MGT Hydraulic Starting	HPU with Pumps and Reservior	14.8 m^3/hr @414 bar	MMR	556	2x2x2
12, 13	2	Main Engine Exhaust Duct	GE LM2500 Marine Turbine	79.4 kg/sec	MMR and up	234	mininum 5.8 m2 duct area and 16.8 trunk area
14, 15	2	Secondary Engine Exhaust Duct	CAT 3616	7.1 kg/sec	MMR and up	234	mininum .5 m2 duct area and 3.6 trunk area
16, 17	2	Main Engine Inlet Duct	GE LM2500 Marine Turbine	6.1 m/s	MMR and up	234	4.52m L x 2.65m W duct xsect, min. 14.1 trunk area
18, 19	2	Secondary Engine Inlet Duct	CAT 3616	6.1 m/s	MMR and up		1.4m L x .7m W duct xsect, min. 1.5 trunk area
20	1	Console, Main Control	Main Propulsion	NA	MMR Engineering Operation Station (EOS)	252	3x1x2

System: Power Generation and Distribution							
21	2	Diesel Generator, Ships Service	CAT 3516B	1491 kW	MMR	311	9.217 x 1.813 x 3.466
22	2	Diesel Generator, Ships Service	CAT 3516B	1491 kW	AMR	311	9.217 x 1.813 x 3.466
23, 24	2	SSGTG Exhaust Duct	CAT 3516B	16.9 kg/sec	MMR, AMR and up	311	1.1 m3
25, 26	2	SSGTG Inlet Duct	CAT 3516B	15 kg/sec	MMR, AMR and up	311	2.2 m3
27	1	Switchboard, Ships Service	Generator Control Power Distribution	-	MMR EOS	324	.5x2x2
28	1	Switchboard, Ships Service	Generator Control Power Distribution	-	AMR EOS	324	.5x1x2
29	6	MMR and AMR ladders	Inclined ladders		MMR,AMR		1.0x2.0
30	2	MMR and AMR escape trunks	Vertical ladders with fire tight doors at each level		MMR, AMR		1.5x1.5
31	2	MN Machinery Space Fan	Supply	94762 m^3/hr	FAN ROOM	512	1.118 (H)x 1.384 (dia)
32	2	MN Machinery Space Fan	Exhaust	91644 m^3/hr	MMR	512	1.118 (H)x 1.384 (dia)
33	2	Aux Machinery Space Fan	Supply	61164 m^3/hr	FAN ROOM	512	1.092 (H)x 1.118 (dia)
34	2	Aux Machinery Space Fan	Exhaust	61164 m^3/hr	AMR	512	1.092 (H)x 1.118 (dia)
System: Salt Water Cooling							
35	2	Pump, Main Seawater Circ	Centrifugal, Vertical, Motor Driven	230 m^3/hr @ 2 bar	MMR	256	.622 x .622 x 1.511

System: Lube Oil Service and Transfer							
36	2	Assembly, MGT Lube Oil Storage and Conditioning	Includes Oil Storage and Cooler	NA	MMR	262	1 x 1 x2
37	2	Strainer, Reduction Gear Lube Oil	Duplex	200 m^3/hr	MMR	262	0.5 x 0.5 x 1
38	2	Cooler, Reduction Gear Lube Oil	Plate Type	NA	MMR	262	1.5 x 1.5 x 1
39	2	Pump, Reduction Gear Lube Oil Service	Pos. Displacement, Horizontal, Motor Driven	200 m^3/hr @ 5 bar	MMR	262	1 x 0.5 x 0.5
40	2	Purifier, Lube Oil	Centrifugal, Self Cleaning, Partial Discharge Type	1.1 m^3/hr	MMR	264	.830 x .715 x 1.180
41	2	Pump, Lube Oil Transfer	Pos. Displacement, Horizontal, Motor Driven	4 m^3/hr @ 5 bar	MMR	264	.699 x .254 x .254
System: Fuel Oil Service and Transfer							
42	2	Filter Separator, MGT Fuel	2-Stage, Static, 5 Micron	30 m^3/hr	MMR	541	1.6 (L) x.762 (dia)
43	2	Purifier, Fuel Oil	Self Cleaning, Centrifugal, Partial Discharge Type	7.0 m^3/hr	MMR	541	1 x 1 x 1.5
44	2	Pump, Fuel Transfer	Gear, Motor Driven	45.4 m^3/hr @ 5.2 bar	MMR	541	1 x 0.5 x 0.5
	2	Fuel Oil Service Tanks			MMR		size for 4 hours at endurance speed
System: Air Conditioning and Refrigeration							
45	4	Air Conditioning Plants	150 Ton, Centrifugal Units	150 ton	AMR	514	2.353 x 1.5 x 1.5
46	4	Pump, Chilled Water	Centrifugal, Horizontal, Motor Driven	128 m^3/hr @4.1 bar	AMR	532	1.321 x .381 x .508
47	2	Refrig Plants, Ships Service	R-134a	4.3 ton	AMR	516	2.464 x .813 x 1.5
System: Salt Water: Firemain, Bilge, Ballast							
48	4	Pump, Fire	Centrifugal, Horizontal, Motor Driven	454 m^3/hr @ 9 bar	VARIOUS	521	2.490 x .711 x .864
49	1	Pump, Fire/Ballast	Centrifugal, Horizontal, Motor Driven	454 m^3/hr @ 9 bar	AMR	521	2.490 x .711 x .864
50	2	Pump, Bilge	Centrifugal, Horizontal, Motor Driven	227 m^3/hr @3.8 bar	MMR	529	1.651 x .635 x 1.702
51	1	Pump, Bilge/Ballast	Centrifugal, Horizontal, Motor Driven	227 m^3/hr @3.8 bar	AMR	529	1.651 x .635 x .737
52	2	Station, AFFF	Skid Mounted	227 m^3/hr @3.8 bar	above MMR	555	2.190 x 1.070 x 1.750

System: Potable Water							
53	2	Distiller, Fresh Water	Distilling Unit	76 m^3/day (3.2 m^3/hr)	AMR	531	2 x 3 x 2
54	2	Brominator	Proportioning	1.5 m^3/hr	AMR	531	0.3 x 0.2 x 0.4
55	2	Brominator	Recirculation	5.7 m^3/hr	AMR	533	0.3 x 0.2 x 0.4
56	2	Pump, Potable Water	Centrifugal, Horizontal, Motor Driven	22.7 m^3/hr @4.8 bar	AMR	533	0.5 x 0.5 x 0.3
System: JP-5 Service and Transfer							
57	2	Pump, JP-5 Transfer	Rotary, Motor Driven	11.5 m^3/hr @4.1 bar	JP-5 PUMP ROOM	542	1.194 x .483 x .508
58	2	Pump, JP-5 Service	Rotary, Motor Driven	22.7 m^3/hr @7.6 bar	JP-5 PUMP ROOM	542	1.194 x .483 x .508
59	1	Pump, JP-5 Stripping	Rotary, Motor Driven	5.7 m^3/hr @ 3.4 bar	JP-5 PUMP ROOM	542	.915 x .381 x .381
60	2	Filter/Separ., JP-5 Transfer	Static, Two Stage	17 m^3/hr	JP-5 PUMP ROOM	542	.457 (L) x 1.321 (dia)
61	2	Filter/Separ., JP-5 Service	Static, Two Stage	22.7 m^3/hr	JP-5 PUMP ROOM	542	.407 (L) x 1.219 (dia)
System: Compressed Air							
62	2	Receiver, Starting Air	Steel, Cylindrical	2.3 m^3	MMR	551	1.067 (dia) x 2.185 (H)
63	2	Compressor, MP Air	Reciprocating Motor Driven, Water Cooled	80 m^3/hr FADY @30 bar	MMR	551	1.334 x .841 x .836
64	1	Receiver, Ship Service Air	Steel, Cylindrical	1.7 m^3	MMR	551	1.830 (H) x .965 (dia)
65	1	Receiver, Control Air	Steel, Cylindrical	1 m^3	MMR	551	3.421 (H) x .610 (dia)
66	2	Compressor, Air, LP Ship Service	Reciprocating, Rotary Screw	8.6 bar @ 194 SCFM	MMR	551	1.346 x 1.067 x 1.829
67	2	Dryer, Air	Refrigerant Type	250 SCFM	MMR	551	.610 x .864 x 1.473
System: Steering Gear Hydaulics							
68	2	Hydraulic Pump and Motor	Steering Gear		aft Steering Gear Room	561	0.5x0.8x0.8
69	1	Hydraulic Steering Ram	Steering Gear		aft Steering Gear Room	561	1.2x8.5x1.5
System: Environmental							
70	2	Pump, Oily Waste Transfer	Motor Driven	12.3 m^3/hr @7.6 bar	MMR	593	1.219 x .635 x .813
71	2	Separator, Oil/Water	Coalescer Plate Type	2.7 m^3/hr	MMR	593	1.321 x .965 x 1.473
72	1	Unit, Sewage Collection	Vacuum Collection Type w/ Pumps	28 m^3	SEWAGE TREATMENT ROOM	593	2.642 x 1.854 x 1.575
73	1	Sewage Plant	Biological Type	225 people	SEWAGE TREATMENT ROOM	593	1.778 x 1.092 x 2.007

Appendix E - Weights and Centers

SWBS	COMPONENT	WT-MT	VCG-m	Moment	LCG-m	Moment
	FULL LOAD WEIGHT + MARGIN	5039.58	5.78	29145.50	75.43	380159.63
	MINOP WEIGHT AND MARGIN	4509.87	6.11	27541.78	76.83	346501.11
	LIGHTSHIP WEIGHT + MARGIN	4190.12	6.35	26600.27	78.30	328076.92
	LIGHTSHIP WEIGHT	3809.20	6.35	24182.06	78.30	298251.75
	MARGIN	380.92	6.35	2418.21	78.30	29825.17
100	HULL STRUCTURES	1695.10	5.98	10136.98	63.47	107593.69
	BARE HULL	0.00	0.00	0.00	0.00	0.00
110	SHELL + SUPPORTS	475.60	2.51	1193.76	57.56	27375.54
120	HULL STRUCTURAL BULKHDS	86.40	5.64	487.30	56.96	4921.34
130	HULL DECKS	321.50	7.89	2536.64	61.68	19830.12
140	HULL PLATFORMS/FLATS	2.10	3.60	7.56	65.93	138.45
150	DECK HOUSE STRUCTURE	237.00	14.64	3469.68	62.38	14784.06
160	SPECIAL STRUCTURES	170.70	4.24	723.77	82.03	14002.52
170	MASTS+KINGPOSTS+SERV PLATFORM	1.00	27.00	27.00	63.92	63.92
180	FOUNDATIONS	312.00	3.77	1176.24	66.80	20841.60
190	SPECIAL PURPOSE SYSTEMS	88.80	5.80	515.04	63.47	5636.14
200	PROPULSION PLANT	840.80	3.21	4025.60	77.05	112885.38
	BASIC MACHINERY	0.00	6.58	0.00	120.00	0.00
230	PROPULSION UNITS	140.10	4.32	605.23	64.00	8966.40
233	DIESEL ENGINES	81.30	4.53	368.29	64.00	5203.20
234	GAS TURBINES	58.80	4.02	236.38	64.00	3763.20
235	ELECTRIC PROPULSION			0.00		0.00
240	TRANSMISSION+PROPULSOR SYSTEMS	480.20	1.50	720.30	83.90	40288.78
241	REDUCTION GEARS	227.40	2.16	491.18	64.00	14553.60
242	CLUTCHES + COUPLINGS			0.00		0.00
243	SHAFTING	116.70	0.92	107.36	89.25	10415.48
244	SHAFT BEARINGS	44.80	1.26	56.45	86.69	3883.71
245	PROPULSORS	91.30	0.69	63.00	116.00	10590.80
250	SUPPORT SYSTEMS, UPTAKES	115.10	8.64	994.46	69.75	8028.23
260	PROPUL SUP SYS- FUEL, LUBE OIL	54.40	3.73	202.91	64.79	3524.58
290	SPECIAL PURPOSE SYSTEMS	51.00	3.53	180.03	71.91	3667.41
300	ELECTRIC PLANT, GENERAL	366.80	7.31	3279.19	64.78	23762.34
310	ELECTRIC POWER GENERATION	125.20	4.90	613.48	63.14	7905.13
	BASIC MACHINERY	0.00	9.32	0.00	105.00	0.00
311	SHIP SERVICE POWER GENERATION	92.20	3.58	330.08	40.00	3688.00
312	EMERGENCY GENERATORS			0.00		0.00
314	POWER CONVERSION EQUIPMENT	30.00	8.81	264.30	38.00	1140.00
320	POWER DISTRIBUTION SYS	145.40	9.31	1353.67	40.00	5816.00
330	LIGHTING SYSTEM	30.30	11.00	333.30	64.04	1940.41
340	POWER GENERATION SUPPORT SYS	42.30	6.78	286.79	40.00	1692.00
390	SPECIAL PURPOSE SYS	24.70	3.95	97.57	64.00	1580.80
400	COMMAND+SURVEILLANCE	168.00	8.02	1346.71	46.45	7803.34

	PAYLOAD	0.00	20.96	0.00	95.00	0.00
	CABLING	0.00	11.98	0.00	103.00	0.00
	MISC	0.00	11.98	0.00	105.00	0.00
410	COMMAND+CONTROL SYS	9.90	7.85	77.72	56.00	554.40
420	NAVIGATION SYS	8.50	22.54	191.59	49.73	422.71
430	INTERIOR COMMUNICATIONS	26.70	7.53	201.05	53.45	1427.12
440	EXTERIOR COMMUNICATIONS	23.10	7.85	181.34	60.88	1406.33
450	SURF SURVEILLANCE SYS (RADAR)	18.90	16.00	302.40	60.88	1150.63
460	UNDERWATER SURVEILLANCE SYSTEMS	19.50	-0.35	-6.83	8.00	156.00
470	COUNTERMEASURES	25.50	6.51	166.01	54.13	1380.32
480	FIRE CONTROL SYS	5.30	12.06	63.92	60.88	322.66
490	SPECIAL PURPOSE SYS	30.60	5.54	169.52	32.13	983.18
500	AUXILIARY SYSTEMS, GENERAL	600.60	7.74	4648.92	66.04	39661.97
	WAUX	0.00	10.65	0.00	100.00	0.00
	PAYLOAD	0.00		0.00		0.00
510	CLIMATE CONTROL	135.30	10.57	1430.12	66.97	9061.04
	CPS	0.00	17.00	0.00	100.00	0.00
520	SEA WATER SYSTEMS	81.40	6.12	498.17	66.97	5451.36
530	FRESH WATER SYSTEMS	40.10	7.41	297.14	66.97	2685.50
540	FUELS/LUBRICANTS,HANDLING+STORAGE	30.10	3.66	110.17	66.97	2015.80
550	AIR,GAS+MISC FLUID SYSTEM	82.30	7.88	648.52	66.97	5511.63
560	SHIP CNTL SYS	44.90	3.63	162.99	119.78	5378.12
570	UNDERWAY REPLENISHMENT SYSTEMS	40.20	6.38	256.48	66.97	2692.19
581	ANCHOR HANDLING+STOWAGE SYSTEMS	43.90	7.56	331.88	7.00	307.30
582	MOORING+TOWING SYSTEMS	12.60	9.11	114.79	66.97	843.82
583	BOATS,HANDLING+STOWAGE SYSTEMS	5.20	6.00	31.20	119.00	618.80
585	AIRCRAFT WEAPONS ELEVATORS	0.00	7.00	0.00	120.00	0.00
586	AIRCRAFT RECOVERY SUPPORT SYS	0.00	26.00	0.00	150.00	0.00
587	AIRCRAFT LAUNCH SUPPORT SYSTEM	0.00	19.00	0.00	60.00	0.00
588	AIRCRAFT HANDLING, SUPPORT	32.40	13.00	421.20	82.00	2656.80
589		0.00	17.00	0.00	100.00	0.00
593	ENVIRONMENTAL POLLUTION CNTL SYS	9.90	3.70	36.63	66.97	663.00
598	AUX SYSTEMS OPERATING FLUIDS	42.30	7.32	309.64	42.00	1776.60
600	OUTFIT+FURNISHING,GENERAL	33.20	2.71	90.04	75.24	2498.02
610	SHIP FITTINGS	11.80	0.92	10.86	75.68	893.02
640	LIVING SPACES	21.40	3.70	79.18	75.00	1605.00
700	ARMAMENT	104.70	6.25	654.63	38.65	4047.01
710	GUNS+AMMUNITION	9.50	11.35	107.83	60.88	578.36
720	MISSLES+ROCKETS	84.70	5.39	456.53	34.00	2879.80
750	TORPEDOES	2.70	12.00	32.40	60.88	164.38
760	SMALL ARMS+PYROTECHNICS	7.80	7.42	57.88	54.42	424.48
	FULL LOAD CONDITION					
F00	LOADS	849.46	3.00	2545.24	61.31	52082.71
F10	SHIPS FORCE	9.10	6.81	61.97	57.23	520.79
F20*	MISSION RELATED EXPENDABLES	175.50	7.28	1277.64	60.88	10684.44
F21	SHIP AMMUNITION	11.30	7.87	88.93	50.00	565.00
F22	ORD DEL SYS AMMO	11.20	3.35	37.52	60.88	681.86

F23	ORD DEL SYS (AIRCRAFT)	19.00	12.35	234.65	68.00	1292.00
F26	ORD DEL SYS SUPPORT EQUIP	20.60	12.35	254.41	60.88	1254.13
F31	PROVISIONS+PERSONNEL STORES	16.50	4.98	82.17	65.75	1084.88
F32	GENERAL STORES	3.20	5.64	18.05	65.75	210.40
F41	DIESEL FUEL MARINE	497.78	0.75	373.34	58.00	28871.24
F42	JP-5	55.00	1.00	55.00	89.00	4895.00
F46	LUBRICATING OIL	17.88	2.16	38.62	67.37	1204.58
F51	SEA WATER			0.00		0.00
F52	FRESH WATER	12.40	1.85	22.94	66.00	818.40
	MINIMUM OPERATING CONDITION					
F00	LOADS	319.75	2.94	941.51	57.62	18424.19
F10	SHIPS FORCE	9.10	6.81	61.97	57.23	520.79
F20*	MISSION RELATED EXPENDABLES	58.50	6.81	398.39	60.88	3561.48
F21	SHIP AMMUNITION	3.77	7.87	29.64	50.00	188.33
F22	ORD DEL SYS AMMO	3.73	3.35	12.51	60.88	227.29
F23	ORD DEL SYS (AIRCRAFT)	19.00	12.35	234.65	68.00	1292.00
F26	ORD DEL SYS SUPPORT EQUIP	20.60	12.35		60.88	
F31	PROVISIONS+PERSONNEL STORES	5.50	4.98	27.39	65.75	361.63
F32	GENERAL STORES	1.07	5.64	6.02	65.75	70.13
F41	DIESEL FUEL MARINE	165.93	0.75	124.45	58.00	9623.75
F42	JP-5	18.33	1.00	18.33	89.00	1631.67
F46	LUBRICATING OIL	5.96	2.16	12.87	67.37	401.53
F47	SEA WATER	0.00		0.00		0.00
F52	FRESH WATER	8.27	1.85	15.29	66.00	545.60

Appendix F – SSCS Space Summary

SSCS	GROUP	(asset) VOLUME (m3)	(actual) VOLUME (m3)	(asset) AREA (m2)	(actual) AREA (m2)	Typical Associated Spaces
	TOTAL AVAILABLE		711		6714.676	
	TOTAL REQUIRED	1148		3623		
1	MISSION SUPPORT	72.4	46	369.1	1510.219	
1.1	COMMAND,COMMUNICATION+SURV	0	0	117.7	586.5796	
1.11	EXTERIOR COMMUNICATIONS	0	0	5.9	43.7	
1.111	RADIO				43.7	Communications
1.113	VISUAL COM			5.9	0	Signal Bridge
1.12	SURVEILLANCE SYS	0	0	23.3	95.2975	
1.121	SURFACE SURV (RADAR)				57.34	Electronics Spaces, Radar and Radar Cooling Rooms
1.122	UNDERWATER SURV (SONAR)			23.3	37.9575	Sonar Rooms (2 or 3), TACTASS Winch Room
1.13	COMMAND+CONTROL	0	0	46.7	89.49	
1.131	COMBAT INFO CENTER				89.49	CIC
1.132	CONNING STATIONS	0	0	46.7	0	bridgewings or aft of deckhouse
1.1321	PILOT HOUSE			39.7	43.64	Pilot House
1.1322	CHART ROOM			7	16.16	Chart Room
1.14	COUNTERMEASURES	0	0	0	294.71	
1.141	ELECTRONIC				289.22	deck sensors
1.142	TORPEDO				5.49	Nixie Winch Room
1.143	MISSILE				0	deck launchers
1.15	INTERIOR COMMUNICATIONS			41.8	51.9	IC Room
1.16	ENVIORNMENTAL CNTL SUP SYS				11.4821	Environmental Protection Equipment Room, Environmental Waste Stowage, Sewage Treatment Room, Collection Holding and Transfer (CHT) Room and Tank
1.2	WEAPONS	0	0	0	340.286	
1.21	GUNS	0	0	0	89.9	
1.214	AMMUNITION STOWAGE				89.9	Gun Magazines
1.22	MISSILES				183.386	Vertical Missile Launchers (VLS)

1.24	TORPEDOS				67	Torpedo Stowage and Launchers
1.26	MINES				0	Special Weapons Magazines
1.3	AVIATION	72.4	46	243.8	390.5411	
1.32	AVIATION CONTROL	0	0	20.4	66.829	
1.321	FLIGHT CONTROL			9.3	41.769	Flight Control Station
1.322	NAVIGATION			11.1	12.53	Aviation Planning Rm
1.323	OPERATIONS				12.53	Aviation Ready Room
1.33	AVIATION HANDLING				22.34	RAST Winch Room, Hangar stowage area
1.34	AIRCRAFT STOWAGE	0	0	176	185.234	
1.342	HELICOPTER HANGAR			176	185.234	Hangar
1.35	AVIATION ADMINISTRATION	0	0	8.4	16.5681	
1.353	AVIATION OFFICE			8.4	16.5681	Aviation Office
1.36	AVIATION MAINTENANCE			17.6	0	Aviation Shops
1.37	AIRCRAFT ORDINANCE	0	0	0	17.54	
1.374	STOWAGE				17.54	Aircraft ordinance Magazine(s)
1.38	AVIATION FUEL SYS	72.4	46	0	69.5	
1.381	JP-5 SYSTEM			0	69.5	JP-5 Pumprooms
1.3813	AVIATION FUEL	72.4	46		0	JP-5 Tanks
1.39	AVIATION STORES			21.4	12.53	
1.8	SPECIAL MISSIONS				171.46	Modular System Stowage Spaces
1.9	SM ARMS,PYRO+SALU BAT			7.6	21.352	Small Arms Locker
2	HUMAN SUPPORT	0	0	945.7	1834.473	
2.1	LIVING	0	0	695.8	1366.353	
2.11	OFFICER LIVING	0	0	532.8	916.8552	
2.111	BERTHING	0	0	485.2	777.5992	
2.1111	SHIP OFFICER			242.6	388.7996	
2.11111	COMMANDING OFFICER STATEROOM			20	36.19	CO Stateroom, CO At-Sea Cabin
2.11112	EXECUTIVE OFFICER STATEROOM			16.3	35.16	XO Stateroom
2.11112	DEPARTMENT HEAD STATEROOM			88.8	146.8896	Department Head Staterooms (singles)
2.11113	OFFICER STATEROOM (DBL)			117.5	170.56	Officer Staterooms (mostly doubles, 1 or 2 4-person OK)
2.1114	AVIATION OFFICER				0	
2.112	SANITARY	0	0	47.6	139.256	
2.1121	SHIP OFFICER			23.8	69.628	
2.11211	COMMANDING OFFICER BATH			4.6	8.937	CO WR, WC & SH, At-Sea WC
2.11212	EXECUTIVE OFFICER BATH			2.8	9.071	XO WR, WC & SH
2.11213	OFFICER			16.4	51.62	Officer WCs, WR & SH
2.1124	AVIATION OFFICER				0	
2.12	CPO LIVING	0	0	79.3	142.2008	
2.121	BERTHING			61.3	112.41	CPO Berthing
2.122	SANITARY			18	29.7908	CPO WC
2.13	CREW LIVING	0	0	73.8	252.23	
2.131	BERTHING			61.6	192.1	Crew Berthing
2.132	SANITARY			12.2	44.18	Crew WCs

2.133	RECREATION				15.95	Crew Recreation
2.14	GENERAL SANITARY FACILITIES	0	0	2.3	11.59	
2.142	BRIDGE WASHRM & WC			2.3	11.59	Bridge WC
2.15	SHIP RECREATION FAC			4.3	15.95	Crew Recreation Room
2.16	TRAINING			3.3	27.5268	Crew Training
2.2	COMMISSARY	0	0	194.1	350.4896	
2.21	FOOD SERVICE	0	0	117.1	207.57	
2.211	WARDROOM MESSRM & LOUNGE			51.1	74.97	Wardroom Mess
2.212	CPO MESSROOM AND LOUNGE			51.1	44.28	CPO Mess and Lounge
2.213	CREW MESSROOM			14.9	88.32	Crew Mess
2.22	COMMISSARY SERVICE SPACES	0	0	41.6	67.5442	
2.222	GALLEY	0	0	24.9	51.1238	
2.2222	WARD ROOM GALLEY			9.8	20.087	WR Galley
2.2224	CREW GALLEY			15.1	31.0368	Crew Gally
2.223	WARDROOM PANTRY			7.4	9.32	WR Pantry
2.224	SCULLERY			9.3	7.1004	Scullery
2.23	FOOD STORAGE+ISSUE	0	0	35.4	75.3754	
2.231	CHILL PROVISIONS			11.6	24.99	Chill Box
2.232	FROZEN PROVISIONS			7.6	24.7754	Freeze Box
2.233	DRY PROVISIONS			16.2	25.61	Dry Provision SR
2.3	MEDICAL+DENTAL			1.4	21.3331	Sick Bay
2.4	GENERAL SERVICES	0	0	19	22.678	
2.41	SHIP STORE FACILITIES			6.9	0	Ship Store
2.42	LAUNDRY FACILITIES			12.1	22.678	Laundry
2.44	BARBER SERVICE				0	Barber Shop
2.46	POSTAL SERVICE				0	Ship Post office
2.47	BRIG				0	Brig
2.5	PERSONNEL STORES	0	0	7.3	22.5	
2.51	BAGGAGE STOREROOMS			6.7	0	Officer baggage storeroom
2.55	FOUL WEATHER GEAR			0.6	22.5	Bosn Stores, Foul Weather Gear Locker
2.6	CBR PROTECTION	0	0	26.2	40.1792	
2.61	CBR DECON STATIONS				17.262	Decon Stations
2.62	CBR DEFENSE EQUIPMENT			10.7	13.19	CBR stowage
2.63	CPS AIRLOCKS			15.5	9.7272	Airlocks
2.7	LIFESAVING EQUIPMENT			1.9	10.94	life jacket stowage
3	SHIP SUPPORT	1076	665	1472	1235.01	
3.1	SHIP CNTL SYS (STEERING)	0	0	59.1	47.71	
3.11	STEERING GEAR			59.1	47.71	After Steering
3.12	ROLL STABILIZATION				0	
3.15	STEERING CONTROL				0	
3.2	DAMAGE CONTROL	0	0	60.3	95.7364	
3.21	DAMAGE CNTRL CENTRAL				15.6284	DC Central
3.22	REPAIR STATIONS			37.3	61.0157	Repair Lockers
3.25	FIRE FIGHTING			23	19.0923	Fire Fighting Stations
3.3	SHIP ADMINISTRATION	0	0	37.5	105.5238	
3.301	GENERAL SHIP			4.5	16.2529	Ship's Office
3.302	EXECUTIVE DEPT			10.3	16.86	Ship's Office
3.303	ENGINEERING DEPT			6.3	13.9569	Engineering Office

3.304	SUPPLY DEPT			5.2	15.584	Supply Office
3.305	DECK DEPT			2.7	14.11	Deck Department Office
3.306	OPERATIONS DEPT			8.5	16.86	Operations Department Office
3.307	WEAPONS DEPT				11.9	Weapons Department Office
3.5	DECK AUXILIARIES	0	0	53.1	108.277	
3.51	ANCHOR HANDLING			31.4	60.56	Anchor Windlass Room and Chain Lockers
3.52	LINE HANDLING				0	Line Handling Stations / Capstans
3.53	TRANSFER-AT-SEA			21.7	0	Unrep Stations
3.54	SHIP BOATS STOWAGE				47.717	Boat davits or boat ramp aft
3.6	SHIP MAINTENANCE	0	0	88.1	100.8	
3.61	ENGINEERING DEPT	0	0	65.2	60.48	
3.611	AUX (FILTER CLEANING)			9.8	20.16	Filter Cleaning Shop
3.612	ELECTRICAL			23	20.16	Electrical Shop
3.613	MECH (GENERAL WK SHOP)			32.4	20.16	Work Shop
3.62	OPERATIONS DEPT (ELECT SHOP)			17.5	20.16	Electronics Repair Shop
3.63	WEAPONS DEPT (ORDINANCE SHOP)			5.4	20.16	Ordnance Shop
3.64	DECK DEPT (CARPENTER SHOP)				0	Carpenter Shop
3.7	STOWAGE	0	0	265.6	127.4724	
3.71	SUPPLY DEPT	0	0	183.4	93.9604	
3.711	HAZARDOUS MATL (FLAM LIQ)			24	0	Flamable Liquid/Paint Storeroom
3.713	GEN USE CONSUM+REPAIR PART			153.3	46.5778	General Storerooms
3.714	SHIP STORE STORES			6.1	47.3826	General Storerooms
3.72	ENGINEERING DEPT			5	0	Engineering Storage
3.73	OPERATIONS DEPT			7	0	Operations Storage
3.74	BOATSWAIN STORES			62.3	3.728	
3.75	WEAPONS DEPT			4.5	29.784	Weapons Dept Stowage
3.78	CLEANING GEAR STOWAGE			3.4	0	Cleaning Gear Lockers
3.8	ACCESS	0	0	902.1	602	
3.82	INTERIOR	0	0	902.1	602	
3.821	NORMAL ACCESS			891.4	600	Passageways
3.822	ESCAPE ACCESS			10.7	2	Escape trunks
3.9	TANKS	1076	665	6.4	47.49	
3.91	SHIP PROP SYS TNKG	844.2	574	0	0	
3.9111	ENDUR FUEL TANK (INCL SERVICE)	844.2	574			DFM Tanks and Service Tanks
3.914	FEEDWATER TNKG					Feedwater Tanks
3.92	BALLAST TNKG	56	55			Ballast Tanks, Peak Tank
3.93	FRESH WATER TNKG	12.7	8			Fresh Water Tanks
3.94	POLLUTION CNTRL TNKG	28	28	6.4	47.49	
3.941	SEWAGE TANKS			1.6	20.56	Sewage/Holding Tanks
3.942	OILY WASTE TANKS	28	28	4.8	26.93	Oily Waste Tanks

3.95	VOIDS	134.9				Voids
4	SHIP MACHINERY SYSTEM	0	0	836.4	2134.975	
4.1	PROPULSION SYSTEM			543.3	814.4	MMRs, Motor Rooms
4.142	COMBUSTION AIR (INTAKE)			28.6		Intakes
4.143	EXHAUST			68.9		Exhaust
4.2	PROPULSOR & TRANSMISSION SYST	0	0	0	0	
4.23	WATERJET ROOMS				0	WJ Rooms
4.23001	PROP SHAFT ALLEY				0	Shaft Alleys
4.3	AUX MACHINERY	0	0	293.1	1320.575	AMRs and MMRs
4.33	ELECTRICAL	0	0	75	1269.17	
4.331	POWER GENERATION			70.5	1258	AMRs and MMRs
4.334	DEGAUSSING			4.5	11.1695	Degaussing Room
4.34	POLLUTION CONTROL SYSTEMS			5.7	12.3375	Environmental Protection Equipment Room, Environmental Waste Stowage, Sewage Treatment Room, Collection Holding and Transfer (CHT) Room and Tank
4.36	VENTILATION SYSTEMS			212.4	39.0684	Fan Rooms (8-12+)

Appendix G – Power and Propulsion Analysis

$knt \equiv 1.69 \cdot \frac{ft}{sec}$ $mile \equiv knt \cdot hr$ $lton \equiv 2240 \cdot lbf$ $nm := knt \cdot hr$ $MT := g \cdot 1000 \cdot kg$ $\delta_F := 43.6 \cdot \frac{ft^3}{lton}$

From NAVCAD at endurance speed:

$V_e := 20 \cdot knt$ $N_E := 2$ $BHP_{SPGM} := 13494.7 \cdot hp$ $BHP_{eSPGM} := 11436.8 \cdot hp$ $GPH_{eENG} := 295.6 \cdot \frac{gal}{hr}$

From SSSM at cruise condition:

$N_G := 2$ $KW_g := 1321.29 \cdot kW$ $KW_{gtot} := N_G \cdot KW_g$

$KW_{24AVG} := 1629.8 \cdot kW$ $SFC_g := .3382 \cdot \frac{lbf}{hp \cdot hr}$ $V_{F41} := 574 \cdot m^3$

Conversion of units:

$GPH_e := N_E \cdot GPH_{eENG}$ $GPH_e = 79.032 \cdot \frac{ft^3}{hr}$ $SFC_{eSPGM} := \frac{GPH_e}{\delta_F \cdot BHP_{eSPGM}}$ $SFC_{eSPGM} = 0.355 \cdot \frac{lbf}{hp \cdot hr}$

Calculate the endurance range for the specified fuel tank volume - for Propulsion:

Correction for instrumentation inaccuracy and machinery design changes:

$$f_1 := \begin{cases} 1.04 & \text{if } BHP_{eSPGM} \le \frac{1}{3} \cdot BHP_{SPGM} \\ 1.02 & \text{if } BHP_{eSPGM} \ge \frac{2}{3} \cdot BHP_{SPGM} \\ 1.03 & \text{otherwise} \end{cases} \qquad f_1 = 1.02$$

$$\begin{cases} 1.02 & \text{if } KW_{24AVG} \ge \frac{2}{3} \cdot KW_{gtot} \\ 1.03 & \text{otherwise} \end{cases}$$

Specified fuel rate: $FR_{SPg} := f_{g1} \cdot SFC_g$ $FR_{SPg} = 0.348 \cdot \frac{lbf}{hp \cdot hr}$

Average fuel rate allowing for plant deterioration over 2 years:

$FR_{AVGg} := 1.05 \cdot FR_{SPg}$ $FR_{AVGg} = 0.366 \cdot \frac{lbf}{hp \cdot hr}$