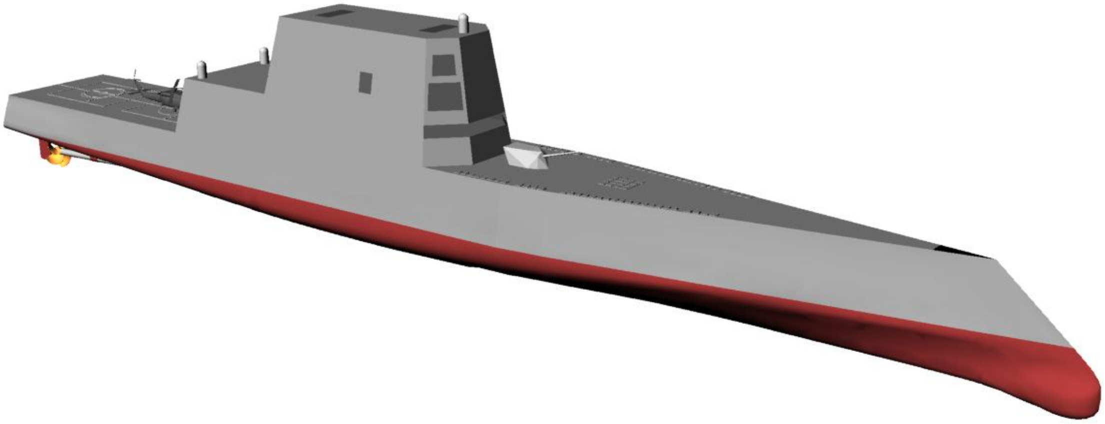
Design Report

Medium Surface Combatant (MSC)

VT Total Ship Systems Engineering



MSC Variant 130 I
Ocean Engineering Design Project
AOE 4065/4066
Fall 2009 – Spring 2010
Virginia Tech Team 1

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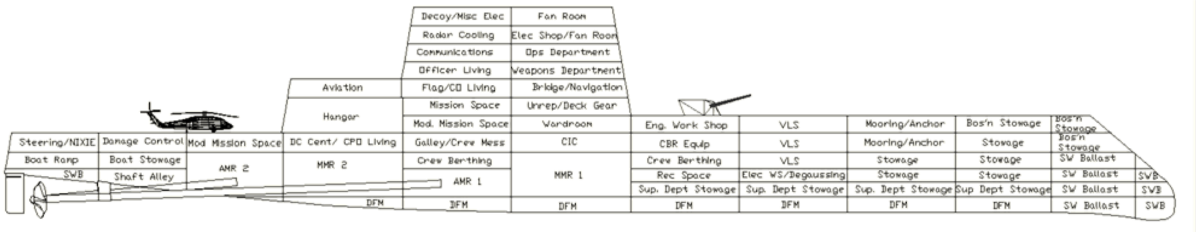
Executive Summary



This report describes the Concept Exploration and Development of medium surface combatant (MSC) for the United States Navy. This concept design was completed in a two-semester ship design course at Virginia Tech.

The MSC requirement is based on the Navy's requirement for an agile and flexible ship that is able to handle many missions in one hull form. The MSC requirement dictates that the ship has reduced manning but combines the capabilities of several different types of ships. This ship will be large enough for independent operations yet still capable of stationkeeping with a fleet. In a word the ship must be versatile.

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 MSC is a somewhat risky alternative that was selected after the MOGO, however it is also at the high end of effectiveness. The risk stems largely from the wave piercing tumblehome hullform and its departure from the normal conventions of ship design. However this hullform offers significant stealth advantages by reducing radar cross section due to the angled hull. This ship offers powerful radars and an effective combat system for area air or ballistic missile defense, as well as a heavy gun for naval surface fire support. The MSC also offers plenty of modular mission space to give it the flexibility to perform a whole host of different missions.

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 with additional work required to ensure that the stability of a wave piercing tumblehome hull is adequately approximated by a linear seakeeping program. Further iterations of this design will also determine the tradeoffs for exchanging various components of the combat system, and whether the suite of combat systems currently embarked is adequate, overstated, or lacking.

Ship Characteristic	Value
LWL	192.3 m
Beam	23.06 m
Draft	7.21 m
D10	16.13 m
Lightship weight	MT
Full load weight	18,298 MT
Sustained Speed	33 knots
Endurance Speed	20 knots
Endurance Range	8420 nm
Propulsion and Power	IPS 4 x RR MT 30 (36MW ea) PMM 2 x 5 Bladed B-series Props
BHP	144,000kW
Personnel	112
OMOE (Effectiveness)	0.7795
OMOR (Risk)	0.5489
Ship Acquisition Cost	$2,387M
Life-Cycle Cost	$26,830M
Combat Systems (Modular and Core)	64 MK 57 PVLS 4x4 Modular VLS MK 45 5" Gun 3 x CIWS 2 x LAMPS 2 x 7 m RHIBs VSR++ SPY-3 Radar BMD 2014

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1 Introduction, Design Process and Plan

1.1 Introduction

This report describes the concept exploration and development of an Medium Surface Combatant (MSC) for the United States Navy. The MSC requirement is based on the MSC Initial Capabilities Document (ICD), and Virginia Tech MSC Acquisition Decision Memorandum (ADM), Appendix A and Appendix B. This concept design was completed in a two-semester ship design course at Virginia Tech. The MSC must perform the following:

- Provide flexible BMD, NSFS, strike, and mulit-mission capability through modularity with different configurations of similar platforms. Full capabilities may be provided in the coordinated force, in support of a larger force, or individually with combinations of inherent multi-mission capabilities and tailored modular capabilities
- Must be capable of performing unobtrusive peacetime presence missions in an area of hostility, and immediately respond to escalating crisis and regional conflict.
- Operate in forward locations in international waters, and readily move to new maritime locations as needed
- Will be among the first naval forces present in a region and will arrive with several smaller Littoral Combat Ships and MSC's and possibly a CSG or ESG.

1.2 Design Philosophy, Process, and Plan

The design process will initially start with a broad range of possibilities outlined in the initial capabilities document (ICD) in the concept exploration phase. Once these options have been investigated and mission alternatives have been studied, the decision process will narrow the design space, requirements, and constraints of the mission, and a more detailed development and analysis of systems and subsystems will be performed. This process is illustrated in Figure 1.

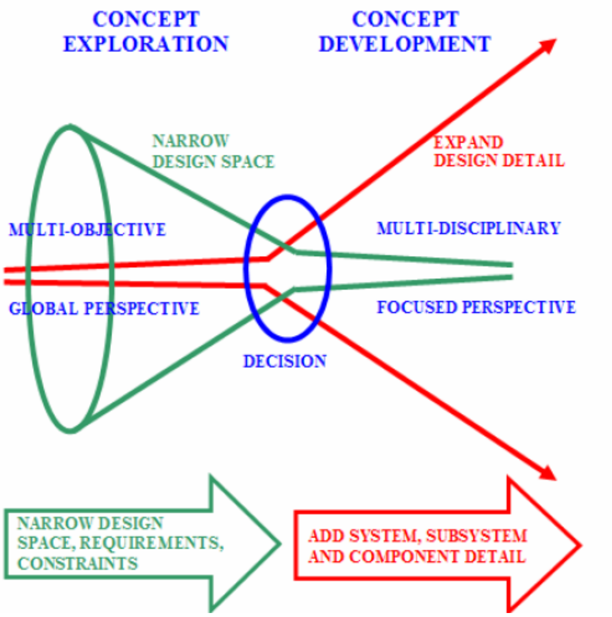


Figure 1: Design Philosophy

Figure 2 illustrates the concept exploration phase which focuses on searching the design space. The mission details are characterized by the Initial Capabilities Document (ICD) and Acquisition Decision Memorandum (AMD). From these documents, the Required Operational Capabilities (ROC's) and Measures of Performance (MOP's) are developed. A synthesis model is used to balance and assess the design alternatives. It is used to analyze the trade-offs associated with each design. An Overall Measure of Effectiveness (OMOE), Overall

Measure of Risk (OMOE), and total ownership cost are used as objective attributes in a multi-objective genetic optimization (MOGO). The synthesis models to allow them to analyze the countless alternatives more efficiently. From this process, several design alternatives are selected for continued development and investigation. The ship acquisition decision, specified in a Capability Development Document establishes the ship concept baseline design, and identifies the selected technologies.

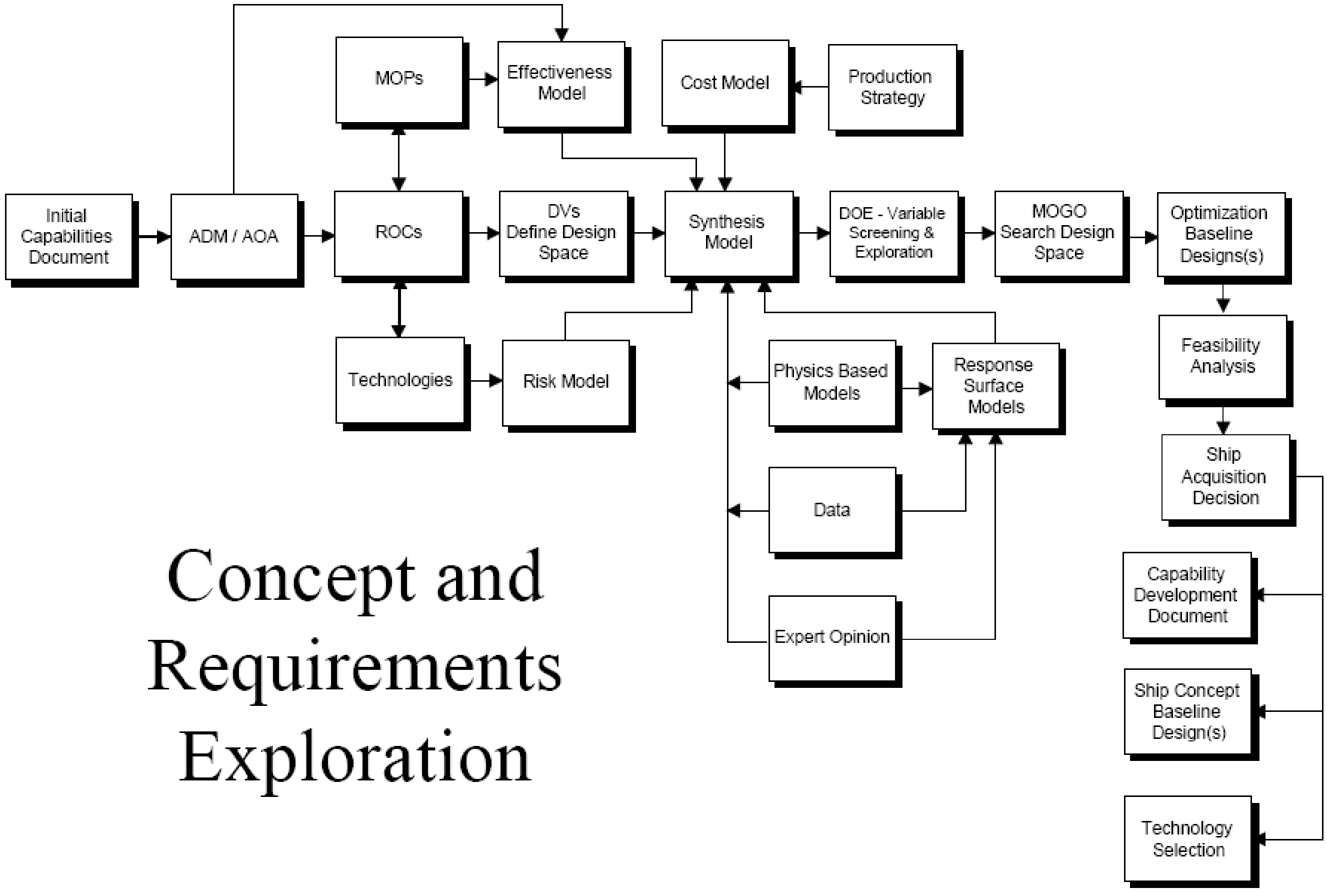


Figure 2 - Concept and requirements exploration process(Brown 2009)

Figure 3 represents the design spiral for concept development for the MSC. This recurring process demonstrates a cyclical method of progress for the design. A single iteration will be performed in this project due to time constraints.

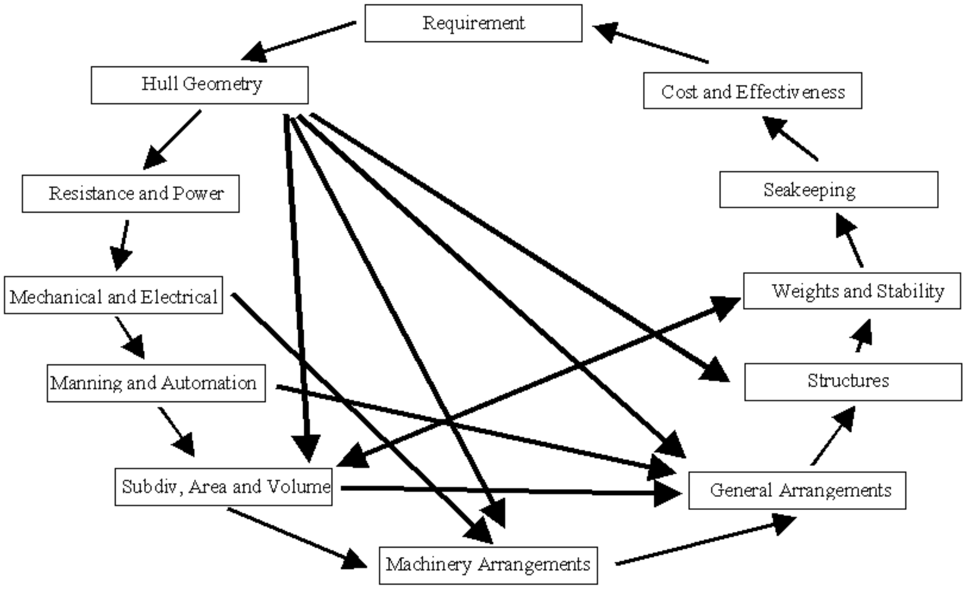


Figure 3 - VT Concept Development Design Spiral (Brown 2009)

1.3 Work Breakdown

MSC Team 1 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. This allows the students to concentrate on a particular area of the design process.

Table 1 - Work Breakdown

Name	Specialization
Eric Schmid	Feasibility, Cost, Risk, Seakeeping
Mathew Newborn	Writer, Effectiveness
Conner Sherin	General Arrangements, Machinery Arrangements
Steven Wright	Hull Form, Structures, Combat Systems
Mark Pelo	Weights and Stability, Subdivision
Kevin Byers	Propulsion and Resistance, Electrical, Manning and Automation

1.4 Resources

Computational and modeling tools used in this project are listed in Table 2. The software programs listed below are used to quantify and create the concept design model of the ship. ASSET is used in concept exploration for feasibility studies. Rhino and HECSALV will be important in defining the general arrangements of the ship subsystems and performing hydrostatic calculations. The ship structural analysis will be performed by MAESTRO.

Table 2 - Tools

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

2 Mission Definition

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

2.1 Concept of Operations

The concept of operations is based on the initial capabilities document (ICD) and the acquisition decision memorandum (ADM). It describes what the ship will do. The MSC is expected to perform the following:

- Provide flexible BMD, NSFS, strike, and mulit-mission capability through modularity with different configurations of similar platforms. Full capabilities may be provided in the coordinated force, in support of a larger force, or individually with combinations of inherent multi-mission capabilities and tailored modular capabilities
- It must be capable of performing unobtrusive peacetime presence missions in an area of hostility, and immediately respond to escalating crisis and regional conflict.
- Operate in forward locations in international waters, and readily move to new maritime locations as needed
- Will be among the first naval forces present in a region and will arrive with several smaller Littoral Combat Ships and MSC's and possibly a CSG or ESG

2.2 Projected Operational Environment (POE) and Threat

The threat summary is an ongoing assessment of the threat in various areas around the world. It addresses specific time frames, weapons systems, and other specific situations that could potentially affect the military effectiveness of a naval ship. The following threats and environment are expected for MSC:

- Open water threats including land based air assets, surface vessels, chemical/biological weapons, anti-ship missiles
- Major threats including long and short range ballistic missiles and other long range weapons
- Countries that support, promote, and perpetrate activities that cause regional instabilities detrimental to international security.
- Degraded radar picture

Often the threat and projected operational environment are summarized together. The POE specifies the environments in which a particular ship will operate, and the requirements it needs to operate in these locations.

- Fully operational in sea states 1-5; Survivable to sea state 9
- Defend fleet in aggressive defense in large range of international waters
- Littoral
- Hostile environments
- Shallow often crowded waters.

2.3 Specific Operations and Missions

Mission types define a particular ship's role in the fleet. Some ships may have multiple purposes, depending on the situation. Potential mission types for MSC are listed below.

- Surface Action Group (SAG) Command/ Strike/ISR
- Ballistic Missile Defense/ Independent Ops
- Carrier Strike Group (CSG)
- Expeditionary Strike Group (ESG)

2.4 Mission Scenarios

Mission scenarios for the primary MSC mission types are provided in Table 3 through Table 5. Modularity will be employed to modify ship configurations to best counter specific anticipations.

Table 3: Carrier Battle Group (CGB) Mission

Day	Mission scenario
1-14	Leave homeport, rendezvous with Carrier Battle Group
14-40	ISR/ Escort CSG
34	Engage Anti-Ship Ballistic Missile threat against carrier
37	Launch cruise missiles at land target
50-55	Port call for repairs and replenishment
57	Rejoin CBG
62-85	ISR/ Escort CBG
75	SAR of crew from damaged aircraft
76	Engage Submarine (ASW) w/ lamps
79	Depart CBG
80	Return transit to home port
90+	Port call/ Restricted availability

Table 4: Surface Action Group Scenario

Day	Mission scenario
1-3	Transit with Other MSC's to area of hostility from forward base
5-10	Patrol grid looking for launch of ballistic missile
11	Receive tasking for TLAM strike
12	Cruise to 25 nm offshore
27-29	Cruise to new grid
30	Sustain damage (radar down) due to SS9
31-44	Cruise back to port for repairs
32	Engage ASW
45-60	Repairs
61-68	Transit back to area of hostility
69	Detect ICBM launch against homeland; engage and kill with KEI
70-71	Cruise to station, 35 nm offshore
72-73	Conduct recon with AAV
75-77	Back to forward base

Table 5: Expeditionary Strike Group Scenario

Day	Mission scenario
1-20	Transit with other MSC's to area of hostility from forward base
4	Detect, engage and kill incoming anti-sip missile attack
5-10	Patrol grid looking for launch of ballistic missile
11	Receive tasking for TLAM strike
12	Cruise to 25 nm offshore
15-25	Patrol grid for launch of BM
26	Detect IRBM attack against ally, engage and destroy with SM-3
27-29	Cruise to new grid
30	Sustain damage (radar down) due to SS9
31-44	Cruise back to port for repairs
32	Engage ASW

2.5 Required Operational Capabilities

In order to support the missions and mission scenarios described in Section 2.4, the capabilities listed in Table 6 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 6: 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
AAW 10	Provide Area BMD
AAW 11	Support ICBMD
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

ROCs	Description
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	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 16	Provide routine and emergency dental care

ROCs	Description
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 1	Conduct underway replenishment
LOG 2	Transfer/receive cargo and personnel
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
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 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.

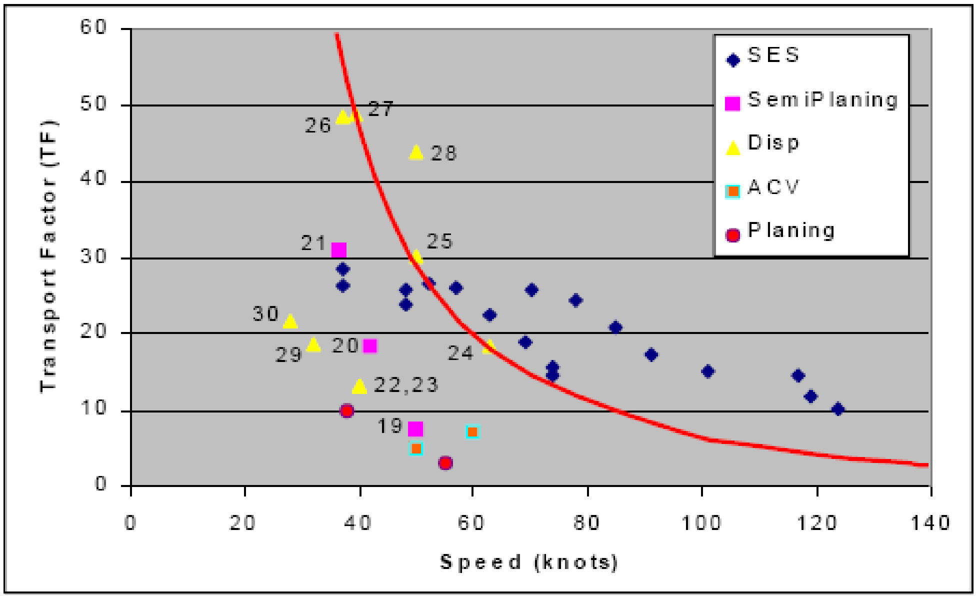
3.1.1 Hull Form Alternatives

The hull form is selected using transport factor methodology to identify alternate hull form types. The important parameters in this selection are payload, cargo weight, required sustained speed and range. This method uses the given design lanes for destroyers to guide hull form design parameter selection. An alternative to this method is to use a parametric model which uses standard series or regression methods for resistance and sea keeping calculations. The formula for calculating the transport factor is show below.

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

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

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



The projected characteristics of the MSC are based on mission and similar ships. This includes the need to accommodate large and heavy major combat systems to exceed the capabilities of the DDG 51 class. The characteristics include a range of 4000 – 8000 NM in major surface combatant operations operating with a CSG, a SAG or independently. The sustained speed requirement is 30 - 35 knots and the expected displacement is in the range of 8000 – 14000 MT. Taking all of these requirements, a transport factor of 38 was calculated for a sustained speed of 32 knots. Transport factor indicates that the hull form choice is a slender monohull.

The important characteristics of the hull are transport factor and capacity for a high degree of modularity to allow for interchanging weapons systems and mission modules. The hull must be efficient incorporating a bulbous bow and making space for large objects. There must be a helo deck with sufficient flight capabilities to incorporate the SH-60 Seahawk as well as various UAVs. Radar cross section will be reduced while making sure that sea keeping is as robust as possible. All of this will be done while endeavoring to minimized cost. There are tradeoffs between the WPTH and flared hullforms. A traditional flared hull form offers improved seakeeping over the WPTH and affords a much drier deck area. However the WPTH offers significant advantages in reducing radar cross section. In order to analyze both hull forms, different teams have been assigned each hull type. Our team has been assigned the Wave Piercing Tumblehome Hull.

The final design space for our MSA hull form will be a wave piercing tumblehome monohull having the following characteristics:

Displacement approximately between 8000 and 14000 MT
Length of 160 - 210 m
L/B: 7-10
L/D: 11-14
B/T: 2.9-3.2
Cp: .594
Cx: .893
Crd between .7-.8

The hull form will be developed using ASSET and response surface models. Offsets from a parent hull will be used as a baseline. Response surface models will be made using ASSET working with Model Center. These will be used to ultimately define which hull form is the optimum for the WPTH in this design.

3.1.2 Propulsion and Electrical Machinery Alternatives

3.1.2.1 Machinery Requirements

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

General Requirements – The machinery requirements will be made by the customer, in this case the Navy. The machinery must be low risk and reliable as well as being certified for Navy use. The machinery of the ship must meet or exceed the requirements of the Navy laid out in the remainder of this section.

Sustained Speed and Propulsion Power – The MSC will have a power plant capable of producing power alternatives across the 70-120 MW range. These will drive the ship at a required minimum speed of 30 knots using no more than 80% MCR at full load. The goal will be 35 knots for the MSC. The ship must be capable of operating at speeds conducive to operations with a carrier strike group or a surface action group.

Ship Control and Machinery Plant Automation – The bridge of this ship will have an integrated bridge system containing integrated navigation, radio and interior communications, and ship maneuvering and control systems. It will conform to the ABS guide for One Man Bridge Operated Ships. The ships machinery plant will be able to be continuously monitored from the SCC, MCC, and Chief Engineer’s office.

Propulsion Engine and Ship Service Generator Certification – Because of the criticality of propulsion and ship service power to many aspects of the ship’s mission and survivability, this equipment shall be non-nuclear, Navy qualified, grade A shock certified, and comply with the ABS ACCU requirements for periodically unattended machinery spaces.

3.1.2.2 Machinery Plant Alternatives

During the concept exploration process the MSC design team will develop machinery general requirements and guidelines and will then select viable machinery alternatives based on these guidelines. We will develop an alternative machinery hierarchy and gather and develop data on viable machinery alternatives. The ship systems and machinery modules were updated consistent with the machinery alternatives and a machinery system trade off will be performed as part of total ship synthesis and optimization.

The propulsors considered for the MSC were 2 podded propulsion units or 2 fixed pitch propellers. The pods offer advantages in maneuverability and flexibility in arrangements. However, the FPPs are a much more proven design with much less inherent risk than the pods. One of the major considerations when discounting the pods as an alternative is their susceptibility to shock damage caused by underwater explosions. This renders them very vulnerable to torpedoes and mines, and let to them being ruled out as a design possibility for the MSC. A picture of the pods can be seen in Figure 4 below.

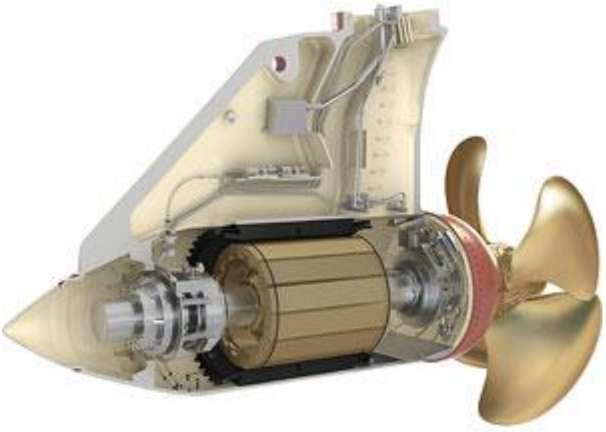


Figure 4: Podded Propulsor

The propulsion for this ship will be provided by 3 main engines with a range of 20000-30000 kW each. The power density required for this ship mandates the use of gas turbines because using diesel prime movers for this type of power output would result in excess weight for the power plant. While diesel engines are far more efficient at part loads and require much less airflow than gas turbines, the power density of the gas turbines makes up for all of the shortcomings of the turbines. The only gas turbines that have been certified for use by the navy are the Rolls Royce MT30 and the GE LM2500+. Another option for the prime movers is PEM fuel cells. They are the latest technology and are very quiet and efficient. However these fuel cells have a very high level of technical risk and have never been used in a naval application and thus are too risky for this application. A picture of a PEM fuel cell can be seen below in Figure 7. These are pictured in Figure 5 and Figure 6 respectively below.

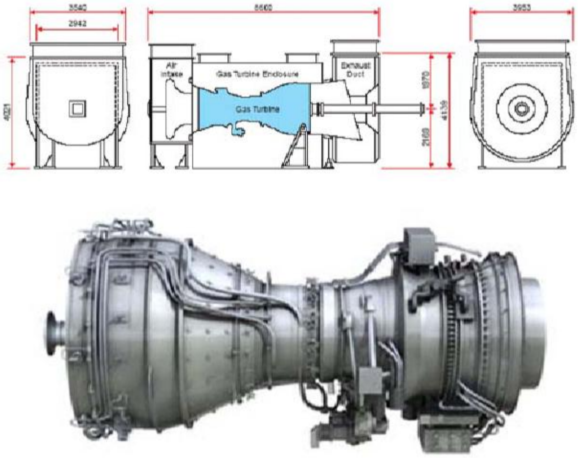


Figure 5: Rolls Royce MT30

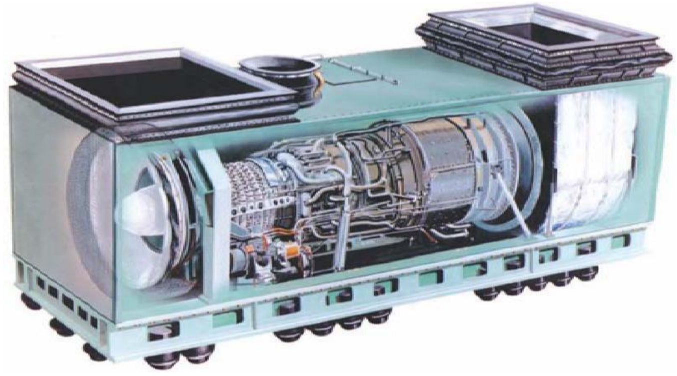


Figure 6: GE LM2500+

Figure 7: PEM Fuel Cell

The electrical system for this ship will be Integrated Power System as mandated by the navy. It will have DC Bus, zonal distribution, and advanced induction motors. This will provide arrangement and operational flexibility, future power growth, and improved fuel consumption. Since the engines will not be mechanically connected to the drive shaft, they will be able to be run continuously at their optimum speed. Images describing the components of the IPS system as well as the distribution can be seen below in Figure 8 and Figure 9.

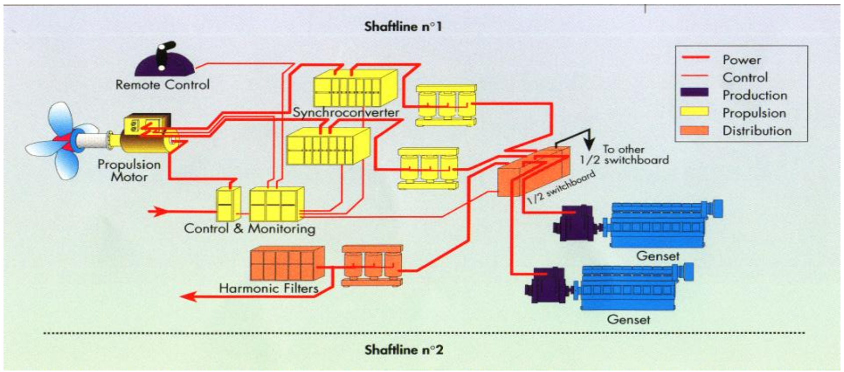


Figure 8: IPS components

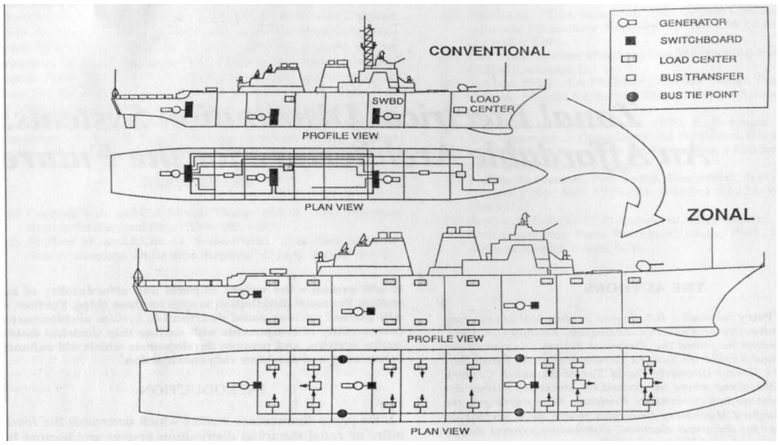


Figure 9: IPS distribution in a ship

The generators and motors considered for this design were the Advanced Induction Motor and the Permanent Magnet Motor. Both of these motors would work well in the MSC. The AIM has a more proven technology and has modern drives enable high efficiencies. The PMM is much smaller and lighter than the AIM. However, it is unproven technology that is high risk and very expensive. Pictures of the AIM and PMM can be seen in Figure 10 and Figure 11 respectively.

Figure 10: AIM

Figure 11: PMM

The options for power combinations are shown below in Table 7.

Table 7: Power Options

PGM	Power Generation Module	1 = 3 x LM2500+, AC Synch, 4160VAC 2 = 2 x MT30, AC Synch, 4160VAC 3 = 3 x MT30, AC Synch, 4160VAC 4 = 3 x LM2500+, AC Synch, 13800VAC 5 = 2 x MT30, AC Synch, 13800VAC 6 = 3 x MT30, AC Synch, 13800VAC
SPGM	Secondary Power Generation Module	1 = NONE 2 = 2 x LM2300 G, AC Synch, (DDG 1000) 3 = 2 x CAT 3608 Diesel 4 = 2 x PC 2.5/18 Diesel 5 = 2 x PEM 3 MW Fuel Cells (NSWCCD) 6 = 2 x PEM 4 MW Fuel Cells (NSWCCD) 7 = 2 x PEM 4 MW Fuel Cells (NSWCCD)
PROP TYPE	Propulsion Type	Option 1) = 2 x FPP Option 2)= 2 x Pods Option 3) = 1 FPP +SPU
PD TYPE	Power Distribution Type	1 = AC ZEDS 2 = DC ZEDS (DDG 1000)
PMM	Propulsive Motor Module	1 = (AIM) Advanced Induction Motor (DDG 1000) 2 = (PMM) Permanent Magnet Motor

Finally, machinery data can be seen below in Table 8. This data was derived in ASSET.

Table 8 Machinery Data

Propulsion Option	PGM Option	Total Propulsion Engine BHP $P_{BPENGTOT}$(kw)	Endurance Brake Propulsion Power, Pbpengend (kw)	Endurance Propulsion SFC SFC_{ePE}(kg/kw hr)	Machinery Box Minimum Length L_{MBreq}(m)	Machinery Box Minimum Height H_{MBreq}(m)	Machinery Box Required Volume V_{MBreq}(m^3)	Basic Propulsion Machinery Weight W_{BM}(MT)	Basic Electric Machinery Weight W_{BME}(MT)	PGM Inlet and Uptake Area A_{PIE}(m^2)	Number of PGMs	Propulsion Engine Type
3xLM2500+, 4160VAC, FPP	1	78297	26099	0.226	17.21	7.78	7838	1074.4	1389.0	84.6	3	48
3xLM2500+, 13800 VAC, FPP	2	78297	26099	0.226	17.21	7.78	6532	895.3	1157.5	84.6	3	48
4xLM2500+, 4160VAC, FPP	3	104396	26099	0.226	17.21	7.78	8998	1247.8	1404.0	112.8	4	48
4xLM2500+, 13800 VAC, FPP	4	104396	26099	0.226	17.21	7.78	7498	1040	1170.0	112.8	4	48
2xMT30, 4160VAC, FPP	5	72000	36000	0.213	16.50	8.00	6990	892.4	1380.7	81.0	2	72
2xMT30, 13800 VAC, FPP	6	72000	36000	0.213	16.50	8.00	5825	744	1151	81.0	2	72
3xMT30, 4160VAC, FPP	7	108000	36000	0.213	16.50	8.00	8321	1062.9	1394.1	121.5	3	72
3xMT30, 13800 VAC, FPP	8	108000	36000	0.213	16.50	8.00	6934	886	1162	121.5	3	72
4xMT30, 4160VAC, FPP	9	144000	36000	0.213	16.50	8.00	9652	1233.6	1410.0	162.0	4	72
4xMT30, 13800 VAC, FPP	10	144000	36000	0.213	16.50	8.00	8033	1028	1175	162.0	4	72

3.1.3 Automation and Manning Parameters

Over the life of a ship, manning is the largest single cost. The Navy spends 60% of its budget on manning; 30% of the direct operating cost of DDG51 is manpower. Manning is a significant driver of the size of a ship, as crewmembers require more space to live and work in than equipment does to operate. The manning of a ship also determines to amount of stores required by the ship and a significant portion of the freshwater requirements. Reductions in manning are also desirable to reduce the number of personnel in harm's way. Manning requirements are driven by three factors: watchstanding, maintenance, and damage control. To minimize the manning, these three areas must be addressed early in the design of a ship.

Automation refers to the use of computers or machinery to reduce the manpower requirements for a task. Automation can result in large reductions to the manning requirements for watchstanding and damage control. Firefighting is a good example of automation reducing manning. Automated firefighting systems can fight a fire with extinguishing agents when smoke or excessive heat is detected. In addition to reducing the manpower needed, the response time is also decreased, reducing the salvage requirements.

Similar to automation, remote sensing and operation of equipment can also reduce the manning requirements and the danger to the crew. The need for roving watches can be decreased by monitoring critical temperatures, pressures, and other indications from the maneuvering compartment or the bridge. Remote operation of valves and pumps simplifies routine operations and reduces the possibility for error. Remote sensors built into equipment can accurately monitor the level of wear and be used to predict maintenance requirements. Combined with automation for basic tasks, remote sensing can reduce the bridge watchstanding requirements by consolidating navigational watches into the OOD/JOOD. At the extreme end, cameras, infrared, and radar can be integrated and displayed on 360° screens in the CIC, providing the exact same picture that is available on the bridge, but enhanced with sensor data.

Besides automation and remote sensing, many other technologies can be used to reduce the manning requirements. Communications technologies have advanced to the point where many specialists can be shore-based. Not only does shore-basing reduce the manning onboard the ship, by having a squadron or group share specialists, the fleet wide requirement and expense can be reduced. Shore-basing can be applied to administrative and supply functions. Shore-based simulators can be used to reduce the onboard time and personnel requirements for training. GPS and digital charts simplify voyage planning and navigation, reducing the personnel requirements in the Operations department. Wireless communications reduce the requirements for phone talkers. New paints and coatings can reduce the paint maintenance requirements by 50%, while also providing better protection for the hull and higher resistance to fouling. Standardization of consoles and use of COTS equipment reduces training time and maintenance costs. Maintenance schedules are developed for the worst-case scenario, and can often be relaxed when the op-tempo is low. Moving to condition-based maintenance from the current scheduled maintenance reduces maintenance costs and manpower requirements by only performing maintenance when required.

The fundamental disadvantage of reduced manning is an increase in risk. As watchbills are reduced, the responsibilities of watchstanders increase. Automation and other enabling technologies can relieve some of the increased load, but not all. Automated equipment that can radically reduce manpower is typically untested and unproven; otherwise it would already be in use. Failure of automated equipment may have consequences ranging from a simple local override for an inoperative valve, to severe damage to the ship if automated fire detection systems fail.

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 12. 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 12. A more detailed manning analysis is performed in concept development.

Figure 12 - "Standard" Manning Calculation

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

3.1.4 Combat System Alternatives

Combat Systems alternatives provide to means to accomplish the missions of the ship. The alternatives are grouped by these missions into Anti-Air Warfare and Ballistic Missile Defense (AAW/BMD), Anti-Surface

Warfare (ASUW), Anti-Submarine Warfare and Mine Countermeasures (ASW/MCM), Modular Mission (MMOD), Guided Missile Launch Support, Strike, and Naval Surface Fire Support (GMLS/STK/NSFS), Command, Control, Communications, Computers, and Intelligence (C^4I), and Helicopter operations (LAMPS).

3.1.4.1 AAW/BMD

The AAW/BMD combat systems detect, track, and manage airborne threats, both aircraft and ballistic missiles. Table 9 shows the options for AAW/BMD systems.

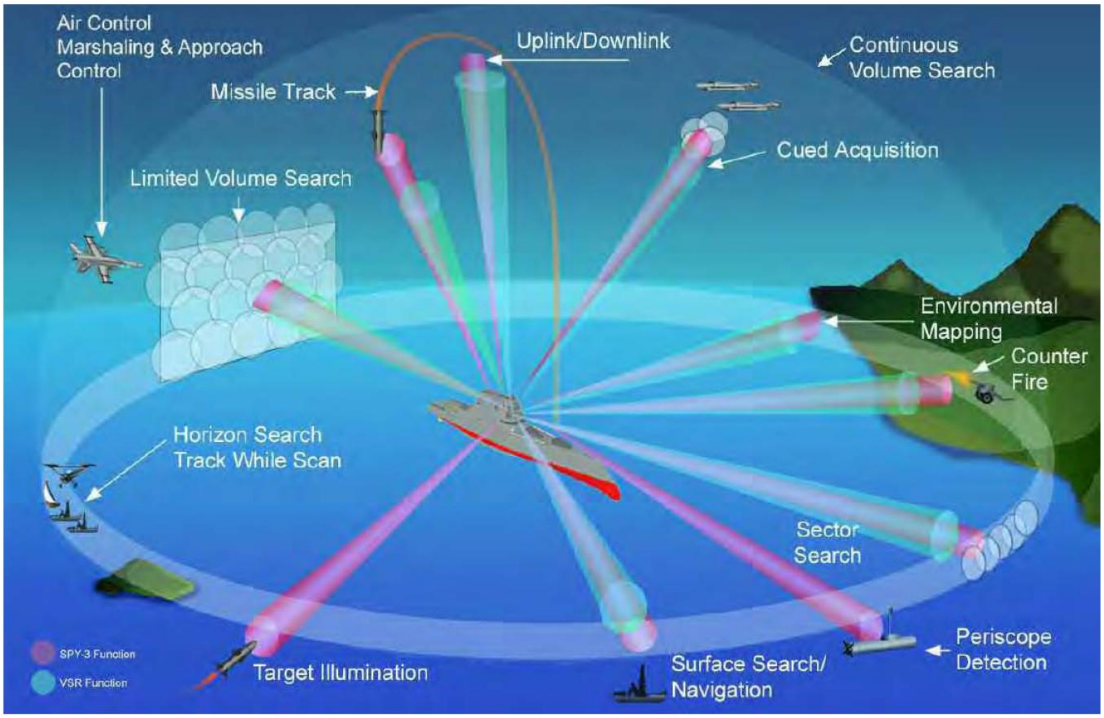
Table 9 AAW/BMD Combat Systems Options Table

Warfighting System	Options
AAW/BMD	Option 1) SPY-3/VSR+++ DBR Option 2) SPY-3/VSR++ DBR Option 3) SPY-3/VSR+ DBR Option 4) SPY-3/VSR DBR
	All Options: IRST, AEGIS BMD 2014 Combat System, AIEWS, CIFF-SD, MK36 SRBOC with NULKA.

The AN/SPY-3 Radar is an X-Band radar designed to provide search, tracking, and fire control in high clutter environments. X-band radar has the narrow beam width, wide frequency bandwidth, and the good low-altitude propagation necessary to detect small targets in cluttered environments. The radar can provide the fire control illumination required by the Evolved Sea Sparrow and the SM-2. It has long range 2-D search and limited volume search capabilities. The radar is capable of tracking targets ranging from surface contacts, periscopes, and sea-skimming anti-ship cruise missiles to ballistic missiles.

The Volume Search Radar (VSR) provides long range volume search capability using S-Band radar. It can track ballistic missiles and other targets in 3-D at extreme ranges. While the S-band radar cannot track small targets in cluttered environments as the X-band, it offers superior propagation loss over long range, is not affected by weather, and can use a more powerful aperture to track long range targets. The VSR capability is dependent on its size, larger radars give better performance. Even the smallest VSR option draws enormous amounts of power, and requires large glycol-water cooling systems; higher performance requires proportional increases in power, weight, and aperture sizes.

The S-Band VSR and the X-Band SPY-3 together make up the Dual Band Radar (DBR). Rather than being two separate systems, the DBR uses two separate frequencies with the same resource manager. The system seamlessly shifts taskings between the two bands, resulting in greater flexibility and capability than previously possible. Figure 13 shows the different capabilities of the DBR.



The DBR can perform all of these functions simultaneously; many at either X-band or S-band.

Figure 13 DBR Capabilities

The Centralized ID Friend or Foe (CIFF-SD) system is a centralized, controller processor-based, system that associates different sources of target information, IFF and SSDS. It processes all IFF sensor inputs and correlates them into on tracking picture.

Infrared Search and Track (IRST) detects heat signatures from anti-ship cruise missiles. The system provides bearing, elevation angle, and can give relative thermal intensity readings. The system is typically set to scan within a few degrees of the horizon, but can be set to search higher.

The MK36 SRBOC (Super Rapid Blooming Offboard Chaff) launches chaff or flares to defeat incoming anti-ship missiles. The MK53 NULKA is a rocket propelled, active decoy that is launched to defend against incoming anti-ship missiles. It hovers over the water while attempted to deceive the incoming missile. The decoy is effective when used by ships cruiser sized and smaller. Figure 14 shows the NULKA in flight.

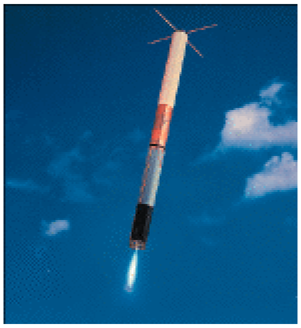


Figure 14 NULKA in flight

The AN/SLY-2(V) Advanced Integrated Electronic Warfare System (AIEWS) provides electronic warfare capabilities. The system intercepts radiation, and provides direction finding, specific emitter identification, and high probability of intercept information. The system also provides Radio Frequency and IR electronic attack capabilities.

The AEGIS BMD 2014 combat system integrates and manages the DBR, CIFF-SD, IRST, and AIEWS systems. The AEGIS 2914 system can autonomously detect, track, and engage hostile aircraft and ballistic missiles. The system does not have a human operator, reducing reaction time and eliminating human error. The behavior of the radar system is determined by the tactical action officer.

3.1.4.2 ASUW

Anti-Surface Warfare combat systems provided protection from hostile surface targets. Hostile surface targets encompass a broad range of vessels and capabilities, from a modern destroyer to speedboats. Combat system options for ASUW are listed in Table 10.

Table 10 ASUW Combat Systems Options Table

Warfighting System	Options
ASUW	Option 1) AGS Option 2) MK45 MOD4 5”/62 gun Option 3) MK110 57 mm gun
	All Options: 3x30mm CIGS, small arms and pyro lockers, FLIR, 1x7m RHIB, GFCS, SPS-73 Surface Search Radar, Thermal Imaging Sensor System (TISS),

The Advanced Gun System (AGS) is a 155mm (6.1”) gun designed for the DDG-1000 program. It is capable of firing guided rocket assisted rounds to ranges of 60 nm, with a CEP of 50m at 60 nm. The gun is capable of 10 rounds per minute, limited only by magazine capacity. The barrel is water cooled, and is concealed within the turret when not firing, reducing the radar cross-section of the gun.

The MK45 MOD 4 is a 5” 62 caliber gun capable of engaging hostile surface targets. It has a range of 13 nm, firing unguided rounds. With the development of a guided rocket assisted round, its range could be extended to 60 nm. The MK45 is capable of firing 16 rounds per minute. The Naval Surface Fire Support capability of the gun is limited by its relatively small shell and low range. Figure 15 shows a schematic of the MK45 MOD4, including the below deck areas.

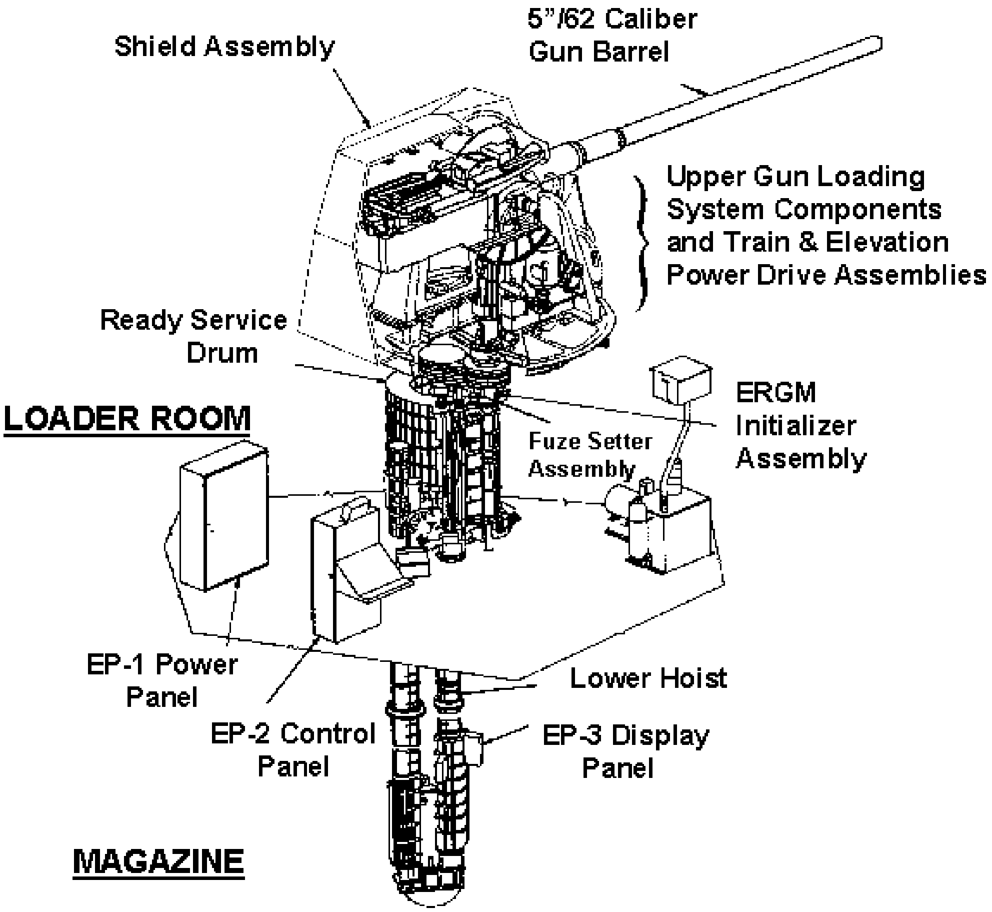


Figure 15 MK 45 MOD 4 5"/63 Gun

The MK 110 57mm fires a much smaller round at high rates of fire. It is capable of firing salvos at 220 round per minute. It is capable of tracking high speed targets in heavy seas with servo controlled electro-hydraulic systems. The MK 110 is suitable for engaging smaller craft that might be encountered in a littoral environment. Figure 16 shows the MK 110.

Figure 16 MK 110 57mm gun

The close in gun system (CIGS) is designed to intercept incoming missiles autonomously. It consists of a 30mm cannon mated to a Ku-band radar and FLIR system. When an incoming missile is detected, it fires at 4200 rounds per minute until the missile is destroyed.

Additional systems include rigid hulled inflatable boats (RHIBs) and small arms lockers. RHIBS provide small boat capability. They can be used to transfer personnel, board suspicious vessels, recover a man overboard or put special operations forces ashore. Small arms lockers contain an assortment of rifles, shotguns, and pistols, as well ammunition for deck mounted machineguns. Small arms are used for security while entering or leaving ports, and can be issued in the event it is necessary to repel boarders.

3.1.4.3 ASW/MCM

Anti-Submarine Warfare systems detect and engage hostile subsurface contacts. The Mine Countermeasures Systems onboard a ship of this class are designed to detect mines to allow their avoidance. Table 11 lists the ASW/MCM combat systems options.

Table 11 ASW/MCM Combat Systems Options Table

Warfighting System	Options
ASW	Option 1) Dual Frequency Sonar Bow array, ISUW Option 2) SQS-53 Sonar, ISUW Option 3) SQS-56 sonar, ISUW Option 4) No permanent SONAR
	All Options: Mine Avoidance Sonar, 2xMK32 SVTT, AN/SLQ-25B NIXIE

The dual frequency sonar bow array combines the AN/SQS-60 mid frequency sonar and the AN/SQS-61 high-frequency sonar. This system is part of the Integrated Undersea Warfare (ISUW) system. This combination provides the most capable sonar system

The SQS-56 is a smaller, proven sonar that has been used on the FFG-7 class. It is a lower cost alternative the dual frequency sonar bow array, with reduced manning, space, and power requirements.

The MK32 Surface Vessel Torpedo Tube is capable of launching the Mk54, MK50, and MK56 Lightweight Torpedoes. The triple mounted tubes pivot outwards to launch torpedoes pneumatically. The launch can be conducted locally or remotely from the ISUW system. Figure 17 shows the MK32 SVTT.

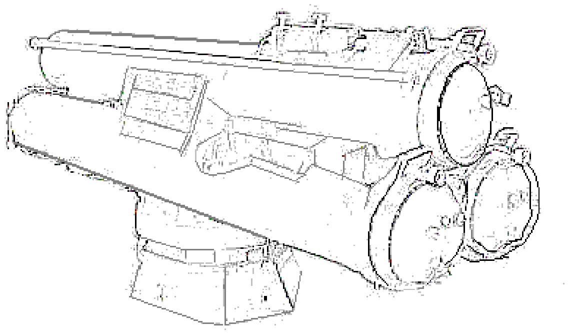


Figure 17 MK 32 SVTT

The AN/SLQ-25B NIXIE is a towed decoy that is used to deceive incoming acoustic torpedoes. It projects noise similar to a surface combatant, drawing to torpedo away from the actual ship. It can be used either in pairs, or singly.

3.1.4.4 MMOD

The Modular Mission payload of the ship enhances its versatility, allowing enhancement of selected missions with minimal refit time. Options for the modular mission payload are listed in Table 12.

Table 12 Mission Module Combat Systems options

Warfighting System	Options
MMOD	Option 1) 150% LCS Mission Module Capacity Option 2) LCS Mission Module Capacity Option 3) 50% LCS Mission Module capacity

Mission modules can be used to enhance the ships capabilities in certain areas. For heavily mined waters, UUVs and support facilities could be added to give the ship standoff mine countermeasures. Other possible payloads include VTUAVs, USVs, support facilities for special operations forces, more capable ISR sensors and equipment, and any module that can be fitted to the LCS class of ships.

3.1.4.5 GMLS/STK/NSFS

The guided missile launch system is responsible for the primary offensive armament of the ship, launching ordnance to support the AAW, BMD, and strike missions. Additionally, through the replacement of a modular MK57 VLS module with an AGS system or railgun, the ship can provide significant naval surface fire support capability. Options for the GMLS are listed in Table 13.

Table 13 GMLS/STK/NSFS Combat Systems Options

Warfighting System	Options
GMLS/STK/NSFS	Option 1) 4x4 MK57 VLS or 1x railgun or AGS, 64xMK57 PVLS or VLS Option 2) 4x4 MK57 VLS or 1x railgun or AGS, 56xMK57 PVLS or VLS Option 3) 4x4 MK57 VLS or 1x railgun or AGS, 48xMK57 PVLS or VLS Option 3) 4x4 MK57 VLS or 1x railgun or AGS, 40xMK57 PVLS or VLS.
	All Options: Tomahawk WCS

The MK57 GMLS system carries one SM-2, SM-3, or SM-6 missile, one BGM-109E Tomahawk cruise missile, or four RIM 162 Evolved Sea Sparrow Missiles. It can be employed as either a standard inboard VLS system, or as a Peripheral VLS system. The PVLS approach places the missiles along the outside of the hull, where they act as a layer of reactive armor. If hit, the missile explodes outwards, limiting the damage to the ship and reducing the probability of damaging the remaining missiles. A 16 cell MK57 module can be replaced by an AGS turret and magazine or by a railgun when that technology becomes available. The power and chill water systems onboard are designed to accommodate any of the three modules. Figure 18 shows a 4 cell MK57 module with a Standard Missile.

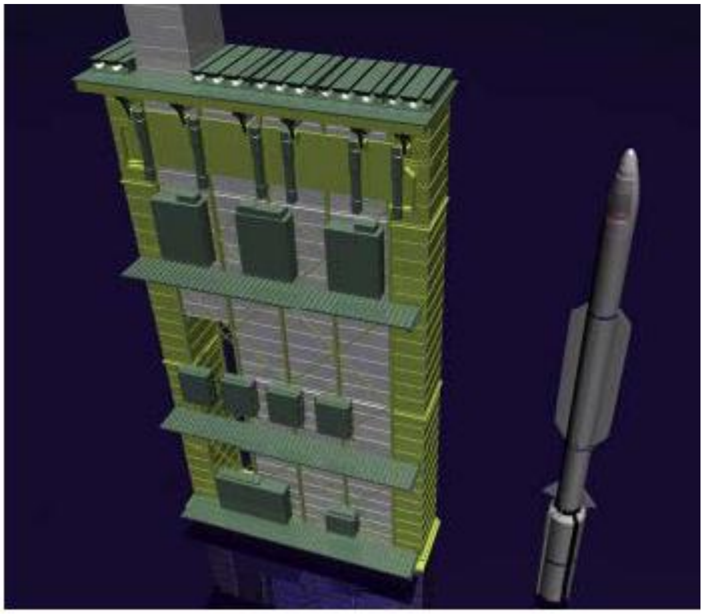


Figure 18 MK57 with Standard Missile

The railgun system is a future technology that can be outfitted to the ship after construction be removing the modular MK57 VLS system. The railgun will have a range of over 200 nm at a rate of 6-12 rounds per minute in all weather conditions. The rounds are inert and GPS guided, relying on accuracy and kinetic energy to destroy the target, which is hit velocities in excess of mach 5. The inert rounds have no explosive or propellant to pose a danger in the event of fire. The power requirements of the railgun are so great that the ship must be stationary in order to fire, using all available power to recharge the railgun's capacitor banks. Many of the systems used by AGS are shared with the railgun, including the turret shell and similar cooling systems. Figure 19 shows the flight profile of the railgun's rounds; Figure 20 shows an installation of the railgun next to an AGS system on a DDG-1000 class ship, displaying the planned commonalities in the turret systems.

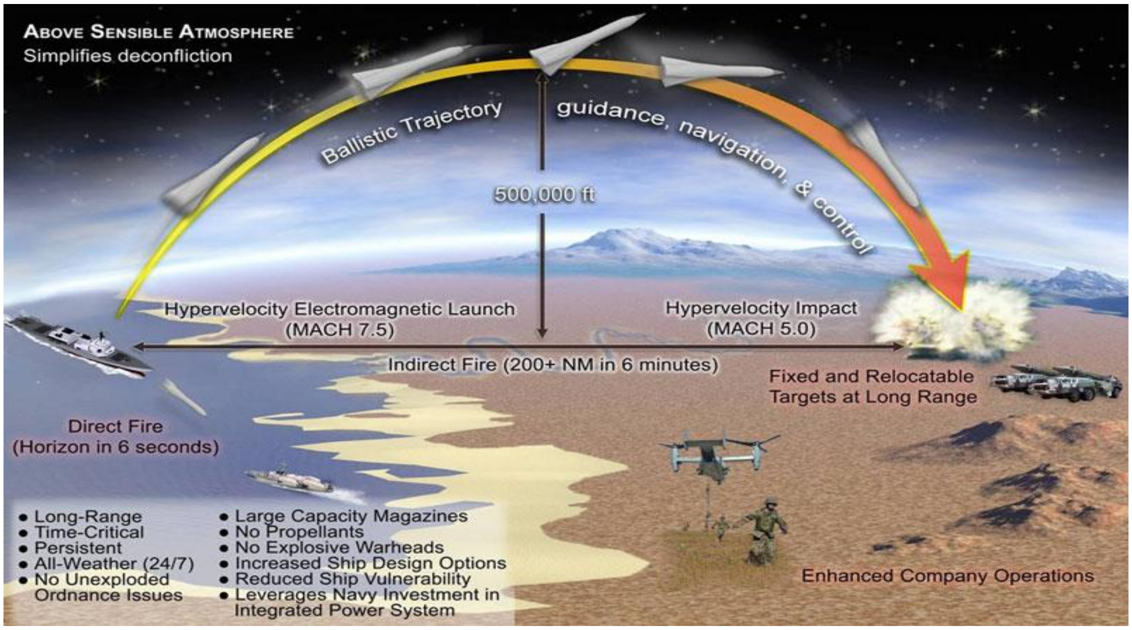


Figure 19 Railgun Ballistics

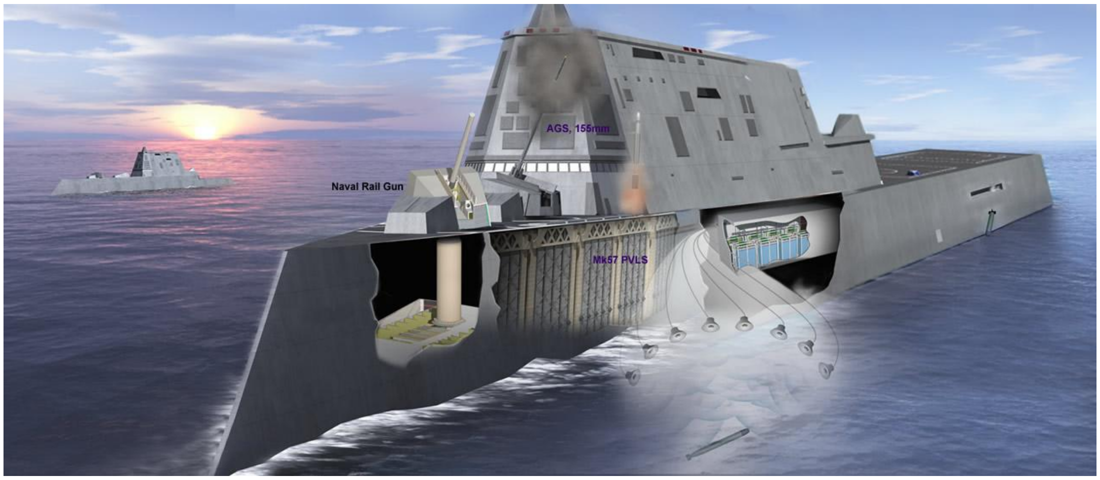


Figure 20 Railgun and AGS mounting

The Standard Missile family is designed to fulfill high end AAW missions. The RIM-156 SM-2 Block IV missile is the current long range fleet AAW weapon. It has a range in excess of 130NM. It is a semi-active radar homing missile, requiring the target to be illuminated by the SPY-3 radar until impact. The RIM-174 SM-6 Missile is an SM-2 Block IV with the semi-active seeker replaced by the active homing package from the AIM-120 AMRAAM. This allows the SM-6 to engage and destroy threats outside the illumination range of the SPY-3 radar. The RIM-161 SM-3 is designed for ABM and ASAT capabilities, and is used with the DBR to provide BMD capabilities. It carries a kinetic warhead, destroying targets through impact. To achieve velocities required to intercept ballistic missiles and satellites, it is equipped with a third stage booster. Terminal guidance for the SM-3 is provided by an infrared seeker.

The ESSM is a medium ranged AAW missile. The ESSM can provide for ownship AAW capabilities, but lacks the range for the fleet AAW mission. It is a smaller missile than the SM-2, as a result, 4 ESSMs can be carried in 1 MK57 cell, as see in Figure 21.

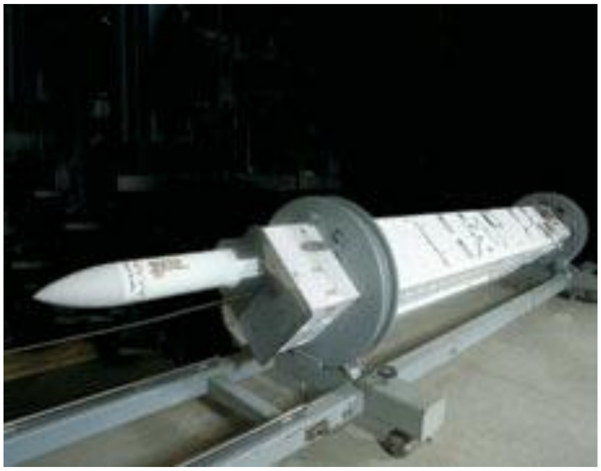


Figure 21 Quad-packed ESSM MK57 cell

3.1.4.6 C^{4}I

A ship's Command, Control, Communications, Computers and Intelligence systems connect all of the data systems onboard the ship, and connect the ship to the rest of the fleet and to higher commands. Table 14 shows the necessary C^{4}I systems

Table 14 C^{4}I Systems

Warfighting System	Options

C^4I	Option 1) Enhanced Radio/Excomm Option 2) Basic Radio/Excomm
	All Options: TSCE, underwater communications, alarm systems, security systems

3.1.4.7 LAMPS

The Light Airborne Multi-Purpose System (LAMPS) is the system for the launch, recovery, holding, and refueling of MH-60R helicopters onboard a surface combatant. Table 15 shows the LAMPS combat systems

Table 15 LAMPS Combat Systems

Warfighting System	Options
LAMPS	Option 1) 2x MH60 helicopters embarked with hanger, RAST Option 2) 2x MH60 helicopters embarked with hanger Option 3) No embarked helicopter detachment
	All Options: VTUAV Support, Helicopter refueling systems

The LAMPS system is centered on the MH-60R Seahawk helicopter. The MH-60R is an upgraded variant of the SH-60B LAMPS Mk III helicopter, the standard multirole helicopter embarked onboard surface combatants. Upgrades from the SH-60B include more advanced active dipping sonar, improved radar, a more capable ESM suite, improved flight control computer, FLIR, and an all-glass cockpit. The MH-60R carries the MK54 LWT for engaging submarines, and AGM-114 Hellfire missiles for engaging surface targets. The MH-60R can undertake missions ranging from ASW to SAR to VERTREPs.

3.1.4.8 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 16 are included in the ship synthesis model data base.

Table 16 - Combat System Ship Synthesis Characteristics

ID	NAME	DV	WTGRP	ID	SingleD	WT (MT)	HD10 (m)	HAREA (m2)	DHAREA (m2)	CRSKW	BATKW
1	VOLUME SEARCH RADAR [S BAND]-VSR	AAW	W456	1	400	198	7.5	0	304	2100	2100
2	GLYCOL WATER COOLING SYSTEM FOR VSR	AAW	W532	2	500	54.04	4.5	0	100	1900	1900
3	VOLUME SEARCH RADAR [S BAND]-VSR+	AAW	W456	3	400	256	7.5	0	393	2714	2714
4	GLYCOL WATER COOLING SYSTEM FOR VSR+	AAW	W532	4	500	98.76	4.5	0	183	2300	2300
5	VOLUME SEARCH RADAR [S BAND]-VSR++	AAW	W456	5	400	398	7.5	0	610	4181	4181
6	GLYCOL WATER COOLING SYSTEM FOR VSR++	AAW	W532	6	500	158.13	4.5	0	293	3500	3500
7	VOLUME SEARCH RADAR [S BAND]-VSR+++	AAW	W456	7	400	425	7.5	0	651	4462	4462
8	GLYCOL WATER COOLING SYSTEM FOR VSR+++	AAW	W532	8	500	189.76	4.5	0	352	4200	4200
9	AN/SPY-3 MFR - MULTIPLE MODE	AAW	W456	9	400	75.71	10.5	0	108.68	382.7	382.7

	RADAR										
10	GLYCOL WATER COOLING SYSTEM FOR SPY-3 MFR / EWS	AAW	W532	10	500	22.92	1.43	0	25.14	300	300
11	AEGIS BMD 2014 COMBAT SYSTEM AND CIC	AAW	W411	11	400	17.6183	-1.09728	184.784	0	74.5	74.5
12	CIFF-SD	AAW	W455	12	400	4.47	16.22	0	0	2.7	2.4
13	MK53 NULKA DECOY LAUNCHING SYSTEM - DLS	AAW	WF21	13	20	0.82	-1.4	0	0	0	0
14	MK 36 SRBOC DECOY LAUNCHING SYSTEM - DLS	AAW	WF21	14	20	3.06	1.6	0	0	0	0
15	EWS - ACTIVE ECM - SLQ/32R	AAW	W471	15	400	9.88	1.4	0	6.5	0.32	0.32
16	IRST - INFRARED SENSING & TRACKING	AAW	W459	16	400	0	4.45	0	0	0	0
17	RAM/SEARAM LAUNCHER - 11 CELL LAUNCHER 1 OF 3	AAW	721	17	700	3.4	2	0	0	4.8	4.8
18	RAM/SEARAM LAUNCHER - 11 READY SERVICE MISSILES 2 OF 3	AAW	21	18	20	1.1	2	0	0	0	0
19	RAM/SEARAM LAUNCHER - 11 CELL - 11 RAM MISSILE MAGAZINE 3 OF 3	AAW	21	19	20	1.1	2	0	0	0	0
20	155 MM AGS PROTECTION	ASUW	W164	20	100	19	0.86	0	0	0	0
21	155 MM AGS FOUNDATIONS	ASUW	W187	21	100	47	-0.15	0	0	0	0
22	155 MM AGS MAGAZINE SUPPORT	ASUW	W187	22	100	8.4	-13.65	0	0	0	0
23	155 MM AGS STOREROOM PROTECTION	ASUW	W164	23	100	12.75	-8.9	0	0	0	0
24	155 MM AGS GUN MOUNT	ASUW	W711	24	700	44.1	1.35	54.14	0	30	275
25	155 MM AGS ENERGY STORAGE SUBSYSTEM	ASUW	W711	25	700	7.49	-1.9	0	0	0	0
26	155 MM AGS CABLE	ASUW	W711	26	700	2.99	-2.9	0	0	0	0
27	155 MM AGS GUN HANDLING SYSTEM	ASUW	W712	27	700	105	-9.91	0	0	0	0
28	155 MM AGS AMMO PALLETS [304 ROUNDS]	ASUW	WF21	28	20	54.4	-8.65	342	0	0	0
29	155 MM AGS AMMO LOADOUT - 304 ROUNDS	ASUW	WF21	29	20	44.2	-7.9	0	0	0	0
30	SPS-73 SURFACE SEARCH RADAR	ASUW	W451	30	400	0.24	9.02818	0	6.50321	0.2	0.2
31	THERMAL IMAGING SENSOR SYSTEM - TISS	ASUW	W452	31	400	0.13	10.85	0	0	0	1
32	FLIR	ASUW	W452	32	400	0.16	10.8	1	0	0	1.5
33	GFCS	ASUW	W481	33	400	0.762035	-1.8288	0	13.9355	12.3	42.7
34	2 X 7M RHIB	ASUW	W583	34	500	7	-3	38.02	0	0	0
35	1 X MK110 57MM GUN	ASUW	W710	35	700	18	-1.88976	26.4774	0	36.6	50.2
36	MK110 57MM AMMO - 600 RDS	ASUW	WF21	36	20	16	-8.65632	65.4966	0	0	0
37	MK110 57MM GUN HY-80 ARMOR LEVEL	ASUW	W164	37	100	10	-2.4384	0	0	0	0

	II										
38	1X MK45 5IN/62 GUN	ASUW	W710	38	700	37.3905	-1.88976	26.4774	0	36.6	50.2
39	MK45 5IN AMMO - 600 RDS	ASUW	WF21	39	20	33.6312	-8.65632	65.4966	0	0	0
40	MK45 5IN/62 GUN HY-80 ARMOR LEVEL II	ASUW	W164	40	100	20.5243	-2.4384	0	0	0	0
41	RAILGUN PROTECTION	ASUW	W164	41	100	19	0.86	0	0	0	0
42	RAILGUN FOUNDATIONS	ASUW	W187	42	100	47	-0.15	0	0	0	0
43	RAILGUN MAGAZINE SUPPORT	ASUW	W187	43	100	8.4	-13.65	0	0	0	0
44	RAILGUN STOREROOM PROTECTION	ASUW	W164	44	100	12.75	-8.9	0	0	0	0
45	RAILGUN MOUNT	ASUW	W711	45	700	44.1	1.35	54.14	0	30	275
46	RAILGUN CAPACITOR BANKS	ASUW	W711	46	700	150	-5	386.4766	0	200	16000
47	RAILGUN CABLE	ASUW	W711	47	700	6	-2.9	0	0	0	0
48	RAILGUN HANDLING SYSTEM	ASUW	W712	48	700	105	-9.91	0	0	0	0
49	RAILGUN AMM0 - 2400 RDS	ASUW	WF21	49	20	48	-7.9	342	0	0	0
50	DUAL FREQUENCY BOW ARRAY SONAR DOME STRUCTURE	ASW	W165	50	100	22.5	-18.5	0	0	0	0
51	DUAL FREQUENCY BOW ARRAY SONAR ELEX	ASW	W463	51	400	26.73	-11.8	104.2	0	94.3	94.3
52	DUAL FREQUENCY BOW ARRAY SONAR HULL DAMPING	ASW	W636	52	600	10.1	-16.9	0	0	0	0
53	SQS-56 SONAR DOME STRUCTURE	ASW	W165	53	100	7.43	-17.5	0	0	0	0
54	SQS-56 SONAR ELEX	ASW	W462	54	400	5.88	-11.8	126.86	0	19.7	19.7
55	SQS-56 SONAR HULL DAMPING	ASW	W636	55	600	2.01	-16.9	0	0	0	0
56	SQS-53 SONAR DOME STRUCTURE	ASW	W165	56	100	85.7	-18.9	0	0	0	0
57	SQS-53 SONAR ELEX	ASW	W462	57	400	67.4	-11.8	271.7	0	100	100
58	SQS-53 SONAR HULL DAMPING	ASW	W636	58	600	20.1	-16.9	0	0	0	0
59	MINEHUNTING SONAR	ASW	W462	59	400	2.1	-16.5	21	0	3.7	3.7
60	ISUW - INTEGRATED UNDERSEA WARFARE SYS	ASW	W483	60	400	4.87703	-3.3528	0	0	19.5	19.5
61	SQR-19 TACTAS	ASW	W462	61	400	23.6739	-3.6096	43.9431	0	26.6	26.6
62	AN/SLQ-25 NIXIE	ASW	W473	62	400	3.65777	-3.6096	15.9793	0	3	4.2
63	BATHYTHERMOGRAPH	ASW	W465	63	400	2.63	-1.25	0	0	0	0
64	TORPEDO DECOYS	ASW	W473	64	400	5.09	-7.29	46	0	2.4	2.4
65	C+S OPERATING FLUIDS	ASW	W498	65	400	72.31	-16.15	0	0	0	0
66	2X MK32 SVTT ON DECK	ASW	W750	66	700	2.74333	-2.0856	0	0	0.6	1.1
67	6 X MK46 LIGHTWEIGHT ASW TORPEDOES	ASW	WF21	67	20	1.38182	-2.0856	0	0	0	0
68	TOTAL SHIP COMPUTING ENVIR SYSTEM	CCC	W412	68	400	73.38	-6.93	763.6	0	435.68	435.68
69	ENHANCED RADIO/EXCOMM	CCC	W441	69	400	51	11.31	0	265	227.89	228.19
70	BASIC RADIO/EXCOMM	CCC	W440	70	400	32.9098	10	0	158	93.3	96.4
71	TOMAHAWK	CCC	W482	71	400	5.70002	-2.37744	0	0	11.5	11.5

	WEAPON CONTROL SYSTEM										
72	UNDERWATER COMMUNICATIONS	CCC	W442	72	400	2.88	-11.22	0	0	0	0
73	VISUAL & AUDIBLE SYSTEMS	CCC	W443	73	400	0.32	-5.46	0	0	0	0
74	SECURITY EQUIPMENT SYSTEMS	CCC	W446	74	400	0.88	-7.27	0	0	0	0
75	PVLS NON-STRUCTURE FRAG ARMOR 160 CELLS	GMLS	W164	75	100	213.75	-7.68	0	0	0	0
76	PVLS NON-STRUCTURE FRAG ARMOR 128 CELLS	GMLS	W164	76	100	171	-7.68	0	0	0	0
77	PVLS NON-STRUCTURE FRAG ARMOR 96 CELLS	GMLS	W164	77	100	128.25	-7.68	0	0	0	0
78	PVLS FOUNDATIONS 160 CELLS	GMLS	W187	78	100	60.5	-4.65	0	0	0	0
79	PVLS FOUNDATIONS 128 CELLS	GMLS	W187	79	100	48.4	-4.65	0	0	0	0
80	PVLS FOUNDATIONS 96 CELLS	GMLS	W187	80	100	36.3	-4.65	0	0	0	0
81	PVLS COOLING UNIT-VLS MAG 160 CELLS	GMLS	W514	81	500	59.48	-4	0	0	0	0
82	PVLS COOLING UNIT-VLS MAG 128 CELLS	GMLS	W514	82	500	47.58	-4	0	0	0	0
83	PVLS COOLING UNIT-VLS MAG 96 CELLS	GMLS	W514	83	500	35.69	-4	0	0	0	0
84	PVLS COOLING EQUIPMENT OPERATING FLUIDS 160 CELLS	GMLS	W598	84	500	27.47	-4	0	0	0	0
85	PVLS COOLING EQUIPMENT OPERATING FLUIDS 128 CELLS	GMLS	W598	85	500	21.98	-4	0	0	0	0
86	PVLS COOLING EQUIPMENT OPERATING FLUIDS 96 CELLS	GMLS	W598	86	500	16.48	-4	0	0	0	0
87	PVLS 160 CELLS	GMLS	W721	87	700	628.92	-4.33	1900	0	724.6	724.6
88	PVLS 128 CELLS	GMLS	W721	88	700	503.14	-4.33	1520	0	579.68	579.68
89	PVLS 96 CELLS	GMLS	W721	89	700	377.35	-4.33	1140	0	434.76	434.76
90	PVLS MISSLE HANDLING	GMLS	W722	90	700	0.25	14	0	0	0	0
91	PVLS LOADOUT 160 CELLS	GMLS	WF21	91	20	332.375	-3.77	0	0	0	0
92	PVLS LOADOUT 128 CELLS	GMLS	WF21	92	20	265.9	-3.77	0	0	0	0
93	PVLS LOADOUT 96 CELLS	GMLS	WF21	93	20	199.43	-3.77	0	0	0	0
94	KEI LS FOUNDATIONS 8(x4)=32 CELLS	GMLS	W187	94	100	12.1	-4.65	0	0	0	0
95	KEI LS NON-STRUCTURE FRAG ARMOR 8x4 CELLS	GMLS	W164	95	100	42.75	-7.68	0	0	0	0
96	KEI LS COOLING UNIT 8 CELLS	GMLS	W514	96	500	12.69	-4	0	0	0	0
97	KEI LS COOLING EQUIPMENT OPERATING FLUIDS 8x4 CELLS	GMLS	W598	97	500	5.4	-4	0	0	0	0
98	KEI LS 8x4 CELLS	GMLS	W721	98	700	125.8	-4.33	1140	0	434.76	434.76
99	KEI MISSILE LOADOUT 8(x4)=32 CELLS	GMLS	WF21	99	20	66.5	-3.77	0	0	0	0

100	DUAL HELO/UAV DET - 2X SH60R HANGAR UPPER LEVEL 17 X 15.7	LAMPS	NONE	100	100	0	0	0	266.9	0	0
101	DUAL HELO/UAV DET - 2X SH60R HANGAR LOWER LEVEL 17 X 15.7	LAMPS	NONE	101	100	0	0	0	266.9	0	0
102	DUAL HELO/UAV DET - FUEL SYSTEM	LAMPS	W542	102	500	21	-9.84	0	2.77	0	0
103	DUAL HELO/UAV DET - HNDLG/SUPPORT/MAINT/WKSP - AREA ONLY	LAMPS	NONE	103	500	0	0	0	34.1	0	0
104	DUAL HELO/UAV DET - RAST/RAST CONTROL - AREA ONLY	LAMPS	NONE	104	500	0	0	44.4	0	0	0
105	DUAL HELO/UAV DET - HANDLING/SERVICE/STOWAGE - WEIGHT ONLY	LAMPS	W588	105	500	26.04	-1.69	0	0	0	0
106	DUAL HELO/UAV DET - MAGAZINE HANDLING	LAMPS	W712	106	700	0.001	-1.55	0	0	0	0
107	DUAL HELO/UAV DET - MAGAZINE 12-MK46 24-HELLFIRE 6-PENQUIN	LAMPS	WF22	107	20	0.001	-1.5	0	57.46	0	0
108	DUAL HELO/UAV DET - VTUAV	LAMPS	WF23	108	20	3.47	-2	0	0	0	0
109	DUAL HELO/UAV DET - 2X SH60R	LAMPS	WF23	109	20	10.66	-2	0	0	0	0
110	DUAL HELO/UAV DET - SUPPORT/SPARES	LAMPS	WF26	110	20	0	-2	0	158.08	0	0
111	SONOBOUY MAGAZINE STOWAGE - NONE IN PARENT	LAMPS	W713	111	700	0.001	-1.5	0	0	0	0
112	SONOBOUY MAGAZINE - 300 BUOYS - 88 MARKERS	LAMPS	WF22	112	20	0.001	-1.5	0	10.12	0	0
113	SQQ-28 LAMPS MK III ELECTRONICS	LAMPS	W460	113	400	3.51552	0.9144	0	0	5.3	5.5
114	LAMPS MKIII:AVIATION FUEL [JP-5]	LAMPS	WF42	114	40	65.4334	-12.4376	0	0	0	0
115	LAMPS MKIII:HELO IN-FLIGHT REFUEL SYS	LAMPS	W542	115	500	7.72196	-7.572	4.08773	0	1.3	1.3
116	BATHYTHERMOGRAPH PROBES	LAMPS	WF29	116	20	0.21337	-8.56359	0	0	0	0
117	SINGLE SH-60 MODULAR DET - 1 HELO AND HANGAR	LAMPS	23	117	20	9.49	3	0	88	0	0
118	SINGLE SH-60 MODULAR DET - MISSION FUEL	LAMPS	42	118	40	27.5	-6	0	0	0	0
119	SINGLE SH-60 MODULAR DET - SUPPORT MOD 1	LAMPS	26	119	20	6.938	3	0	37.52	0	0
120	SINGLE SH-60 MODULAR DET - SUPPORT MOD 2	LAMPS	26	120	20	6.721	3	0	37.52	0	0
121	SINGLE SH-60 MODULAR DET - SUPPORT MOD 3	LAMPS	26	121	20	3.345	3	0	37.52	0	0
122	SINGLE SH-60	LAMP	26	12	20	3.347	3	0	37.52	0	0

	MODULAR DET - SUPPORT MOD 4	S		2						
123	DUAL SH-60 MODULAR DET - 2 HELOS AND HANGAR	LAMPS	23	123	20	18.98	3	0	176	0	0
124	DUAL SH-60 MODULAR DET - MISSION FUEL	LAMPS	42	124	40	55	-6	0	0	0	0
125	DUAL SH-60 MODULAR DET - SUPPORT MOD 1	LAMPS	26	125	20	6.938	3	0	37.52	0	0
126	DUAL SH-60 MODULAR DET - SUPPORT MOD 2	LAMPS	26	126	20	6.721	3	0	37.52	0	0
127	DUAL SH-60 MODULAR DET - SUPPORT MOD 3	LAMPS	26	127	20	3.601	3	0	37.52	0	0
128	DUAL SH-60 MODULAR DET - SUPPORT MOD 4	LAMPS	26	128	20	3.347	3	0	37.52	0	0
129	SMALL ARMS AND PYRO STOWAGE	SDS	W760	129	700	5.94387	-1.92024	18.8593	0	0	0
130	SMALL ARMS AMMO - 7.62MM + 50 CAL + PYRO	SDS	WF21	130	20	4.16579	-1.8288	0	0	0	0
131	3 X 30MM CIGS GUN	SDS	W164	131	100	2.5	1.83	0	0	0	0
132	SWBS 187 2 X 30MM CIGS GUN FOUNDATION	SDS	W187	132	100	9	4.35	0	0	0	0
133	3 X CIGS SYSTEMS	SDS	W711	133	700	16.94	4.9	23.84	0	20	40
134	3 X CIGS HOIST EXTENTIONS	SDS	W711	134	700	0.89	0.1	0	0	0	0
135	3 X CIGS AMMO HOIST	SDS	W712	135	700	0.45	2.6	0	0	0	0
136	3 X CIGS CASE CAPTURE	SDS	W712	136	700	4.96	3.57	0	0	0	0
137	3 X 30MM CIGS GUN AMMO	SDS	WF21	137	20	4.29	-1.5	0	0	0	0

3.1.5 Modularity Alternatives

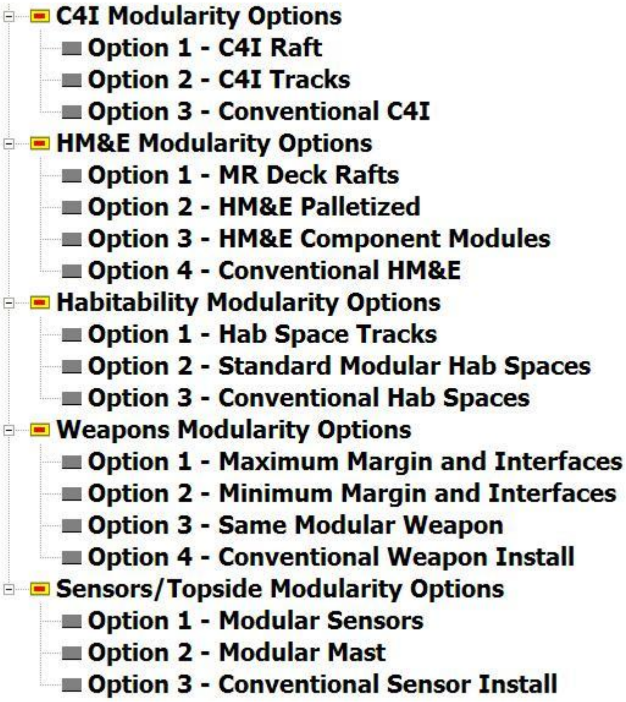
Modularity is the arrangement of coupled elements of a complex system connected by pre-specified interfaces. The benefits of modularity include reduced life cycle costs by five to eleven percent, improved renovation and maintenance costs and schedule, and reduced acquisition schedule. Modularity allows for various hull and module components to be build simultaneously at different locations, then assembled at a main facility. Because these elements do not need to be fabricated on site, this saves a large amount of time during the construction process. Also if the ship needs repair or renovation while deployed, it does not need to return to a shipyard for extensive work. The module can be sent to the ships location, and the necessary parts can be installed on site in a fraction of time with little intensive work needed. The key to modularity are the interfaces. Having standard inputs such as electrical power, sensors, and HVAC allow the components to be removed or replaced quickly with slight modification of the ship.

Not every aspect of a ship can benefit from modularity. The application of modularity is most promising where change is likely to occur. Some areas include combat systems, sensors, Command Control Communications Computers and Intelligence (C4I), Hull Mechanical and Electrical (HM&E), and habitability. The advances in technology allow these areas to benefit most from modularity. Also there may be some issues with modularity in a ship. The addition of platforms and interfaces to a ship may result in higher acquisition cost. Also displacement and fuel consumption may increase due to the increased weight from interfaces and other required structure; however these increases are less than five percent for a Medium Surface Combatant (MSC).

There are many types of modularity, some more applicable to a MSC than others. One option is a prepackaged containers or pallets. This choice is best suited for elements on the exterior of the ship, such as weapons and sensor systems. Containers and pallets are easily installed on a ship and have little effect on the surrounding structure. A good example of container modularity is the weapon shown in Figure 22. It is essentially self contained and simply attaches to the deck of the ship. Unfortunately with the Wave Piercing Tumblehome (WPTH) hull of the MSC, the containers would negate radar reduction gains. Another form of modularity is construction modularity or hull segments. This is the process of constructing large sub-assemblies of a ship's hull individually, then combining all at once. This method has been used in the past as a way to renovate ships to update for modern threats and needs. Hull segments are an inefficient way to update a ship or to construct a new one.

Figure 22 Open and Closed Container Weapons Module

Figure 23 shows the possible modularity design variables. The last option for each modularity sector is considered to be "conventional". These options are comprised of standard components with no modularity capabilities. They are the lowest upfront cost, however if it is in an area that is prone to upgrade and repairs, operational costs are significantly higher. The higher ranked an option is, the more modular its elements are.



- **C4I Modularity Options**
  - **Option 1 - C4I Raft**
  - **Option 2 - C4I Tracks**
  - **Option 3 - Conventional C4I**
- **HM&E Modularity Options**
  - **Option 1 - MR Deck Rafts**
  - **Option 2 - HM&E Palletized**
  - **Option 3 - HM&E Component Modules**
  - **Option 4 - Conventional HM&E**
- **Habitability Modularity Options**
  - **Option 1 - Hab Space Tracks**
  - **Option 2 - Standard Modular Hab Spaces**
  - **Option 3 - Conventional Hab Spaces**
- **Weapons Modularity Options**
  - **Option 1 - Maximum Margin and Interfaces**
  - **Option 2 - Minimum Margin and Interfaces**
  - **Option 3 - Same Modular Weapon**
  - **Option 4 - Conventional Weapon Install**
- **Sensors/Topside Modularity Options**
  - **Option 1 - Modular Sensors**
  - **Option 2 - Modular Mast**
  - **Option 3 - Conventional Sensor Install**

Figure 23 Modularity Design Variables

Though modularity is not yet prevalent in the US Navy, it is not a new concept. Modularity was effectively implemented in Germany and Europe through the MEKO program starting in the late 1970's. Since then over 60 MEKO ships have been built using modular platforms. Figure 24 shows an example of the arrangement and modularity of the MEKO ships. The MEKO ship incorporated a number of different types modularity, primarily mission and container/palletized module packages. Later designs also included modular mast options to complement the existing modularity options. The MEKO went on to be the basis for a number of other ship modularity and commonality programs, both in the United States and abroad.

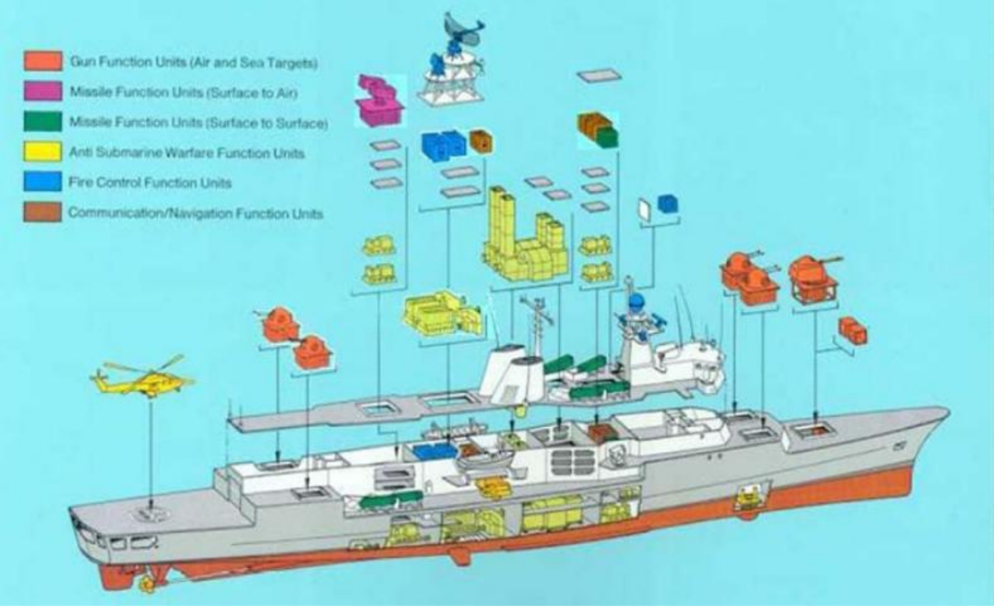


Figure 24 MEKO Modularity Arrangement

The Navy is dependent on the most advanced weapons and combat systems to safely meet the challenges of current and future threats. That is why any new ship should be outfitted with the most modular combat system possible. This allows the ship to adapt to changing needs and environments while the Navy gets the longest possible life span out of the ship. Nearly as important as combat systems are sensors and C4I elements. The ability to destroy any enemy is nothing without the ability to track and monitor them. With respect to C4I components, a tracks mounting system is easy to implement on future technologies, and current equipment can be adapted to this system if not already. An example of a C4I tracks system is given in Figure 25. The tracks are attached to the wall using bolts and welding then equipment is connected to the tracks. A modular mast to house all radar and antenna apparatus may be impractical under current technological restraints, but is not ignored as an option for the future. Habitability is an area where modularity is least valuable. That is why standard habitability and berthing spaces would best fit a MSC. Finally HM&E would best benefit from a component type of modularity. This would allow individual parts to be updated or changed as technology leads to increased efficiencies. Also, if an element needs repair or replacing, just that one part can be changed instead of having to remove an entire system to replace one section.

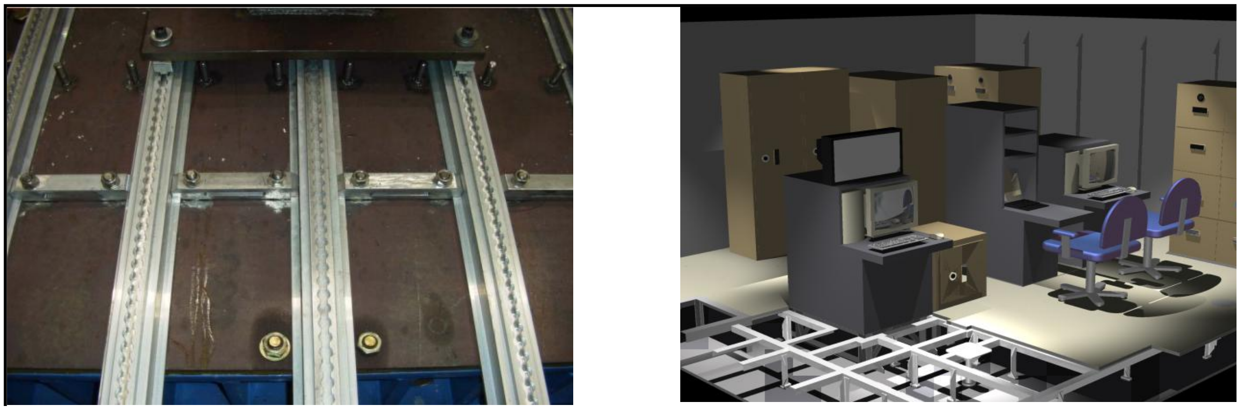


Figure 25 C4I Tracks Modularity and Layout Example

The benefits of modularity derive from the ability to avoid costly and time consuming removal and reinstallation of modules and components. The interfaces of the modules ensure the surrounding structure of the ship is not affected by repair or replacement. Despite the potential of an increased acquisition cost, the reduced life cycle and follow ship cost make modularity worth the initial investment.

3.2 Design Space

Table 17 - Design Variables (DVs)

DV #	DV Name	Description	Design Space
1	**LBP**		160-200 m
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	VD	Deckhouse volume	5000-15000 m^3
6	Cdmat	Hull Material	1 = Steel, 2 = Aluminum, 3 = Advanced Composite
8	PGM	Power Generation Module	1 = 3 x LM2500+, AC Synch, 4160VAC 2 = 2 x MT30, AC Synch, 4160VAC 3 = 3 x MT30, AC Synch, 4160VAC 4 = 3 x LM2500+, AC Synch, 13800VAC 5 = 2 x MT30, AC Synch, 13800VAC 6 = 3 x MT30, AC Synch, 13800VAC
8	SPGM	Secondary Power Generation Module	1 = NONE 2 = 2 x LM2300 G, AC Synch, (DDG 1000) 3 = 2 x CAT 3608 Diesel 4 = 2 x PC 2.5/18 Diesel 5 = 2 x PEM 3 MW Fuel Cells (NSWCCD) 6 = 2 x PEM 4 MW Fuel Cells (NSWCCD) 7 = 2 x PEM 4 MW Fuel Cells (NSWCCD)
9	PROP TYPE	Propulsion Type	Option 1) = 2 x FPP Option 2)= 2 x Pods Option 3) = 1 FPP +SPU
10	PD TYPE	Power Distribution Type	1 = AC ZEDS 2 = DC ZEDS (DDG 1000)
11	PMM	Propulsive Motor Module	1 = (AIM) Advanced Induction Motor (DDG 1000) 2 = (PMM) Permanen Magnet Motor
12	Ts	Prvosions Duration	60-75 days
13	Ncps	Collective Protection System 0	0=none 1 = partial 2 = full

14	Ndegaus	Degaussing system	0 = none 1 = degaussing system
15	Cman	Manning Reduction and automation factor	0.5 - 1.0
16	AAW	Anti-Air warfare alternatives	Option 1) SPY-3/VSR+++ DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA Option 2) SPY-3/VSR++ DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA Option 3) SPY-3/VSR+ DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA Option 4) SPY-3/VSR (DDG-1000 3L) DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA
17	ASUW	Anti-Surface Warfar alternatives/Naval Surface Fire support alternatives	Option 1) 1x155m AGS, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod1 3x CIGS Anti-Surface Warfare Anti-Air Warfare 20 AAW alternatives Option 2) 1xMK45 5”/62 gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod1 3x CIGS Option 3) 1xMK110 57mm gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod1 3x CIGS
18	ASW	Anti-Submarine Warfare Alternatives/ Mine Counter Measures	Option 1) Dual Frequency Bow Array, ISUW, NIXIE, 2xSVTT, mine-hunting sonar Option 2) SQS-53C, NIXIE, SQR-19 TACTAS, ISUW, 2xSVTT, mine-hunting sonar

			Option 3) SQS-56, NIXIE, ISUW, 2xSVTT, mine-hunting sonar Option 4) NIXIE, 2xSVTT, mine-hunting sonar
19	NSFS	Naval Surface Fire Suppor Alternatives	Option 1) 1x155m AGS, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod1 3x CIGS Option 2) 1xMK45 5”/62 gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod1 3x CIGS Option 3) 1xMK110 57mm gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod1 3x CIGS
20	CCCI	Command Control Communication Computer	Option 1) Enhanced CCCCI Option 2) Basic CCCCI (CG 47)
21	GMLS	Guided Missile Launching System	Option 1) 192 cells, MK 41 and/or MK57 PVLS Option 2) 160 cells, MK 41 and/or MK57 PVLS Option 3) 144 cells, MK 41 and/or MK57 PVLS Option 4) 128 cells, MK 41 and/or MK57 PVLS
22	LAMPS	LAMPS Alternatives	Option 1) Embarked 2 LAMPS w/Hangars Option 2) Embarked 1 LAMPS w/Hangar Option 3) LAMPS haven (flight deck)

3.3 Ship Synthesis Model

A surrogate ship synthesis model was constructed using Phoenix Integration’s Model Center Software. Design variables were analyzed over the entire design space using the multi objective genetic optimization (MOGO) feature built into Model Center. The MOGO worked to develop concept design models on the non-dominated frontier. A number of steps, which are outlined below, went into the development of the multi objective genetic optimization and a following single objective optimization. The MOGO consisted of a series of response surface models (RSMs) and FORTRAN analysis code, linked together in Model Center to analyze inputs over the design space, and produce a large number of concept designs in a relatively short period of time. In doing so, hundreds of ship models were analyzed and an optimized design with appropriate levels of risk, effectiveness, and cost was be chosen.

Computer programs were developed in FORTRAN which determined outputs variables for portions of the ship design process. FORTRAN code was developed to be used in the determination of the combat systems, hull form, propulsion machinery, space available and required, electric loads, weights, tankage volume, feasibility, cost, overall measure of effectiveness, and a design's overall measure of risk. The combat system module contained data from the combat system payload summary which it used to output weight and power requirements of the system being analyzed. The hull module output hull form coefficients and scantlings from length to beam, draft, and depth ratios. Fuel requirements and machinery efficiencies were calculated in the propulsion machinery module. The usable space of a ship was calculated in the space available module, given ship size characteristics. Electric loads received input from previous modules, including propulsion and combat systems, and calculated the 24 hour electric load and the required shaft horsepower. The tankage module produced a breakdown of the tankage volumes and the weights module produces a weights breakdown following the SWBS structure.

In addition to Fortran models, response surface models were developed to produce hull volume characteristics, effective horsepower and propulsive efficiency models, electric loads, sustained speed calculations, and weight and space estimates. These response surface models were generated using ASSET 5.3.0 in combination with Model Center. Model Center inputs were linked to ASSET which allowed for a large number of ship concepts to be produced by ASSET in a short period of time. By limiting which design variables were changed, it became possible to analyze how that specific variable or group of variables influenced a ship's characteristics. This relationship was plotted and RSM's were subsequently developed. Figure 26 through Figure 29 show how the response surface module output variable compared to the ASSET output. For example, Figure 26 compares the hull volume that was calculated using the RSM versus the hull volume that was calculated using ASSET. The black line on the graph depicts where the calculated value using the RSM would equal the actual value produced by ASSET. A closer fit RSM would more closely follow this trendline.

The hull volume RSM, shown in Figure 26 and Figure 27 estimated the hull volume and structural weight, given ratios of length to depth, draft, and beam. A RSM for propulsion also receives these ratios and calculates effective horsepower, depicted in Figure 28, and the propulsive coefficient. The twenty four hour electric load and the maximum marginal electric load are calculated in an RSM which receives the length, length to beam, length to draft, the power available, and a manning array. The sustained speed RSM, Figure 29 , used inputs including length, length to draft, length to beam, beam to draft, and the power available. Lastly, weight and space RSMs were calculated using length, length to draft, length to beam, and the manning array.

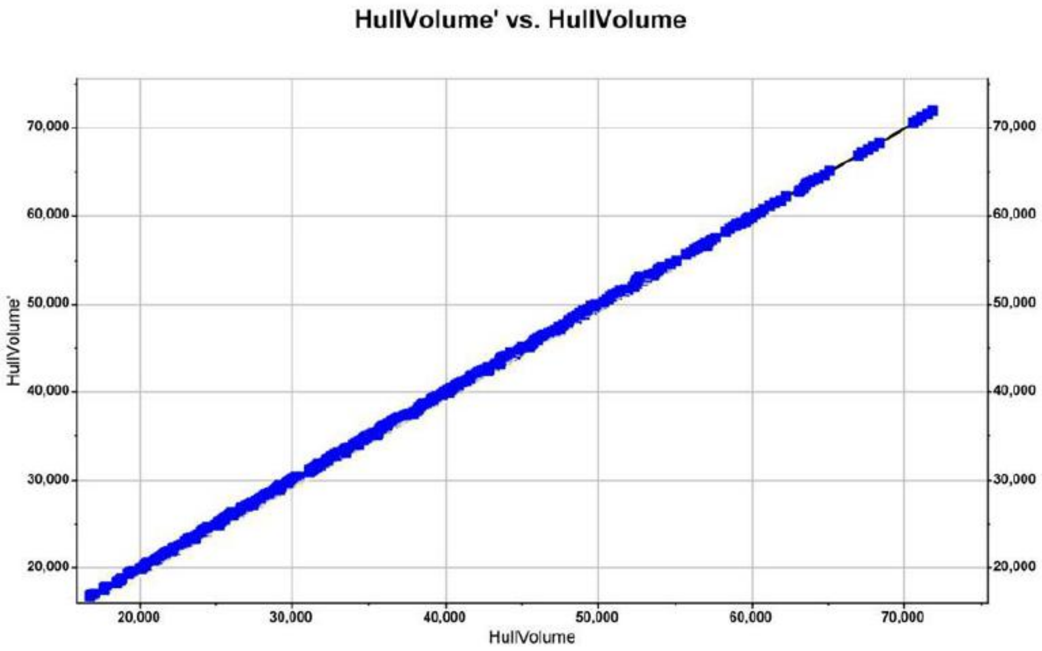


Figure 26 Hull Volume RSM

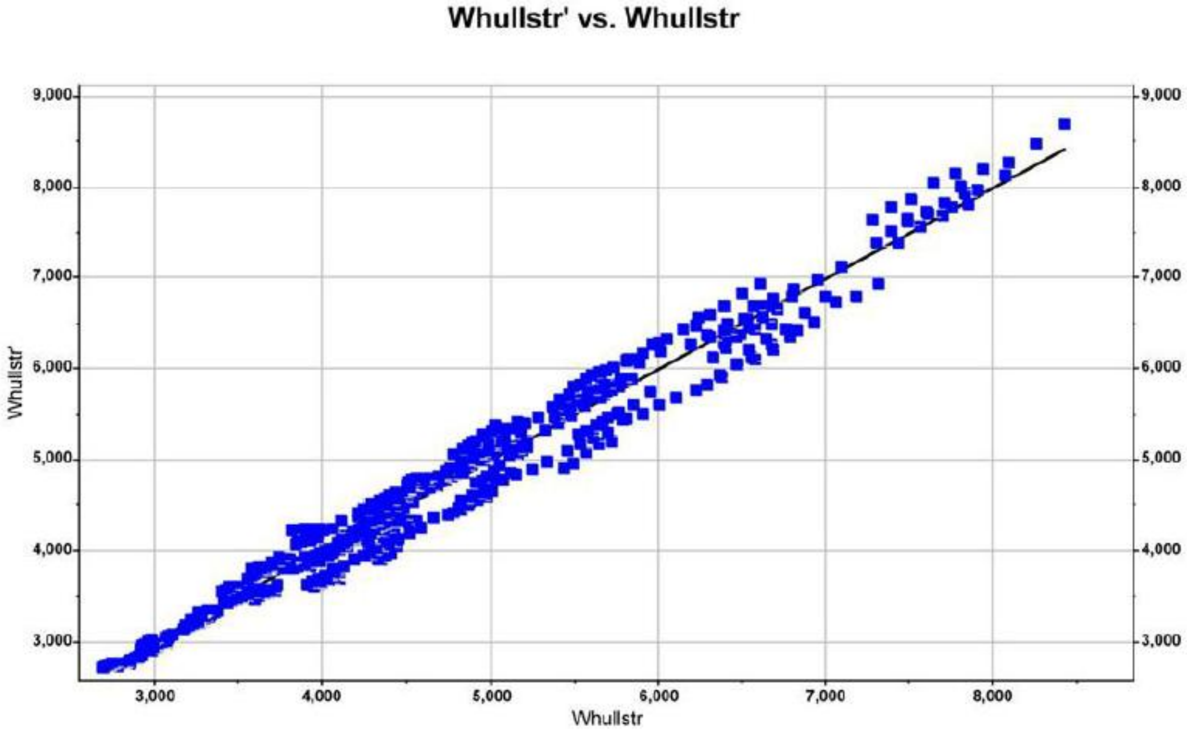


Figure 27: Weight RSM

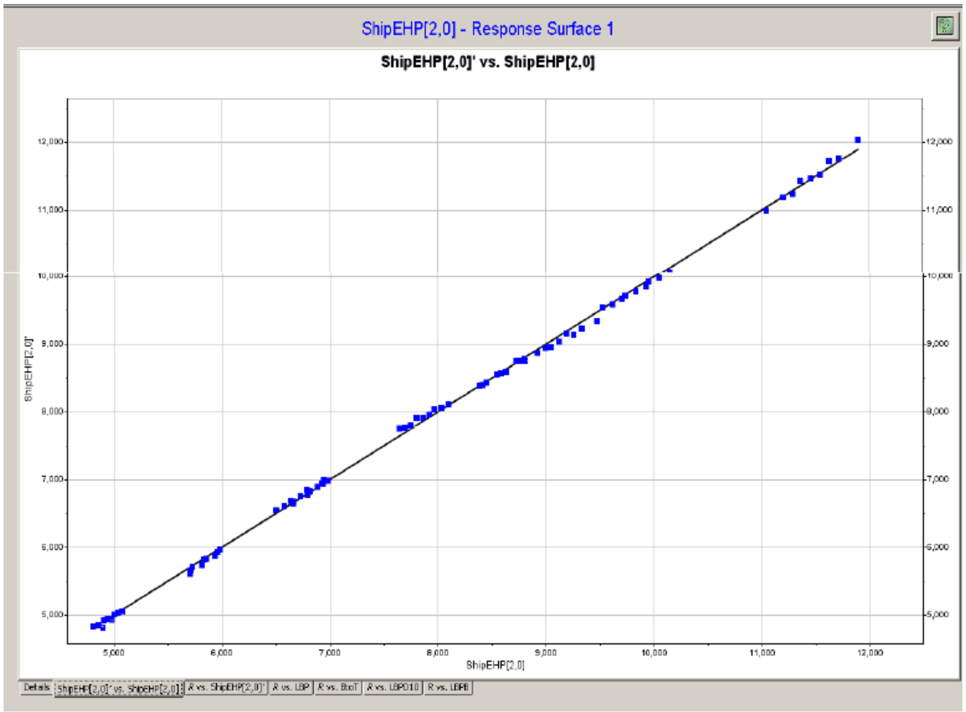


Figure 28: Effective horsepower RSM

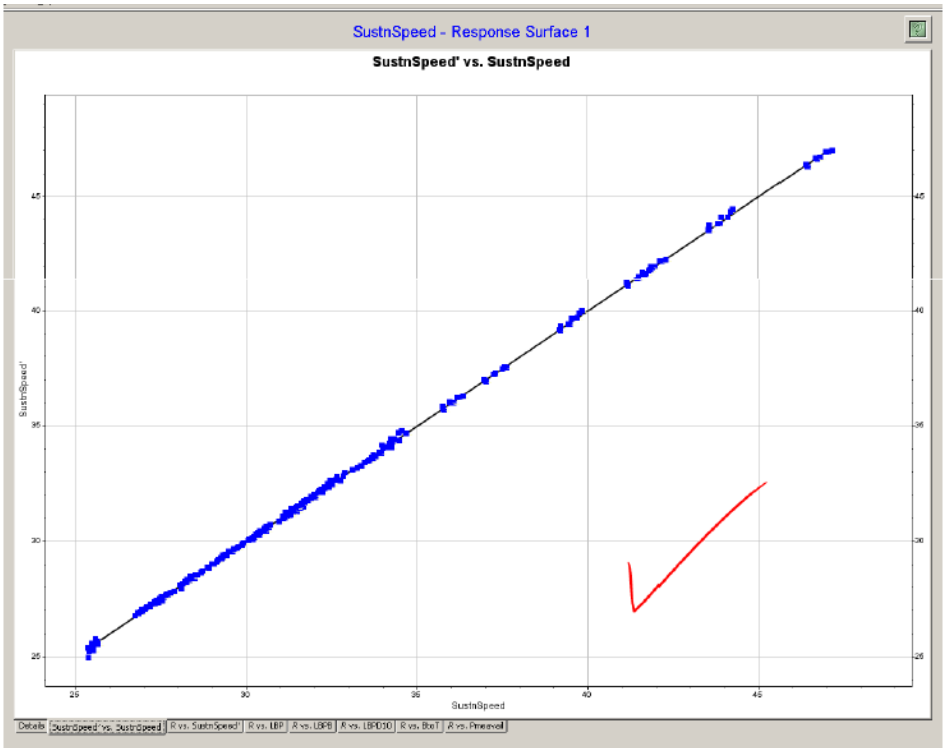


Figure 29: Sustained Speed RSM

Each of the modules produced were linked together as seen in Figure 30. An input module was created in addition to the modules previously discussed in order to input the design variables necessary for preliminary calculations. All other variables in the ship design process were produced by each of the modules. By linking each module to subsequent modules, design variables were updated continuously. As a run completed this design process, the inputs were altered for the next run to maximize risk and effectiveness, while minimizing cost. Once the multi objective genetic optimization failed to improve on a run after a set number of attempts, the analysis was halted and it was possible to compare one run with another, thus manually deciding upon which baseline model to continue on with in the design process.

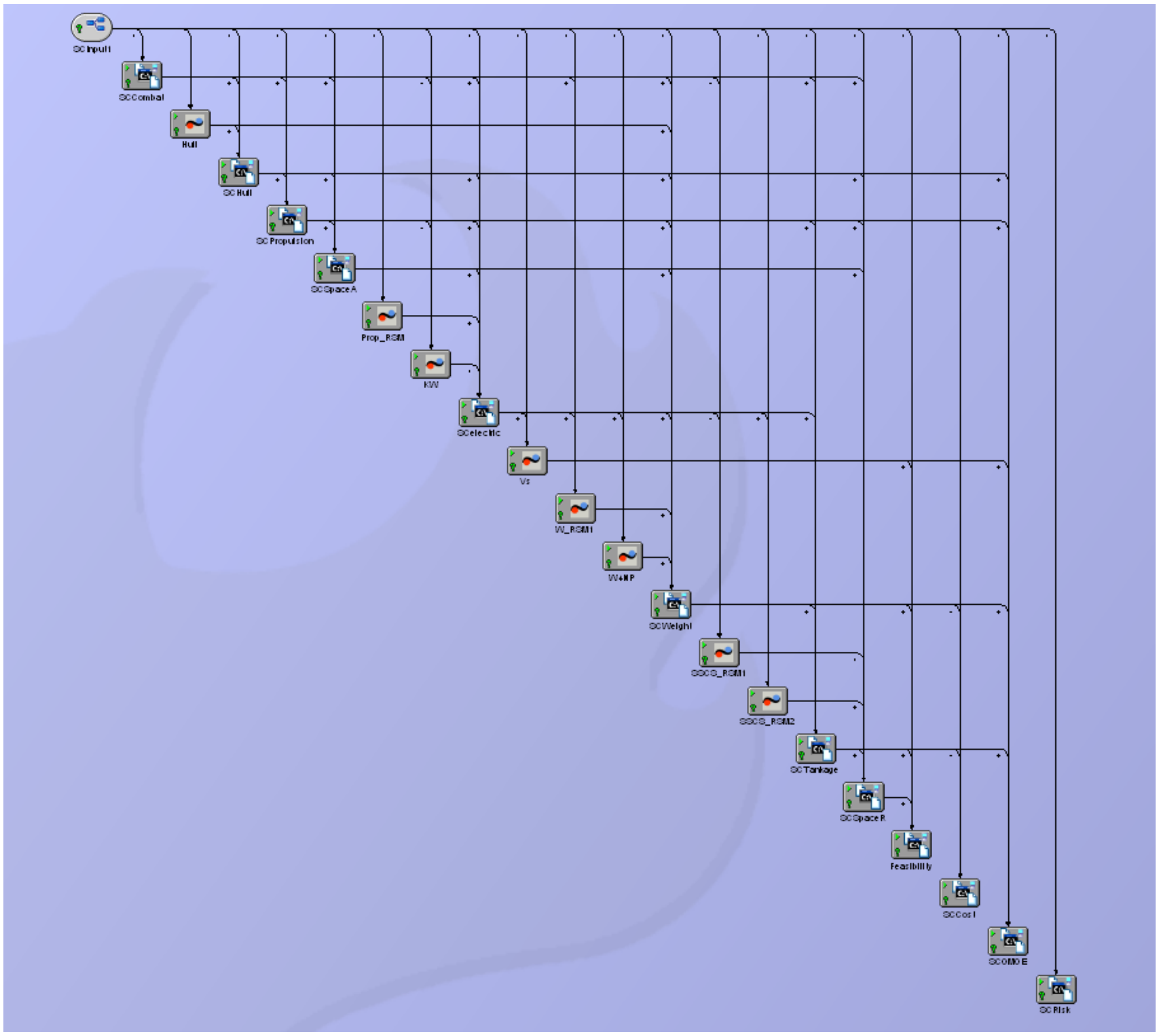


Figure 30 - Ship Synthesis Model in Model Center (MC)

3.4 Objective Attributes

3.4.1 Overall Measure of Effectiveness (OMOE)

The Overall Measure of Effectiveness (OMOE) is an overall figure of merit with an index number between 0 and 1 that describes the ships effectiveness in a collection of specified missions. The OMOE is based on several considerations including: the ship Measures of Performance (MOP's), environment, threat, defense and goals, missions, and mission scenarios. The Analytical Hierarchy Process (AHP) utilizes pair wise comparison to provide quantitative feedback for the Measures of Performance. The OMOE function is used to assess designs that have not been assembled yet. The first step is to identify the MOP's for goals and threshold values. The AHP and pairwise comparison will be used to calculate the weights of the different MOP's. To normalize the weights to a 0 (threshold) or 1 (goal) index, value functions are built for all the MOP metrics. The MOP values will then be input to the OMOE weight equation (shown below) to determine the overall measure of effectiveness.

$$\mathrm{OMOE} = g[\mathrm{VOP}_i(\mathrm{MOP}_i)] = \Sigma\ w_i \mathrm{VOP}_i(\mathrm{MOP}_i)$$

Table 18 - 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=7	LtoB=4
		MOP 15 - Es	LtoD	LtoD=11	LtoD=12
		MOP 15 - Es	BtoT	BtoT=3.2	BtoT=2.8
		MOP 15 - Es	PSYS	PSYS=1	PSYS=8
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=11	LtoD=15
		MOP 11 - Seakeeping and Stability	BtoT	BtoT=2.8	BtoT=3.2
		MOP 10 - RCS	VD	VD=200,000ft^3	VD=140,000ft^3
		MOP 12 - VUL	Cdmat	Cdmat=1	Cdmat=2 or 3
		MOP 12 - VUL	HULLtype	HULLtype=2	HULLtype=1
		MOP 7 - IR	PSYS	PSYS=1	PSYS=8
		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=7	LtoB=10
		MOP 15 - Es	LtoD	LtoD=11	LtoD=15
		MOP 15 - Es	BtoT	BtoT=3.2	BtoT=2.8
		MOP 15 - Es	PSYS	PSYS=1	PSYS=8
		MOP 14 - Ts	Ts	Ts=35 days	Ts=20 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=11	LtoD=15
		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=3
		MOP 18 - GMLS/NSFS/STK	GMLS/NSFS/STK	GMLS/NSFS/STK=1	GMLS/NSFS/STK=4
AAW 2	Provide anti-air defense in cooperation with other forces	MOP 1 - AAW	AAW/SEW	AAW/SEW=1	AAW/SEW=3
		MOP 1 - AAW	C4ISR	C4I=1	C4I=2
		MOP 18 - GMLS/NSFS/STK	GMLS/NSFS/STK	GMLS/NSFS/STK=1	GMLS/NSFS/STK=4
AAW 5	Provide passive and soft kill anti-air defense	MOP 1 - AAW	AAW/SEW	AAW/SEW=1	AAW/SEW=3
AAW 6	Detect, identify and track air targets	MOP 1 - AAW	AAW/SEW	AAW/SEW=1	AAW/SEW=3
AAW 9	Engage airborne threats using surface-to-air armament	MOP 1 - AAW	AAW/SEW	AAW/SEW=1	AAW/SEW=3
ASU 1	Engage surface threats with anti-surface armaments	MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3
		MOP 2 - ASUW	LAMPS	LAMPS=1	LAMPS=3

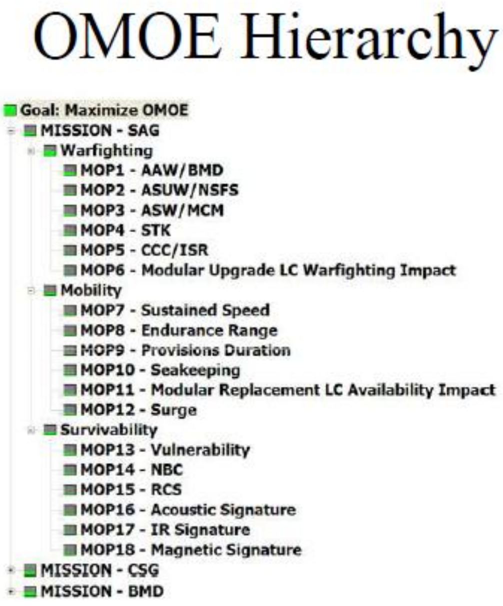
ASU 1.3	Engage surface ships at close range (gun)	MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3
ASU 1.5	Engage surface ships with medium caliber gunfire	MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3
ASU 1.6	Engage surface ships with minor caliber gunfire	MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3
ASU 1.9	Engage surface ships with small arms gunfire	MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3
ASU 2	Engage surface ships in cooperation with other forces	MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3
		MOP 4 - C4ISR	C4ISR	C4ISR=1	C4ISR=2
ASU 4.1	Detect and track a surface target with radar	MOP 2 - AAW	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	LAMPS	LAMPS=1	LAMPS=3
		MOP 3 - ASW	ASW/MCM	ASW/MCM=1	ASW/MCM=3
		MOP 3 - ASW	C4ISR	C4ISR=1	C4ISR=2
ASW 5	Support airborne ASW/recon	MOP 3 - ASW	LAMPS	LAMPS=1	LAMPS=3
		MOP 3 - ASW	C4ISR	C4ISR=1	C4ISR=2
ASW 8	Disengage, evade, avoid and deceive submarines	MOP 13 - Vs	LtoB	LtoB=7	LtoB=4
		MOP 13 - Vs	LtoD	LtoD=11	LtoD=12
		MOP 13 - Vs	BtoT	BtoT=3.2	BtoT=2.8
		MOP 13 - Vs	PSYS	PSYS=1	PSYS=8
		MOP 3 - ASW	ASW/MCM	ASW/MCM=1	ASW/MCM=3
MIW 4	Conduct mine avoidance	MOP 3 - ASW	ASW/MCM	ASW/MCM=1	ASW/MCM=3
MIW 6.7	Maintain magnetic signature limits	MOP 12 - VUL	Cdmat	Cdmat=2 or 3	Cdmat=1
		MOP 12 - VUL	Ndegaus	Ndegaus=1	Ndegaus=0
CCC 1	Provide command and control facilities	Required in All Designs	C4ISR		
CCC 3	Provide own unit Command and Control	Required in All Designs	C4ISR		
CCC 4	Maintain data link capability	Required in All Designs	C4ISR		
CCC 6	Provide communications for own unit	Required in All Designs	C4ISR		
CCC 9	Relay communications	Required in All Designs	C4ISR		
CCC 21	Perform cooperative engagement	Required in All Designs	C4ISR		
SEW 2	Conduct sensor and ECM operations	MOP 1 - AAW	AAW/BMD	AAW/BMD=1	AAW/SEW=3
SEW 3	Conduct sensor and ECCM operations	MOP 1 - AAW	AAW/BMD	AAW/BMD=1	AAW/SEW=3
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	LtoB	LtoB=7	LtoB=4
		MOP 13 - Vs	LtoD	LtoD=11	LtoD=12
		MOP 13 - Vs	BtoT	BtoT=3.2	BtoT=2.8
		MOP 13 - Vs	PSYS	PSYS=1	PSYS=8
		MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3
		MOP 5 - FSO/NCO	LAMPS	LAMPS=1	LAMPS=1
FSO 9	Provide routine health care	Required in All Designs			
FSO 10	Provide first aid assistance	Required in All Designs			
INT 1	Support/conduct intelligence collection	MOP 19 - MMOD	MMOD	MMOD=1	MMOD=4
INT 2	Provide intelligence	MOP 19 - MMOD	MMOD	MMOD=1	MMOD=4

INT 3	Conduct surveillance and reconnaissance	MOP 19 - MMOD	MMOD	MMOD=1	MMOD=4
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)	Required in All Designs			
NCO 3	Provide upkeep and maintenance of own unit	Required in All Designs			
NCO 19	Conduct maritime law enforcement operations	MOP 2 - ASUW	ASUW	ASUW=1	ASUW=3
		MOP 13 - Vs	LtoB	LtoB=7	LtoB=4
		MOP 13 - Vs	LtoD	LtoD=11	LtoD=12
		MOP 13 - Vs	BtoT	BtoT=3.2	BtoT=2.8
		MOP 13 - Vs	PSYS	PSYS=1	PSYS=8
	Conduct Naval Surface Fire Support (NSFS) operations	MOP 18 - GMLS/NSFS/STK	GMLS/NSFS/STK	GMLS/NSFS/STK=1	GMLS/NSFS/STK=4
	Detect and Engage Hostile Ballistic Missiles	MOP 18 - GMLS/NSFS/STK	GMLS/NSFS/STK	GMLS/NSFS/STK=1	GMLS/NSFS/STK=4
		MOP 1 - AAW	AAW/BMD	AAW/BMD=1	AAW/BMD=4
	Conduct Long Range precision strike operations	MOP 18 - GMLS/NSFS/STK	GMLS/NSFS/STK	GMLS/NSFS/STK=1	GMLS/NSFS/STK=4

Table 19 - MOP Table

MOP#	MOP	Goal	Threshold	Related DV
1	AAW/ BMD	AAW/BMD=1 C4I=1	AAW/BMD=4	AAW/BMD option C4I option
2	ASUW/ NSFS	ASUW=1	ASUW=3	ASUW option
		MMOD=1	MMOD=4	MMOD
		LAMPS=1 C4I=1		LAMPS option C4I option
3	ASW	ASW/MCM=1 MMOD=1 MMOD=1 LAMPS=1 C4I=1	ASW/MCM=3 MMOD=4 MMOD=4	ASW/MCM option MMOD MMOD LAMPS option C4I option
4	C4ISR	C4I=1		C4I option
5	STK	C4I=1 GMLS		
7	IR	SPGM		
8	NBC	Ncps=2	Ncps=0	CPS option
9	RCS	VD=140,000	VD=200,000	Deckhouse volume, ft^3
10	Seakeeping and Stability	HullTYPE=1	HullTYPE=0	LBP 480-630 ft LtoB 7-10 LtoD 11-15 BtoD 2.8-3.2
11	VUL (Vulnerability)	Cdmat=1	Cdmat=3	Ship material (Steel)
12	Vs (Sprint Speed)	35	30	knots
13	Ts (Provisions)	75	60	days

14	Es (Endurance range at 18 kt)	8000	4000	nm
15	Acoustic signature	SPGM		
16	Magnetic Signature	Degaus=1	Degaus=0	Degaussing
17	Modularity for VPG			
18	Modularity for Replacement			
19	MMOD	MMOD=1	MMOD=4	MMOD

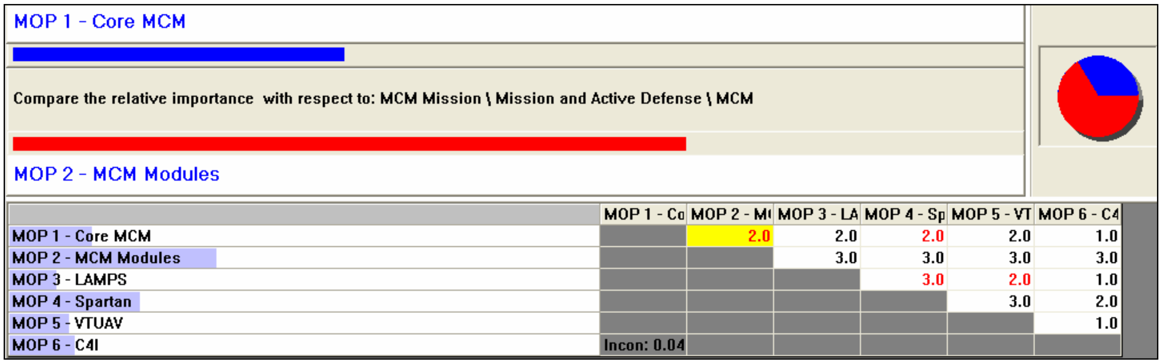


OMOE Hierarchy

- Goal: Maximize OMOE
  - MISSION - SAG
    - Warfighting
      - MOP1 - AAW/BMD
      - MOP2 - ASUW/NSFS
      - MOP3 - ASW/MCM
      - MOP4 - STK
      - MOP5 - CCC/ISR
      - MOP6 - Modular Upgrade LC Warfighting Impact
    - Mobility
      - MOP7 - Sustained Speed
      - MOP8 - Endurance Range
      - MOP9 - Provisions Duration
      - MOP10 - Seakeeping
      - MOP11 - Modular Replacement LC Availability Impact
      - MOP12 - Surge
    - Survivability
      - MOP13 - Vulnerability
      - MOP14 - NBC
      - MOP15 - RCS
      - MOP16 - Acoustic Signature
      - MOP17 - IR Signature
      - MOP18 - Magnetic Signature
  - MISSION - CSG
  - MISSION - BMD

Figure 31 - OMOE Hierarchy

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



MOP 1 - Core MCM

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

MOP 2 - MCM Modules

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

Figure 32 - AHP Pairwise Comparison

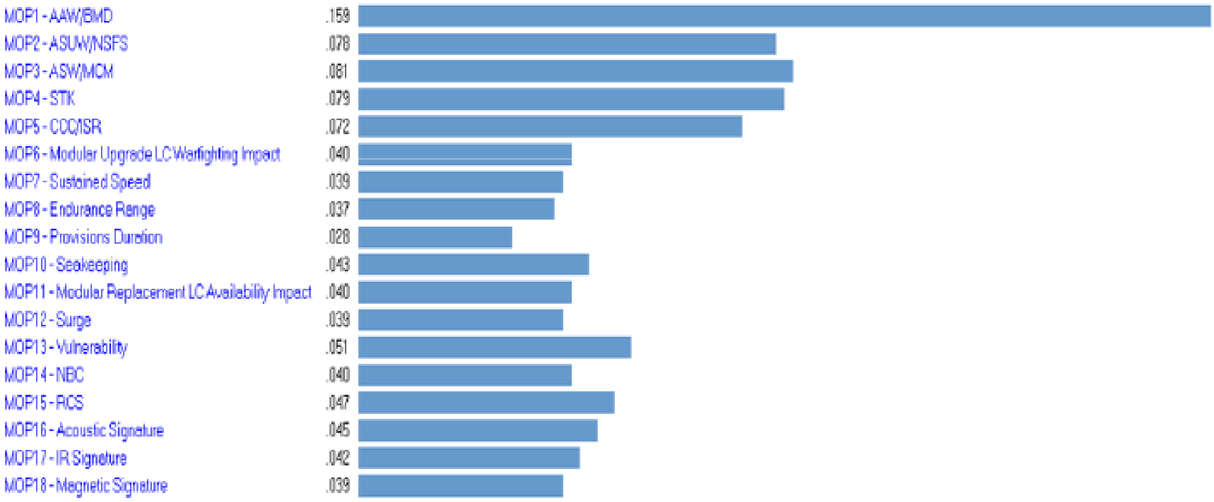


Figure 33 – Bar Chart Showing MOP Weights

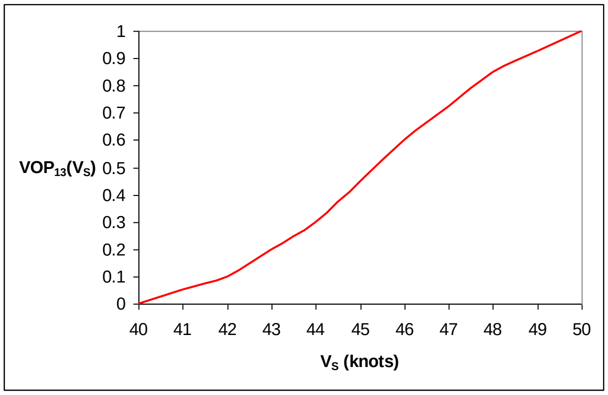


Figure 34 - Value of Performance Function for Sprint (Sustained) Speed

3.4.2 Overall Measure of Risk (OMOR)

The risk inherent in a particular design is something that is very important to consider in the design of a ship. Depending on the desires of the customer, a higher level of risk may be desired in order to achieve advanced performance metrics. On the other hand risk may need to be minimized in order to provide the customer with a safe and proven design. This risk is defined as the product of the probability of the event occurring and the consequences of that event occurring. Each of these measures is on the scale of from 0 to 1, with 1 being a certainty and 0 being impossible. Detailed metrics for analyzing the probability and consequence values are found in Table 20 and Table 21 respectively.

There are three types of risk: performance, schedule, and cost. Performance risk takes into account a component of the design not being able to perform up to the promised standards. Schedule risk accounts for a delay in the timeline of production of the ship or its components which could lead to other risk events. Cost risk takes into account components of a ship being more expensive than originally promised. An equation for summing these risks has been developed and is called the overall measure of risk. This equation, seen below, gives a quantitative measure of just how risky the design of a ship is. It was used to develop the risk register for the MSC, which can be seen below in Table 19.

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

Table 20 - Risk Register

SWBS	Risk Type	Related DV #	DV Options	DV Description	Risk Event Ei	Event #	Pi	Ci	Ri
2	Performance	DV9	3	Podded Propulsion	Does not meet performance TLRs specifically in vulnerability to underwater shock	1	0.7	0.7	0.49
2	Performance	DV7-11	6,7,3,2,2	Integrated electric drive	Does not meet performance TLRs	2	0.3	0.6	0.18
2	Schedule	DV7-11	6,7,3,2,3	Integrated electric drive	Schedule delays impact program	3	0.3	0.3	0.09
2	Cost	DV7-11	6,7,3,2,4	Integrated electric drive	Development and acquisition cost overruns	4	0.3	0.6	0.18
2	Performance	DV11	2	Prop Motor	Does not meet performance TLRs	5	0.5	0.4	0.2
2	Schedule	DV11	2	Prop Motor	Schedule delays impact program	6	0.5	0.4	0.2
2	Cost	DV11	2	Prop Motor	Development and acquisition cost overruns	7	0.3	0.4	0.12
4	Performance	DV21/23	3	AGS Primary gun mount	Does not meet performance TLRs	8	0.4	0.5	0.2
4	Schedule	DV21/23	3	AGS Primary gun mount	Schedule delays impact program	9	0.3	0.35	0.105
4	Cost	DV21/23	3	AGS Primary gun mount	Development and acquisition cost overruns	10	0.3	0.65	0.195
7	Performance	DV19	1	Automation Factor	Does not meet performance TLRs	11	0.4	0.45	0.18
7	Schedule	DV19	1	Automation Factor	Schedule delays impact program	12	0.4	0.3	0.12
7	Cost	DV19	1	Automation Factor	Development and acquisition cost overruns	13	0.4	0.7	0.28
7	Performance	DV20	3	VSR	Does not meet performance TLRs	14	0.4	0.4	0.16
7	Schedule	DV20	3	VSR	Schedule delays impact program	15	0.3	0.5	0.15
7	Cost	DV20	3	VSR	Development and acquisition cost overruns	16	0.4	0.5	0.2

Table 21 - 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 22 - 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

The cost model used is a weight based cost model. The model takes the SWBS 100-700 weights as inputs, along with crew size, endurance speed, engine power, fuel consumption, propulsion system, and materials. Inflation rate, a base year, total class size, and the rate of procurement are used to predict follow ship acquisition costs and total lifecycle costs. An inflation factor is calculated from the inflation rate and the base year. Complexity factors for the SWBS groups are calculated based on design variables. These complexity factors relate the relative complexity in design and construction of the chosen equipment to the complexity of the design variables that the estimate is based off of. New technologies have higher complexity factors compared with proven designs and equipment, and the relative complexity of a system declines with time. Each SWBS weight is multiplied by the complexity factor and the cost estimate from the empirical data. The average cost per ton for SWBS 100-700 groups is multiplied by the margin weight and added to the SWBS 800-900 costs. This gives the basic cost of construction of the lead ship. Added to this are other acquisition costs, including profit for the shipbuilder, change order costs, government costs, outfitting costs, and payload costs. The government cost is a percentage of the weights for the payload, based on an estimate of the payload that the government furnishes. The government cost also includes costs for government provided hull, mechanical and electrical equipment, and the outfitting costs to install the equipment and payloads. A delivery cost is added to the overall cost, giving the total lead ship acquisition cost. Figure 35 shows a hierarchy of the lead ship acquisition cost.

Follow ship costs are based on the SWBS 100-700 costs from the lead ship, adjusted for inflation to the middle year of production. Added to this are significantly reduced SWBS 800-900 costs to reflect the lower requirements for design and engineering support work for follow ships. These costs are reduced slightly for every follow ship to reflect the learning curve that occurs as shipyards build the same design repeatedly and make improvements in construction techniques. Similar additional costs are added as for the lead ship to reflect the government provided equipment, shipbuilder profit, and delivery costs.

Life cycle costs can be determined by multiplying the annual costs for fuel and manning by the life of the ship and a factor that reflects the time value of money; money now is worth more now than money in the future is worth now. This gives an operating cost that can be added to the acquisition cost to give the lifecycle cost.

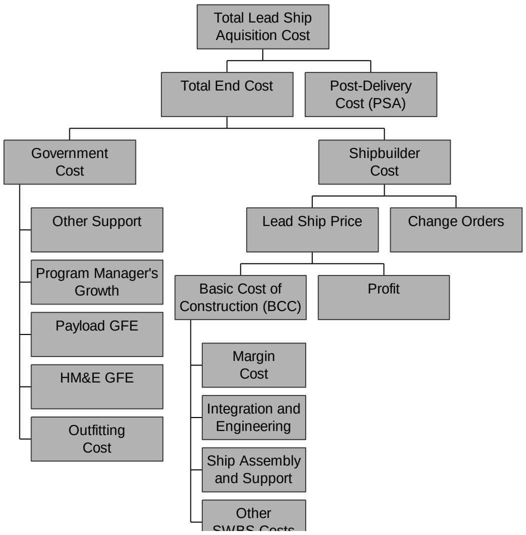
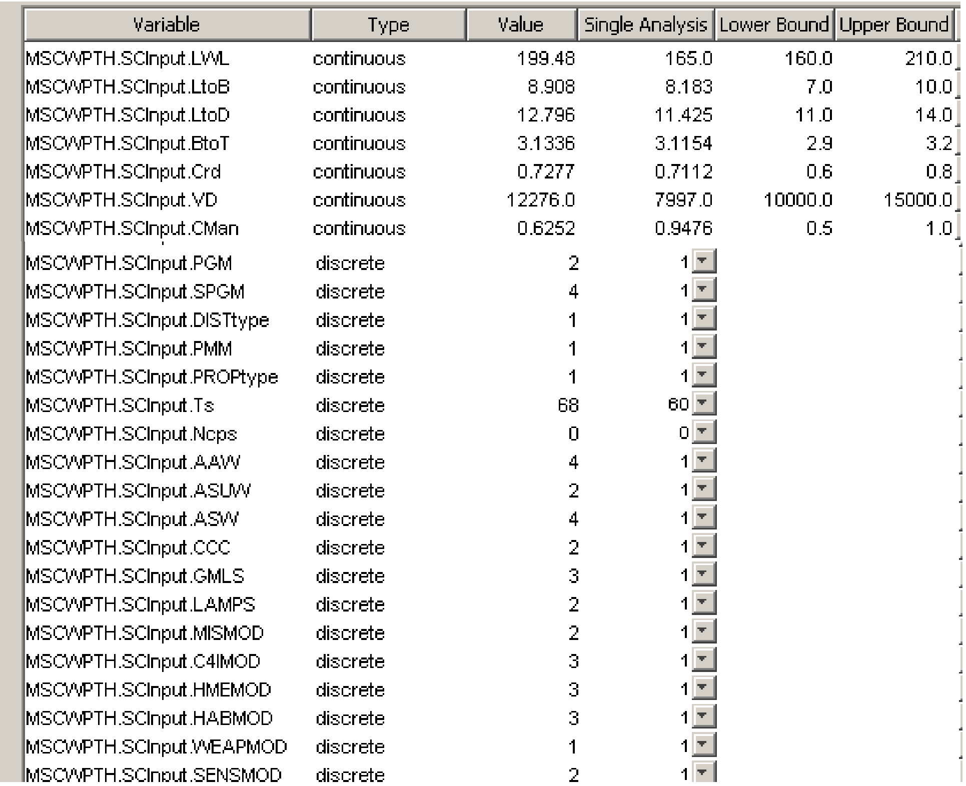


Figure 35 Lead Ship Acquisition Cost

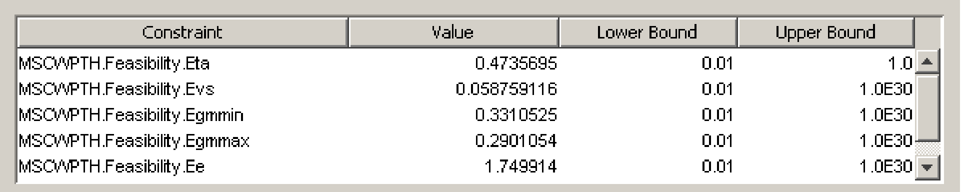
3.5 Multi-Objective Optimization

The multi-objective genetic optimization (MOGO) of the synthesis model was performed in Model Center, specifically the Darwin genetic algorithm. The MOGO consists of three components: objectives, constraints, and design variables. Objectives for the optimization are the total overall cost (CTOC), overall measure of risk (OMOR), and overall measure of effectiveness (OMOE). The total overall cost and overall measure of risk were minimized while overall measure of effectiveness was maximized. The constraints of the optimization were defined as the error functions of the feasibility module. The design variables were primarily the inputs for the synthesis model; consisting of continuous variables such as, overall length, beam to depth ratio, coefficient of manning, and also discrete variables such as weapons module, sensor module, and anti aircraft warfare type. The tolerance must be adjusted for the continuous variables in order to obtain the correct amount of discrete choices. The objectives, constraints, and design variables used in the MOGO are shown below in Figure 36.



Variable	Type	Value	Single Analysis	Lower Bound	Upper Bound
MSCWPTH.SCInput.LWL	continuous	199.48	165.0	160.0	210.0
MSCWPTH.SCInput.LtoB	continuous	8.908	8.183	7.0	10.0
MSCWPTH.SCInput.LtoD	continuous	12.796	11.425	11.0	14.0
MSCWPTH.SCInput.BtoT	continuous	3.1336	3.1154	2.9	3.2
MSCWPTH.SCInput.Crd	continuous	0.7277	0.7112	0.6	0.8
MSCWPTH.SCInput.VD	continuous	12276.0	7997.0	10000.0	15000.0
MSCWPTH.SCInput.CMan	continuous	0.6252	0.9476	0.5	1.0
MSCWPTH.SCInput.PGM	discrete	2	1		
MSCWPTH.SCInput.SPGM	discrete	4	1		
MSCWPTH.SCInput.DISTtype	discrete	1	1		
MSCWPTH.SCInput.PMM	discrete	1	1		
MSCWPTH.SCInput.PROPtype	discrete	1	1		
MSCWPTH.SCInput.Ts	discrete	68	60		
MSCWPTH.SCInput.Ncps	discrete	0	0		
MSCWPTH.SCInput.AAW	discrete	4	1		
MSCWPTH.SCInput.ASUW	discrete	2	1		
MSCWPTH.SCInput.ASW	discrete	4	1		
MSCWPTH.SCInput.CCC	discrete	2	1		
MSCWPTH.SCInput.GMLS	discrete	3	1		
MSCWPTH.SCInput.LAMPS	discrete	2	1		
MSCWPTH.SCInput.MISMOD	discrete	2	1		
MSCWPTH.SCInput.C4IMOD	discrete	3	1		
MSCWPTH.SCInput.HMEMOD	discrete	3	1		
MSCWPTH.SCInput.HABMOD	discrete	3	1		
MSCWPTH.SCInput.WEAPMOD	discrete	1	1		
MSCWPTH.SCInput.SENSMOD	discrete	2	1		

Figure 36- Design variable table from Darwin genetic optimizer



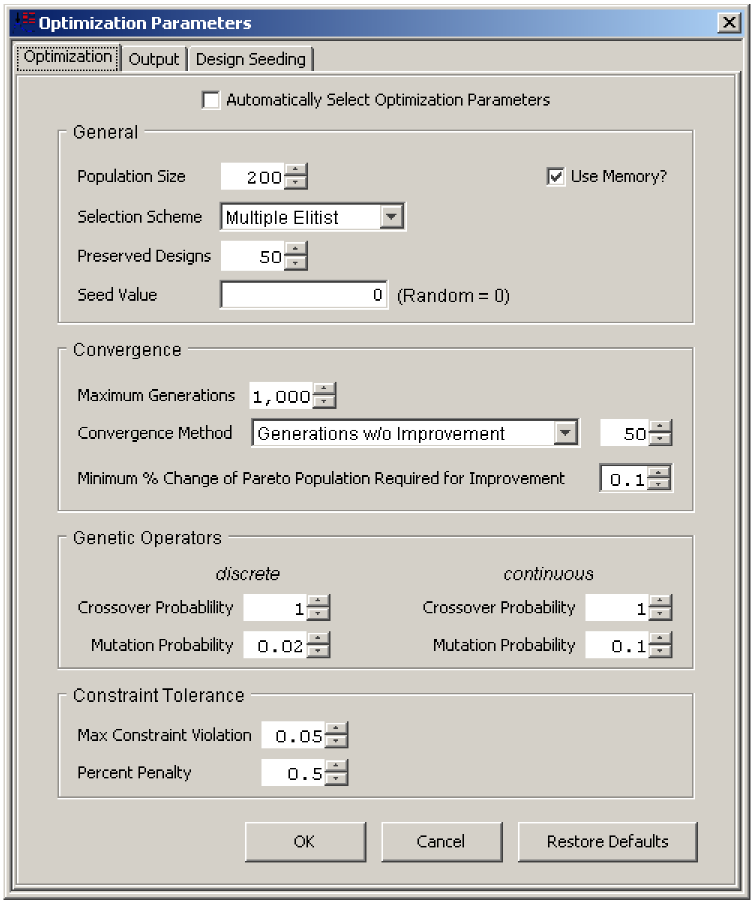
Constraint	Value	Lower Bound	Upper Bound
MSCWPTH.Feasibility.Eta	0.4735695	0.01	1.0
MSCWPTH.Feasibility.Evs	0.058759116	0.01	1.0E30
MSCWPTH.Feasibility.Egmmin	0.3310525	0.01	1.0E30
MSCWPTH.Feasibility.Egmmax	0.2901054	0.01	1.0E30
MSCWPTH.Feasibility.Ee	1.749914	0.01	1.0E30

Figure 37- Constraint table from Darwin genetic optimizer

Objective	Value	Goal
MSCWPTH.SCCost.CTOC	3075.273	minimize
MSCWPTH.SCRisk.OMOR	0.1246637	minimize
MSCWPTH.SCOMOE.OMOE	0.4770024	maximize

Figure 38- Objective table from Darwin genetic optimizer

The tables above show upper and lower bounds for the constraints and design variables. The constraints have a lower bound near zero, a small but non-zero number works better for the optimization. The upper bound is somewhat inconsequential. The upper and lower bounds for the design variables were set at reasonable margins higher and lower than the synthesis model values. The optimization parameters are then set for population size (150), preserved designs (50), convergence method (50 generations w/o improvement), and mutation probability (.02). The optimization was saved and linked to the model and then ran.



☐ Automatically Select Optimization Parameters

General

Population Size 200

☑ Use Memory?

Selection Scheme Multiple Elitist

Preserved Designs 50

Seed Value 0 (Random = 0)

Convergence

Maximum Generations 1,000

Convergence Method Generations w/o Improvement 50

Minimum % Change of Pareto Population Required for Improvement 0.1

Genetic Operators

	discrete		*continuous*
Crossover Probablility	1	Crossover Probability	1
Mutation Probability	0.02	Mutation Probability	0.1

Constraint Tolerance

Max Constraint Violation 0.05

Percent Penalty 0.5

Figure 39- Optimization parameters settings

3.6 Optimization Results and Initial Baseline Design (Variant XX)

The optimization generates a population of 200 designs and selects 50 “best” designs. The population of designs forms a non-dominated frontier that can be shown in Figure 40 below.

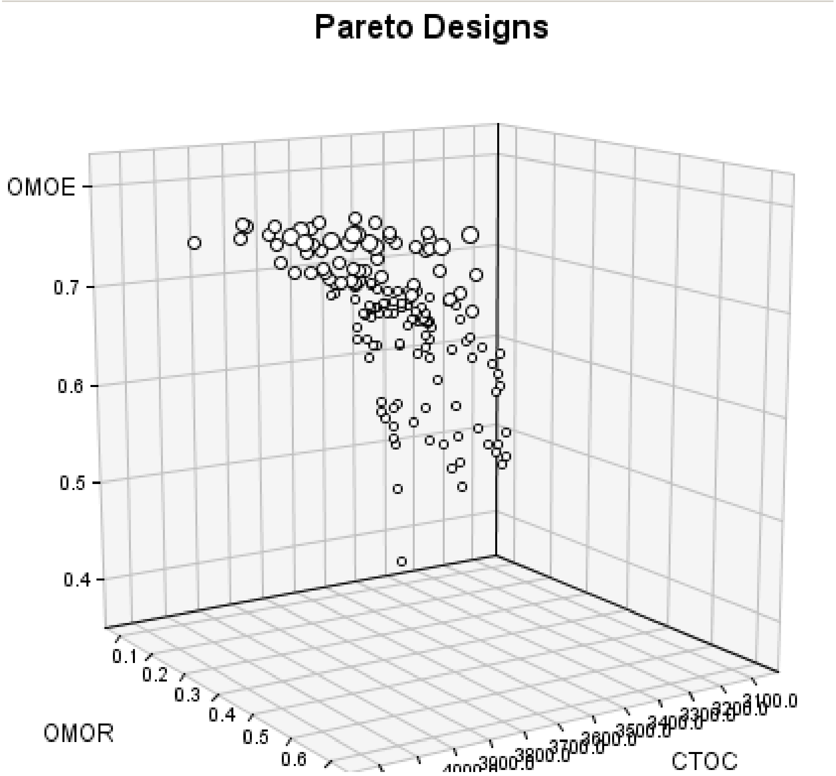


Figure 40- Non-Dominated Frontier

The data explorer was opened and shows the 50 best designs in tabular format. Each design can be looked at individually for its structure, modularity characteristics, etc… either in the data explorer or by clicking on a dot. The designs can be viewed in a Design Variable scatter plot in order to access the population for characteristics.

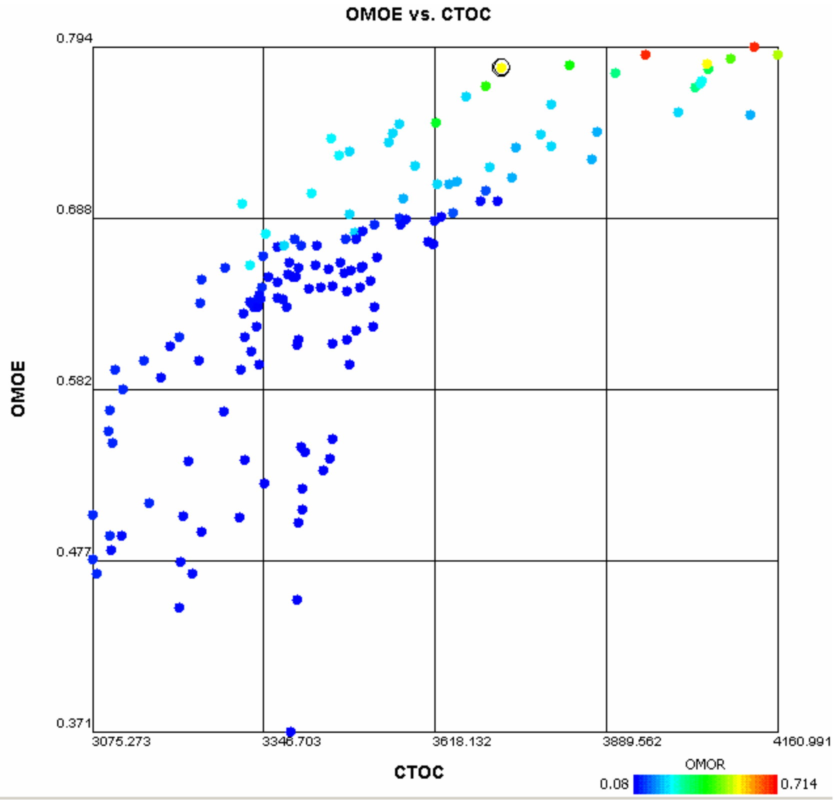
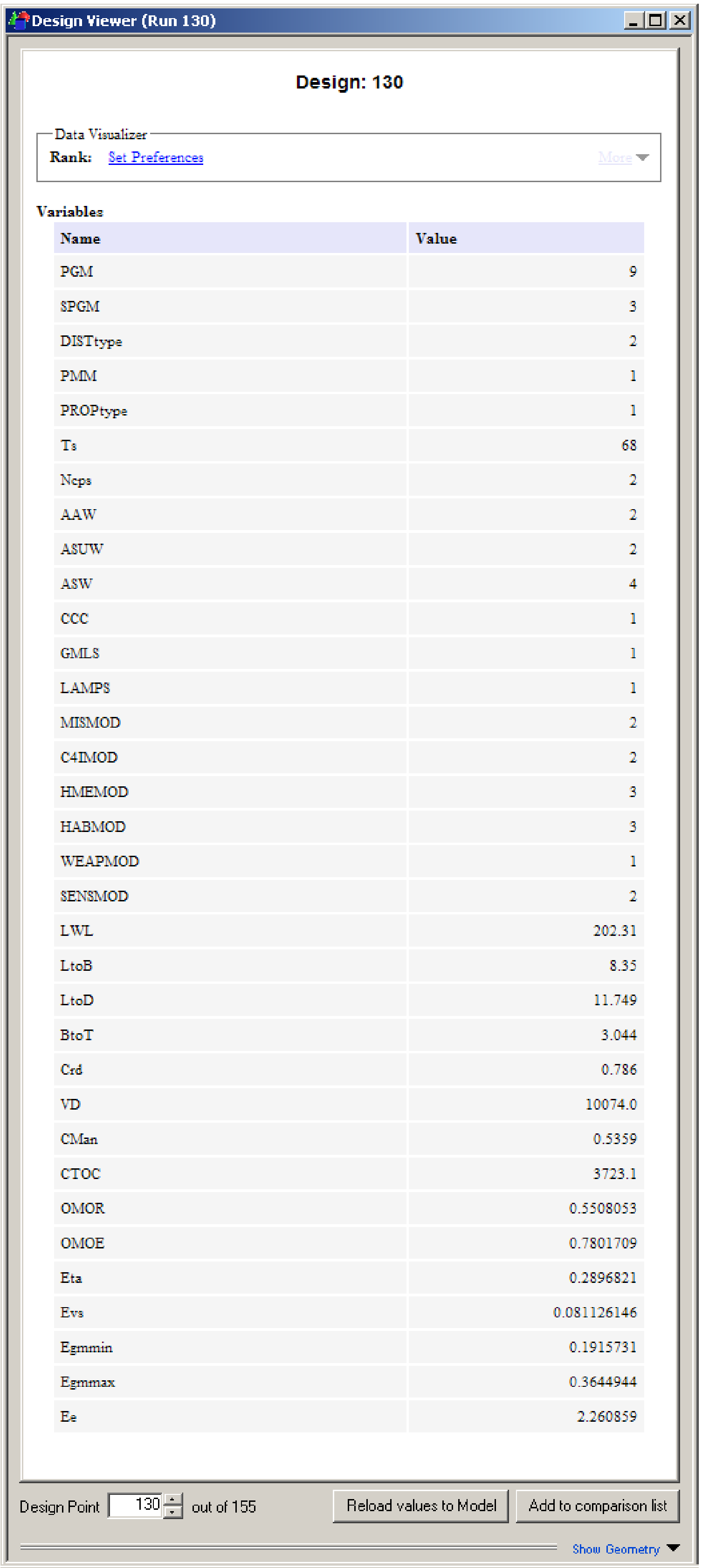


Figure 41: Plot of OMOE vs CTOC color coded by OMOR

This plot shows OMOE vs. CTOC vs. OMOR the higher the dot the more effective, the more left the dot the less expensive, and the cooler the color the less risky the design. Using this information the design above, circled in the graph above (design 130), was selected. This selection was made because that point is an "elbow" in the curve where it takes a lot more cost to get a small amount of effectiveness. The design is also below the maximum risk which is ideal. The design viewer below shows the ship characteristics of the design selected to be optimized further, design 130.



Design: 130

Variables

Name	Value
PGM	9
SPGM	3
DISTtype	2
PMM	1
PROPtype	1
Ts	68
Ncps	2
AAW	2
ASUW	2
ASW	4
CCC	1
GMLS	1
LAMPS	1
MISMOD	2
C4IMOD	2
HMEMOD	3
HABMOD	3
WEAPMOD	1
SENSMOD	2
LWL	202.31
LtoB	8.35
LtoD	11.749
BtoT	3.044
Crd	0.786
VD	10074.0
CMan	0.5359
CTOC	3723.1
OMOR	0.5508053
OMOE	0.7801709
Eta	0.2896821
Evs	0.081126146
Egmmin	0.1915731
Egmmax	0.3644944
Ee	2.260859

Design Point 130 out of 155

Figure 42: Design characteristics for the selected design, Design 130

The following plots are more design variable scatter plots of the population created by the optimization. Each plot shows the overall measure of risk plotted against total overall cost for each design. The designs are each specified a color based on a chosen characteristic that varies between the designs.

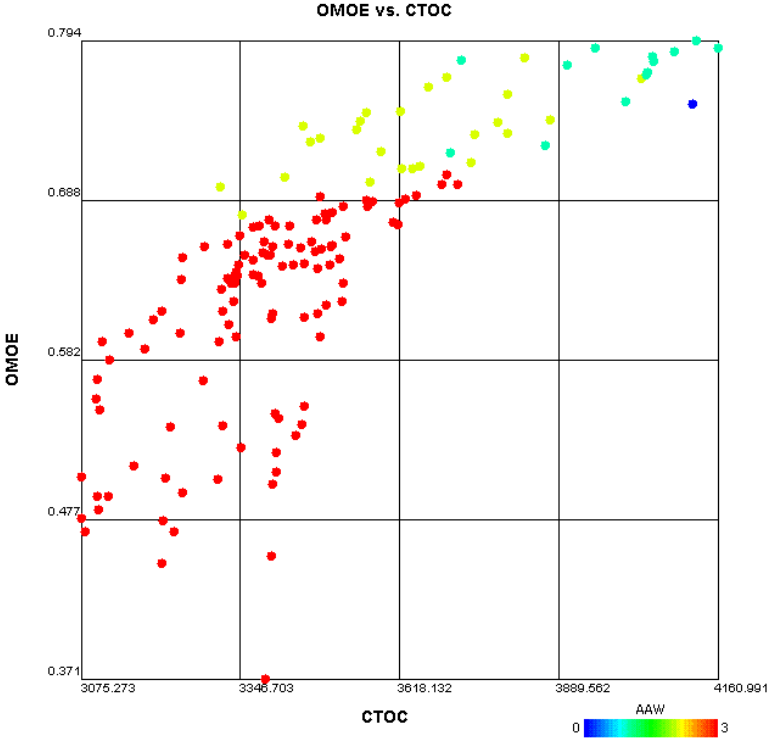


Figure 43: Plot of OMOE vs. CTOC color coded by Anti-Aircraft Warfare option

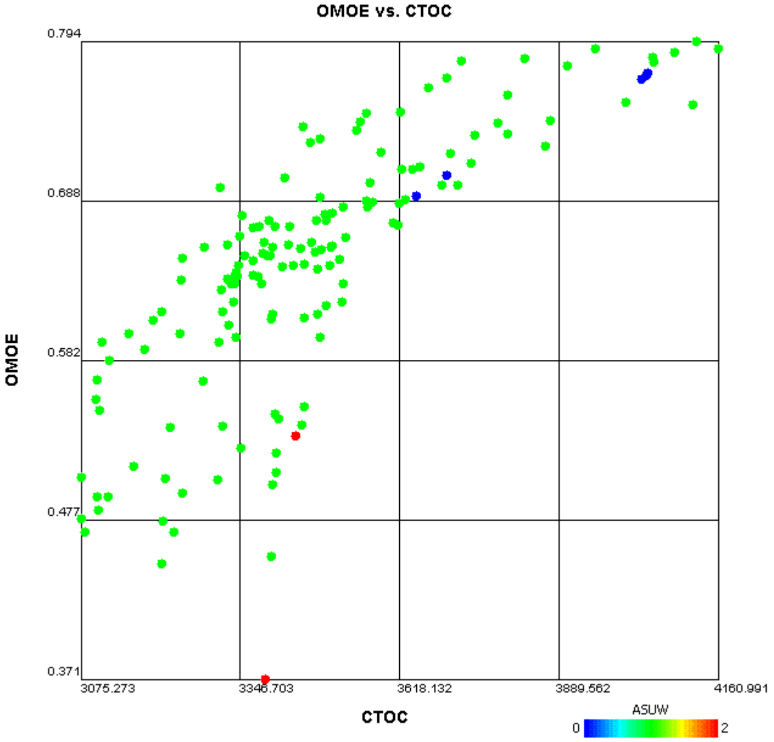


Figure 44: Plot of OMOE vs. CTOC color coded by Anti-Submersible Warfare option

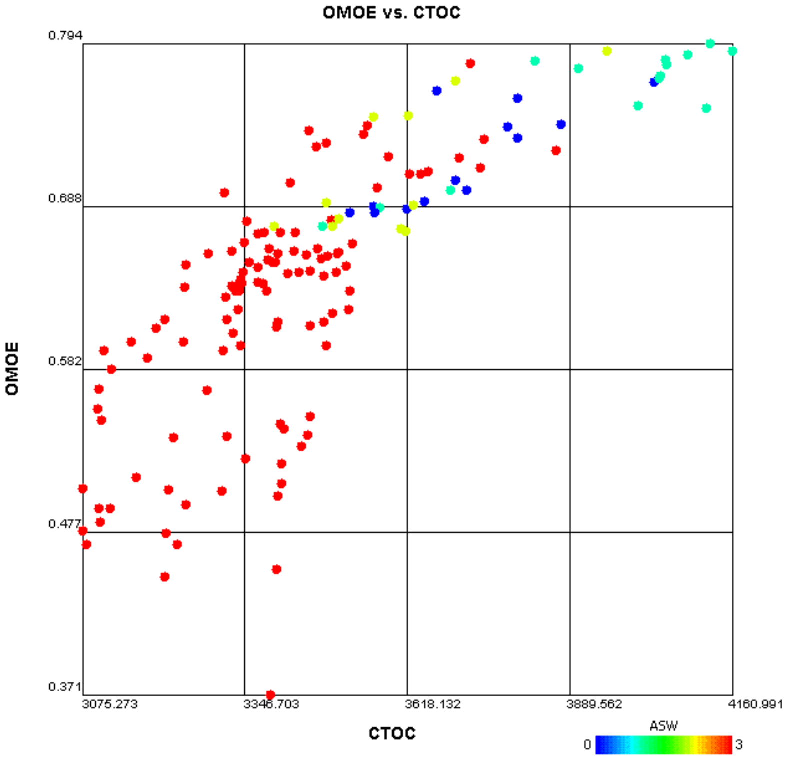


Figure 45: Plot of OMOE vs. CTOC color coded by Anti-Surface Warfare option

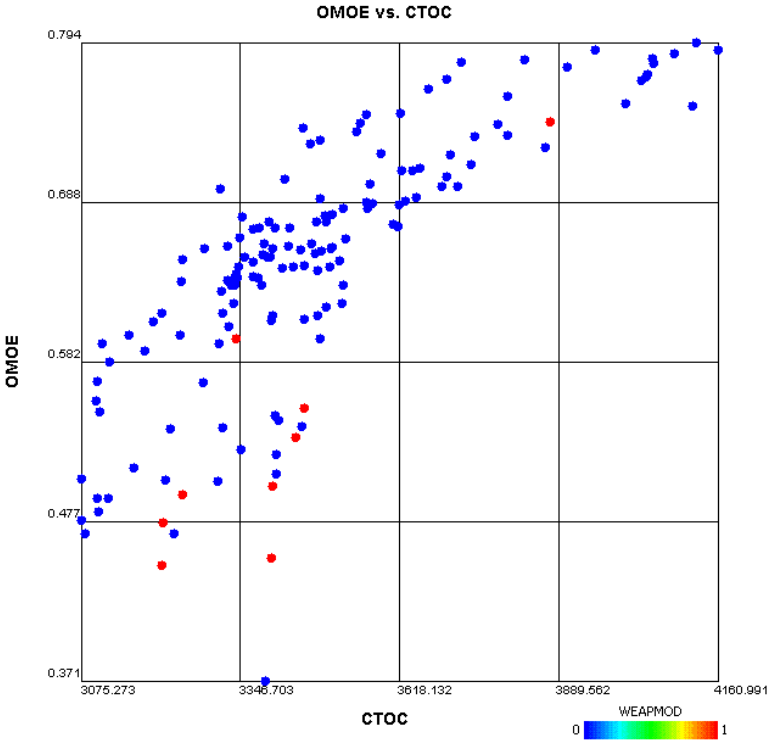


Figure 46: Plot of OMOE vs. CTOC color coded by Weapon Modularity option

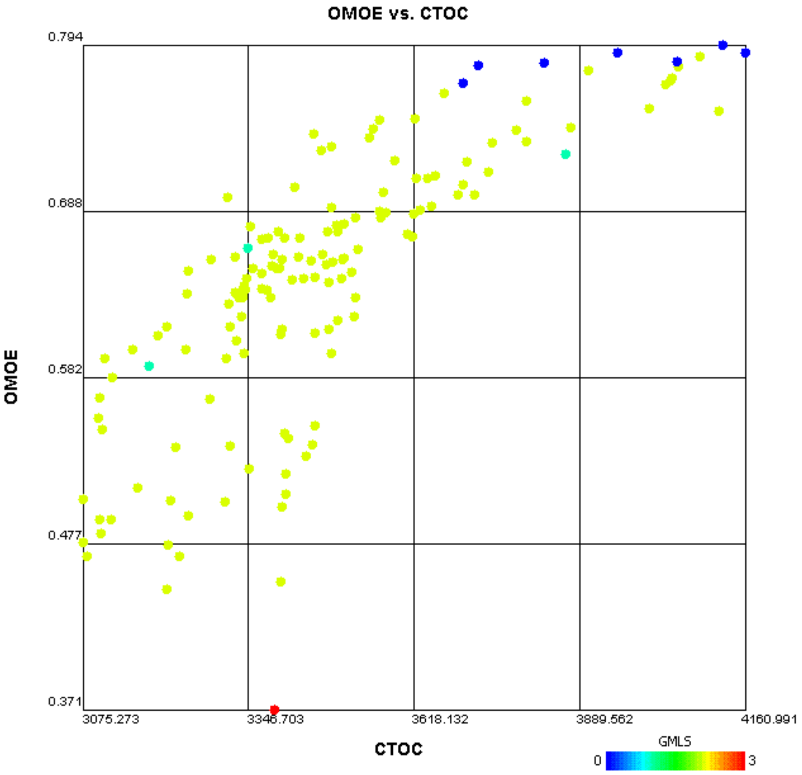


Figure 47: Plot of OMOE vs. CTOC color coded by Guided Missile Launching System option

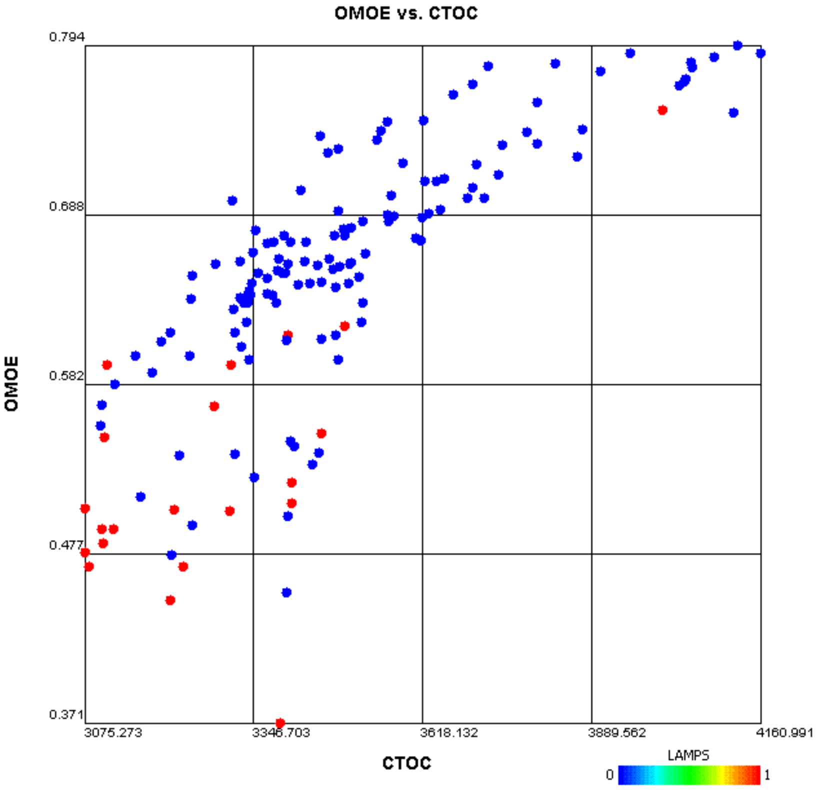


Figure 48: Plot of OMOE vs. CTOC color coded by LAMPS option

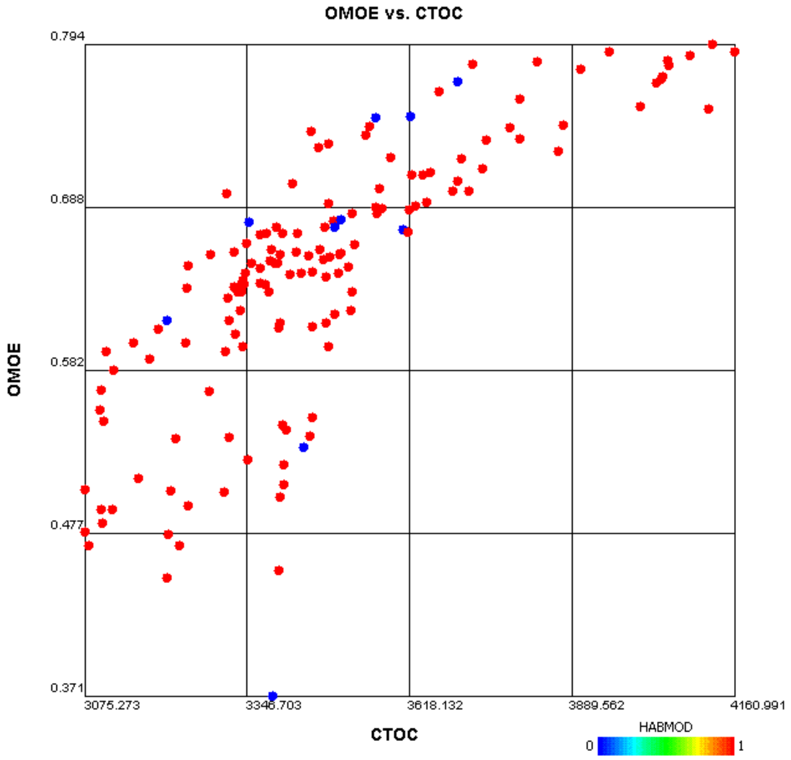


Figure 49: Plot of OMOE vs. CTOC color coded by Habitation Modularity option

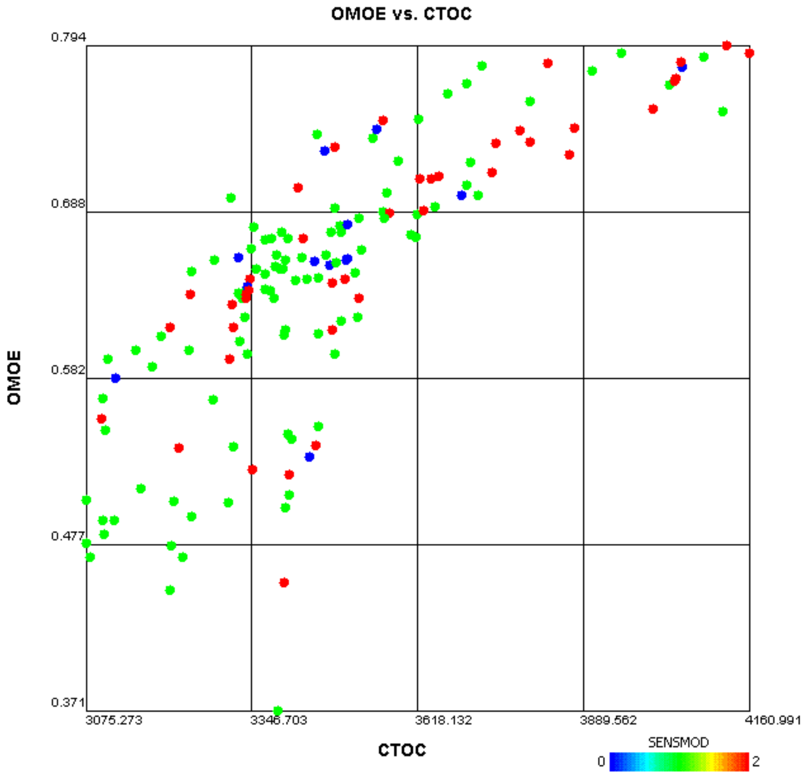


Figure 50: Plot of OMOE vs. CTOC color coded by Sensor Modularity option

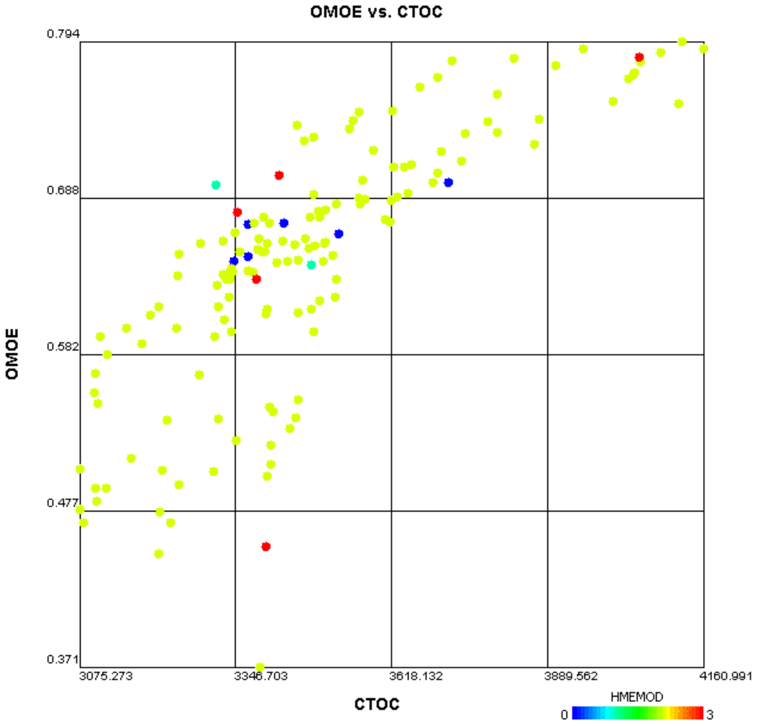


Figure 51: Plot of OMOE vs. CTOC color coded by HME Modularity option

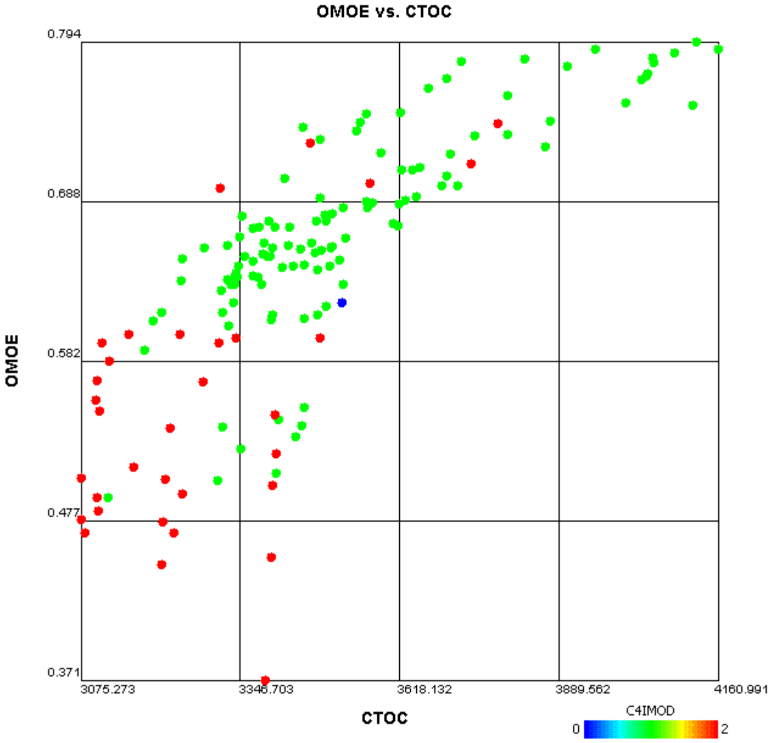


Figure 52: Plot of OMOE vs. CTOC color coded by C4I Modularity option

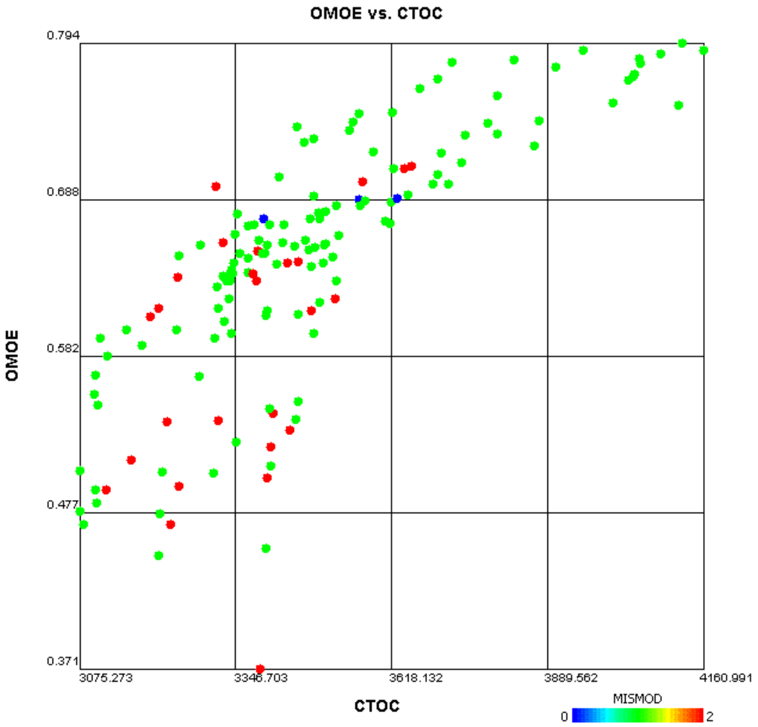


Figure 53: Plot of OMOE vs. CTOC color coded by Missile Modularity option

3.7 Improved Baseline Design – Single Objective Optimization

Using Design 130 from the multi objective genetic optimization, the design was again optimized in order to minimize the cost following the lead acquisition ship. Continuous variables were used as inputs in this optimization including length between perpendiculars, length to beam, length to depth, beam to draft, deckhouse volume, and manning automation factor. Discrete variables which were determined in the MOGO were held constant over this optimization. The cost of a ship following the lead acquisition was reduced to $2.49 billion. A design variable summary is given in Table 18. The optimized ship design has a length of 192.3 meters between perpendiculars, a length to beam ratio of 8.34, and a manning and automation factor of 0.54. This automation factor indicates a fairly advanced and automated ship, which would help in lowering life cycle costs by decreasing the manning required. Lower manning requirements do increase the risk of this design, but this risk was accounted for in the optimization. Further characteristics of the Single Optimization Design 130i are available in Tables 19 through 23.

Table 23: Design Variables Summary for Design 130i

DV #	DV Name	Description	Design Space	Design Value
1	LBP	Length Between Perpendiculars	160-205 m	192.3
2	LtoB	Length to Beam ratio	7-10	8.34
3	LtoD	Length to Depth ratio	11-14	11.92
4	BtoT	Beam to Draft ratio	2.9-3.2	3.19
5	VD	Deckhouse volume	5000-15000 m^3	10777
6	Cdmat	Hull Material	1 = Steel, 2 = Aluminum, 3 = Advanced Composite	Option 1
8	PGM	Power Generation Module	1 = 3 x LM2500+, AC Synch, 4160VAC 2 = 2 x MT30, AC Synch, 4160VAC	Option 9

			3 = 3 x MT30, AC Synch, 4160VAC 4 = 3 x LM2500+, AC Synch, 13800VAC 5 = 2 x MT30, AC Synch, 13800VAC 6 = 3 x MT30, AC Synch, 13800VAC 7= 3xMT30, 13800 VAC 8= 4xMT30, 4160VAC 9= 4xMT30, 13800 VAC	
8	SPGM	Secondary Power Generation Module	1 = NONE 2 = 2 x LM2300 G, AC Synch, (DDG 1000) 3 = 2 x CAT 3608 Diesel 4 = 2 x PC 2.5/18 Diesel 5 = 2 x PEM 3 MW Fuel Cells (NSWCCD) 6 = 2 x PEM 4 MW Fuel Cells (NSWCCD) 7 = 2 x PEM 4 MW Fuel Cells (NSWCCD)	Option 1
9	PROP TYPE	Propulsion Type	Option 1) = 2 x FPP Option 2)= 2 x Pods Option 3) = 1 FPP +SPU	Option 1
10	DIST	Power Distribution Type	1 = AC ZEDS 2 = DC ZEDS (DDG 1000)	2
11	PMM	Propulsive Motor Module	1 = (AIM) Advanced Induction Motor (DDG 1000) 2 = (PMM) Permanent Magnet Motor	Option 1
12	Ts	Prvosions Duration	60-75 days	68
13	Ncps	Collective Protection System 0	0=none 1 = partial 2 = full	Option 2
14	Ndegaus	Degaussing system	0 = none 1 = degaussing system	Option 1
15	Cman	Manning Reduction and automation factor	0.5 - 1.0	0.544
16	AAW	Anti-Air warfare alternatives	Option 1) SPY-3/VSR+++ DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA Option 2) SPY-3/VSR++ DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA Option 3) SPY-3/VSR+ DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA Option 4) SPY-3/VSR (DDG-1000 3L) DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA	Option 2

17	ASUW	Anti-Surface Warfar alternatives/Naval Surface Fire support alternatives	Option 1) 1x155m AGS, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod1 3x CIGS Anti-Surface Warfare Anti-Air Warfare 20 AAW alternatives Option 2) 1xMK45 5”/62 gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod1 3x CIGS Option 3) 1xMK110 57mm gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod1 3x CIGS	Option 2
18	ASW	Anti-Submarine Warfare Alternatives/ Mine Counter Measures	Option 1) Dual Frequency Bow Array, ISUW, NIXIE, 2xSVTT, mine-hunting sonar Option 2) SQS-53C, NIXIE, SQR-19 TACTAS, ISUW, 2xSVTT, mine-hunting sonar Option 3) SQS-56, NIXIE, ISUW, 2xSVTT, mine-hunting sonar Option 4) NIXIE, 2xSVTT, mine-hunting sonar	Option 4
20	CCCI	Command Control Communication Computer	Option 1) Enhanced CCCCI Option 2) Basic CCCCI (CG 47)	Option 1
21	GMLS	Guided Missile Launching System	Option 1) 192 cells, MK 41 and/or MK57 PVLS Option 2) 160 cells, MK 41 and/or MK57 PVLS Option 3) 144 cells, MK 41 and/or MK57 PVLS	Option 1
22	LAMPS	LAMPS Alternatives	Option 1) Embarked 2 LAMPS w/Hangars Option 2) Embarked 1 LAMPS w/Hangar Option 3) LAMPS haven (flight deck)	Option 1

Table 24: Improved Baseline Weights Summary

Group	Weight (MT)	KG (m)
SWBS 100	6158	11.78
SWBS 200	1714	
SWBS 300	2099	8.87
SWBS 400	1064	21.60
SWBS 500	1720	16.56
SWBS 600	744	16.12
SWBS 700	580	12.35
Loads	467	10.19
Lightship	15489	9.05
Lightship w/Margin	17015	9.05
Full Load w/Margin	18298	9.05

Table 25: Improved Baseline Area Summary

Area	Required (m^2)	Available (m^2)
Total Arrangeable	8163	8939
Deck House	3099	3592
Hull	3806	5346

Table 26: Improved Baseline Electric Power Summary

Group	Description	Power (kW)
KW_{NP}	Non-Payload Functional Load	5374
KW_{MFLM}	Max. Functional Load w/ Margins	23741
KW_{24}	24 Hour Electrical Load	11157

Table 27: Improved Baseline MOP/ VOP/ OMOE/ OMOR Summary

Measure	Description	Value of Performance
MOP 1	BMD	0.96
MOP 2	AAW	0.85
MOP 3	ASUW/ NSFS	0.62
MOP 4	ASW/MCM	1
MOP 5	CCC	1
MOP 6	ISR/SOF	0.68
MOP 7	Surge Speed	0.82
MOP 8	Vs	0.89
MOP 9	E	0.77
MOP 10	Ts	0.05
MOP 11	Seakeeping	0.74
MOP 12	VUL	0.85
MOP 13	NBC	0.88
MOP 14	RCS	1
MOP 15	Acoustic Signature	1
MOP 16	IR Signature	0.09
MOP 17	Magnetic Signature	0.12
OMOE	Overall Measure of Effectiveness	0.7795
OMOR	Overall Measure of Risk	0.5498

Table 28: Improved Baseline / ASSET Design Principal Characteristics

Characteristic	Value
Hull Form	WPTH
Δ (MT)	18298
LWL (m)	192.3
Beam (m)	23.06
Draft (m)	7.21
D10 (m)	16.1
Displacement to Length Ratio (MT/m^3)	95.15
Beam to Draft Ratio, C_{BT}	3.198
W1 (MT)	6158
W2 (MT)	1714
W3 (MT)	2099
W4 (MT)	1064
W5 (MT)	1720
W6 (MT)	744
W7 (MT)	580
Wp (MT)	
Lightship Δ (MT)	15489
KG (m)	9.05
GM/B =	3.66
Propulsion System	Option 9
ASW System	Option 4
ASUW System	Option 2
AAW System	Option 2
Average Deck Height (m)	3
Total Officers	23
Total Enlisted	54
Total Manning	77
Number of VTUAVs	6
Number of LAMPS	2
Follow Ship Acquistion Cost (million dollars)	2495
Life Cycle Cost (million dollars)	4405

3.8 ASSET Feasibility Study

An ASSET feasibility study was performed in order to validate the optimized design produced with the synthesis model. Design variables calculated using the synthesis model were input into ASSET 5.3 and output variables were compared. The design characteristics of the improved baseline design shown in Table 23 are compared to ASSET calculated variables in Table 24. A ship machinery layout produced by ASSET in the Machinery Module is shown in Figure 54.

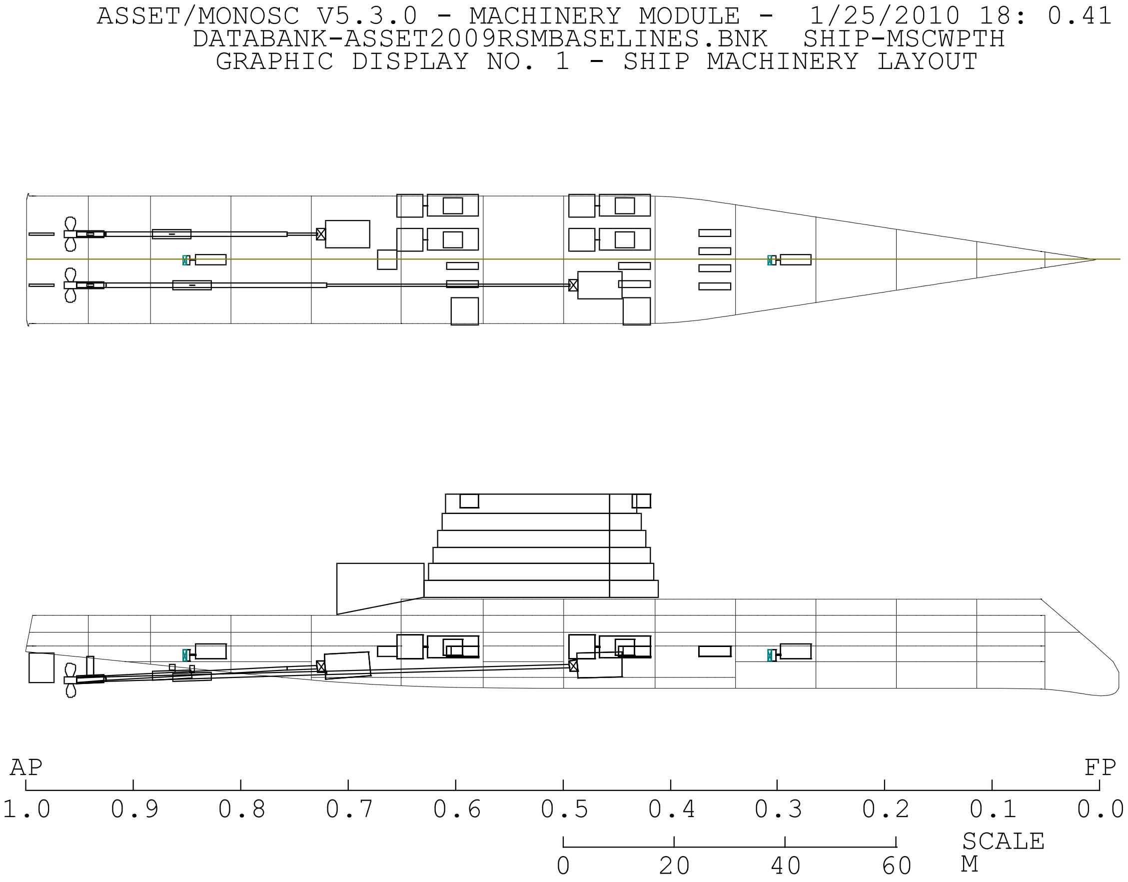


Figure 54 - Ship machinery layout produced by ASSET as validation for the synthesis model

Table 29: SSSM and ASSET Comparison Study

Characteristic	Design 130i Value	ASSET Value
Hull Form	WPTH	WPTH
Δ (MT)	18298	17157
LWL (m)	192.3	192.3
Beam (m)	23.06	23.06
Draft (m)	7.21	7.21
D10 (m)	16.1	16.1
Displacement to Length Ratio (MT/m^3)	95.15	89.22
Beam to Draft Ratio, C_{BT}	3.2	3.2
W1 (MT)	6158	6096.3
W2 (MT)	1714	2147.2
W3 (MT)	2099	1008.7
W4 (MT)	1064	870.9
W5 (MT)	1720	1484
W6 (MT)	744	936.9

W7 (MT)	580	78.2
Wp (MT)	2809	3273
Lightship Δ (MT)	15489	13884.4
KG (m)	9.05	8.47
GM (m)	1.92	3.97
GM/B =	.083	0.172
Propulsion System	Option 9	Option 9
ASW System	Option 4	Option 4
ASUW System	Option 2	Option 2
AAW System	Option 2	Option 2
Average Deck Height (m)	3	3
Total Officers	23	23
Total Enlisted	54	54
Total Manning	77	77
Number of VTUAVs	6	6
Number of LAMPS	2	2
Follow Ship Acquisition Cost (million dollars)	2495	
Life Cycle Cost (million dollars)	4405	

4 Concept Development (Feasibility Study)

Concept Development of ASC 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 (or Sail)

4.1.1 Hullform

The hullform was generated using ASSET and developed in Rhinoceros 3D. Baseline design characteristics input into ASSET scaled a set of parent offsets for a wave piercing tumblehome hullform. Once the hullform offsets were generated, a set of points were exported from ASSET into Rhinoceros where all 3-D modeling was performed. The offsets were lofted into port, starboard and transom hull surfaces, the hull surface was faired, and hydrostatic calculations were performed using ORCA3D, a ship modeling tool in Rhinoceros 3D. Figure 56 gives a view of the wave piercing tumblehome hull form. Lines drawings in Figure 55 were also created to better show the geometry of the hull form.

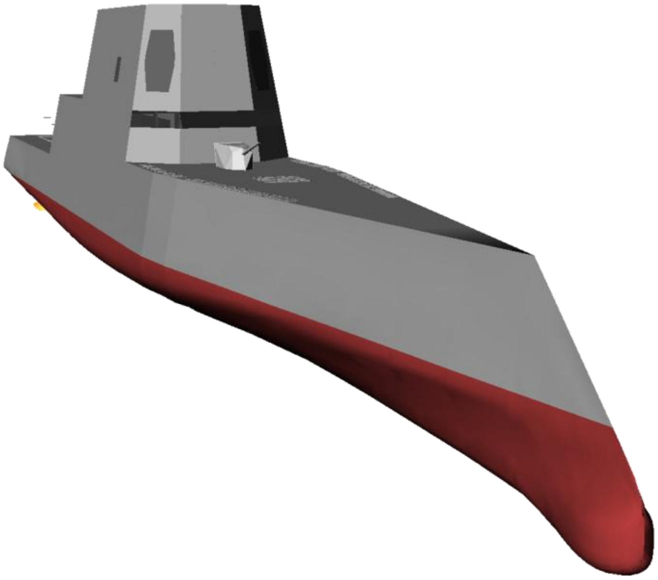


Figure 55: **Wave Piercing Tumblehome Hull Form**

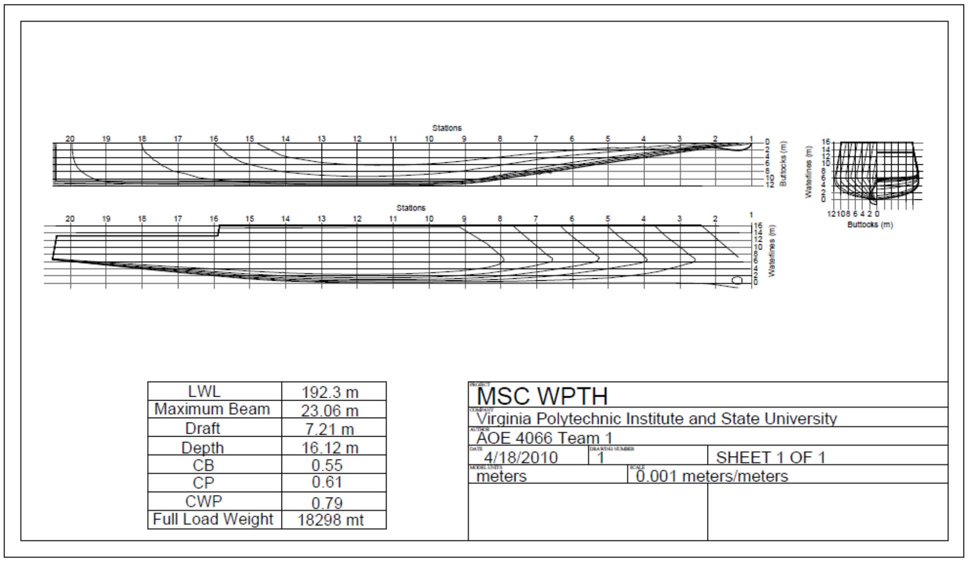


Figure 56: **Lines Drawings**

Figure 57 shows righting arm curves at waterline levels between 2 and 12 meters for heel angles up to 90°. The center of gravity for each draft level was taken as 9.05 meters, which comes from the baseline design. The design draft, as indicated by the improved baseline design, was 7.21 meters.

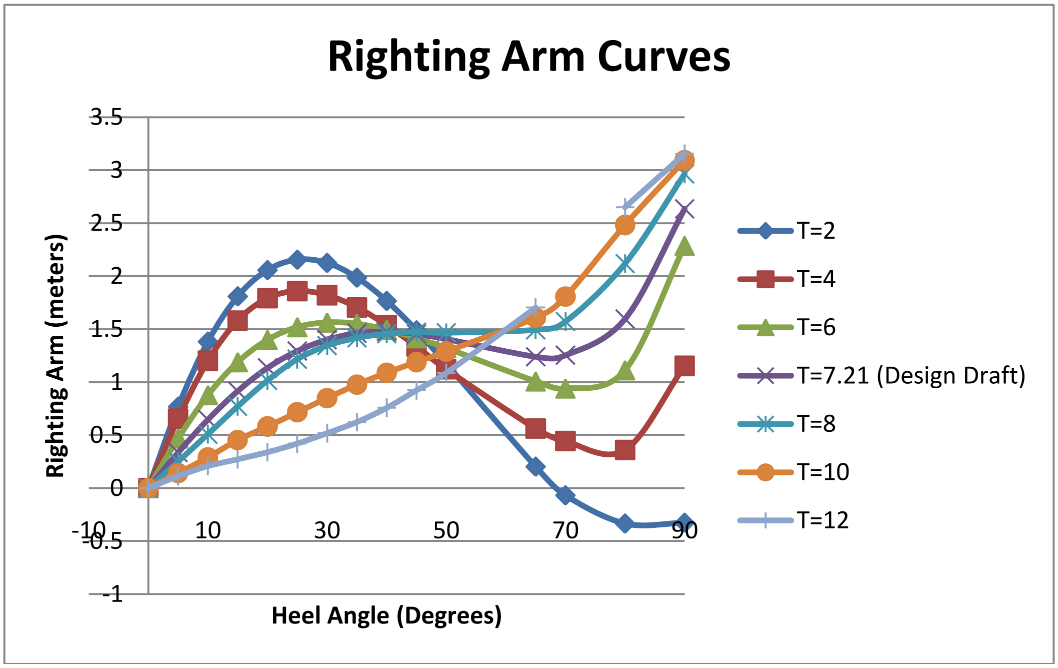


Figure 57: Righting Arm Curve

Centers of volume are plotted over a range in draft between 2 and 12 meters in Figure 58. The vertical center of buoyancy (VCB), longitudinal center of floatation (LCF), and longitdunal center of buoyancy (LCB) are plotted and normalized over the depth at station 10 (for VCB) or the length between perpendiculars (for LCF and LCB). At the design draft of 7.21 meters, the VCB is at 4.5 meters, the LCB is at 105.1 meters from the forward perpendicular, and the LCF is at 116.9 meters from the forward perpendicular. A longitudinal center of buoyancy and floatation aft of amidships is expected do to the shape of the hull form.

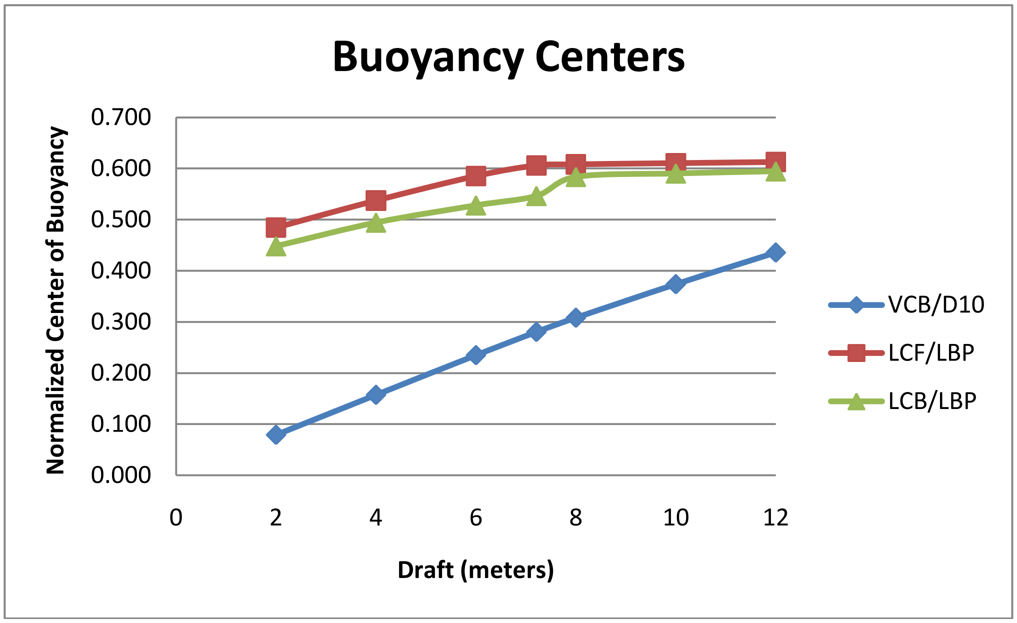


Figure 58: Buoyancy Centers

The wetted surface area of the hullform and the waterplane area is plotted in Figure 59 over a range of waterlines. Wetted surface area at the design draft is near 5000 square meters and the waterplane area is near 3500 square meters. As expected the waterplane area is near maximum at the design draft, due to the tumblehome hullform.

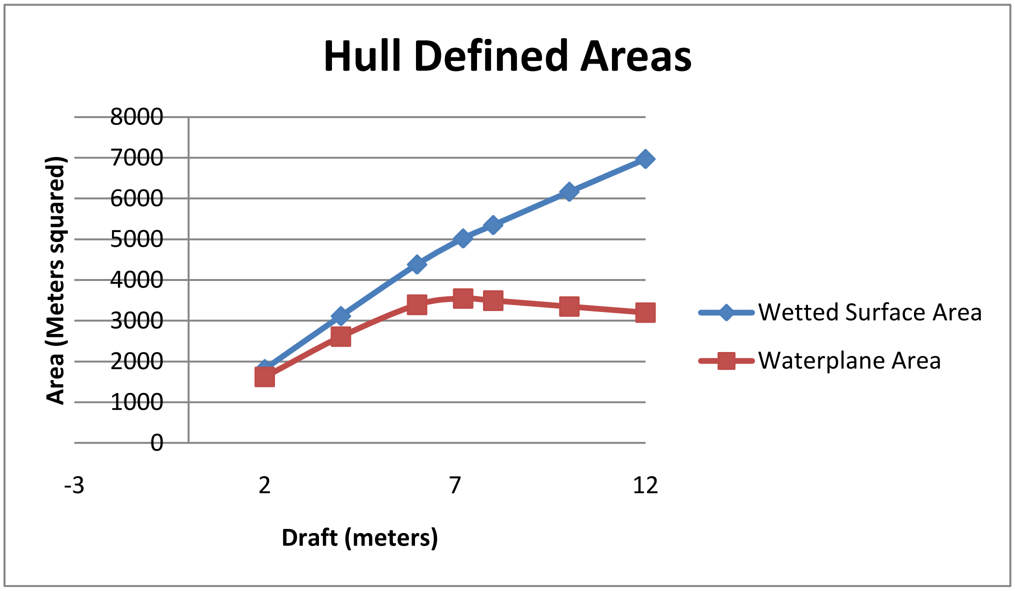


Figure 59: Hull Defined Areas

Figure 60 plots displacement characteristics for the hullform generated in Rhinoceros. The displacement as a function of draft is plotted on the left axis, and the tons/cm immersion (MT/cm) and Moment to trim one centimeter (MT) are plotted versus draft on the right axis. The displacement of the hullform at the design draft was calculated to be 16798 tonnes, 9% short of the 18298 tonnes derived from the improved baseline design. Differences in the displacement may be attributed to the fairing of the hullform in Rhinoceros.

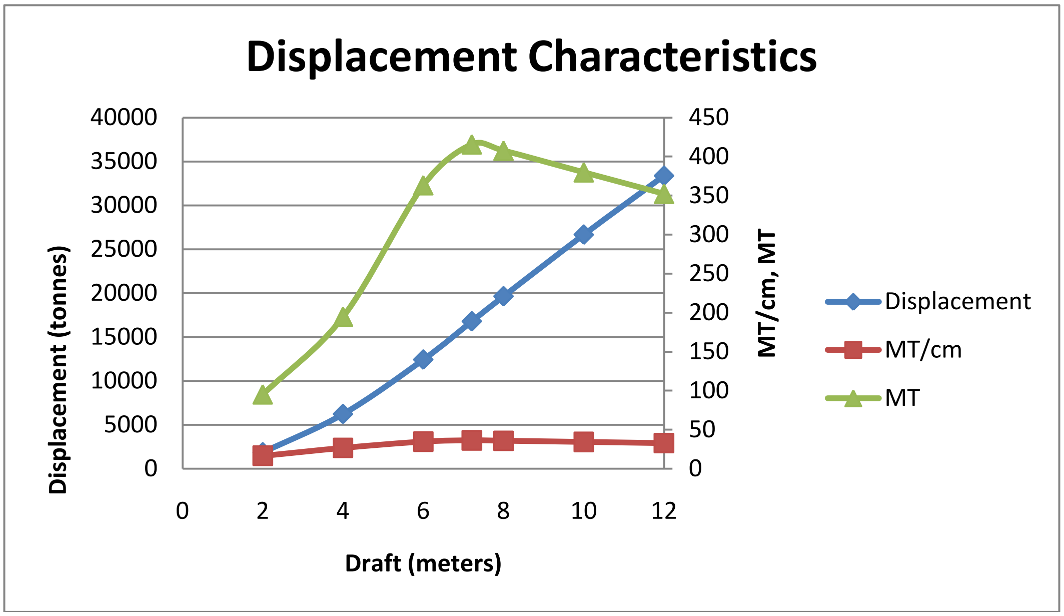


Figure 60: Displacement Characteristics

Several coefficients of form describing the hullform are plotted in Figure 61. The block coefficient (Cb), Midship coefficient and prismatic coefficient are plotted versus draft. At a draft of 7.21 meters, characteristics of the hull include a block coefficient of 0.428, a midship coefficient of 0.703, and a prismatic coefficient of 0.61. A low block coefficient can be attributed to the wave piercing tumblehome hullform.

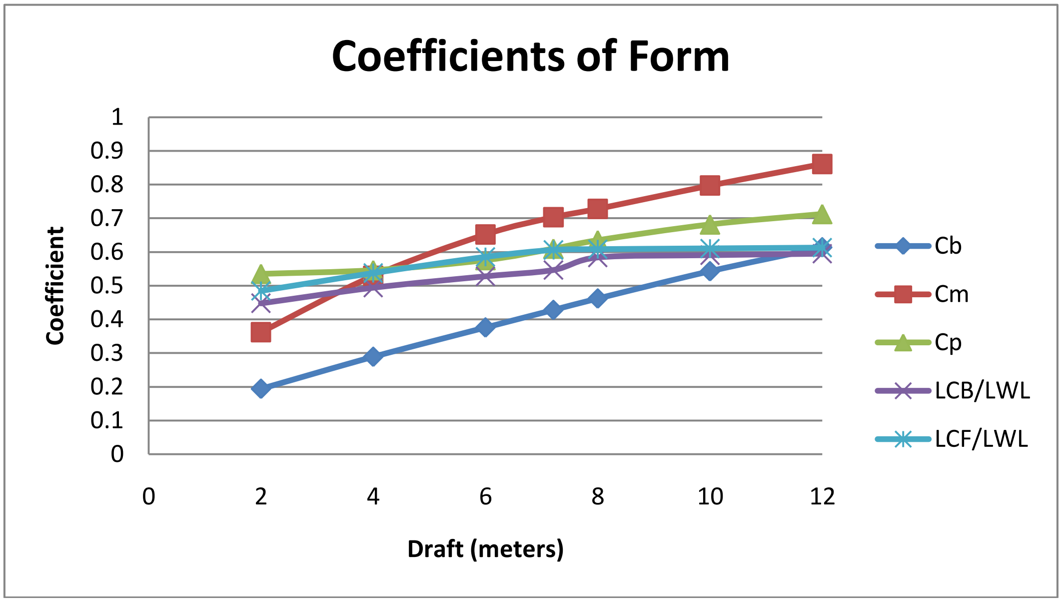


Figure 61: Coefficients of Form

The cross sectional area at drafts between 2 and 12 meters are plotted versus the longitudinal location from the forward perpendicular in Figure 62. There is an initial hump 5 meters aft of the forward perpendicular where the bulbous bow is at a maximum and then narrows down into a wave piercing hullform.

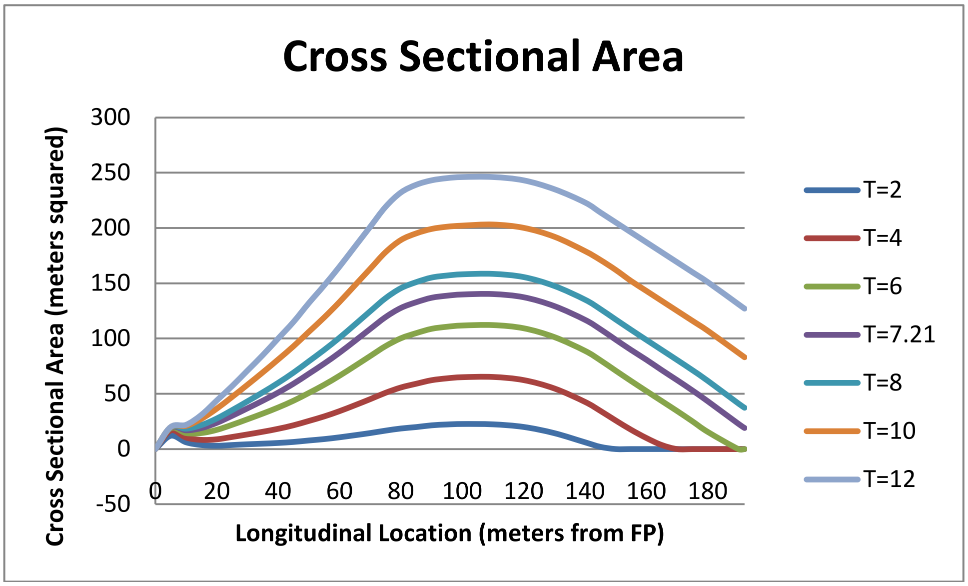


Figure 62: Cross Sectional Area

4.1.2 Deck House

The deck house of the ship, shown in Figure 63, is designed with a minimized radar cross section in mind, continuing the 10° tumblehome slope from the hull. The volume of the deck house did increase from the baseline design, from 10777 m^3 to 12700 m^3, in order to accommodate substantial intakes and exhausts for the 4 MT-30 gas turbines. The hangars, capable of housing two SH-60R Helicopters, are located in the aft of the deck house, port and starboard. The main portion of the deck house contains six levels.

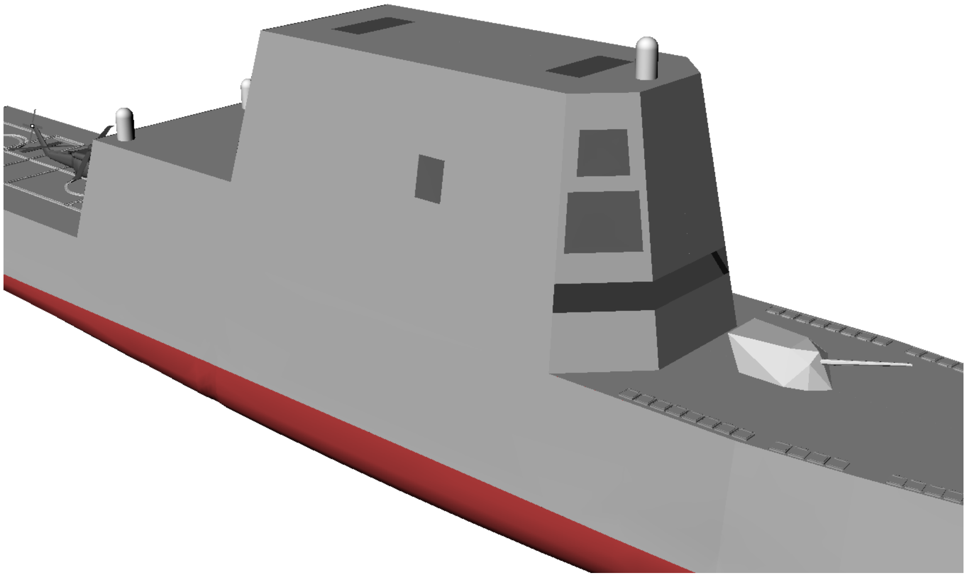


Figure 63: Deck House

4.2 Preliminary Arrangement (Cartoon)

The preliminary arrangement cartoon served as an outline for the rest of the arrangement process. The hullform and deckhouse were taken from Rhino and turned into 2 dimensional plan and profiles views so that the team could sketch by hand the location of transverse and longitudinal subdivision, weapons systems, intakes and exhausts, shafting, tankage, and other important spaces within the hull. This was done in order to layout the ship while considering stability, trim, radar cross section, survivability, structural efficiency, and overall function. The hullform that was taken from Rhino can be seen below in Figure 64.

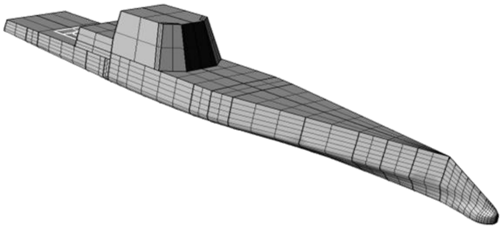


Figure 64: Hullform and Deckhouse from Rhino

In order to efficiently go about the cartoon process, it was necessary to generate the required area and volume that would need to be arranged in the hull. This included deckhouse areas and volume as well as the machinery box and the intakes and exhaust. These figures were determined from the improved baseline design and can be seen below in Figure 30.

Table 30: Required Areas and Volumes for the MSC

1. VD = 10777 m^3 [deckhouse volume]
2. Vht = 41276.5 m^3 [total hull volume]
3. Vmb = 3844.47 m^3 [propulsion machinery box volume]
4. ADPR = 2192.19 m^2 [required deckhouse payload area]
5. AHPR = 3134.78 m^2 [required hull or deckhouse payload area]
6. AHie = 453.6 m^2 [required hull propulsion inlet and exhaust area]
7. ADie = 907.2 m^2 [required deckhouse propulsion inlet and exhaust area]
8. Ts = 68 [endurance days]
9. CN = 4.76155 [hull cubic number]
10. NT = 77 [total crew]
11. NO = 23 [number of officers]
12. NA = 30 [number of additional accommodations through modularity]
13. Adr = 3099.39 m^2 [total deckhouse required area]
14. Ada = 3592.51 m^2 [available deckhouse area]
15. Atr = 8163 .65 m^2 [total required arrangeable area]
16. Ata = 8939.19 m^2 [total available arrangeable area]

Once all of these factors were taken into consideration the cartoon was generated by hand. The result of this iteration can be seen below in Figure 65.

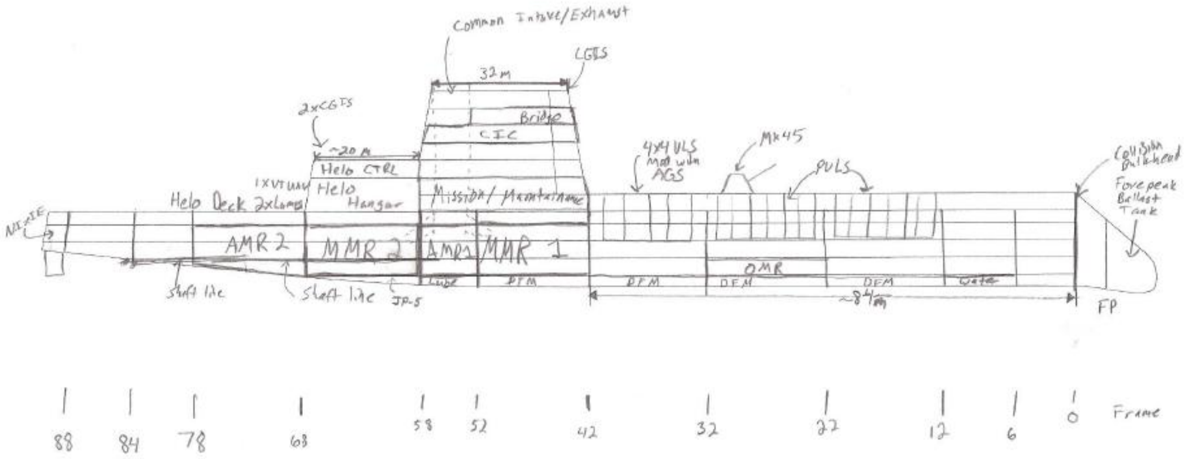


Figure 65: Arrangements Cartoon

An important feature of the cartoon was the layout of the machinery spaces and the weapons systems, as these are the most demanding drivers of arrangements based on volume and arrangeable area. The initial estimates for subdivision also served as a starting point for determining the best subdivision for survivability. The weapons systems arrangements are detailed further in Figure 66 below.

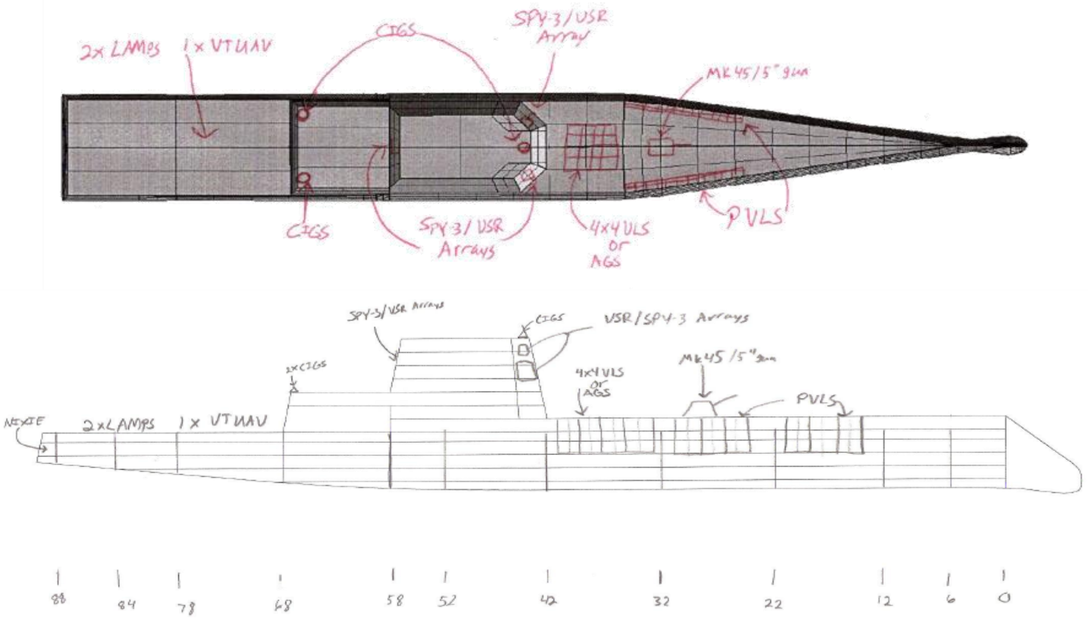


Figure 66: Weapons Systems Cartoon

4.3 Design for Production

A production strategy was developed as part of the concept exploration portion of the design in order to ensure that producibility was kept in mind throughout the design process. There are great cost savings to be had when a ship's design is favorable for production. Several design features which are pointed out in Figure 67 help in the producibility of the ship.

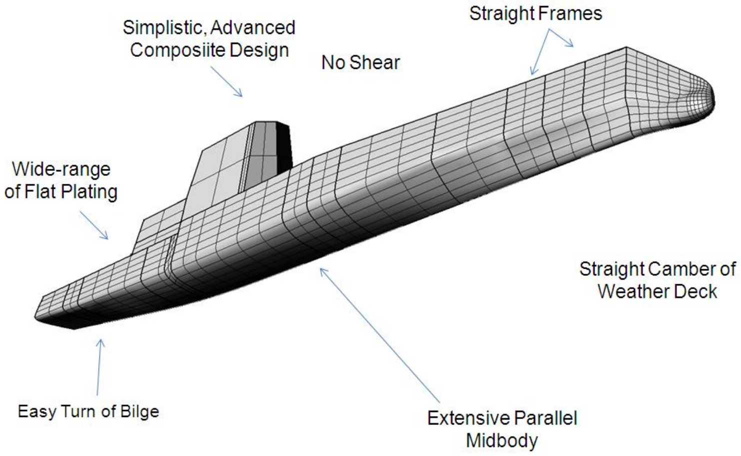


Figure 67: Producible Hull and Deck House Features

A modular build strategy will be used throughout the construction of the hull and deckhouse by using group classifications and zones. Table 31 shows the breakdown the construction process into general group classification.

Table 31: Group Construction Classifications and Zones

Group/ Classification Number	Characteristics of Zone
1000/4000 – Bow/Stern	more curvature of plates, transition to transverse stiffening
2000 – Hull Cargo	Midsection of the ship
3000 – Machinery	Machinery systems and outfitting
5000 – On-Board	Electrical Wiring, HVAC
6000 – Special	High Skill Areas, Electronics, CS, Accommodations

Using the group classifications, the ship's structure can be broken down into blocks. Each modular block is to be built separate, then lifted into place and attached to the rest of the ship structure. In order for this strategy to be successful, blocks must obey certain criteria which include a maximum width of 10 meters, a maximum height of 1 deck (excluding wing tanks), and a maximum weight of 100 Tonnes. Zonal electric, HVAC, and firemains will be incorporated into the design, which will reduce build time and also promote redundancy and survivability in the design. If damage were taken to one zone, other zones would remain functional. Outfit packages and testing before installation will also be another part of the modular design of the ship.

The general strategy for the construction process is shown in Figure 68 in conjunction with the Claw Chart in Table 32. The Claw Chart shows the time frame for construction of an individual block, while the erection unit profile and assembly unit breakdown show where each construction block is located.

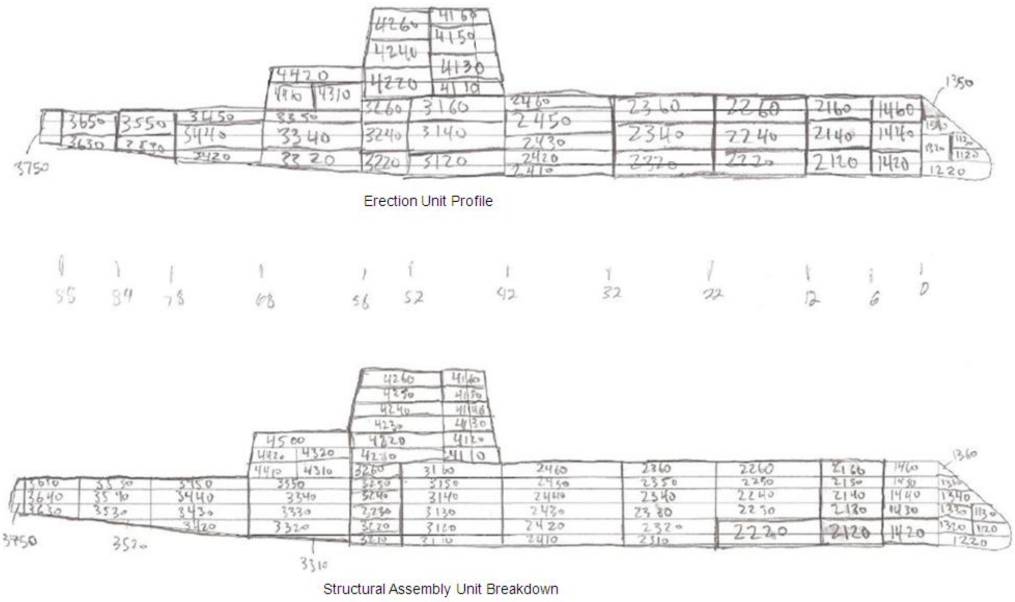
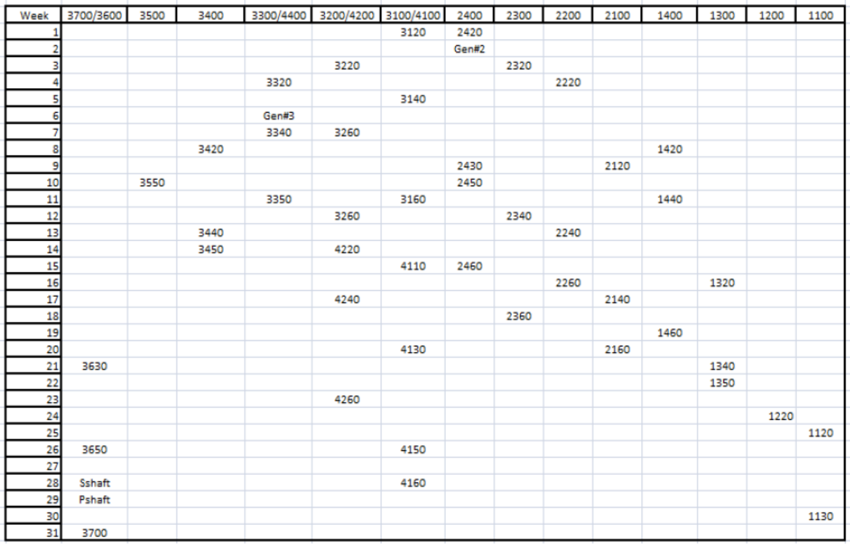


Figure 68: Erection and Structural Assembly Breakdown

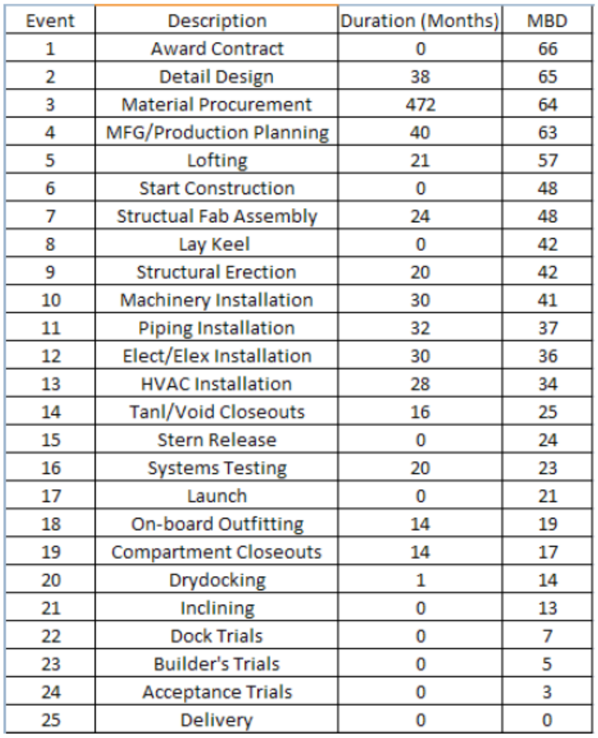
Table 32: Claw Chart for the Build Process



Week	3700/3600	3500	3400	3300/4400	3200/4200	3100/4100	2400	2300	2200	2100	1400	1300	1200	1100
1						3120	2420							
2							Gen#2							
3					3220			2320						
4				3320					2220					
5						3140								
6				Gen#3										
7				3340	3260									
8			3420								1420			
9							2430			2120				
10		3550					2450							
11				3350		3160					1440			
12					3260			2340						
13			3440						2240					
14			3450		4220									
15						4110	2460							
16									2260			1320		
17					4240					2140				
18								2360						
19											1460			
20						4130				2160				
21	3630											1340		
22												1350		
23					4260									
24													1220	
25														1120
26	3650					4150								
27														
28	Sshaft					4160								
29	Pshaft													
30														1130
31	3700													

Lastly, the total design schedule of the ship building process was laid out, beginning 66 months before delivery at the award contract. Major dates in the design schedule include the beginning of construction, 48 months before delivery, and the launch of the ship 21 months before delivery. Table 33 outlines the entire design schedule.

Table 33: Design Schedule



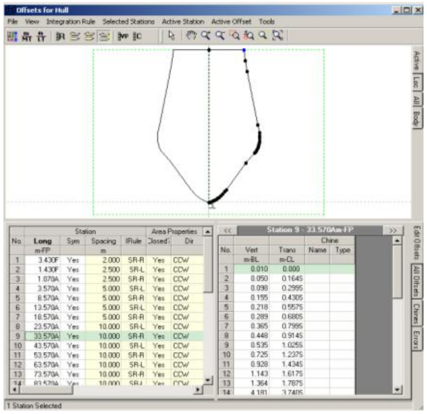
Event	Description	Duration (Months)	MBD
1	Award Contract	0	66
2	Detail Design	38	65
3	Material Procurement	472	64
4	MFG/Production Planning	40	63
5	Lofting	21	57
6	Start Construction	0	48
7	Structual Fab Assembly	24	48
8	Lay Keel	0	42
9	Structural Erection	20	42
10	Machinery Installation	30	41
11	Piping Installation	32	37
12	Elect/Elex Installation	30	36
13	HVAC Installation	28	34
14	Tanl/Void Closeouts	16	25
15	Stern Release	0	24
16	Systems Testing	20	23
17	Launch	0	21
18	On-board Outfitting	14	19
19	Compartment Closeouts	14	17
20	Drydocking	1	14
21	Inclining	0	13
22	Dock Trials	0	7
23	Builder's Trials	0	5
24	Acceptance Trials	0	3
25	Delivery	0	0

4.4 Subdivision

The subdivision for the ship was determined in HECSALV. The hullform was exported from Rhino into HECSALV where it was cleaned up and optimized. From there longitudinal and transverse subdivision was developed and a floodable length curve was generated to ensure that the subdivision would meet a 3 compartment standard. After the subdivision was determined, the tankage volumes as determined by the ASSET space module must be accommodated in the hull. Tanks were then inserted into the hull in the inner bottom starting at midships and working fore and aft. All of this was done while considering survivability, functionality, producability, damage stability, floodable length, deck height, continuous deck requirement, mission requirement, trim, and structural design.

4.4.1 Hullform in HECSALV

Once the hullform was exported from Rhino and imported into HECSALV, the offsets were modified to clean up the hullform to ensure that there were no discontinuities. A picture from this process can be seen below in Figure 69.



	Station				Area Properties	
No.	Long m-FP	Sym	Spacing m	IRule	Closed?	Dir
1	3.430F	Yes	2.000	SR-R	Yes	CCW
2	1.430F	Yes	2.500	SR-L	Yes	CCW
3	1.070A	Yes	2.500	SR-R	Yes	CCW
4	3.570A	Yes	5.000	SR-L	Yes	CCW
5	8.570A	Yes	5.000	SR-R	Yes	CCW
6	13.570A	Yes	5.000	SR-L	Yes	CCW
7	18.570A	Yes	5.000	SR-R	Yes	CCW
8	23.570A	Yes	10.000	SR-L	Yes	CCW
9	33.570A	Yes	10.000	SR-R	Yes	CCW
10	43.570A	Yes	10.000	SR-L	Yes	CCW
11	53.570A	Yes	10.000	SR-R	Yes	CCW
12	63.570A	Yes	10.000	SR-L	Yes	CCW
13	73.570A	Yes	10.000	SR-R	Yes	CCW
14	83.570A	Yes	10.000	SR-L	Yes	CCW

Station 9 : 33.570Am-FP

			Chine	
No.	Vert m-BL	Trans m-CL	Name	Type
1	0.010	0.000		
2	0.050	0.164S		
3	0.098	0.299S		
4	0.155	0.430S		
5	0.218	0.557S		
6	0.289	0.680S		
7	0.365	0.799S		
8	0.448	0.914S		
9	0.535	1.025S		
10	0.725	1.237S		
11	0.928	1.434S		
12	1.143	1.617S		
13	1.364	1.787S		
14	4.181	3.740S		

Figure 69: Hullform Clean up in HECSALV

This process was repeated for all 52 hull sections that were imported from Rhino. The final simplified and cleaned up hullform can be seen below in Figure 70.

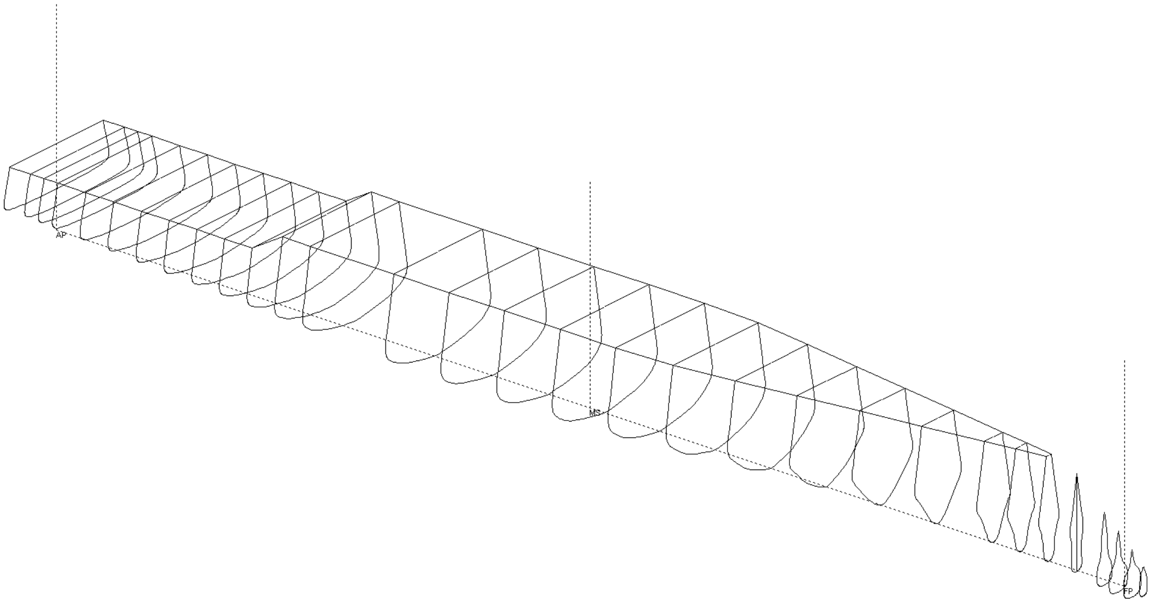


Figure 70: Hullform in HECSALV

The final task for importing the hull was defining the margin line relative to the deck edge. Our margin line was defined to be 3 inches below the edge of the deck. The margin line is visible below in Figure 71.

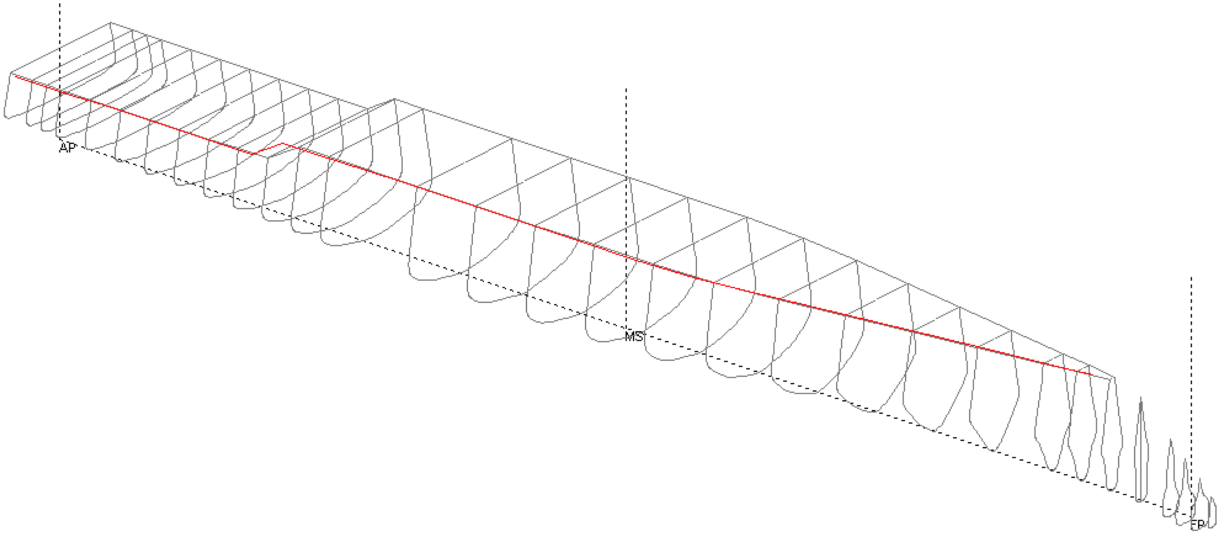


Figure 71: Hull with Margin Line

4.4.2 Transverse Subdivision, Floodable Length and Preliminary Tankage

The deck heights were an important thing to determine for the design. This was done taking overhead clearance as well as volumes necessary for tankage into consideration. The deck heights can be seen in Table 34.

Table 34: Deck Height Locations

Location	Vertical Location (m)
Keel	0
Inner Bottom	2.6
Deck 4	5.1
Deck 3	7.3
Deck 2	10.0
Deck 1	13.0
Level 1	16.0

A visual representation of these deck heights can be seen below in Figure 72.

Figure 72: Deck Heights

The bulkhead locations were then determined and manipulated to ensure a 3 compartment ship was possible throughout. The initial location for each of these bulkheads was taken from the preliminary arrangements cartoon. After these initial bulkhead locations were input, the floodable length curve was consulted, and the bulkheads were then manipulated in an iterative process until a 3 compartment standard was met. The final locations of the bulkheads can be seen below in Table 35.

Table 35: Bulkhead Locations

Bulkhead	Longitudinal Location (m from FP)
1	6.57
2	20.57
3	36.57
4	54.57
5	72.57
6	90.57
7	110.57
8	128.57
9	148.57
10	164.57
11	187.57

The location of the bulkheads can be seen below in the plan and profile views presented in Figure 73.

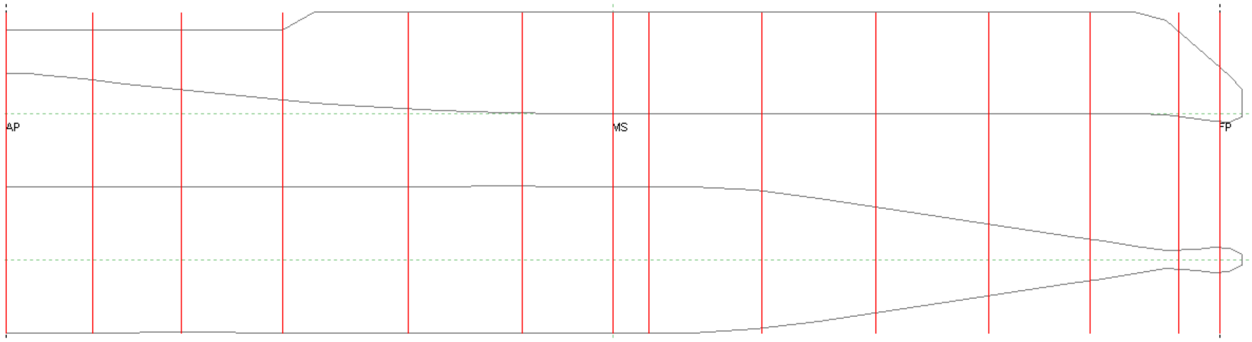


Figure 73: Bulkhead Locations

The total subdivision of the ship can be seen put together below in Figure 74.

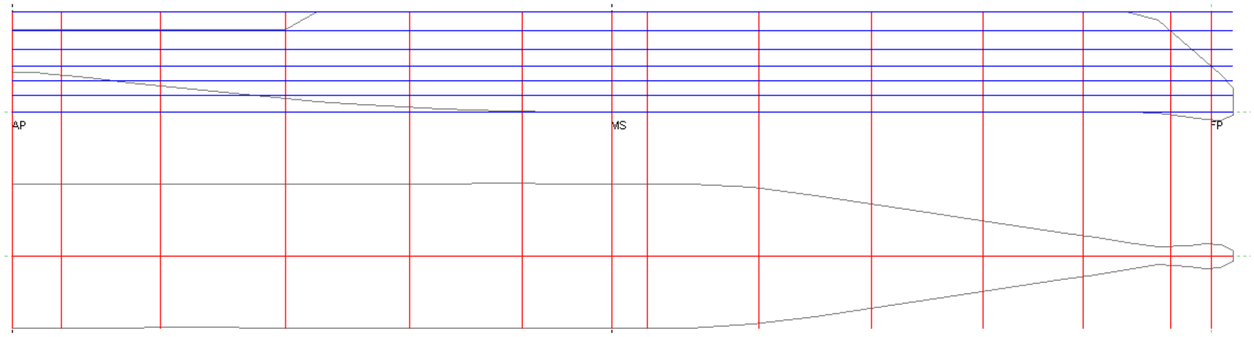


Figure 74: Decks and Bulkheads

The floodable length curve that was used to determine the bulkhead location can be seen below in Figure 75. It would appear on the floodable length curve that there are two locations where a three compartment standard is not met. However, this is not deemed to be an issue because the floodable length program in HECSALV assumes that each compartment has a permeability of 100 percent. This is nowhere near realistic, because even in a MinOp condition, the compartment will not be more than 90 to 95 percent. The damaged length is 28.8 meters which is 15 percent of the hull length.

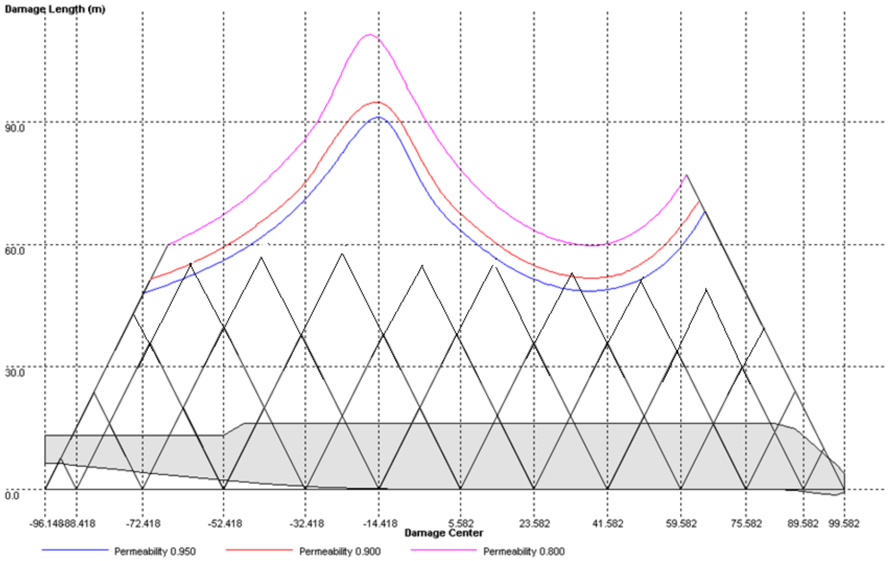
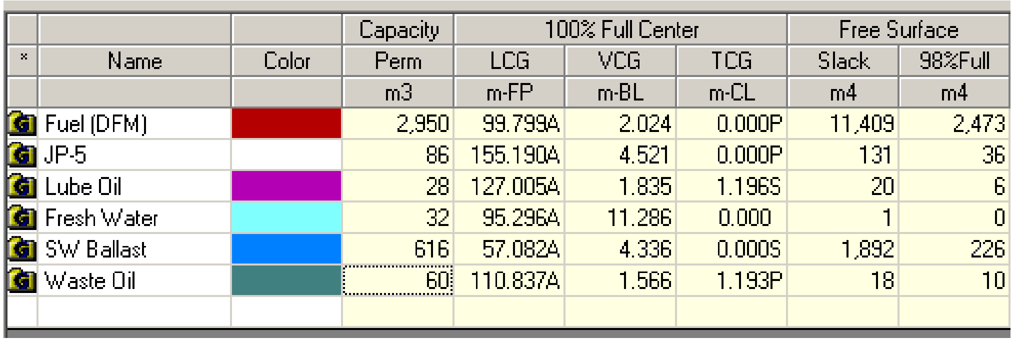


Figure 75: Floodable Length

Once the deck heights and bulkhead locations had been determined the location of the tanks could be determined. Most of the tankage is located in the inner bottom of the ship. The lube oil and waste oil were located inside of diesel fuel marine compartments which are directly below the main engine rooms. All of the tankage volumes were taken from ASSET. A summary of the tankage can be seen below in Table 36. The locations of the tanks can be seen in Figure 76.

Table 36: Tankage Summary



			Capacity	100% Full Center			Free Surface	
*	Name	Color	Perm	LCG	VCG	TCG	Slack	98%Full
			m3	m-FP	m-BL	m-CL	m4	m4
G	Fuel (DFM)	🟥	2,950	99.799A	2.024	0.000P	11,409	2,473
G	JP-5	⬜	86	155.190A	4.521	0.000P	131	36
G	Lube Oil	🟪	28	127.005A	1.835	1.196S	20	6
G	Fresh Water	🟦	32	95.296A	11.286	0.000	1	0
G	SW Ballast	🟦	616	57.082A	4.336	0.000S	1,892	226
G	Waste Oil	🟩	60	110.837A	1.566	1.193P	18	10

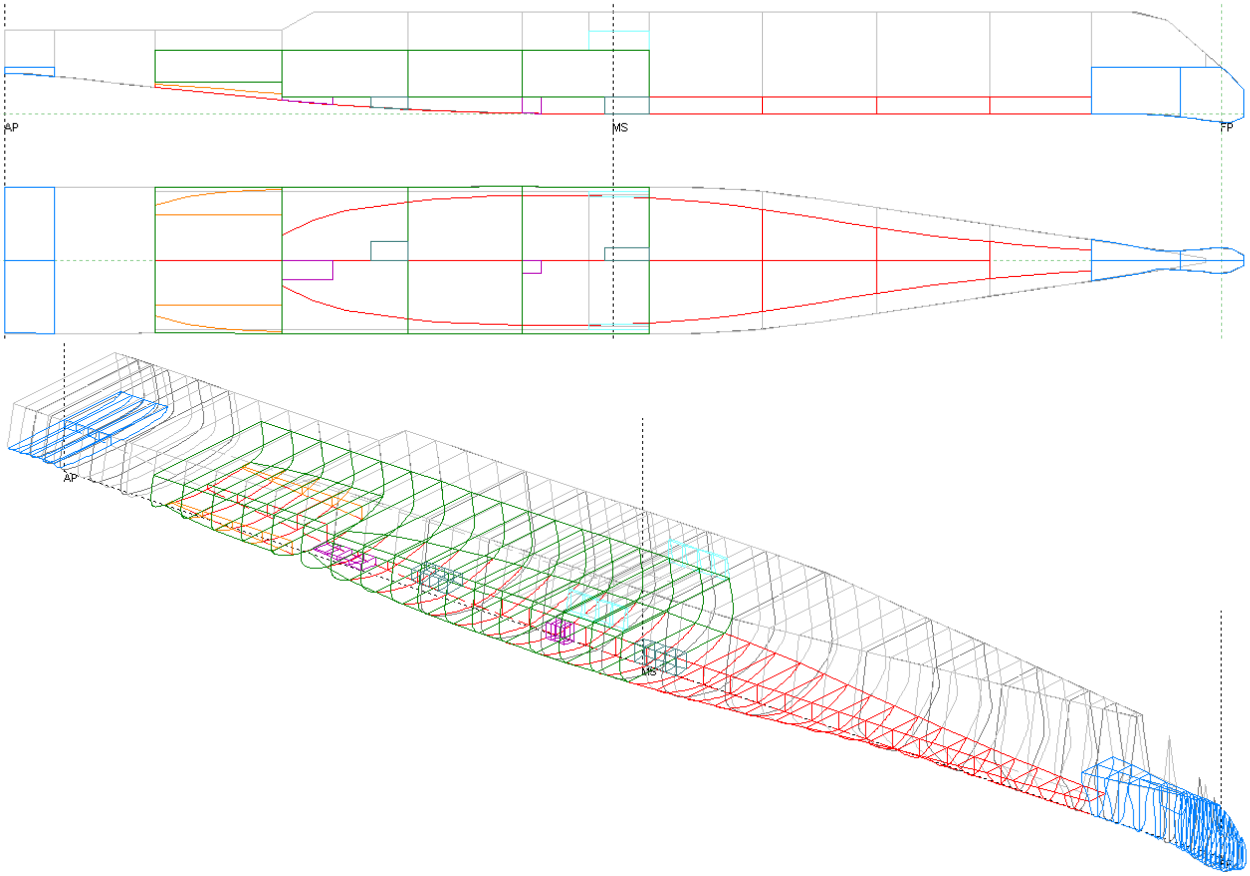
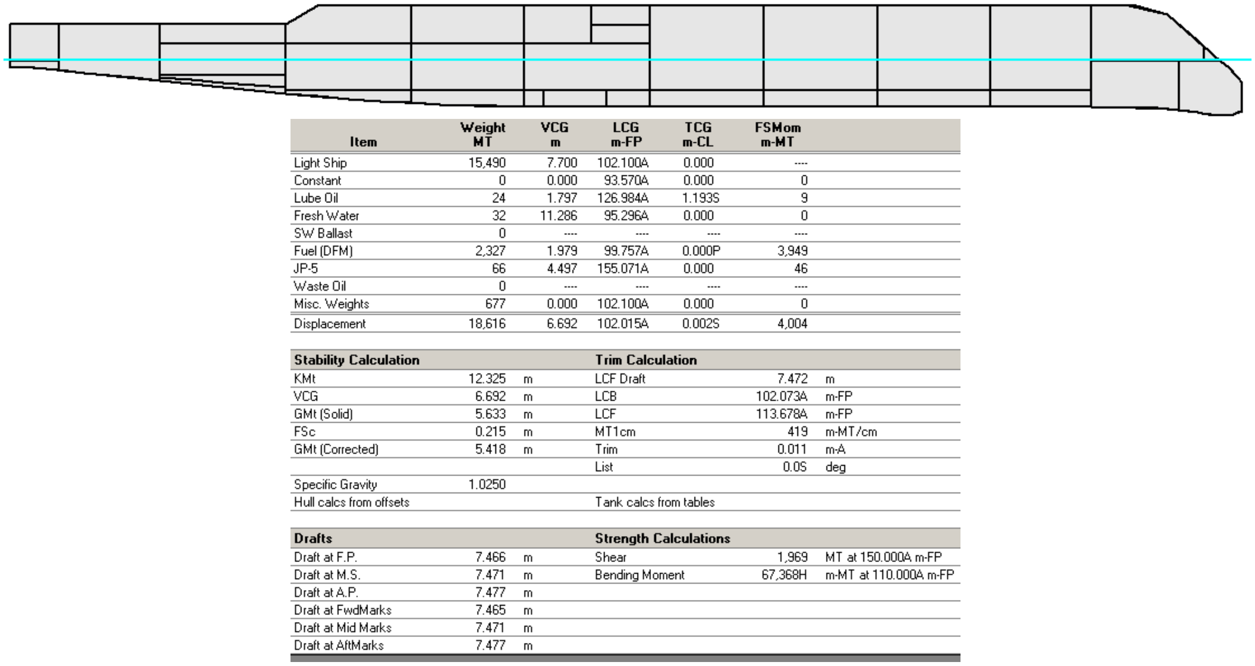


Figure 76: Tankage Locations

4.4.3 Loading Conditions and Preliminary Stability Analysis

Once all of the tanks were in place and the required volumes were satisfied, the LCG of the ship was determined by HECSALV by taking the centers of the loads in the tanks. With the LCG determined, two loading conditions were created: Full Load and MinOp. These conditions were done according to Navy standards outlined in DDS079-1_2003. The shear and bending moments were looked at to ensure that there was nothing out of the ordinary with the way the ship was loaded. This was done as a preliminary stability analysis only as a final stability analysis was done on the ship later. The details of the full load condition as well as the bending moment can be seen below in Figure 77 and Figure 78.



Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT
Light Ship	15,490	7.700	102.100A	0.000	----
Constant	0	0.000	93.570A	0.000	0
Lube Oil	24	1.797	126.984A	1.193S	9
Fresh Water	32	11.286	95.296A	0.000	0
SW Ballast	0	----	----	----	----
Fuel (DFM)	2,327	1.979	99.757A	0.000P	3,949
JP-5	66	4.497	155.071A	0.000	46
Waste Oil	0	----	----	----	----
Misc. Weights	677	0.000	102.100A	0.000	0
Displacement	18,616	6.692	102.015A	0.002S	4,004

Stability Calculation			Trim Calculation		
KMt	12.325	m	LCF Draft	7.472	m
VCG	6.692	m	LCB	102.073A	m-FP
GMt (Solid)	5.633	m	LCF	113.678A	m-FP
FSc	0.215	m	MT1cm	419	m-MT/cm
GMt (Corrected)	5.418	m	Trim	0.011	m-A
			List	0.0S	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		

Drafts			Strength Calculations		
Draft at F.P.	7.466	m	Shear	1,969	MT at 150.000A m-FP
Draft at M.S.	7.471	m	Bending Moment	67,368H	m-MT at 110.000A m-FP
Draft at A.P.	7.477	m			
Draft at FwdMarks	7.465	m			
Draft at Mid Marks	7.471	m			
Draft at AftMarks	7.477	m			

Figure 77: Full Load Condition Details

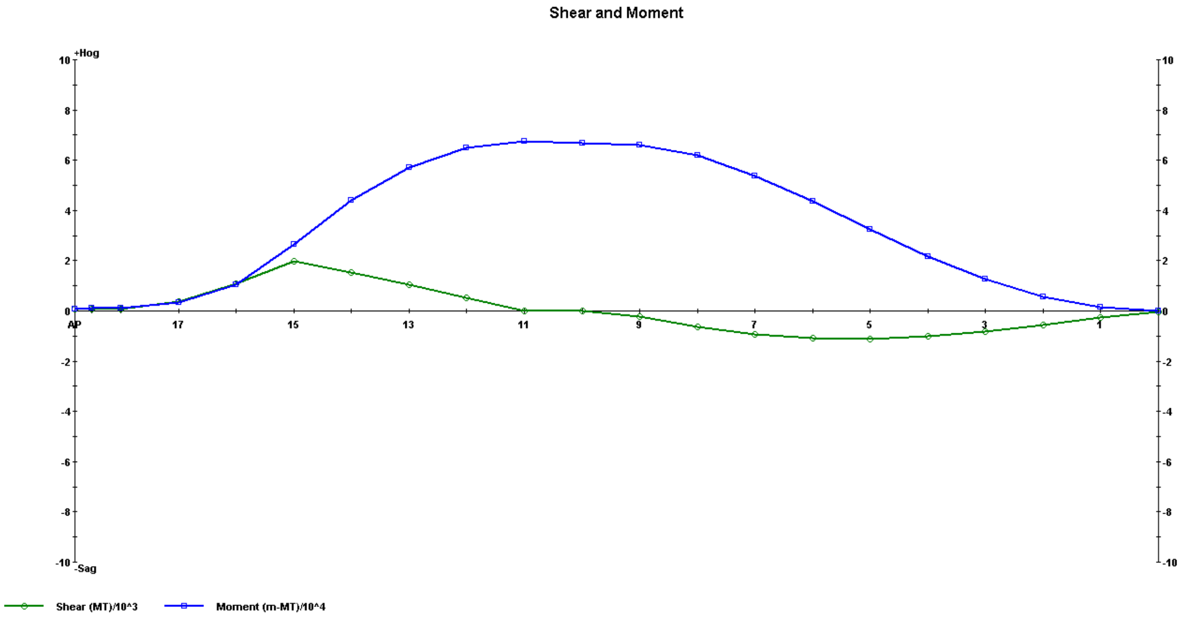
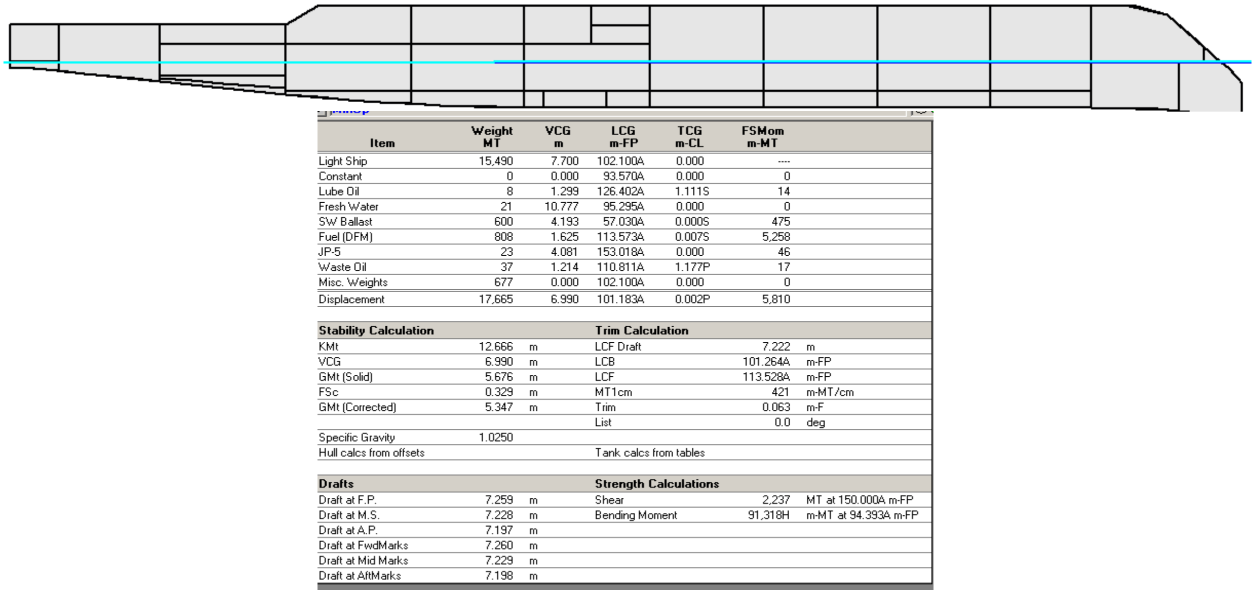


Figure 78: Full Load Bending Moments

The details of the MinOp loading condition and the shear and bending moment diagram can be seen below in



Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT
Light Ship	15,490	7.700	102.100A	0.000	----
Constant	0	0.000	93.570A	0.000	0
Lube Oil	8	1.299	126.402A	1.111S	14
Fresh Water	21	10.777	95.295A	0.000	0
SW Ballast	600	4.193	57.030A	0.000S	475
Fuel (DFM)	808	1.625	113.573A	0.007S	5,258
JP-5	23	4.081	153.018A	0.000	46
Waste Oil	37	1.214	110.811A	1.177P	17
Misc. Weights	677	0.000	102.100A	0.000	0
Displacement	17,665	6.990	101.183A	0.002P	5,810

Stability Calculation			Trim Calculation		
KMt	12.666	m	LCF Draft	7.222	m
VCG	6.990	m	LCB	101.264A	m-FP
GMt (Solid)	5.676	m	LCF	113.528A	m-FP
FSc	0.329	m	MT1cm	421	m-MT/cm
GMt (Corrected)	5.347	m	Trim	0.063	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.	7.259	m	Shear	2,237	MT at 150.000A m-FP
Draft at M.S.	7.228	m	Bending Moment	91,318H	m-MT at 94.393A m-FP
Draft at A.P.	7.197	m			
Draft at FwdMarks	7.260	m			
Draft at Mid Marks	7.229	m			
Draft at AftMarks	7.198	m			

Figure 79: MinOp Condition Details

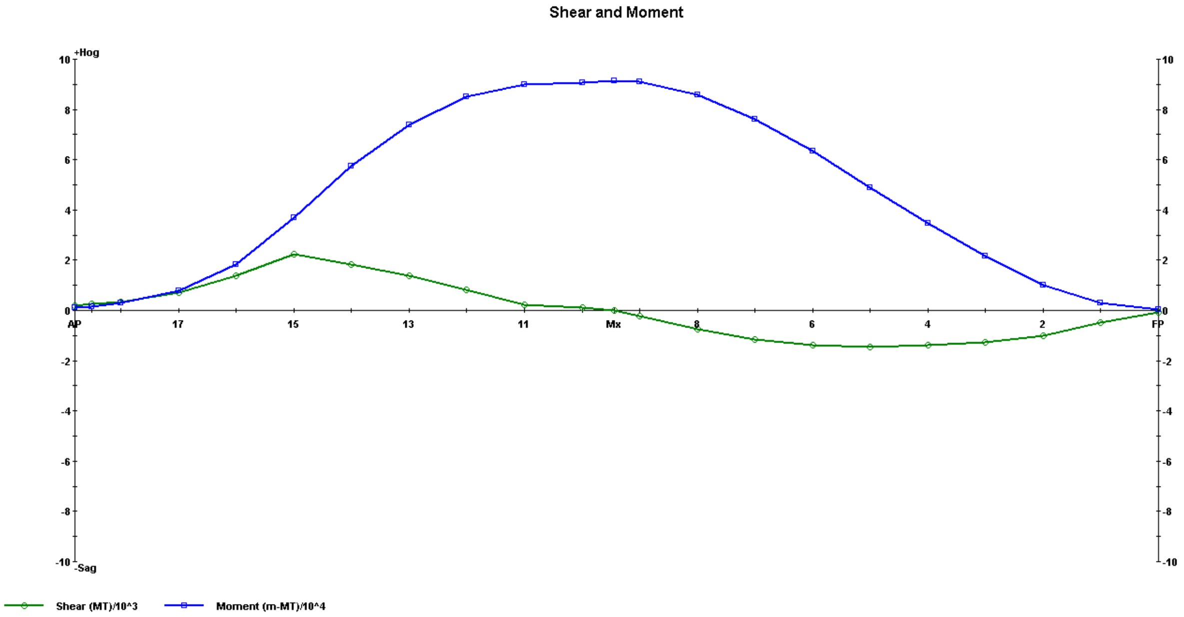


Figure 80: MinOp Bending Moments

4.5 Structural Design and Analysis

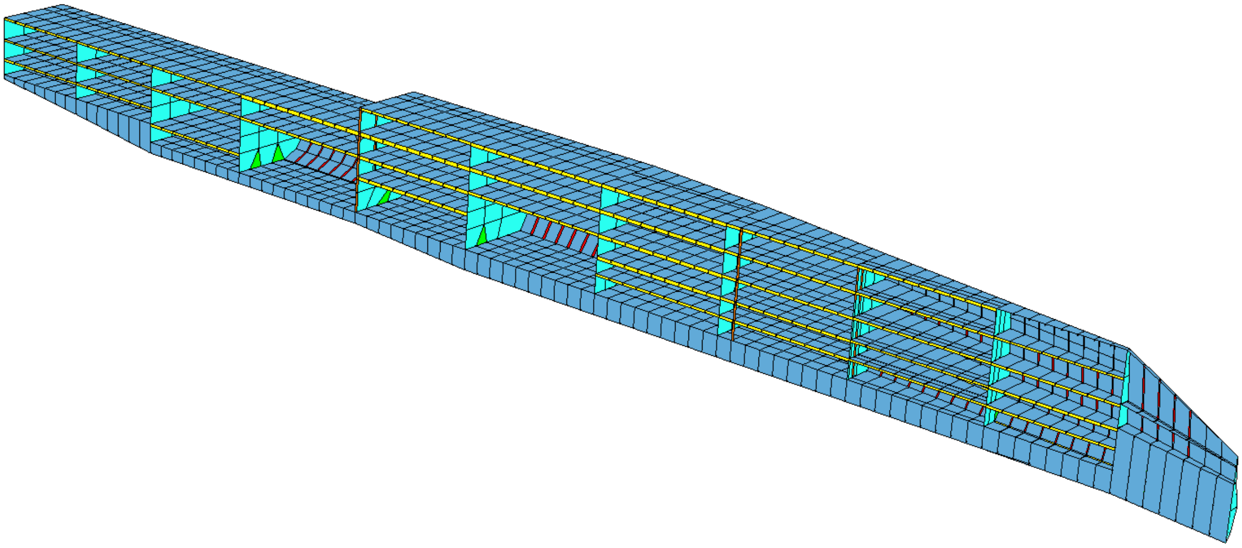


Figure 81 MAESTRO Full Ship Model

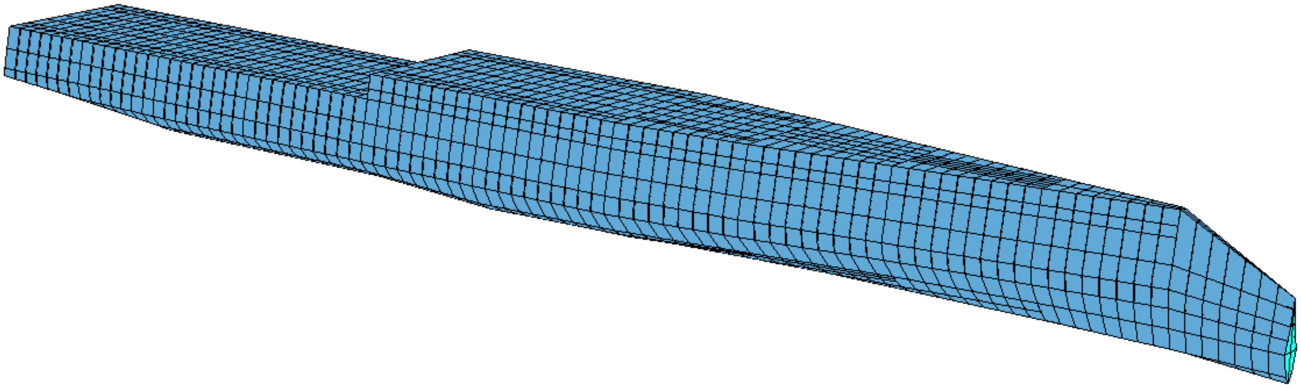


Figure 82 MAESTRO Full Ship Model

The iterative process that drives the structural design of the Medium Surface Combatant is illustrated in Figure 83. After initial stresses, modes of failure, and strengths are determined, scantlings are modified and the process is repeated. MAESTRO is used to solve the stresses on the hull and optimize the scantlings. MAESTRO is a coarse-mesh finite element solver that has the ability to evaluate individual modes of failure.

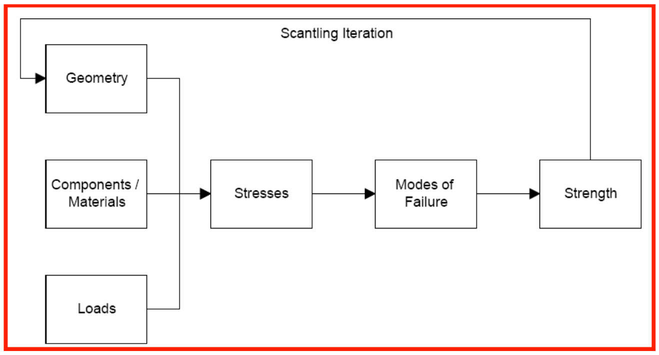


Figure 83 Structural Design Process

4.5.1 Geometry, Components and Materials

A full ship was modeled in MAESTRO for analysis with the exception of the bulbous bow. Figure 81 and Figure 82 show the eleven modules that make up the full ship MAESTRO model. The limitations of MAESTRO, being a linear program, make a bulbous bow difficult to model with few benefits. The locations of points along the hull and inner decks are given by the Hull Structure Module output reports in ASSET. The Module is run for each transverse bulkhead location, which is determined in Rhino. These point locations are input into MAESTRO as endpoint locations and are connected by strakes creating modules that span transverse bulkheads. The material used for the MSC is HSLA-80 steel, as determined by ASSET. Properties of HSLA-80 steel are given in Table 37. Also given in ASSET are the scantlings of all components in the ship; the beams, girders, stiffeners, and plates. These elements are shown in Figure 84 for the fifth module in the ship. Transverse bulkheads are created using quad and tri elements that connect four or three points without extending the length of the module. Longitudinal strakes and transverse compounds in the inner bottom provide the support required for the tankage volumes. Stanchions are added where needed and are defined as beam elements.

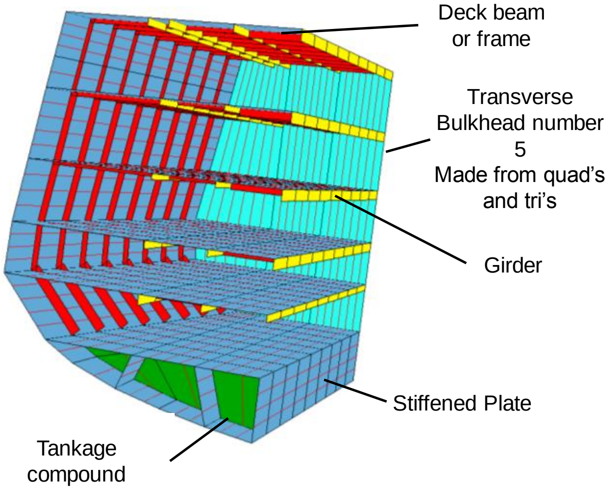


Figure 84 Module in MAESTRO with various components

Table 37 Material properties of HSLA-80

Young’s Modulus (GPa)	204
Poisson Ratio	0.3
Density (kg/mm^3)	7.83341E-6
Yield Stress (MPa)	552
Ultimate Stress (MPa)	379

4.5.2 Loads

Analysis of loading condition in MAESTRO takes into account lightship mass distribution, internal tank fluid mass loads, pressure loads (both actual and design), and hydrostatic loads. Further iterations of the design would include studies of accelerations, cargo masses, and point loads. For this process two loading conditions are considered: full load and minimum operation loading conditions. For full load condition, all fuel tanks are at 95% capacity and saltwater ballast is empty. Minimum operating condition refers to all fuel tanks at 33% and saltwater ballast at 95%. Figure 85 shows the tankage arrangement within the model.

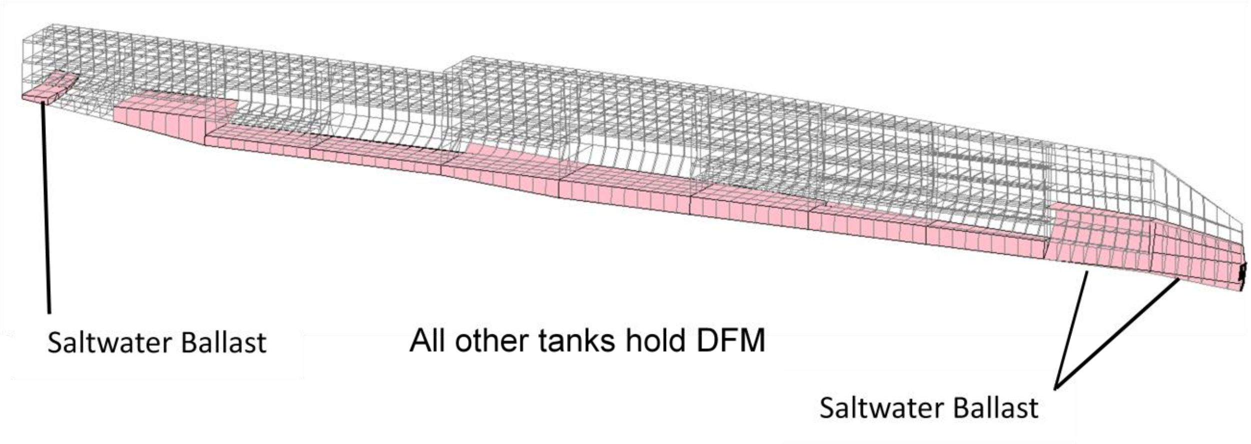


Figure 85 Tankage arrangement

For each of these loading conditions, there are three wave conditions considered: still water, sagging and hogging waves. The wave modeled is a worst case scenario condition, with the height equal to 8.32 meters or an equivalent of Sea State 7. All three wave conditions are shown in Figure 86.

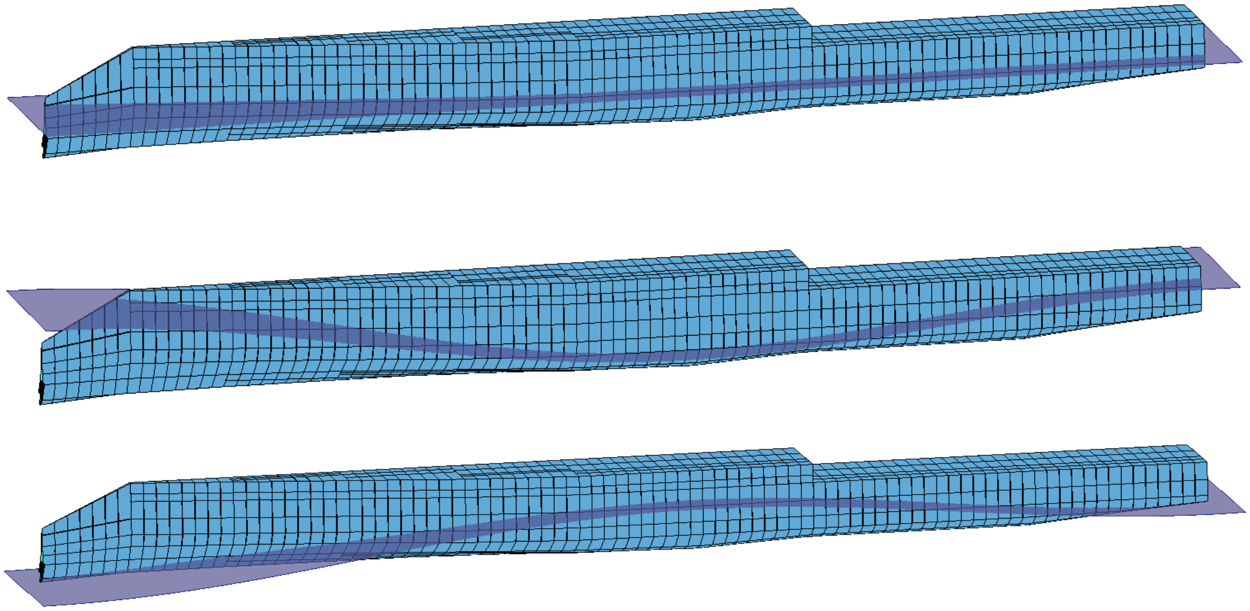


Figure 86 Wave conditions for MAESTRO analysis

4.5.3 Adequacy

After the model is built and loading is applied, the ship is balanced to calculate the emergence and pitch angle under the given loading conditions. Once the model is balanced an analysis and evaluation is performed. The user can view the deformed model and the maximum stress values for one module or the full ship. Perhaps the best tools for analysis of the model are minimum plate and beam adequacy values. These tools examine over eleven modes of plate failure, including various yield, collapse, and serviceability variations, as well as seven modes of beam failure that evaluate tripping, yielding, and collapse. Stresses for each plate and beam are compared to limit state values for the various failure modes to create a strength ratio using the MAESTRO Scalable Solver. Each of the six loading cases has different values and modes of failure. Table 38 shows the minimum adequacy of plates and beams for each loading case. The minimum adequacy is given in a normalized range from negative one to one by taking (1-r)/(1+r). If a plate or beam has a value in the negative range it is failing with the severity increasing as it reaches one. A positive minimum adequacy value corresponds to an adequately designed element. As the minimum adequacy approaches one, the component is deemed to be over designed and reduction in scantlings can be made to save on cost. Shown below in Figure 87 and Figure 88 are the minimum plate and beam adequacies for the full load hogging loading condition, which is the worst of the six cases. The minimum adequacy for the elements range from -0.28 to 1.0. In further iterations of the design, changes would be made to the beam and plate properties as needed to shift the minimum adequacy value to the ideal range of 0.2 to 0.6. Results showing the maximum stress are given in Figure 89. These values are significantly below the yield stress giving a good starting point for the design.

Table 38 Minimum Adequacy of Plates and Beams

Loading Condition	Min. Plate Adequacy	Min. Beam Adequacy
Full load Stillwater	0.00	-0.23
Full load Hogging	-0.28	-0.24
Full load Sagging	-0.20	-0.24
Min. Op Stillwater	0.00	-0.23
Min. Op Hogging	-0.24	-0.27
Min. Op Sagging	-0.26	-0.23

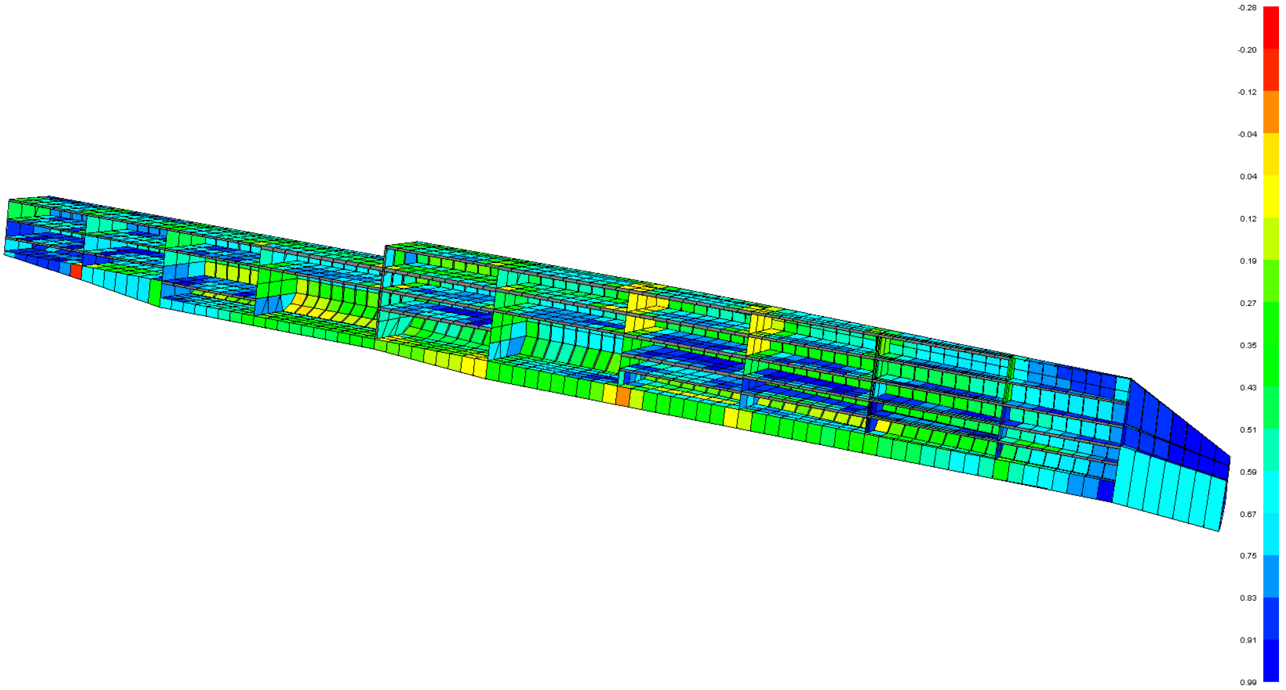


Figure 87 Minimum Plate Adequacy for Full Load Hogging Condition

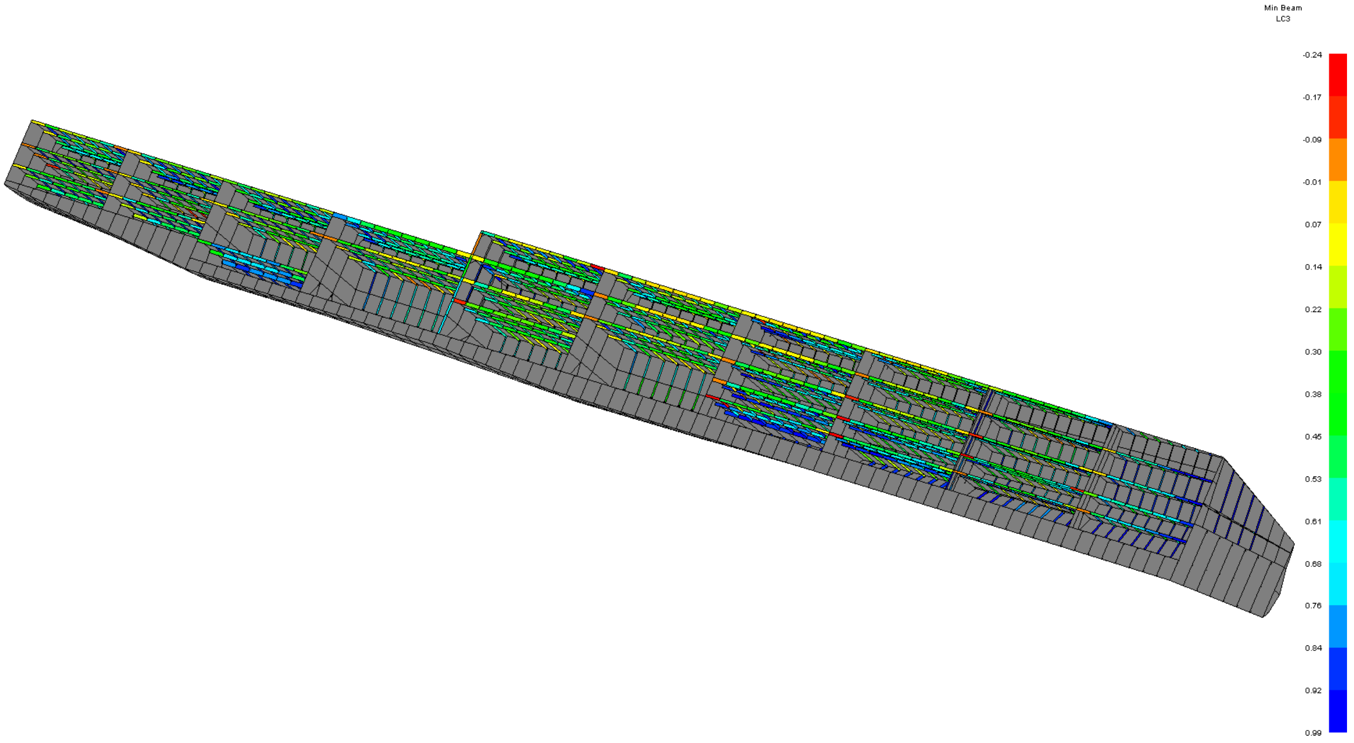


Figure 88 Minimum Beam Adequacy for Full Load Hogging Condition

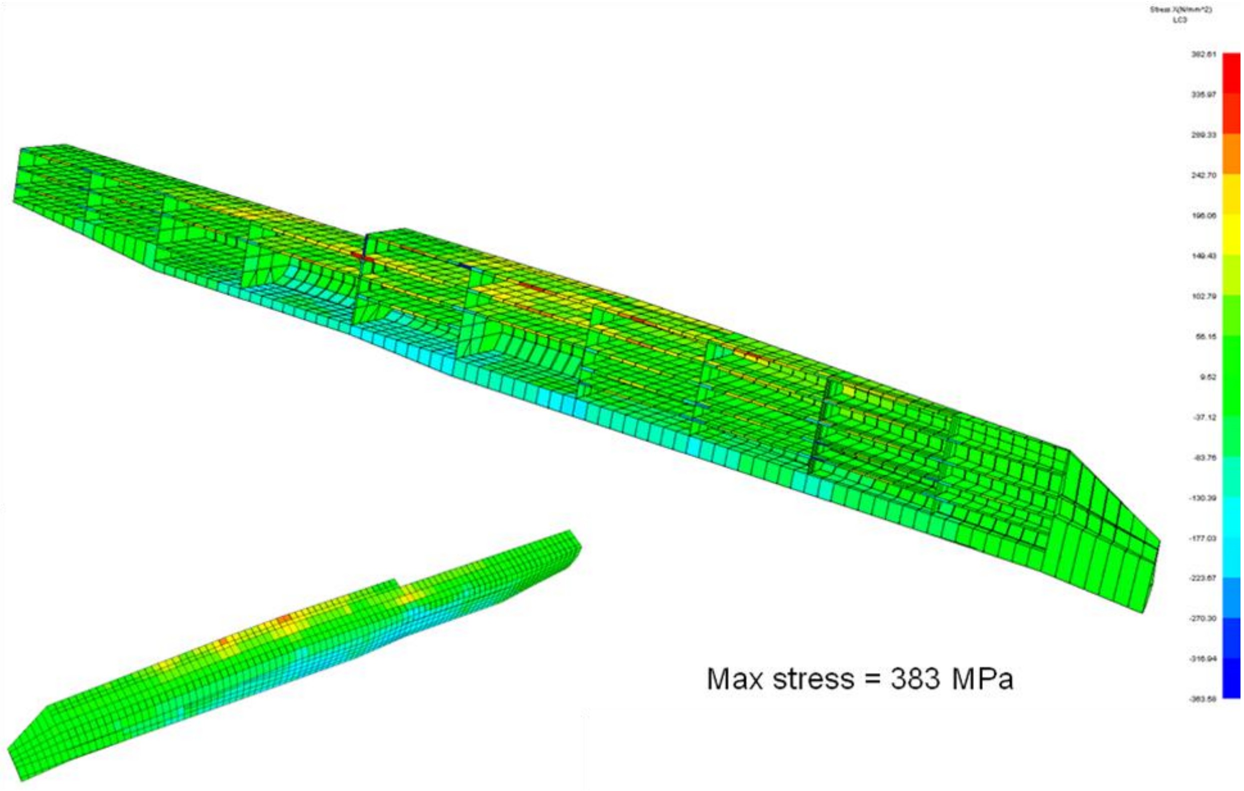


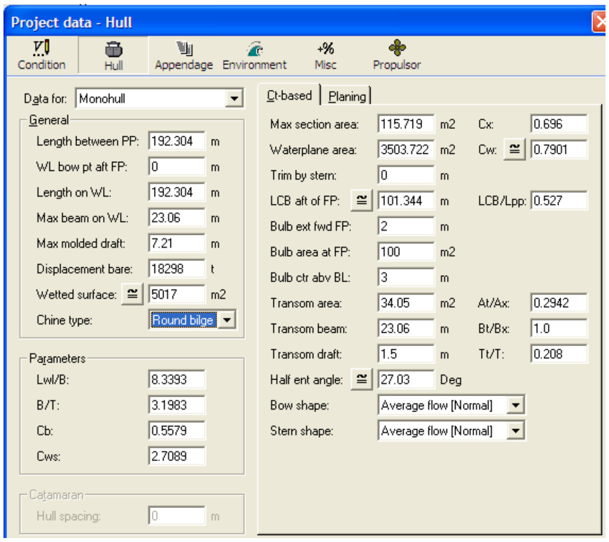
Figure 89 Maximum Longitudinal Stress Full Load Hogging Loading Condition

4.5.4 Revisions and Final Structural Design

The majority of structural issues occur in sections near transverse bulkheads. In further iterations of the design, bracket elements will be implemented to alleviate these high stress concentrations. Another modification that will be made in the next revision is to change the beam and plate properties to increase the minimum adequacies to acceptable levels. The loading conditions considered are important; however there are other situations that need to be analyzed. Conditions such as water on deck and flooding of compartments can be studied to make sure the ship is safe. Finally many of the beams output by ASSET had similar dimensions. This leads to poor producibility and increases the time to complete a project as well as the cost of the ship. Also comparing the beam sizes to commonly used industry components ensures material will not have to be custom made, also saving on time and cost for the project.

4.6 Power and Propulsion

The power and propulsion analysis for this design was performed in NavCad. The ship’s hull form characteristics and geometric parameters were input to NavCad to obtain an overall resistance calculation using the Holtrop-Mennen method. The hull form inputs and sectional area coefficients are shown in Figure 90 below.



Data for: Monohull

General
Length between PP: 192.304 m
WL bow pt aft FP: 0 m
Length on WL: 192.304 m
Max beam on WL: 23.06 m
Max molded draft: 7.21 m
Displacement bare: 18298 t
Wetted surface: 5017 m2
Chine type: Round bilge

Parameters
Lwl/B: 8.3393
B/T: 3.1983
Cb: 0.5579
Cws: 2.7089

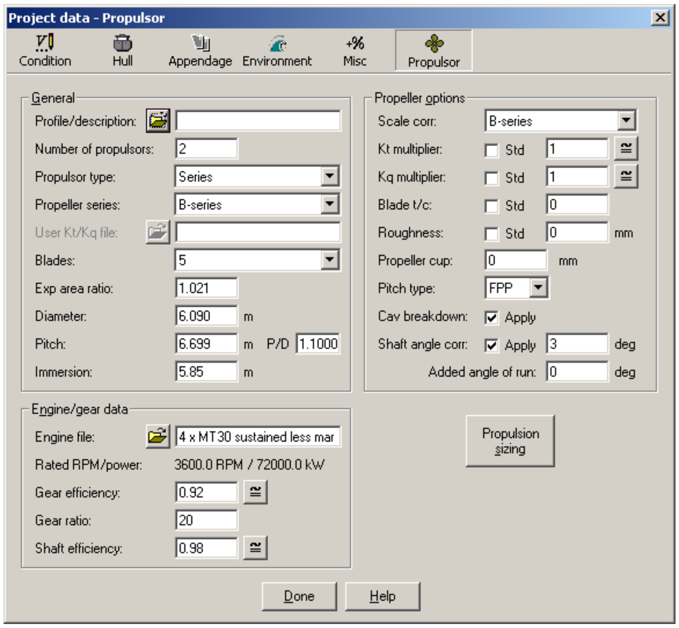
Catamaran
Hull spacing: 0 m

Max section area: 115.719 m2
Cx: 0.696
Waterplane area: 3503.722 m2
Cw: 0.7901
Trim by stern: 0 m
LCB aft of FP: 101.344 m
LCB/Lpp: 0.527
Bulb ext fwd FP: 2 m
Bulb area at FP: 100 m2
Bulb ctr abv BL: 3 m
Transom area: 34.05 m2
At/Ax: 0.2942
Transom beam: 23.06 m
Bt/Bx: 1.0
Transom draft: 1.5 m
Tt/T: 0.208
Half ent angle: 27.03 Deg
Bow shape: Average flow [Normal]
Stern shape: Average flow [Normal]

Figure 90: Hull Form Inputs

Resistance calculations were performed for both endurance and sustained speeds. The propulsion system consists of 4 Rolls Royce MT30 gas turbine engines that drive two 5-bladed Wageningen b-series propellers. MSC-WPTH employs an integrated power system which allows electricity be sent to the electric drive motors, weapons, or radar. The operating characteristics of these systems, in conjunction with the resistance calculations were used to determine the specific fuel consumption at endurance and sustained speeds, as well as an endurance range. The propulsion selection and arrangement characteristics are as follows in Figure 91:

-Twin Screw
-5 Bladed
- Propeller Diameter of 6.09 m
- P/D ratio of 1.2
- Shaft RPM (endurance) – 100 rpm (effective reduction gear ratio of 35)
- Shaft RPM (sustained) – 180 rpm (effective reduction gear ration of 20)



General
Profile/description:
Number of propulsors: 2
Propulsor type: Series
Propeller series: B-series
User Kt/Kq file:
Blades: 5
Exp area ratio: 1.021
Diameter: 6.090 m
Pitch: 6.699 m P/D 1.1000
Immersion: 5.85 m

Propeller options
Scale corr: B-series
Kt multiplier: ☐ Std 1
Kq multiplier: ☐ Std 1
Blade t/c: ☐ Std 0
Roughness: ☐ Std 0 mm
Propeller cup: 0 mm
Pitch type: FPP
Cav breakdown: ☑ Apply
Shaft angle corr: ☑ Apply 3 deg
Added angle of run: 0 deg

Engine/gear data
Engine file: 4 x MT30 sustained less mar
Rated RPM/power: 3600.0 RPM / 72000.0 kW
Gear efficiency: 0.92
Gear ratio: 20
Shaft efficiency: 0.98

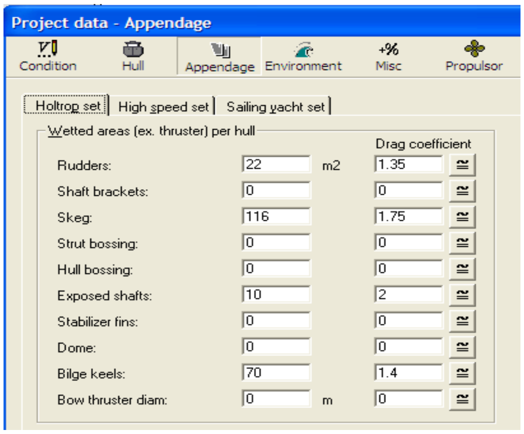
Figure 91: Sustained Speed Propulsion inputs

4.6.1 Resistance

As previously stated in this report, the resistance calculation is performed at endurance and sustained speeds using the Holtrop-Mennen method in NavCad. This method approximates the bare hull viscous surface friction drag and the wave-making mass movement drag. The total resistance is a sum of:

- Viscous Drag (uses ITTC estimates, friction)
- Wave-making Drag (force to move mass of water around the hull)
-Appendage Drag (drag of propellers, skig, bilge keels, etc.)
- Bulb Drag
- Transom Drag

NavCad requires additional input to calculate the appendage drag as seen in Figure 92 below.

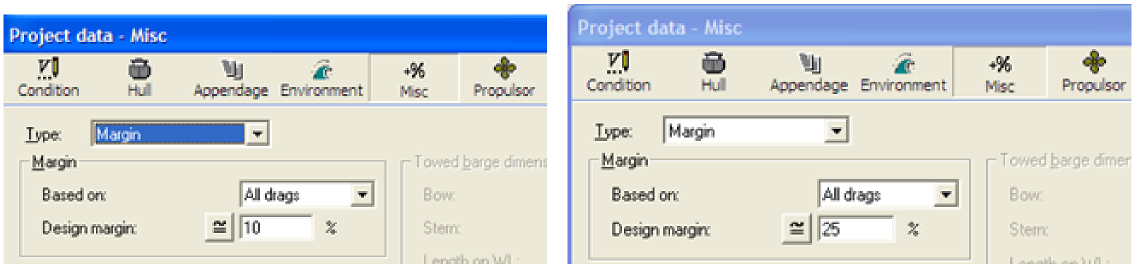


Wetted areas (ex. thruster) per hull

	Wetted area		Drag coefficient
Rudders:	22	m2	1.35
Shaft brackets:	0		0
Skeg:	116		1.75
Strut bossing:	0		0
Hull bossing:	0		0
Exposed shafts:	10		2
Stabilizer fins:	0		0
Dome:	0		0
Bilge keels:	70		1.4
Bow thruster diam:	0	m	0

Figure 92: Appendage Drag input

The power is calculated and includes a 10% margin at endurance speed and a 25% margin at sustained speed. Effective horsepower required is a sum of power needed to overcome the total bare hull resistance, appendage drag, and air resistance. The inputs can be seen below in Figure 93.

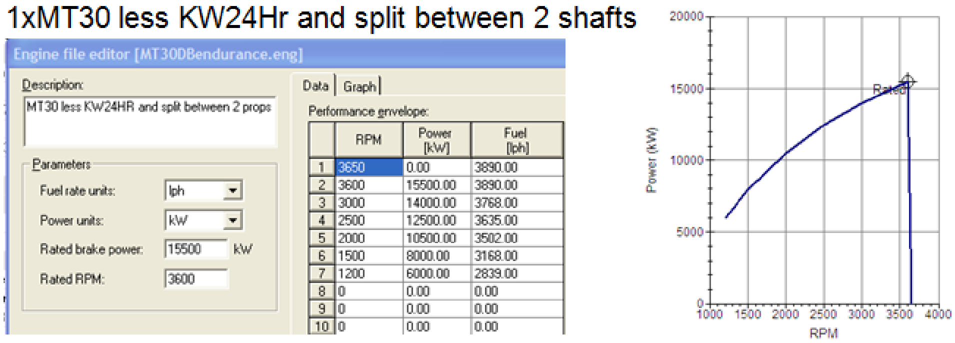


Type: Margin
Margin
Based on: All drags
Design margin: 10 %

Type: Margin
Margin
Based on: All drags
Design margin: 25 %

Figure 93: Margin Inputs for Endurance (left) and Sustained (right) Speeds

Figure 94below illustrates the engine profile performance envelope for 1 MT30 operating at endurance speed. Because NavCad does not have a way of directly modeling an integrated power system, it was necessary to manipulate the performance envelope of the engine by subtracting the 24 hour kilowatt average and dividing the engine power in half. The fuel consumption was also modified.



1xMT30 less KW24Hr and split between 2 shafts

Engine file editor [MT30DBendurance.eng]

Description: MT30 less KW24HR and split between 2 props

Parameters

Fuel rate units: lph

Power units: kW

Rated brake power: 15500 kW

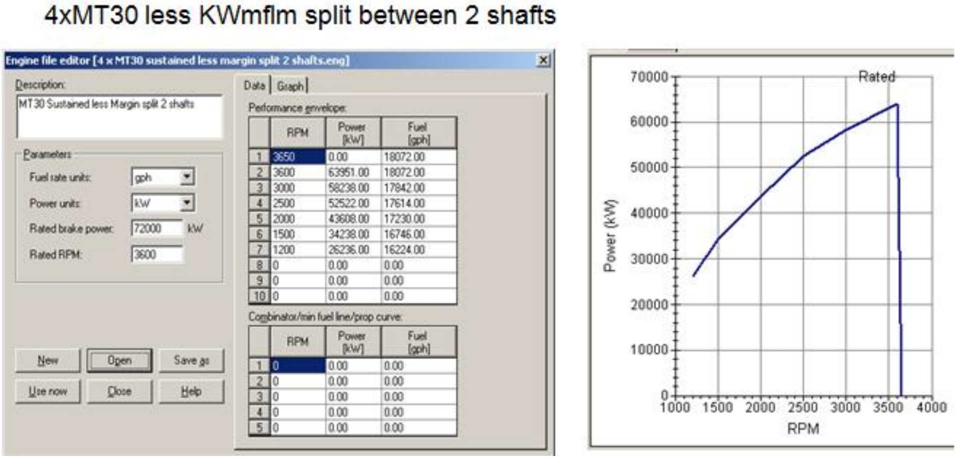
Rated RPM: 3600

Performance envelope:

	RPM	Power [kW]	Fuel [lph]
1	3650	0.00	3890.00
2	3600	15500.00	3890.00
3	3000	14000.00	3768.00
4	2500	12500.00	3635.00
5	2000	10500.00	3502.00
6	1500	8000.00	3168.00
7	1200	6000.00	2839.00
8	0	0.00	0.00
9	0	0.00	0.00
10	0	0.00	0.00

Figure 94: Engine Performance Inputs

A similar operation was performed for the sustained speed calculation. The 4 gas turbines used in sustained speed were modeled as a single engine by multiplying the power and fuel consumption by 4, less the maximum functional load with margins. These inputs can be seen below in Figure 95.



4xMT30 less KWmflm split between 2 shafts

Engine file editor [4 x MT30 sustained less margin split 2 shafts.eng]

Description: MT30 Sustained less Margin split 2 shafts

Parameters

Fuel rate units: gph

Power units: kW

Rated brake power: 72000 kW

Rated RPM: 3600

Performance envelope:

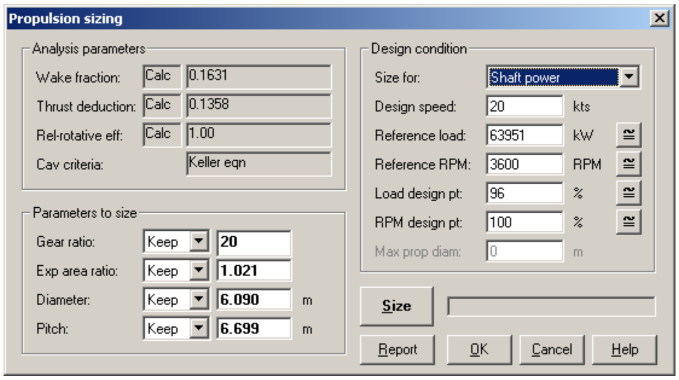
	RPM	Power [kW]	Fuel [gph]
1	3650	0.00	18072.00
2	3600	63951.00	18072.00
3	3000	58238.00	17842.00
4	2500	52522.00	17614.00
5	2000	43608.00	17230.00
6	1500	34238.00	16746.00
7	1200	26236.00	16224.00
8	0	0.00	0.00
9	0	0.00	0.00
10	0	0.00	0.00

Combinator/min fuel line/prop curve:

	RPM	Power [kW]	Fuel [gph]
1	0	0.00	0.00
2	0	0.00	0.00
3	0	0.00	0.00
4	0	0.00	0.00
5	0	0.00	0.00

Figure 95: Performance Inputs

The propulsion system assumes 98% transmission efficiency and a 92% motor, generator and frequency control efficiency for electrical losses. The Integrated Power System (IPS) is modeled in NavCad as a variable reduction gear ratio and the total power is split between shafts. Figure 96 below shows the inputs for sizing the propulsion system.



Propulsion sizing

Analysis parameters

Wake fraction: Calc 0.1631

Thrust deduction: Calc 0.1358

Rel-rotative eff: Calc 1.00

Cav criteria: Keller eqn

Parameters to size

Gear ratio: Keep 20

Exp area ratio: Keep 1.021

Diameter: Keep 6.090 m

Pitch: Keep 6.699 m

Design condition

Size for: Shaft power

Design speed: 20 kts

Reference load: 63951 kW

Reference RPM: 3600 RPM

Load design pt: 96 %

RPM design pt: 100 %

Max prop diam: 0 m

Figure 96: Propulsion Sizing

In addition to the MT30's, MSC-WPTH will also be equipped with 2 CAT 3608 diesel generators for emergency ship service. For endurance speed, the ship will operate on 1 MT30 gas turbine engine, splitting the power between 2 shafts through the IPS. Sustained speed operation will employ all 4 MT30 gas turbines.

4.6.2 Propulsion Analysis – Endurance Range and Sustained Speed

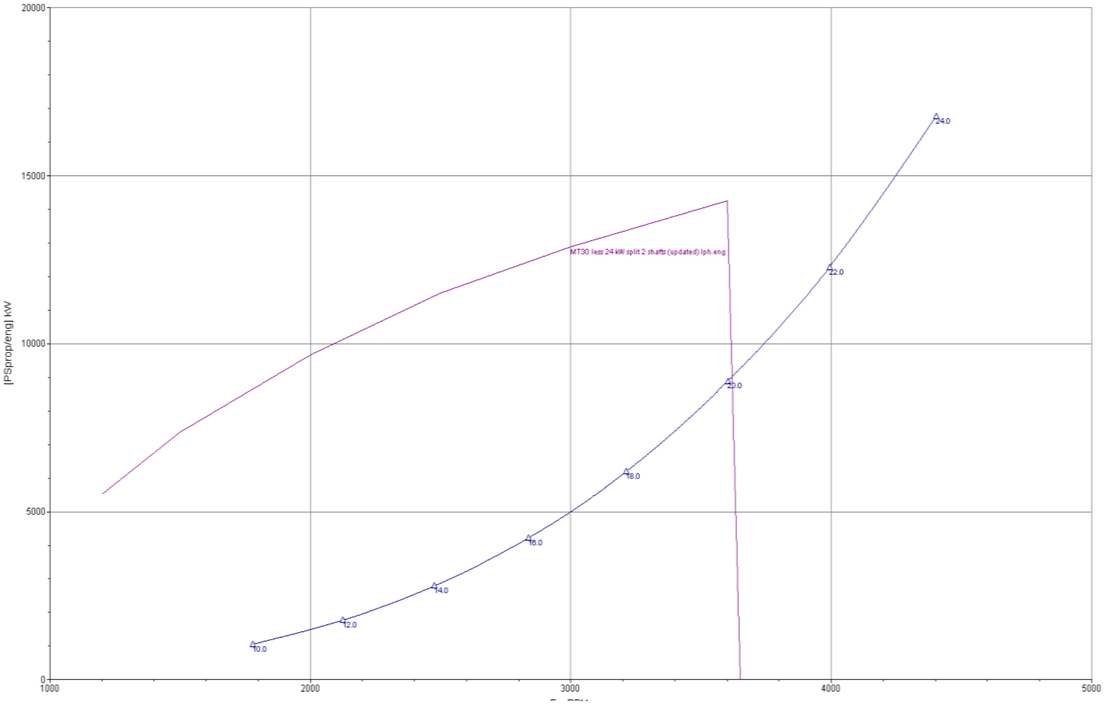


Figure 97: Endurance Speed Propulsion Analysis

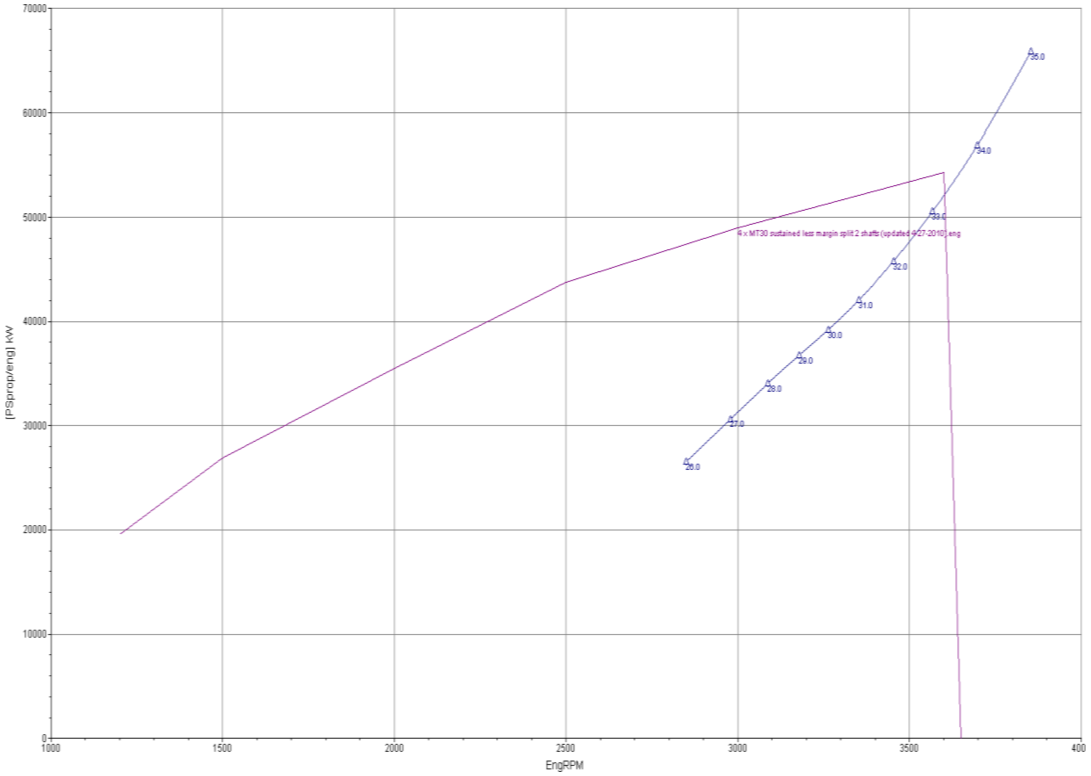


Figure 98: The Sustained Speed Propulsion Analysis

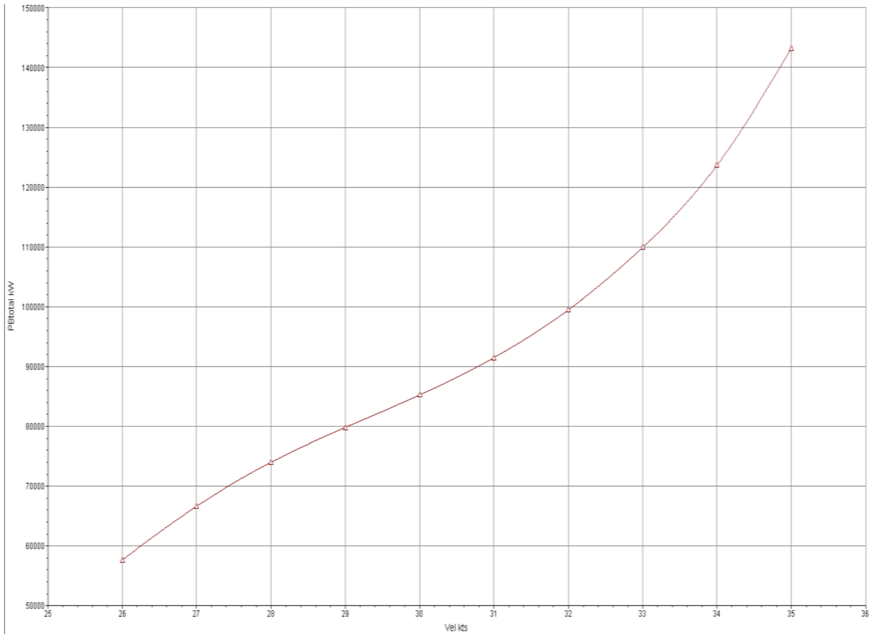


Figure 99: Brake Horsepower Required (BHP) at sustained speed less Kw maximum functional load with margins

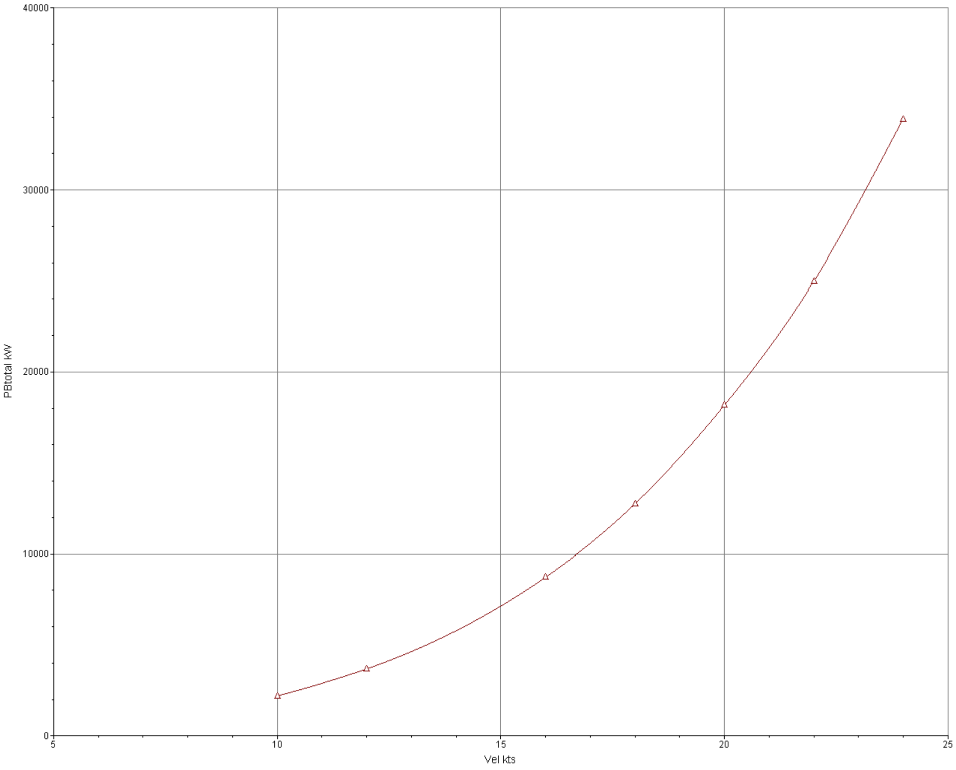


Figure 100: Brake Horsepower Required (BHP) at endurance speed less Kw maximum functional load with margins

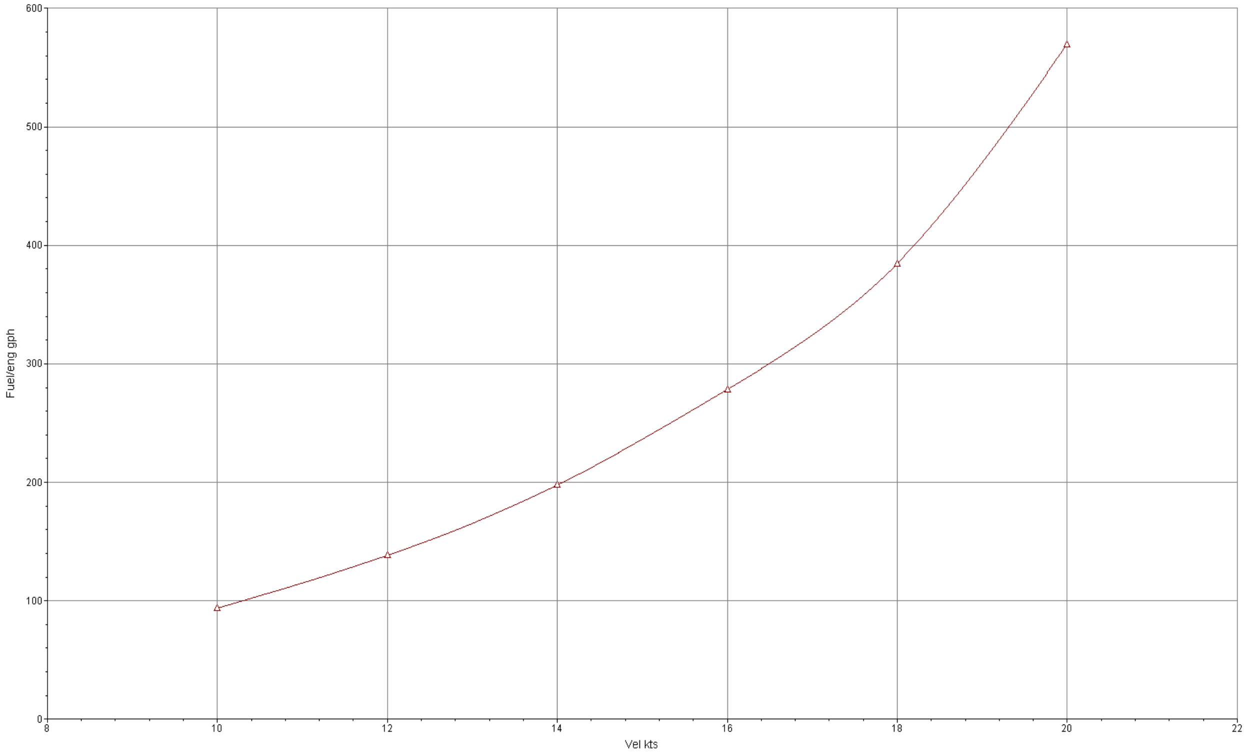
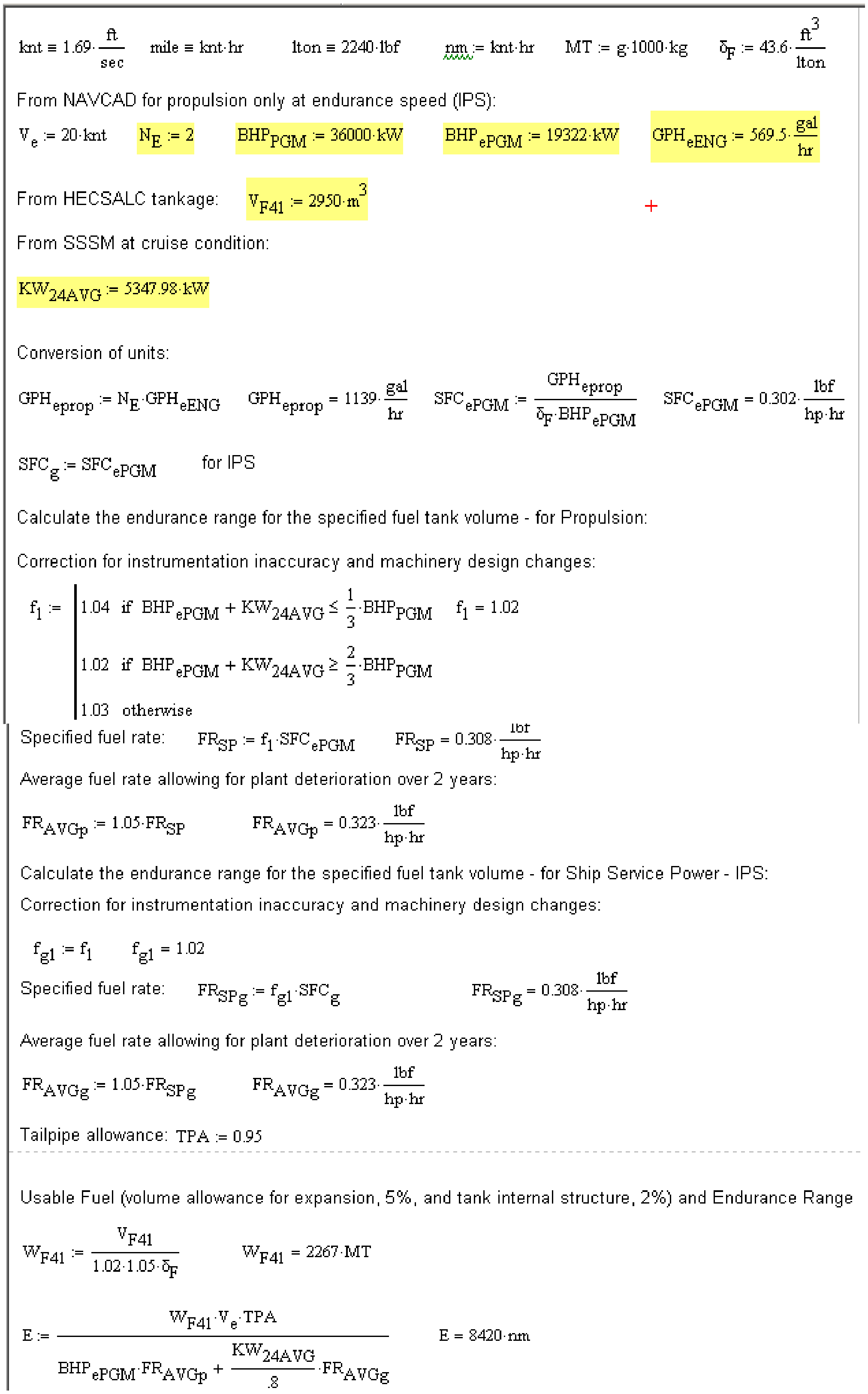


Figure 101: Endurance Speed Fuel Consumption (gph)

The operating characteristics of these systems, in conjunction with the resistance calculations were used to determine the specific fuel consumption at endurance and sustained speeds, as well as an endurance range. The calculation for the endurance range, performed in MathCad, is illustrated below in Figure 102. The highlighted sections denote the input parameters that were obtained from NavCad and HECSALV.



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

From NAVCAD for propulsion only at endurance speed (IPS):

$V_e := 20\cdot\text{knt}$ $\quad$ $N_E := 2$ $\quad$ $BHP_{PGM} := 36000\cdot\text{kW}$ $\quad$ $BHP_{ePGM} := 19322\cdot\text{kW}$ $\quad$ $GPH_{eENG} := 569.5\cdot\frac{\text{gal}}{\text{hr}}$

From HECSALC tankage: $V_{F41} := 2950\cdot\text{m}^3$

From SSSM at cruise condition:

$KW_{24AVG} := 5347.98\cdot\text{kW}$

Conversion of units:

$GPH_{eprop} := N_E\cdot GPH_{eENG}$ $\quad$ $GPH_{eprop} = 1139\cdot\frac{\text{gal}}{\text{hr}}$ $\quad$ $SFC_{ePGM} := \frac{GPH_{eprop}}{\delta_F\cdot BHP_{ePGM}}$ $\quad$ $SFC_{ePGM} = 0.302\cdot\frac{\text{lbf}}{\text{hp}\cdot\text{hr}}$

$SFC_g := SFC_{ePGM}$ $\quad$ for IPS

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

Correction for instrumentation inaccuracy and machinery design changes:

$$f_1 := \begin{cases} 1.04 & \text{if } BHP_{ePGM} + KW_{24AVG} \le \frac{1}{3}\cdot BHP_{PGM} \\ 1.02 & \text{if } BHP_{ePGM} + KW_{24AVG} \ge \frac{2}{3}\cdot BHP_{PGM} \\ 1.03 & \text{otherwise} \end{cases} \qquad f_1 = 1.02$$

Specified fuel rate: $FR_{SP} := f_1\cdot SFC_{ePGM}$ $\quad$ $FR_{SP} = 0.308\cdot\frac{\text{lbf}}{\text{hp}\cdot\text{hr}}$

Average fuel rate allowing for plant deterioration over 2 years:

$FR_{AVGp} := 1.05\cdot FR_{SP}$ $\quad$ $FR_{AVGp} = 0.323\cdot\frac{\text{lbf}}{\text{hp}\cdot\text{hr}}$

Calculate the endurance range for the specified fuel tank volume - for Ship Service Power - IPS:

Correction for instrumentation inaccuracy and machinery design changes:

$f_{g1} := f_1$ $\quad$ $f_{g1} = 1.02$

Specified fuel rate: $FR_{SPg} := f_{g1}\cdot SFC_g$ $\quad$ $FR_{SPg} = 0.308\cdot\frac{\text{lbf}}{\text{hp}\cdot\text{hr}}$

Average fuel rate allowing for plant deterioration over 2 years:

$FR_{AVGg} := 1.05\cdot FR_{SPg}$ $\quad$ $FR_{AVGg} = 0.323\cdot\frac{\text{lbf}}{\text{hp}\cdot\text{hr}}$

Tailpipe allowance: $TPA := 0.95$

Usable Fuel (volume allowance for expansion, 5%, and tank internal structure, 2%) and Endurance Range

$W_{F41} := \frac{V_{F41}}{1.02\cdot 1.05\cdot\delta_F}$ $\quad$ $W_{F41} = 2267\cdot\text{MT}$

$$E := \frac{W_{F41}\cdot V_e\cdot TPA}{BHP_{ePGM}\cdot FR_{AVGp} + \frac{KW_{24AVG}}{.8}\cdot FR_{AVGg}} \qquad E = 8420\cdot\text{nm}$$

Figure 102: Endurance Range Calculation

4.6.3 Electric Load Analysis (ELA)

Table 39 shown below is the electric load analysis for the MSC. It is based on power requirements that were taken from ASSET. Any numbers that ASSET did not provide were generated by multiplying the connected load by the power factor that is expected at that condition. Note that in a battle condition there are 4 MT 30s on the line, but in all other conditions there is either one or no MT 30s on the line. The emergency generators are not intended for propulsion, but just for providing power in an emergency or in an at anchor or in port situation.

Table 39: Electric Load Analysis Summary

		Connected Load	Battle		Cruise		Anchor		In Port		Emergency	
SWBS	Description	(kW)	Power Factor	(kW)	Power Factor	(kW)	Power Factor	(kW)	Power Factor	(kW)	Power Factor	(KW)
200	Propulsion	117182		114344		18307		2592		0		400
	Propulsion Direct	113043	1.00	113043	0.15	17521	0.02	2457	0.00	0	0.00	400
	Propulsion support	4139	0.31	1301	0.19	786	0.03	135	0.00	0	0.00	0
300	Electric	1924	0.25	475	0.24	465	0.17	318	0.40	770	0.14	264
400	CCC	9725	0.57	5497	0.56	5463	0.12	1126	0.00	42	0.25	2442
	Combat Systems	9304	0.56	5232	0.56	5191	0.11	1000	0.00	0	0.25	2315
	Miscellaneous	421	0.63	266	0.64	271	0.30	126	0.10	42	0.30	127
500	Auxiliary	11917	0.33	3977	0.32	3812	0.44	3485	0.27	3192	0.09	1096
510	HVAC	5418	0.35	1919	0.45	2417	0.35	1900	0.40	2167	0.17	909
520	Sea Water Systems	553	0.34	187	0.29	163	0.29	162	0.40	221	0.34	187
530	Fresh Water System	579	0.56	323	0.72	417	0.72	417	0.72	417	0.00	0
540	Fuel Handling	1498	0.34	508	0.17	254	0.03	51	0.10	150	0.00	0
550	Air System	3080	0.34	1041	0.18	561	0.18	560	0.00	0	0.00	0
580	Deck Machinery	790	0.00	0	0.00	0	0.50	395	0.30	237	0.00	0
600	Services	639	0.10	66	0.19	123	0.15	95	0.40	256	0.00	3
700	Weapons	270	0.34	91	0.21	57	0.11	29	0.00	0	0.34	92
	Total Required	141658		124451		28226		5053		4259		4295
	24 Hour Average	13531		118672		22554		3767		2166		2116

Number	Generator	Rating (kW)	Total Connected (kW)	Online	(kW)	Online	(kW)	Online	(kW)	Online	(kW)	Online	(KW)
4	MT30	36000.0	144000	4	144000	1	36000	0	0	0	0	1	36000
2	CAT 3608	2527.9	5056	0	0	1	2528	2	5056	2	5056	0	0
	Total		149056		144000		38528		5056		5056		36000

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. The Machinery Equipment List (MEL) of major mechanical and electrical systems includes quantities, dimensions, weights, and locations. The complete MEL is provided in Appendix D.

4.7.1 Integrated Power System (IPS) and Electrical Distribution

Integrated Power Systems enable flexibility for future electrical distributions. These systems are designed to distribute power more readily through the ship. In recent years modularity has become increasingly important for naval ships, and the utilization of an integrated power system eases the transition for modernization. Figure 103 below shows some of the components of an IPS.

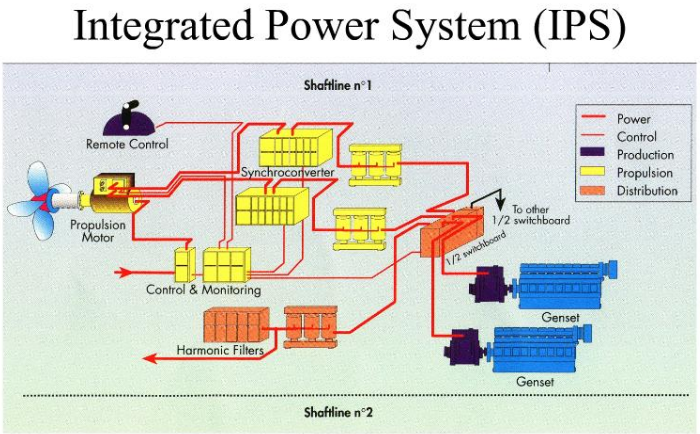


Figure 103: Integrated Power System

IPS allows the distribution of power to be altered, based on the components necessary for the mission of the ship. Generators are distributed in a zonal fashion throughout the ship which is designated to feed the necessary power requirements within the assigned zone. This zonal distribution is shown below in Figure 104.

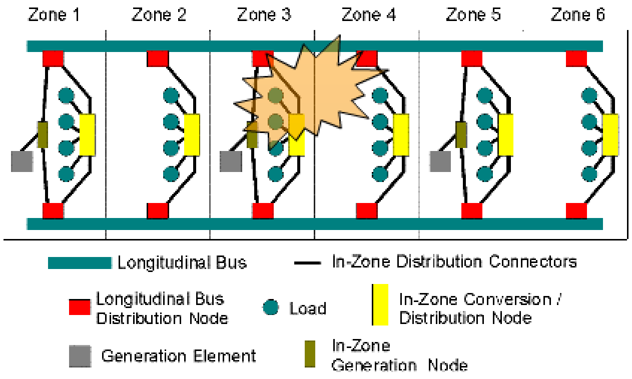


Figure 104: Zonal Distribution

This technique increases the effectiveness of the power supply. In addition, due to limited bulkhead penetration from cables, zonal distribution limits ship vulnerability and increases survivability. Below is a list of power system component modules associated with an integrated power system.

Integrated Power System (IPS) Standard Modules

- Power Generation Module (PGM)
- Propulsion Motor Module (PMM)
- Power Distribution Module (PDM)
- Power Conversion Module (PCM)
- Power Control (PCON)
- Energy Storage Module (ESM)
- Load (PLM)

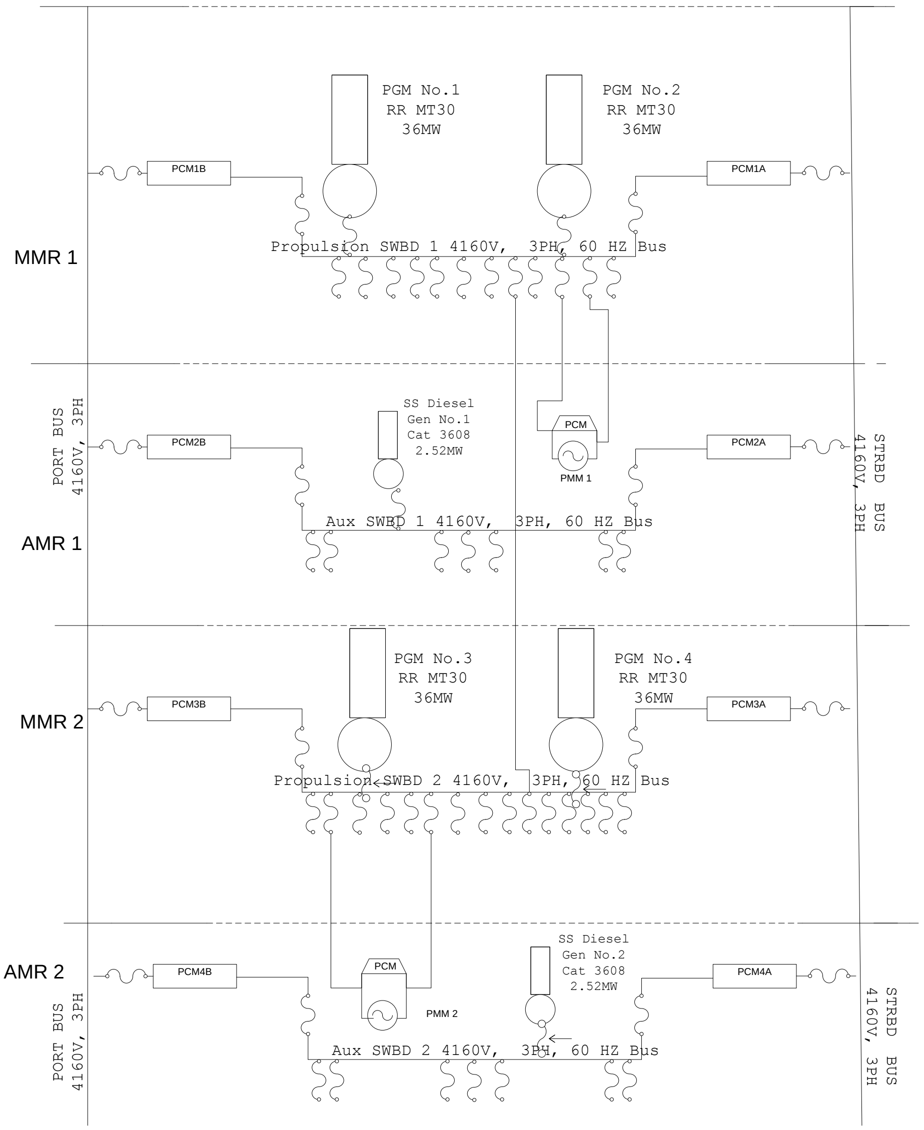


Figure 105 - One-Line Electrical Diagram

4.7.2 Main and Auxiliary Machinery Spaces and Machinery Arrangement

The main and auxiliary machinery spaces occupy spaces between transverse bulkhead 6 and 10. The two main machinery rooms are each three platforms high, and the two auxiliary machinery rooms are two platforms high. Figure 106 shows a 3D image of the 4 machinery rooms, while the details of the arrangements are shown in 2-D images that follow. The arrangement of the machinery rooms split the two main and the two auxiliary machinery rooms up, providing for increased survivability in the case of a breached hull.

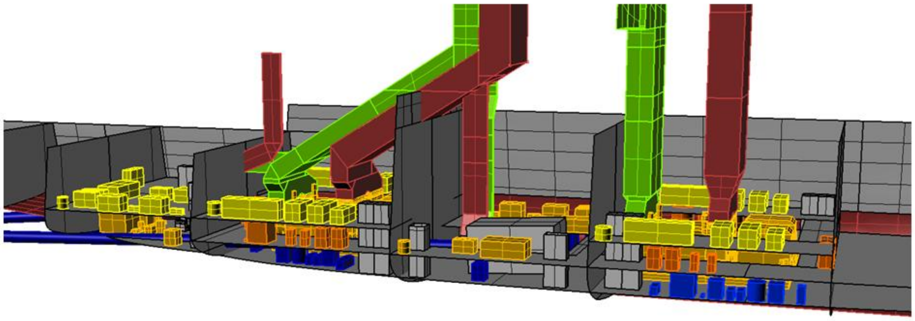
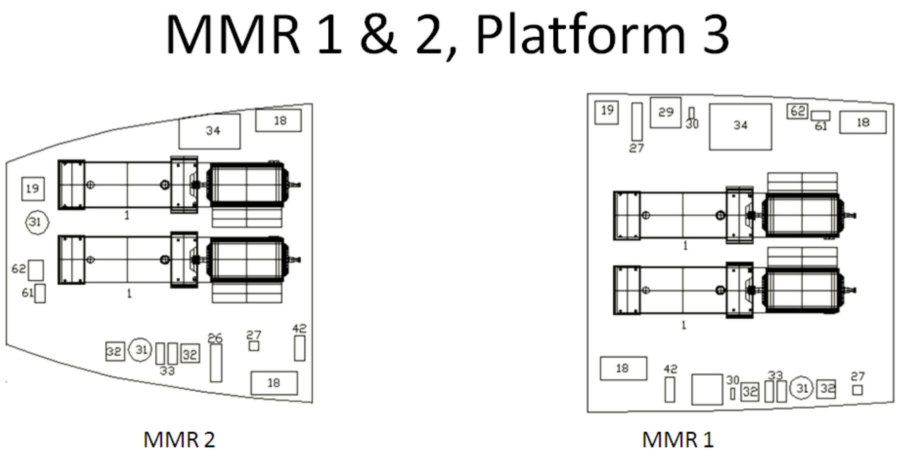


Figure 106: 3D Machinery Arrangements

The Machinery Equipment List (MEL) is located in Appendix D. Machinery equipment which is labeled in subsequent figures corresponds to machinery in that list. The item number is given in the 2-D diagrams and the name of the piece of equipment is given below the drawing. In Appendix D, information regarding the capacity rating, SWBS number, location, and dimensions can be found.

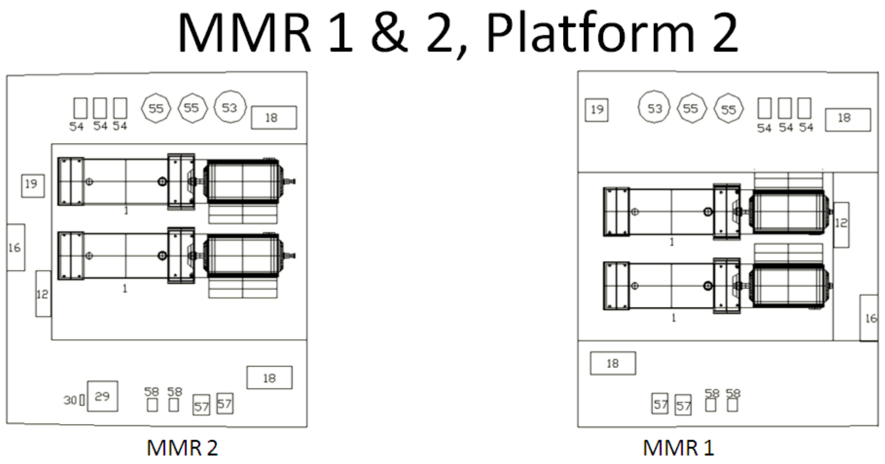
Figure 107 diagrams the third platform in main machinery room 1 and 2. The four MT-30 Gas Turbines are split between the two main machinery rooms are located on this platform. Much of the machinery that is associated with the gas turbines is located on this platform including purifiers, transfer pumps, and service tanks. Machinery was arranged in a way to give access to the front panels of all machinery.



1	Rolls Royce MT-30	32	Fuel Oil Purifier
18	Ladders	33	Fuel Oil Transfer Pump
19	Escape Trunk	34	Fuel Oil Service Tank
26	Dynamic Resistor	37	Ship Service Refrigeration Plant
27	Main Seawater Circulation Pump	42	Bilge/ Ballast Pump
29	Lube Oil Purifier	61	Oily Waste Transfer Pump
30	Lube Oil Transfer Pump	62	Oil/ Water Separator
31	Main GT Fuel Filter Separator		

Figure 107: Machinery Arrangements, MMR 1&2, Platform 3

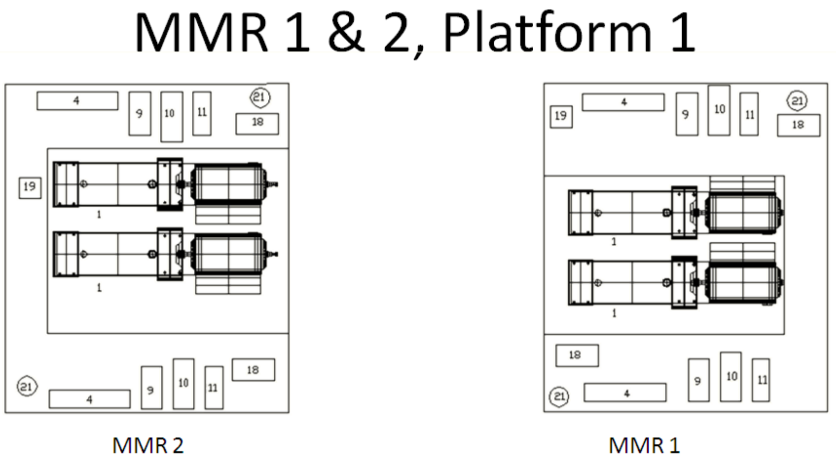
Platform 2 of each of the main machinery room is shown in Figure 108. Each house the main control console of the machinery room and are positioned to overlook the gas turbines. Low and high pressure air compressors, as well as the starting air receiver are also located on this platform.



1	Rolls Royce MT-30	53	Starting Air Receiver
12	Main Control Console	54	MP Air Compressor
16	Ship Service Switchboard	55	Ship Service Air Receiver
18	Ladder	57	LP Ship Service Air Compressor
19	Escape Trunk	58	Air Dryer
29	Lube Oil Purifier		
30	Lube Oil Transfer Pump		

Figure 108: MMR 1&2, Platform 2

Figure 109 below shows the first platform in MMR 1 and 2 where most of the electrical machinery is located. This is purposely done to keep the electrical equipment centrally located and also to keep water or oil from dripping onto the machinery. Power conversion modules and harmonic filters and switchgear occupy much of this space.



1	Rolls Royce MT-30
4	Power Conversion Module
9	Dynamic Braking Resistor
10	Harmonic Filter Swithgear
11	Harmonic Filter
18	Ladders
19	Escape Trunk
21	Main Machinery Space Fan

Figure 109: MMR 1&2, Platform 1

The first and second auxiliary machinery rooms house the permanent magnet motors and the CAT-3608 emergency generators. Permanent magnet motors are positioned in line with the location of the propellers and also to minimize the shaft angle. The shaft beginning in the second auxiliary machinery room has an angle of 5° and the shaft beginning in the first AMR has an angle of 2.5°. The fresh water distillers and potable water pump are also located in the auxiliary machinery rooms on the second platform. Figure 110 diagrams the second platform in AMR 1 and 2.

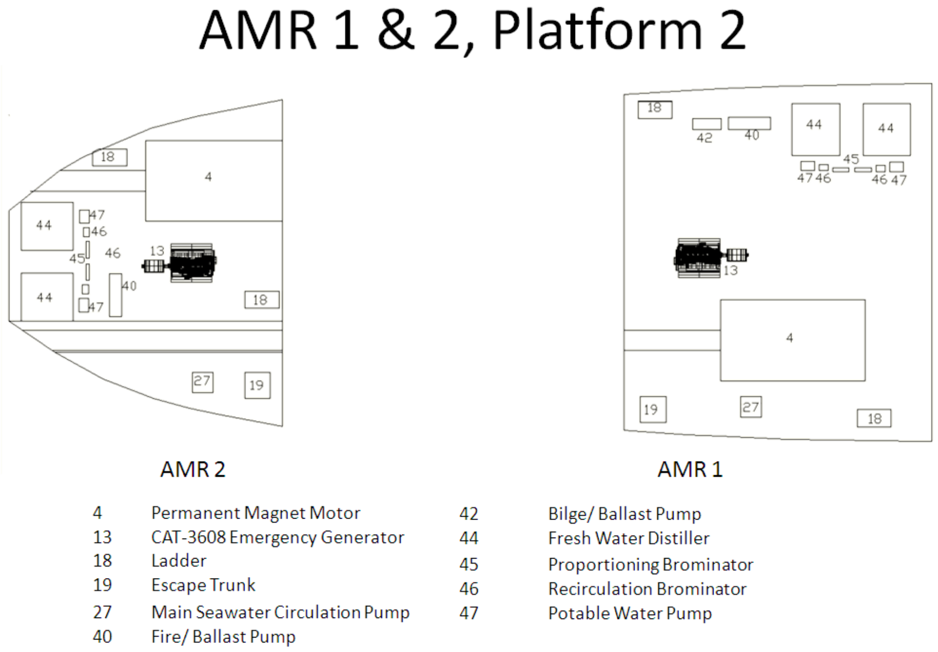


Figure 110: AMR 1&2, Platform 2

Located on the 1st platform in the auxiliary machinery rooms is the electrical equipment associated with the emergency diesel generators and the permanent magnet motors. Refrigeration and air conditioning plants are also on this platform as seen in Figure 111.

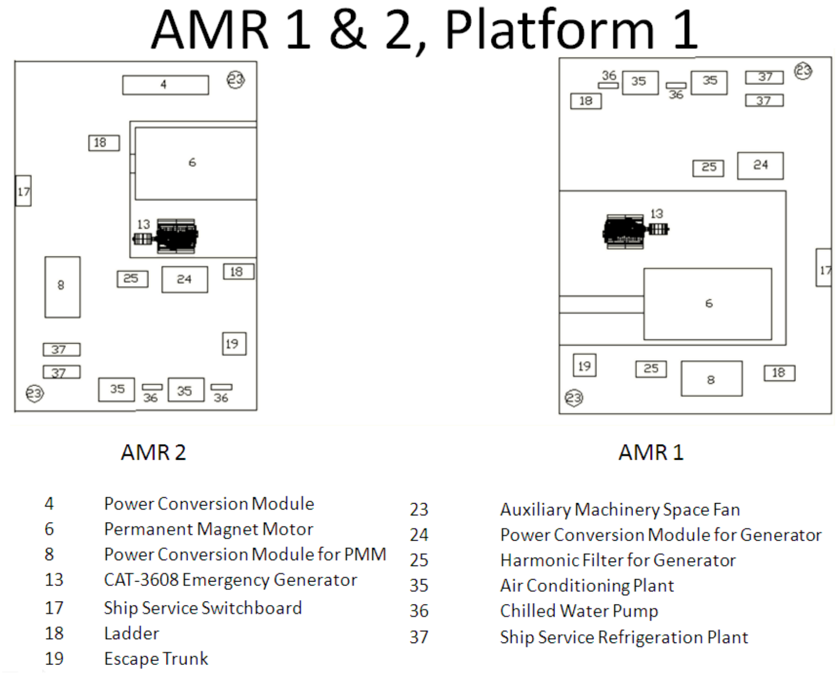


Figure 111: AMR 1&2, Platform 1

4.8 Manning

The MSC makes extensive use of automation to reduce the required manning. Overall manning is at 15 Officers, 15 CPOs and 69 enlisted men. The ship's complement is organized into 5 departments and 13 divisions. Every department other than the Executive department is headed by a Department Head. The executive department reports to the XO. Each division outside of the Supply Department is headed by a division officer, with the exception of the Navigation and Control and Boat and Vehicle divisions. The Navigation and Control Division, Boat and Vehicle, and the three Supply divisions are headed by Chief Petty Officers. The minimal manning arrangement necessitates a high skill level at the outset. As a result, most of the enlisted crew will be PO2 or PO3, having already qualified on older vessels. Junior Officers will likely be on their second division officer tour, also having already qualified.

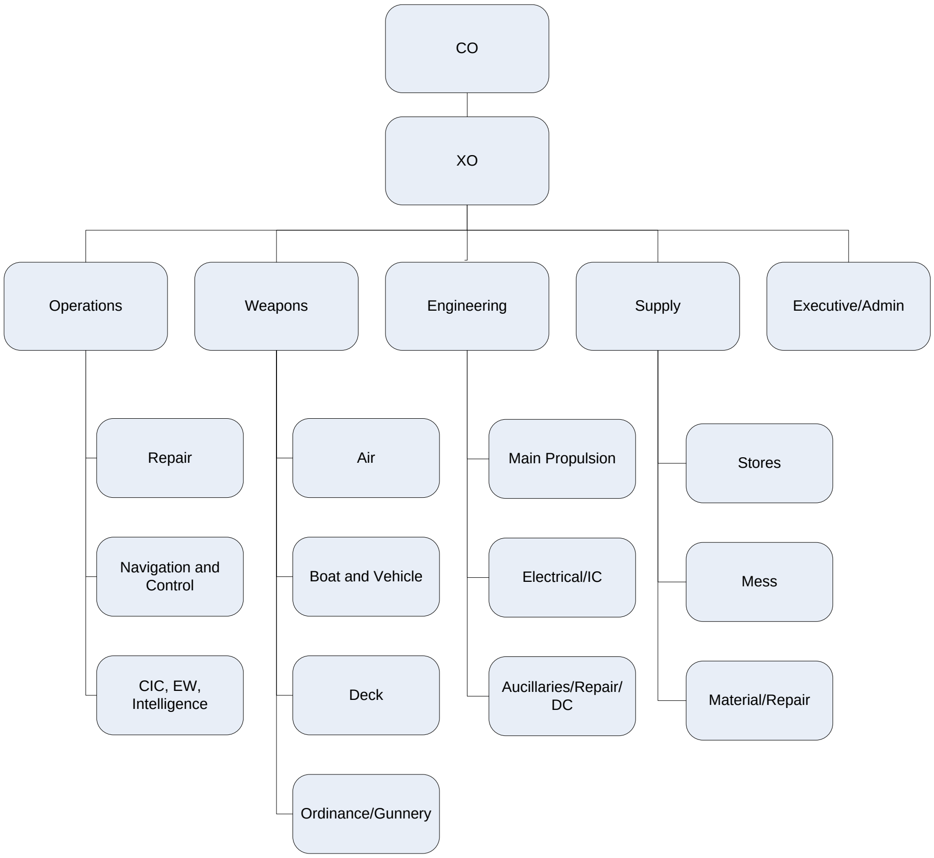


Figure 112 - Manning Hierarchy

Table 40 - Manning Breakdown

Departments	Division	Officers	CPO	Enlisted	Total Department
	CO/XO	2			2
	Department Heads	4			4
Executive/Admin	Executive/Admin		1		1
Operations	Communications/Electronic Repair	1	1	5	23
	Navigation & Control	0	1	5	
	CIC, EW, Intelligence	1	1	8	
Weapons	Air	2	1	5	32
	Boat & Vehicle	0	1	5	
	Deck	1	1	8	
	Ordinance/Gunnery	1	1	6	
Engineering	Main Propulsion	1	1	8	27
	Electrical/IC	1	1	6	

	Auxiliaries/Repair/DC	1	2	6	
Supply	Stores	0	1	2	7
	Mess	0	1	3	
	Material/Repair	0	1	2	
	Total	15	15	69	99
	Accommodations	16	16	80	112

4.9 Space and General Arrangements

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. A profile view can be seen below in Figure 113.

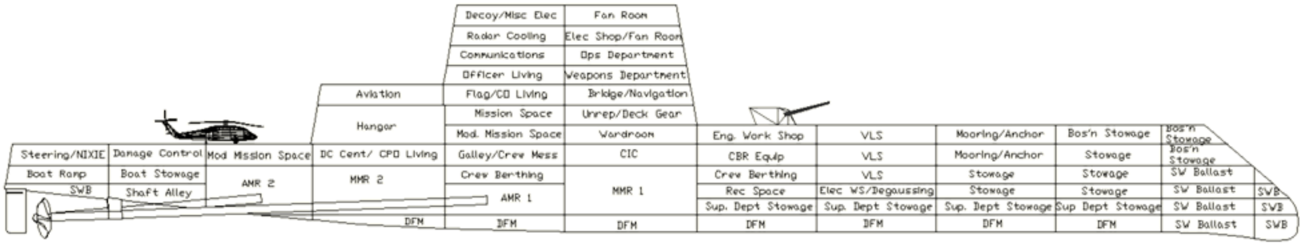


Figure 113: Profile View

4.9.1 Internal Arrangements

The internal arrangements took into account all of the arrangeable area requirements generated by the ASSET space module. All compartments were sized based off of these space requirements. Damage control and fire fighting stations were expanded past ASSET recommendations because of the reduced crew. This means there will be a higher necessity for automated systems to help control the damage. The top three levels can be seen below in Figure 114.

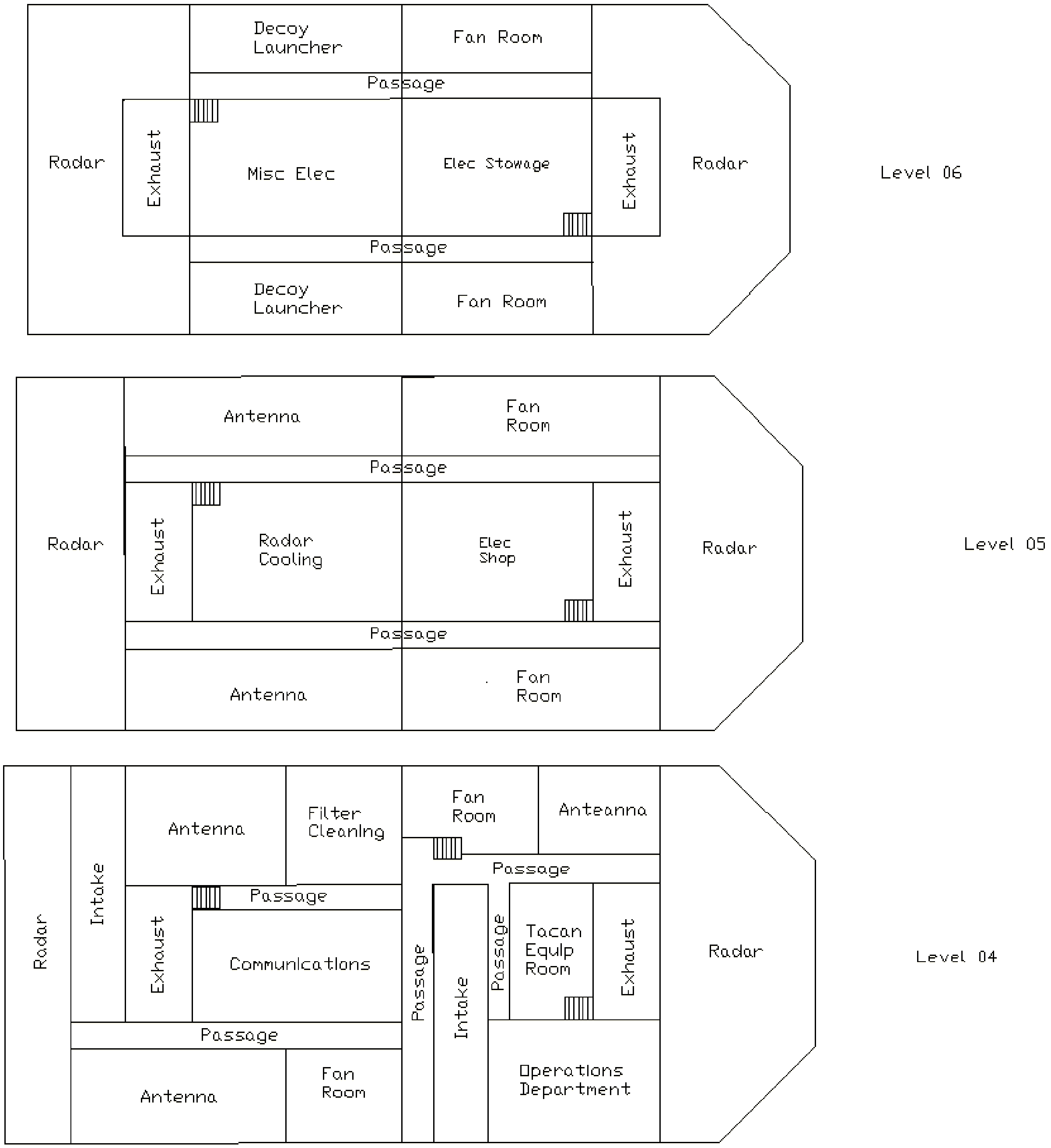


Figure 114: General Arrangements Levels 04- 06

An important design feature of these upper levels is the interior passageways. Instead of a port and starboard passageway on the skin of the deckhouse, the passageways are located inside the deckhouse. This is to provide room for all of the antennae and apertures that are a part of the integrated mast/deckhouse concept. There is also significant space for radar cooling units and ventilation on these upper decks. The general arrangements for the 03 down to the 01 level can be seen below in Figure 115.

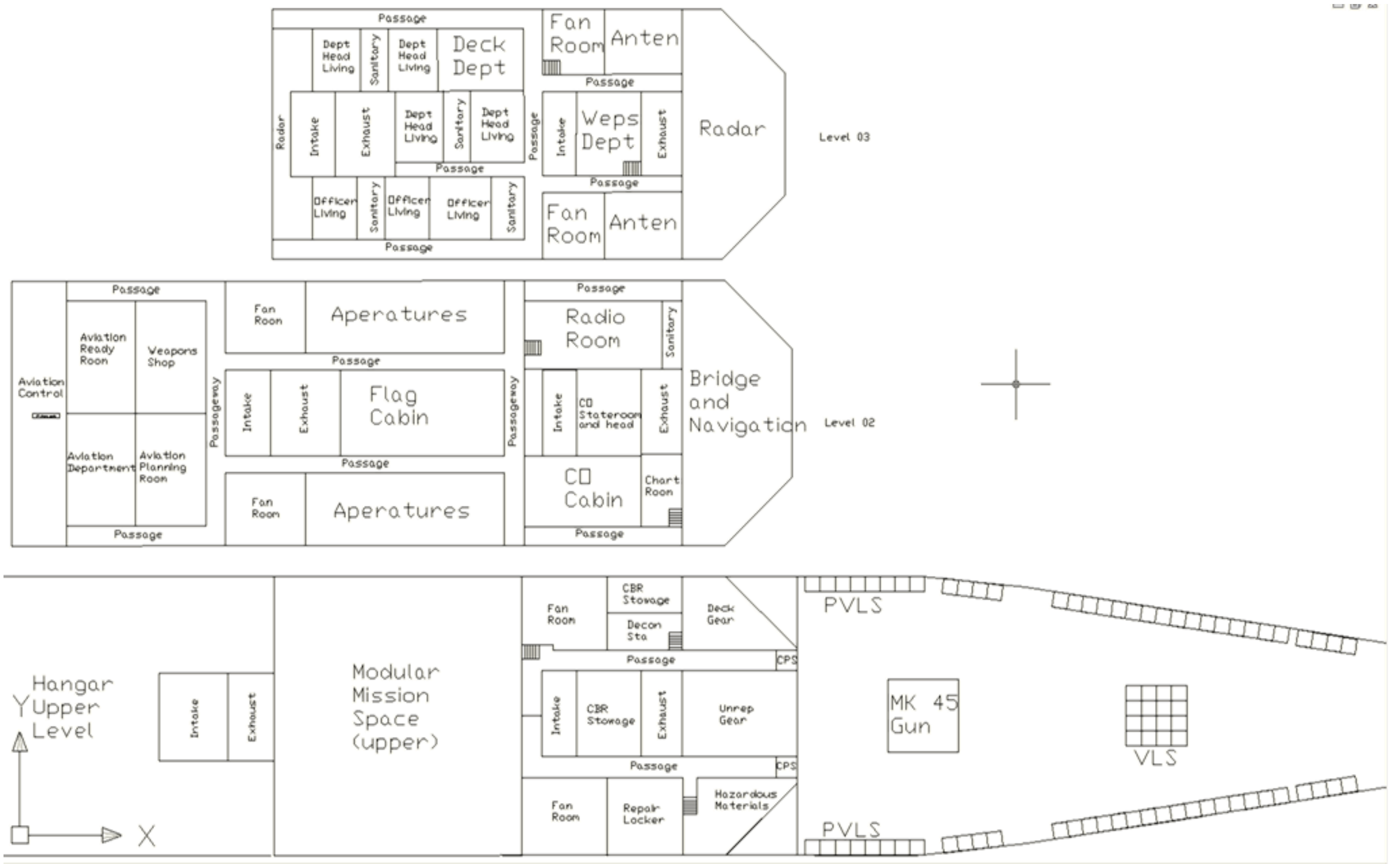


Figure 115: General Arrangements Level 01-03

In these levels you can see officer's country on the 03 level as well as the CO and Flag cabins on the 02 level. These locations provide easy access to the department offices and the bridge and radio room for all of the officers. The internal passageways are continued where possible on these levels to provide for as much space for antenna as possible. All passageways on this level are 1.3 meters wide at a minimum. In Figure 116 and Figure 117 below you will see the general arrangements for the main deck, damage control deck, and 3rd deck.

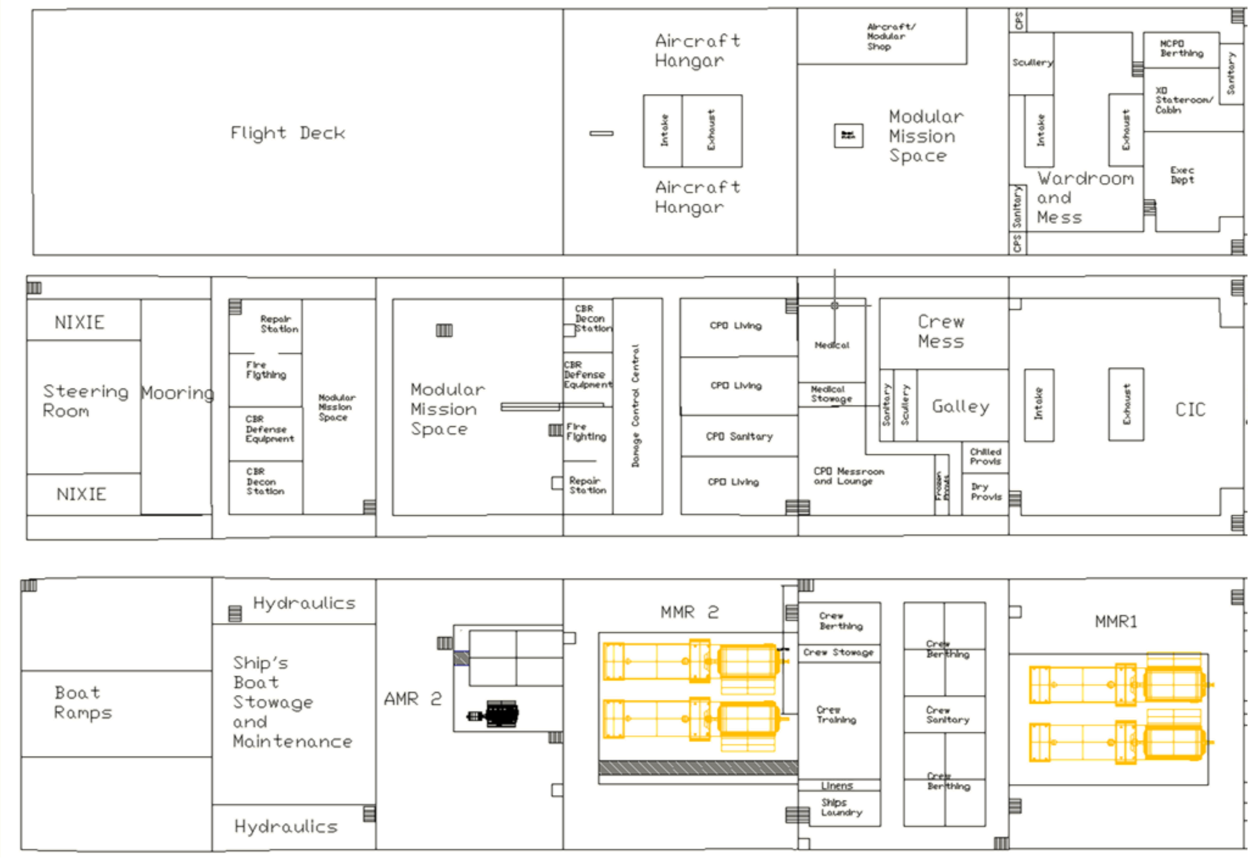


Figure 116: General Arrangements Main Deck through 3rd Deck Aft

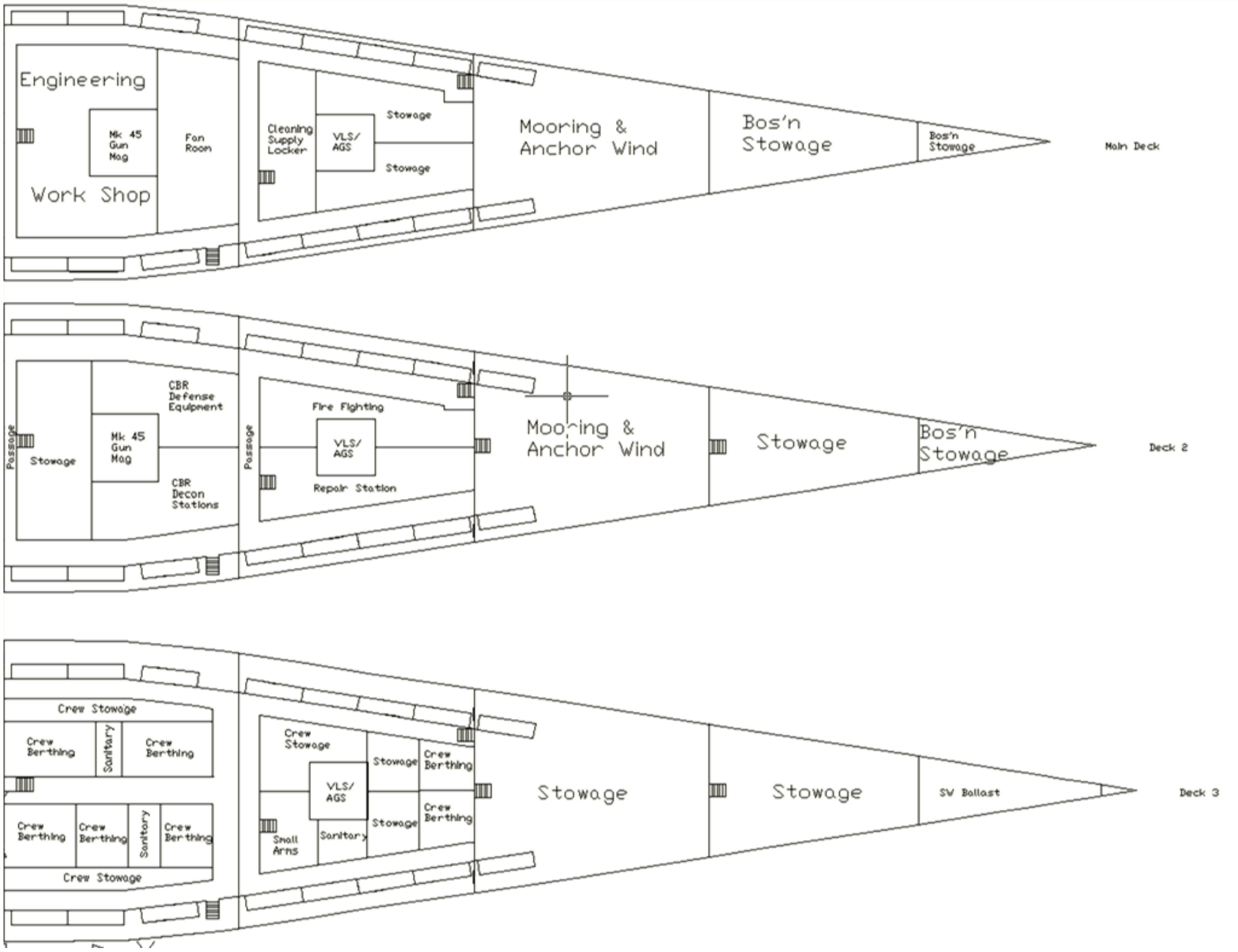


Figure 117: General Arrangements Main Deck through 3rd Deck Forward

On the damage control (2nd) deck there are two continuous passageways; one starboard and one port, which are separated by as much distance as possible for survivability. The passageways are 2 meters wide on this deck and 1.6 meters wide on the main deck and deck 3. The extra width to the passageways on the main deck is to ensure that there is clear passage for stretchers and damage control equipment. There are 3 damage control stations on the damage control deck to ensure that the whole ship is adequately supplied with damage control equipment. An important feature to recognize is that one galley serves the entire ship. The wardroom shares a common bulkhead with the galley and is serviced by a dumbwaiter. This allows a reduction in the number of crew that are needed for messing activities. There is also substantial space on these decks for modular mission equipment. This space allows the MSC to embark the LCS mission modules as well as many others that will be introduced in the coming years. This gives the ship the wide flexibility that it is seeking. In Figure 118 below you see the general arrangements for the bottom most decks, which are primarily used up with machinery room and stowage space.

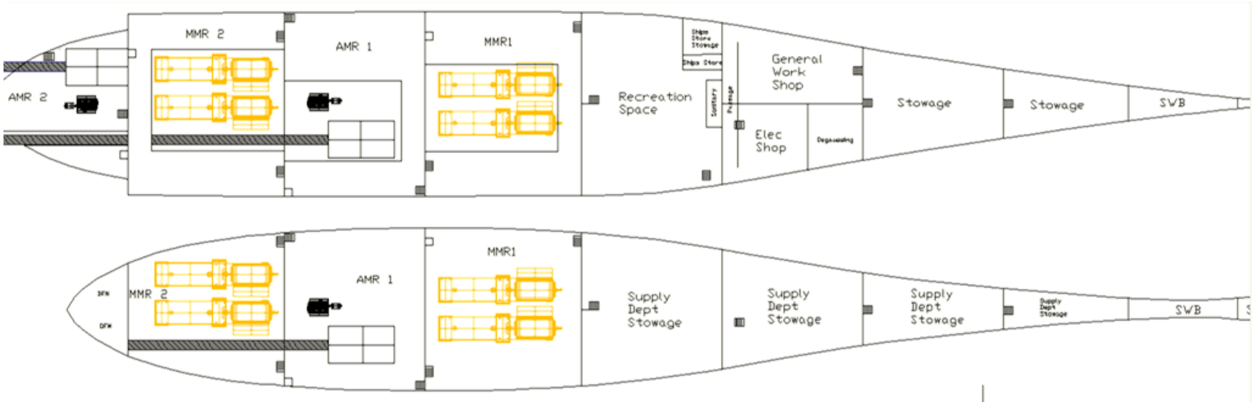


Figure 118: General Arrangements Deck 4 and Inner Bottom

4.9.2 Living Arrangements

The living arrangements aboard the MSC reflect the expectation of embarking more senior ratings as a result of having a reduced crew compliment. As a result all of the berthing, messing, and recreation spaces are larger than they have been on previous navy ships. The accommodation standards on this ship were based off of the berthing arrangements on the DDG 1000. There are accommodations for 80 crew in 2 eight person bunkrooms, 4 six person bunkrooms, and 10 four person bunkrooms. These bunkrooms allot 2.79, 2.25, and 3 square meters of space per person respectively. There are 4 four person bunkrooms for the chiefs with 3.2 square meters of space per person allotted. There is a private berth for the master chief which is 14 square meters. The officers have 3 four person staterooms with 3.6 square meters per person as well as 4 single cabins for department heads with 14 square meters of space allotted. The executive officer, captain, and flag officer also have private cabins with 30, 60, and 65 square meters of space respectively.

4.9.3 External Arrangements

The MSC has two helicopters spots aft of the deck house where it can accommodate two LAMPS helos. Forward of the deckhouse there is a 5” naval gun and a 16 cell VLS on the centerline. This is the VLS that can be modularly swapped for the advanced gun system based on mission requirements. Also forward of the deckhouse are 64 PVLS cells mounted 32 on a side. There are two CIWS mounted on the aft end of the hangar and one on the centerline at the forward edge of the deckhouse. All of these can be seen below in

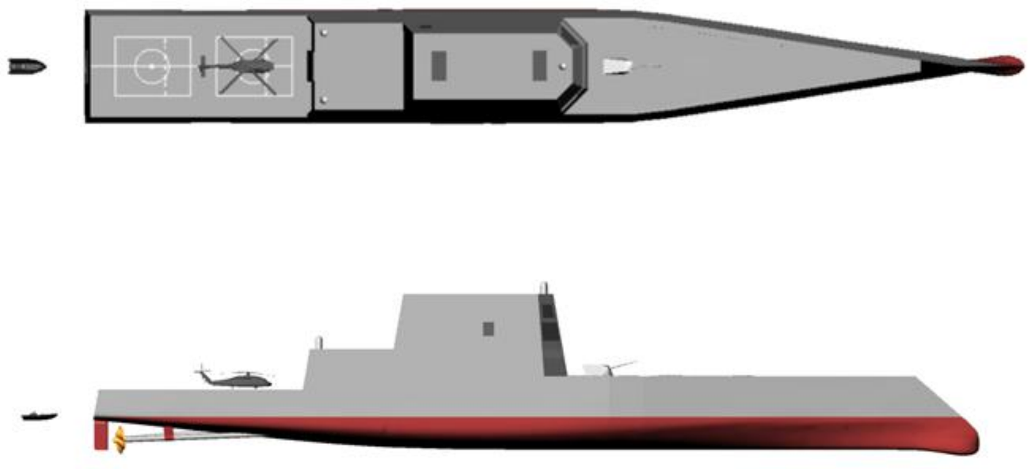


Figure 119: External Views

4.10 Weights, Loading and Stability

4.10.1 Lightship Weights

Ship weights are broken into SWBS groups. Where possible, manufacturers' weights were used for equipment; otherwise parametric estimates from ASSET or the SSSM are used. The machinery arrangements and the general arrangement of the ship are used to determine the VCGs and LCGs. **Table 41** provides Lightship weights and CGs by SWBS group. A more detailed breakdown is located in Appendix E.

Table 41 - Lightship Weight Summary

SWBS Group	Weight (MT)	VCG (m-Abv BL)	LCG (m-Aft FP)
100	6158.60	6.52	101.71
200	1814.00	5.97	129.11
300	1958.60	6.35	104.69
400	994.11	21.36	97.93
500	1720.39	6.70	119.78
600	917.7	6.86	67.22
700	488.00	12.18	62.02
Margin	1405.14		
Total (LS)	15456.54	7.72	103.98

4.10.2 Loads and Loading Conditions

Loading conditions are derived from DDS 079-1, which defines Full-Load and Minimum Operating (MINOP) conditions. The full load condition assumes a 95% load of fuel and oil, and a 100% load of fresh water and ammunition, a detailed breakdown is seen in Table 42. The MINOP condition assumes depletion of ammunition, fuel, stores, and oil to one-third capacity, and depletion of fresh water to two-thirds capacity; Table 43 provides a more detailed breakdown of the loading assumptions for MINOP. The summary of stability at Full Load can be found in Table 44, where the MINOP condition is shown in Table 45.

Table 42 - Full Load

Item	Loads
Crew and effects	Wartime complement
Provisions and personnel stores	Complement * # of days endurance. Quantities not to exceed available capacity. 30 day limit on chill stores. Medical and troop stores in normal amounts.
General Stores	All stores other than personnel stores which are consumable. Based on Design Characteristics.
Ammunition	Full allowance of ammunition with maximum quantities in ready-service stowage and remainder in magazines. For missiles and torpedoes, least favorable quantity and disposition is assumed.
Lube Oil	Storage tanks are 95% full, settling tanks are empty.
Reserve feed and Fresh water	All tanks 100% full.
Diesel Oil (other than for propulsion)	All tanks 95% full. Overflow tanks filled as necessary for endurance. Contaminated oil settling tanks (COST) are empty.
Aviation or vehicle fuel	All tanks are 95% full.
Airplanes and aviation stores	Full design complement of aircraft, empty. Full allowance of repair parts and stores. Distribution of aircraft shall be most unfavorable from stability standpoint.

Propulsion fuel	All tanks 95% full.
Anti-roll tanks	Operating level
Sewage Holding Tanks (CHT)	Empty
Water ballast tanks	Empty

Table 43 - MINOP Loads

Item	Loads
Crew and effects	Same as Full Load
Provisions and personnel stores	One-third of Full Load
General Stores	One-third of Full Load
Ammunition	One-third of Full load with maximum quantities in ready-service stowage and remainder in magazines. For missiles and torpedoes, least favorable quantity and disposition is assumed.
Lube Oil	One-third full load
Reserve feed and Fresh water	Two-thirds full load
Diesel Oil (other than for propulsion)	All tanks 95% full. Overflow tanks filled as necessary for endurance. Contaminated oil settling tanks (COST) are empty.
Aviation or vehicle fuel	One-third full load
Airplanes and aviation stores	Same as Full Load
Propulsion fuel	One-third full load with remaining tanks loaded in accordance with liquid loading instructions
Anti-roll tanks	Operating level
Sewage Holding Tanks (CHT)	Full
Water ballast tanks	Empty

Table 44 - Full Load Trim and Stability

	Weight	VCG	LCG	TCG	FSMom	
Item	**MT**	**m**	**m**	**m**	**m-MT**	
Light Ship	15,456	7.7	104.530A	0	----	
Constant	0	0	93.570A	0	0	
Lube Oil	24	1.797	126.984A	1.193S	9	
Fresh Water	32	11.286	95.296A	0	0	
SW Ballast	0	----	----	----	----	
Fuel (DFM)	2,327	1.979	99.757A	0.000P	3,949	
JP-5	66	4.497	155.071A	0	46	
Waste Oil	0	----	----	----	----	
Misc. Weights	148	9.398	89.146A	0	0	
Ships Force	14	10.2	90.380A	0	0	
Expendables	278	10.698	80.852A	0	0	
Stores	17	7	33.520A	0	0	
Displacement	18,213	7.003	103.681A	0.002S	4,004	
Stability Calculation			**Trim Calculation**			
KMt	12.491	m	LCF Draft		7.367	m
VCG	7.003	m	LCB (even keel)		101.711A	m-FP

GMt (Solid)	5.488	m	LCF		113.552A	m-FP
FSc	0.22	m	MT1cm		418	m-MT/cm
GMt (Corrected)	5.268	m	Trim		0.857	m-A
			List		0S	deg
Specific Gravity	1.025		TPcm		38	MT/cm
Hull calcs from tables			**Tank calcs from tables**			
Drafts			Strength Calculation			
Draft at F.P.	6.86	m	Shear		634	MT at 148.57A m-FP
Draft at M.S.	7.289	m	Bending Moment		27,992H	m-MT at 110.0A m-FP
Draft at A.P.	7.718	m				
Draft at FwdMarks	6.849	m				
Draft at Mid Marks	7.278	m				
Draft at AftMarks	7.706	m				

Table 45 - MINOP Trim and Stability

Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT	
Light Ship	15,456	7.7	104.530A	0	----	
Constant	0	0	93.570A	0	0	
Lube Oil	8	1.299	126.402A	1.111S	14	
Fresh Water	21	10.777	95.295A	0	0	
SW Ballast	0	----	----	----	----	
Fuel (DFM)	808	1.303	99.095A	0.000P	5,107	
JP-5	23	4.081	153.018A	0	46	
Waste Oil	0	----	----	----	----	
Misc. Weights	0	----	----	----	----	
Ships Force	14	10.2	90.380A	0	0	
Expendables	102	11.983	72.390A	0	0	
Stores	6	11.43	33.520A	0	0	
Displacement	16,438	7.411	104.095A	0.001S	5,167	
Stability Calculation			**Trim Calculation**			
KMt	13.14	m	LCF Draft		6.9	m
VCG	7.411	m	LCB (even keel)		100.482A	m-FP
GMt (Solid)	5.729	m	LCF		113.172A	m-FP
FSc	0.314	m	MT1cm		421	m-MT/cm
GMt (Corrected)	5.415	m	Trim		1.412	m-A
Specific Gravity	1.025		TPcm		38	MT/cm
Hull calcs from tables			**Tank calcs from tables**			
Drafts			Strength Calculation			
Draft at F.P.	6.069	m	Shear		-723	MT at 60.000A m-FP

Draft at M.S.	6.775	m	Bending Moment	37,166H	m-MT at 110.000A m-FP
Draft at A.P.	7.481	m			
Draft at FwdMarks	6.05	m			
Draft at Mid Marks	6.756	m			
Draft at AftMarks	7.462	m			

4.10.3 Final Hydrostatics and Intact Stability

The hydrostatic properties of the MSC hullform were determined using HECSALV. The hullform geometry generated for subdivision and tankage was modified in the HECSALV Ship Project editor to account for the deckhouse, and to update the centers of gravity to correspond to the detailed weight analysis. After finalizing the weight distribution, Full and MINOP loading conditions were created using HECSALV.

Intact stability at each condition is compared to the criteria presented in DDS 079-1. DDS 079-1 establishes standards for rolling with beam winds. Two conditions must be met: the area (A1) above the heeling arm but below the righting arm must be at least 1.4 times the area (A2) below the heeling arm, but above the righting arm, and the ratio between the heeling arm and GZ_{max} must be less than 0.6 where the curves cross. For both MINOP and Full Load, the conditions are met. At Full Load, A1 is 1.7, compare to the minimum of 0.6. The ratio of the wind heeling arm to GZmax is 0.04, compare to a maximum of 0.60. The righting arm curve for Full-Load is given in Figure 120, with additional details in Table 46. At MINOP, A1 is 1.46, compare to a minimum of 0.59. The ratio of wind heel to GZmax is 0.06, less than the maximum of 0.60. The righting arm curve for MINOP is given in Figure 121, with additional stability data in Table 47.

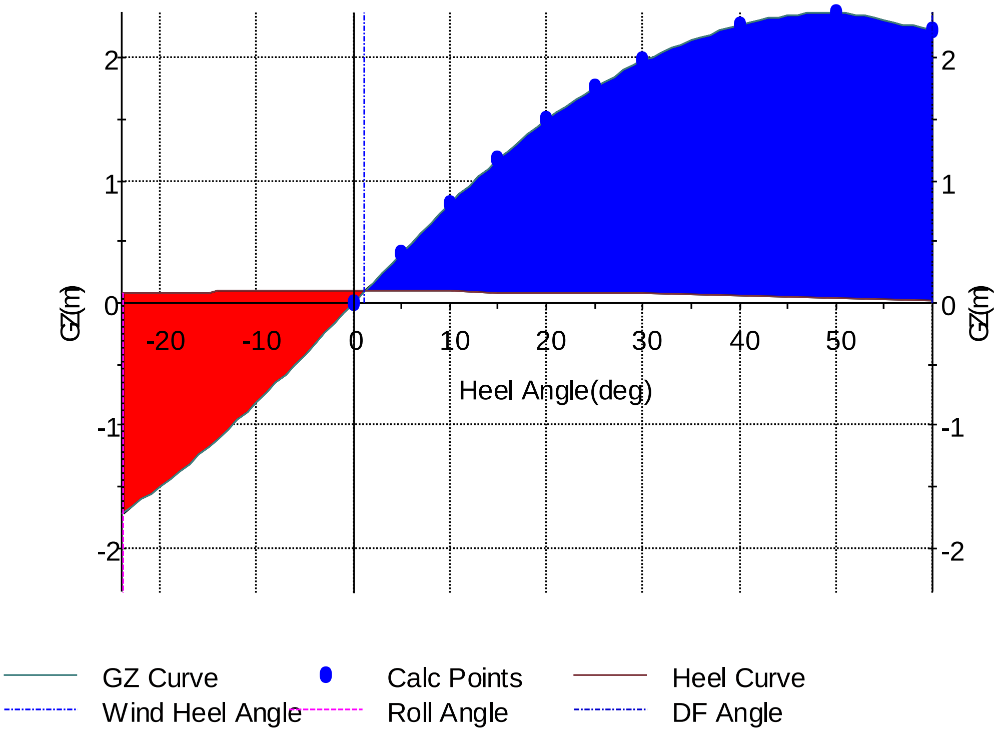


Figure 120 - Full Load Righting Arm Curve

Table 46 – Full Load Intact Stability

U.S. Navy DDS079-1 Beam Wind and Rolling	Units	Value	Required
Wind Heel	deg	1	---
Wind Heeling Arm Lw	m	0.097	---
Maximum Righting Arm Ratio		0.04	0.60
Capsizing Area A2	m-rad	0.43	---
Righting Area A1	m-rad	1.7	0.60
Angle Limiting Area	deg	60	---
Maximum Righting Arm	m	2.373	---
Angle at Max. GZ	deg	49	---
Projected Sail Area	m2	1,517.41	---
Heeling Arm at 0 deg.	m	0.097	---
Wind Pressure	bar	0.02	---

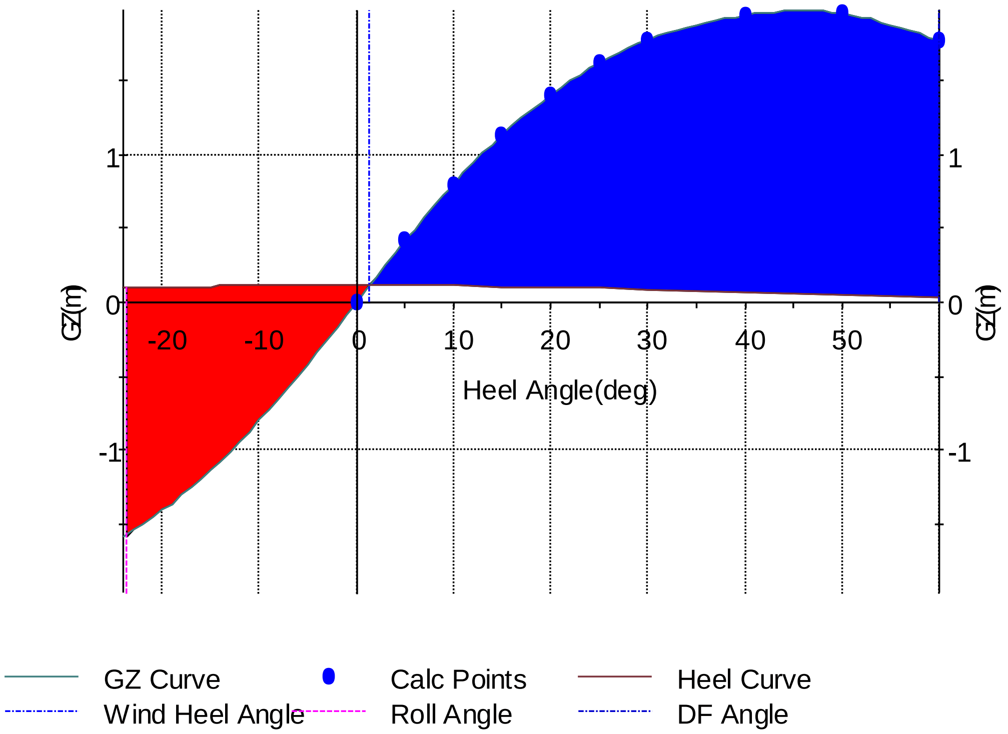


Figure 121 - MINOP Righting Arm Curve

Table 47 - MINOP Load Intact Stability

U.S. Navy DDS079-1 Beam Wind and Rolling	**Units**	**Value**	**Required**
Wind Heel	deg	1	---

Wind Heeling Arm Lw	m	0.117	---
Maximum Righting Arm Ratio		0.06	0.60
Capsizing Area A2	m-rad	0.42	---
Righting Area A1	m-rad	1.46	0.59
Angle Limiting Area	deg	60	---
Maximum Righting Arm	m	1.973	---
Angle at Max. GZ	deg	46	---
Projected Sail Area	m2	1,617.03	---
Heeling Arm at 0 deg.	m	0.117	---
Wind Pressure	bar	0.02	---

4.10.4 Damage Stability

HECSALV Damage Stability module was used to evaluate the damage stability of the MSC hullform. Eleven distinct cases were modeled based on the assumption of damage extent of 15% LWL. The two worst cases were examined in detail using HECSALV.

Table 48 - MINOP Damage Cases

	Intact Stability			Damage Stability			Damage Equilibrium						
	T AP	T FP	GMt	T AP	T FP	Heel	Wind Speed	Roll	Area A1	GZ Margin	AngE	A Ratio	Frbd ML
1	7.134	6.510	1.593	6.589	7.903	1.7	40.56	7.9	0.0173	0.093	1.7	2.5768	5.931
2	7.134	6.510	2.050	5.795	10.164	3.1	40.56	7.9	0.0201	0.091	3.1	4.2586	5.827
3	7.134	6.510	2.642	4.526	14.259	7.7	40.56	7.9	0.0231	0.084	7.7	19.8255	2.373
4	7.134	6.510	3.007	5.033	15.544	13.5	40.56	7.9	0.0213	0.080	13.5	29.3618	0.878
5	7.134	6.510	3.335	6.775	13.228	13.9	40.56	7.9	0.0220	0.083	13.9	17.9612	2.331
6	7.134	6.510	3.520	8.235	10.401	15.0	40.56	7.9	0.0219	0.093	15.0	13.9233	1.489
7	7.134	6.510	3.509	9.672	8.031	14.2	40.56	7.9	0.0158	0.087	14.2	9.0741	0.671
8	7.134	6.510	3.943	10.855	6.019	11.6	40.56	7.9	0.0582	0.143	11.6	29.7735	0.000
9	7.134	6.510	4.848	12.330	4.102	4.4	40.56	7.9	0.3053	0.822	4.4	36.4752	0.000
10	7.134	6.510	3.486	10.464	4.449	13.4	40.56	7.9	0.0608	0.187	13.4	28.6716	0.000
11	7.134	6.510	1.393	7.134	6.510	1.0	40.56	7.9	0.0158	0.094	1.0	2.1572	5.807

Table 49 - Full Load Damage Cases

	Intact Stability			Damage Stability			Damage Equilibrium						
	T AP	T FP	GMt	T AP	T FP	Heel	Wind Speed	Roll	Area A1	GZ Margin	AngE	A Ratio	Frbd ML
1	7.391	6.911	1.453	6.790	8.458	3.9	41.20	7.7	0.0188	0.090	3.9	4.1601	5.253
2	7.391	6.911	1.821	5.946	10.943	5.7	41.20	7.7	0.0244	0.088	5.7	10.1720	5.065
3	7.391	6.911	2.271	4.583	15.441	12.8	41.20	7.7	0.0197	0.081	12.8	26.0391	0.988
4	7.391	6.911	3.677	5.074	16.967	4.9	41.20	7.7	0.3128	0.676	4.9	36.8834	0.000
5	7.391	6.911	2.946	6.954	14.363	15.0	41.20	7.7	0.0399	0.133	15.0	47.1928	1.722
6	7.391	6.911	3.232	8.549	11.157	15.0	41.20	7.7	0.0456	0.149	15.0	35.8493	1.074
7	7.391	6.911	3.272	10.104	8.559	15.0	41.20	7.7	0.0196	0.091	15.0	13.6610	0.069
8	7.391	6.911	4.107	11.460	6.352	8.7	41.20	7.7	0.1719	0.438	8.7	103.181	0.000
9	7.391	6.911	12.727	13.239	4.197	0.8	41.20	7.7	2.6835	7.893	0.8	32.0857	-.213
10	7.391	6.911	3.604	11.274	4.510	9.6	41.20	7.7	0.1766	0.512	9.6	86.4646	0.001
11	7.391	6.911	1.308	7.391	6.911	3.2	41.20	7.7	0.0172	0.092	3.2	3.1999	5.133

From the Damage Stability module, Full Load cases 7 and 9 were selected. Case 7 corresponds to the maximum heel with minimal freeboard to the margin line and minimal GZ margin. Case 7 also results in the loss of MMR1 and MMR2, as well as AMR1. This limits available power to one diesel generator, hindering DC efforts.

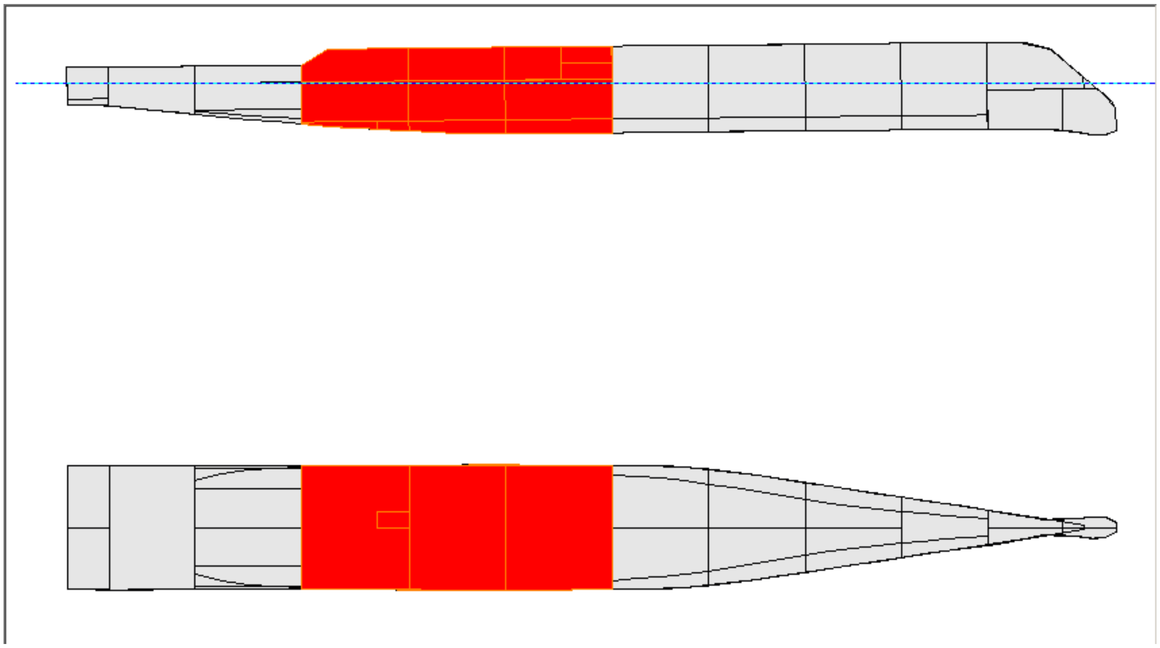


Figure 122 – Full Load Case 7 Extent of Damage

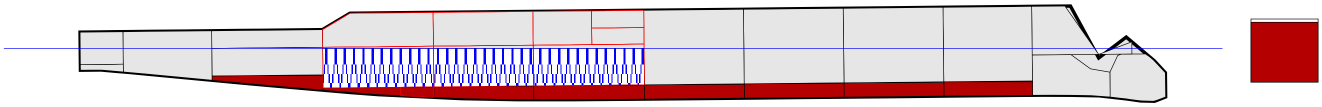


Figure 123 - Full Case 7

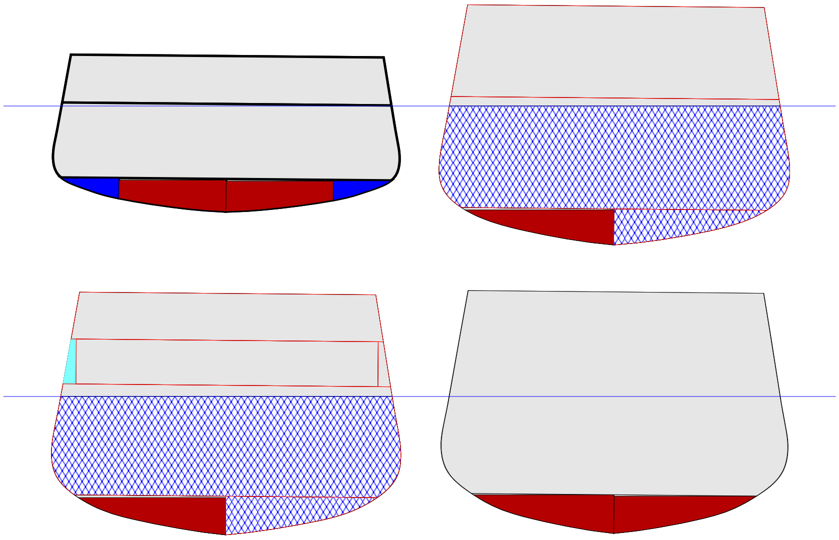


Figure 124 - Full Case 7

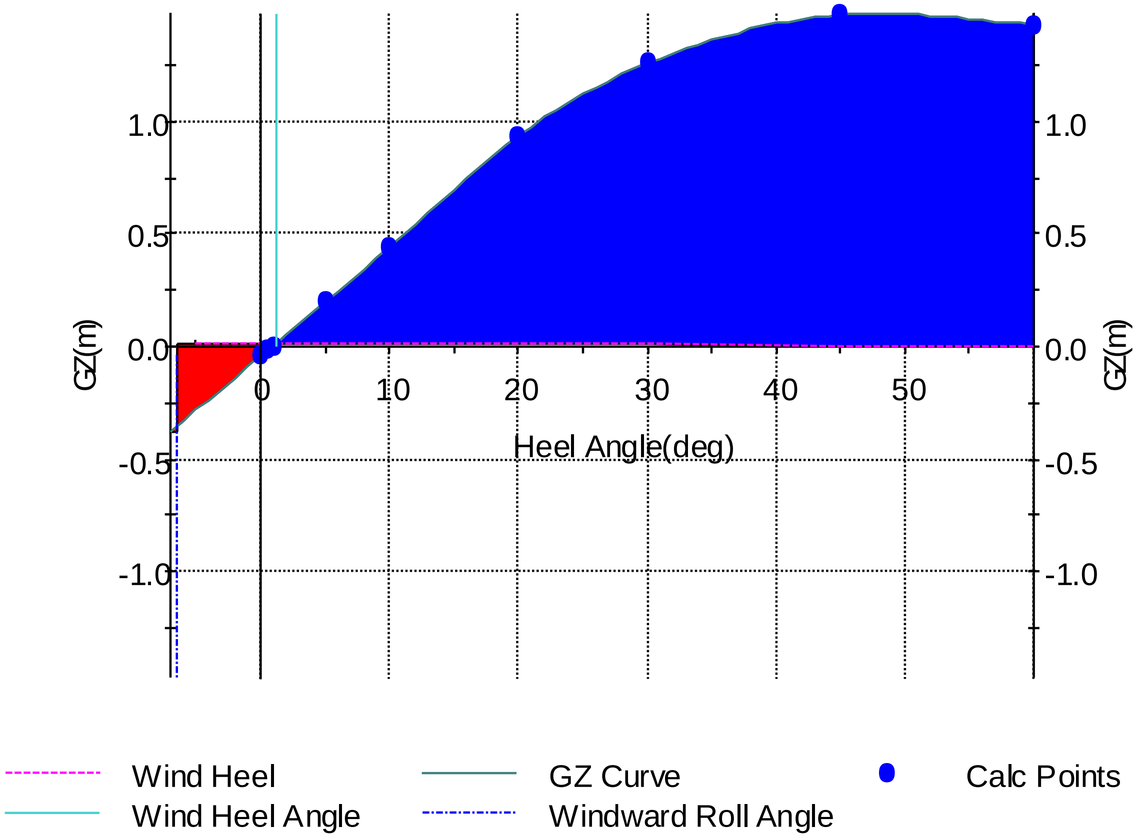


Figure 125 Full Load Case 7 Righting Arm

Case 9 consists of damage between the 7th and 10th transverse bulkhead (Figure 126). This results in the submergence of the margin line at the stern by 0.543 meters, as can be seen in Figure 127. The probable cause is due to the shallow transom, which already has very little freeboard. Additionally, MMR2 and AMR2 are in the damaged area and cannot contribute to fighting the casualty. If case 9 occurs flooding the forward saltwater ballast tanks and the aft saltwater ballast tank opposite the damaged sections will increase the minimum freeboard at the margin to 0.225 meters; compare Figure 129 with Figure 130.

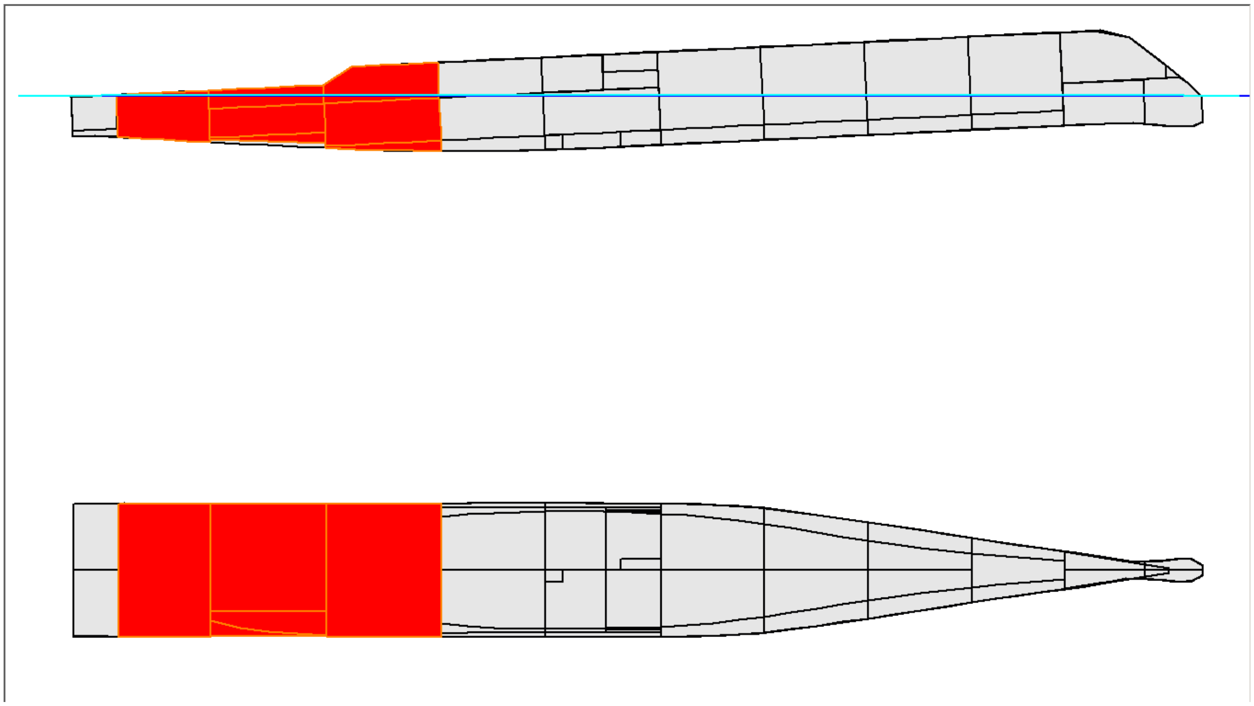


Figure 126 - Full Case 9 Extent of Damage

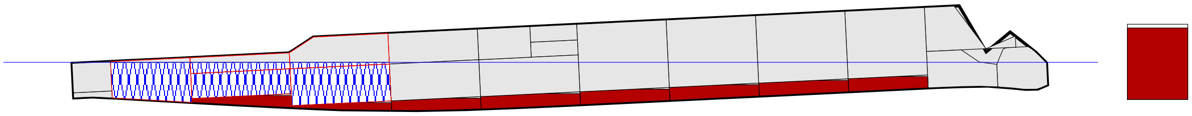


Figure 127 – Full Load Case 9

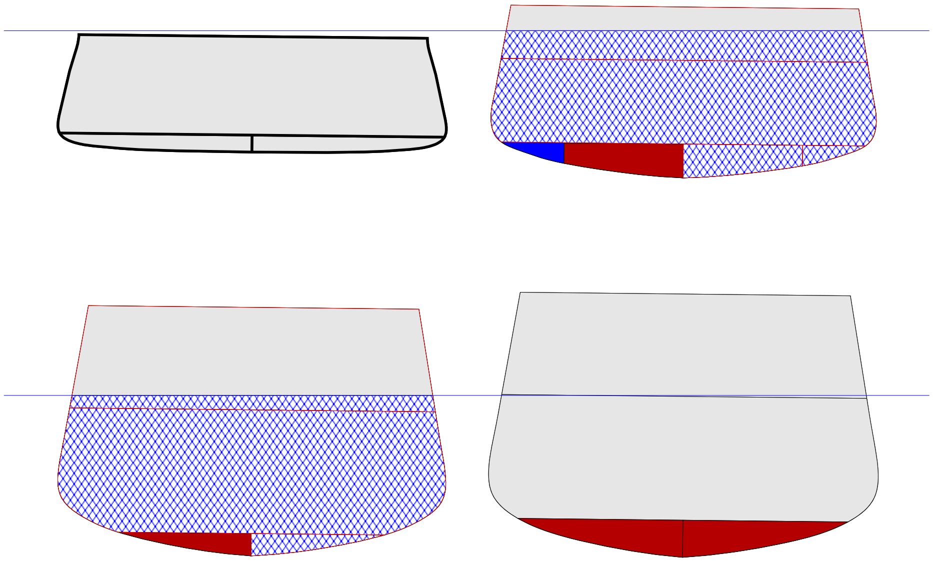


Figure 128 – Full Load Case 9

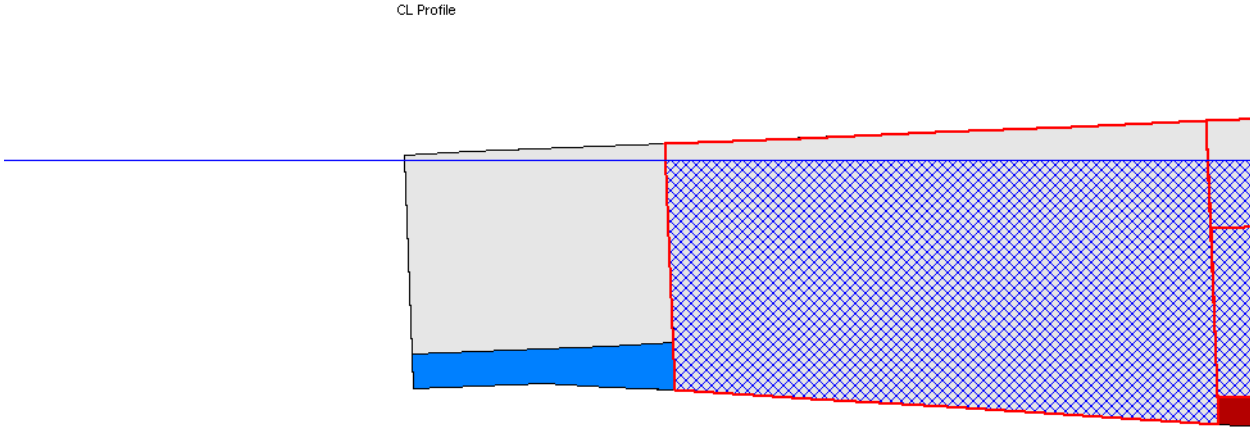


Figure 129 – Full Load Case 9 Unballasted

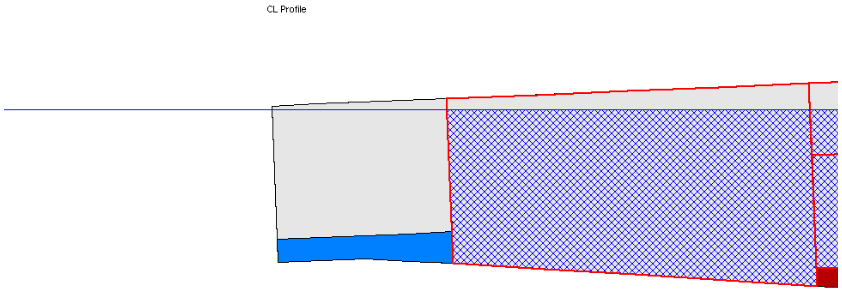


Figure 130 – Full Load Case 9 with Saltwater Ballast

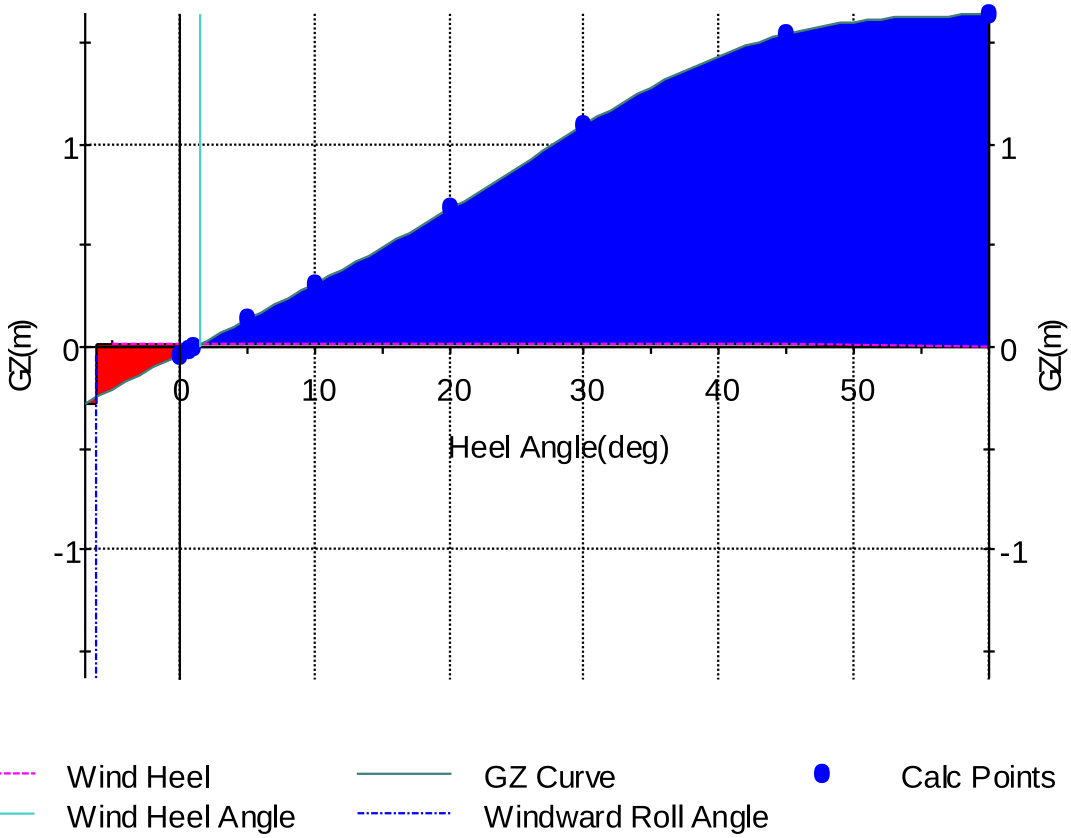


Figure 131 - Full Load Case 9 Righting Arm

4.11 Seakeeping, Maneuvering and Control

The seakeeping performance of the hullform was assessed using SMP. The HECSMP pre-processor was used to generate input files for SMP from the HECSALV model of the ship. Both the section geometry of the hull form and the loading conditions (Full and MINOP) were imported. SMP was used to add the rudders and bilge keels to the model. A 3 meter bilge keel from STA8 to STA16 was added to the ship to improve its seakeeping. A Bretschneider wave spectrum was used, evaluating seakeeping in sea states ranging from SS4-SS7 (Table 50). In addition to the movement of the ship, absolute motions were calculated at the VLS system, the Mk-45 mount, the bridge, and the flight deck, with the Motion Sickness Index(MSI) also calculated at the bridge. Relative motions were evaluated at the forward end of the weather deck and at the keel at STA3 to determine the extent of deck immersion and slamming. The operational limits for the ship's motions are given in Table 51.

Sea State	Significant Wave Height (m)	Modal Period (s)
SS4	1.88	9.0
SS5	3.25	10.0
SS6	5.00	12.0
SS7	7.50	14.0

Table 50 - Sea States for Evaluation

Application	Sea State	Location	Roll	Pitch	V Vel	L Acc	T Acc	V Acc	Slam	Wet
Keel Slam	SS7	Keel STA3							20/hr	
Bow Wetness	SS7	Bow STA 0								30/hr
VLS Launch	SS6	CG	17.5°	3°		.3g	.7g	.6g		
RADAR	SS7		25°							
Gun	SS5		7.5°	7. 5°	1 m/s					
Torpedo	SS5		7.5°							
UNREP	SS5		4°	1.5°						
Helo	SS5		5°		2 m/s					
Personnel	SS7	Bridge	8°	3°			.2g	.4g		

Table 51 - Seakeeping Limits

The Mk-57 VLS system has limitations in roll, pitch, and acceleration. It is expected to operate in sea states up to SS6. Because the PVLS cells are located off center, their accelerations must be calculated separately from the modular 16-cell block. Based on the speed polar plots in Figure 103 through, neither the 16-cell modular block nor the 64 PVLS cells will be limited by the ship's motion.

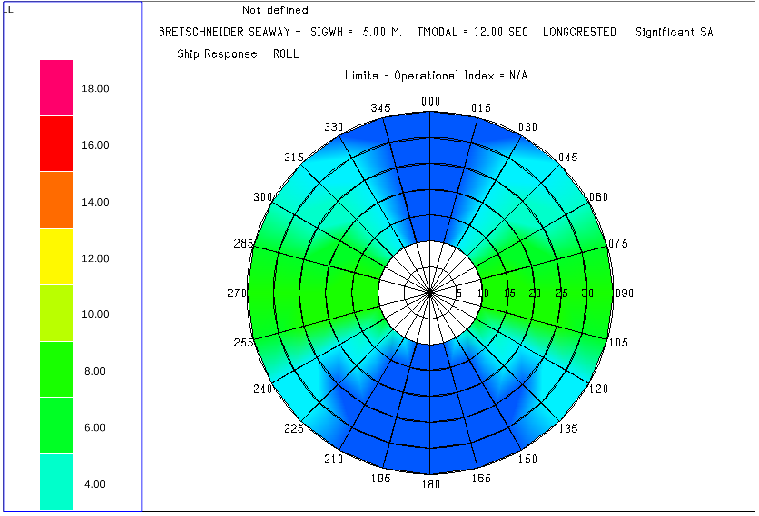


Figure 132 - VLS Roll at Full Load

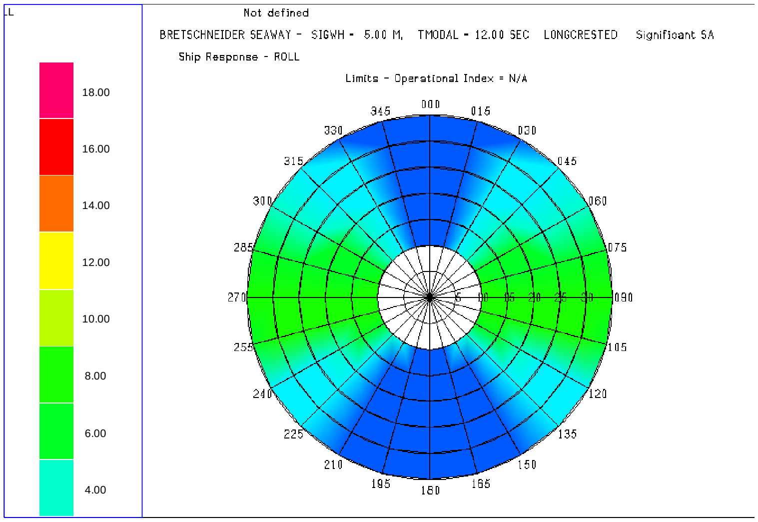


Figure 133 - VLS Roll at MINOP

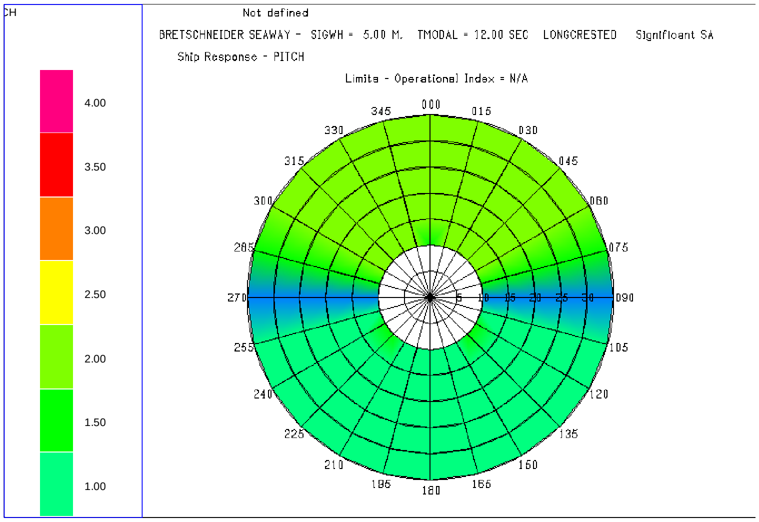


Figure 134 - VLS Pitch at Full Load

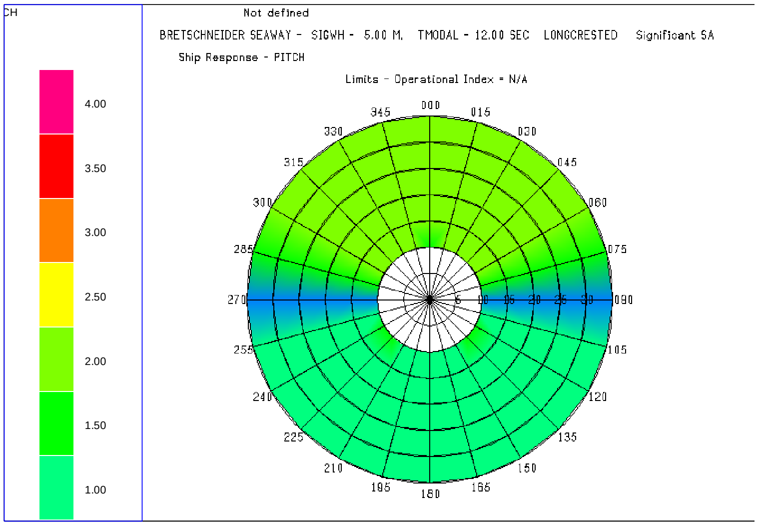


Figure 135 - VLS Pitch at MINOP

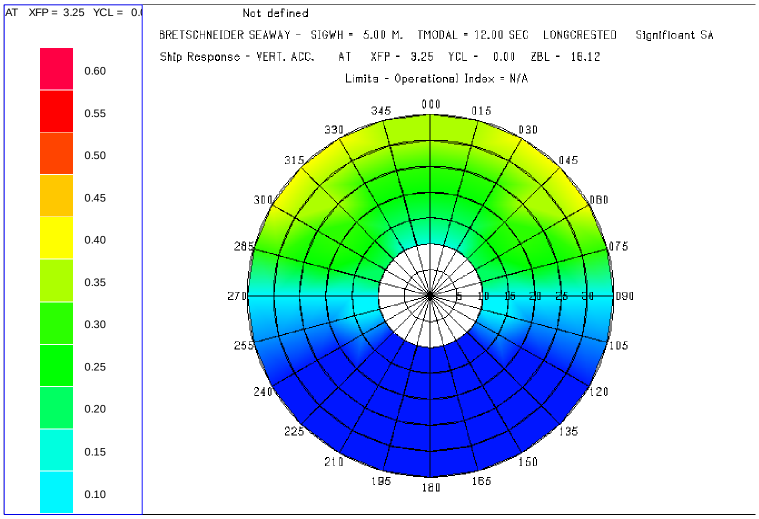


Figure 136 - VLS Vertical Acceleration at Full Load

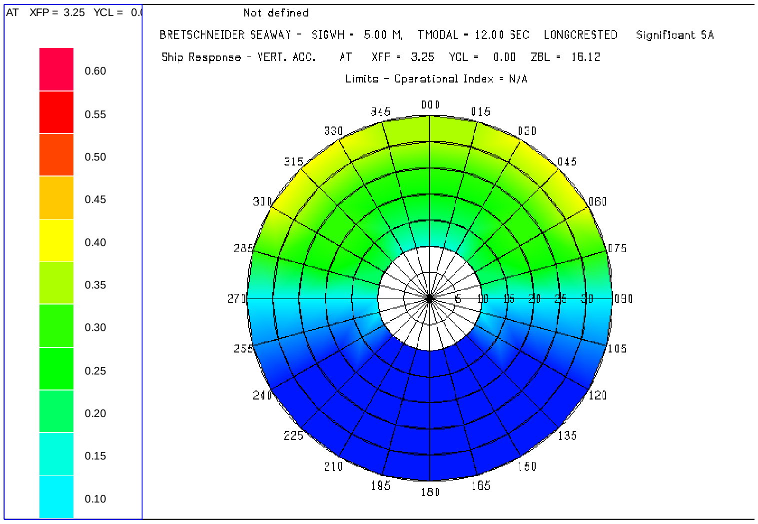


Figure 137 - VLS Vertical Acceleration at MINOP

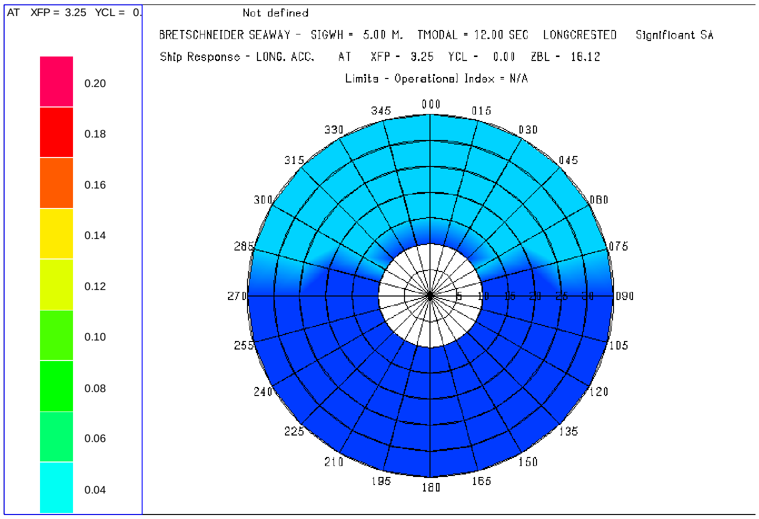


Figure 138 - VLS Transverse Acceleration at Full Load

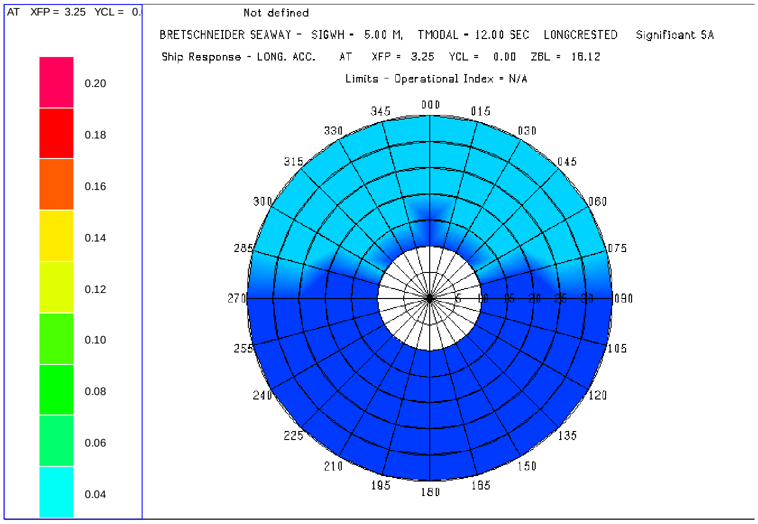


Figure 139 - VLS Transverse Acceleration at MINOP

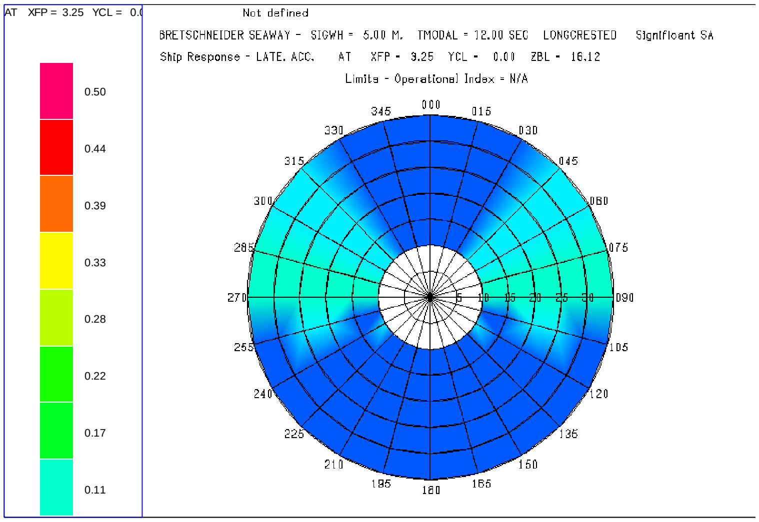


Figure 140 - VLS Longitudinal Acceleration at Full Load

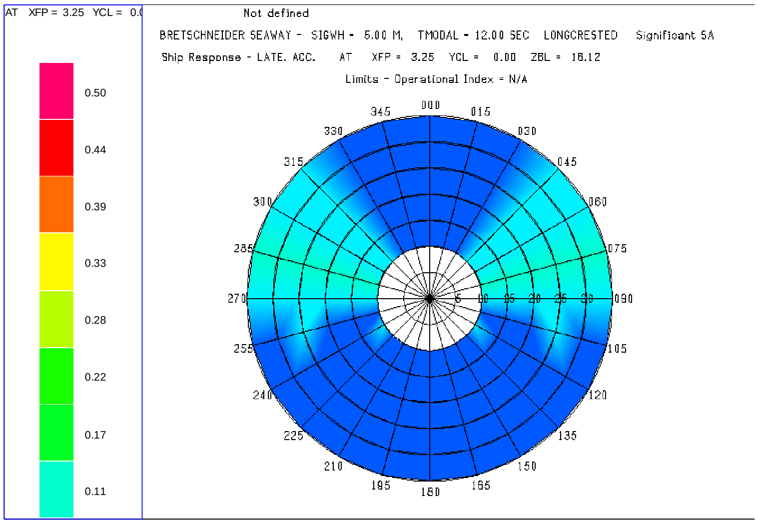


Figure 141 - VLS Longitudinal Acceleration at MINOP

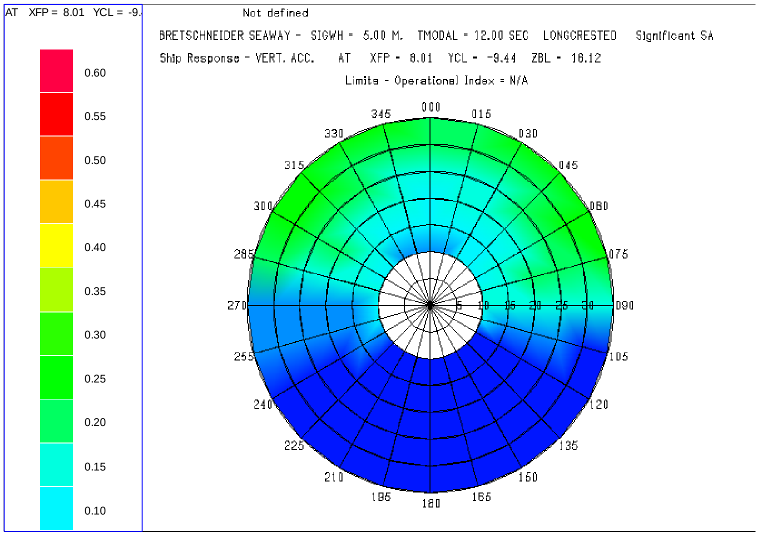


Figure 142 - PVLS Vertical Acceleration at Full Load

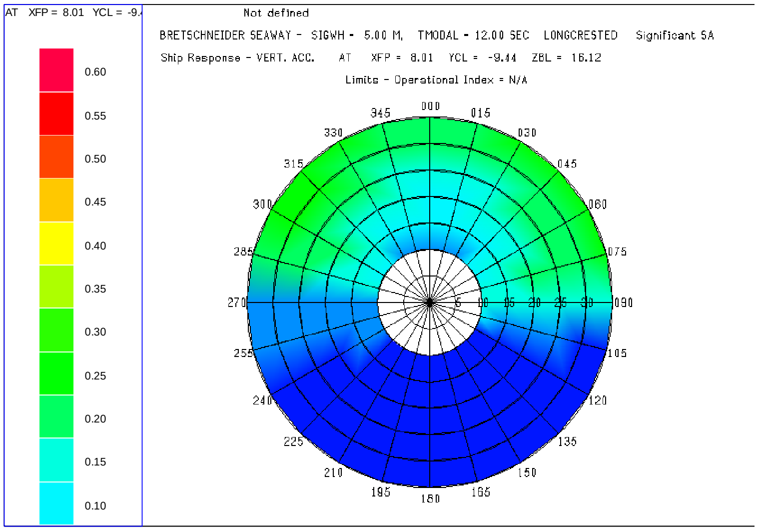


Figure 143 – PVLS Vertical Acceleration at MINOP

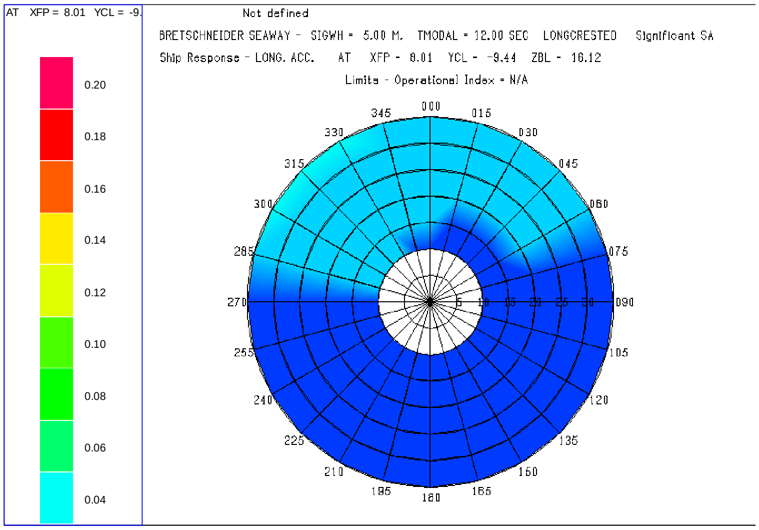


Figure 144 – PVLS Longitudinal Acceleration at Full Load

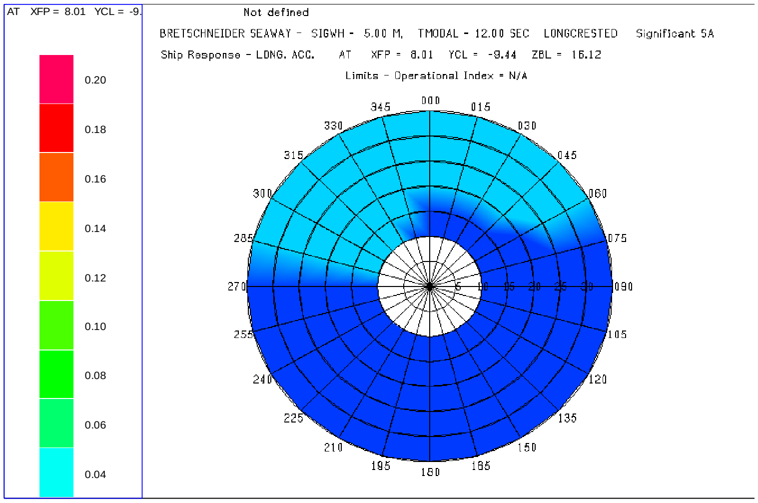


Figure 145 - PVLS Longitudinal Acceleration at MINOP

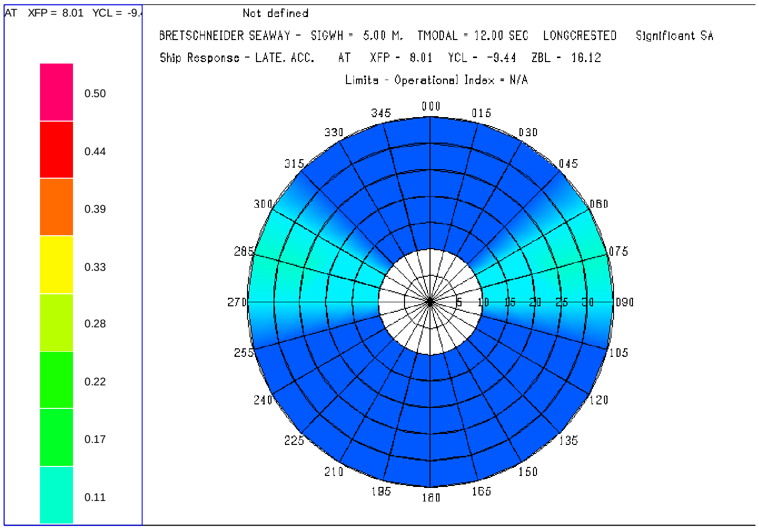


Figure 146 – PVLS Transverse Acceleration at Full Load

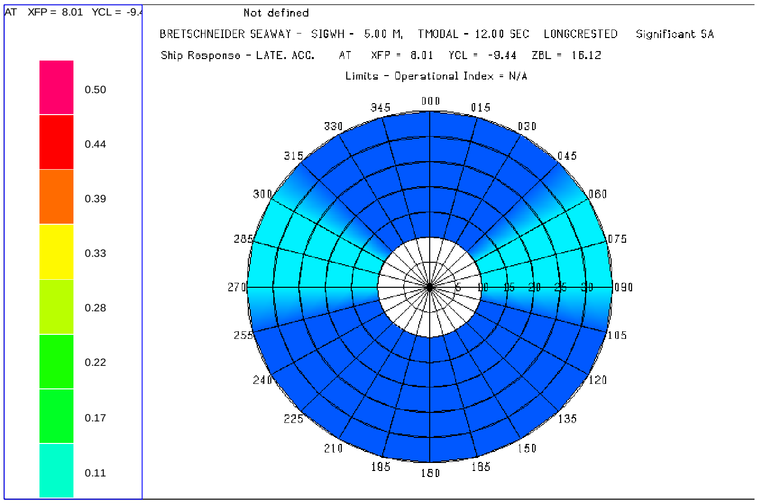


Figure 147 - PVLS Transverse Acceleration at MINOP

The Mk-45 5” gun has limitations in roll, pitch and vertical velocity. It is expected to be functional in sea states up to SS5. At both Full Load (Figure 152) and MINOP (Figure 153), the vertical velocity limitation of 1 m/s is exceeded in seas off the port or starboard bow while traveling above 10 knots.

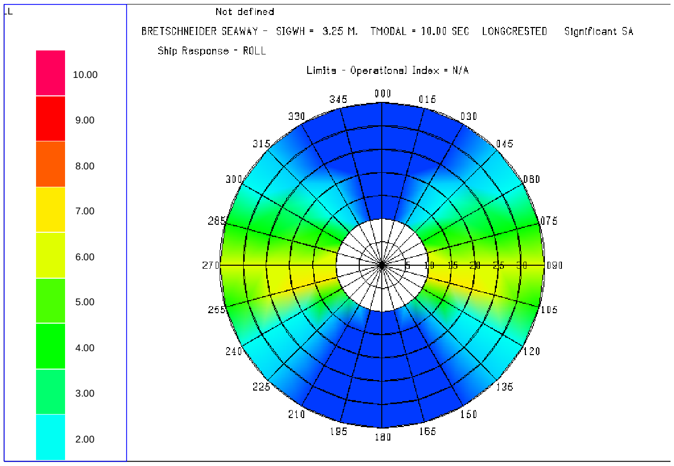


Figure 148 - Gun Roll at Full Load

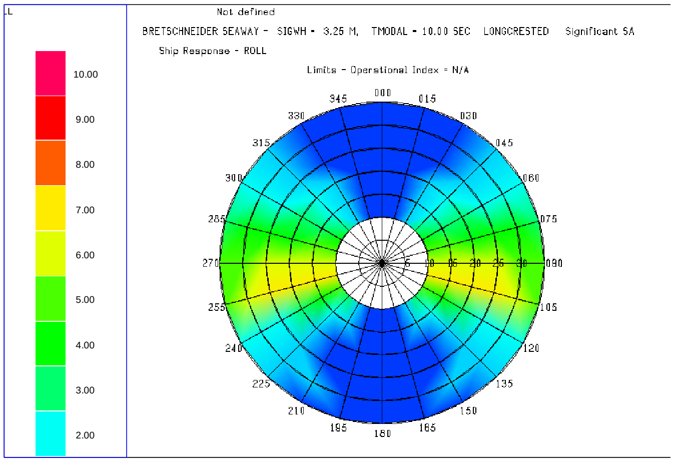


Figure 149 - Gun Roll at MINOP

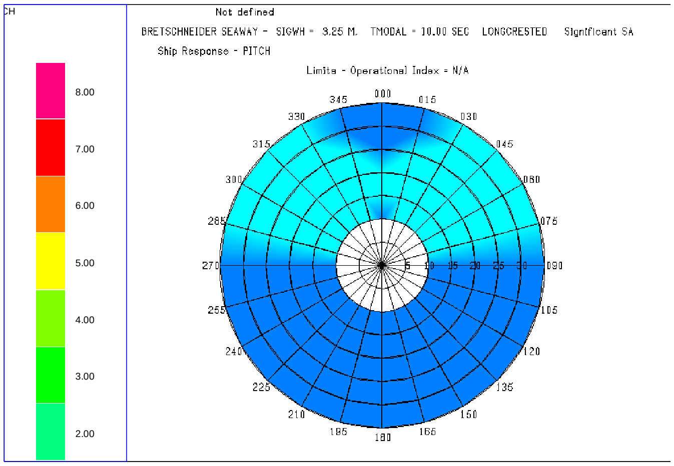


Figure 150 - Gun Pitch at Full Load

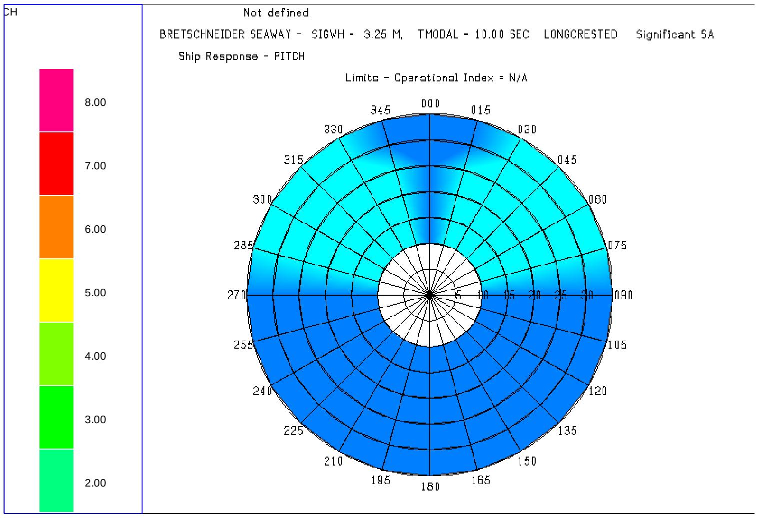


Figure 151 - Gun Pitch at MINOP

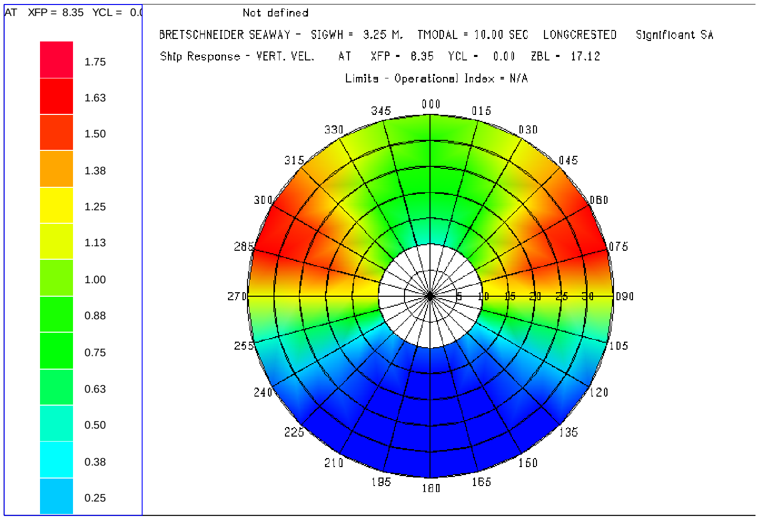


Figure 152 - Gun Vertical Velocity at Full Load

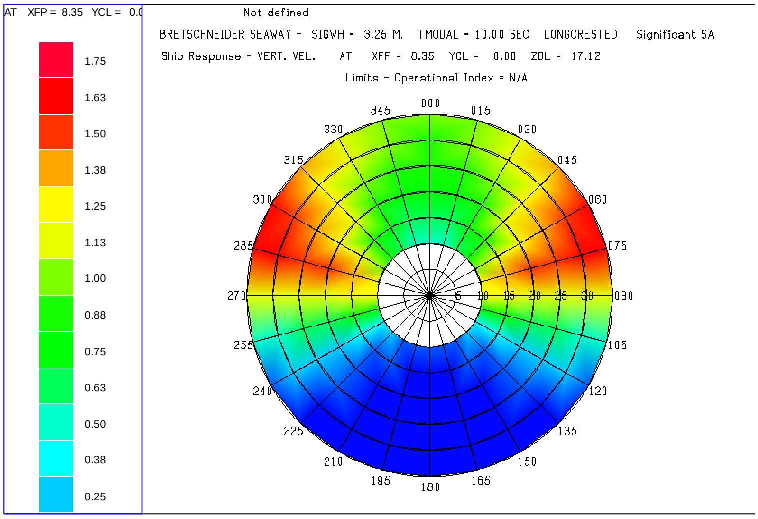


Figure 153 - Gun Vertical Velocity at MINOP

The SPY-3D/VSR++ radar is limited by roll; if the roll is too large, the radar’s field of view is filled by the ocean. The SPU-3D/VSR++ is expected to be operational in sea states up to SS7. It is fully operational in Sea State 7 in both MINOP and Full Conditions

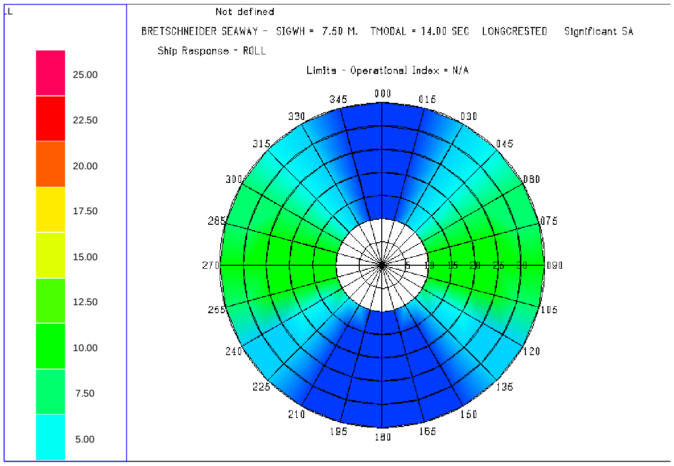


Figure 154 - Radar Roll at Full Load

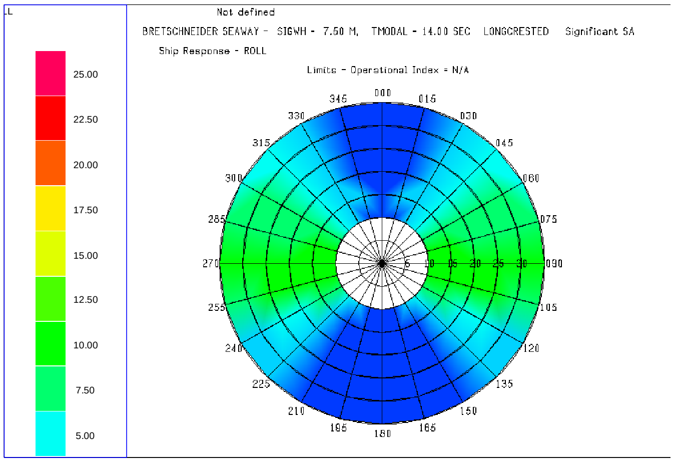


Figure 155 - Radar Roll at MINOP

The Mk-32 SVTT is limited by roll. It is expected to be operational in sea states up to SS5. It is fully operational in SS5.

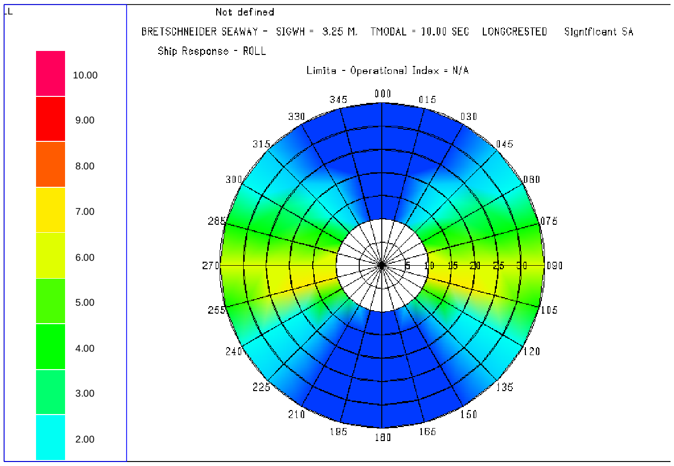


Figure 156 - Torpedo Roll at Full Load

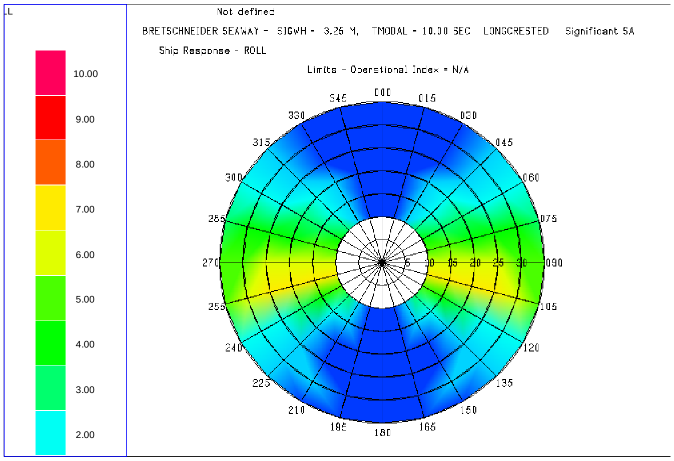


Figure 157 - Torpedo Roll at MINOP

Underway Replenishments are limited by roll and pitch. They are expected to be conducted in sea states up to SS5. UNREP operations are restricted in beam seas due to roll in both Full Load (Figure 158) and MINOP (Figure 159) condtions.

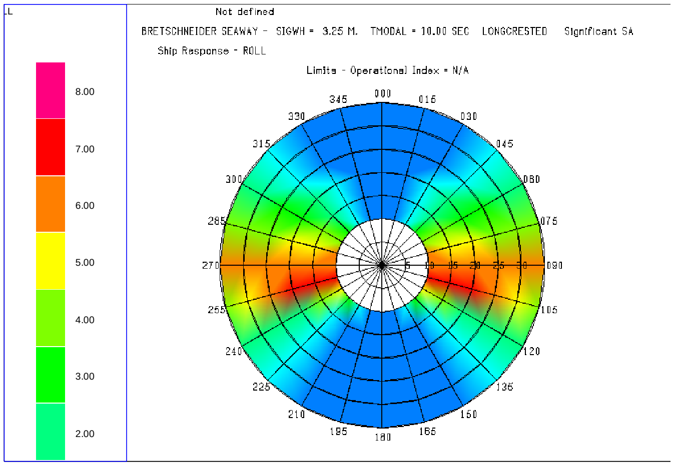


Figure 158 - UNREP Roll at Full Load

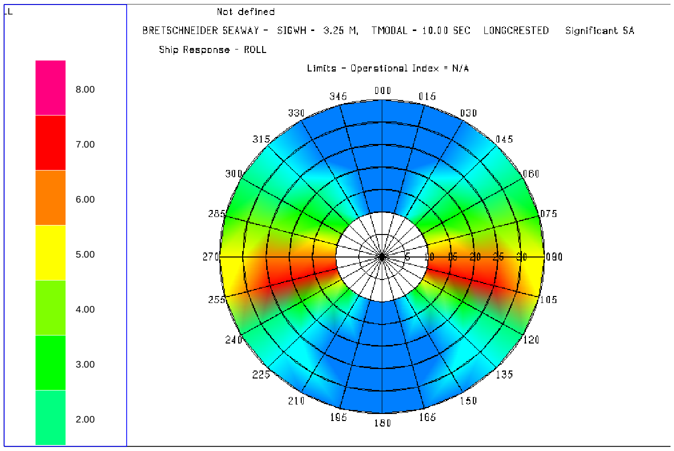


Figure 159 UNREP Roll at MINOP

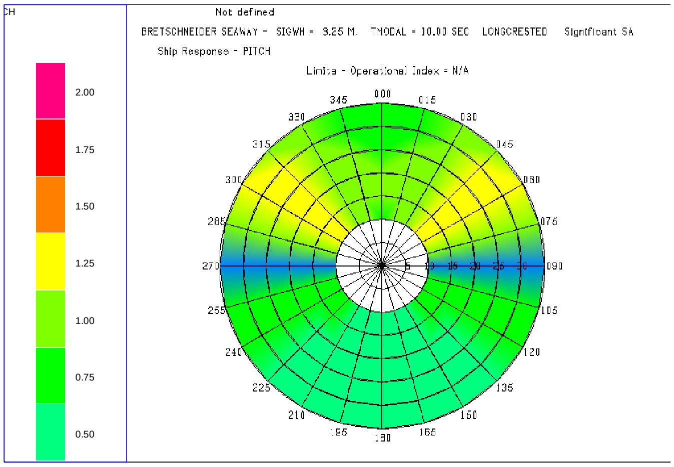


Figure 160 - UNREP Pitch at Full Load

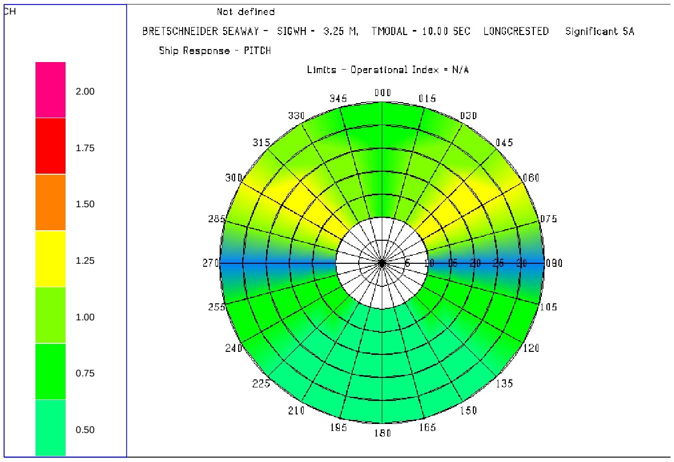


Figure 161 - UNREP Pitch at MINOP

MH-60R flight operations are limited by roll and vertical velocity at the flight deck. Flight operations are expected in sea states up to SS5. Flight operations are restricted in beam seas at both Full Load (Figure 162) and MINOP (Figure 163) conditions due to roll.

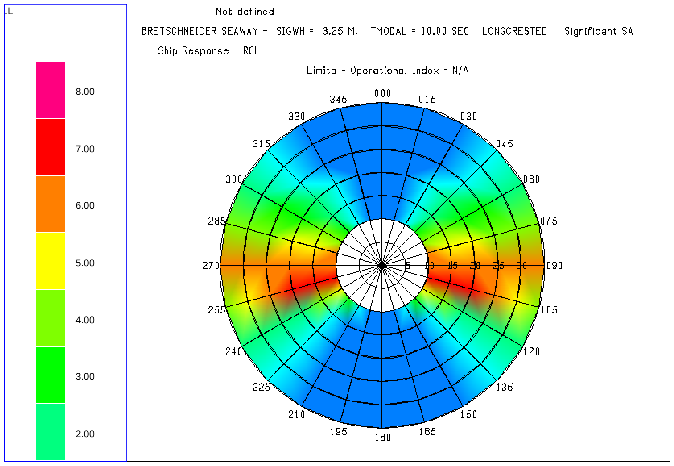


Figure 162 - Flight Operations Roll at MINOP

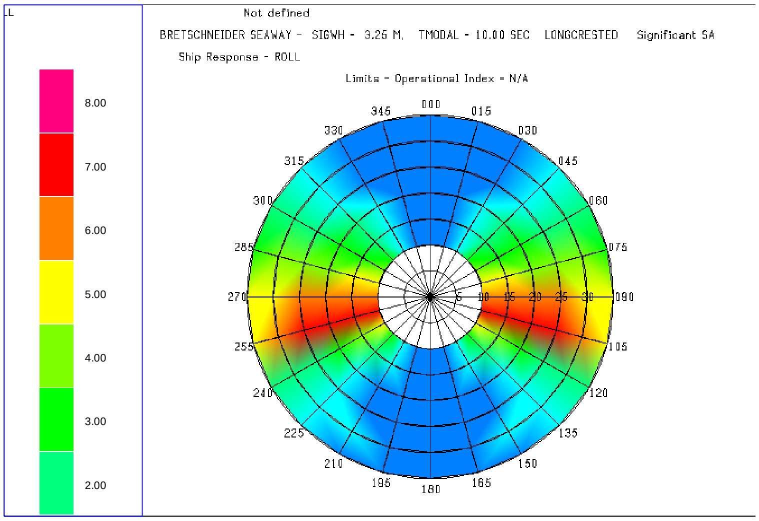


Figure 163 Flight Operations Roll at MINOP

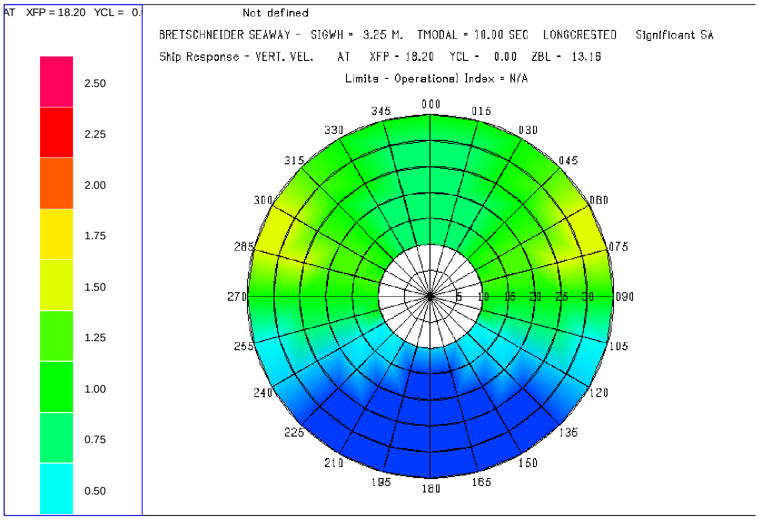


Figure 164 - Flight Operations Vertical Velocity at Full Load

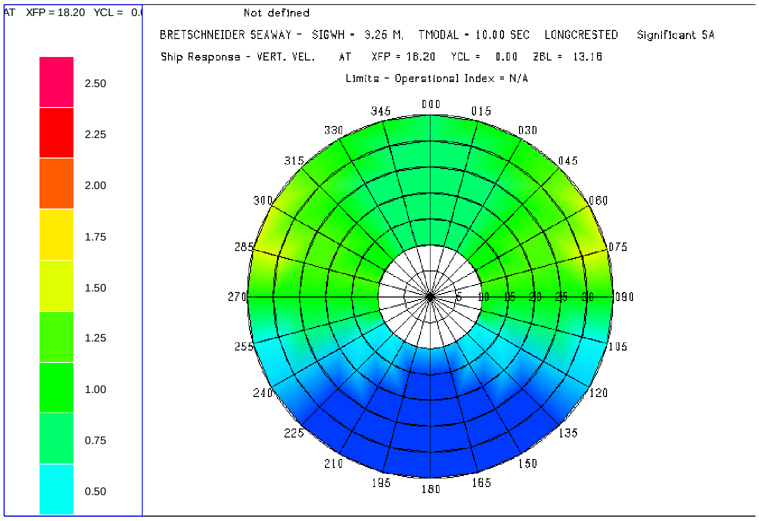


Figure 165 - Flight Operations Vertical Velocity at MINOP

The ship is expected to operate in sea states up to SS7 without excess fatigue on the ship or discomfort among the crew. The ship is structurally limited by slamming, which increases structural fatigue. Bow Wetness, pitch, roll, accelerations at the bridge, and the Motion Sickness Index (MSI) all limit the effectiveness of the crew. It should be noted that the standard limit on bow wetness assumes a traditional flared hull, where the crew may be expected to operate in the forecastle area. With the wave piercing tumblehome design, there is no such expectation, and a much wetter bow is acceptable. The ship is limited by slamming to speeds under 15knots in head seas in both Full Load (Figure 168) and MINOP (Figure 169) conditions. The crew is limited by pitch and MSI in head seas to speeds less than 15 knots in both Full Load (Figure 172, Figure 178) and MINOP (Figure 173, Figure 179) conditions. The crew is limited by roll in beam seas in both Full Load (Figure 170) and MINOP (Figure 171) conditions.

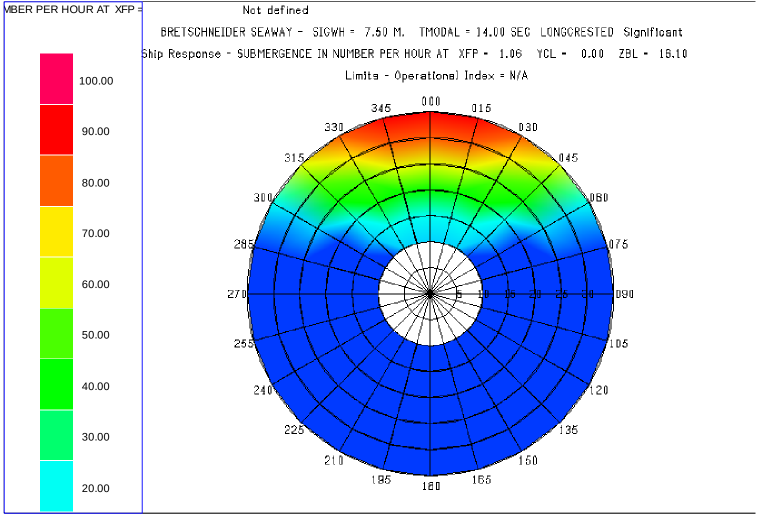


Figure 166 - Bow Wetness at Full Load

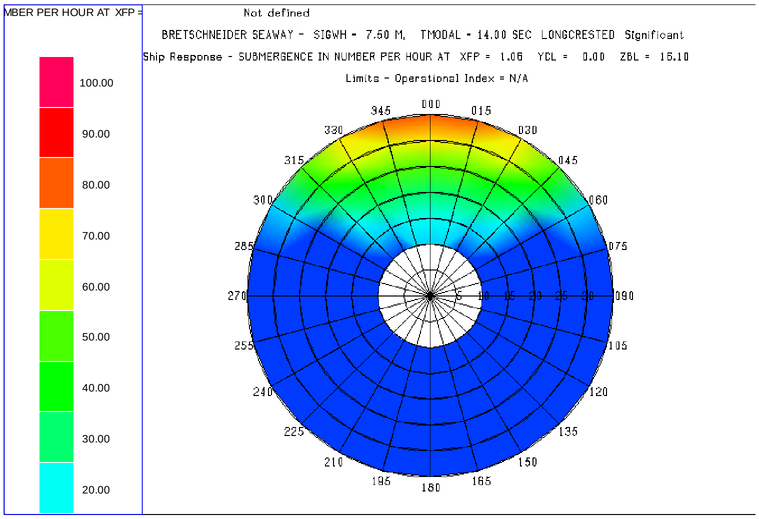


Figure 167 - Bow Wetness at MINOP

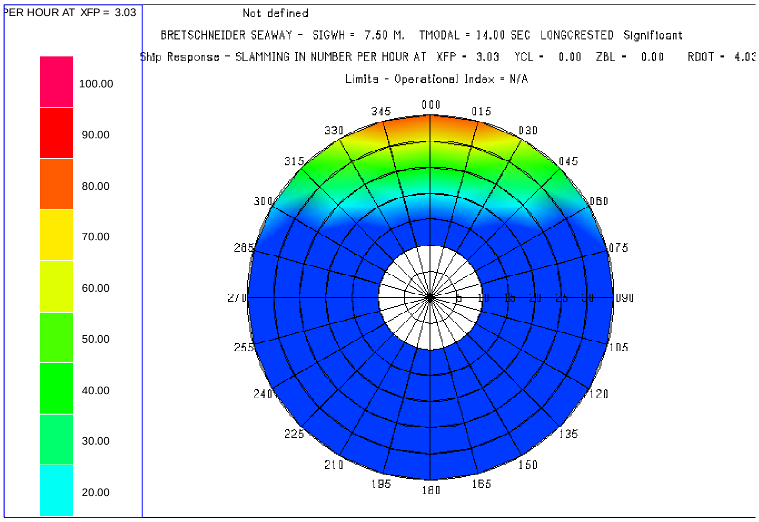


Figure 168 - Slamming at Full Load

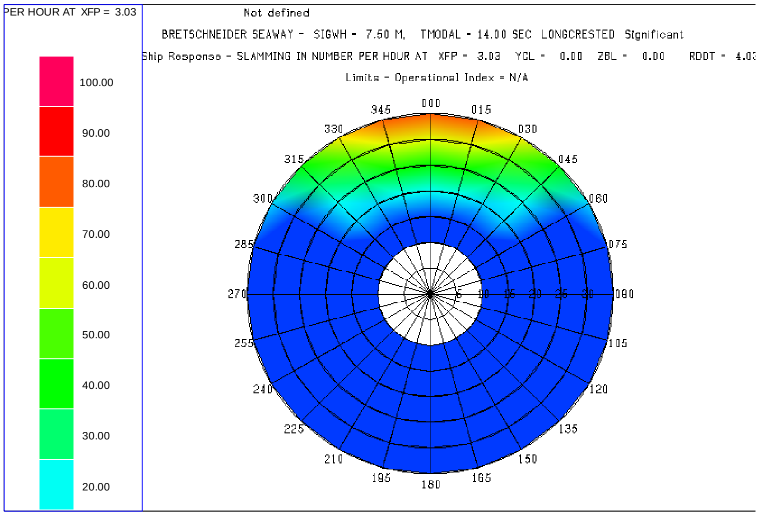


Figure 169 - Slamming at MINOP

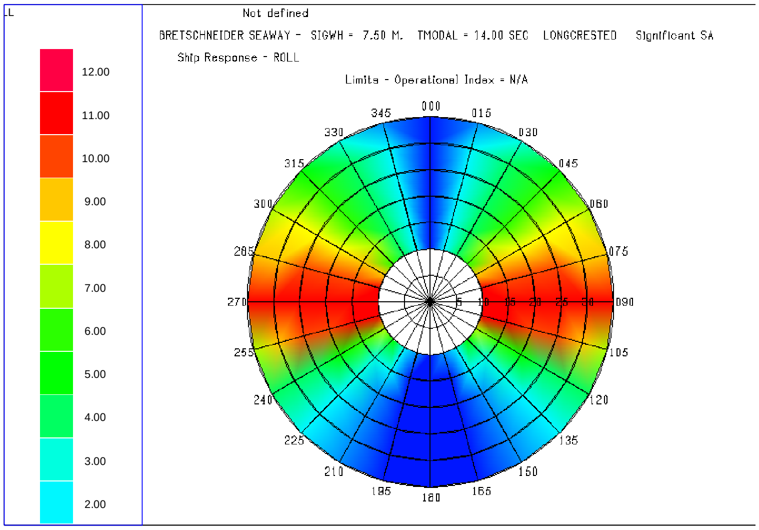


Figure 170 - Roll at Full Load

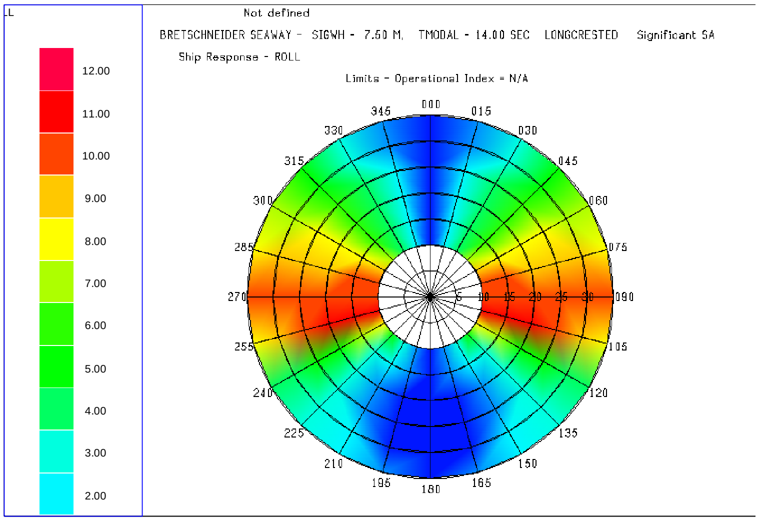


Figure 171 - Roll at MINOP

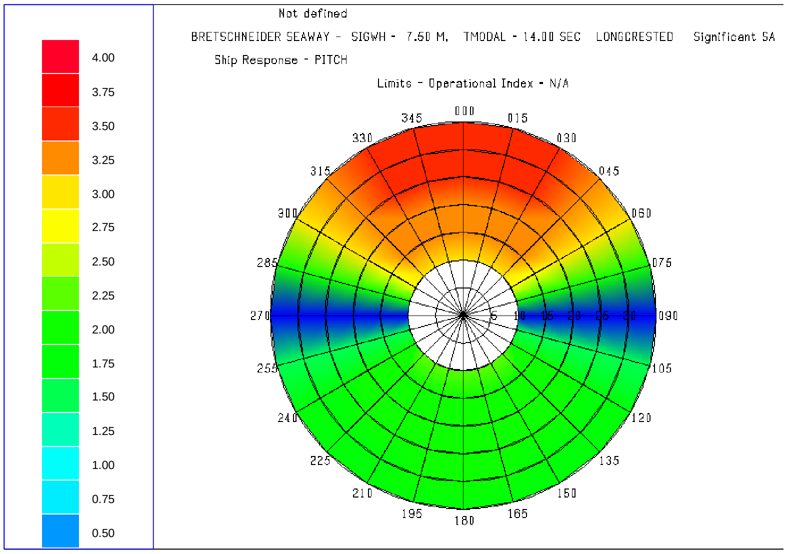


Figure 172 - Pitch at Full Load

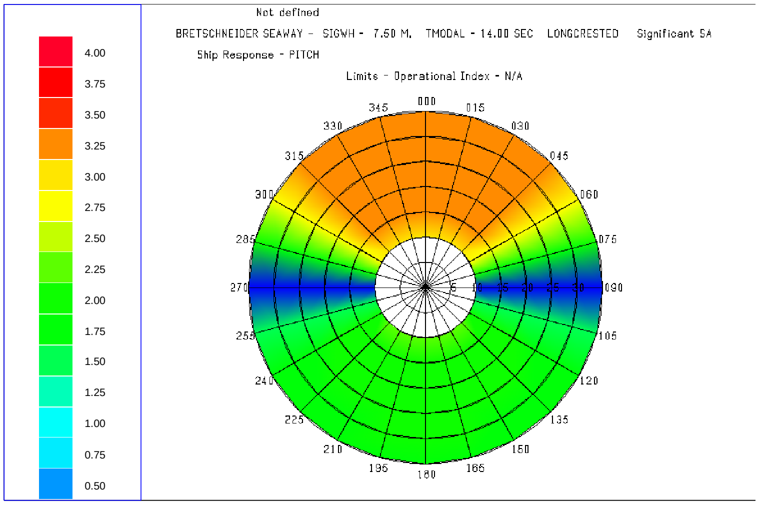


Figure 173 - Pitch at MINOP

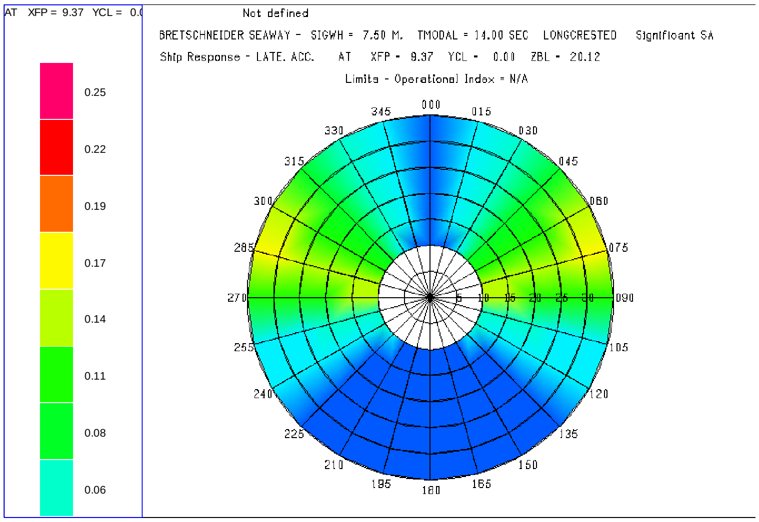


Figure 174- Transverse Acceleration at Bridge at Full Load

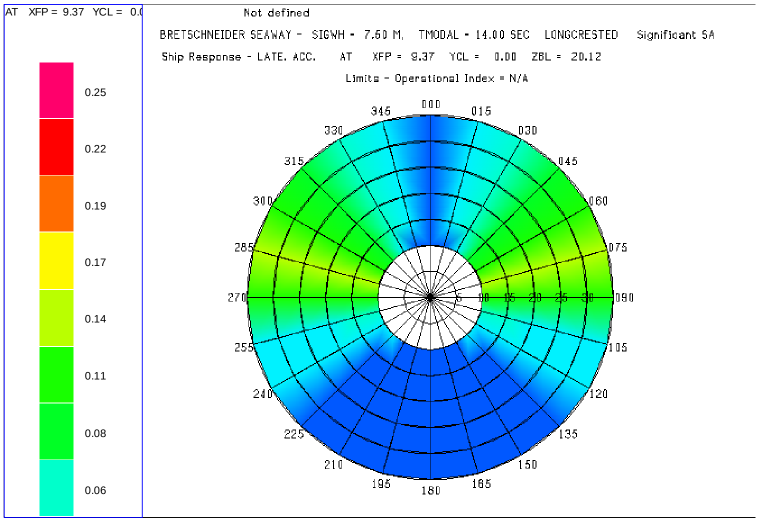


Figure 175 - Transverse Acceleration at Bridge at MINOP

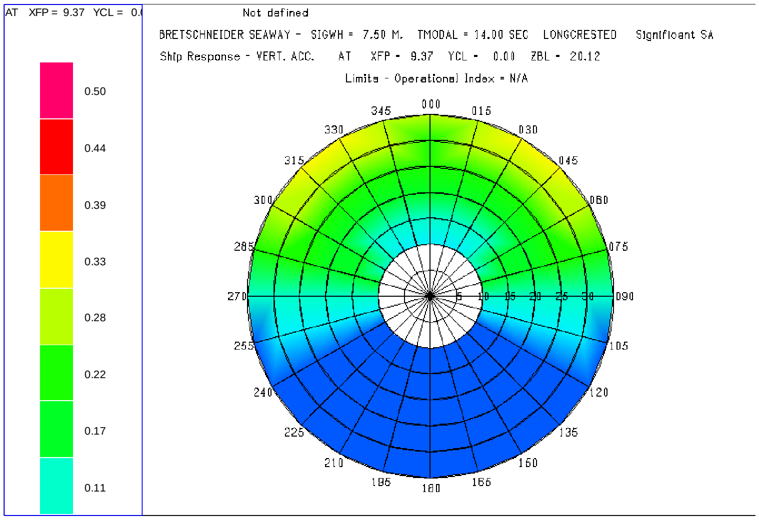


Figure 176 - Vertical Acceleration at Bridge at Full Load

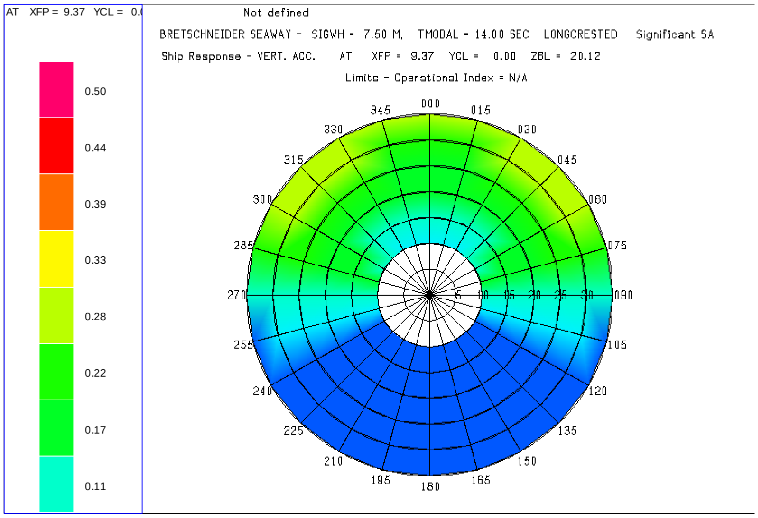


Figure 177 - Vertical Acceleration at Bridge at MINOP

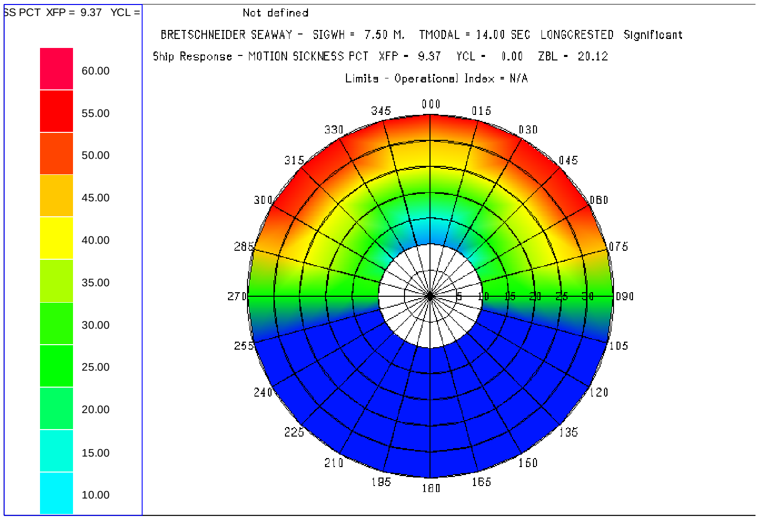


Figure 178 - MSI at Bridge at Full Load

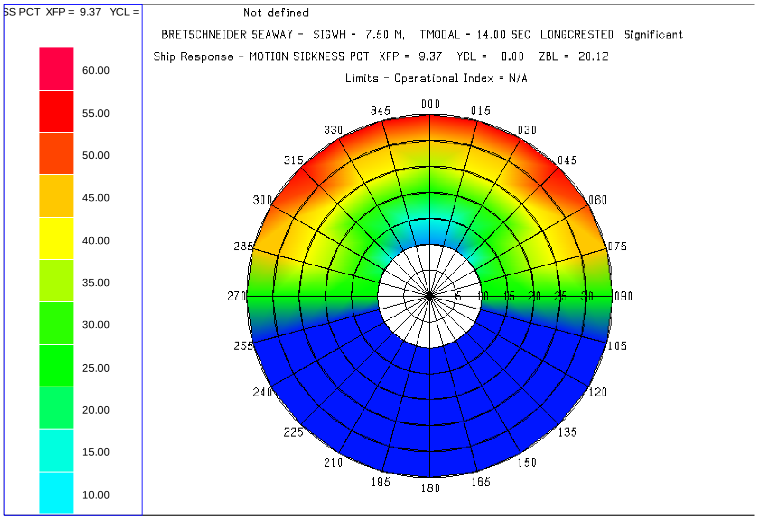


Figure 179 - MSI at Bridge at MINOP

4.12 Cost and Risk Analysis

Initial estimates for cost were generated during the multi-objective optimization that developed the baseline design (see **Error! Reference source not found.** for more detail). A weight based parametric model generated stimates for both the lead ship and follow ships. The model uses SWBS weights, installed power, endurance range, and complexity added by certain design variables into account. It also accounts for shipbuilder profit, and government costs and change orders.

A final estimate was generated near the end of the concept development using the same model. The final estimate uses the refined weights, power, tankage, and other design variables that were changed during the concept development phase. Final costs estimates for the lead ship and follow ships are in Table 52, Table 53, and Table 54. The final estimates fall within the specified $3.5 billion lead ship and $2.5 billion follow ship limits.

Table 52 - Ship Builder Costs

	Lead Ship (million $)	Follow Ship (million $)
SWBS	722.39	606.87
800	471.27	282.76
900	65.68	62.46
Total Construction	1246.28	1012.79
Profit	124.63	101.28
Shipbuilder Price	1370.91	1114.07
Change Orders	164.51	110.99
Total Shipbuilder Portion	1535.42	1225.06

Table 53 - Government Costs

	Lead Ship (million $)	Follow Ship (million $)
Other Support	34.68	27.85
Program Manager's Growth	138.74	55.70
Payload GFE	1,547.00	946.79
HM&E GFE	27.75	22.28
Outfitting	55.50	44.56
Total Gov't Portion	1,803.66	1,097.19

Table 54 - Total Costs

	Lead Ship (million $)	Follow Ship (million $)
Total Shipbuilder Portion	1,535.42	1,225.06
Total Gov't Portion	1,802.00	1,097.00
Total End Cost	3,337.42	2,322.00
Post Delivery Cost	69.37	55.70
Total Acquisition Cost	3,406.79	2,377.70
Average Ship Acquisition Cost		2,387.00

Table 55 - Life Cycle Costs

	Undiscounted (million $)	Discounted (million $)
R&D Costs	2,262.00	2,190.00
Investment	68,666.00	20,298.00
Operations and Support	90,063.00	4,356.00
Residual Value	3,530.00	13.16
Total	157,461.00	26,830.84

5 Conclusions and Future Work

5.1 Assessment

Because of the nature of the concept exploration and the importance put on certain measures of performance (MOP), the design meets all operational requirements that were given. A number of the MOP's actual reach or exceed the goals that the team set for the design. Table 56 shows the compliance of the design with the operational requirements that were given.

Table 56 - Compliance with Operational Requirements

Technical Measures of Performance (MOP)	Threshold from CDD	Original Goal	Concept BL	Final Concept BL
Endurance Range (nm)	4000	8000	7400	8420
Sustained Speed (knots)	30	35	32.9	33
Endurance Speed (knots)	18	20	20	20
Stores Duration (days)	60	75	68	68
Crew Size	120	100	77	112
Deckhouse Volume (m^3)	15000	10000	10777	12700
Maximum Draft (m)	7.95	7.21	7.3	7.3

5.2 Future Work

There are a number of issues that arose with the design of this ship. All of these issues will need to be reevaluated in later cycles of the design spiral. One major concern is the arrangement of the main and auxiliary machinery rooms within the ship. The current locations increase the shaft angle thus reducing the survivability of the ship. Another issue related to the general arrangement of the ship is the ships ability to maintain three compartment survivability. Floodable length should be revisited to ensure the requirements are met. Also for overall ship design, the deck heights may be impractical and need to be reassessed. Perhaps eliminating a deck will provide more appropriate heights for the entire ship.

Due to restrictions on software the linear sea keeping program SMP was the best resource available to study the ship. Also with the tumblehome hull form, there is a large concern for stability in rough seas. Therefore in further phases of design, a nonlinear sea keeping program would provide a more accurate study of the Medium Surface Combatant.

In reference to power and propulsion, a number of assumptions were taken when performing the calculations related to power, resistance, and endurance range. In later iterations of the design, more accurate engine profiles would be used and this will yield more realistic results for these calculations. Also a closer look at the integrated power system (IPS) and the electric load (EL) would also provide a more accurate representation of what electrical equipment is needed for this ship. This would affect the SWBS 300 weight estimations as well as cost.

As the design of the ship gets more detailed, issues related to ship production become more important. A timetable of the ship building phases can be more accurately estimated, which has a large effect on the cost of the ship. Also what elements are chosen so that the ship is structurally sound yet as cost effective as possible also need to be addressed in future design spirals? The cost estimations for the ship at this phase are very rough. A more thorough study of the components of the ship will produce more precise cost estimates. A large factor in cost is the size of the crew. As with cost, the manning estimations in this iteration are very rough and need to be refined.

5.3 Conclusions

This version of the MSC represents an agile well balanced surface combatant that will be able to serve the Navy in a flexible role for the next 40 years. The ship embraces modularity and flexibility allowing it to serve nearly any mission that could be asked of a surface combatant. With an excellent top speed and range, this ship will project power across the globe. The weapons suite is both powerful and flexible; the potential to exchange VLS cells for an advanced gun system means that not only is this ship an asset to the future navy, but also to shore based operations. This ship's flexibility and effectiveness offset the risk, and with a reasonable cost, the MSC will be a prized asset to the Navy for years to come.

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Appendix A – Initial Capabilities Document (ICD)

UNCLASSIFIED

INITIAL CAPABILITIES DOCUMENT

FOR A

Small Surface Combatant (MSC)

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 small surface combatant capabilities <u>in sufficient numbers</u> 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. *<u>Ideas for Non-Materiel Approaches (DOTMLPF Analysis).</u>*

- Increased reliance on foreign small surface combatant 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 small surface combatant 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

VIRGINIA POLYTECHNIC INSTITUTE
AND STATE UNIVERSITY

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

August 24, 2009

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

Subject: ACQUISITION DECISION MEMORANDUM FOR a Small Surface Combatant

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– Concept Development Document (CDD)

UNCLASSIFIED

CAPABILITY DEVELOPMENT DOCUMENT

FOR

MEADIUM SURFACE COMBATANT (WAVE PIERCING TUMBLEHOME HULL VARIANT)

VT Team 1 – MSCWPTH Variant 130I

Capability Discussion.

The Initial Capabilities Document (ICD) for this CDD was issued by the Virginia Tech Acquisition Authority on 21 August 2009. The overarching capability gap addressed by the ICD is the need to provide demanding surface combatant capabilities in an affordable medium surface combatant (MSC) ship (8000-14000MT). Some of the demanding surface combatant capabilities include providing area air, surface and subsurface defense at sea, providing a sea-based layer of homeland defense including BMD, provide persistent surveillance and reconnaissance, and provide strike and naval surface fire support. The need is for a very robust ship or group of ships at a very affordable cost. As a result there is a need for an efficient, balanced and effective design that is easy to produce and easy to upgrade and maintain. All the capabilities may not be met in each ship at all times, but the capabilities may be spread out between multiple ships at concurrent times. Due to the demanding requirements and long service life (40 years), a high degree of modularity needs to be incorporated into the design to enable flexible mission modules and facilitate overhauls and upgrades. The specific capability gaps and requirements include:

Priority	Capability Description	Threshold Systems or Metric	Goal Systems or Metric
1	LRS&T Radar	SPY-3 X-band radar; S-Band VSR	SPY-3 X-band radar; large S-Band VSR
2	Missile Capacity	32 MK57 VLS	128 MK57 VLS
3	NSFS-Major Gun(s)	1 5in/62 (+AGS module in 4x4 VLS option)	2 AGS
4	MSC Platform Mobility	30 knt, full SS4, 4000 nm, 60 days	35 knots, full SS5, 8000 nm, 75 days
5	Platform Passive Susceptibility	DDG-51 signatures	DDG1000 signatures
6	Platform Self and Area Defense, Other Multi-Mission	CIGS, LAMPS haven, TSCE, 5m passive sonar	IUSW, SOF and ASUW stern launch, CIGS, Embarked LAMPS/AAV w/hangar, TSCE

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 Medium Surface Combatant with emphasis on providing a robust ship in an affordable package. Required core capabilities are AAW/BMD and blue/green water ASW. The platforms must be highly producible, maintainable and upgradable through significant modularization, minimizing the time from concept to delivery and maximizing system commonality with DDG1000. The platforms must operate within current logistics support capabilities. Inter-service and Allied C^4/I (inter-operability) must be considered. The new ship must have minimum manning.

Concept Exploration was conducted from 2 September 2009 through 11 December 2009. A Concept Design and Requirements Review was conducted on 20 January 2010. This CDD presents the baseline requirements approved in this review.

Available technologies and concepts necessary to provide required functional capabilities were identified and defined in terms of performance, cost, risk and ship impact (weight, area, volume, power). Trade-off studies were performed using technology and concept design parameters to select trade-off options in a multi-objective genetic optimization (MOGO) for the total ship design. The result of this MOGO was a non-dominated frontier, Figure 1. This frontier includes designs with a wide range of risk and cost, each having the highest effectiveness for a given risk and cost. Preferred designs are often "knee in the curve" designs at the top of a large increase in effectiveness for a given cost and risk, or designs at high and low extremes. The Baseline design selected for Virginia Tech Team 1, and specified in this CDD, was Variant 130, a highly effective medium risk design chosen from Figure 1. Selection of a point on the non-dominated frontier specifies requirements, technologies and the baseline design. Principle characteristics and manning for this design were further refined in a single objective optimization minimizing follow-ship acquisition cost as the objective attribute. The requirements for this Improved Baseline design (130I) are specified in this CDD.

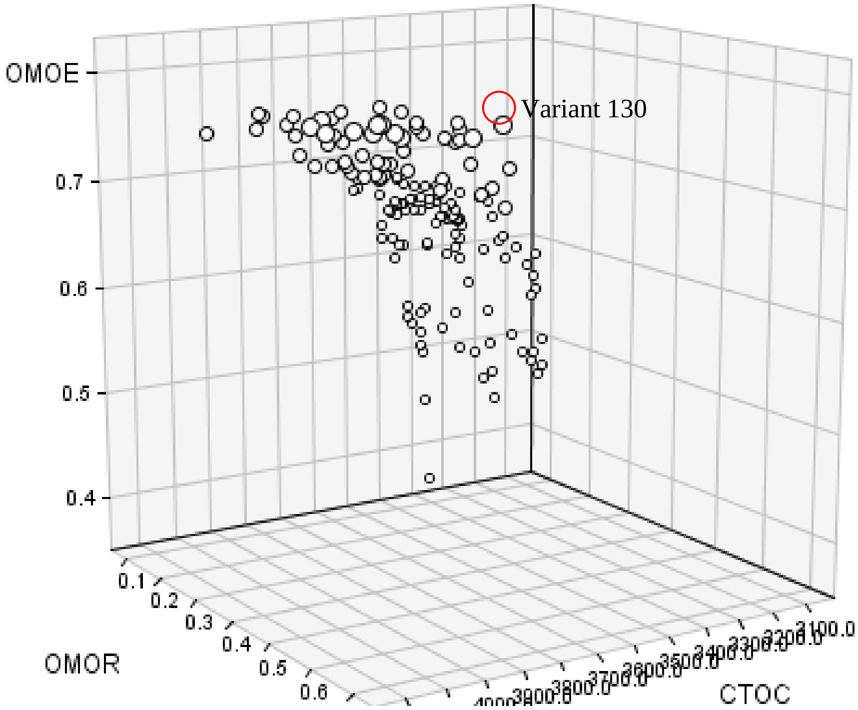

Figure 1 – MSC Non-Dominated Frontier

Concept of Operations Summary

Ballistic Missile Defense (BMD). Current Aegis ships are being configured to intercept short and medium-range BM threats, but cannot effectively counter long-range intercontinental ballistic missiles that could target the US from China, North Korea and Iran. Current ships are also fully multi-mission ships. The radar and missile capabilities of some future surface combatants must be greater than the Navy's current Aegis ships. Some multi-mission capabilities may have to be sacrificed to control cost. Conducting BMD operations may require MSCs to operate in a location that is unsuitable for performing one or more other missions. Conducting BMD operations may reduce the ability to conduct air-defense operations against aircraft and cruise missiles due to limits on ship radar capacity. BMD interceptors may occupy ship weapon-launch tubes that might otherwise be used for air-defense, land-attack, or antisubmarine weapons. Maintaining a standing presence of a BMD ship in a location where other Navy missions do not require deployment, and where there is no nearby U.S. home port, can require a total commitment of several ships, to maintain ships on forward deployment. Critical capabilities for BMD-capable ships include high-altitude long-range search and track (LRS&T), and missiles with robust ICBM BMD terminal, mid-course, and potentially boost-phase capability. A ship with both of these is considered an ICBM engage-capable ship. The extent of these capabilities will have a significant impact on the ship's Concept of Operations. BMD requirements may change over time.

Major Caliber Naval Surface Fire Support. There is a verified need for major caliber NSFS for the foreseeable future. DDG1000 was to provide this capability with the Advanced Gun System (AGS), but affordability issues may limit the number of these ships that can be built. An alternative strategy is required for placing one or two AGS on other MSCs, possibly as a modular system, and possibly without full multi-mission capability. These ships would operate with and ahead of marine amphibious task groups to prepare for and support marines operating from the sea.

CSGs, ESGs and SAGs. It is expected that MSCs will continue to operate with Carrier Strike Groups and Expeditionary (Amphibious) Strike Groups providing AAW, ASUW and ASW support. MSC Surface Action Groups (SAGs) will perform various ISR and Strike missions in addition to providing their own AAW, ASUW and ASW defense. ISR missions will include the use of autonomous air surface and subsurface vehicles and LAMPS. Deployments will typically be have 6 month duration with underway replenishment, a few port visits, all-weather operations, cluttered air and shipping environments, blue water and littoral and limited maintenance opportunities. MSCs will typically deploy and return to CONUS.

Threat Summary

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

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

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

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

The extraordinary level of resources North Korea and Iran are now devoting to developing their own ballistic missile capabilities poses a substantial and immediate danger to the U.S., its vital interests and its allies. While these nations' missile programs may presently be aimed primarily at regional adversaries, they inevitably and inescapably engage the vital interests of the U.S. as well. Their targeted adversaries include key U.S. friends and allies. U.S. deployed

forces are already at risk from these nations' growing arsenals. Each of these nations places a high priority on threatening U.S. territory, and each is even now pursuing advanced ballistic missile capabilities to pose a direct threat to U.S. territory.

Since many potentially unstable nations are located on or near geographically constrained (littoral) bodies of water, the tactical picture may be at smaller scales relative to open ocean warfare. Threats in such an environment include: (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 9) and littoral, all weather
- 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

System Capabilities and Characteristics Required for the Current Development Increment.

Key Performance Parameter (KPP)	Development Threshold or Requirement
AAW	SPY-3/VSR ++ DBR, IRST, Aegis 2014 BMD Combat System, CIFF-SD
ASUW/NSFS	1xMK45 5”/62 gun, SPS-73 (emergency), Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod1 3x CIGS; option for AGS in place of 4x4 MK57 VLS
ASW	2xSVTT, NIXIE, mine avoidance sonar, Mission Modular ASW (see below)
CCCC	Enhanced CCCC
LAMPS	2xSH60, 3 VTUAV (hangar, flight deck, refueling, rearming), SQQ-28 LAMPS electronics
SDS	AIEWS - SLQ-32(R), MK 36 SRBOC with NULKA
GMLS	64 x MK 57 VLS and/or PVLS; 1xAGS or 16 additional MK57 VLS (modular)
Mission Modules	1 x LCS capacity
Hull	Wave Piercing Tumblehome
Power and Propulsion	2 shaft IPS 4xMT30, DC ZEDS, 2xAdvanced Induction Motors
Endurance Range (nm)	7400 nm
Sustained Speed (knots)	32.9 knots
Endurance Speed (knots)	20 knots
Stores Duration (days)	68
Collective Protection System	full

Crew	77 plus 20% allowance to support modular mission systems
Maximum Draft (m)	7.3
Vulnerability (Hull Material)	Steel
Ballast/fuel system	Clean ballast tanks
Degaussing System	Yes
Seakeeping	Fully effective to SS5

KG margin (D&B + SLA, WPTH)	1 meter
Resistance margin (endurance speed)	10%
Resistance margin (sustained speed)	25% (0.8 MCR)
Net D&B Ship Service Electric margin	20%
Net Electric Service Life Allowance (IPS ship)	5%
Weight margin (Design and Build)	10%
Weight Margin (Service Life)	5%

Program Affordability.

The average follow-ship acquisition cost shall not exceed $2.5B (FY2013) with a lead ship acquisition cost less than $3.8B. It is expected that 30 ships of this type will be built with IOC in 2018. The service life of this ship will be 40 years, which will require flexibility in upgrade and capability over time through modularity.

Appendix D: Machinery Equipment List

ITEM	QTY	NOMENCLATURE	DESCRIPTION	CAPACITY RATING	LOCATION	SWBS #	REMARKS	DIMENSIONS LxWxH (m)
System: Main Engines and Transmission								
1	4	PGM	RR MT30 Marine Gas Turbine and Generator	36MW	MMR	234	Includes Acoustic Enclosure	9.18 x 3.84 x 3.78
2	2	Shaft, Line	575 mm (OD), 380 mm (ID)	-	various	243	ABS Grade 2 Steel, calculate size and weight	0.6m D, L as reqd
3	5	Bearing, Line Shaft	Journal	575 mm Line Shaft	various	244	Calculate number required and locate	1 x .125 x .125
4	4	Power Conversion Modules	1 per MT30, 1 per CAT3608, 1 per PMM	Various	MMR		1 For Each Gas Turbine, Located in upper levels of MMR's	5.72 x 1.22 x 1.83
5	2	Main Engine Exhaust Duct	RR MT30 Marine Gas Turbine	75 kg/sec	MMR and up	234	Needs to follow almost vertical path up through hull, deckhouse and out stack	4.9 m2
6	2	IPS Propulsion Motors PMMS	Permanent Magnet Motors	~45 MW	AMR			8.21 x 4.73 x 4.37
7	2	Main Engine Inlet Duct	RR MT30 Marine Gas Turbine	65 kg/sec	MMR and up	234	Needs to follow almost vertical path up through hull, deckhouse and out side of stack or deckhouse	9.8 m2
8	2	Power Conversion Modules for PMM	PMM	4160 VAC to 1000 VDC	AMR		Upper level	3 x 1.74 x 1.28
9	2	Dynamic Breaking Resistor	for PMM's		MMR		Upper level	3.5 x 1.5 x 1.6
10	2	Harmonic Filter Switchgear	for PGM's		MMR		Upper Level	3 x 1.5 x 1.7
11	2	Harmonic Filter	for PCM's / PGM's		MMR		Upper Level	3 x 1.25 x 1.6
12	1	Console, Main Control	Main Propulsion	NA	MMR Engineering Operation Station (EOS)	252	MMR 2nd or upper level in EOS looking down on RG	3x1x2
System: Power Generation and Distribution								
13	2	Emergency Generator, Ships Service	CAT 3608 and Generator	2527 kW, 480 V, 3 phase, 60 Hz, 0.8 PF	AMR	311	Includes enclosure, 2nd or upper level, orient F&A	4.5 x 4.14 x 4.23
14	2	DG Exhaust Duct	CAT 3608	16.9 kg/sec	MMR, AMR and up	311	Needs to follow almost vertical path up through hull, deckhouse and out stack	1.1 m3
15	2	DG Inlet Duct	CAT 3608	15 kg/sec	MMR, AMR and up	311	Needs to follow almost vertical path up through hull, deckhouse and out side of stack or deckhouse	2.2 m3
16	1	Switchboard, Ships Service	Generator Control Power Distribution	-	MMR EOS	324	MMR upper level in EOS	3.096 x 1.220 x 2.286

17	1	Switchboard, Ships Service	Generator Control Power Distribution	-	AMR EOS	324	AMR upper level	2.5x1x2
18	6	MMR and AMR ladders	Inclined ladders		MMR,AMR		May have single or double inclined ladders between levels depending on space	1.0x2.0
19	2	MMR and AMR escape trunks	Vertical ladders with fire tight doors at each level		MMR, AMR		One per space in far corners, bottom to main deck	1.5x1.5
20	2	MN Machinery Space Fan	Supply	94762 m^3/hr	FAN ROOM	512	above, outside MMR	1.118 (H) x 1.384 (dia)
21	2	MN Machinery Space Fan	Exhaust	91644 m^3/hr	MMR	512	Upper level in corners	1.118 (H) x 1.384 (dia)
22	2	Aux Machinery Space Fan	Supply	61164 m^3/hr	FAN ROOM	512	above, outside AMR	1.092 (H) x 1.118 (dia)
23	2	Aux Machinery Space Fan	Exhaust	61164 m^3/hr	AMR	512	Upper level in corners	1.092 (H) x 1.118 (dia)
24	2	Power Conversion Modules	Generator Control Power Distribution		AMR		Upper Levels	2.89 x 3.02 x 2.13
25	2	Harmonic Filters	Generator Control Power Distribution		AMR		Upper Levels	2.0 x 1.05 x 1.6
26	2	Dynamic Resistor	Generator Control Power Distribution		AMR		Upper Levels	.95 x .7 x .58
System: Salt Water Cooling								
27	2	Pump, Main Seawater Circ	Centrifugal, Vertical, Motor Driven	230 m^3/hr @ 2 bar	MMR	256	P&S MMR lower level near hull and ME	1.2 x 1.2 x 1.511
System: Lube Oil Service and Transfer								
28	2	Assembly, MGT Lube Oil Storage and Conditioning	Includes Oil Storage and Cooler	NA	MMR	262	next to each engine	1.525 x 2.60 x 1.040
29	2	Purifier, Lube Oil	Centrifugal, Self Cleaning, Partial Discharge Type	1.1 m^3/hr	MMR	264	next to LO transfer pump, 2nd or upper level MMR	.830 x .715 x 1.180
30	2	Pump, Lube Oil Transfer	Pos. Displacement, Horizontal, Motor Driven	4 m^3/hr @ 5 bar	MMR	264	next to LO purifier	.699 x .254 x .254
System: Fuel Oil Service and Transfer								
31	2	Filter Separator, MGT Fuel	2-Stage, Static, 5 Micron	30 m^3/hr	MMR	541	next to FO purifiers	1.6 (L) x.762 (dia)
32	2	Purifier, Fuel Oil	Self Cleaning, Centrifugal, Partial Discharge Type	7.0 m^3/hr	MMR	541	2nd or upper level MMR	1.2 x 1.2 x 1.6
33	2	Pump, Fuel Transfer	Gear, Motor Driven	45.4 m^3/hr @ 5.2 bar	MMR	541	next to FO purifiers	1.423 x .559 x .686
34	2	Fuel Oil Service Tanks			MMR		lower level MMR P&S	4 x 3 x 2
System: Air Conditioning and Refrigeration								
35	4	Air Conditioning Plants	150 Ton, Centrifugal Units	150 ton	AMR	514	either level, side by side	2.353 x 1.5 x 1.5
36	4	Pump, Chilled Water	Centrifugal, Horizontal, Motor Driven	128 m^3/hr @4.1 bar	AMR	532	next to AC plants	1.321 x .381 x .508
37	2	Refrig Plants, Ships Service	R-134a	4.3 ton	AMR	516	either level, side by side	2.464 x .813 x 1.5
38	4	Radar Cooling Units			MMR		upper level	2.5 x .837 x.864
System: Salt Water: Firemain, Bilge, Ballast								
39	4	Pump, Fire	Centrifugal, Horizontal, Motor Driven	454 m^3/hr @ 9 bar	VARIOUS	521	lower levels	2.490 x .711 x .864
40	1	Pump, Fire/Ballast	Centrifugal, Horizontal, Motor Driven	454 m^3/hr @ 9 bar	AMR	521	lower levels	2.490 x .711 x .864

41	2	Pump, Bilge	Centrifugal, Horizontal, Motor Driven	227 m^3/hr @3.8 bar	MMR	529	lower levels	1.651 x .635 x 1.702
42	1	Pump, Bilge/Ballast	Centrifugal, Horizontal, Motor Driven	227 m^3/hr @3.8 bar	AMR	529	lower levels	1.651 x .635 x .737
43	2	Station, AFFF	Skid Mounted	227 m^3/hr @3.8 bar	above MMR	555	for entering space	2.190 x 1.070 x 1.750
System: Potable Water								
44	2	Distiller, Fresh Water	Distilling Unit	76 m^3/day (3.2 m^3/hr)	AMR	531	lower or 2nd level	2.794 x 3.048 x 2.794
45	2	Brominator	Proportioning	1.5 m^3/hr	AMR	531	next to distillers	.965 x .203 x .406
46	2	Brominator	Recirculation	5.7 m^3/hr	AMR	533	next to distillers	.533 x.356 x 1.042
47	2	Pump, Potable Water	Centrifugal, Horizontal, Motor Driven	22.7 m^3/hr @ 4.8 bar	AMR	533	next to distillers	.787 x .559 x .356
System: JP-5 Service and Transfer								
48	2	Pump, JP-5 Transfer	Rotary, Motor Driven	11.5 m^3/hr @ 4.1 bar	JP-5 PUMP ROOM	542	in JP-5 pump room	1.194 x.483 x .508
49	2	Pump, JP-5 Service	Rotary, Motor Driven	22.7 m^3/hr @ 7.6 bar	JP-5 PUMP ROOM	542	in JP-5 pump room	1.194 x .483 x .508
50	1	Pump, JP-5 Stripping	Rotary, Motor Driven	5.7 m^3/hr @ 3.4 bar	JP-5 PUMP ROOM	542	in JP-5 pump room	.915 x .381 x .381
51	2	Filter/Separ., JP-5 Transfer	Static, Two Stage	17 m^3/hr	JP-5 PUMP ROOM	542	in JP-5 pump room	.457 (L) x 1.321 (dia)
52	2	Filter/Separ., JP-5 Service	Static, Two Stage	22.7 m^3/hr	JP-5 PUMP ROOM	542	in JP-5 pump room	.407 (L) x 1.219 (dia)
System: Compressed Air								
53	2	Receiver, Starting Air	Steel, Cylindrical	2.3 m^3	MMR	551	near ME, compressors and bulkhead	1.067 (dia) x 2.185 (H)
54	2	Compressor, MP Air	Reciprocating Motor Driven, Water Cooled	80 m^3/hr FADY @ 30 bar	MMR	551	2nd or upper level	1.334 x .841 x .836
55	1	Receiver, Ship Service Air	Steel, Cylindrical	1.7 m^3	MMR	551	near ME, compressors and bulkhead	1.830 (H) x .965 (dia)
56	1	Receiver, Control Air	Steel, Cylindrical	1 m^3	MMR	551	near ME, compressors and bulkhead	3.421 (H) x .610 (dia)
57	2	Compressor, Air, LP Ship Service	Reciprocating, Rotary Screw	8.6 bar @ 194 SCFM	MMR	551	2nd or upper level	1.346 x 1.067 x 1.829
58	2	Dryer, Air	Refrigerant Type	250 SCFM	MMR	551	near LP air compressors	.610 x .864 x 1.473
System: Steering Gear Hydaulics								
59	2	Hydraulic Pump and Motor	Steering Gear		aft Steering Gear Room	561	next to ram	0.5x0.8x0.8
60	1	Hydraulic Steering Ram	Steering Gear		aft Steering Gear Room	561	over rudders	1.2x8.5x1.5
System: Environmental								
61	2	Pump, Oily Waste Transfer	Motor Driven	12.3 m^3/hr @ 7.6 bar	MMR	593	lower level	1.219 x .635 x .813
62	2	Separator, Oil/Water	Coalescer Plate Type	2.7 m^3/hr	MMR	593	lower level near oily waste transfer pump	1.321 x .965 x 1.473
63	1	Unit, Sewage Collection	Vacuum Collection Type w/ Pumps	28 m^3	SEWAGE TREATMENT ROOM	593	sewage treatment room	2.642 x 1.854 x 1.575

64	1	Sewage Plant	Biological Type	225 people	SEWAGE TREATMENT ROOM	593	sewage treatment room	1.778 x 1.092 x 2.007