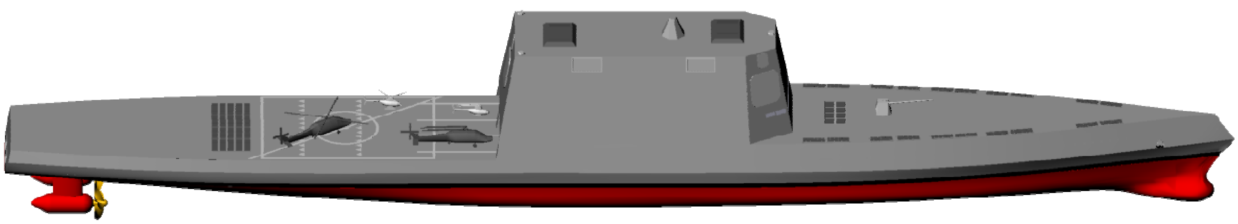
Virginia Tech
Aerospace & Ocean Engineering

Design Report

Ballistic Missile Defense Cruiser

(CGX/BMD)

VT Total Ship Systems Engineering



CGX/BMD Variant 13
Ocean Engineering Design Project
AOE 4065/4066
Fall 2007 – Spring 2008
Virginia Tech Team 2

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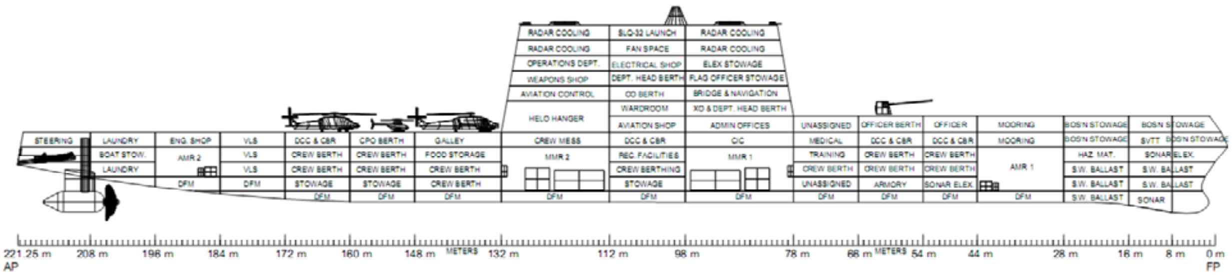
Executive Summary



Ship Characteristics

This report describes the Concept Exploration and Development of a Ballistic Missile Defense (BMD) Cruiser (CGX) for the United States Navy. This concept design was completed in a two-semester ship design course at Virginia Tech.

The CGX/BMD requirement is based on the CGX Initial Capabilities Document (ICD) and Virginia Tech CGX Acquisition Decision Memorandum (ADM), Appendix A and Appendix B.

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 a Capability Development Document (CDD) based on the customer's preference for cost, risk and effectiveness.

CGX/BMD variant 13 is a low to medium risk, high cost, and very high effectiveness alternative on the non-dominated frontier.

CGX/BMD will address the need for a new Aegis-type ship with more capable core systems and modular systems similar to DDG-1000, with particular emphasis on providing robust ICBM defense. CGX/BMD will have the ability to operate forward deployed to conduct BMD operations from advantageous locations at sea that are inaccessible to ground-based systems. CGX/BMD will employ large, powerful, phased-array radar, and a large battery of SM-3's and KEI's to defend a large down-range territory against potential attack by ballistic missiles.

CGX/BMD has a hybrid flare-tumblehome hullform to balance between seakeeping capability and reduced radar cross section. Its large installed power plant and IPS will enable CGX/BMD to adapt to changing mission conditions and provide flexibility for future growth.

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 CDD within cost and risk constraints.

Parameter	Value
Hull	Hybrid flare-tumblehome
LWL	221.4 m
Beam	23.5 m
Depth	16.0 m
Draft	7.6 m
Cp	0.678
Cx	0.871
Full Load Displacement	24,940 MTON
Power and Propulsion	Full IPS 2 pods FPP, PMM 4x 36MW MT30 marine turbines 2x 5.1MW CAT 3616 diesels 2X 5MW PEM fuel cells EMR PWR
Total Installed Power	155.2 MW
Sustained Speed	32.7 knots
Endurance Speed	20 knots
Endurance Range	8007 nm
CPS	Full
Vulnerability (Material)	Steel
Ballast/fuel system	Clean, separate ballast tanks
Total Manning	452 (31 officers, 35 CPO, 386 enlisted)
AAW/BMD/STK	SPY-3/VSR+++ DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA
ASUW/NSFS	1xMK45 5"/62 gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod2 3x CIGS
ASW/MCM	Dual Frequency Bow Array, ISUW, NIXIE, 2xSVTT, mine-avoidance sonar
CCC	Enhanced CCC
LAMPS	2 x Embarked LAMPS w/Hangar, 2xVTUAV
SDS	SLQ-32(V) 3, SRBOC, NULKA, ESSM
GMLS	160 cells MK57, 8 cells KEI
OMOE (Effectiveness)	0.852
OMOR (Risk)	0.286
Lead Ship Acquisition Cost	$4.454 Billion
Avg. Follow Ship Acq. Cost	$3.676 Billion
Avg. Ship Acq. Cost	$3.650 Billion

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1 Introduction, Design Process and Plan

1.1 Introduction

This report describes the concept exploration and development of a Ballistic Missile Defense Cruiser (CGX/BMD) for the United States Navy. The CGX/BMD requirement is based on the CGX/BMD Initial Capabilities Document (ICD), and Virginia Tech CGX/BMD Acquisition Decision Memorandum (ADM), Appendix A and Appendix B respectively. This concept design was completed in a two-semester ship design course at Virginia Tech. CGX/BMD must perform the following primary missions:

- Ballistic Missile Defense (BMD)
- Carrier Battle Group (CBG) Anti-Air Warfare (AAW) and escort

CGX/BMD will be capable of intercepting ballistic missile warheads in boost, early ascent, and mid-course of the flight via SM-3's and/or Kinetic Energy Interceptor's (KEIs). It will use a large, powerful, Dual Band Radar (DBR) array. DBR is a phased-array radar system consisting of AN/SPY 3 and the Volume Search Radar (VSR). It gives the ability to detect objects, from ballistic missiles to periscopes, at long range with high accuracy, supporting the Ballistic Missile Defense mission while requiring little maintenance.

CGX/BMD is to be deployed for missions up to seventy-five days in length in regions that pose a strategic threat to the United States, including open ocean and littoral waters both shallow and deep. It will operate in all-weather conditions with dense contacts and threats with complicated targeting. CGX/BMD shall have a minimum endurance range of 5000 nautical miles at 20 knots, a minimum sustained speed at 30 knots, carry at least 96 mixed missiles and use SPY-3 X/S-band and Volume Search (VSR) radars.

Ship options should consider a new CGX/BMD ship with limited multi-mission capability to a fully multi-mission ship with extensive BMD capability and maximum DDG-1000 commonality. The design must minimize personnel vulnerability in combat through automation. Average follow-ship acquisition cost shall not exceed $3.7B ($FY2012) with a lead ship acquisition cost less than $5.3B. It is expected that 18 ships of this type will be built with IOC in 2018.

The concepts introduced in the CGX/BMD may include medium to high-risk alternatives.

1.2 Design Philosophy, Process, and Plan

The traditional approach to ship design is largely an 'ad hoc' process. Experience, design lanes, rules of thumb, preference, and imagination guide the selection of design components for assessment. Often, objective attributes are not adequately synthesized or presented to support efficient and effective decisions. This project uses a total systems approach for the design process, including a structured search of the design space based on multi-objective consideration of effectiveness, cost, and risk.

Most naval ships go through five stages of design processes, taking a total of 15 to 20 years to complete. In this Virginia Tech design project, only two are performed: concept exploration and concept development. Concept exploration considers past ships and new developments in technology. The CGX/BMD may be closely related to the DDG-1000 and a modified-repeat DDG-1000 is considered. Concept exploration generates a baseline concept design and is the focus of the first semester of the ship design course at Virginia Tech. The second semester is spent maturing the baseline design in concept development. Figure 1 shows the design process.

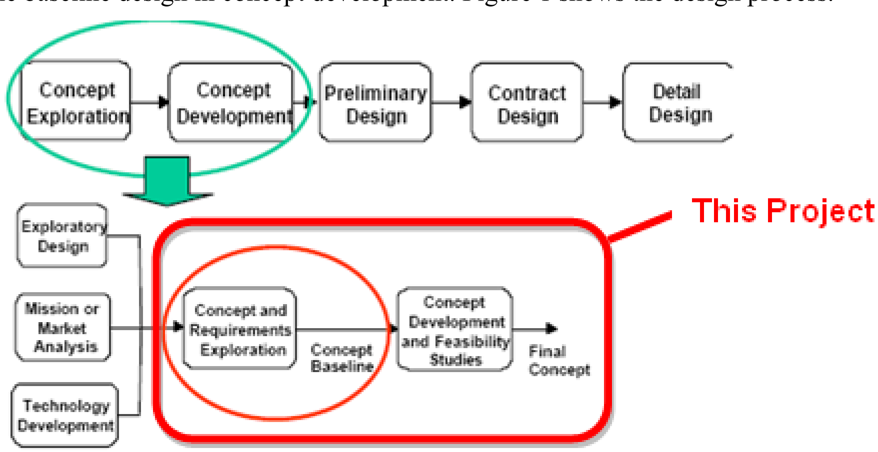


Figure 1 – Design Process

Concept and requirements exploration and concept development are the main focus of this project. Figure 2 shows the concept exploration process that is used. The process involves constructing a design space of design variables and then searching that design space for the "best designs" in terms of cost, effectiveness and risk. The results are the selection of a baseline design, a Capability Development Document (CDD), and a selection of technology.

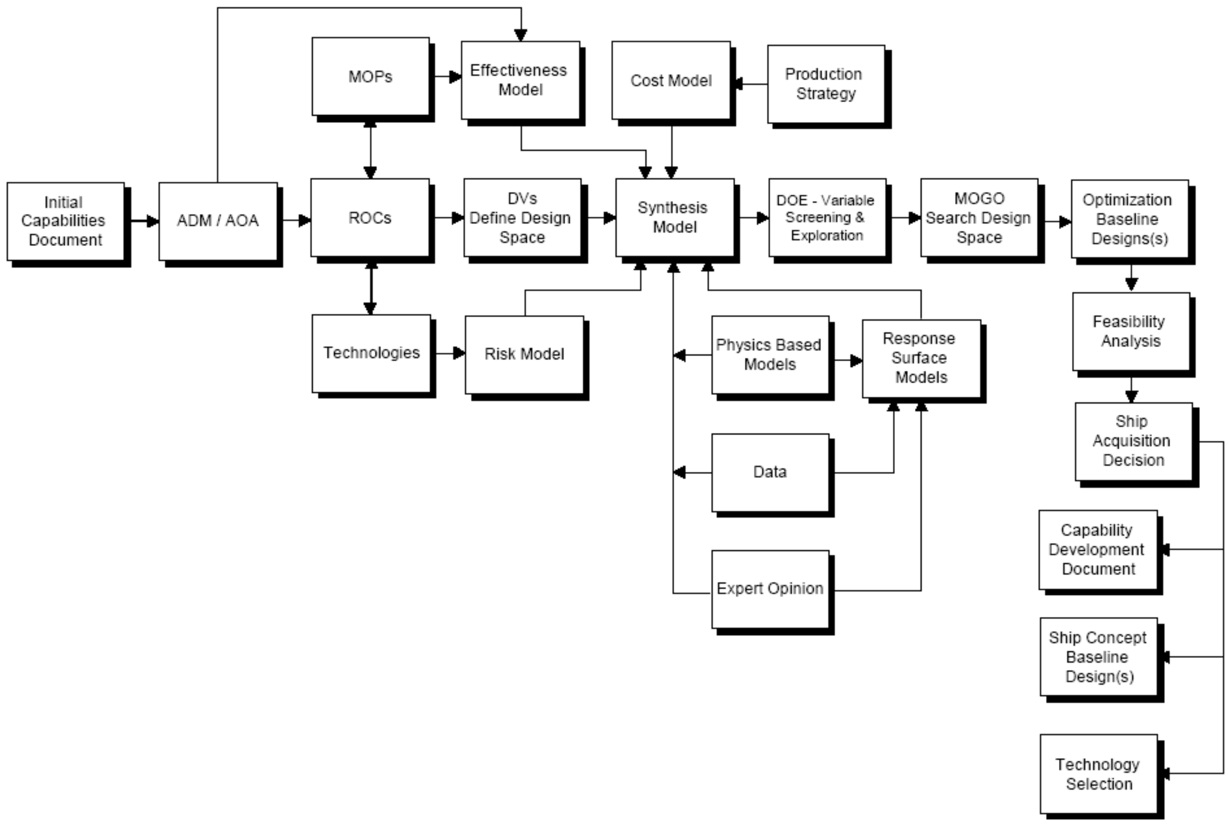


Figure 2 – Concept Exploration

Figure 2 shows the process that begins by identifying a need that must be fulfilled, specified in an Initial Capabilities Document (ICD). Based on the ICD, an Acquisition Decision Memorandum (ADM) directs that concept exploration should be performed, and specifies the general requirements that need to be met by a design. Models, incorporating many components, are then constructed to balance and assess design options in the design space. These include a ship synthesis model, a risk model based on the ICD and ADM, and a cost model that considers possible production strategies. Past data and expert opinion are also used to develop the models. Physics-based models are used when parametric models are inadequate. There are uncertainties associated with a fully modeled design space. These uncertainties are identified and quantified as much as possible.

The fully-modeled design space is then searched using a genetic algorithm to find designs with the best possible effectiveness for a given cost and risk. The result of optimization is a non-dominated frontier, which is then used to pick one to three baseline designs. Based on these baseline designs, a CDD is created and development of technology for the design is begun, at which point concept development begins.

Figure 3 shows the more traditional feasibility study design spiral process that is used in concept development for this project. The feasibility study investigates each step in the spiral at a level of detail necessary to demonstrate that assumptions and results obtained are both balanced and feasible. During this process, a second layer of detail is added to the design and risk is reduced.

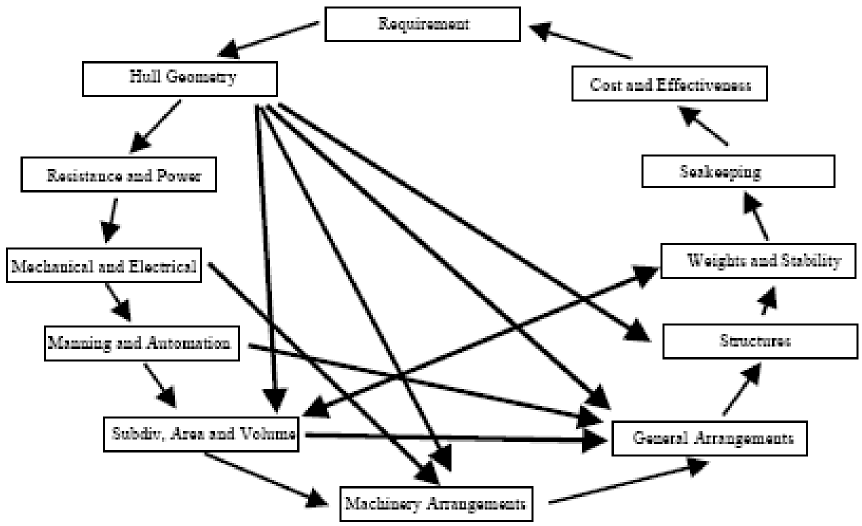


Figure 3 – Concept Development Design Spiral

1.3 Work Breakdown

CGX/BMD Team 2 consists of six students from Virginia Tech. Table 1 lists areas of work assigned to each team member according to his or her interests and special skills. A team leader is assigned to assure the team efficiently coordinates its efforts and maximizes the overall understanding to create an integrated ship design. Each team member is responsible for an area of specialization based on a great level of understanding of that particular area. However, specializations do overlap to guarantee integration.

Table 1 - Work Breakdown

Name	Specialization
Joe Schaffer (Team Leader)	Hullform, Propulsion, Rhino, ASSET
Carrie Gonsoulin	General Arrangements, Combat Systems
Brian Scott	Producibility, Machinery Arrangements and Electrical Loads, Manning, ASSET
Dave Donnelly	Structures, Manuevering and Seakeeping
Andrew Bloxom	Hullform, Tankage and Subdivision, Weights, Stability and Trim, Manuevering and Seakeeping
Kevin Loyer	Resistance and Propulsion, Cost and Risk

1.4 Resources

Table 2 lists computational and modeling tools used in this project. When using computer software, a great deal of time is spent learning the theory behind the inputs and outputs of each program to better understand the results. Approximate order of magnitude calculations were also performed by hand to validate computer-aided results.

Table 2 - Tools

Analysis	Software Package
Arrangement Drawings	Rhino
Hullform Development	Rhino, ASSET
Hydrostatics	Rhino, HECSALV
Resistance/Power	MathCAD
Ship Motions	SMP
Ship Synthesis Model	MathCad, Model Center, ASSET
Structure Model	MAESTRO

2 Mission Definition

The CGX/BMD requirement is based on the CGX/BMD Initial Capabilities Document (ICD), and Virginia Tech CGX/BMD 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 CGX concept of operations is based on the Initial Capabilities Document and the Acquisition Decision Memorandum for a Ballistic Missile Defense Cruiser that will have the ability to conduct BMD operations from advantageous locations at sea. It must have the ability to operate in forward locations in international waters and readily move to new maritime locations as needed. It must be able to operate over the horizon from observers ashore, and evade detection and targeting by enemy forces. It also must be able to move to locations that lie along a ballistic missile's potential flight path to facilitate tracking and intercepting the attacking missile, or move to locations to permit the CGX/BMD radar to view a ballistic missile from a different angle to allow the CGX systems to track the attacking missile more effectively.

CGX/BMD must be capable of defending a large down-range territory against potential attack by ballistic missiles. It will use very fast interceptors to intercept ballistic missiles fired from launchers during the boost phase and mid-flight. CGX/BMD must be equipped with high-altitude long-range search and track radar capable of detecting and establishing precise tracking information on ballistic missiles, discriminating missile warheads from decoys and debris, providing data for updating ground-based interceptors in flight, and assessing the results of intercept attempts.

CGX/BMD radar will be a large, powerful, phased-array radar operating in the X and S band frequencies. The X-band frequency is necessary for tracking missile warheads with high accuracy. To intercept the ballistic missile warheads in boost, early ascent, and mid-course of the flight, SM-3's and Kinetic Energy Interceptor's (KEIs) will be considered for the CGX/BMD weapons payload.

Additionally, the CGX/BMD will perform Carrier Battle Group (CBG) and Expeditionary Readiness Group (ERG) escort, providing area Anti-Air Warfare (AAW) defense and limited Anti-Submarine Warfare (ASW) and Anti-Surface Warfare (ASUW) defense in support of these units. The CGX/BMD will also perform Tomahawk Land Attack Missile (TLAM) strikes in conjunction with the CBG, ERG, Surface Action Group (SAG) or operating independently.

2.2 Projected Operational Environment (POE) and Threat

The current threat to the United States involves the acquisition and intent to use missiles capable of medium to long range flight against the U.S. and its allies by powers who wish to inflict large damage with nuclear, biological, or chemical attacks. The advances in technology since the Cold War have made the acquisition of such missiles within the hands of hostile states or terrorist actors who do not require the same quality or quantity of U.S. missile arsenals. Lower quality missiles capable of devastating strikes could be bought, reverse-engineered, or stolen by these hostiles, within a time scale that leaves the U.S. with little to no warning of an impending attack. For this reason, a BMD ship with the ability to detect and track Intercontinental Ballistic Missiles (ICBM) and Intermediate Range Ballistic Missiles (IRBM) from the boost phase of flight is important.

To successfully detect and track such a launch from the early stages requires the strategic positioning of the CGX/BMD. The ability to stealthily enter foreign waters without permission to achieve the best vantage point from which to conduct surveillance and reconnaissance operations is critical. The best vantage point for this lies in geographically constrained (littoral) bodies of water. Due to this, the tactical defense strategy will be at a smaller scale than that of open ocean warfare. A wider array of threats will evolve including: (1) highly advanced weapons – cruise missiles, fast surface gunboats, diesel submarines, and land launched attack aircraft; and (2) less sophisticated weapons including mines, chemical and biological weapons, shore gunfire, and improvised explosives like that seen in the attack on the USS Cole.

The littoral environment will be densely crowded with contacts, commercial, personal, and hostile. The radar picture will be severely affected resulting and complicated targeting of close in surface threats and reduced effectiveness in the critical BMD mission. The CGX/BMD will perform in all weather, shallow and deep water, and maintain survivability through sea state 9.

2.3 Specific Operations and Missions

The CGX will perform tasks consistent with the BMD mission, working to prevent strikes against the U.S. and its allies. At other times, it will serve as CBG escort, providing vital AAW support with its large radar capabilities and weapons outfit.

2.4 Mission Scenarios

Table 3 shows a mission scenario for the primary CGX/BMD mission. This mission scenario was developed to showcase the entire range of capabilities of the ship during a highly active 77 day period. It reflects the diversity of detection and strike abilities possessed by the combat systems.

Table 3 - CGX Ballistic Missile Defense Mission

Day	Mission Scenario
1-3	Transit with Frigates/escorts (for ASW support) to area of hostility from forward base
4	Detect, engage and kill incoming anti-ship missile attack
5-10	Patrol grid for launch of ballistic missile (BM)
11	Receive tasking for TLAM strike
12	Cruise to 25 nm offshore
13	Embark Special Forces by helo
14	Insert Special Forces by RIB
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
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
74	AAV detects terrorist activity
74	Intelligence indicates high-value target with terrorist cell; conduct TLAM strike and kill target
75-77	Cruise back to forward base
77	Arrive at forward base

2.5 Required Operational Capabilities

Table 4 lists the Required Operational Capabilities (ROCs) needed to support the missions and mission scenarios described in Sections 2.3 and 2.4. Each ROC is related to functional capabilities required of the ship design. In 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 4 - List of Required Operational Capabilities (ROCs)

ROCs	Description	MOP
AAW 1	Provide anti-air defense	AAW
AAW 1.1	Provide area anti-air defense	AAW
AAW 1.2	Support area anti-air defense	AAW
AAW 1.3	Provide unit anti-air self defense	AAW, RCS, IR
AAW 2	Provide anti-air defense in cooperation with other forces	AAW
AAW 3.1	Initial Phase Ballistic Missile Defense (I-BMD)	AAW
AAW 3.2	Mid-Course Phase Ballistic Missile Defense (MC-BMD)	AAW
AAW 5	Provide passive and soft kill anti-air defense	AAW, IR, RCS
AAW 6	Detect, identify and track air targets	AAW, IR, RCS
AAW 9	Engage airborne threats using surface-to-air armament	AAW, IR, RCS
AMW 6	Conduct day and night helicopter, Short/Vertical Take-off and Landing and airborne autonomous vehicle (AAV) operations	ASW, ASUW, FSO (NCO)
AMW 6.3	Conduct all-weather helo ops	ASW, ASUW, FSO (NCO)
AMW 6.4	Serve as a helo hangar	ASW, ASUW, FSO (NCO)
AMW 6.5	Serve as a helo haven	ASW, ASUW, FSO (NCO)
AMW 6.6	Conduct helo air refueling	ASW, ASUW, FSO (NCO)
AMW 12	Provide air control and coordination of air operations	ASW, ASUW, FSO (NCO)
AMW 14	Support/conduct Naval Surface Fire Support (NSFS) against designated targets in support of an amphibious operation	NSFS
ASU 1	Engage surface threats with anti-surface armaments	ASUW
ASUW 1.1	Engage surface ships at long range	ASUW
ASUW 1.2	Engage surface ships at medium range	ASUW
ASUW 1.3	Engage surface ships at close range (gun)	ASUW
ASUW 1.5	Engage surface ships with medium caliber gunfire	ASUW
ASUW 1.6	Engage surface ships with minor caliber gunfire	ASUW
ASUW 1.9	Engage surface ships with small arms gunfire	ASUW
ASUW 2	Engage surface ships in cooperation with other forces	ASUW, FSO
ASUW 4	Detect and track a surface target	ASUW
ASUW 4.1	Detect and track a surface target with radar	ASUW
ASUW 6	Disengage, evade and avoid surface attack	ASUW
ASW 1	Engage submarines	ASW
ASW 1.1	Engage submarines at long range	ASW
ASW 1.2	Engage submarines at medium range	ASW
ASW 1.3	Engage submarines at close range	ASW
ASW 4	Conduct airborne ASW/recon	ASW
ASW 5	Support airborne ASW/recon	ASW
ASW 7	Attack submarines with antisubmarine armament	ASW
ASW 7.6	Engage submarines with torpedoes	ASW
ASW 8	Disengage, evade, avoid and deceive submarines	ASW
CCC 1	Provide command and control facilities	CCC
CCC 1.6	Provide a Helicopter Direction Center (HDC)	CCC, ASW, ASUW
CCC 2	Coordinate and control the operations of the task organization or functional force to carry out assigned missions	CCC, FSO
CCC 3	Provide own unit Command and Control	CCC

ROCs	Description	MOP
CCC 4	Maintain data link capability	ASW, ASUW, AAW
CCC 6	Provide communications for own unit	CCC
CCC 9	Relay communications	CCC
CCC 21	Perform cooperative engagement	CCC, FSO
FSO 5	Conduct towing/search/salvage rescue operations	FSO
FSO 6	Conduct SAR operations	FSO
FSO 8	Conduct port control functions	FSO
FSO 9	Provide routine health care	All designs
FSO 10	Provide first aid assistance	All designs
FSO 11	Provide triage of casualties/patients	All designs
INT 1	Support/conduct intelligence collection	INT
INT 2	Provide intelligence	INT
INT 3	Conduct surveillance and reconnaissance	INT
INT 8	Process surveillance and reconnaissance information	INT, CCC
INT 9	Disseminate surveillance and reconnaissance information	INT, CCC
INT 15	Provide intelligence support for non-combatant evacuation operation (NEO)	INT, CCC
MIW 6	Conduct magnetic silencing (degaussing, deperming)	Magnetic Signature
MOB 1	Steam to design capacity in most fuel efficient manner	Sustained Speed, Endurance Range @20 knt, Surge to Theater
MOB 2	Support/provide aircraft for all-weather operations	ASW, ASUW, FSO (NCO)
MOB 3	Prevent and control damage	VUL
MOB 3.2	Counter and control NBC contaminants and agents	NBC
MOB 5	Maneuver in formation	All designs
MOB 7	Perform seamanship, airmanship and navigation tasks (navigate, anchor, mooring, scuttle, life boat/raft capacity, tow/be-towed)	All designs
MOB 10	Replenish at sea	All designs
MOB 12	Maintain health and well being of crew	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	provisions
MOB 16	Operate in day and night environments	All designs
MOB 17	Operate in heavy weather	Seakeeping index
MOB 18	Operate in full compliance of existing US and international pollution control laws and regulations	All designs
NCO 3	Provide upkeep and maintenance of own unit	All designs
NCO 19	Conduct maritime law enforcement operations	NCO
SEW 2	Conduct sensor and ECM operations	AAW
SEW 3	Conduct sensor and ECCM operations	AAW
SEW 5	Conduct coordinated SEW operations with other units	AAW
STW 3	Support/conduct multiple cruise missile strikes	All designs

3 Concept Exploration

Chapter 3 describes the Concept Exploration process. 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 technology selection process is a meticulous procedure. The first step is considering the Transport Factor which uses methodology to identify alternative hullform types. Important parameters are payload (or cargo weight), required sustained speed, endurance speed and range. Figure 4 shows the calculation.

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

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

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

Figure 4 - Transport Factor Calculation

The estimated Transport Factor for CGX/BMD is based on mission capabilities and similar ships. Large and heavy combat systems (radar, cooling, missiles, AAV and a hangar), which are not included in a DDG51 or CG47, need to be considered in the transport factor calculation. Major combatant, worldwide operations require endurance range from 5000 to 8000 nm at 20 knots. The estimated transport factor is 21.5 for CGX/BMD. This suggests a monohull design.

The second step in the hullform process is to estimate and consider important characteristics to select hullform types. These include the transport factor, efficient endurance and sustained speed resistance. There also needs to be sufficient deck area for a helicopter deck, and sufficient large object space for the vertical launch system (VLS) and integrated power system (IPS). Low radar cross section (RCS) is required to keep the ship stealthy and unobserved. An approach to accomplish low RCS is tumblehome. Producibility, structural efficiency, and seakeeping are also important criteria.

The third step is to use the design lanes to specify hullform design parameter ranges for the design space. The hullform types considered are tumblehome monohull and the flare monohull (flare = ±10°)

- Δ = 14000-26000 MT
- L = 180 m - 230 m
- B = 18 m - 33 m
- D = 10m - 22 m
- T = 5 m - 12 m
- L/B = 7 – 10

- $L/D = 10.75 – 17.8$
- $B/T = 2.8 – 3.2$
- $V_{DH} = 10,000 – 20,000\ m^3$
- $C_p = 0.56 - 0.64$
- $C_x = 0.75 - 0.85$
- $C_{rd} = 0.7 - .8$

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 –

CGX/BMD will use an Integrated Power System (IPS) with Zonal Electrical Distribution (ZEDS). System flexibility and Fight-Through Power with future growth requires IPS. IPS module types are:

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

CGX/BMD speed and power requires high power density alternatives. For each IPS module, several advanced technologies are considered. The power requirement shall be satisfied with 2-4 Power Generation Modules (PGMs) of 25-40 MW, and 1-2 Secondary PGMs (SPGMs) of 5-10 MW. The power generation modules shall be Navy qualified gas turbines coupled to AC synchronous or superconducting homopolar (SCH) generators. The propulsion motor modules shall be advanced induction motors (AIM), SCH motors, or permanent magnet motors (PMM). AC and DC ZEDS are both considered. IPS with ZEDS provides arrangement and operational flexibility, future power growth, improved fuel efficiency, and survivability with moderate weight and volume penalties. The ship must be designed for continuous operation using distillate fuel in accordance with DFM (NATO Code F-76).

Sustained Speed and Propulsion Power – The ship shall have a minimum sustained speed of 30 knots in the full load condition, calm water, and clean hull using no more than 80% of the installed engine rating (MCR) of main propulsion engines or motors. The goal sustained speed is 35 knots to allow travel with a CBG. The ship shall have a minimum range of 5000 nautical miles using a 20 knot endurance speed. The ship's power range must span 80000-120000 SHP with ship service power greater than 10000 kW MFLM.

Ship Control and Machinery Plant Automation – Ship control and machinery plant automation makes use of an integrated bridge system. The integrated bridge system includes integrated navigation, radio communications, interior communications, and ship maneuvering equipment and systems. It shall comply with the ABS Guide for One Man Bridge Operated (OMBO) Ships and with ABS ACCU requirements for periodically unattended machinery spaces.

Sufficient manning and automation will be provided to continuously monitor auxiliary systems, electric plant and damage control systems from the SCC, MCC and Chief Engineer's office, and control the systems from the MCC and local controllers.

Propulsion Engine and Ship Service Generator Certification – Because of the criticality of propulsion and ship service power to many aspects of the ship's mission and survivability, this equipment shall be non-nuclear and gas turbine alternatives shall be Navy-qualified and grade A shock certified.

3.1.2.2 Machinery Plant Alternatives

CGX/BMD will use an Integrated Power System (IPS). IPS uses power generation modules which provide electrical power to all components of the ship, including propulsion and combat systems. The options for power and propulsion for the CGX/BMD are based on five design variables: Power Generation Module (PGM), Secondary PGM (SPGM), propulsor type, power distribution type, and propulsion motor module type. Table 5 shows power and propulsion options, which total 2880 options. Each design variable is detailed in this section.

Table 5 – Power and Propulsion Options Table

DV Name	Description	Design Space
PGM	Power Generation Module	Option 1) 3xLM2500+, AC synchronous, 4160 VAC Option 2) 3xLM2500+, AC synchronous, 13800 VAC Option 3) 3xLM2500+, SCH generator, 4160 VAC Option 4) 3xLM2500+, SCH generator, 13800 VAC Option 5) 4xLM2500+, AC synchronous, 4160 VAC Option 6) 4xLM2500+, AC synchronous, 13800 VAC Option 7) 4xLM2500+, SCH generator, 4160 VAC Option 8) 4xLM2500+, SCH generator, 13800 VAC Option 9) 2xMT30, AC synchronous, 4160 VAC *(DDG 1000) Option 10) 2xMT30, AC synchronous, 13800 VAC Option 11) 2xMT30, SCH generator, 4160 VAC Option 12) 2xMT30, SCH generator, 13800 VAC Option 13) 3xMT30, AC synchronous, 4160 VAC Option 14) 3xMT30, AC synchronous, 13800 VAC Option 15) 3xMT30, SCH generator, 4160 VAC Option 16) 3xMT30, SCH generator, 13800 VAC Option 17) 4xMT30, AC synchronous, 4160 VAC Option 18) 4xMT30, AC synchronous, 13800 VAC Option 19) 4xMT30, SCH generator, 4160 VAC Option 20) 4xMT30, SCH generator, 13800 VAC
SPGM	Secondary Power Generation Module	Option 1) none Option 2) 2xLM500G, geared, w/AC sync *(DDG 1000) Option 3) 2xMC5.0 Fuel Cells Option 4) 2xMC8.5 Fuel Cells Option 5) 2xPEM5.0 Fuel Cells Option 6) 2xPEM8.5 Fuel Cells Option 7) 2xCAT 3618 Diesel Option 8) 2xPC 2/18 Diesel
PROPtype	Propulsor type	Option 1) 2xFPP *(DDG 1000) Option 2) 2xPods Option 3) 1xFPP + SPU (7.5MW)
DISTtype	Power distribution type	Option 1) AC ZEDS Option 2) DC ZEDS *(DDG 1000)
PMM	Propulsion Motor Module	Option 1) AIM (Advanced Induction Motor) *(DDG 1000) Option 2) PMM (Permanent Magnet Motor) Option 3) SCH (Superconducting Homopolar Motor)

The PGM options are a combination of 2-4 Navy qualified gas turbines, and two types of generators with two voltage ratings totaling 20 options. The function of the PGM is to convert fuel into electrical power.

The SPGM will use gas turbine, diesel engine, or fuel cell technologies. Gas turbines and diesel engines are familiar to the US Navy, but fuel cells provide many advantages, including high efficiency (35-60%), and no large dedicated intakes-uptakes. The challenges presented by fuel cells include reforming fuel into hydrogen with an onboard chemical plant, eliminating sulfur from fuels, a slow dynamic response, and slow startup. They are sized to provide fuel efficiency at endurance speed.

The propulsors are either two fixed-pitch propellers (FPP), which are standard on US Navy combatants, two podded propulsors, which offer more maneuverability and flexibility, or a combination of one stern FPP and one forward secondary propulsor unit (SPU), which offers maneuverability and increased survivability. The podded and secondary propulsors are promising options, but are higher risk because they are not yet proven.

The power distribution system will be either AC or DC ZEDS. ZEDS offers zonal survivability, which is the ability of a distributed system, when experiencing internal faults, to ensure loads in unmanned zones do not experience a service interruption. It limits the damage propagation to the fewest number of zones, enabling concentration of damage control and recoverability efforts.

The power distribution system is made up of Power Conversion Modules (PCMs), a Power Distribution Module (PDM), and a Power Control Module (PCON). Figure 5 shows how the PCMs are arranged in a ZEDS system. The PDM includes switchboards, load centers, power panels, and cable. It functions as a transport between other modules, provides ability to configure the distribution system (including the paralleling of busses), detect and isolate faults, and provides measurements of system voltages, currents, frequency, and power, etc. to PCON. PCON is software and logic embedded in the machinery control system. Its functions are resource and load management, reconfiguration, system protection, remote monitoring, and control and diagnostics.

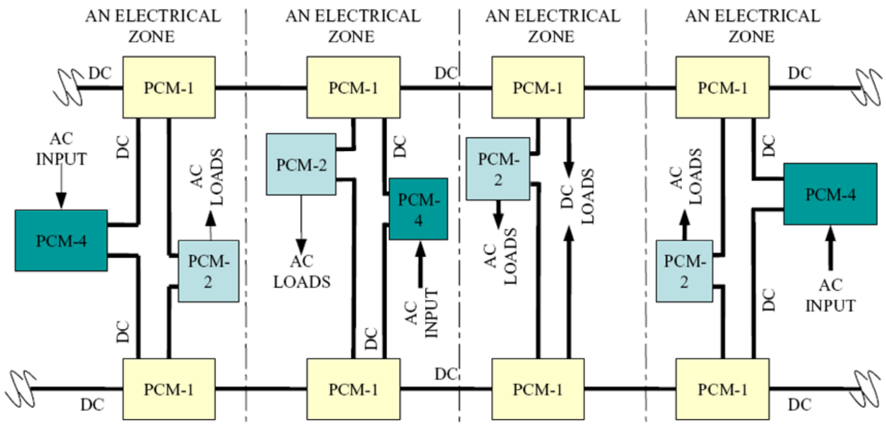


Figure 5– DC ZEDS (Doerry, 2005)

The Propulsion Motor Modules considered are advanced induction motors (AIM), SCH motors, or permanent magnet motors (PMM). AIMs are a proven technology, and modern drives enable higher efficiencies, but are large and heavy, and still not as efficient as other motor types. Superconducting motors can achieve significantly higher magnetic flux densities, and promise to significantly reduce the size and weight of propulsion motors. The Navy is currently investing in superconducting motor technology. SCH motors, specifically, are true DC motors, and have low noise, low torque pulsations, low weight, small size, use low voltage and high current, use high-current brushes, but they are still developmental. Permanent magnet motors are low weight, quieter, and have better part load efficiency, but are still developmental and costly.

3.1.3 Automation and Manning Parameters

Manning is required to perform specific tasks. The cost of manning, however, is sixty percent of the Navy's budget! The cost of the ship's crew is the largest expense incurred over the ship's lifetime. There are several issues and observations associated with manning. Manning puts personnel in harm's way. Firefighting and damage control are managed by manpower with a very high risk to the personnel. Computer literacy, reduced response time and job enrichment are human factors that can be responsible for the life of a fellow sailor. Another issue is the background of each sailor on a ship. Different backgrounds come with different cultures and traditions that must be addressed on the ship. There is also the "manning triad": watch standing, maintenance and damage control. The triad has a high need for manpower. Automation has to be taken into consideration where manning can be decreased. When applied to ships early in their development and throughout their design, human systems (analysis) have the potential to substantially reduce requirements for personnel, leading to significant cost savings.

Automation is the use of computers or machinery to get a task done with fewer personnel. Firefighting may be replaced by automated sprinkler systems designed to go off when excessive heat or smoke is sensed. This helps reduce the manpower needed to fight fires on board a ship, which in turn can reduce the number of people injured during a critical mission. Response time can be reduced with an automated system. Maintenance can be made easier for personnel by implementing a system that can "check" the functionality or maintenance schedules of all parts.

There are many technologies that can help with automation and computers and software are some of the most important. With an automated watch station, a computer can monitor and control ship automation. Watch-standing technology has been improved with GPS, automated route planning, electronic charting and navigation, collision avoidance and electronic log keeping. Video teleconferencing provides a way to access experts without bringing extra personnel on board. Computers can also make training much easier. Hands-on-experience isn't necessary for training on board a ship. Crews can learn the computer systems on shore with programs that can be replayed. These technologies call for a paperless ship, in which administration personnel can stay on shore and receive what they need to do their jobs electronically.

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. A manning factor of 1.0 corresponds to a "standard" fully-manned ship of today, using current ship automation technologies already implemented in the Navy. 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. A more detailed manning analysis is performed in concept development.

A Manning Response Surface Model (RSM) calculates the manning requirement for the ship. ISMAT (Integrated Simulation Manning Analysis Tool) was used to create a scenario of personnel assigned to maintenance tasks based on systems and their department. The same scenario is used for all designs. ISMAT calculates optimum manning based on crew cost. The RSM is used in the overall ship synthesis program instead of ISMAT to reduce computation time. The level of automation also effects cost and risk for the design. The total crew size is calculated as shown in the equation below:

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

where: *NT* = total crew size, *LevAuto* = level of automation, *MAINT* = maintenance level, *LWLComp* = length of the waterline, *PSYS* = propulsion system, *ASUW* = anti-surface warfare, and *CCC* = command, control and communication.

3.1.4 Combat System Alternatives

Combat System Alternatives are grouped as Anti-Air Warfare (AAW), Ballistic Missile Defense (BMD), Strike Warfare (STK), Anti-Surface Warfare (ASUW), Anti-Submarine Warfare (ASW), Naval Surface Fire Support (NSFS), Mine Countermeasures (MCM), Command, Control and Communications (CCC), Guided Missile Launching Support (GMLS), and Light Airborne Multi-Purpose System (LAMPS).

3.1.4.1 AAW/BMD/STK

The AAW/BMD goal and threshold options are listed in Table 6, and discussed in the following paragraphs.

Table 6 – AAW/BMD Combat Systems Options Table

Warfighting System	Options
AAW/BMD/STK	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

AN/SPY-3 is a multi-function radar (MFR) that provides X-band capability allowing ships to operate and target enemies in a high clutter environment. AN/SPY-3 meets all horizon search and fire control requirements for the twenty-first century fleet, and supports all BMD missions. It detects the most advanced low observable Anti-Ship Cruise Missile (ASCM) threats, and provides fire-control illumination requirements for the Evolved Sea Sparrow Missile (ESSM). AN/SPY-3 supports new ship design requirements for reduced cross-section, limiting different ship signatures to avoid detection. It has a long range 2-D search and limited volume search.

Dual Band Radar (DBR) consists of AN/SPY 3 and the Volume Search Radar (VSR). VSR is an S-Band frequency, 3-D tracking, and long range volume search radar. It can be used for enhanced BMD. DBR is a horizon and volume search radar, which can detect stealthy targets in sea-land clutter. It also includes periscope detection, allowing the ship to have anti-submarine warfare capabilities. The DBR combines the functionality of the X-Band AN/SPY-3 MFR with an S-Band VSR. It provides low maintenance with no dedicated operator or display console, and supports stealth operations with low radar cross section (RCS) and infrared (IR) signature. BMD capabilities in DBR include the ability to do combat control, including air control, missile tracking, periscope detection, and target illumination, as well as functional details such as environmental mapping and uplink/downlink. See Figure 6 for a visual description. DBR meets next-generation naval radar challenges by performing multiple functions automatically and simultaneously, including detecting and tracking advanced high and low altitude anti-ship cruise missiles.

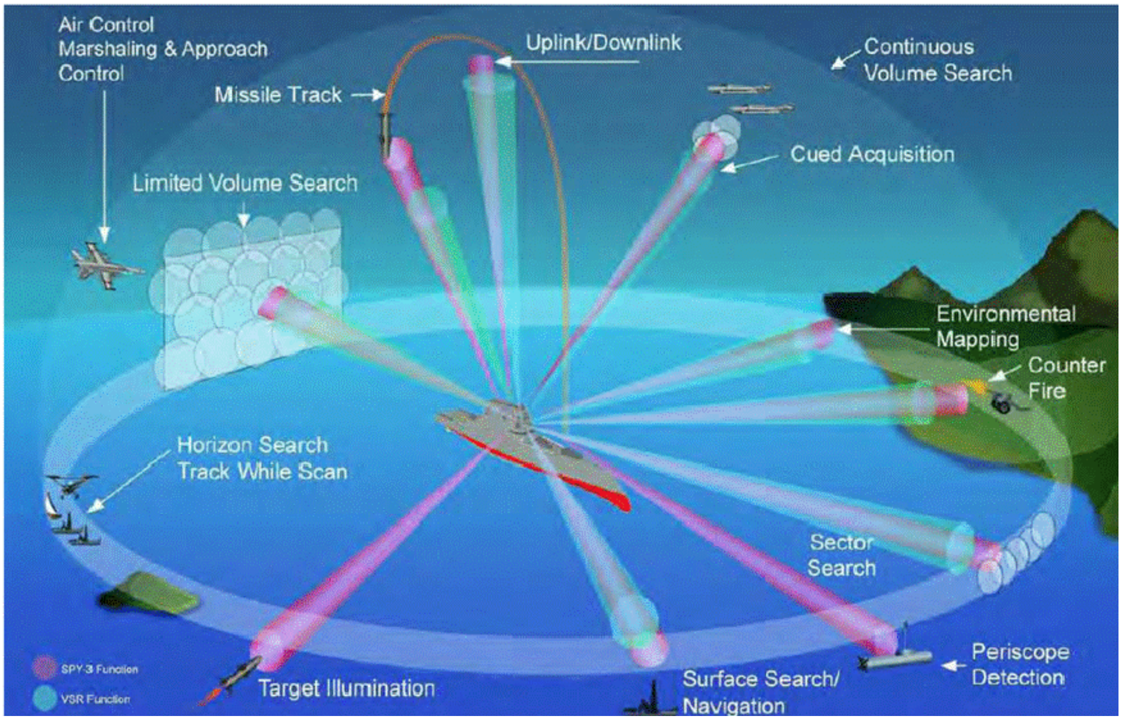


Figure 6 - Dual Band Radar (DBR) capabilities (Raytheon, 2007)

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

AN/UPS-26(V) CIFF-SD is the Centralized ID Friend or Foe (CIFF) system. It is a centralized, controller processor-based system that associates different sources of target information. It accepts, processes, correlates and combines sensor inputs into one large track picture.

The AN/SLQ-32(R) Improved is a Space and Electronic Warfare component that provides early warning of threats. It automatically dispenses chaff decoys, which is part of the MK36 SRBOC and NULKA systems, which are shown in Figure 7. Super Rapid Bloom Offboard Countermeasures (SRBOC) is a decoy launching system. NULKA is specifically a rapid response Active Expendable Decoy (AED), which is capable of providing highly effective defense for ships of cruiser size and below against modern radar homing anti-ship missiles.

Figure 7 - MK 36 SRBOC and NULKA systems

3.1.4.2 ASUW/NSFS

Anti-Surface Warfare and Naval Surface Fire Support combat systems operate to detect and protect from other surface combatants and provide sea and land gunfire support. Combat systems options for ASUW and NSFS are listed in Table 7.

Table 7 – ASUW/NSFS Combat Systems Options Table

Warfighting System	Options
ASUW/NSFS	Option 1) 1x155mm AGS, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod2 3x CIGS Option 2) 1xMK45 5"/62 gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod2 3x CIGS Option 3) 1xMK110 57mm gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod2 3x CIGS

Figure 8 shows the 155 mm Advanced Gun Systems (AGS). It is a high-volume gun, which sustain fires in support of amphibious operations and the joint land battle. AGS fires up to 12 rounds per minute from an automated magazine, storing up to as many as 750 rounds. The round is 6.1 inches in diameter, and includes the development of the 155 mm version of the Extended-Range Guided Munitions (ERGM). AGS is a conventional, single barrel, low-signature gun system with fast-reaction, fully stabilized train and elevation capabilities. The AGS is planned for DDG 1000.

Figure 8 – 155 mm Advance Gun System (AGS)

The MK 45 5"/62 gun and gun mount has a range of over 60 nautical miles with the ERGM rounds. The gun mount is a basic MK 45 gun mount with a 62-caliber barrel, strengthened trunnion supports and a lengthened recoil stroke. It also has an ERGM initialization interface, round identification capability and an enhanced control system. Figure 9 shows the new gun mount shield which reduces overall radar signature, maintenance and production cost.

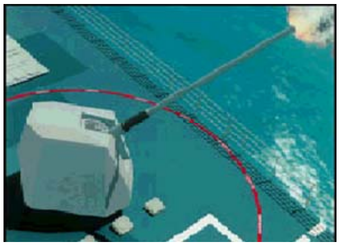


Figure 9 – MK45 5"/62 Gun

The 1xMK110 57 mm gun (Figure 10) is capable of firing 2.4 kilogram shells at a rate of 220 rounds per minute. Its range is of nine miles. The MK110 57 mm gun is a multi-purpose, medium caliber gun.

Figure 10 – MK110 57 mm Naval Gun

The Thermal Imaging Sensor System (TISS) is a stabilized imaging system which provides a visual infrared and television image to assist operators in identifying a target by its contrast or infrared characteristics. It detects, recognizes, laser ranges and automatically tracks targets under day, night or reduced visibility conditions, complementing and augmenting existing shipboard sensors. TISS is a manually operated system which can receive designations from the command system and provide azimuth, elevation, and range for low cross section air targets, floating mines, fast attack boats, navigation operations, and search and rescue missions. See Figure 11.

Figure 11 – TISS (Thermal Imaging Sensor System)

Figure 12 shows a Forward Looking Infrared Radar Sensor (FLIR). FLIR uses detection of thermal energy to create a picture of the forward surroundings. It can be used at night, in heavy fog and all different types of weather. FLIR is a good investment in military operations for several reasons. It distinguishes heat from a distance of a few miles, which is hard for an enemy to camouflage. It can see through many atmospheric changes (fog, haze, smoke etc.) which is a major benefit for safety reasons and military options.

Figure 12 – Forward Looking Infrared Radar (FLIR)

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

Mk46 Mod2 3x CIGS (Close-In Gun System) is a two-axis stabilized chain gun that can fire up to 250 rounds per minute. This system uses FLIR to optimize accuracy against small, high-speed surface targets. It can be operated locally at the gun's turret or fired remotely by a gunner in the ship's combat station.

RHIBs, or Rigid Hull Inflatable Boats are 7 m long, weigh 4400 lbs, and have a beam of 9 ft, 6 in. and draft of 13 inches. With a Cummins 6-cycle, 234 horsepower engine, it can carry up to 18 personnel. See Figure 13 for a picture of a RHIB.

Figure 13 – Rigid Hull Inflatable Boat (RHIB)

The stern launch/recovery ramp is a major CGX design consideration. Figure 14 shows how it will be able to accommodate two standard 7 m RHIBs. Only one person is needed to operate machinery rather than as many as nine for a frapping line/hydraulic side recovery. The stern launch/recovery ramp will be enclosed to reduce the radar cross section for the CGX.

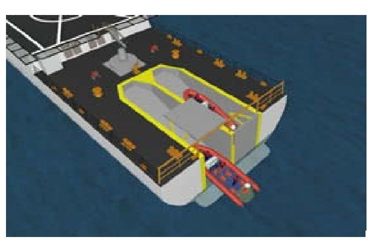


Figure 14 – Stern Launch/Recovery Design

3.1.4.3 ASW/MCM

Anti-Submarine Warfare and Mine Counter-Measures protect the CGX from possible underwater damage. The purpose is to detect submarines and mines and be able to defend against attacks. The options are listed in Table 8.

Table 8 – ASW/MCM Combat Systems Options Table

Warfighting System	Options
ASW/MCM	Option 1) Dual Frequency Bow Array, NIXIE, IUSW, 2xSVTT, mine-avoidance sonar Option 2) SQS-53C, NIXIE, SQR-19 TACTAS, IUSW, 2xSVTT, mine-avoidance sonar Option 3) SQS-56, NIXIE, IUSW, 2xSVTT, mine-avoidance sonar Option 4) NIXIE, 2xSVTT, mine-avoidance sonar

The Dual Frequency Bow Array is part of the Integrated Underwater Surface Warfare made from Raytheon. More information can be found in the IUSW section.

SQS-53C is a bow-mounted sonar with both active and passive operating capabilities providing precise information for ASW weapons control and guidance. It is a computer-controlled surface-ship sonar, and performs direct path ASW search, detection, localization and tracking from hull mounted transducer array. It has higher power and improved signal processing equipment with direct linkage to the computer ensuring swift, accurate processing of target information. Functions of the system are the detection, tracking and classification of underwater targets. It can also be used for underwater communications, countermeasures against acoustic underwater weapons and certain oceanographic recording uses. Figure 15 shows a depiction of this bow sonar.

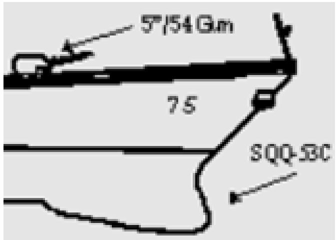


Figure 15 – SQS-53C Bow-Mounted Sonar Array

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

IUSW is the Integrated Undersea Warfare system. IUSW incorporates two types of sonar arrays in one automated system. The high frequency sonar provides in-stride mine avoidance capabilities, while the medium frequency sonar optimizes anti-submarine and torpedo defense operations. The suite integrates all acoustic undersea warfare systems and subsystems, including the dual frequency bow array, towed array, towed torpedo countermeasures, expendable bathythermograph, data sensor, acoustic decoy launcher, underwater communications, and associated software.

Figure 16 shows NIXIE, a tow-behind decoy that employs an underwater acoustic projector. It provides deceptive countermeasures against acoustic homing torpedoes and can be used in pairs or singles.

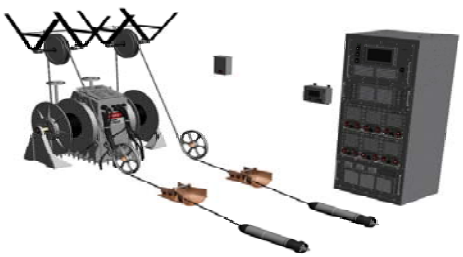


Figure 16 – NIXIE

Figure 17 shows the MK32 Surface Vessel Torpedo Tube (SVTT). It is an ASW launching system that pneumatically launches torpedoes over the side. It can handle the MK46 and MK50 torpedoes and is capable of stowing and launching up to three torpedoes under either local control or remote control from an ASW fire control system.

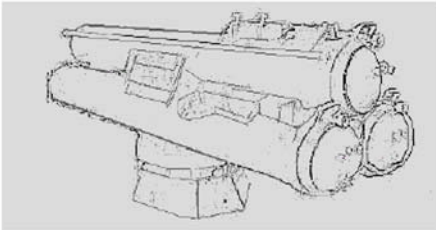


Figure 17 – MK32 Surface Vessel Torpedo Tube (SVTT)

Mine Avoidance Sonar is a multi-purpose sonar system VANGUARD is a versatile two frequency active and broadband passive sonar system. It is conceived for use on surface vessels to assist navigation and permit detection of dangerous objects. The system is designed primarily to detect mines but will also be used to detect other moving or stationary underwater objects. Mine Avoidance Sonar can be used as navigation sonar in narrow or dangerous waters. In addition it can complement the sensors on board anchoring surface vessels with regard to surveillance and protection against divers. Figure 18 is an illustration of the mine avoidance sonar.

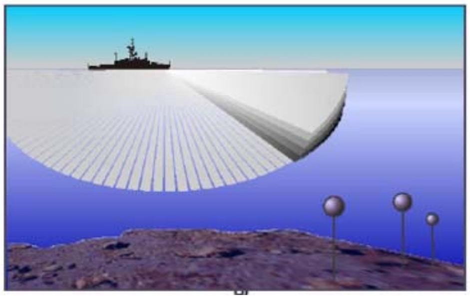


Figure 18 – Mine Avoidance Sonar

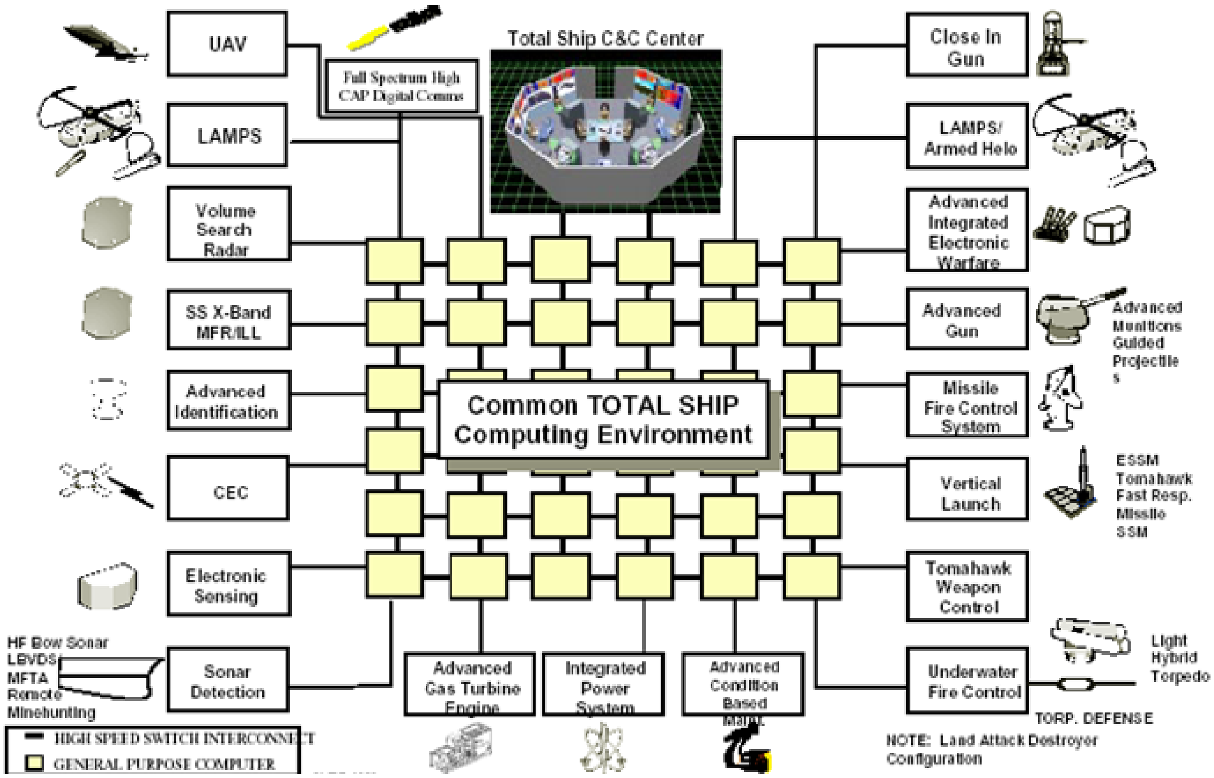


Figure 19 - Total Ship Combat Environment

3.1.4.4 CCC

Command, Control and Communications (CCC) refers to the ability of shipboard personnel to communicate with its own crew or off-ship personnel, control ship systems, and manage the battle space. All launch abilities, radar screens and any communication ability are located in or nearby the CCC. Table 9 lists the CCC combat systems options.

Table 9 – CCC Combat Systems Options Table

Warfighting System	Options
CCC	Option 1) Enhanced CCC, TSCE Option 2) Basic CCC, TSCE

The total ship concept of CCC with a common computing environment is represented in Figure 19. CCC is an important warfighting system that allows ships to communicate with other ships of the same navy and its own crew members.

3.1.4.5 GMLS

GMLS stands for Guided Missile Launching System. GMLS options are listed in Table 10.

Table 10 – GMLS Combat Systems Options Table

Warfighting System	Options
GMLS	Option 1) 160 cells MK57 + 8 cells KEI Option 2) 160 cells MK57 Option 3) 120 cells MK57 Option 4) 80 cells MK57

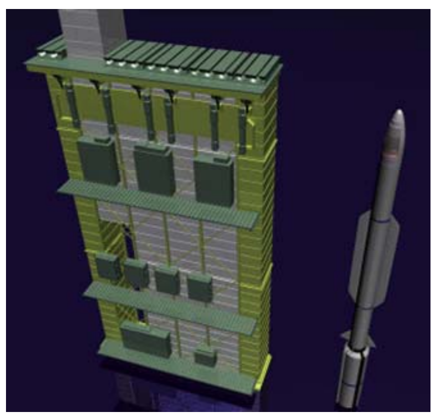


Figure 20 - MK57 VLS

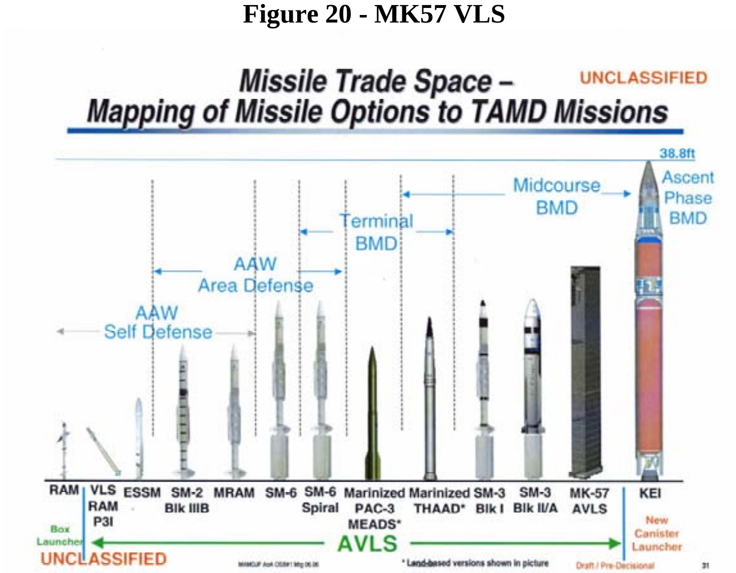


Figure 21 – Range of Weapons available to the VLS

The MK57 VLS is a component of all four combat systems options. Each option has a different number of cells available. Figure 20 shows the MK57 Vertical Launching System (VLS), which has a 4-cell module height of 26 feet, capable of handling a range of weapons, which are shown in Figure 21. MK 57 VLS can be configured in a peripheral VLS arrangement (PVLS) for increased survivability. In this arrangement, the cells are located around the periphery of the hull, so that in the event of an explosion, the energy is expelled outwards, away from vital ship systems.

Figure 21 also shows the KEI, the Kinetic Energy Interceptor missile. It has been designed to intercept and destroy enemy ballistic missiles during their boost, ascent and early midcourse phases of flight. It is also the first ballistic missile defense weapon system to be developed without the constraints of the Anti-Ballistic Missile Treaty. The KEI missile will provide the nation with the capability of defeating future sophisticated threats before their payloads are released.

3.1.4.6 LAMPS

Light Airborne Multi-Purpose System (LAMPS) refers to the system for holding, refueling, and launch and recovery of SH-60 helicopters on a ship. The ship must have an area for a flight deck. The LAMPS combat systems options are listed in Table 11.

Table 11 - LAMPS Combat Systems Options Table

Warfighting System	Options
LAMPS	Option 1) 2xEmbarked LAMPS w/Hangar, 2xVTUAV Option 2) LAMPS haven (flight deck), 2xVTUAV Option 3) in-flight refueling, 2xVTUAV

The major component of LAMPS is the SH-60 Seahawk, or LAMPS MK III (Figure 22). It can do a wide range of things, including ASW, ASUW, SPECOPS, cargo lift, and search and rescue. It can deploy sonobuoys, torpedoes (MK46 or MK50) and AGM-119 penguin missiles, as well as house two 7.62 mm machine guns. The Seahawk can extend the ship's radar capabilities and has a retractable in-flight fueling probe, designed to refuel aircraft in need of fuel.

Figure 22 – SH-60 Seahawk (LAMPS MK III)

Vertical Takeoff Unmanned Aircraft Vehicles (VTUAV) can extend the ship's sensors and is suited for high-risk missions, with virtually no risk to personnel. It is small in size, and can easily be stored onboard. Very little space is required for take-off. Figure 23 is a picture of a VTUAV.

Figure 23 – VTUAV

3.1.4.7 Combat Systems Payload Summary

To trade-off combat system alternatives with other alternatives in the total ship design, combat system characteristics are included in the ship synthesis model data base. **Table 12** lists these characteristics.

Table 12 - Combat System Ship Synthesis Characteristics

ID	NAME	DV	WTGRP	SingleD	WT (MT)	HD10 (m)	HAREA (m2)	DHAREA (m2)	CRSKW	BATKW
2	155 MM AGS PROTECTION	ASUW	W164	100	19	33.76	0	0	0	0
3	155 MM AGS FOUNDATIONS	ASUW	W187	100	47	32.75	0	0	0	0
4	155 MM AGS MAGAZINE SUPPORT	ASUW	W187	100	8.4	19.25	0	0	0	0
5	155 MM AGS STOREROOM PROTECTION	ASUW	W164	100	12.75	24	0	0	0	0
6	155 MM AGS GUN MOUNT	ASUW	W711	700	44.1	34.25	54.14	0	30	275
7	155 MM AGS ENERGY STORAGE SUBSYSTEM	ASUW	W711	700	7.49	31	0	0	0	0
8	155 MM AGS CABLE	ASUW	W711	700	2.99	30	0	0	0	0
9	155 MM AGS GUN HANDLING SYSTEM	ASUW	W712	700	105	22.99	0	0	0	0
10	155 MM AGS AMMO PALLETS [304 ROUNDS]	ASUW	WF21	20	54.4	24.25	342	0	0	0
11	155 MM AGS AMMO LOADOUT - 304 ROUNDS	ASUW	WF21	20	44.2	25	0	0	0	0
12	SPS-73 SURFACE SEARCH RADAR	ASUW	W451	400	0.24	9.02818	0	6.50321	0.2	0.2
13	SMALL ARMS AND PYRO STOWAGE	ASUW	W760	700	5.94387	-1.92024	18.8593	0	0	0
14	SMALL ARMS AMMO - 7.62MM + 50 CAL + PYRO	ASUW	WF21	20	4.16579	-1.8288	0	0	0	0
15	THERMAL IMAGING SENSOR SYSTEM - TISS	ASUW	W452	400	0.13	10.85	0	0	0	1
16	FLIR	ASUW	W452	400	0.16	10.8	1	0	0	1.5
17	GFCS	ASUW	W481	400	0.76203	-1.8288	0	13.9355	12.3	42.7
18	3 X 30MM CIGS GUN	ASUW	W164	100	2.5	14.33	0	0	0	0
19	SWBS 187 2 X 30MM CIGS GUN FOUNDATION	ASUW	W187	100	9	37.25	0	0	0	0
20	3 X CIGS SYSTEMS	ASUW	W711	700	16.94	37.8	23.84	0	20	40
21	3 X CIGS HOIST EXTENTIONS	ASUW	W711	700	0.89	33	0	0	0	0
22	3 X CIGS AMMO HOIST	ASUW	W712	700	0.45	35.5	0	0	0	0
23	3 X CIGS CASE CAPTURE	ASUW	W712	700	4.96	36.47	0	0	0	0
24	3 X 30MM CIGS GUN AMMO	ASUW	WF21	20	4.29	1.5	0	0	0	0
25	2 X 7M RHIB	ASUW	W583	500	7	-3	38.02	0	0	0
26	1 X MK110 57MM GUN	ASUW	W710	700	18	-1.88976	26.4774	0	36.6	50.2
27	MK110 57MM AMMO - 600 RDS	ASUW	WF21	20	16	-8.65632	65.4966	0	0	0
28	MK110 57MM GUN HY-80 ARMOR LEVEL II	ASUW	W164	100	10	-2.4384	0	0	0	0
29	1X MK45 5IN/62 GUN	ASUW	W710	700	37.3905	-1.88976	26.4774	0	36.6	50.2
30	MK45 5IN AMMO - 600 RDS	ASUW	WF21	20	33.6312	-8.65632	65.4966	0	0	0
31	MK45 5IN/62 GUN HY-80 ARMOR LEVEL II	ASUW	W164	100	20.5243	-2.4384	0	0	0	0
33	PVLS NON-STRUCTURE FRAG ARMOR 160 CELLS	GMLS	W164	100	213.75	25.22	0	0	0	0
34	PVLS NON-STRUCTURE FRAG ARMOR 128 CELLS	GMLS	W164	100	171	25.22	0	0	0	0
35	PVLS NON-STRUCTURE FRAG ARMOR 96 CELLS	GMLS	W164	100	128.25	25.22	0	0	0	0
36	PVLS FOUNDATIONS 160 CELLS	GMLS	W187	100	60.5	28.25	0	0	0	0

ID	NAME	DV	WTGRP	SingleD	WT (MT)	HD10 (m)	HAREA (m2)	DHAREA (m2)	CRSKW	BATKW
37	PVLS FOUNDATIONS 128 CELLS	GMLS	W187	100	48.4	28.25	0	0	0	0
38	PVLS FOUNDATIONS 96 CELLS	GMLS	W187	100	36.3	28.25	0	0	0	0
39	PVLS COOLING UNIT-VLS MAG 160 CELLS	GMLS	W514	500	59.48	-4	0	0	0	0
40	PVLS COOLING UNIT-VLS MAG 128 CELLS	GMLS	W514	500	47.58	-4	0	0	0	0
41	PVLS COOLING UNIT-VLS MAG 96 CELLS	GMLS	W514	500	35.69	-4	0	0	0	0
42	PVLS COOLING EQUIPMENT OPERATING FLUIDS 160 CELLS	GMLS	W598	500	27.47	-4	0	0	0	0
43	PVLS COOLING EQUIPMENT OPERATING FLUIDS 128 CELLS	GMLS	W598	500	21.98	-4	0	0	0	0
44	PVLS COOLING EQUIPMENT OPERATING FLUIDS 96 CELLS	GMLS	W598	500	16.48	-4	0	0	0	0
45	PVLS 160 CELLS	GMLS	W721	700	628.92	28.57	1900	0	724.6	724.6
46	PVLS 128 CELLS	GMLS	W721	700	503.14	28.57	1520	0	579.68	579.68
47	PVLS 96 CELLS	GMLS	W721	700	377.35	28.57	1140	0	434.76	434.76
48	PVLS MISSLE HANDLING	GMLS	W722	700	0.25	14	0	0	0	0
49	PVLS LOADOUT 160 CELLS	GMLS	WF21	20	332.375	29.13	0	0	0	0
50	PVLS LOADOUT 128 CELLS	GMLS	WF21	20	265.9	29.13	0	0	0	0
51	PVLS LOADOUT 96 CELLS	GMLS	WF21	20	199.43	29.13	0	0	0	0
52	KEI LS FOUNDATIONS 8 CELLS	GMLS	W187	100	12.1	28.25	0	0	0	0
53	KEI LS NON-STRUCTURE FRAG ARMOR 8 CELLS	GMLS	W164	100	42.25	25.22	0	0	0	0
54	KEI LS COOLING UNIT 8 CELLS	GMLS	W514	500	12.69	-4	0	0	0	0
55	KEI LS COOLING EQUIPMENT OPERATING FLUIDS 8 CELLS	GMLS	W598	500	5.4	-4	0	0	0	0
56	KEI LS 8 CELLS	GMLS	W721	700	120	28.57	1140	0	434.76	434.76
57	KEI MISSILE LOADOUT 8 CELLS	GMLS	WF21	20	60	29.13	0	0	0	0
59	TOTAL SHIP COMPUTING ENVIR SYSTEM	CCC	W412	400	73.38	-6.93	763.6	0	435.68	435.68
60	ENHANCED RADIO/EXCOMM	CCC	W441	400	101.93	11.31	0	465.17	227.89	228.19
61	BASIC RADIO/EXCOMM	CCC	W440	400	32.9098	-2.42926	117.987	8.82579	93.3	96.4
62	TOMAHAWK WEAPON CONTROL SYSTEM	CCC	W482	400	5.70002	-2.37744	0	0	11.5	11.5
63	UNDERWATER COMMUNICATIONS	CCC	W442	400	2.88	21.68	0	0	0	0
64	VISUAL & AUDIBLE SYSTEMS	CCC	W443	400	0.32	27.44	0	0	0	0
65	SECURITY EQUIPMENT SYSTEMS	CCC	W446	400	0.88	25.63	0	0	0	0
67	DUAL FREQUENCY BOW ARRAY SONAR DOME STRUCTURE	ASW	W165	100	22.5	14.4	0	0	0	0
68	DUAL FREQUENCY BOW ARRAY SONAR ELEX	ASW	W463	400	26.73	21.1	104.2	0	94.3	94.3
69	DUAL FREQUENCY	ASW	W636	600	10.1	16	0	0	0	0

ID	NAME	DV	WTGRP	SingleD	WT (MT)	HD10 (m)	HAREA (m2)	DHAREA (m2)	CRSKW	BATKW
	BOW ARRAY SONAR HULL DAMP									
70	SQS-56 SONAR DOME STRUCTURE	ASW	W165	100	7.43	15.4	0	0	0	0
71	SQS-56 SONAR ELEX	ASW	W462	400	5.88	21.1	126.86	0	19.7	19.7
72	SQS-56 SONAR HULL DAMPING	ASW	W636	600	2.01	16	0	0	0	0
73	SQS-53 SONAR DOME STRUCTURE	ASW	W165	100	85.7	14	0	0	0	0
74	SQS-53 SONAR ELEX	ASW	W462	400	67.4	21.1	271.7	0	100	100
75	SQS-53 SONAR HULL DAMPING	ASW	W636	600	20.1	16	0	0	0	0
76	MINEHUNTING SONAR	ASW	W462	400	2.1	16.4	21	0	3.7	3.7
77	ISUW - INTEGRATED UNDERSEA WARFARE SYS	ASW	W483	400	4.87703	-3.3528	0	0	19.5	19.5
78	SQR-19 TACTAS	ASW	W462	400	23.6739	8.8904	43.9431	0	26.6	26.6
79	AN/SLQ-25 NIXIE	ASW	W473	400	3.65777	8.8904	15.9793	0	3	4.2
80	BATHYTHERMO-GRAPH	ASW	W465	400	2.63	31.65	0	0	0	0
81	TORPEDO DECOYS	ASW	W473	400	5.09	25.61	46	0	2.4	2.4
82	C+S OPERATING FLUIDS	ASW	W498	400	72.31	16.75	0	0	0	0
83	2X MK32 SVTT ON DECK	ASW	W750	700	2.74333	0.9144	0	0	0.6	1.1
84	6 X MK46 LIGHTWEIGHT ASW TORPEDOES	ASW	WF21	20	1.38182	0.9144	0	0	0	0
86	VOLUME SEARCH RADAR [S BAND]- VSR	AAW	W456	400	198	7.5	0	304	2100	2100
87	GLYCOL WATER COOLING SYSTEM FOR VSR	AAW	W532	500	54.04	4.5	0	100	1900	1900
88	VOLUME SEARCH RADAR [S BAND]- VSR+	AAW	W456	400	256	7.5	0	393	2714	2714
89	GLYCOL WATER COOLING SYSTEM FOR VSR+	AAW	W532	500	98.76	4.5	0	183	2300	2300
90	VOLUME SEARCH RADAR [S BAND]- VSR++	AAW	W456	400	398	7.5	0	610	4181	4181
91	GLYCOL WATER COOLING SYSTEM FOR VSR++	AAW	W532	500	158.13	4.5	0	293	3500	3500
92	VOLUME SEARCH RADAR [S BAND]- VSR+++	AAW	W456	400	425	7.5	0	651	4462	4462
93	GLYCOL WATER COOLING SYSTEM FOR VSR+++	AAW	W532	500	189.76	4.5	0	352	4200	4200
94	AN/SPY-3 MFR - MULTIPLE MODE RADAR	AAW	W456	400	75.71	10.5	0	108.68	382.7	382.7
95	GLYCOL WATER COOLING SYSTEM FOR SPY-3 MFR / EWS	AAW	W532	500	22.92	34.33	0	25.14	300	300
96	AEGIS BMD 2014 COMBAT SYSTEM AND CIC	AAW	W411	400	17.6183	15.4027 2	184.784	0	74.5	74.5
97	CIFF-SD	AAW	W455	400	4.47	49.12	0	0	2.7	2.4
98	MK53 NULKA DECOY LAUNCHING SYSTEM - DLS	AAW	WF21	20	0.82	31.5	0	0	0	0
99	MK 36 SRBOC DECOY LAUNCHING SYSTEM - DLS	AAW	WF21	20	3.06	34.5	0	0	0	0
100	EWS - ACTIVE ECM - SLQ/32R	AAW	W471	400	9.88	34.3	0	6.5	0.32	0.32

ID	NAME	DV	WTGRP	SingleD	WT (MT)	HD10 (m)	HAREA (m2)	DHAREA (m2)	CRSKW	BATKW
101	IRST - INFRARED SENSING & TRACKING	AAW	W459	400	0	37.35	0	0	0	0
103	DUAL HELO/UAV DET - 2X SH60R HANGAR UPPER LEVEL 17 X 15.7	LAMPS	NONE	100	0	16.5	0	266.9	0	0
104	DUAL HELO/UAV DET - 2X SH60R HANGAR LOWER LEVEL 17 X 15.7	LAMPS	NONE	100	0	16.5	0	266.9	0	0
105	DUAL HELO/UAV DET - FUEL SYSTEM	LAMPS	W542	500	21	23.06	0	2.77	0	0
106	DUAL HELO/UAV DET - HNDLG/SUPPORT/MAINT/WKSP - AREA ONLY	LAMPS	NONE	500	0	16.5	0	34.1	0	0
107	DUAL HELO/UAV DET - RAST/RAST CONTROL - AREA ONLY	LAMPS	NONE	500	0	16.5	44.4	0	0	0
108	DUAL HELO/UAV DET - HANDLING/SERVICE/STOWAGE - WEIGHT ONLY	LAMPS	W588	500	26.04	31.21	0	0	0	0
109	DUAL HELO/UAV DET - MAGAZINE HANDLING	LAMPS	W712	700	0.001	1.45	0	0	0	0
110	DUAL HELO/UAV DET - MAGAZINE 12-MK46 24-HELLFIRE 6-PENQUIN	LAMPS	WF22	20	0.001	1.5	0	57.46	0	0
111	DUAL HELO/UAV DET - VTUAV	LAMPS	WF23	20	3.47	1	0	0	0	0
112	DUAL HELO/UAV DET - 2X SH60R	LAMPS	WF23	20	10.66	1	0	0	0	0
113	DUAL HELO/UAV DET - SUPPORT/SPARES	LAMPS	WF26	20	0	1	0	158.08	0	0
114	SONOBOUY MAGAZINE STOWAGE - NONE IN PARENT	LAMPS	W713	700	0.001	1.5	0	0	0	0
115	SONOBOUY MAGAZINE - 300 BUOYS - 88 MARKERS	LAMPS	WF22	20	0.001	1.5	0	10.12	0	0
116	SQQ-28 LAMPS MK III ELECTRONICS	LAMPS	W460	400	3.51552	0.9144	0	0	5.3	5.5
117	LAMPS MKIII:AVIATION FUEL [JP-5]	LAMPS	WF42	40	65.4334	20.4624	0	0	0	0
118	LAMPS MKIII:HELO IN-FLIGHT REFUEL SYS	LAMPS	W542	500	7.72196	-4.572	4.08773	0	1.3	1.3
119	BATHYTHERMOGRAPH PROBES	LAMPS	WF29	20	0.21337	24.33641	0	0	0	0

3.2 Design Space

Table 13 shows the complete design space to be explored as represented by 24 design variables (DVs). The design variables are either continuous variables (options 1-8, 15, 18), or discrete options. Each design variable is meant to represent a design space value that would be consistent with a cruiser and the CGX-BMD mission. DVs 1-9 are hullform options and were discussed in section 3.1.1. DVs 10-14 are propulsion and electrical machinery options and were discussed in section 3.1.2. DV 18 represents the automation level of the ship, as discussed in section 3.1.3. DVs 19-24 are combat system options and were discussed in section 3.1.4.

Table 13 - Design Variables (DVs)

DV #	DV Name	Description	Design Space
1	LWL	Waterline Length	180-300m
2	LtoB	Length to Beam ratio	7.0-10.0

DV #	DV Name	Description	Design Space
3	LtoD	Length to Depth ratio	10.75-17.8
4	BtoT	Beam to Draft ratio	2.8-3.2
5	Cp	Prismatic coefficient	0.56 – 0.64
6	Cx	Maximum section coefficient	0.75 – 0.85
7	Crd	Raised deck coefficient	0.7 – 0.8
8	VD	Deckhouse volume	10,000-20,000 m^3
9	HULLtype	Hull: Flare or DDG 1000	1: flare= 10 deg; 2: flare = DDG 1000
10	PGM	Power Generation Module	Option 1) 2xLM2500+, AC synchronous, 4160 VAC Option 2) 2xLM2500+, AC synchronous, 13800 VAC Option 3) 2xLM2500+, SCH generator, 4160 VAC Option 4) 2xLM2500+, SCH generator, 13800 VAC Option 5) 3xLM2500+, AC synchronous, 4160 VAC Option 6) 3xLM2500+, AC synchronous, 13800 VAC Option 7) 3xLM2500+, SCH generator, 4160 VAC Option 8) 3xLM2500+, SCH generator, 13800 VAC Option 9) 2xMT30, AC synchronous, 4160 VAC *(DDG 1000) Option 10) 2xMT30, AC synchronous, 13800 VAC Option 11) 2xMT30, SCH generator, 4160 VAC Option 12) 2xMT30, SCH generator, 13800 VAC Option 13) 3xMT30, AC synchronous, 4160 VAC Option 14) 3xMT30, AC synchronous, 13800 VAC Option 15) 3xMT30, SCH generator, 4160 VAC Option 16) 3xMT30, SCH generator, 13800 VAC Option 17) 4xMT30, AC synchronous, 4160 VAC Option 18) 4xMT30, AC synchronous, 13800 VAC Option 19) 4xMT30, SCH generator, 4160 VAC Option 20) 4xMT30, SCH generator, 13800 VAC
11	SPGM	Secondary Power Generation Module	Option 1) none Option 2) 2xLM500G, geared, w/AC sync *(DDG 1000) Option 3) 2xMC5.0 Fuel Cells Option 4) 2xMC8.5 Fuel Cells Option 5) 2xPEM5.0 Fuel Cells Option 6) 2xPEM8.5 Fuel Cells Option 7) 2xCAT 3618 Diesel Option 8) 2xPC 2/18 Diesel
12	PROPtype	Propulsor Type	Option 1) 2xFPP *(DDG 1000) Option 2) 2xPods Option 3) 1xFPP + SPU (7.5MW)
13	DISTtype	Power Distribution Type	Option 1) AC ZEDS Option 2) DC ZEDS *(DDG 1000)
14	PMM	Propulsion Motor Module	Option 1) AIM (Advanced Induction Motor) *(DDG 1000) Option 2) PMM (Permanent Magnet Motor) Option 3) SCH (Superconducting Homopolar Motor)
15	Ts	Provisions Duration	60-75 days
16	Ncps	Collective Protection System	0 = none, 1 = partial, 2 = full
17	Ndegaus	Degaussing System	0 = none, 1 = degaussing system
18	CMan	Manning Reduction and Automation Factor	0.5 – 0.1
19	AAW/BMD/ STK	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
20	ASUW/ NSFS	Anti-Surface Warfare	Option 1) 1x155m AGS, SPS-73, Small Arms, TISS, FLIR, GFCS,

DV #	DV Name	Description	Design Space
		Alternatives	2x7m RHIB, MK46 Mod2 3x CIGS Option 2) 1xMK45 5"/62 gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod2 3x CIGS Option 3) 1xMK110 57mm gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod2 3x CIGS
21	ASW/MCM	Anti-Submarine Warfare Alternatives	Option 1) Dual Frequency Bow Array, IUSW, NIXIE, 2xSVTT, mine-avoidance sonar Option 2) SQS-53C, NIXIE, SQR-19 TACTAS, IUSW, 2xSVTT, mine-avoidance sonar Option 3) SQS-56, NIXIE, IUSW, 2xSVTT, mine-avoidance sonar Option 4) NIXIE, 2xSVTT, mine-avoidance sonar
22	CCC	Command Control Communication Alternatives	Option 1) Enhanced CCC, TSCE Option 2) Basic CCC, TSCE
23	LAMPS	LAMPS Alternatives	Option 1) 2 x Embarked LAMPS w/Hangar, 2xVTUAV Option 2) LAMPS haven (flight deck), 2xVTUAV Option 3) in-flight refueling, 2xVTUAV
24	GMLS	Guided Missile Launching System Alternatives	Option 1) 160 cells MK57 + 8 cells KEI Option 2) 160 cells MK57 Option 3) 120 cells MK57 Option 4) 80 cells MK 57

3.3 Ship Synthesis Model

The ship synthesis model was integrated and run in Phoenix Integration's Model Center. The Model Center model is comprised of many different modules. Each module extracts variables from the initial input module or from preceding modules, runs FORTRAN code to calculate more variables, and outputs variables for use by subsequent modules. Figure 24 shows the synthesis model in Model Center. The boxes represent modules, which proceed from top left to bottom right, and the arrows represent variables passed from module to module.

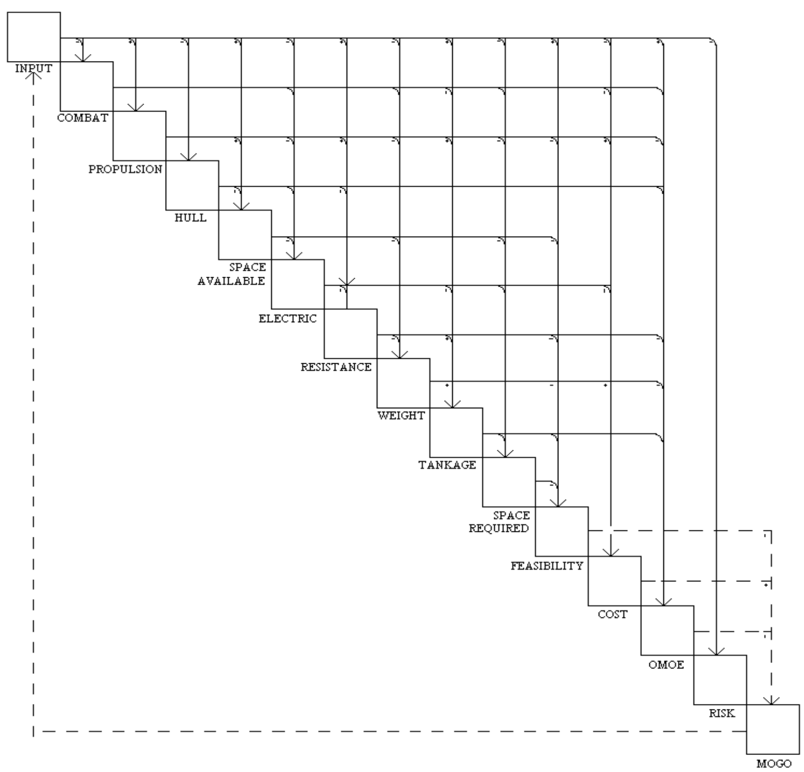


Figure 24 - Ship Synthesis Model in Model Center

The input module simply passes starting design variable values to other modules. These values are a set of selections from the defined design space. There are thirteen other modules: Combat, Propulsion, Hull, Space Available, Electric, Resistance, Weight, Tankage, Space Required, Feasibility, Cost, OMOE and Risk. The Combat module calculates variables relating to combat options (AAW, ASUW, etc.). The Combat module outputs weight group, vertical center of gravity (VCG), electric power, and area data for the combat systems. The Propulsion module calculates variables relating to propulsion power, required dimensions, required intake/exhaust area, SFC, etc. The Hull module uses a parametric model of the ship, calculating displacement and surface area using simple geometric equations. The Space Available module estimates how much space is available inside the hull form, using key characteristics from the hull module. The Electric module approximates the amount of ship service power and total number of accommodations the ship requires. The Resistance module estimates shaft horsepower needed to move at sustained and endurance speed. It also calculates propeller diameter needed, as well as the sustained speed. The Weight module calculates and estimates the total weight, VCGs, KG and GM of the ship by SWBS group. The Tankage module estimates the total tank space required, and the Space Required module estimates the total space required by the ship's various systems. It also approximates the deckhouse space required and available. The Feasibility module is important because it calculates various feasibility ratio parameters and determines whether or not the ship is a feasible design. The Cost module estimates cost values for the ship including lead and follow ship costs. The OMOE (overall measure of effectiveness) module calculates the overall effectiveness of the ship. The OMOE is further described in section 3.4.1. The Risk systems module calculates a level of risk associated with the ship design.

3.4 Objective Attributes

3.4.1 Overall Measure of Effectiveness (OMOE)

The overall measure of effectiveness is a single parameter ranging from zero to one. This parameter quantifies the performance of a ship with respect to specific mission requirements. To obtain the value of the OMOE, the following equation is used:

$$OMOE = g\left[VOP_i(MOP_i)\right] = \sum_i w_i VOP_i(MOP_i) \qquad (1)$$

In this equation, MOP stands for measure of performance, which is a system performance metric in required capabilities which is independent of the mission. VOP stands for value of performance, which is a figure of merit index from zero to one specifying a MOP value to a mission area for a mission type. The variable *w* is a weighting factor that is applied to the measure of performance. It places more emphasis on important components with respect to certain missions. Table 14 lists combat system MOPs with its goal and thresholds for CGX. The threshold value is the minimum components or values a ship must have to perform the mission, and its goal is the best components or value.

Table 14 - MOP Table

MOP #	MOP	Metric	Goal	Threshold
1	BMD	AAW, GMLS, CCC	BMD=1 GMLS=1 CCC=1	BMD=4 GMLS=4 CCC=2
2	AAW	AAW, GMLS, CCC	AAW=1 GMLS=1 CCC=1	AAW=3 GMLS=2 CCC=2
3	ASUW/NSFS	ASUW, LAMPS, CCC	ASUW=1 LAMPS=1 CCC=1	ASUW=2 LAMPS=3 CCC=2
4	ASW/MCM	ASW, LAMPS, CCC, MCM	ASW=1 LAMPS=1 CCC=1 MCM=1	ASW=3 LAMPS=3 CCC=2 MCM=1
5	CCC	CCC	CCC=1	CCC=2
6	ISR/SOF	LAMPS, CCC	LAMPS=1 CCC=1	LAMPS=3 CCC=2
7	Surge Speed	knots	35 knt	20 knts
8	Vs	knots	35 knt	30 knts
9	E	nm	8000nm	5000nm
10	Ts	days	75	60
11	Seakeeping	McCreight index	20	10
12	Surge Refuel	Number of refuels	2	3
13	VUL	Redundancy		IPS
14	NBC	CPS option	Ncps=2	Ncps=0
15	RCS	Deckhouse volume	VD=3000m^3	VD=5000m^3
16	Acoustic Signature	SPGM	SPGM=1	SPGM=8
17	IR Signature	PGM, SPGM	PGM=2xTurbine SPGM=1	PGM=3xTurbine SPGM=2-8
18	Magnetic Signature	Degaussing option	Ndegaus = 1	Ndegaus = 0

Table 15 summarizes each ROC, MOP and DV. Design variables (DVs) correspond with CGX/BMD ROCs which are specified in Table 4. To calculate the weighting factors, an analytical hierarchy process (AHP) is used. AHP breaks up the OMOE into the different missions that the ship will perform. In each mission type, areas (war fighting, mobility, survivability) essential to the mission are listed, and under them are the MOPs that are relevant to those areas. Figure 25 shows the hierarchy consisting of three different mission types.

Table 15 - ROC/MOP/DV Summary

ROCs	Description	MOP	Related DV	Goal	Threshold
AAW 1	Provide anti-air defense	AAW	AAW, GMLS, SEW	AAW=1 GMLS=1 SEW=1	AAW=3 GMLS=2 SEW=1
AAW 1.1	Provide area anti-air defense	AAW	AAW, GMLS SEW	AAW=1 GMLS=1 SEW=1	AAW=3 GMLS=2 SEW=1
AAW 1.2	Support area anti-air defense	AAW	AAW, GMLS SEW	AAW=1 GMLS=1 SEW=1	AAW=3 GMLS=2 SEW=1
AAW 1.3	Provide unit anti-air self defense	AAW, RCS, IR	SSD, VD, PSYS	SDS=1 1500m3	SDS=2 2000m3
AAW 2	Provide anti-air defense in cooperation with other forces	AAW	CCC	CCC=1	CCC=2
AAW 3	Support Theater Ballistic Missile Defense (TBMD)	AAW	CCC	CCC=1	CCC=2
AAW 5	Provide passive and soft kill anti-air defense	AAW, IR, RCS	SEW, VD, PSYS	SEW=1 1500m3	SEW=1 2000m3
AAW 6	Detect, identify and track air targets	AAW, IR, RCS	SEW, VD, PSYS	SEW=1 1500m3	SEW=1 2000m3
AAW 9	Engage airborne threats using surface-to-air armament	AAW, IR, RCS	SEW, VD, PSYS	SEW=1 1500m3	SEW=1 2000m3
AMW 6	Conduct day and night helicopter, Short/Vertical Take-off and Landing and airborne autonomous vehicle (AAV) operations	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
AMW 6.3	Conduct all-weather helo ops	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
AMW 6.4	Serve as a helo hangar	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
AMW 6.5	Serve as a helo haven	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
AMW 6.6	Conduct helo air refueling	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
AMW 12	Provide air control and coordination of air operations	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
AMW 14	Support/conduct Naval Surface Fire Support (NSFS) against designated targets in support of an amphibious operation	NSFS	NSFS	NSFS=1	NSFS=4
ASU 1	Engage surface threats with anti-surface armaments	ASUW	ASUW LAMPS	ASUW=1 LAMPS=1	ASUW=2 LAMPS=3
ASU 1.1	Engage surface ships at long range	ASUW	ASUW LAMPS	ASUW=1 LAMPS=1	ASUW=2 LAMPS=3
ASU 1.2	Engage surface ships at medium range	ASUW	ASUW LAMPS	ASUW=1 LAMPS=1	ASUW=2 LAMPS=3
ASU 1.3	Engage surface ships at close range (gun)	ASUW	NSFS	NSFS=1	NSFS=4
ASU 1.5	Engage surface ships with medium caliber gunfire	ASUW	NSFS	NSFS=1	NSFS=4
ASU 1.6	Engage surface ships with minor caliber gunfire	ASUW	NSFS	NSFS=1	NSFS=4
ASU 1.9	Engage surface ships with small arms gunfire	ASUW	NSFS	NSFS=1	NSFS=4
ASU 2	Engage surface ships in cooperation with other forces	ASUW, FSO	CCC	CCC=1	CCC=2
ASU 4	Detect and track a surface target	ASUW	ASUW LAMPS	ASUW=1 LAMPS=1	ASUW=2 LAMPS=3
ASU 4.1	Detect and track a surface target with radar	ASUW	ASUW LAMPS	ASUW=1 LAMPS=1	ASUW=2 LAMPS=3
ASU 6	Disengage, evade and avoid surface attack	ASUW	ASUW	ASUW=1	ASUW=2
ASW 1	Engage submarines	ASW	ASW	ASW=1	ASW=3
ASW 1.1	Engage submarines at long range	ASW	ASW	ASW=1	ASW=3
ASW 1.2	Engage submarines at medium range	ASW	ASW	ASW=1	ASW=3
ASW 1.3	Engage submarines at close range	ASW	ASW, PSYS	ASW=1 PSYS=5-16	ASW=3 PSYS=1-4
ASW 4	Conduct airborne ASW/recon	ASW	LAMPS	LAMPS=1	LAMPS=3
ASW 5	Support airborne ASW/recon	ASW	LAMPS CCC	LAMPS=1, CCC=1	LAMPS=3 CCC=2

ROCs	Description	MOP	Related DV	Goal	Threshold
ASW 7	Attack submarines with antisubmarine armament	ASW	ASW LAMPS CCC	ASW=1 LAMPS=1 CCC=1	ASW=3 LAMPS=3 CCC=2
ASW 7.6	Engage submarines with torpedoes	ASW	ASW, LAMPS, CCC	ASW=1 LAMPS=1 CCC=1	ASW=3 LAMPS=3 CCC=2
ASW 8	Disengage, evade, avoid and deceive submarines	ASW	ASW	ASW=1	ASW=3
CCC 1	Provide command and control facilities	CCC	CCC	CCC=1	CCC=2
CCC 1.6	Provide a Helicopter Direction Center (HDC)	CCC, ASW, ASUW	CCC	CCC=1	CCC=2
CCC 2	Coordinate and control the operations of the task organization or functional force to carry out assigned missions	CCC, FSO	CCC	CCC=1	CCC=2
CCC 3	Provide own unit Command and Control	CCC	CCC	CCC=1	CCC=2
CCC 4	Maintain data link capability	ASW, ASUW, AAW	CCC	CCC=1	CCC=2
CCC 6	Provide communications for own unit	CCC	CCC	CCC=1	CCC=2
CCC 9	Relay communications	CCC	CCC	CCC=1	CCC=2
CCC 21	Perform cooperative engagement	CCC, FSO	CCC	CCC=1	CCC=2
FSO 5	Conduct towing/search/salvage rescue operations	FSO	LAMPS	LAMPS=1	LAMPS=3
FSO 6	Conduct SAR operations	FSO	LAMPS	LAMPS=1	LAMPS=3
FSO 8	Conduct port control functions	FSO	CCC, ASUW, LAMPS	CCC=1 ASUW=1 LAMPS=1	CCC=2 ASUW=3 LAMPS=3
FSO 9	Provide routine health care	All designs			
FSO 10	Provide first aid assistance	All designs			
FSO 11	Provide triage of casualties/patients	All designs			
INT 1	Support/conduct intelligence collection	INT			
INT 2	Provide intelligence	INT			
INT 3	Conduct surveillance and reconnaissance	INT	LAMPS	LAMPS=1	LAMPS=3
INT 8	Process surveillance and reconnaissance information	INT, CCC			
INT 9	Disseminate surveillance and reconnaissance information	INT, CCC			
INT 15	Provide intelligence support for non-combatant evacuation operation (NEO)	INT, CCC			
MIW 4	Conduct mine avoidance	MIW	Degaus	Yes	Yes
MIW 6	Conduct magnetic silencing (degaussing, deperming)	Magnetic Signature	Degaus	Yes	Yes
MIW 6.7	Maintain magnetic signature limits	Magnetic Signature	Degaus	Yes	Yes
MOB 1	Steam to design capacity in most fuel efficient manner	Sustained Speed, Endurance Range	Hullform PSYS	Vs = 35 knts E=4000	Vs = 28 knt E = 5000 nm
MOB 2	Support/provide aircraft for all-weather operations	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
MOB 3	Prevent and control damage	VUL	Cdhmat	Cdmat =1 Composite	Cdmat = 3 steel
MOB 3.2	Counter and control NBC contaminants and agents	NBC	CPS	CPS=2 (full)	CPS=0 (none)
MOB 5	Maneuver in formation	All designs			
MOB 7	Perform seamanship, airmanship and navigation tasks (navigate, anchor, mooring, scuttle, life boat/raft capacity, tow/be-towed)	All designs			
MOB 10	Replenish at sea	All designs			
MOB 12	Maintain health and well being of crew	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	provisions	Ts	60 days	45 days
MOB 16	Operate in day and night environments	All designs			
MOB 17	Operate in heavy weather	Sea-keeping index	hullform	MCR=15	MCR=4
MOB 18	Operate in full compliance of existing US and international pollution control laws and regulations	Compensated Fuel System/ Clean Ballast	BalType	BalType=1	BalType=1
NCO 3	Provide upkeep and maintenance of own unit	All designs			
NCO 19	Conduct maritime law enforcement operations	NCO	ASUW NSFS	ASUW =1 NSFS=1	ASUW = 1 NSFS = 4

ROCs	Description	MOP	Related DV	Goal	Threshold
SEW 2	Conduct sensor and ECM operations	AAW	SEW	SEW=1	SEW=1
SEW 3	Conduct sensor and ECCM operations	AAW	SEW	SEW=1	SEW=1
SEW 5	Conduct coordinated SEW operations with other units	AAW	CCC	CCC=1	CCC=2
STW 3	Support/conduct multiple cruise missile strikes	STK	GMLS CCC	GMLS=1 CCC=1	GMLS=2 CCC=2

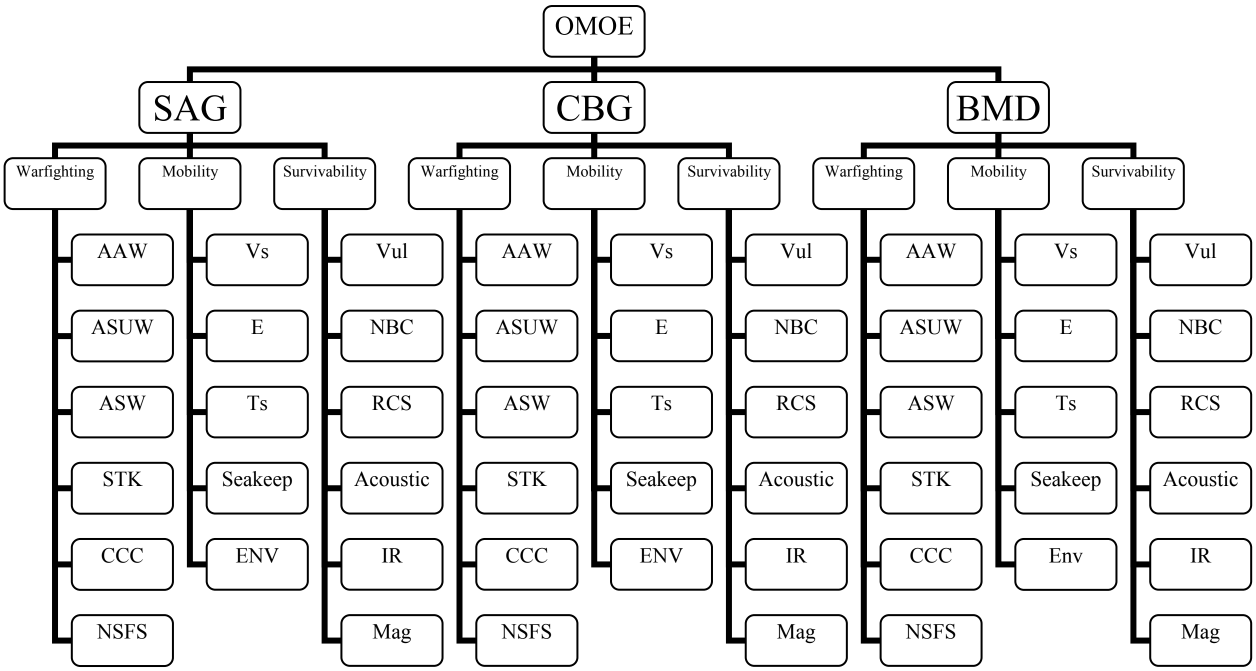


Figure 25 - OMOE Hierarchy

AHP uses pairwise comparison to calculate the MOP weights. Appendix C, lists the pairwise comparison results of each MOP. Figure 26 shows the value of each MOP weight.

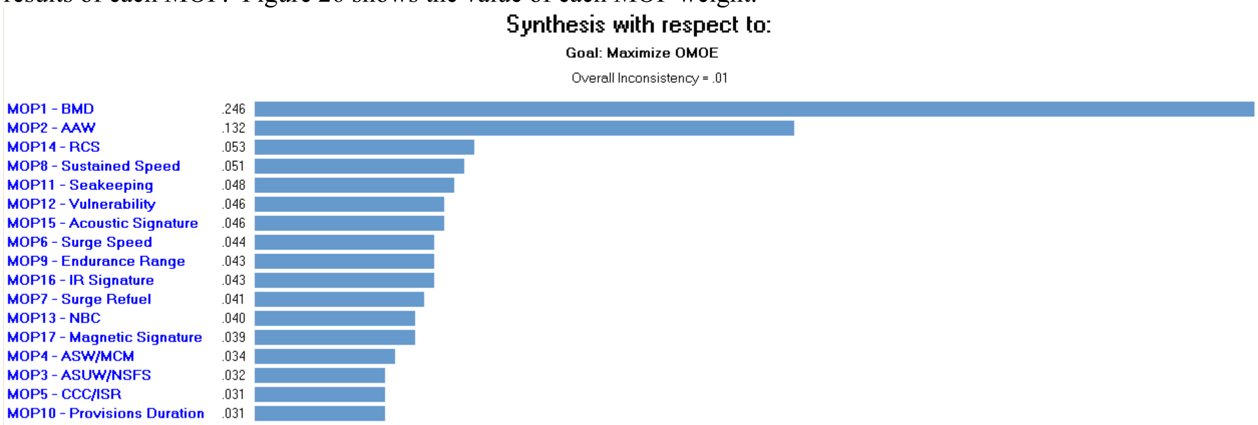


Figure 26 – Bar Chart Showing MOP Weights

The result of pairwise comparison shows that the highest regarded MOP is BMD, which is the primary purpose of the CGX. Anti-Air Warfare (AAW) is the second highest ranked MOP, which allows the CGX to defend against missiles or any airborne threat. These VOP functions are used to calculate the value of performance for each MOP.

3.4.2 Overall Measure of Risk (OMOR)

To develop the OMOR risk events associated with specific design variables, required capabilities, schedule, and cost are identified. Probability of occurrence of major impact on performance, cost, or schedule (Pi) and consequence of occurrence of major impact on performance, cost, or schedule (Ci) are estimated for each event using Table 16 and Table 17. Then, a quantitative overall measure of risk (OMOR) for a specific design based on the selection of technologies is calculated using Equation (2).

$$\text{Risk (Ri)} = \text{Pi} \cdot \text{Ci} \tag{2}$$

Table 16 - 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 17 - 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%

shows the risk table built using a pair-wise comparison to calculate OMOR hierarchy weights. The OMOE formula is listed as:

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

Table 18 - Risk Register

Related DV #	DV Options	DV Description	Risk Event (Ei)	Risk Description	Event #	Pi	Ci	Ri
DV9	2	Hull Type	Tumblehome Seakeeping Performance	Seakeeping not satisfactory	1	0.6	0.8	0.48
DV11	(5-6)	SPGM	PEM Fuel Cell Development and Implementation	Reduced reliability and performance (un-proven)	2	0.6	0.55	0.33
DV11	(5-6)	SPGM	PEM Fuel Cell Development, acquisition and integration cost overruns	Research and Development cost overruns	3	0.6	0.45	0.27
DV11	(5-6)	SPGM	PEM Fuel Cell Schedule delays impact program	In development and test	4	0.7	0.3	0.21
DV11	3-4	SPGM	MC Fuel Cell Development and Implementation	Reduced reliability and performance (un-proven)	2	0.7	0.6	0.42
DV11	3-4	SPGM	MC Fuel Cell Development, acquisition and integration cost overruns	Research and Development cost overruns	3	0.9	0.4	0.36
DV11	3-4	SPGM	MC Fuel Cell Schedule delays impact program	In development and test	4	0.8	0.5	0.4
DV12	2	Propeller type	Development and Implementation of podded propulsion	Reduced Reliability (un-proven)	5	0.7	0.5	0.35
DV12	2	Propeller type	Podded Propulsion Implementation Problems	Unproven for USN, large size	7	0.6	0.45	0.27
DV12	2	Propeller type	Podded Propulsion Schedule delays impact program	Unproven for USN, large size	8	0.6	0.6	0.36
DV12	3	Propulsor type	Development and Implementation of SPU	Reduced Reliability (un-proven)	5	0.6	0.5	0.3
DV12	3	Propulsor type	SPU Implementation Problems	Unproven for USN, large size	7	0.6	0.4	0.24
DV12	3	Propulsor type	SPU Schedule delays impact program	Unproven for USN, large size	8	0.6	0.5	0.3
DV13	2	Power distribution type	DC ZEDS Development and	Reduced Reliability	9	0.4	0.7	0.28

Related DV #	DV Options	DV Description	Risk Event (Ei)	Risk Description	Event #	Pi	Ci	Ri
			Implementation					
DV13	2	Power distribution type	DC ZEDS Development and Implementation	Cost overrun	9	0.5	0.5	0.25
DV13	2	Power distribution type	DC ZEDS Development and Implementation	Delay schedule	9	0.5	0.4	0.2
DV14	2	propulsion motor module	PMM development and implementation	Reduced Reliability and Performance (un-proven)	10	0.6	0.7	0.42
DV14	2	propulsion motor module	PMM development, acquisition and integration cost overruns	Unproven for USN, large size	11	0.7	0.45	0.315
DV14	2	propulsion motor module	PMM schedule delays impact program	Unproven for USN, large size	12	0.6	0.5	0.3
DV14	3	propulsion motor module	SCH development and implementation	Reduced Reliability and Performance (un-proven)	10	0.7	0.75	0.525
DV14	3	propulsion motor module	SCH development, acquisition and integration cost overruns	Unproven for USN, large size	11	0.8	0.7	0.56
DV14	3	propulsion motor module	SCH schedule delays impact program	Unproven for USN, large size	12	0.9	0.65	0.585
DV18	0.5	Automation	Automation systems development and implementation	Reduced Reliability and Performance (un-proven)	13	0.5	0.7	0.35
DV18	0.5	Automation	Automation systems development, acquisition and integration cost overruns	Research and Development cost overruns	14	0.5	0.5	0.25
DV18	0.5	Automation	Automation systems schedule delays impact program	Research and Development schedule delays	15	0.5	0.7	0.35
DV19	1,2,3	AAW/BMD/ STK Systems	SPY-3 and VSR+++ DBR Development and implementation	Reduced Reliability and Performance (un-proven)	16	0.4	0.5	0.2
DV19	1,2,3	AAW/BMD/ STK Systems	SPY-3 and VSR+++ DBR Development, acquisition and integration cost overruns	Research and Development cost overruns	17	0.4	0.7	0.28
DV19	1,2,3	AAW/BMD/ STK Systems	SPY-3 and VSR+++ DBR Schedule delays impact program	Research and Development schedule delays	18	0.6	0.7	0.42
DV20	1	ASUW/NSFS	AGS performance and reliability	AGS performance and reliability	19	0.3	0.6	0.18
DV24	2,3	GMLS	KEI development and implementation	Reduced Reliability and Performance (un-proven)	20	0.8	0.7	0.56
DV24	2,3	GMLS	KEI development, acquisition and integration cost overruns	Research and Development cost overruns	21	0.7	0.8	0.56
DV24	2,3	GMLS	KEI schedule delays impact program	Research and Development schedule delays	22	0.7	0.8	0.56
DV10	3,4,7,8,11,12,15,16	PGM	HSC PGM	Research and Development cost overruns	3	0.8	0.6	0.48
DV10	3,4,7,8,11,12,15,16	PGM	HSC PGM	In development and test	4	0.7	0.6	0.42
DV10	3,4,7,8,11,12,15,16	PGM	HSC PGM	Reduced reliability and performance (un-proven)	2	0.7	0.6	0.42

3.4.3 Cost

The cost model used is a weight based cost model, which uses parametric equations to relate weight and other parameters to cost. In the cost model, the inputs are as follows; propulsion system type and power, deck house material, endurance range and speed, fuel volume, SWBS weight groups 100-700, number of personnel, profit margin, inflation rate, number of ships to be built, and base year for cost calculation. The inflation factor is calculated, and then the cost for each SWBS group 100-700 is calculated. This calculation is done by multiplying the weight of the group by complexity factors. This total is multiplied by margin weight and added to the SWBS 800 and 900 costs to come up with the lead ship basic construction cost. Added to this cost are the profit, change order cost, government costs, and delivery cost, to produce the finial lead ship acquisition cost. Figure 27 shows the naval ship acquisition cost components.

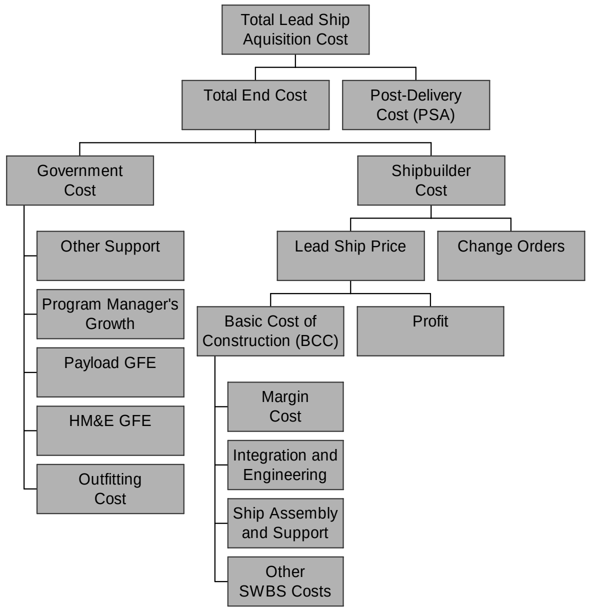


Figure 27 - Naval Ship Acquisition Cost Components

3.5 Multi-Objective Genetic Optimization

Model Center is used to perform the Multi-Objective Genetic Optimization (MOGO) through the use of the Darwin optimization plug-in. The objectives for this optimization are effectiveness, risk, and cost; which are discussed in Section 3.4. Figure 28 is a flow chart showing the MOGO process. The optimizer defines a random set of 200 balanced ships to populate the first generation. The ship synthesis model, described in Section 3.3, is used to calculate each ship's measure of effectiveness, measure of risk, and cost. Each design is then assigned a fitness level and ranked according to the design's dominance in the optimization objectives. Designs are penalized for bunching, known as a niche, or for infeasibility before being randomly selected to populate the second generation. These randomly selected designs are weighted to ensure higher selection probabilities for ships with higher fitness levels. Twenty-five percent of the second generation's designs are selected to swap some of their design variable values, known as crossover. A small percentage of randomly selected design variable values are selected for mutation, which replaces it with a new random value. Each generation of ships are spread across the effectiveness/cost/risk three-dimensional design space. After about 300 generations of evolution, a non-dominated frontier forms a surface of designs with the highest effectiveness for a given cost and risk. Figure 30 shows the non-dominated frontier. The optimal design is determined by preferences for effectiveness, cost, and risk.

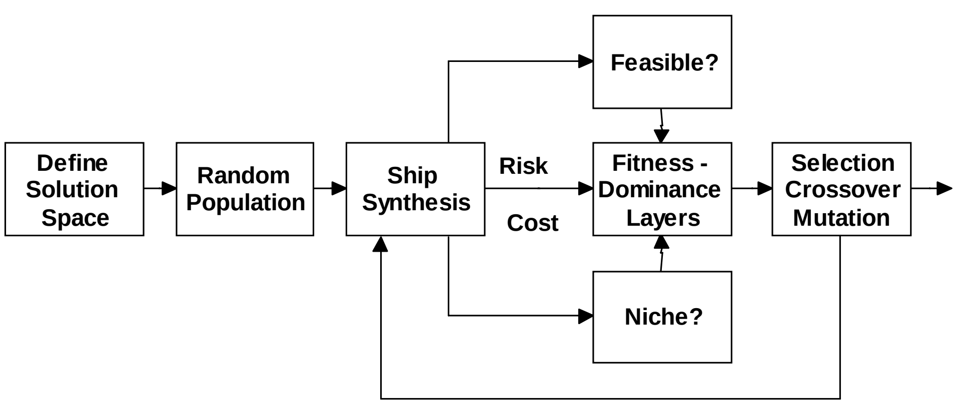


Figure 28 - Multi-Objective Genetic Optimization (MOGO)

Quantitative objective functions are developed for each optimization objective before performing the optimization. Cost is already quantitative, while an overall measure of effectiveness (OMOE) and overall measure of risk (OMOR) are used to quantify effectiveness and risk. Figure 29 illustrates the development of the OMOR and OMOE which are described in Sections 3.4.1 and 3.4.2.

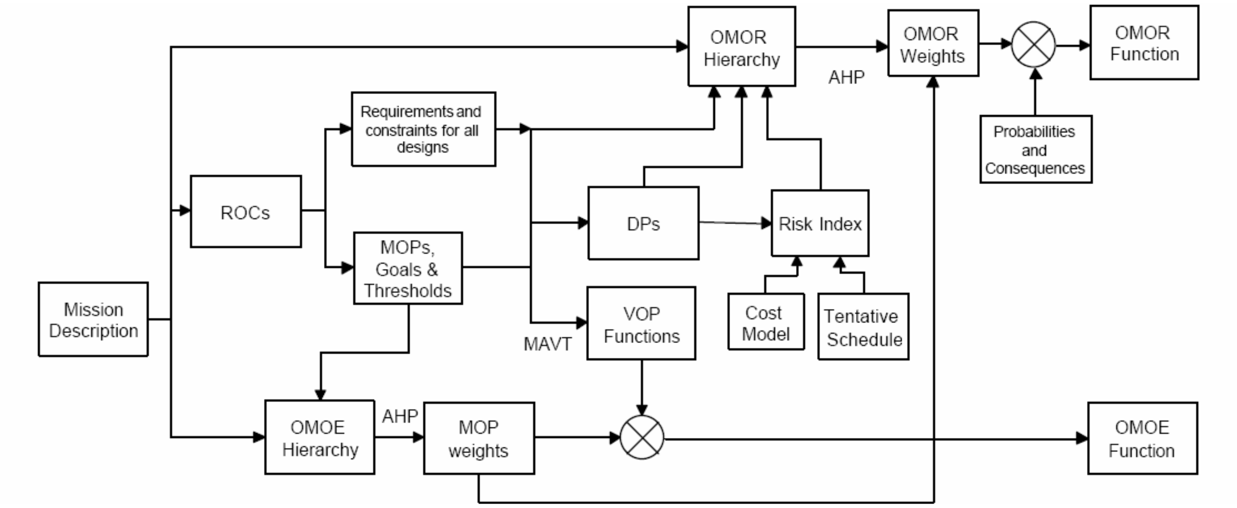


Figure 29 – OMOE and OMOR Development Process

3.6 Multi-Objective Genetic Optimization Results

Figure 30 shows the non-dominated frontier for effectiveness/cost/risk produced by the multi-objective genetic optimization. The plot shows the OMOE for a given cost ship design. The OMOR is displayed by color, blue being the lowest risk and red the highest. The highest OMOR displayed is 0.432. Designs that are most attractive to the customer are often those that occur at extremes of the frontier, or at “knees” in the curve. The “knees” represent a sharp increase in effectiveness with a minimal cost or risk increase.

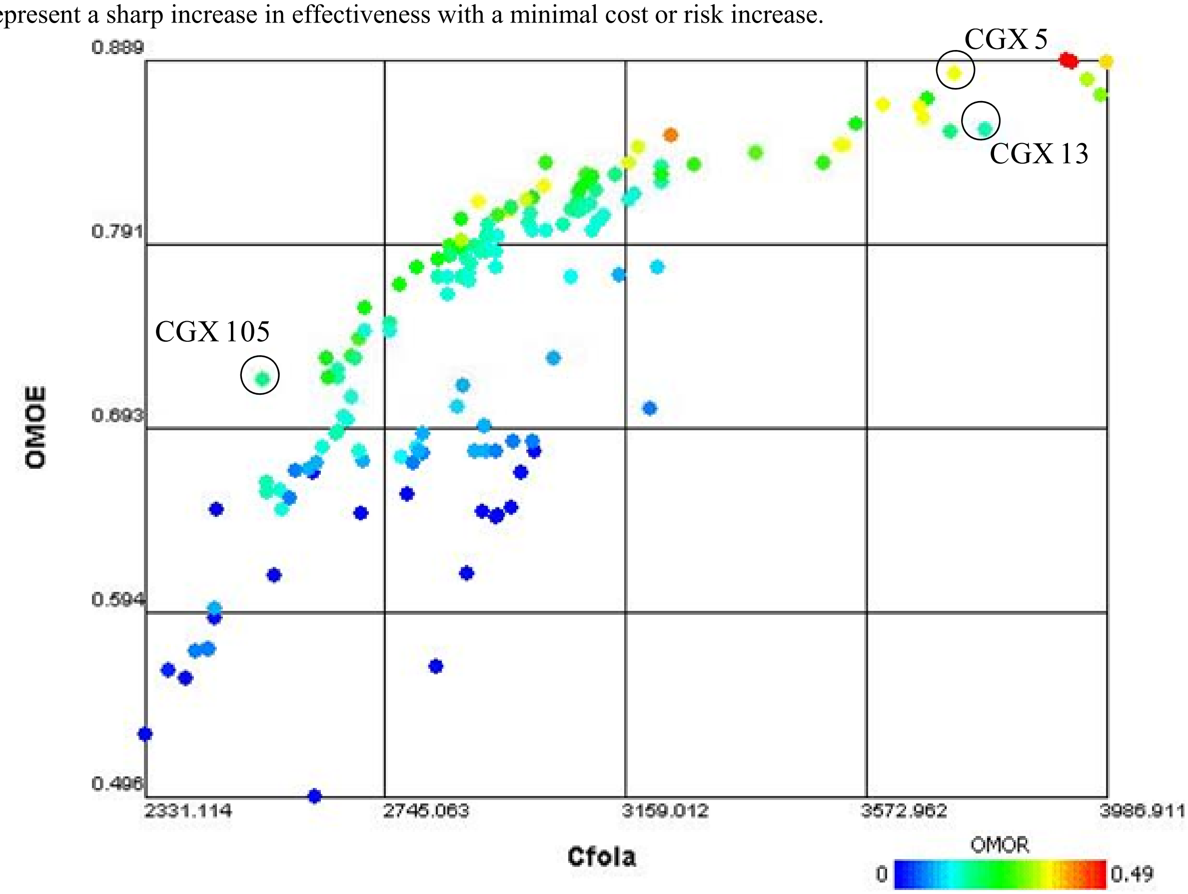


Figure 30 - Non-Dominated Frontier

The design selected for Team 2 is Design 13. CGX 13 is the high end design with low risk compared to similarly priced ships. The design has a cost of 3.63 billion dollars, a high OMOE of 0.852, and a low OMOR of 0.1715. Table 19 is a comparison table of some of the considered designs. It shows the OMOE, Cfola, OMOR, and some design variables for each design. Better explanations of the design variables are in Table 20. CGX 105 is an example of a ship at a "knee" in the curve with the highest OMOE in its low cost range of 2.5 billion dollars. CGX 5 has the highest OMOE in the same price range as the selected CGX 13. Due to its tumblehome hull it has a higher OMOR of 0.354.

Table 19 – Comparison Table

Design	High-end tumblehome CGX 5	High-end, low risk CGX 13	Low-cost ship CGX 105
OMOE	0.8812502	0.8518817	0.7178035
Cfola	3725.702	3781.044	2535.864
OMOR	0.3543412	0.1756953	0.1869418
Hull Type	2 (DDG-1000 mod-repeat)	1	1
SPGM	5	7	5
Prop Type	3	3	1
DISTtype	1	1	1
PMM	1	1	1
Ndegaus	1	0	1
Ts	40	50	33
Ncps	2	2	1
AAW	1	1	3
ASUW	3	2	3
ASW	1	1	4
CCC	1	1	1
GMLS	1	1	4
LAMPS	1	1	1
PGM	17	17	14
LWL	265	240	203
LtoB	7	9.4	9
LtoD	16.2	15.7	15.3
BtoT	2.91	3.03	2.96
Cp	0.621	0.593	0.614
Cx	0.751	0.849	0.815
Crd	0.6	0.66	0.6
VD	15900	13000	10600
CMan	0.69	0.94	0.84

3.7 MOGO Baseline Concept Design

Design 13 has the lowest risk for non-dominated designs in the same price and effectiveness range. Its low level of risk is due in large part to its flared hullform. The tumblehome hull drives up the risk. The manning coefficient, (C_{MAN}) is also very high for Design 13 and this also reduces risk associated with the design. The high C_{MAN} means low automation and this also helps keep cost low. Other options that keep cost low are the ASUW option of one MK45 5"/62 gun and two RHIBs and the ASW option.

Because of the importance of the primary mission of BMD, the largest radar available, the SPY-3/VSR+++, is selected along with 160 MK57 cells and 8 KEI cells.

It is important to note that the cost used for optimization was follow ship cost, not total ownership cost. If total ownership cost were used for optimization and to build the non-dominated frontier for comparison of optimized designs, designs with very high C_{MAN}, such as Design 13, might not have proven to be the best ship choice. This is because high C_{MAN} means very high manning, which results in a significant life cycle cost penalty. However, for the design process used, Design 13 stands out as a "knee in the curve" and a very capable ship. Table 20 shows design variable values corresponding to the multi-objective genetic optimization results for Design 13.

Other characteristics of the MOGO Baseline design are listed in Table 21 through **Table 25**.

Table 20 - Design Variables Summary for Design 13

Design Variable	Description	Trade-off Range	Design Values
DV 1	LWL - Waterline Length	180-300m	240 m
DV 2	LtoB - Length to Beam ratio	7.0-10.0	9.4
DV 3	LtoD - Length to Depth ratio	10.75-17.8	15.7
DV 4	BtoT - Beam to Draft ratio	2.8-3.2	3.03
DV 5	Cp - Prismatic coefficient	0.56 – 0.64	.593
DV 6	Cx - Maximum section coefficient	0.75 – 0.85	.849
DV 7	Crd - Raised deck coefficient	0.7 – 0.8	.66
DV 8	VD - Deckhouse volume	10,000-15,000 m^3	13000 m^3
DV 9	HULLtype - Hull: Flare or DDG 1000	1: flare= 10 deg; 2: flare = DDG 1000	1: flare= 10°
DV 10	PGM - Power Generation Module	Option 1) 2xLM2500+, AC synchronous, 4160 VAC Option 2) 2xLM2500+, AC synchronous, 13800 VAC Option 3) 2xLM2500+, SCH generator, 4160 VAC Option 4) 2xLM2500+, SCH generator, 13800 VAC Option 5) 3xLM2500+, AC synchronous, 4160 VAC Option 6) 3xLM2500+, AC synchronous, 13800 VAC Option 7) 3xLM2500+, SCH generator, 4160 VAC Option 8) 3xLM2500+, SCH generator, 13800 VAC Option 9) 2xMT30, AC synchronous, 4160 VAC (DDG 1000) Option 10) 2xMT30, AC synchronous, 13800 VAC Option 11) 2xMT30, SCH generator, 4160 VAC Option 12) 2xMT30, SCH generator, 13800 VAC Option 13) 3xMT30, AC synchronous, 4160 VAC Option 14) 3xMT30, AC synchronous, 13800 VAC Option 15) 3xMT30, SCH generator, 4160 VAC Option 16) 3xMT30, SCH generator, 13800 VAC Option 17) 4xMT30, AC synchronous, 4160 VAC Option 18) 4xMT30, AC synchronous, 13800 VAC Option 19) 4xMT30, SCH generator, 4160 VAC Option 20) 4xMT30, SCH generator, 13800 VAC	Option 17
DV 11	SPGM - Secondary Power Generation Module	Option 1) none Option 2) 2xLM500G, geared, w/AC sync (DDG 1000) Option 3) 2xMC5.0 Fuel Cells Option 4) 2xMC8.5 Fuel Cells Option 5) 2xPEM5.0 Fuel Cells Option 6) 2xPEM8.5 Fuel Cells Option 7) 2xCAT 3618 Diesel Option 8) 2xPC 2/18 Diesel	Option 7
DV 12	PROPtype - Propulsor type	Option 1) 2xFPP *(DDG 1000) Option 2) 2xPods Option 3) 1XFPP + SPU (7.5MW)	Option 3
DV 13	DISTtype - Power distribution type	Option 1) AC ZEDS Option 2) DC ZEDS *(DDG 1000)	Option 1
DV 14	PMM - Propulsion Motor Module	Option 1) AIM (Advanced Induction Motor) *(DDG 1000) Option 2) PMM (Permanent Magnet Motor) Option 3) SCH (Superconducting Homopolar Motor)	Option 1
DV 15	Ts - Provisions duration	60-75 days	50 days
DV 16	Ncps - Collective Protection System	0 = none, 1 = partial, 2 = full	2 = full
DV 17	Ndegaus - Degaussing system	0 = none, 1 = degaussing system	0 = none
DV 18	CMan - Manning reduction and automation factor	0.5 – 0.1	0.94
DV 19	AAW/BMD/STK - 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	Option 1

Design Variable	Description	Trade-off Range	Design Values
		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 w/ NULKA	
DV 20	ASUW/NSFS - Anti-Surface Warfare 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	Option 2
DV 21	ASW/MCM - Anti-Submarine Warfare alternatives	Option 1) Dual Frequency Bow Array, IUSW, NIXIE, 2xSVTT, mine-hunting sonar Option 2) SQS-53C, NIXIE, SQR-19 TACTAS, IUSW, 2xSVTT, mine-hunting sonar Option 3) SQS-56, NIXIE, IUSW, 2xSVTT, mine-hunting sonar Option 4) NIXIE, 2xSVTT, mine-hunting sonar	Option 1
DV 22	CCC - Command Control Communication alternatives	Option 1) Enhanced CCC, TSCE Option 2) Basic CCC, TSCE	Option 1
DV 23	LAMPS - LAMPS alternatives	Option 1) 2 x Embarked LAMPS w/Hangar, 2xVTUAV Option 2) LAMPS haven (flight deck), 2xVTUAV Option 3) in-flight refueling, 2xVTUAV	Option 1
DV 24	GMLS - Guided Missile Launching System alternatives	Option 1) 160 cells MK57 + 8 cells KEI Option 2) 160 cells MK57 Option 3) 128 cells MK 57 Option 4) 96 cells MK 57	Option 1

Table 21 – MOGO Design 13 Weights and Vertical Center of Gravity Summary

Group	Weight (MT)	VCG (m)
SWBS 100	7791.51	37.53
SWBS 200	1799.18	4.12
SWBS 300	1685.76	7.50
SWBS 400	1256.69	21.90
SWBS 500	2378.11	20.36
SWBS 600	1389.48	29.63
SWBS 700	818.33	40.75
Loads	5610.40	32.04
Lightship	18831	10.71
Lightship w/Margin	20542	10.77
Full Load w/Margin	24441	9.71

Table 22 – MOGO Design 13 Area Summary

Area	Required (m^2)	Available (m^2)
Total Arrangeable	13,941.80	14,037.80
Deck House	2,130.98	4,683.50
Hull	127,131.10	100689.2

Table 23 – MOGO Design 13 Ship Service Electric Power Summary

Group	Description	Power (kW)
SWBS 200	Propulsion	158400.0
SWBS 300	Electric Plant, Lighting	511.4
SWBS 430, 475	Miscellaneous	101.4
SWBS 521	Firemain	269.9
SWBS 540	Fuel Handling	337.1
SWBS 530, 550	Miscellaneous Auxiliary	261.3
SWBS 561	Steering	149.6

Group	Description	Power (kW)
SWBS 600	Services	158.8
CPS	CPS	324.1
KW_{NP}	Non-Payload Functional Load	2749.5
KW_{MFLM}	Max. Functional Load w/Margins	18989.6
KW_{24}	24 Hour Electrical Load	9481.4

Table 24 – MOGO Design 13 MOP/ VOP/ OMOE/ OMOR Summary

Measure	Description	Related Design Variable Selected	Value of Performance
MOP 1	BMD	BMD=1 GMLS=1 CCC=1	1.0
MOP 2	AAW	AAW=1 GMLS=1 CCC=1	1.0
MOP 3	ASUW/NSFS	ASUW=2 LAMPS=1 CCC=1	0.851
MOP 4	ASW/MCM	ASW=1 LAMPS=1 CCC=1 MCM=1	1.0
MOP 5	CCC	CCC=1	1.0
MOP 6	ISR/SOF	LAMPS=1 CCC=1	0.98
MOP 7	Surge Speed	32.2 knt	0.616
MOP 8	Vs	32.2 knt	0.989
MOP 9	E	8000nm	1.0
MOP 10	Ts	50	0.0
MOP 11	Seakeeping	15.5	0.435
MOP 12	VUL		0.683
MOP 13	NBC	Ncps=2	1.0
MOP 14	RCS	VD=13000m^3	0.616
MOP 15	Acoustic Signature	SPGM=7	1.0
MOP 16	IR Signature	PGM=4xTurbine SPGM=7	1.0
MOP 17	Magnetic Signature	Ndegaus = 1	0.149
OMOE	Overall Measure of Effectiveness		0.852
OMOR	Overall Measure of Risk		0.1715

Table 25 – MOGO Design 13 Principal Characteristics

Characteristic	Baseline Value
Hull form	Flared
Δ (MT)	24441.4
LWL (m)	221.7
Beam (m)	23.48
Draft (m)	7.59
D10 (m)	13.64
Displacement to Length Ratio, $C_{\Delta L}$ (lton/ft^3)	0.000073
Beam to Draft Ratio, C_{BT}	3.09
W1 (MT)	7791.51
W2 (MT)	1799.18
W3 (MT)	1685.76
W4 (MT)	1256.69
W5 (MT)	2378.11
W6 (MT)	1389.48
W7 (MT)	818.33

Characteristic	Baseline Value
Wp (MT)	439.75
Lightship Δ (MT)	18831
KG (m)	9.71
GM/B=	0.06
Propulsion system	1XFPP + SPU (7.5MW)
MCM system	Dual Frequency Bow Array, IUSW, NIXIE, 2xSVTT, mine-hunting sonar
ASW system	Dual Frequency Bow Array, IUSW, NIXIE, 2xSVTT
ASUW system	1xMK45 5"/62 gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod1 3x CIGS
AAW system	SPY-3/VSR+++ DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA
Average deck height (m)	3
Total Officers	31
Total Enlisted	421
Total Manning	452
Number of VTUAVs	2
Number of LAMPS	2
Follow Ship Acquisition Cost (million dollars)	3629.54
Life Cycle Cost (million dollars)	4543.6
McCreight Index	57.3

3.8 Single Objective Re-Optimization

With Design 13 chosen from the non-dominated frontier created by multi-objective genetic optimization, another step is taken to further optimize the design. Model Center is reconfigured with a single objective gradient optimizer in place of the multi-objective genetic optimizer. The model is first seeded with the design variables of Design 13 from the non-dominated results. Next, the gradient optimizer is configured to vary only the continuous design variables. The discrete variables, such as combat systems, remain unchanged. The gradient optimizer is set to optimize the design for maximum overall measure of effectiveness (OMOE). The optimizer runs until it converges on a feasible, optimal design. The Model Center gradient optimizer is moderately dependent on starting point. After some trial-and-error, a starting point was found that led to an improved design.

The results of this optimization are shown in the figures and tables below. Figure 31 shows OMOE versus run number, and Figure 32 shows follow ship cost (Cfola) versus run number. These figures show the progression of the single objective optimization process. After single objective optimization, the OMOE and Cfola both improved.

improved design (Design 13I) is because of the significant cost reduction obtained by shortening the ship

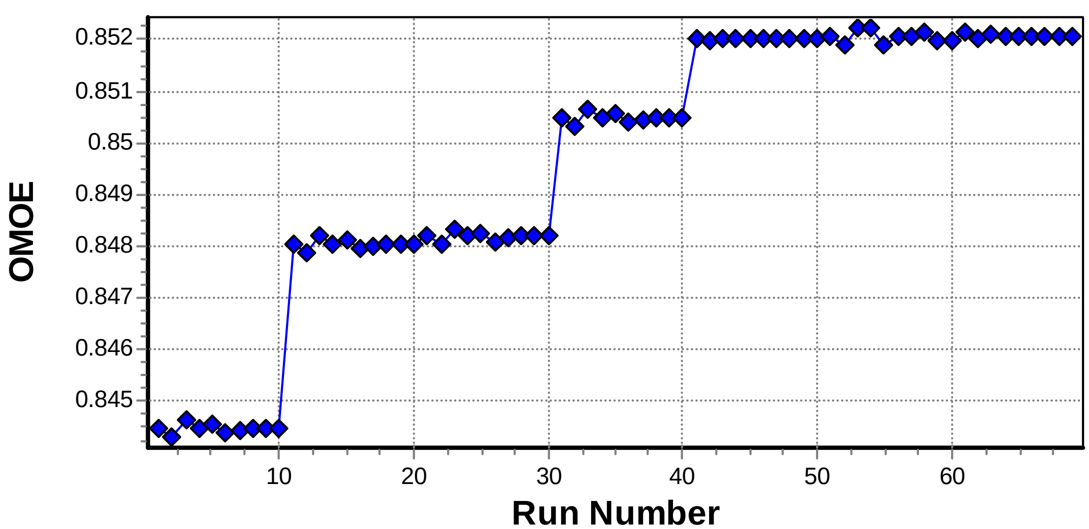


Figure 31 – Run Number versus OMOE

Table 26 shows the continuous variables before and after single objective optimization. The most striking change is the decrease in waterline length from 240m to 221.7m. This decrease in length was made possible by the selection of 4xMT30 turbines as the powering option and a significant increase in prismatic coefficient. With this significant decrease in length comes a significant decrease in cost, and this was the driving factor in the optimization. Cost and Risk from Design 13 were constraints. The manning coefficient (CMan) actually increased to a very conservative 0.9831. Correspondingly, overall risk (OMOR) decreased slightly. The reason such a large change is seen in Single Objective Optimization from Design 13 to the

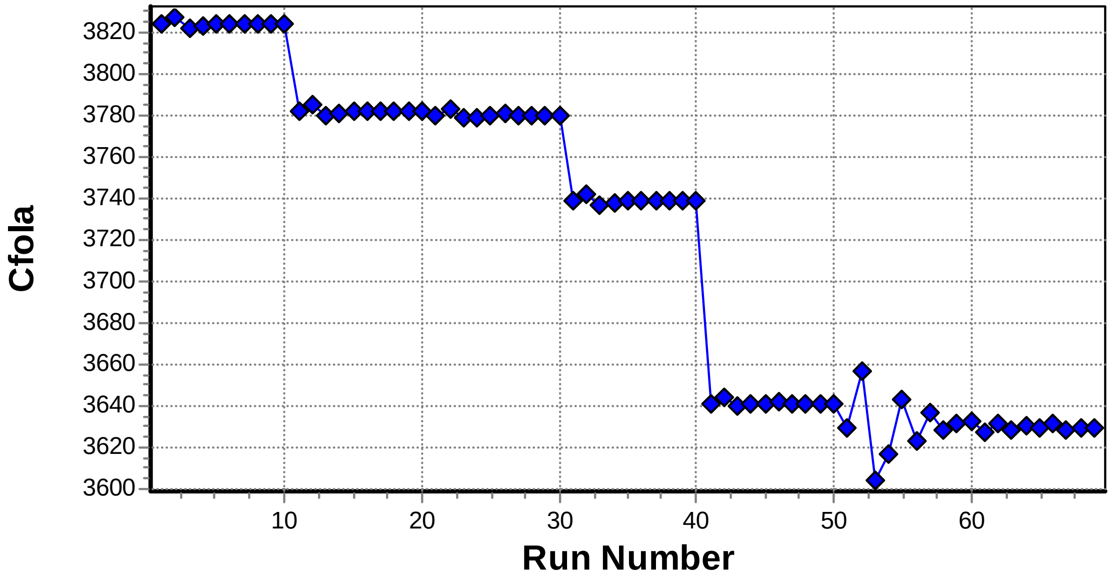


Figure 32 – Run Number versus Cfola

Table 26 – Single Objective Optimization Results

Design	Design 13	Design 13I
OMOE	0.8518817	0.852061
Cfola	3781.044	3629.538
OMOR	0.1756953	0.171502
LWL	240	221.7
LtoB	9.4	9.442073
LtoD	15.7	16.24692
BtoT	3.03	3.092869
Cp	0.593	0.677651
Cx	0.849	0.87049
Crd	0.66	0.521754
VD	13000	14050.47
CMan	0.94	0.9831

3.9 Design 13I Feasibility Study in ASSET

The ship modeling and synthesis tool, ASSET, is next used to study the feasibility of the ship design chosen in optimization. ASSET consists of many "modules" which perform various calculations. The modules work with data input into the "Editor." The Editor is a large spreadsheet-like space where all information pertaining to the ship is stored. For this design, ASSET is first populated with variables from a standard "cruiser" baseline ship from the ASSET databank. Next, principle hullform characteristics resulting from the single objective re-optimization of the chosen ship design are input and the ASSET hullform modules are run. DDG-51 is used as a parent hullform for ASSET to stretch and modify based on specific design characteristics.

Next, ASSET's Editor is populated with the Design 13I variable values, such as combat systems and machinery options, specific to the ship chosen in optimization. Payloads and Adjustments are specified in ASSET according to combat options chosen in optimization. Deck and bulkhead spacing, as well as machinery room location, propulsion type, and many other details must be specified by the user. All of this information is used by ASSET's modules to perform calculations and produce reports.

Each of ASSET's modules are first run one by one in order and adjustments are made to variables in the Editor until the modules are running properly, without errors. Special add-on wizards, such as the ASSET ZEDS wizard, are run to adjust the model's payload and adjustments appropriately. Once all of the modules are running correctly, ASSET "synthesis" is run to converge all the modules results to a single feasible point. Successful convergence implies a feasible design.

After ASSET successfully converged, results were compared to the calculated results from the Model Center optimization. In order to gain close agreement between the optimization results and the ASSET results, some tweaking of the ASSET model was necessary. For example, the structural material properties were corrected to gain agreement on structural weight, and the fuel tankage was reduced. Some other changes were made to improve the layout of the ship. One such change was the movement of the raised deck back to 0.60 of the length of the ship. This was done to ease arrangement of the intake and exhaust stacks for the aft main machinery room.

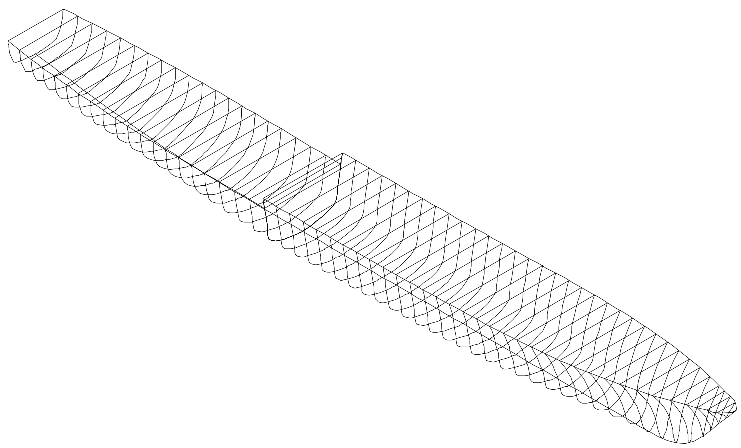


Figure 33 – ASSET 13IA Hullform Isometric View

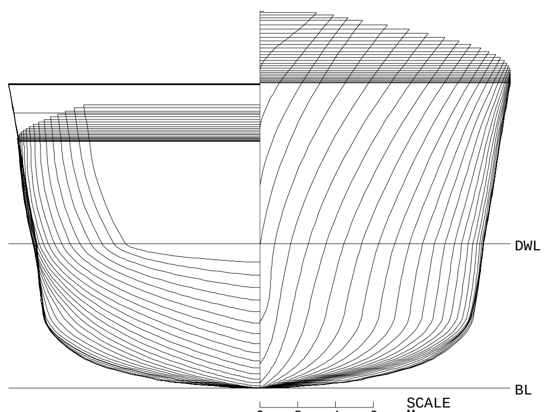


Figure 34 – ASSET Design 13IA Hullform Body Plan View

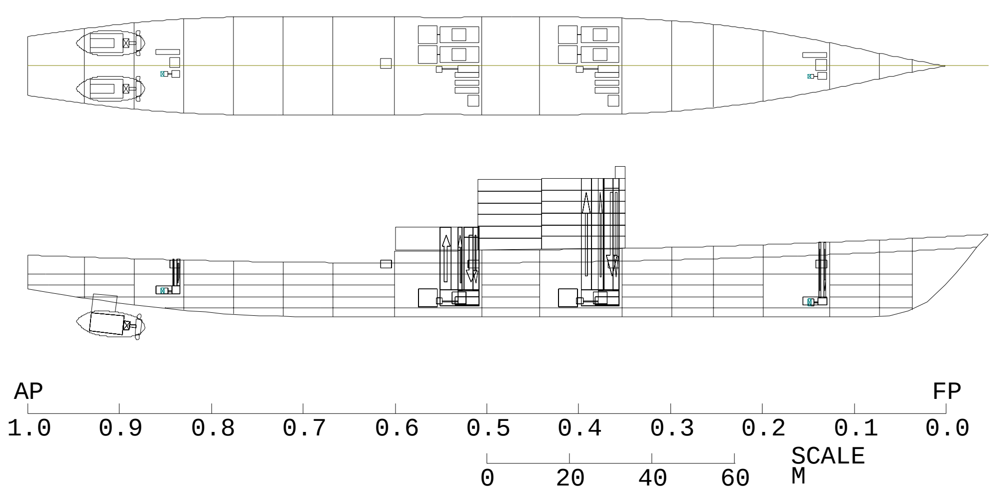


Figure 35 – ASSET Design 13IA Machinery Module Profile View

The results of ASSET modeling are shown below. Figure 33 shows the Hull Geometry Module isometric view of the hullform. This hullform will be further developed in Concept Development. Figure 34 shows the body plan view from the same module. Figure 35 shows the profile view from the Machinery Module. This view shows the primary and secondary propulsion generators in the main machinery rooms and the emergency diesel generators in fore and aft machinery rooms. Table 27 shows the design summary report from ASSET, which includes a SWBS weight summary. The hull structures weight is very high in this ASSET study. This was reduced to 8000 tons in Concept Development. The results of the ASSET study (Design 13IA) serve as the Final Baseline Design. Table 28 shows a comparison between the MOGO results (Design 13), Single Object results (Design 13I), and ASSET results (13IA). The key parameters such as displacement and waterline, agree closely between 13I and 13IA, but deckhouse volume and depth were changed for geometry and arrangement reasons.

Table 27 – ASSET Design Summary

PRINCIPAL CHARACTERISTICS - M		WEIGHT SUMMARY - MTON	
LBP	221.7	GROUP 1 - HULL STRUCTURE	9455.7
HULL LOA	232.0	GROUP 2 - PROP PLANT	1938.7
BEAM, DWL	23.5	GROUP 3 - ELECT PLANT	1039.2
DEPTH @ STA 10	16.0	GROUP 4 - COMM + SURVEIL	1202.2
DRAFT TO KEEL DWL	7.6	GROUP 5 - AUX SYSTEMS	2207.4
DRAFT TO KEEL LWL	7.6	GROUP 6 - OUTFIT + FURN	1553.4
FREEBOARD @ STA 3	10.2	GROUP 7 - ARMAMENT	848.5
GMT	1.9		
CP	0.678	SUM GROUPS 1-7	18245.1
CX	0.871	DESIGN MARGIN	2282.9
LIGHTSHIP WEIGHT	20528.0		
SPEED(KT):	MAX= 34.0, SUST= 32.2	LOADS	4410.8
ENDURANCE:	8158.7 NM AT 20.0 KTS		
FULL LOAD DISPLACEMENT	24938.8		
TRANSMISSION TYPE:	IPS	FULL LOAD KG: M	9.1
MAIN ENG:	4 GT @ 36000.0 KW		
SEC ENG:	2 D DIESEL @ 5059.6 KW	MILITARY PAYLOAD WT- MTON	2798.7
SHAFT POWER/SHAFT:	51999.1 KW	USABLE FUEL WT - MTON	3500.0
PROPULSORS:	2 - FP 6.1 M DIA		
SEP GEN:	2 D DIESEL @ 500.0 KW		
PD GEN:	6 DC-BUS @ 5000.0 KW		
OFF CPO ENL	TOTAL		
24-HR LOAD	13531.4	MANNING	31 35 386 452
MAX MARG ELECT LOAD	28425.2	ACCOM	31 35 386 452
REQUIRED AREA SUMMARY - M2		AVAILABLE AREA SUMMARY - M2	
OTHER AREA	14159.	HULL AREA	13248.
SUPERSTRUCTURE AREA	4362.	SUPERSTRUCTURE AREA	5758.
TOTAL AREA	18521.	TOTAL AREA	19006.
REQUIRED VOLUME SUMMARY - M3		AVAILABLE VOLUME SUMMARY - M3	
OTHER VOLUME	61315.	HULL VOLUME	60115.
SUPERSTRUCTURE VOLUME	12213.	SUPERSTRUCTURE VOLUME	17046.
TOTAL VOLUME	73528.	TOTAL VOLUME	77161.

Table 28 – Baseline Design Comparisons

Characteristic	13	13I	13IA
OMOE	0.852	0.852	0.852
Cfola ($M)	3,780	3,630	3,630
OMOR	0.176	0.171	0.171
LWL (m)	240	221.7	221.7
Beam (m)	25.5	23.5	23.5
Depth (m)	15.3	13.7	16.0
Draft (m)	8.43	7.59	7.6
Cp	0.593	0.678	0.678
Cx	0.849	0.871	0.871
VD (m^3)	13,000	14,050	17,040
Full Load Displacement (MTON)	28,590	24,440	24,940

The final requirements developed to constrain concept development are listed in Table 29. It must be a very capable ship, being able to carry a large armament load, attain 32.2 knots sustained speed, and have a range of over 8000 nm. It will carry a large DBR system and dual embarked LAMPS and RHIBs.

Table 29 – Key Performance Parameters

Key Performance Parameter (KPP)	Development Threshold or Requirement
AAW/BMD/STK	SPY-3/VSR+++ DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ-32(R) improved, MK36 SRBOC with NULKA
ASUW/NSFS	1xMK45 5"/62 gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod2 3xCIGS
ASW/MCM	Dual Frequency Bow Array, ISUW, NIXIE, 2xSVTT, Mine-Avoidance Sonar
CCC	Enhanced CCC
LAMPS	2xEmbarked LAMPS w/Hangar, 2xVTUAV
SDS	SLQ-32(V) 3, SRBOC, NULKA, ESSM
GMLS	160 cells MK57, 8 cells KEI
Hull	Flare - 10 deg.
Power and Propulsion	2 shaft, 2 pods FPP
Endurance Range (nm)	8000
Sustained Speed (knts)	32.2
Endurance Speed (kts)	20
Stores Duration (days)	50
Collective Protection System	full
Crew Size	452
RCS (m3)	14100
Maximum Draft (m)	7.6
Vulnerability (material)	Steel
Ballast/Fuel System	Clean, Separate Ballast Tanks
McCreight Seakeeping Index	15.5

4 Concept Development (Feasibility Study)

Concept Development of CGX/BMD 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 CDD requirements. Design risk is reduced by this analysis and parametrics used in Concept Exploration are validated.

4.1 Preliminary Arrangement (Cartoon)

As a preliminary step in finalizing hull form geometry, deck house geometry, and all general arrangements, an arrangement cartoon was developed for areas supporting mission operations, propulsion, and other critical constrained functions. Mission operation areas include the helo hanger and dual RHIB stern launch/recovery, as well as spaces for the KEI, VLS and Mk 45 5”. Propulsion areas are comprised of two main machinery rooms (MMR) and two auxiliary machinery rooms (AMR). Since we are using pods for propulsion, space for the shaft is not necessary. Figure 36 shows the preliminary arrangement drawing.

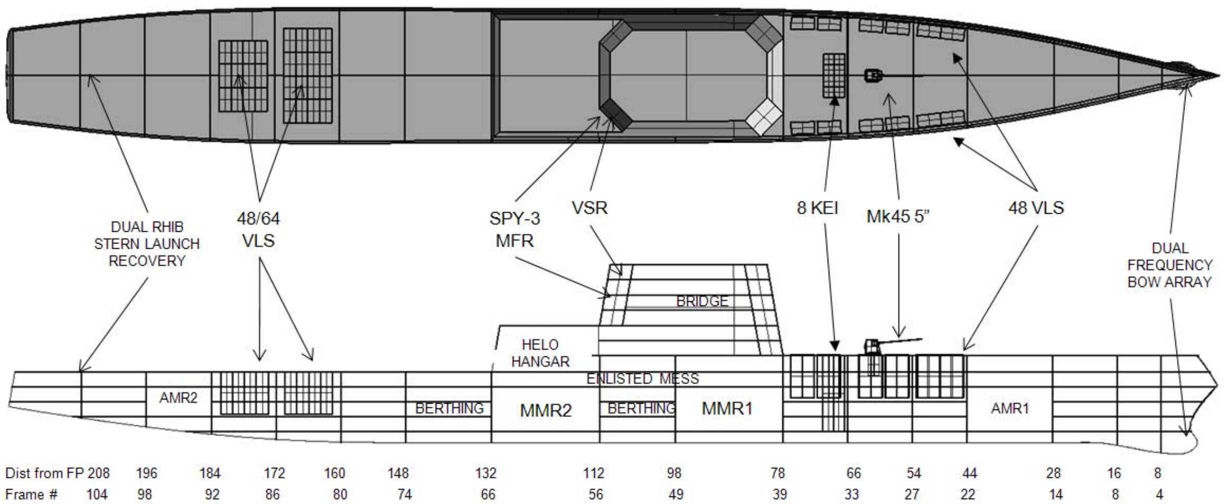


Figure 36 – Preliminary Arrangement

4.2 Hull Form and Deck House

4.2.1 Hullform

The DDG-51 parent hullform was imported directly from ASSET to the RHINO 3D modeling environment to develop a new CGX hullform. No changes were made below the waterline except for shaping the sonar dome, which can be seen in Figure 37. At 3 meters above the waterline, the topsides were angled in 10 degrees for reduced radar cross section. This angle was established in the Zumwalt Class Destroyer Program to provide minimal radar reflection. The resulting geometry of the hull is shown in Figure 38.

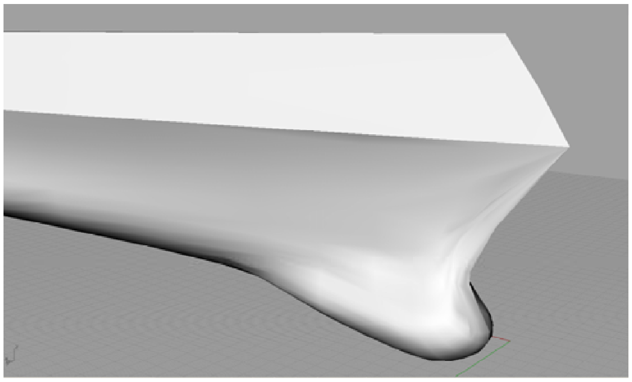


Figure 37 – Bow with Sonar Dome

Table 30 - CGXBMD Hullform Characteristics

	MOGO	Baseline
LWL	240	221.7
B	25.5	23.5
T	8.43	7.59
D_{10}	15.3	16
Δ	28,590	24,940
Cp	0.59	0.68
Cx	0.85	0.87

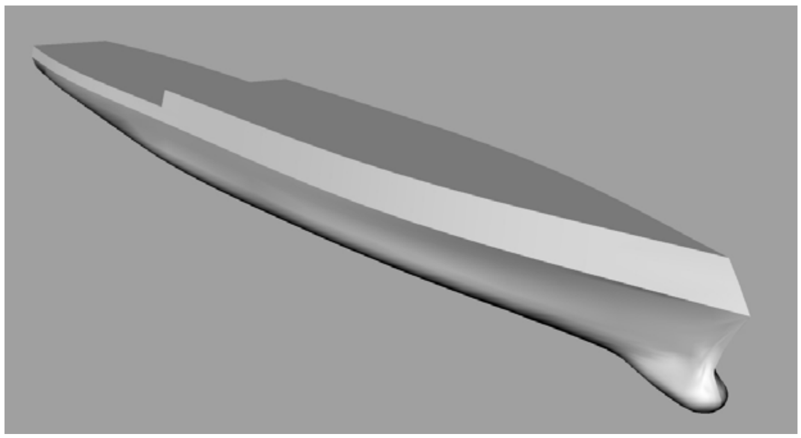


Figure 38 – Final Hull Geometry

The hybrid flare/tumblehome hullform was chosen for this design to limit the degradation of stability caused by a purely tumblehome hullform, while maintaining a stealthy profile. It is believed that the semi-wave piercing tumblehome hullform will significantly improve seakeeping performance over DDG 1000 type hullforms. Current seakeeping codes only consider the hullform below the waterline, so to determine seakeeping characteristics for this hull type, the application of more advanced codes or model testing is needed.

The 10 degree tumblehome from 3m above the waterline also simplifies the geometry of the hull. From 3m up, the hull is only single curvature plating or flat plating, which should increase producibility of the hull. The shear of the decks in the original hullform was also eliminated. The flat decks should increase producibility as well. Table 30 shows some principle characteristics for the hull. The depth at station 10 was set at 16.0 m for the hull to maintain a constant deck height.

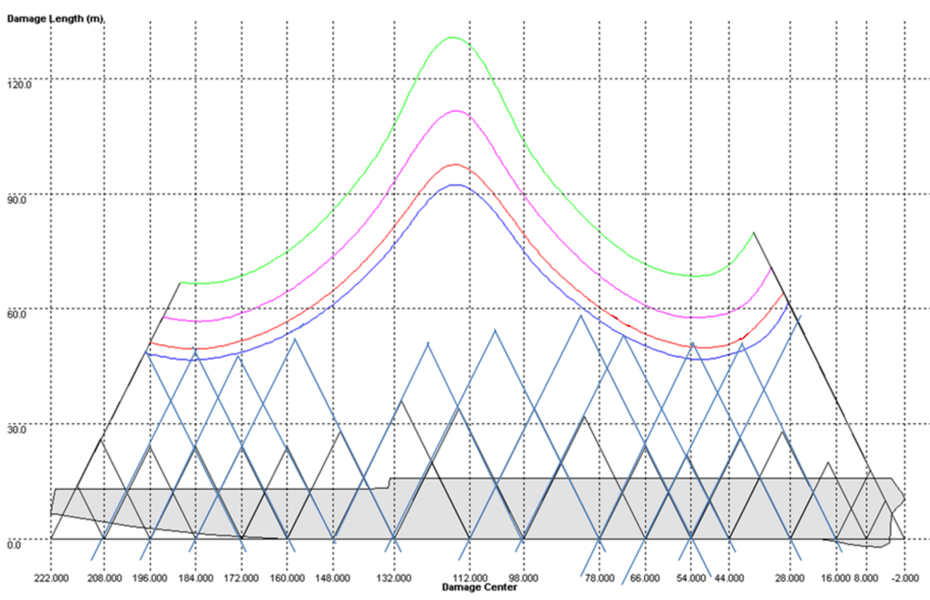


Figure 39 – Floodable Length Curve

Figure 39 shows the floodable length curve for the ship. The transverse bulkheads were placed in the ship so that the ship could survive a 15% damage case. The final damage stability assessment is described in Section 4.9.2. Figure 40 is the sectional area curve for the hull. Curves of form and lines drawing are included in the ship drawings.

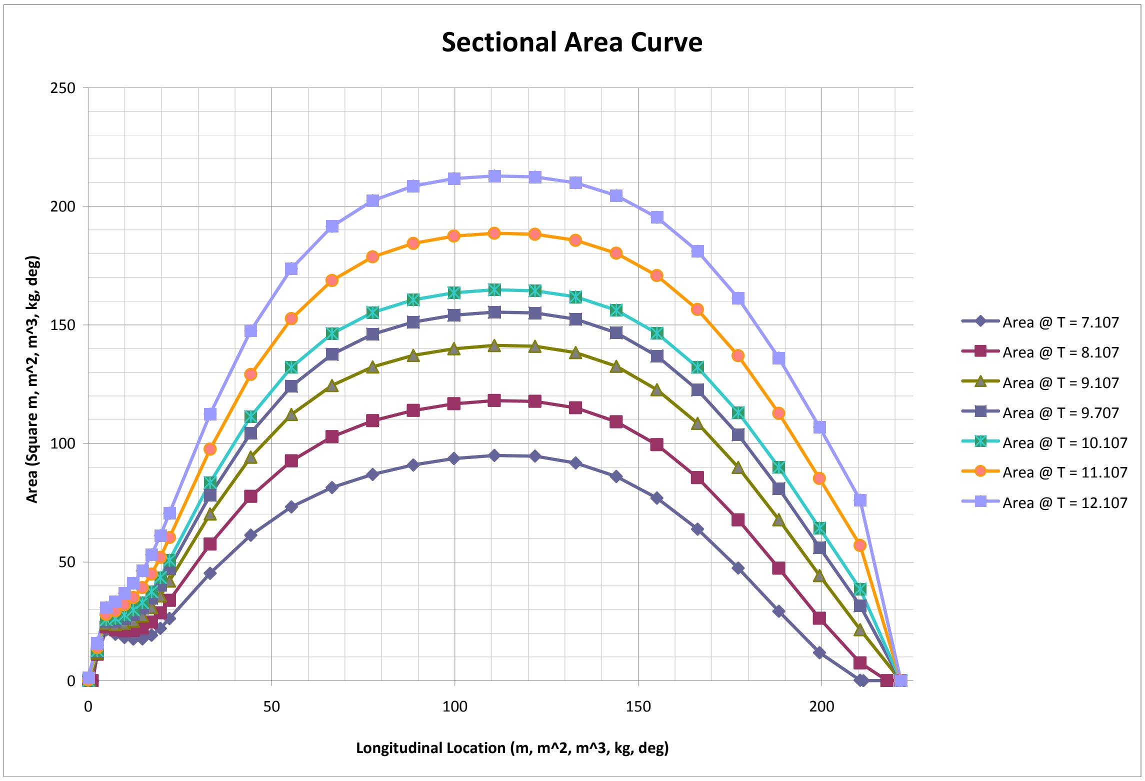


Figure 40 – Hullform Sectional Area

4.2.2 Deck House

After doing machinery arrangements, the deckhouse had to be changed in order to allow for the intake/exhaust stacks to be located inside the deckhouse and with a low radar cross section. The deckhouse was made longer so that the stacks would not penetrate the bulkheads in the deckhouse. In order to reduce the radar cross section of the ship, the composite deckhouse was created to be one unit, as shown in Figure 41, and is located amidships.

The 6 levels within the deckhouse accommodate the aviation hangar, aviation control, CO berthing, bridge, navigation and radio. The low bridge, navigation and radio accommodate the visual and IR sensors up top to maximize the radar height. Also included is the weapons shop and electronics shop. Officer's wardroom and galley is located on the first level, along with XO berthing space and berthing spaces for some department heads. Most of the upper levels contain radar and fan spaces for the SPY-3/VSR+++ DBR. Figure 42 shows detailed level arrangements.

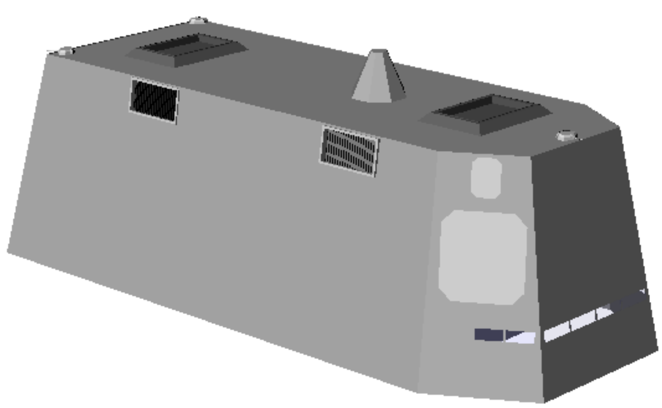
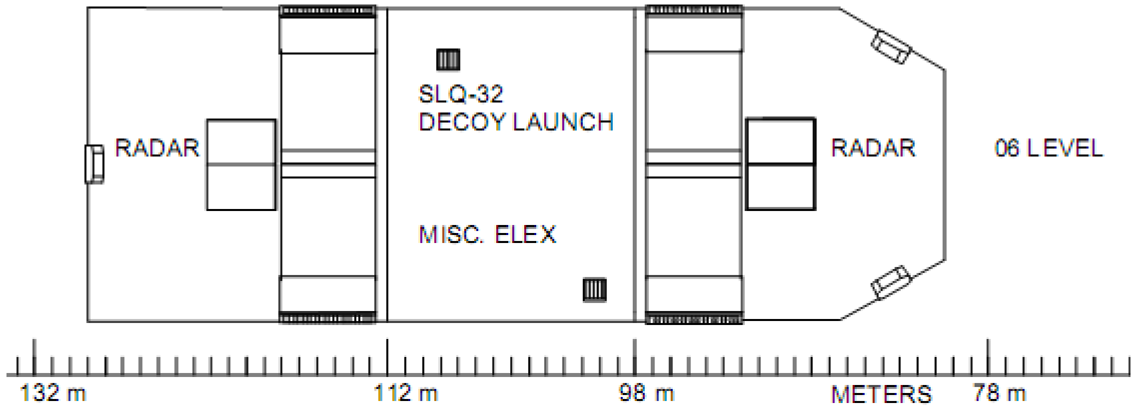


Figure 41 - Deckhouse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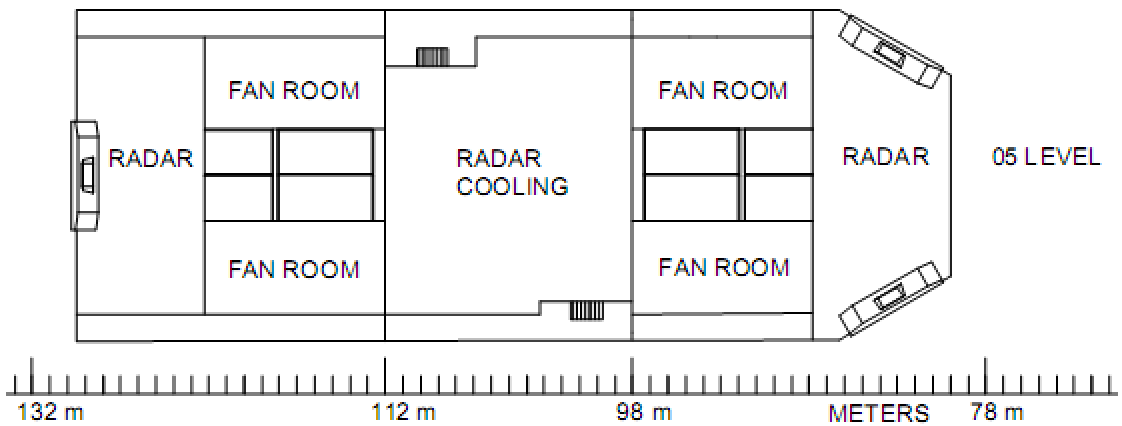
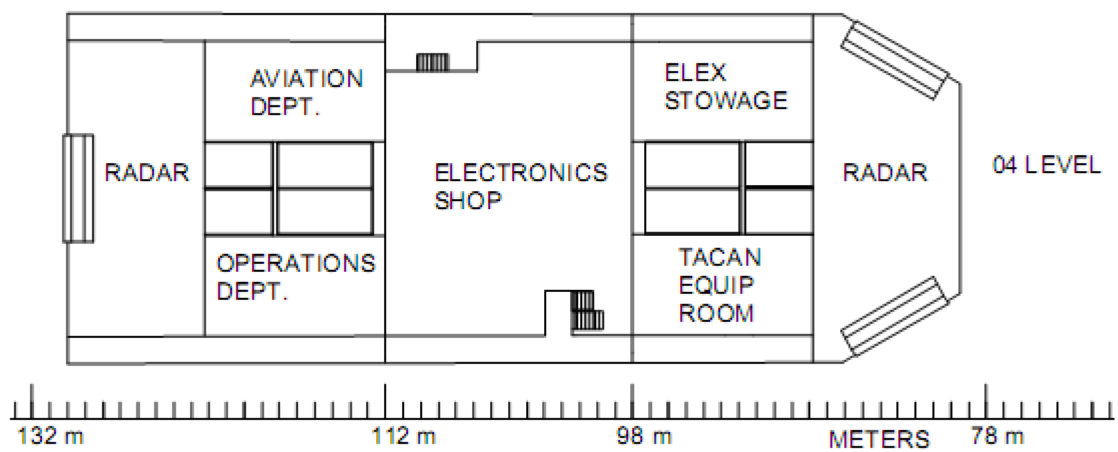
SLQ-32
DECOY LAUNCH
MISC. ELEX
RADAR
06 LEVEL
132 m
112 m
98 m
METERS
78 m


RADAR
FAN ROOM
FAN ROOM
RADAR
COOLING
FAN ROOM
FAN ROOM
RADAR
05 LEVEL
132 m
112 m
98 m
METERS
78 m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DEPT.
OPERATIONS
DEPT.
ELECTRONICS
SHOP
ELEX
STOWAGE
TACAN
EQUIP
ROOM
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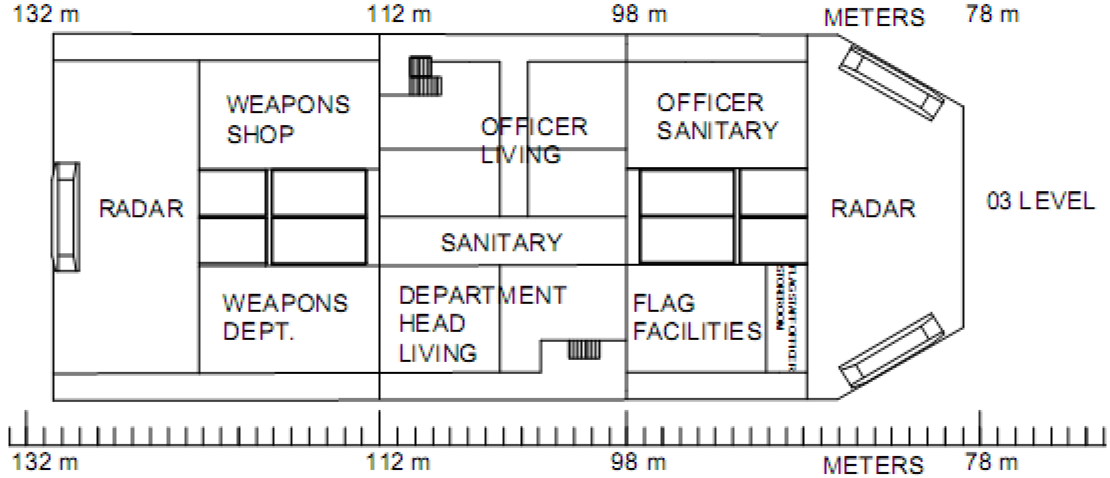
98 m
METERS
78 m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WEAPONS
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DEPARTMENT
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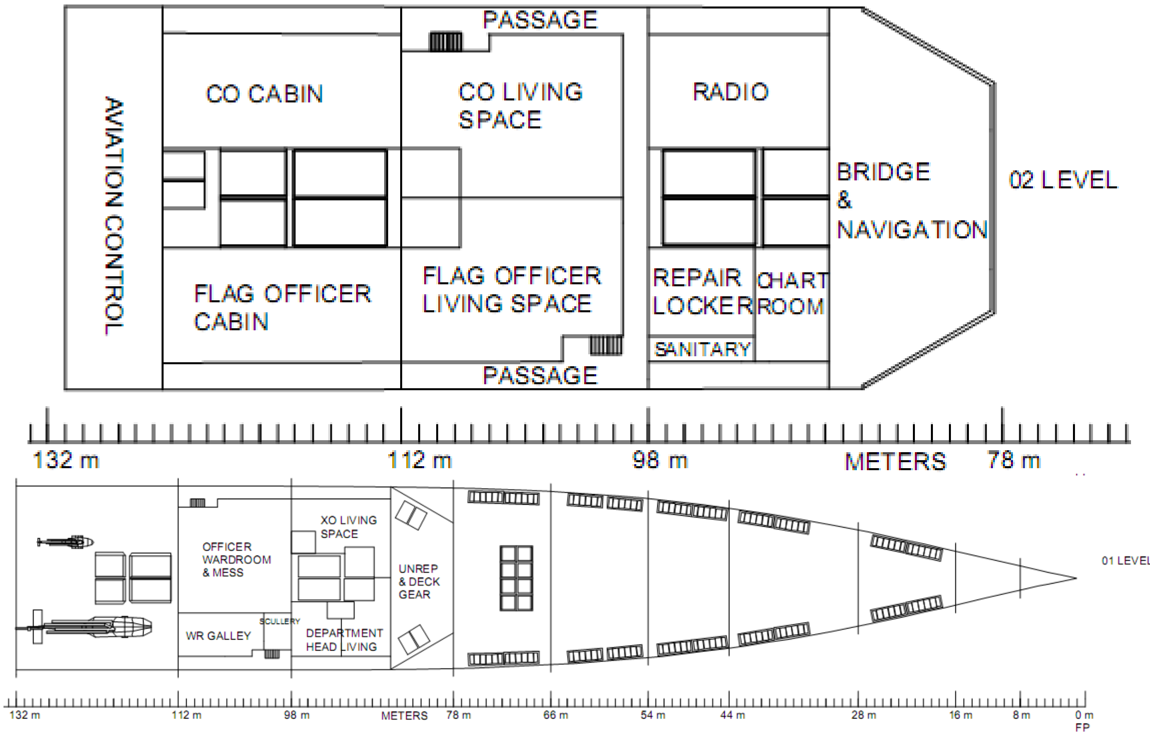


Figure 42 - Deckhouse Arrangements

4.3 Structural Design and Analysis

The iterative process that drives the structural design of the CG(X)-BMD is illustrated in, Figure 43. 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.

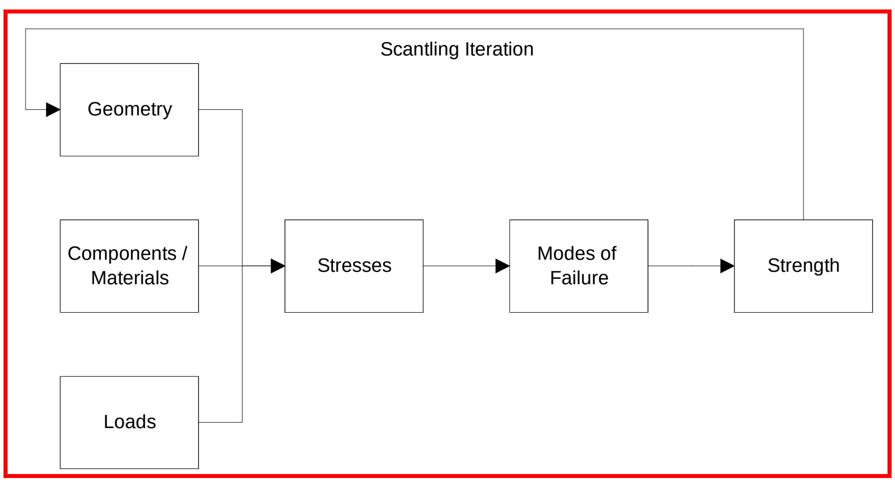


Figure 43 - Structural Design Process

4.3.1 Geometry, Components and Materials

Three midship modules of parallel midbody were modeled, analyzed, and optimized in MAESTRO and are illustrated in Figure 44. For simplicity, the aft section was modeled with a top deck that mirrors that of the fore section. To model the sections a logical number of endpoints are taken from the Rhino model and entered into MAESTRO. These endpoints are then connected with strakes that represent individual plates between girders. Properties for frames, girders, stiffeners, and plating that are produced by the ASSET Structures module must be entered for each strake. Transverse bulkheads are added to each section using quad and tri elements that only connect four or three points, rather than extending the whole length of a section. Longitudinal and transverse floors in the innerbottom are created using compounds of quad and tri elements that do extend the whole length of the section. Stanchions can be defined and added using rod elements. The completed MAESTRO model is illustrated in Figure 45 and Figure 46.

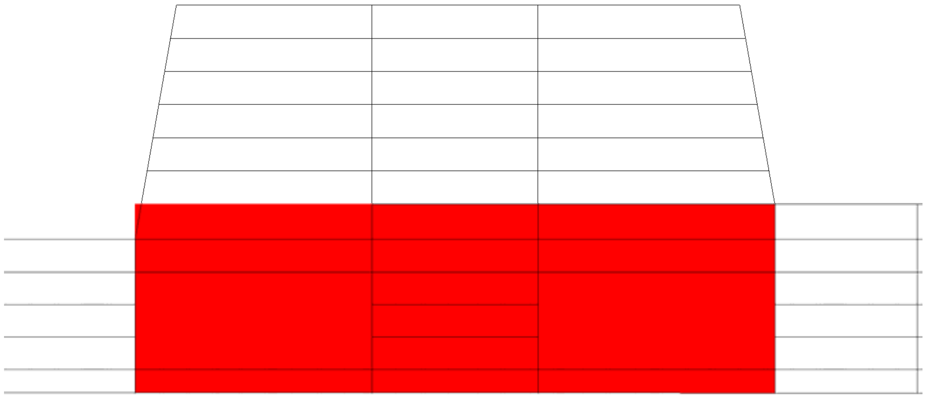


Figure 44 – Sections Modeled in MAESTRO

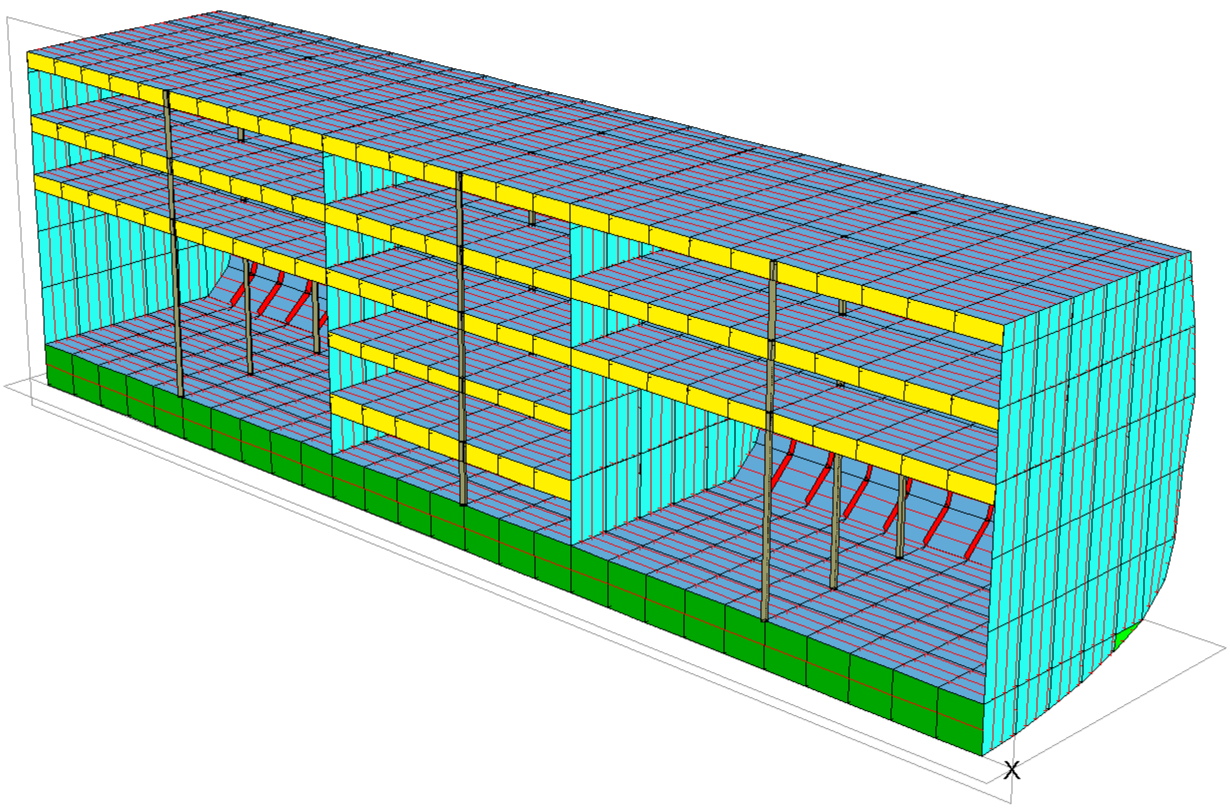


Figure 45 – MAESTRO Model

Once the model is completed load conditions are established by entering loads to each of the bulkheads and shear and moment to either end. The load conditions and process for implementing them in MAESTRO is described in more depth in the next section. The solver is run for the finite element analysis and scantling optimization iterations are begun. This is described better in section 4.3.3. Figure 47 is the final midship section drawing. The materials used are HSS and HY-80 whose properties are shown in Table 32. Table 31 is an enlarged version of the stiffener, girder, frame, and plate property chart found on the midship section drawing. Stanchion properties are shown in Table 33. Maximum Von Mises stresses calculated for each load case are shown in Table 34. In all of the tables any numbered sections are numbered from top to bottom and from the centerline outward.

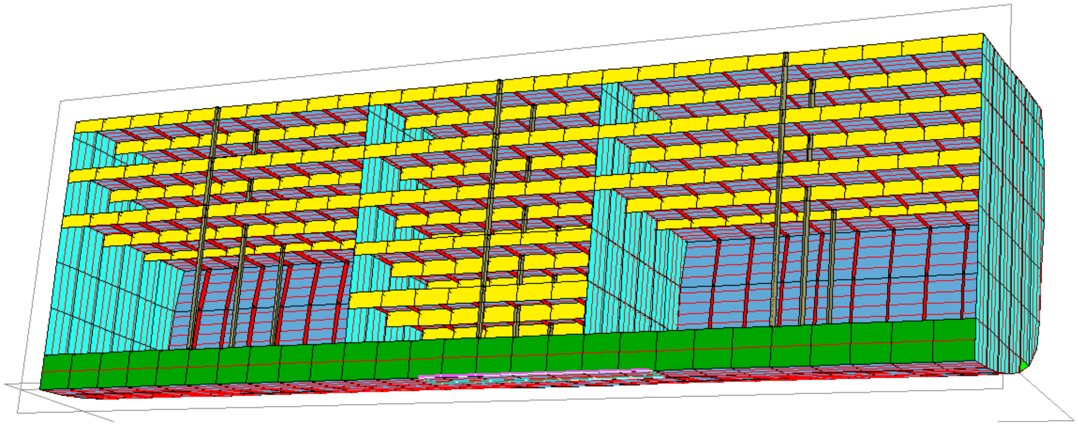
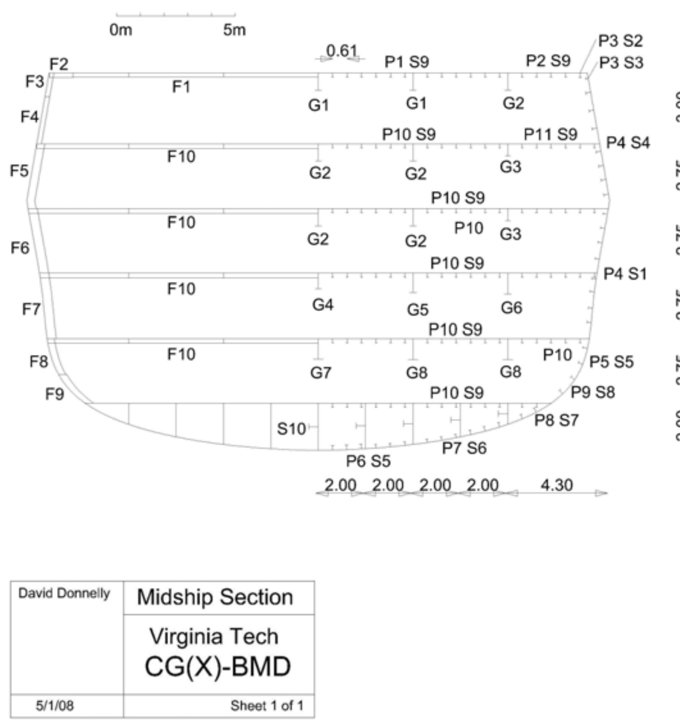


Figure 46 – MAESTRO Model, Alternate View



Stiffeners Frames Girders	Web Height (mm)	Web Thickness (mm)	Flange Width (mm)	Flange Thickness (mm)	Material
S1	177.8	9.525	101.6	12.7	HSS
S2	203.2	9.525	127	12.7	HY-80
S3	100.1	6.35	100.1	6.35	HY-80
S4	203.2	9.525	127	12.7	HSS
S5	195.2	6.35	100.1	6.35	HSS
S6	145.7	6.35	100.8	6.35	HSS
S7	144.4	6.35	100.1	6.35	HSS
S8	203.2	9.525	101.6	12.7	HSS
S9	203.2	6.35	127	9.525	HSS
S10	397.9	10.033	260.1	16.891	HSS
S11	95.1	6.35	100.1	6.35	HSS
S12	120.1	6.35	100.6	6.35	HSS
S13	198	6.223	102.1	8	HSS
S10	397.9	10.033	260.1	16.891	HSS
F1	177.8	9.525	101.6	12.7	HSS
F2	203.2	9.525	127	12.7	HY-80
F3	200.2	6.35	100.6	9.525	HY-80
F4	200.12	6.35	100.6	9.525	HY-80
F5	340.5	6.35	127	9.525	HY-80
F6	392.2	9.525	254	12.7	HY-80
F7	391.9	7.493	177.5	10.922	HY-80
F8	304.8	9.525	203.2	12.7	HY-80
F9	355.6	12.7	254	15.875	HSS
F10	203.2	6.35	127	9.525	HSS
G1	738.1	13.97	266.2	19.304	HSS
G2	738.4	14.986	266.7	23.622	HSS
G3	517.5	10.16	209.3	15.621	HSS
G4	664.2	12.446	253.7	19.05	HSS
G5	824	16.256	293.1	26.924	HSS
G6	888.5	16.51	304.8	25.908	HSS
G7	879.3	19.558	418.3	32.004	HSS
G8	887.2	21.844	421.3	39.878	HSS

Plates	Thickness (mm)	Material
P1	34.925	HSS
P2	38.1	HSS
P3	44.45	HY-80
P3	44.45	HY-80
P4	15.875	HSS
P5	19.05	HSS
P6	25.4	HSS
P7	31.75	HSS
P8	38.1	HSS
P9	44.45	HSS
P10	9.525	HSS
P11	12.7	HSS

Figure 47 – Midship Section Drawing

Table 31 – Stiffener, Girder, Frame, and Plate Properties

Stiffeners	Web Height (mm)	Web Thickness (mm)	Flange Width (mm)	Flange Thickness (mm)	Material
S1	177.8	9.525	101.6	12.7	HSS
S2	203.2	9.525	127	12.7	HY-80
S3	100.1	6.35	100.1	6.35	HY-80
S4	203.2	9.525	127	12.7	HSS
S5	195.2	6.35	100.1	6.35	HSS
S6	145.7	6.35	100.8	6.35	HSS
S7	144.4	6.35	100.1	6.35	HSS
S8	203.2	9.525	101.6	12.7	HSS
S9	203.2	6.35	127	9.525	HSS
S10	397.9	10.033	260.1	16.891	HSS
S11	95.1	6.35	100.1	6.35	HSS

S12	120.1	6.35	100.6	6.35	HSS
S13	198	6.223	102.1	8	HSS
S10	397.9	10.033	260.1	16.891	HSS
Frames	**Web Height (mm)**	**Web Thickness (mm)**	**Flange Width (mm)**	**Flange Thickness (mm)**	**Material**
F1	177.8	9.525	101.6	12.7	HSS
F2	203.2	9.525	127	12.7	HY-80
F3	200.2	6.35	100.6	9.525	HY-80
F4	200.12	6.35	100.6	9.525	HY-80
F5	340.5	6.35	127	9.525	HY-80
F6	392.2	9.525	254	12.7	HY-80
F7	391.9	7.493	177.5	10.922	HY-80
F8	304.8	9.525	203.2	12.7	HY-80
F9	355.6	12.7	254	15.875	HSS
F10	203.2	6.35	127	9.525	HSS
Girders	**Web Height (mm)**	**Web Thickness (mm)**	**Flange Width (mm)**	**Flange Thickness (mm)**	**Material**
G1	738.1	13.97	266.2	19.304	HSS
G2	738.4	14.986	266.7	23.622	HSS
G3	517.5	10.16	209.3	15.621	HSS
G4	664.2	12.446	253.7	19.05	HSS
G5	824	16.256	293.1	26.924	HSS
G6	888.5	16.51	304.8	25.908	HSS
G7	879.3	19.558	418.3	32.004	HSS
G8	887.2	21.844	421.3	39.878	HSS

Plates	Thickness (mm)	Material
P1	34.925	HSS
P2	38.1	HSS
P3	44.45	HY-80
P3	44.45	HY-80
P4	15.875	HSS
P5	19.05	HSS
P6	25.4	HSS
P7	31.75	HSS
P8	38.1	HSS
P9	44.45	HSS
P10	9.525	HSS
P11	12.7	HSS

Table 32 – Material Properties

Material	HSS	HY-80
Young's Modulus (N/m^2)	2.04E+11	2.04E+11
Poisson Ratio	0.30	0.3
Density (kg/m^2)	7833.42	7833.42
Yield Stress (N/m^2)	3.52E+08	5.52E+08
Ultimate Tensile Strength (N/m^2)	5.39E+08	6.89E+08

Table 33 – Stanchion Properties

Stanchions	Outside Diameter (mm)	Wall Thickness (mm)	Material
All	304.8	25.4	HSS

Table 34 – Maximum Von Mises Stress

Condition	Stress (MPa)
Stillwater	49.2
Hogging	133
Sagging	160

4.3.2 Loads

The load data including section weights at the bulkheads, bending moment, and shear force on the model ends was gathered using the strength summary report in HECSALV. The lightship distribution was developed using the lightship distribution generator for a container ship, with weights representative of the deckhouse and inlet/exhaust hardware in the proper position. The lightship distribution is shown in Figure 48. The Full Load condition was modeled in the stillwater, hogging wave, and sagging wave conditions. The bending moment and shear force data and plots for these cases are shown in Table 35/Figure 49, Table 36/Figure 50 and Table 37/Figure 51, respectively. The wave height criterion is a sinusoidal wave with height equal to LWL/20. Yellow highlighted values in the tables are those corresponding to the bulkhead positions that were modeled in MAESTRO. The bending moment and shear forces at the ends were also used as input.

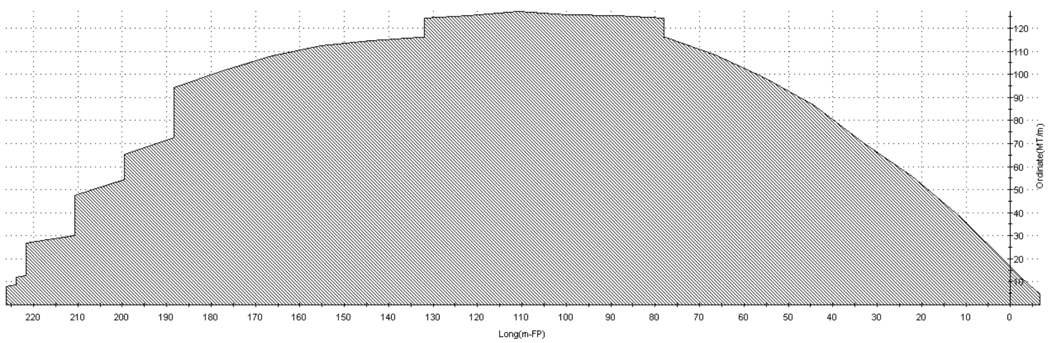


Figure 48 – Lightship Weight Distribution

Table 35 – Full Load Still Water Weight Distribution Summary

Strength Station	Location (m-A FP)	Weight (MT)	Buoyancy (MT)	Shear (MT)	Bending Moment (m-MT)
32	221.700A	46	3	43	91H
31	210.000A	391	343	49	781H
30	203.000A	742	693	49	1,155H
29	196.000A	1,161	1,158	4	1,356H
28	189.000A	1,651	1,738	-87	1,211H
27	182.000A	2,317	2,429	-113	622H
26	175.000A	3,049	3,218	-169	364S
25	168.000A	3,834	4,094	-259	1,981S
24	161.000A	4,673	5,043	-371	4,180S
23	154.000A	5,801	6,054	-254	6,335S
22	147.000A	7,012	7,113	-101	7,477S
21	140.000A	8,157	8,204	-47	8,174S
TBHD 10	132.000A	9,551	9,476	75	8,329S
19	126.000A	10,426	10,441	-15	8,076S
18	119.000A	11,456	11,576	-120	8,367S
TBHD 9	112.000A	12,710	12,716	-6	9,047S
16	105.000A	14,392	13,856	536	7,197S
TBHD 8	98.000A	15,725	14,991	734	3,002S
14	91.000A	16,754	16,118	637	1,698H
13	84.000A	17,775	17,232	543	6,084H
TBHD 7	78.000A	18,640	18,171	470	9,547H
11	70.000A	19,696	19,385	310	13,169H
10	63.000A	20,574	20,402	172	14,814H
9	56.000A	21,399	21,360	39	15,090H

Strength Station	Location (m-A FP)	Weight (MT)	Buoyancy (MT)	Shear (MT)	Bending Moment (m-MT)
8	49.000A	22,168	22,246	-78	14,478H
7	42.000A	22,849	23,042	-193	13,405H
6	35.000A	23,397	23,731	-334	11,564H
5	28.000A	23,874	24,288	-415	8,880H
4	21.000A	24,285	24,700	-415	5,935H
3	14.000A	24,623	24,961	-339	3,247H
2	7.000A	24,878	25,085	-207	1,301H
1	0	25,042	25,110	-69	351H

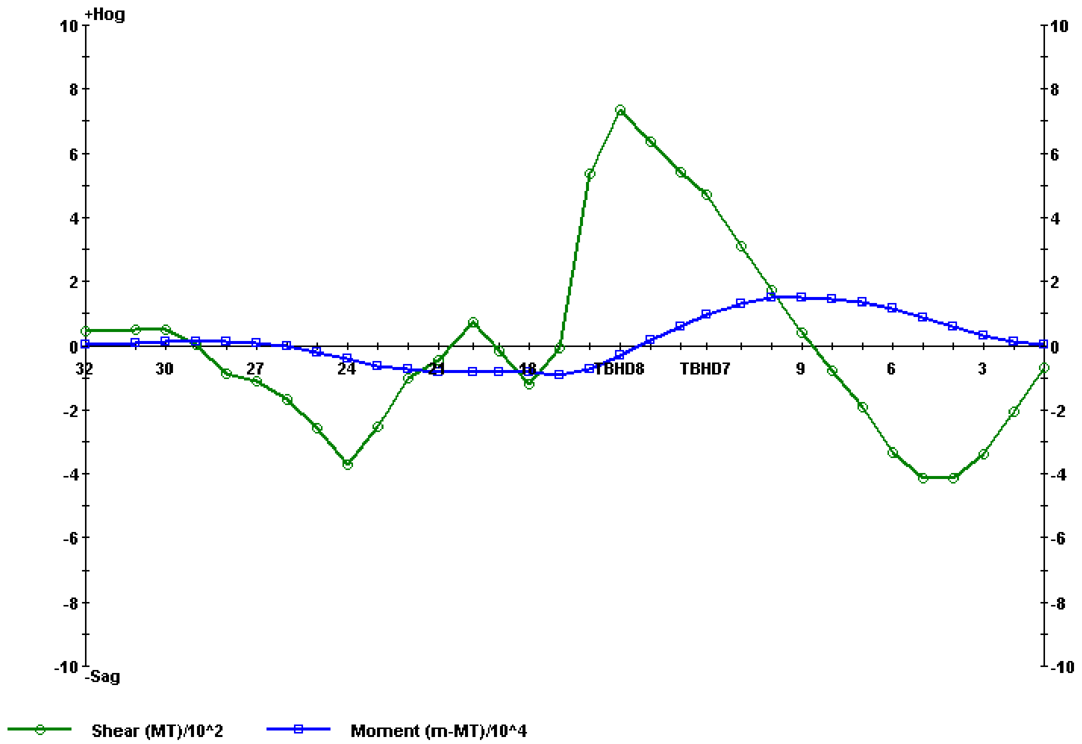


Figure 49 – Full Load Stillwater Shear and Moment Curves

Table 36 – Full Load Hogging Wave Weight Distribution Summary

Strength Station	Location (m-A FP)	Weight (MT)	Buoyancy (MT)	Shear (MT)	Bending Moment (m-MT)
32	221.700A	46	0	46	91H
31	210.000A	391	-2	393	2,565H
30	203.000A	742	-4	745	6,520H
29	196.000A	1,161	0	1,162	13,138H
28	189.000A	1,651	66	1,585	22,681H
27	182.000A	2,317	271	2,045	35,113H
26	175.000A	3,049	662	2,387	50,623H
25	168.000A	3,834	1,272	2,562	68,328H
24	161.000A	4,673	2,123	2,550	86,741H
23	154.000A	5,801	3,215	2,586	105,049H
22	147.000A	7,012	4,515	2,497	122,992H
21	140.000A	8,157	5,987	2,171	138,983H
TBHD 10	132.000A	9,551	7,841	1,710	154,156H
19	126.000A	10,426	9,326	1,100	163,082H
18	119.000A	11,456	11,124	331	169,402H
Mx	114.995A	12,098	12,172	-74	170,507H
TBHD 9	112.000A	12,710	12,958	-248	170,290H
16	105.000A	14,392	14,786	-394	167,646H
TBHD 8	98.000A	15,725	16,561	-836	161,932H
14	91.000A	16,754	18,234	-1,480	152,520H
13	84.000A	17,775	19,759	-1,984	139,791H
TBHD 7	78.000A	18,640	20,927	-2,287	127,014H

11	70.000A	19,696	22,270	-2,574	107,884H
10	63.000A	20,574	23,228	-2,655	89,674H
9	56.000A	21,399	23,978	-2,579	71,100H
8	49.000A	22,168	24,521	-2,353	53,464H
7	42.000A	22,849	24,858	-2,008	38,015H
6	35.000A	23,397	25,025	-1,629	25,263H
5	28.000A	23,874	25,093	-1,219	15,315H
4	21.000A	24,285	25,108	-823	8,169H
3	14.000A	24,623	25,109	-486	3,653H
2	7.000A	24,878	25,110	-232	1,190H
1	0	25,042	25,111	-70	188H

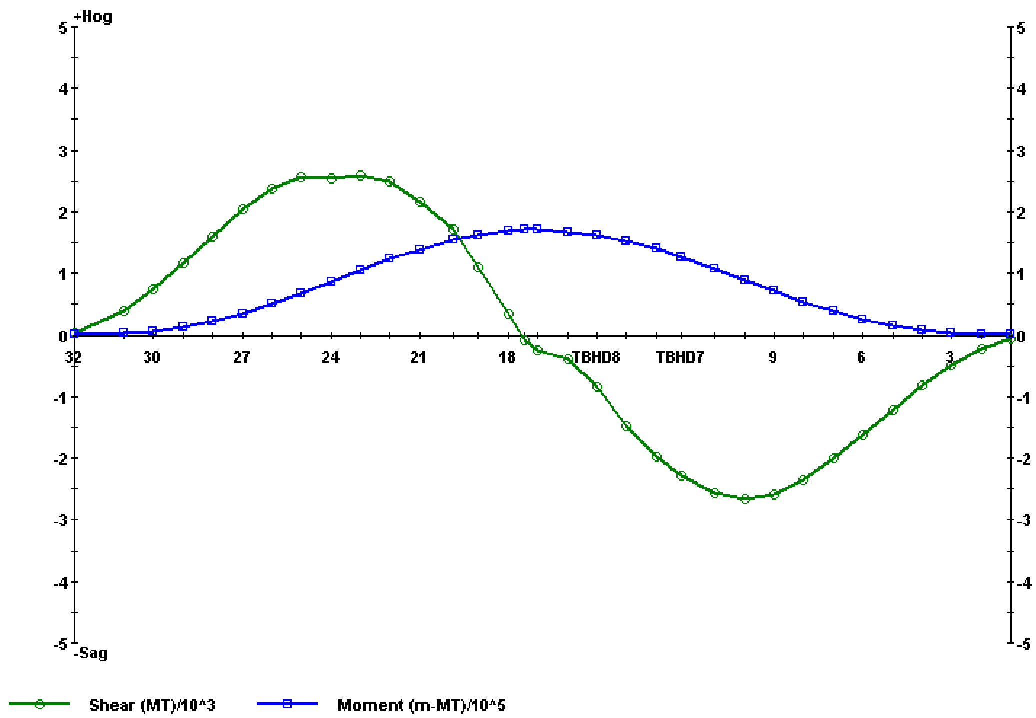


Figure 50 – Full Load Hogging Wave Shear and Moment Curves

Table 37 – Full Load Sagging Wave Weight Distribution Summary

Strength Station	Location (m-A FP)	Weight (MT)	Buoyancy (MT)	Shear (MT)	Bending Moment (m-MT)
32	221.700A	46	15	1	90H
31	210.000A	391	1,340	7,005	4,455S
30	203.000A	742	2,312	19,837	13,339S
29	196.000A	1,161	3,368	40,056	26,982S
28	189.000A	1,651	4,466	67,478	44,580S
27	182.000A	2,317	5,565	102,274	65,555S
26	175.000A	3,049	6,628	144,894	89,427S
25	168.000A	3,834	7,622	195,111	115,583S
24	161.000A	4,673	8,523	251,936	142,662S
23	154.000A	5,801	9,317	314,495	168,719S
22	147.000A	7,012	10,008	382,145	191,506S
21	140.000A	8,157	10,605	454,273	210,560S
TBHD 10	132.000A	9,551	11,176	541,425	227,001S
19	126.000A	10,426	11,541	609,893	235,542S
18	119.000A	11,456	11,929	692,900	241,971S
Mx	114.708A	12,156	12,157	745,076	243,570S
TBHD 9	112.000A	12,710	12,300	778,360	243,191S
16	105.000A	14,392	12,681	865,538	235,362S
TBHD 8	98.000A	15,725	13,106	954,939	219,348S
14	91.000A	16,754	13,615	1,047,482	198,211S
13	84.000A	17,775	14,241	1,144,097	173,967S
TBHD 7	78.000A	18,640	14,881	1,230,894	151,514S

Strength Station	Location (m-A FP)	Weight (MT)	Buoyancy (MT)	Shear (MT)	Bending Moment (m-MT)
11	70.000A	19,696	15,878	1,353,507	120,748S
10	63.000A	20,574	16,882	1,468,316	94,586S
9	56.000A	21,399	17,995	1,590,823	70,158S
8	49.000A	22,168	19,195	1,721,343	48,158S
7	42.000A	22,849	20,458	1,860,182	29,334S
6	35.000A	23,397	21,717	2,007,796	15,046S
5	28.000A	23,874	22,869	2,163,982	5,748S
4	21.000A	24,285	23,836	2,327,538	710S
3	14.000A	24,623	24,546	2,497,108	945H
2	7.000A	24,878	24,963	2,670,562	795H
1	0	25,042	25,107	2,845,946	185H

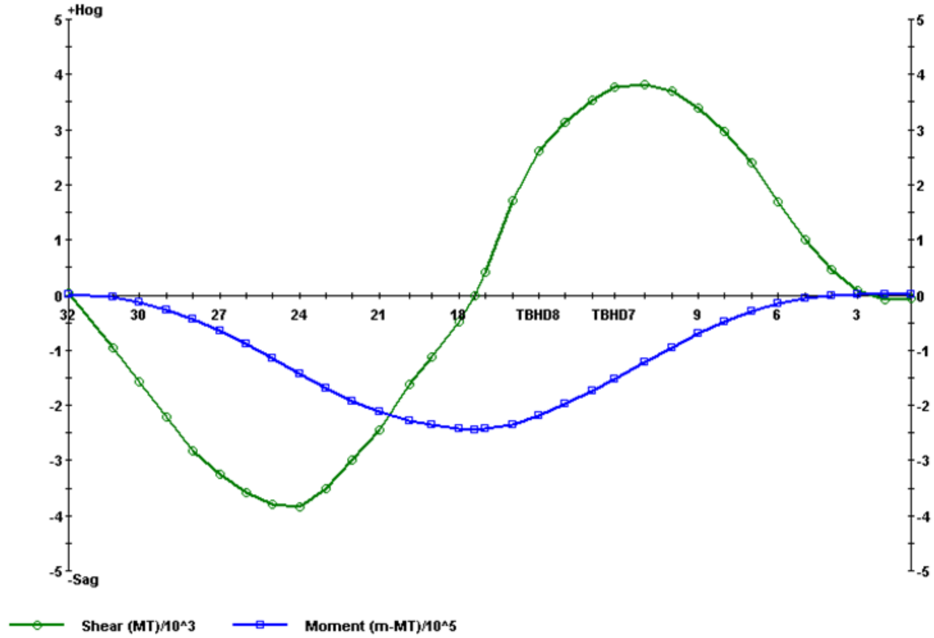


Figure 51 – Full Load Sagging Wave Shear and Moment Curves

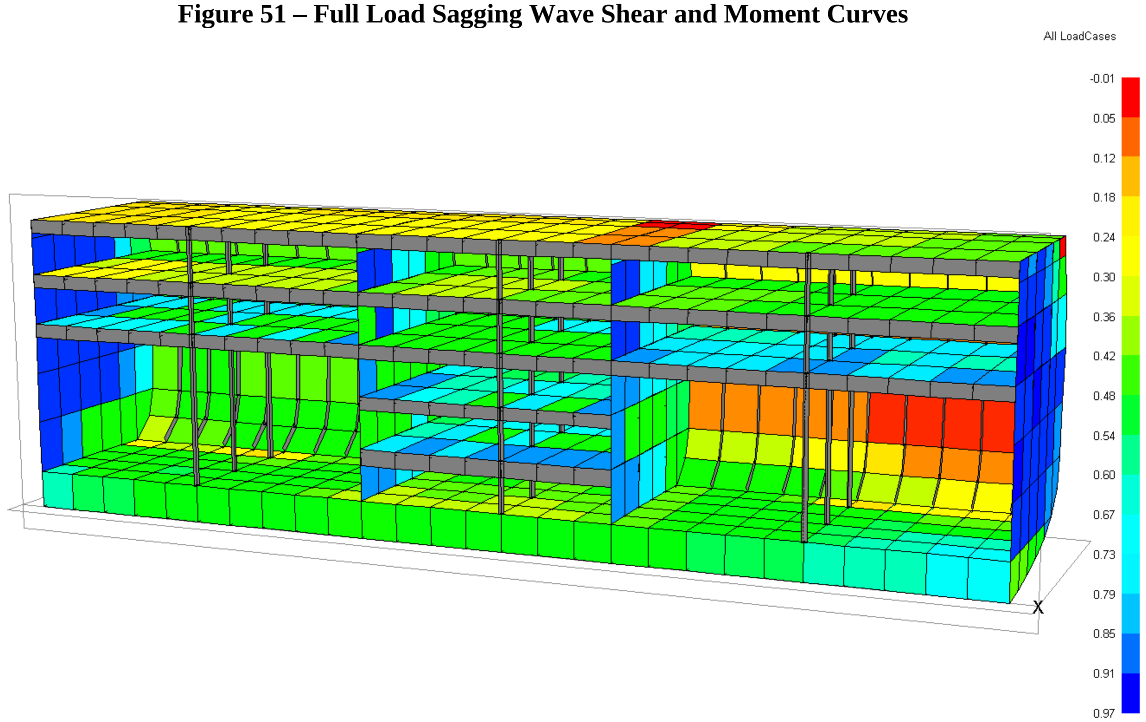


Figure 52 – Overall Minimum Adequacy of Plates for All Load Cases

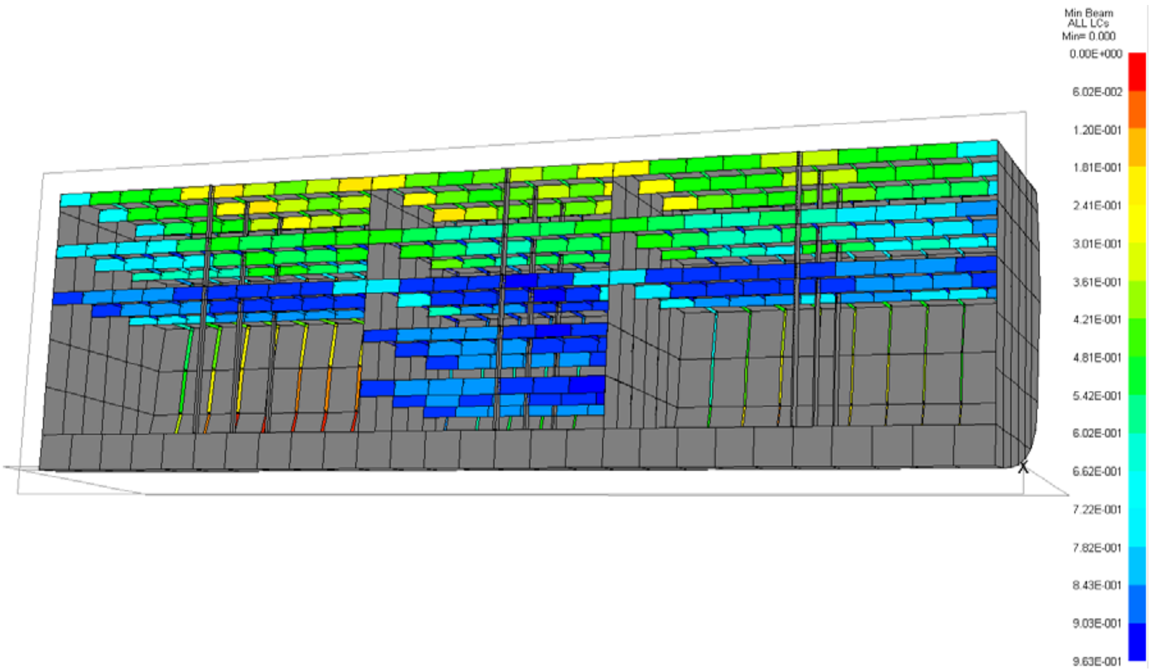


Figure 53 – Overall Minimum Adequacy of Beams for All Load Cases

4.3.3 Adequacy

MAESTRO's Scalable Solver compares stresses for each of the stiffened panels and beams from load to limit state values for different failure modes to create a strength ratio, r. To evaluate the adequacy of scantlings an adequacy parameter is defined as: (1-r)/(1+r). This value ranges from negative one to positive one and is negative when an element is inadequate for preventing failure and positive when an element is over-adequate for preventing failure. A view of the overall minimum adequacy of plates for all load cases is illustrated in Figure 52 and of beams for all load cases in Figure 53. Table **38** shows the minimum adequacy in each load case. The minimum adequacy for plates is -0.1 for the stillwater condition, 0.236 for the hogging condition, and 0 for the sagging condition. The minimum adequacy for beams is 0.498 in the stillwater condition, 0 in the hogging condition, and 0.185 in the sagging condition. The optimizer changes the scantlings using this adequacy parameter between each iteration.

Table 38 – Minimum Adequacy for Each Load Case

Condition	Min Adequacy
Plate: Stillwater	-0.01
Plate: Hogging	0.236
Plate: Sagging	0
Beam: Stillwater	0.498
Beam: Hogging	0
Beam: Sagging	0.185

4.4 Power and Propulsion

The CGX/BMD uses an electric drive system for propulsion. This electric drive system includes two pods, fixed pitch propellers, integrated power system (IPS) driven by four MP30's. In addition, there are two CAT 3616's.

4.4.1 Resistance

Resistance calculations were performed in a MathCAD file that implements the Holtrop-Mennen method. This calculation requires inputs of length of the waterline, beam, draft, prismatic coefficient, block coefficient, endurance speed, and propeller diameter. These inputs are then used to calculate the viscous, wave making drag, and bare hull resistance. Figure 54 displays these resistances versus speed. From this calculation, the total effective horsepower was calculated at speeds from 20 to 35 knots. The values of effective horsepower for these speeds are shown in Table 39 and a plot is shown in Figure 55. The complete calculation is found in Appendix H.

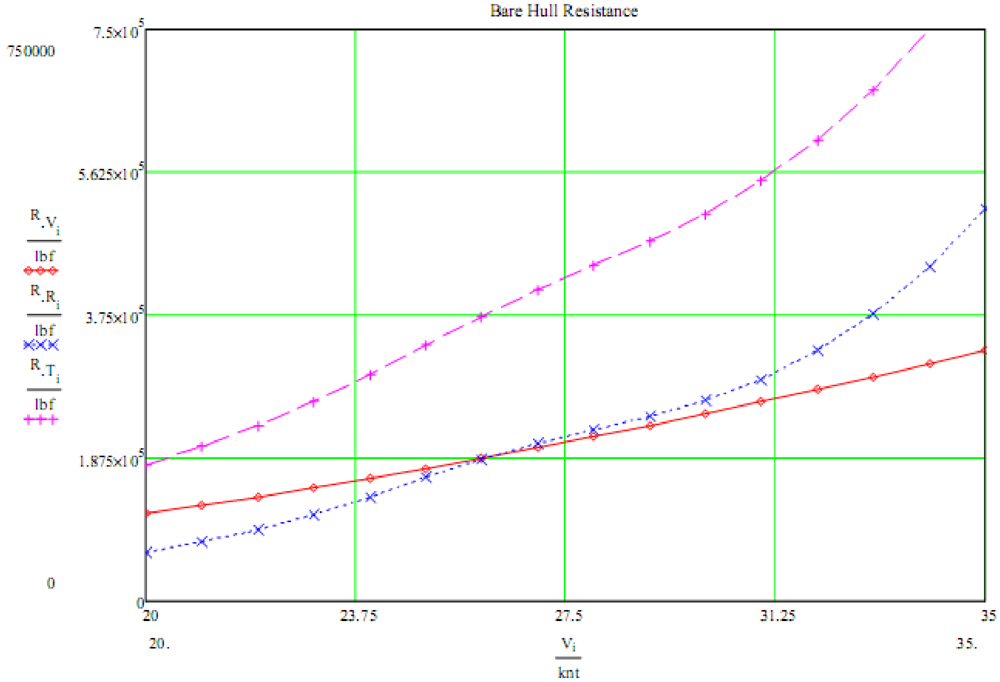


Figure 54 – Bare Hull Resistance

Table 39 – Effective horsepower

V = (·knt)

	1
1	20
2	21
3	22
4	23
5	24
6	25
7	26
8	27
9	28
10	29
11	30
12	31
13	32
14	33
15	34
16	35

EHP = (·hp)

	1
1	17165
2	20301
3	23885
4	28071
5	32945
6	38379
7	44073
8	49805
9	55622
10	61811
11	68751
12	76822
13	86382
14	97763
15	111255
16	127082

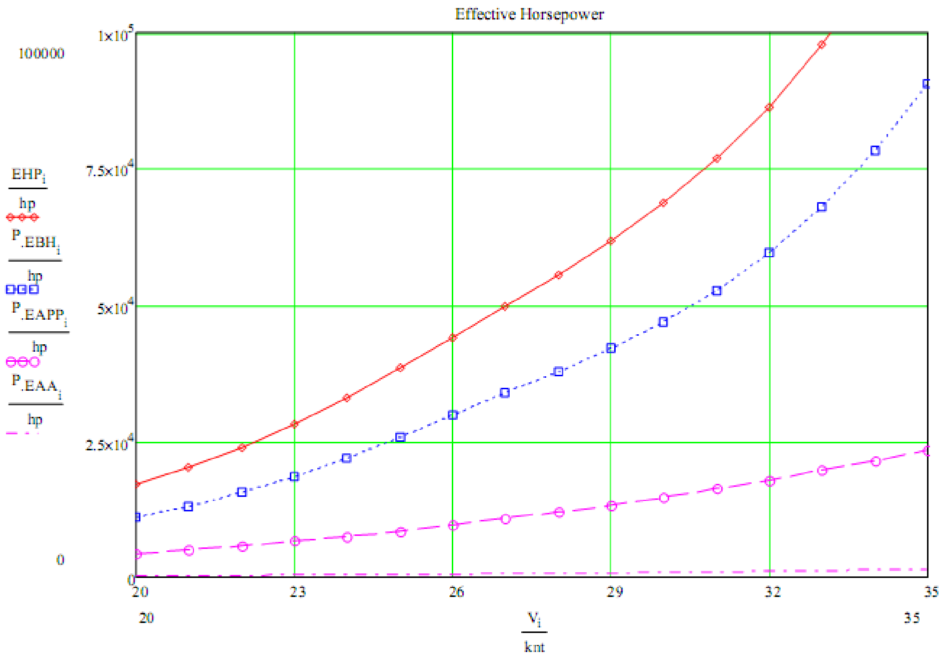


Figure 55 - Effective Horsepower

4.4.2 Propulsion

Two fixed pitch propellers in a pod configuration are used for propulsion of CGX/BMD. Each of these propellers has a diameter of 7.0 meters. The efficiency of the propeller was optimized at endurance speed. The POP program from the University of Michigan was used to calculate the efficiency, RPM, and BHP.

Endurance calculations included propulsive efficiency and operating conditions resulting in endurance range and used the previous input, KW_{MFLM} and KW_{24AVG}. Thrust deduction fraction, wake deduction fraction, and hull efficiency were also calculated. Principal Characteristics are shown in Table 40.

Table 40 – Principal Characteristics for CGX/BMD

Thrust deduction fraction (t)	0.129
Wake fraction (w)	0.098
Hull efficiency	0.966
KW_{MFLM} (kW)	28425
KW_{24AVG} (kW)	13531

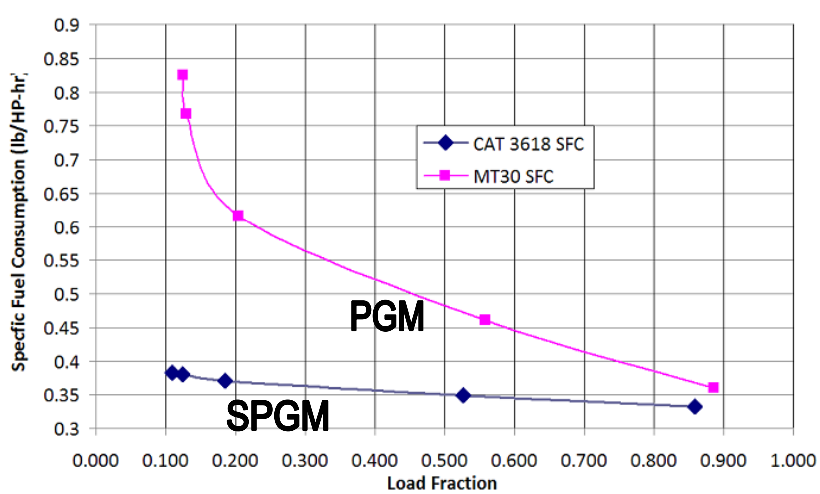


Figure 56 – Performance Curve for the MP30 and CAT 3618

Next, the engine operating characteristics were determined for the PGM and SPGM engines to determine the specific fuel consumption (SFC) for a specific engine speed. The load fraction of the engines was used with Figure 56 to determine the SFC for endurance and sustained speeds. Values for endurance and sustained speed are shown in Table 41. This calculation is shown in Appendix I.

Table 41 – Propulsion Characteristics at Endurance and Sustained Speeds

Characteristic	Endurance	Sustained
SFCPE (lb/hp*hr)	0.375	0.304
No. PGM online	1	4
PGM load fraction	0.95	1.0
No. SPGM online	1	2
SPGM load fraction	0.90	1.0
Speed	20 knots	32.7 knots
Range	8007 nm	---

4.4.3 Electric Load Analysis (ELA)

The values for the connected loads were largely taken from ASSET. There are five different conditions to be calculated; battle, cruise, anchor, in port and emergency. The electric loads are found by multiplying the connected load by a power factor for each case. The power factor represents the average to which each system is loaded and the equipment online. There are different power factors for different systems in each operating condition. Power generation and systems online are also different in each condition. In the battle condition, all power generation modules are running to capacity. In cruise, there is one loaded MT30 and one 3616 running to provide the necessary power for cruise loads. At anchor, the radar system is still operated in a defensive role with the rest of the combat system requiring two 3616 diesels to be online. In port, most systems are shut down so only one 3616 diesel is necessary. In the emergency operating condition, power is provided via two 5MW fuel cells. The ship has relatively high emergency power requirements because the ship is IPS which means that propulsion power must come from the emergency power modules. It is important to note that auxiliary power requirements are very high, this is due to the large amount of cooling required for the VSR+++ radar.

4.4.4 Fuel Calculation

A fuel calculation was performed for endurance range in accordance with DDS 200-1. In this process, the specified fuel rate was determined for operating at endurance speed. The endurance range and fuel volume was determined. This calculation is found in Appendix I. From these calculations, it was determined the fuel volume of the ship was 4720 cubic meters which translates to an endurance range of 8007 nautical miles.

4.5 Mechanical and Electrical Systems

Mechanical and electrical systems are selected based on mission requirements, standard naval requirements for combat ships, and expert opinion. The Machinery Equipment List (MEL) of major mechanical and electrical systems includes quantities, dimensions, weights, and locations. The complete MEL is provided in Appendix E. The major components of the mechanical and electrical systems and the methods used to size them are described in the following two subsections. The arrangement of these systems is detailed in Section 4.7.2.

4.5.1 Integrated Power System (IPS)

The IPS system is powered by four primary generation modules which consist of an MT30 gas turbine powering a 35.5 MW generator. The secondary power generation modules are 3616 CAT diesels which power 5MW generators; there are 2 SPGM in the system. Emergency power is provided by two 5MW fuel cells. During cruising conditions, one PGM and one SPGM are online both are loaded to approximately 95%. For survivability reasons, our emergency power generation modules (EPGM) are located in the AMRs at either end of the ship. They provided enough power to run our combat system at 10% power and the propulsion at 3% power. This allows for a speed of 10 knots to be achieved. Figure 57 shows the online electrical diagram.

Table 42 - Electric Load Analysis Summary

SWBS	Description	Connected Load (kW)	Battle Power Factor	Battle (kW)	Cruise Power Factor	Cruise (kW)	Anchor Power Factor	Anchor (kW)	In Port Power Factor	In Port (kW)	Emergency Power Factor	Emergency (KW)
100	Deck Machinery	790	1.00	790	1.0	790	1.00	790	0.0	0	0.0	0
200	Propulsion	139962		139653		21699		879		0		4527
	Propulsion Direct	138033	1.00	138033	0.2	21394	0.01	828	0.0	0	0.0	4141
	Propulsion support	1929	0.84	1620	0.2	305	0.03	51	0.0	0	0.2	386
300	Electric	939	0.67	629	0.2	228	0.15	137	0.4	376	0.1	141
400	CCC	27862		12973		7852		2786		290		2786
	Combat Systems	24963	0.45	11233	0.3	7019	0.10	2496	0.0	0	0.1	2496
	Miscellaneous	2899	0.60	1739	0.3	833	0.10	290	0.1	290	0.1	290
500	Auxiliary	17498		8370		8409		4610		2703		2207
510	CPS	1690	0.36	608	0.4	658	0.39	658	0.0	0	0.1	122
510	HVAC	4729	0.35	1675	0.4	2110	0.35	1655	0.4	1892	0.2	793
520	Sea Water Systems	665	0.34	225	0.3	196	0.29	195	0.4	266	0.3	225
530	Fresh Water System	9129		4818		5214		1852		516		1067
531	Distilling Unit	95	0.00	0	0.55	52	0.55	52	0.00	0	0.00	0
532	Radar Cooling Water	8200	0.56	4592	0.56	4592	0.15	1230	0.01	82	0.10	820
533	Potable Water	425	0.05	21	0.86	366	0.86	366	0.54	230	0.10	43
536	Aux Freshwater	409	0.50	205	0.50	205	0.50	205	0.50	205	0.50	205
540	Fuel Handling	289	0.34	98	0.2	49	0.24	69	0.1	29	0.0	0
550	Air System	996	0.95	946	0.2	181	0.18	181	0.0	0	0.0	0
600	Services	910	0.10	94	0.4	328	0.36	325	0.4	364	0.0	4
700	Weapons	3701	0.34	1251	0.3	1217	0.15	555	0.0	0	0.0	90
	Total Required	53629		163760		40523		10083		3732		9755
	24 Hour Average	13531		149674		29365		4643		1718		6703

Number	Generator	Rating (kW)	Average 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	0	0
2	CAT 3616	5060.0	10120	2	10120	1	5060	2	10120	1	5060	2	0
2	Fuel Cell 5 MW	5000.0	10000	2	10000	0	0	0	0	0	0	0	10000
	Total		164120		164120		41060		10120		5060		10000
			Available Power		360		537		37		1328		245

4.5.2 Service and Auxiliary Systems

The ship has standard service and auxiliary systems. These systems include: lube oil service, fuel service and transfer, air condition and refrigeration, fire main, potable water, JP-5 service and transfer, compressed air, hydraulics, and environmental systems. Due to the large VSR+++ radar system, there is significantly more cooling machinery required than would normally be required for a ship of this size. All service and auxiliary systems are listed in the MEL in Appendix E.

4.5.3 Ship Service Electrical Distribution

The electrical distribution system is a DC zonal electrical distribution system (DC ZEDS). The primary and secondary power generation modules provide power at 4160 VAC. The emergency generator fuel cells provide power at 1000VCD For each PGM and SPGM there is a PCM-4 which converters the 4160 VAC from the generators to 1000 VDC. Power is then supplied the port and starboard buses at 1000 VDC. In each of the 16 zones, there is one PCM-1 per bus to convert the power from 1000 VDC to 375-800 VDC for DC loads. The PCM-1's also supply power to the PCM-2's which convert 800 VDC to 450 VAC for AC loads. There is one PCM-2 per zone on each bus. All vital loads are connected to both the port and starboard buses for survivability reasons. The one-line electrical diagram is shown in Figure 57.

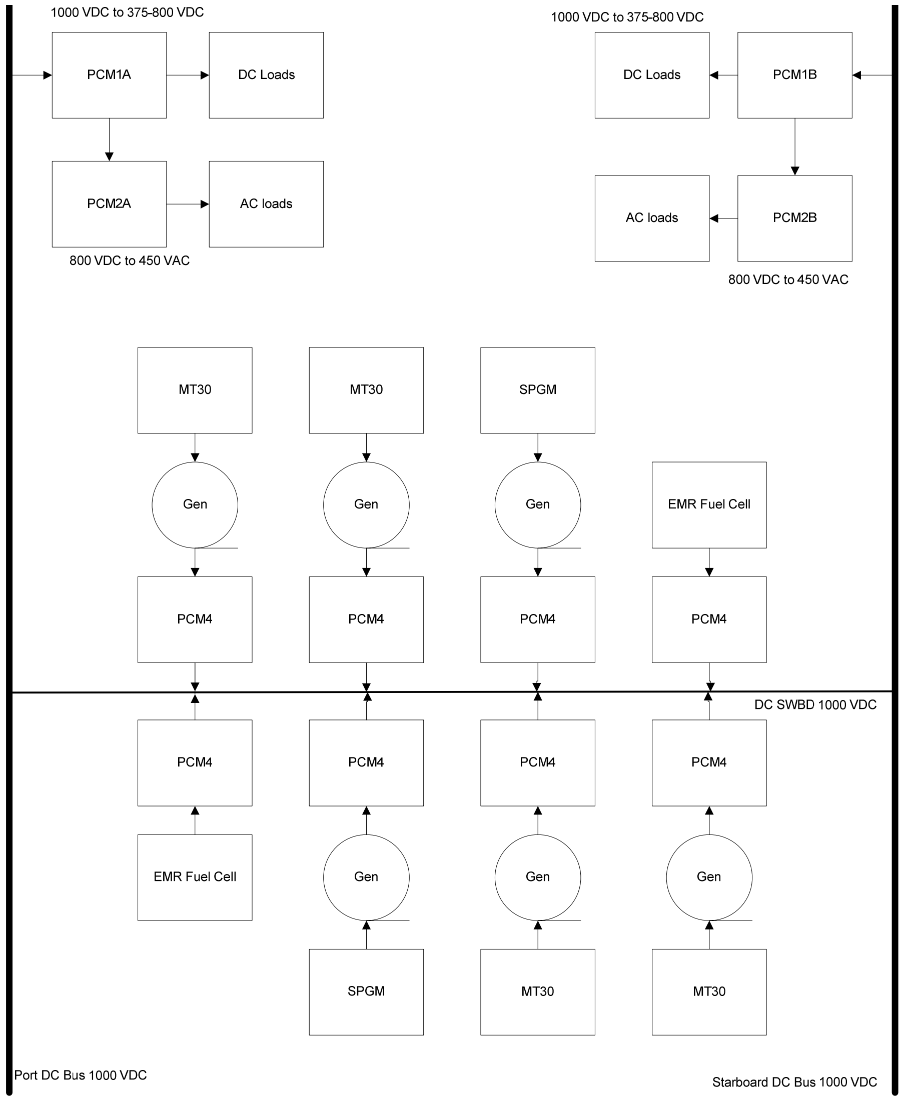


Figure 57 - One-Line Electrical Diagram

4.6 Manning

CGX/BMD has 5 departments and 17 divisions. The departments are: executive/admin, operations, weapons, engineering and supply. The department/division breakdown is shown in Figure 58. Because of the medium risk model that was chosen, our manning automation factor was .98, which means only current, standard automation is used on the ship. The level of automation is approximately equivalent to current naval vessels. Since the automation is low, the crew size is large at 452 men. This breaks down into 31 officers, 35 chief petty officers, and 386 enlisted personnel. The break down for each department and division is found in **Table 43**. Weapons and engineering are the largest departments.

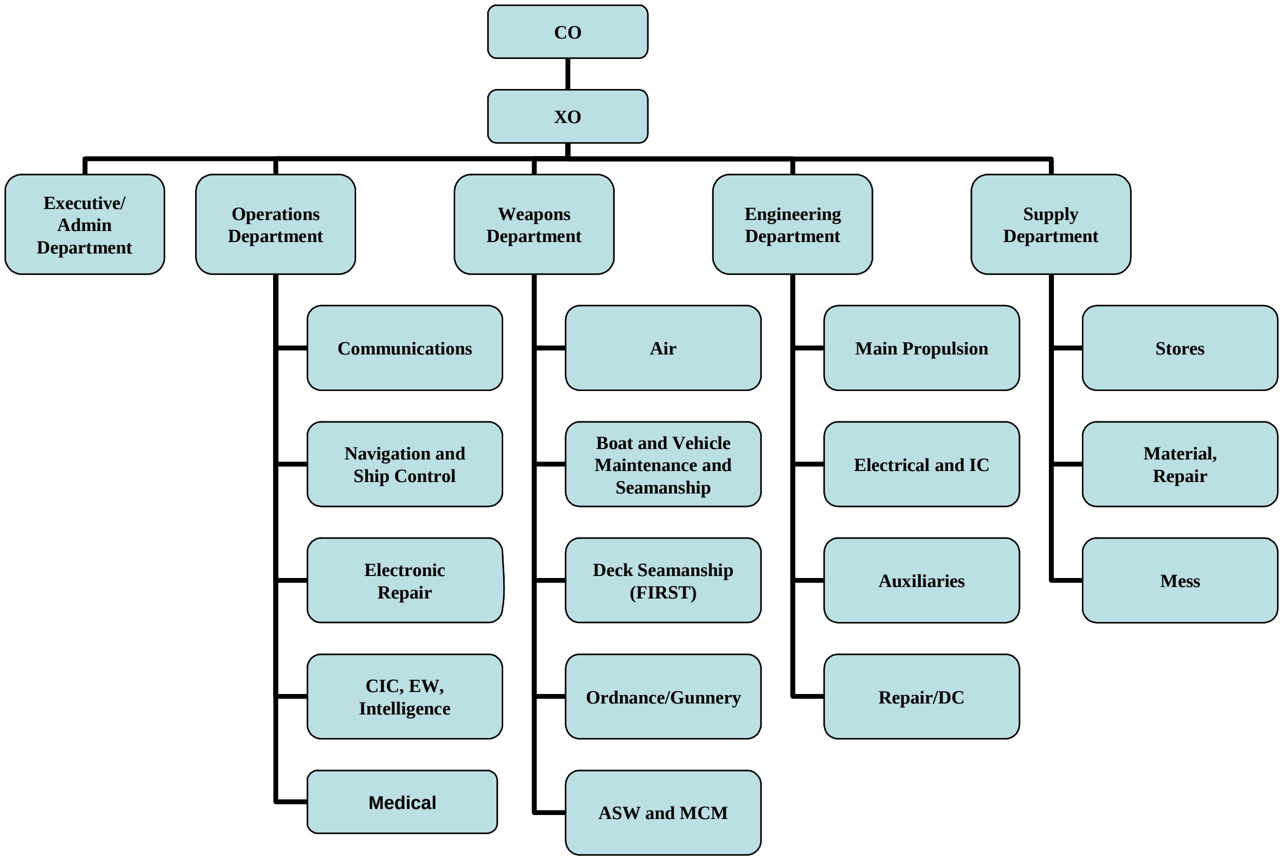


Figure 58 – Manning Organization

Table 43 - Manning Summary

Departments	Division	Officers	CPO	Enlisted	Total Department
	CO/XO	2			2
	Department Heads	4			4
Executive/Admin	Executive/Admin		1	3	4
Operations	Communications	1	1	18	76
	Navigation & Control		1	18	
	Electronic Repair	1	1	16	
	CIC, EW, Intelligence	1	2	16	
Weapons	Air	3	1	18	123
	Boat & Vehicle		1	20	
	Deck	1	2	24	
	Ordinance/Gunnery	1	2	24	
	ASW/MCM	1	1	24	
Engineering	Main Propulsion	1	2	40	131
	Electrical/IC	1	1	24	
	Auxilaries	1	2	30	
	Repair/DC	1	1	30	
Supply	Stores	1	1	10	48
	Material/Repair	1	1	18	
	Mess	1	1	16	
	Total	22	22	349	388
	MOGO totals	31	35	386	452
	Accomodations	30	30	400	460

4.7 Space and Arrangements

HECSALV and RHINO was used to generate and assess subdivision and arrangements. HECSALV is used for primary subdivision, tank arrangements and loading. RHINO is used to construct 2-D drawings of the inboard and outboard profiles, deck and platform plans, detailed drawings of berthing, sanitary, and messing spaces, and a 3-D model of the ship. A profile showing the internal arrangements is shown in Figure 59 and Figure 60.

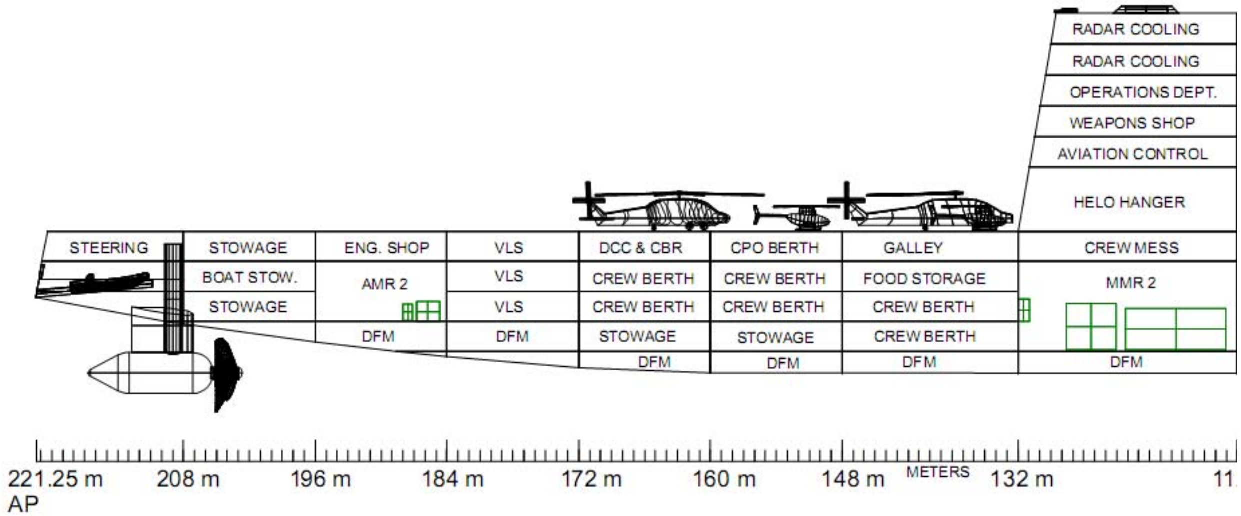


Figure 59 - Profile View Showing Arrangements (Aft)

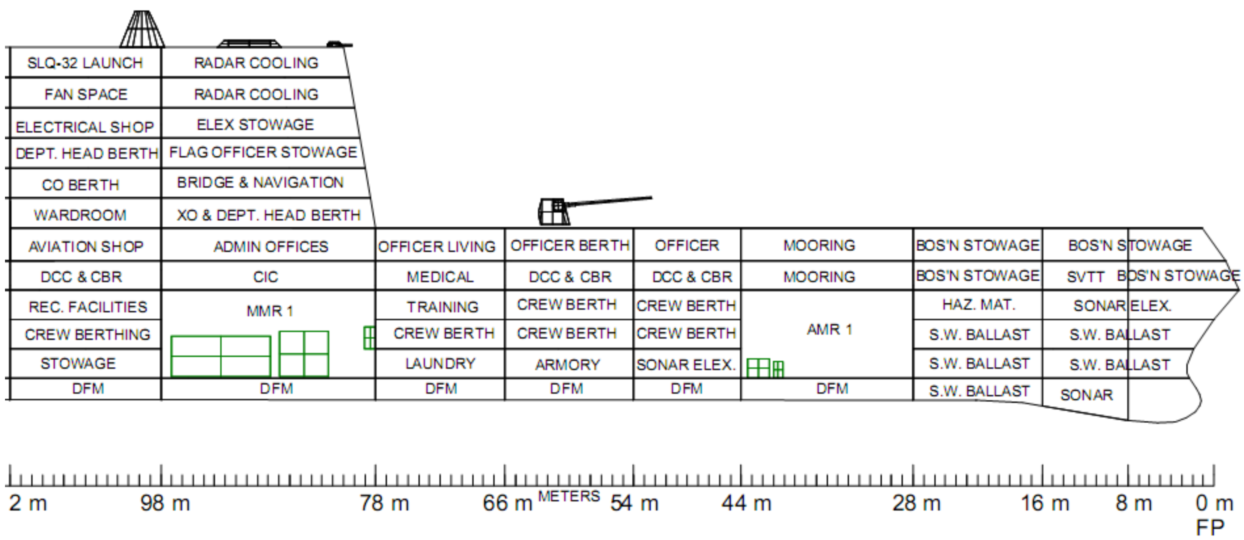


Figure 60 - Profile View Showing Arrangements (Forward)

4.7.1 Volume

Initial space requirements and availability in the ship are determined in the ship synthesis model. Arrangeable area estimates and requirements are refined in concept development arrangements and discussed in Sections 4.7.2 through 4.7.4. Table 44 compares required versus actual tankage volume.

Table 44 – Required vs. Available Tankage Volume

Variable	Required	Final Concept Design
Waste Oil	24	26
Lube Oil	24	26
Potable Water	69	155
Sewage	20	20
Helicopter Fuel (JP5)	65	65
Clean Ballast	1,280	930
Propulsion Fuel (DFM)	4,650	4,770

4.7.2 Main and Auxiliary Machinery Spaces and Machinery Arrangement

There are four machinery spaces in the ship; MMR1, MMR2, AMR1, AMR2 as seen in Figure 61. The AMR's are located at the ends of the ship for survivability. All machinery rooms share the electrical equipment, 2 PCM-1, PCM-2, 1 switchboard and 1 PCM-4 per PGM. The electrical components are primarily placed on the upper levels of the machinery rooms. The PGM's and SPGM's are located in the MMR's on deck 5, the EPGM is located in the AMR's on decks 4 and 5. All lube oil and fuel service and transfer systems are located in the MMR's on deck 5. All air conditioning and potable water systems are located in the AMR's on decks 3, 4 and 5. Refrigeration systems for food storage are located in MMR2 on deck 3 near the galley. Compressed air systems are primarily located in the MMR's on deck 4; ship service air receivers are also located in the AMR's on decks 4 and 5. All environmental systems are in the MMR's on deck 5. The hydraulics for steering is located above the PODS on deck 2. Plan views for each level in the machinery rooms are found in Figure 62 - Figure 72 below.

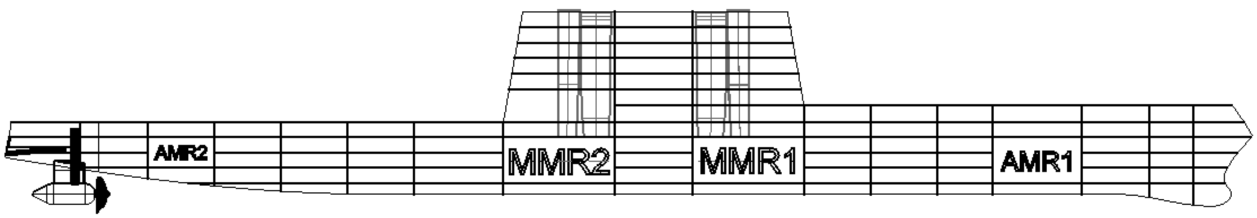


Figure 61 - Profile View Showing Machinery Spaces

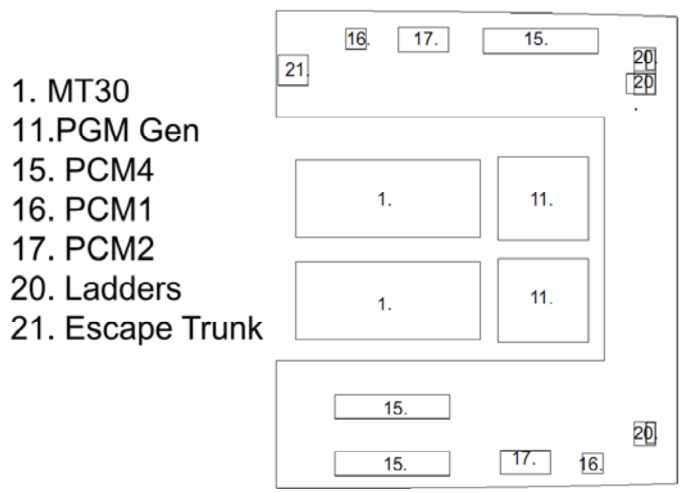


Figure 62 - Plan View Showing MMR1 Deck 3

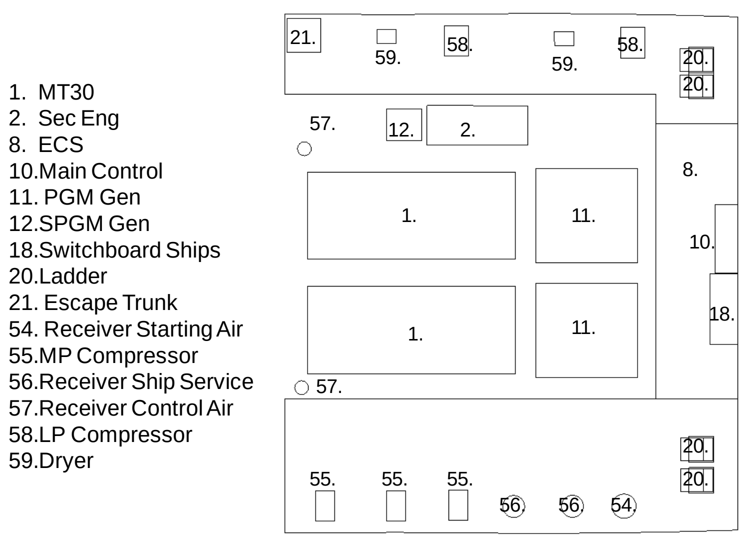


Figure 63 - Plan View Showing MMR1 Deck 4

1. MT30
2. Sec Eng
11. PGM Gen
12. SPGM Gen
20. Ladders
21. Escape Trunk
26. Seawater pump
29. Lube Oil Purifier
30. Lube Oil Pump
31. Fuel filter
32. Fuel Purifier
33. Fuel Pump
34. Fuel Service Tank
41. Fire Pump
43. Bilge Pump
57. Receiver Control
62. Oily Waste Pump
63. Oil/Water Separator

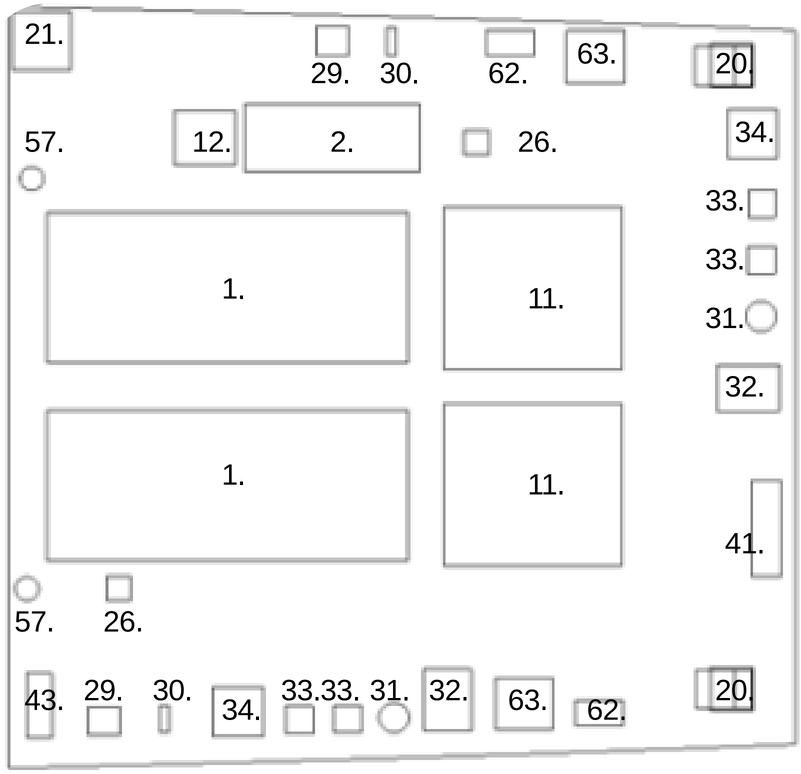


Figure 64 - Plan View Showing MMR1 Deck 5

1. MT30
11. PGM Gen
15. PCM4
16. PCM1
17. PCM2
20. Ladders
21. Escape Trunk
23. Fan Space
38. Ship's Refrigeration

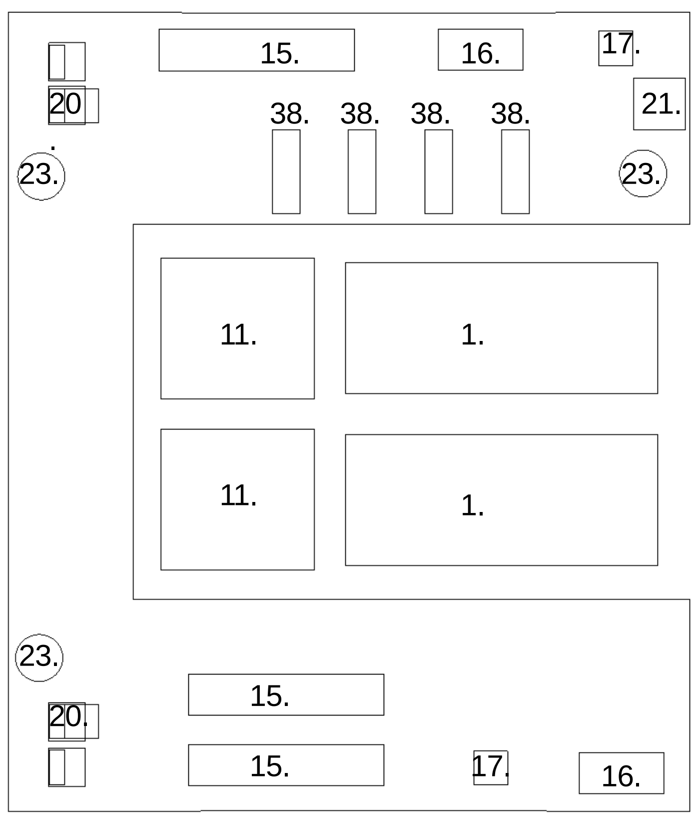


Figure 65 - Plan View Showing MMR2 Deck 3

1. MT30
2. Sec Eng
8. ECS
10. Main Control
11. PGM Gen
12. SPGM Gen
18. Switchboard Ships
20. Ladders
21. Escape Trunk
54. Receiver Starting Air
55. MP Compressor
56. Receiver Ship Service
58. LP Compressor
59. Dryer

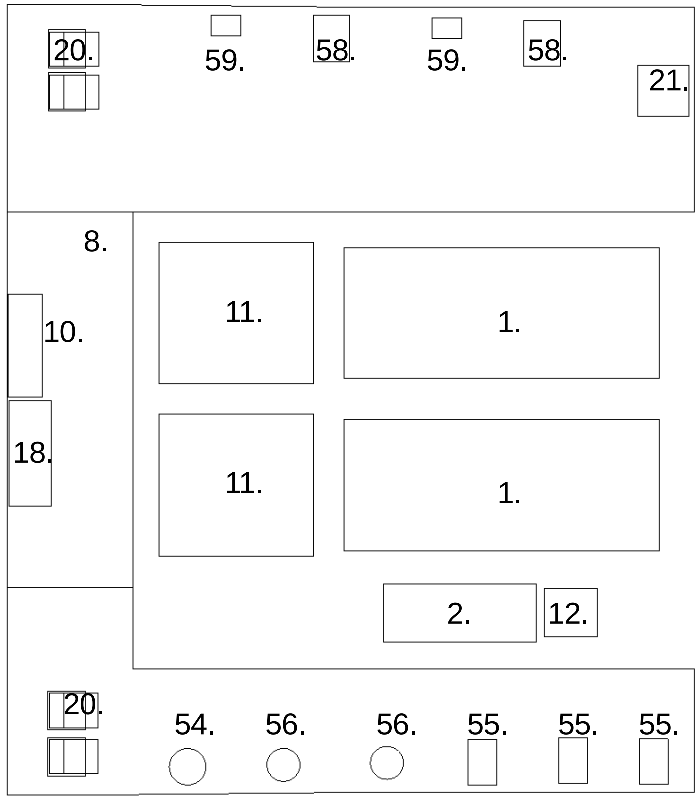


Figure 66 - Plan View Showing MMR2 Deck 4

1. MT30
2. Sec Eng
11. PGM Gen
12. SPGM Gen
20. Ladders
21. Escape Trunk
26. Seawater pump
29. Lube Oil Purifier
30. Lube Oil Pump
31. Fuel filter
32. Fuel Purifier
33. Fuel Pump
34. Fuel Service Tank
41. Fire Pump
43. Bilge Pump
62. Oily Waste Pump
63. Oil/Water Separator

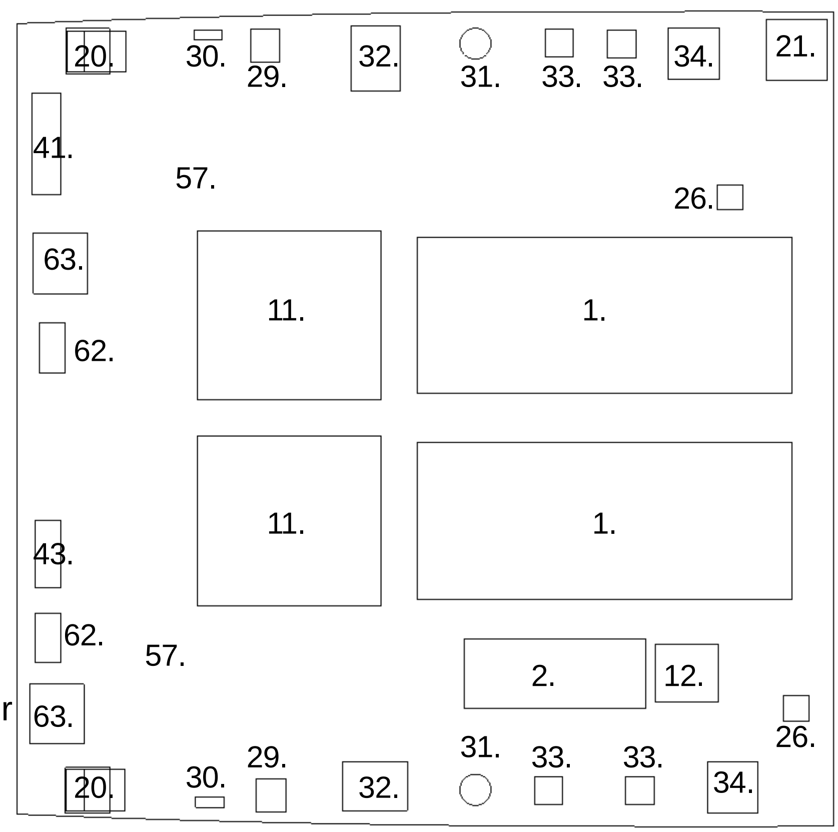


Figure 67 - Plan View Showing MMR2 Deck 5

3. Fuel Cell
15. PCM4
16. PCM1
17. PCM2
19. EMR Switchboard
20. Ladders
21. Escape Trunk
25. Space Fan
47. Brominator Proportioning
48. Brominator Recirculation
49. Potable Water Pump

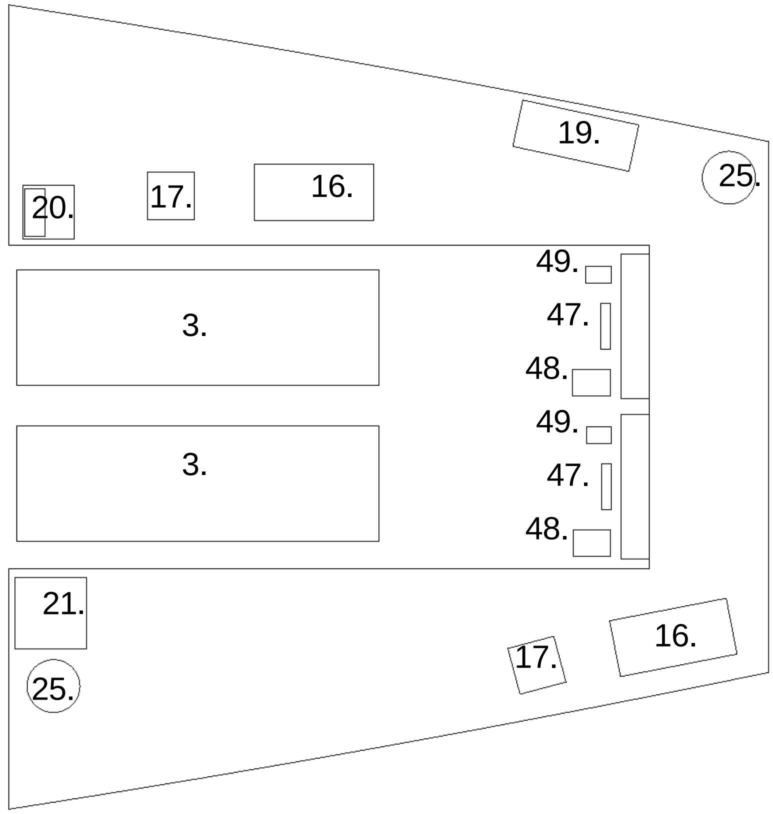


Figure 68 - Plan View Showing AMR1 Deck 3

3. Fuel Cell
20. Ladders
21. Escape Trunk
36. AC Plant
37. Chilled Water
46. Distiller
47. Brominator Proportioning
48. Brominator Recirculation
49. Potable Water Pump
54. Receiver

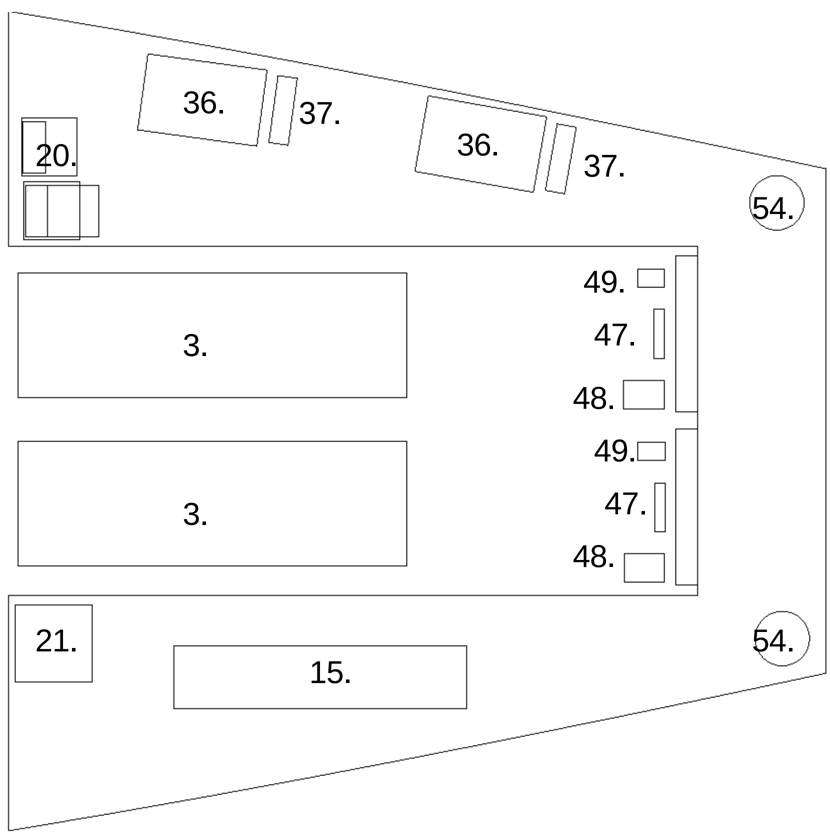


Figure 69 - Plan View Showing AMR1 Deck 4

3. Fuel Cell
20. Ladders
21. Escape Trunk
25. Space Fan
26. Seawater Pump
41. Pump Fire
43. Pump Bilge
46. Distiller
47. Brominator Proportioning
48. Brominator Recirculation
49. Potable Water Pump

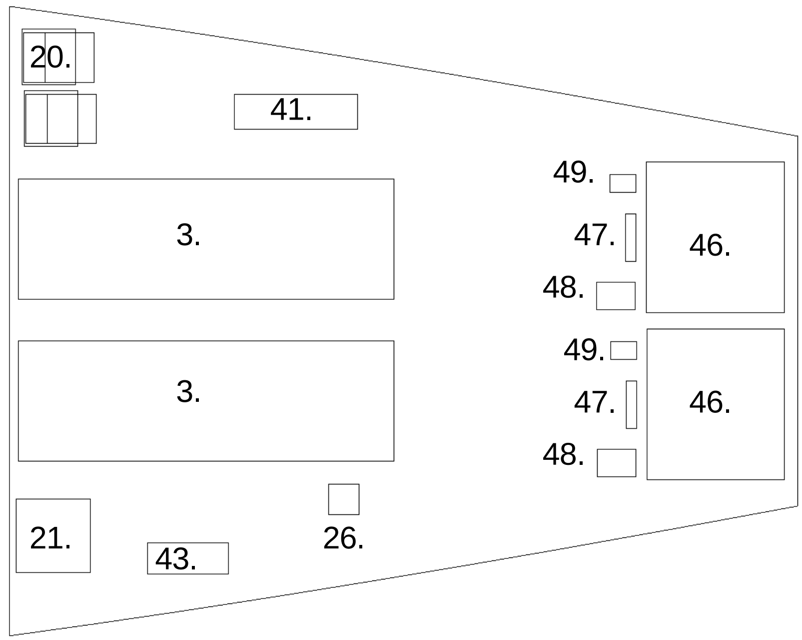


Figure 70 - Plan View Showing AMR1 Deck 5

3. Fuel Cell
15. PCM4
16. PCM1
17. PCM2
19. EMR Switchboard
20. Ladders
21. Escape Trunk
25. Space Fan
36. AC Plant
37. Chilled Water
46. Distiller
47. Brominator Proportioning
48. Brominator Recirculation
49. Potable Water Pump

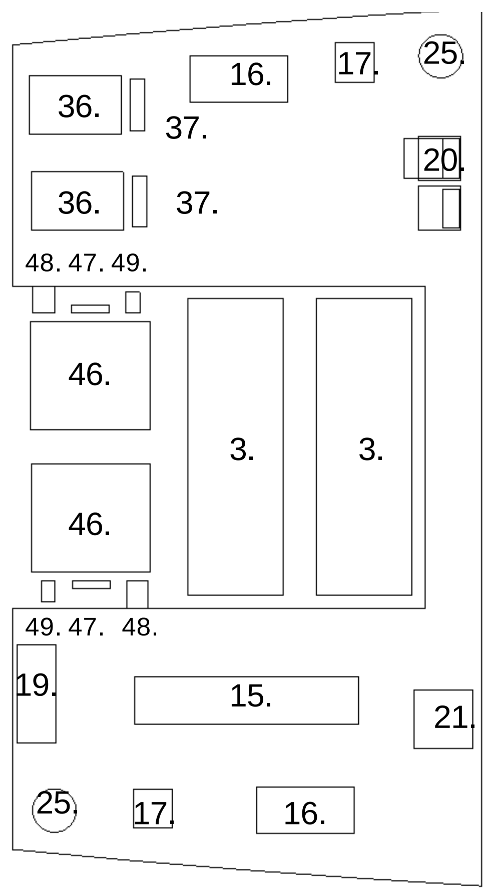


Figure 71 - Plan View Showing AMR2 Deck 3

3. Fuel Cell
20. Ladders
21. Escape Trunk
26. Seawater Pump
41. Fire Pump
46. Distiller
47. Brominator Proportioning
48. Brominator Recirculation
49. Potable Water Pump
54. Receiver

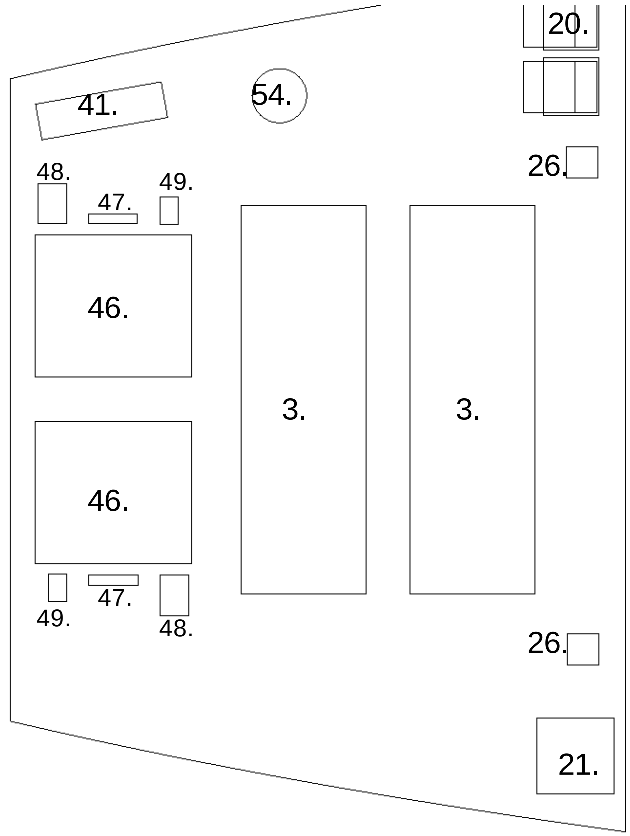


Figure 72 - Plan View Showing AMR2 Deck 4

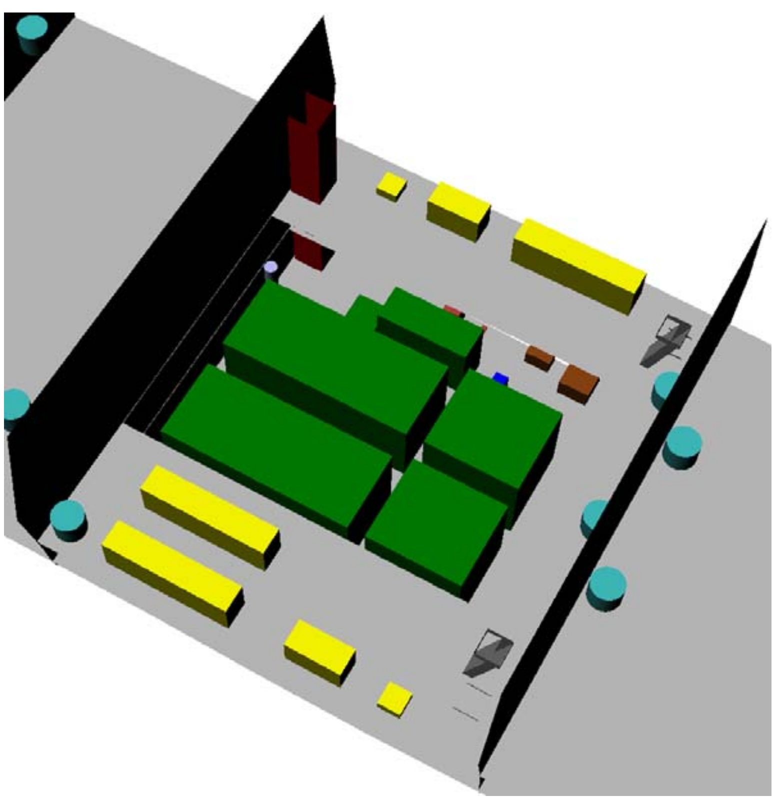


Figure 73 – 3D View Showing MMR1 Deck 3

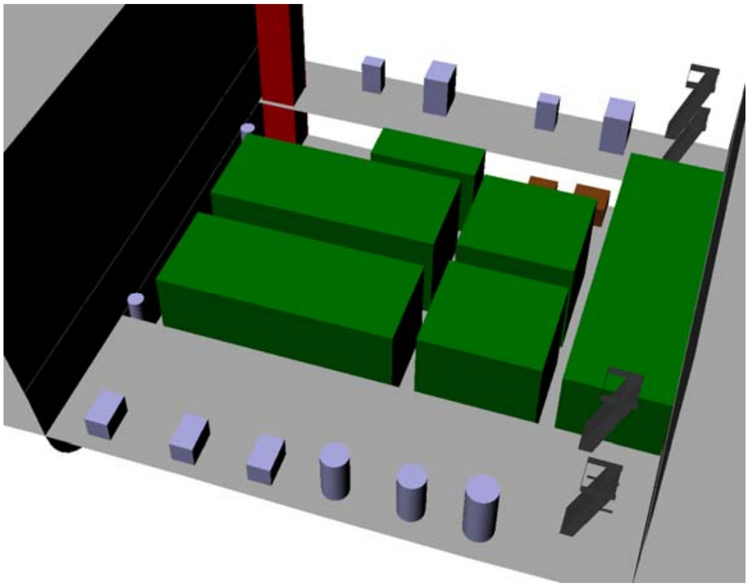


Figure 74 – 3D View Showing MMR1 Deck 4

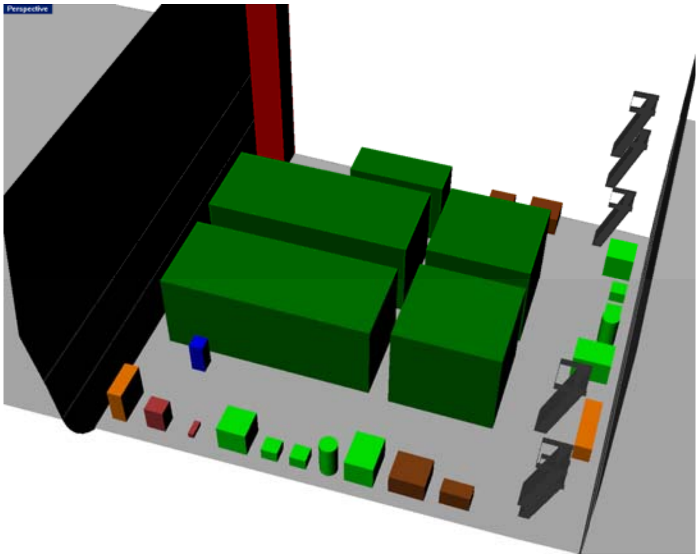


Figure 75 – 3D View Showing MMR1 Deck 5

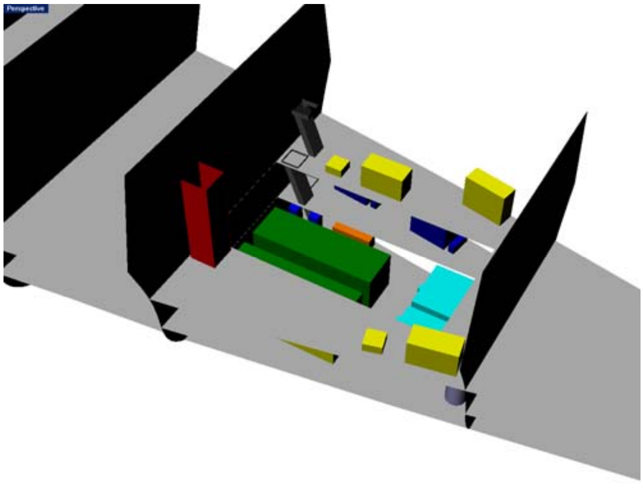


Figure 76 – 3D View Showing AMR1 Deck 3

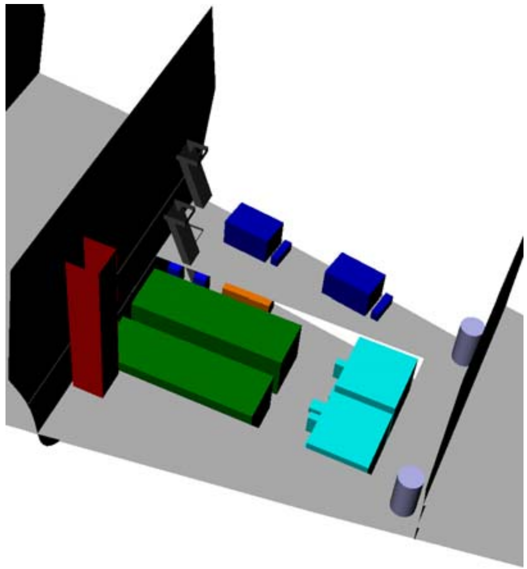


Figure 77 – 3D View Showing AMR1 Deck 4

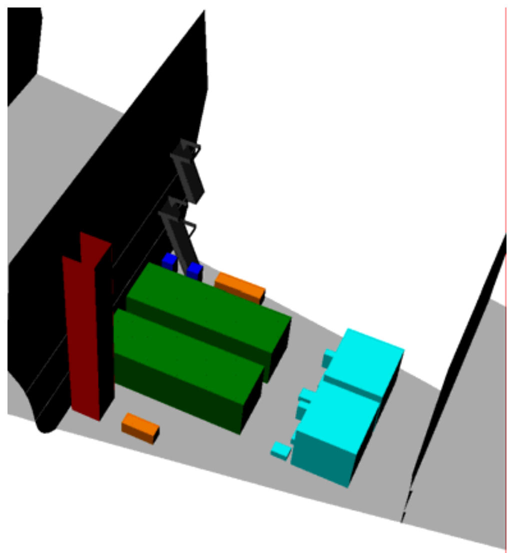
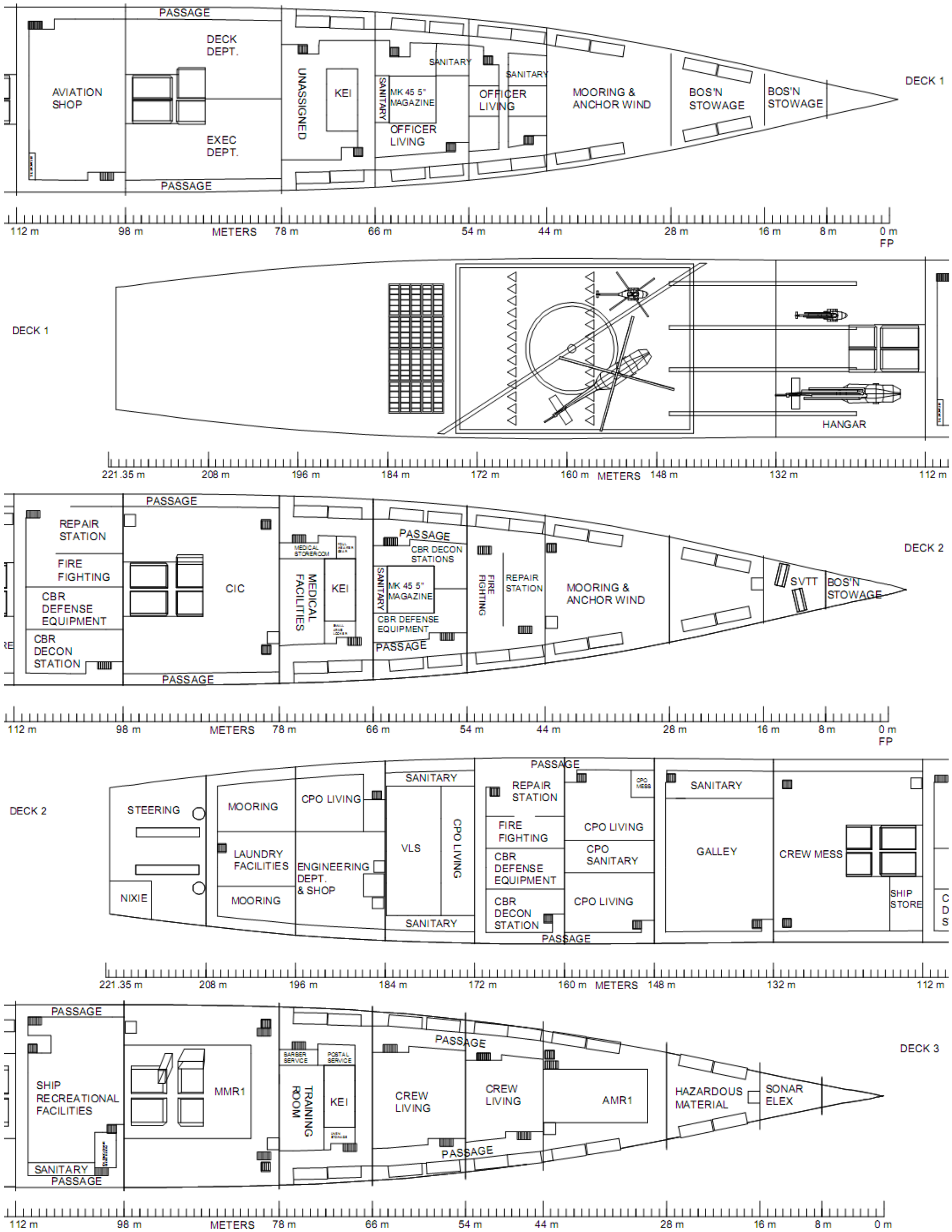


Figure 78 – 3D View Showing AMR1 Deck 5

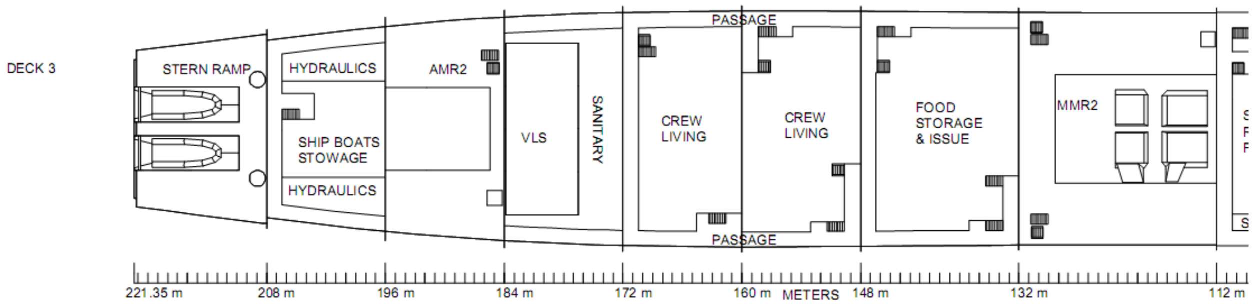
4.7.3 Internal Arrangements

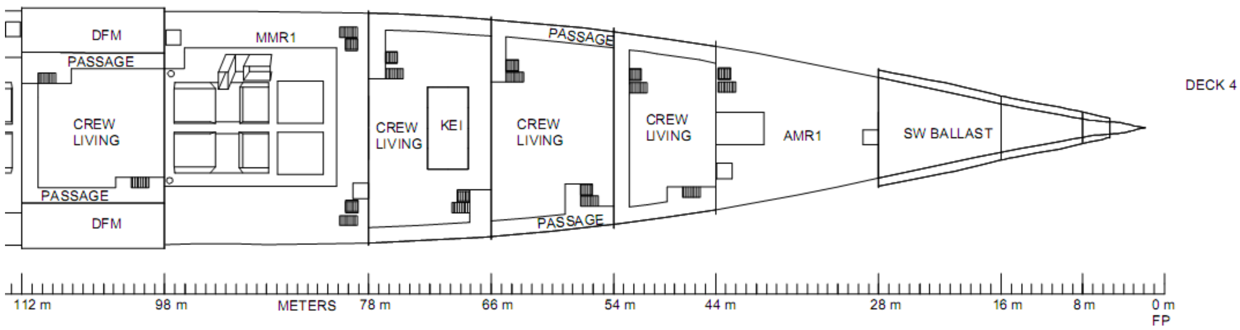
CGX/BMD is internally arranged using the four major space classification categories: Mission Support, Human Support, Ship Support, and Machinery Spaces. Approximate minimum areas and volume summaries for these spaces are listed in Appendix F - SSCS.

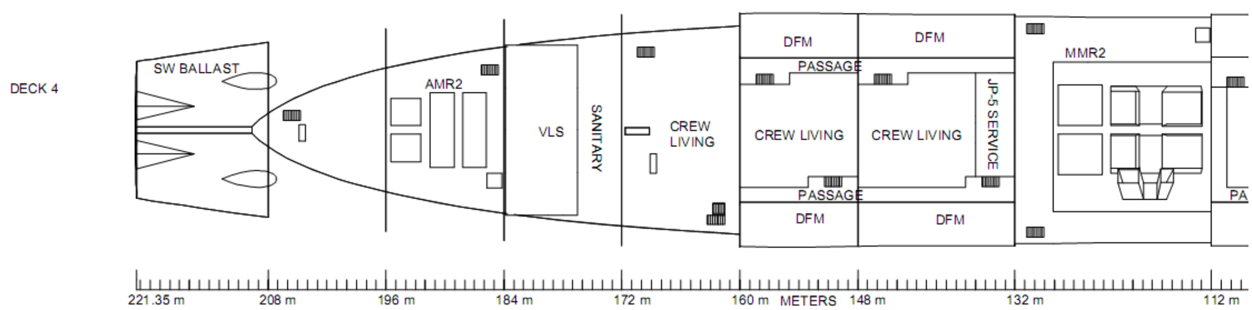
Mission Support includes CG(X) mission operations as well as combat systems and communications. This includes bridge spaces, navigation, aviation control, aviation hangar, and other spaces vital to combat missions. Human Support comprises of living spaces for all crew members, officers and enlisted. It also includes gallery spaces, mess spaces, recreation centers, and general ship spaces for all living on board. Ship Support systems generally include the daily operations of the ship, such as ship administration, ship control, damage control, deck auxiliaries, maintenance, stowage, and tankage. Ship administration is comprised of general ship administration, executive, engineering, supply and operations department offices. Damage control is located on the second deck, with spaces forward, mid and aft for firefighting stations and repair centers. Easy access to ladders is an advantage to these spaces. Ship Support also includes accessibility, including ship passageways and machinery room escape trunks. All major passageways are 1.55 meters wide, which accommodates medical passageways. Transverse passageways are situated about every two compartments. Each passageway through compartments has watertight bulkheads. There are two escape trunks in the main and auxiliary machinery rooms. Machinery spaces are described in the previous section. Figure 79 shows detailed general arrangement drawings.

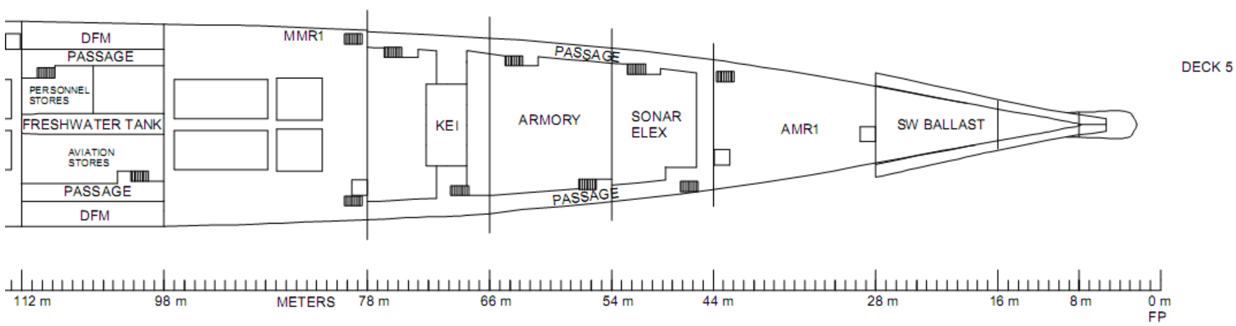


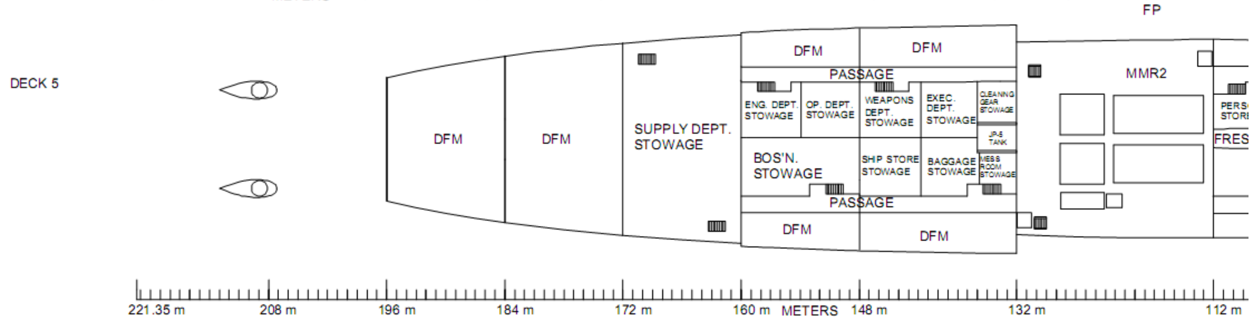
PASSAGE
DECK DEPT.
AVIATION SHOP
EXEC DEPT.
UNASSIGNED
KEI
SANITARY
MK 45 5" MAGAZINE
OFFICER LIVING
OFFICER LIVING
MOORING & ANCHOR WIND
BOS'N STOWAGE
BOS'N STOWAGE
DECK 1
112 m
98 m
METERS
78 m
66 m
54 m
44 m
28 m
16 m
8 m
0 m
FP
DECK 1
HANGAR
221.35 m
208 m
196 m
184 m
172 m
160 m
148 m
132 m
112 m
REPAIR STATION
FIRE FIGHTING
CBR DEFENSE EQUIPMENT
CBR DECON STATION
CIC
MEDICAL FACILITIES
KEI
PASSAGE
CBR DECON STATIONS
MK 45 5" MAGAZINE
CBR DEFENSE EQUIPMENT
FIRE FIGHTING
REPAIR STATION
MOORING & ANCHOR WIND
SVTT
BOS'N STOWAGE
DECK 2
DECK 2
STEERING
NIXIE
MOORING
LAUNDRY FACILITIES
MOORING
CPO LIVING
ENGINEERING DEPT. & SHOP
SANITARY
VLS
CPO LIVING
REPAIR STATION
FIRE FIGHTING
CBR DEFENSE EQUIPMENT
CBR DECON STATION
CPO LIVING
CPO SANITARY
CPO LIVING
SANITARY
GALLEY
CREW MESS
SHIP STORE
SHIP RECREATIONAL FACILITIES
SANITARY
MMR1
BARBER SERVICE
POSTAL SERVICE
TRAINING ROOM
KEI
CREW LIVING
CREW LIVING
AMR1
HAZARDOUS MATERIAL
SONAR ELEX
DECK 3


DECK 3
STERN RAMP
HYDRAULICS
SHIP BOATS STOWAGE
HYDRAULICS
AMR2
VLS
SANITARY
CREW LIVING
CREW LIVING
PASSAGE
PASSAGE
FOOD STORAGE & ISSUE
MMR2
221.35 m
208 m
196 m
184 m
172 m
160 m
METERS
148 m
132 m
112 m


DFM
PASSAGE
CREW LIVING
PASSAGE
DFM
MMR1
CREW LIVING
KEI
CREW LIVING
PASSAGE
PASSAGE
CREW LIVING
AMR1
SW BALLAST
DECK 4
112 m
98 m
METERS
78 m
66 m
54 m
44 m
28 m
16 m
8 m
0 m
FP


DECK 4
SW BALLAST
AMR2
VLS
SANITARY
CREW LIVING
DFM
DFM
PASSAGE
CREW LIVING
CREW LIVING
JP-5 SERVICE
PASSAGE
DFM
DFM
MMR2
221.35 m
208 m
196 m
184 m
172 m
160 m
METERS
148 m
132 m
112 m


DFM
PASSAGE
PERSONNEL STORES
FRESHWATER TANK
AVIATION STORES
PASSAGE
DFM
MMR1
KEI
ARMORY
PASSAGE
SONAR ELEX
PASSAGE
AMR1
SW BALLAST
DECK 5
112 m
98 m
METERS
78 m
66 m
54 m
44 m
28 m
16 m
8 m
0 m
FP


DECK 5
DFM
DFM
SUPPLY DEPT. STOWAGE
DFM
DFM
PASSAGE
ENG. DEPT. STOWAGE
OP. DEPT. STOWAGE
WEAPONS DEPT. STOWAGE
EXEC. DEPT. STOWAGE
BOS'N. STOWAGE
SHIP STORE STOWAGE
BAGGAGE STOWAGE
PASSAGE
DFM
DFM
MMR2
221.35 m
208 m
196 m
184 m
172 m
160 m
METERS
148 m
132 m
112 m

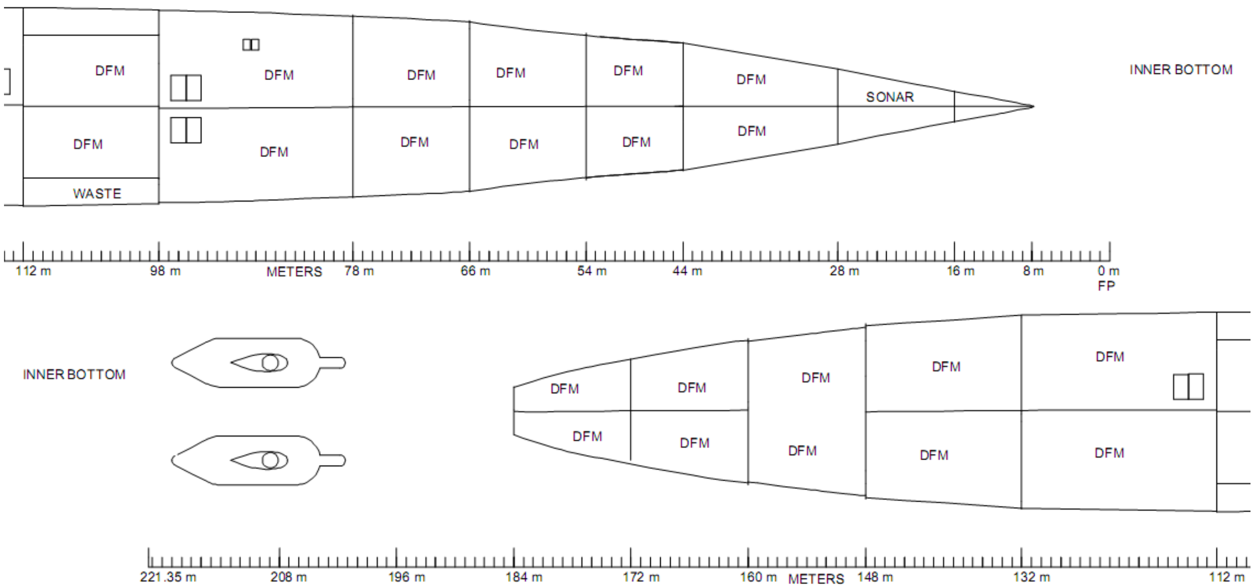


Figure 79-Detailed General Arrangement Drawings

Table 45 - Tank Capacity Plan

Tank	Capacity (m^3)	Tank	Capacity (m^3)
6-57-2-F	229	6-16-1-F	86
6-57-1-F	229	6-16-2-F	86
6-51-2-F	191	6-67-1-F	30
6-51-1-F	191	6-67-2-F	30
6-43-2-F	272	5-47-3-F	286
6-43-1-F	272	5-47-4-F	286
6-37-2-F	170	3-80-0-W	359
6-37-1-F	170	6-0-1-W	97
6-29-2-F	258	6-0-2-W	97
6-29-1-F	258	6-5-1-W	289
6-19-1-F	119	6-5-2-W	289
6-19-2-F	119	3-43-0-AF	65
6-25-1-F	136	6-11-1-WO	14
6-25-2-F	136	6-11-2-WO	12
6-63-1-F	77	6-11-2-LO	14
6-63-2-F	77	6-11-1-LO	12
5-57-3-F	530	5-36-0-W	37
5-57-4-F	530	5-37-0-W	37

4.7.4 Living Arrangements

Living space requirements were initially estimated based on the initial crew size from the ship synthesis model, then refined using the manning estimate. CG(X) final areas are necessary to support a highly capable and versatile crew. Table 46 lists the accommodation space for the crew.

Galley, crew's mess, laundry and medical spaces are located on the main deck. The Officer's Wardroom is located in the deckhouse. The CO and Flag Officer have the largest berthing and sanitary facility on the ship, followed by the XO. The CO, Flag Officer and XO quarters are located in the deckhouse. Department Head berthing is also located in the deckhouse, and CPO berthing is along the main deck. Living space for the enlisted crew members are located mainly on the third deck and a various other spaces. All living spaces are intended to contain both men and women berthing and sanitary facilities. The recreational space is located on the third deck as well. Figure 80 - Figure 83 show typical officer and enlisted berthing and mess areas.

Table 46 - Accommodation Space

Item	Accommodation Quantity	Per Space	Number of Spaces	Area Each (m2)	Total Area (m2)
CO	1	1	1	15	15
XO	1	1	1	10	10
Flag Officer	1	1	1	15	15
Department Head	4	1	4	8	32
Other Officer	33	2	17	8	136
CPO	50	6	9	15	135
Enlisted	425	12	36	15	540
Officer Sanitary	33	6	6	30	180
CPO Sanitary	50	6	9	25	225
Enlisted Sanitary	425	12	36	20	720
Total			120		2008

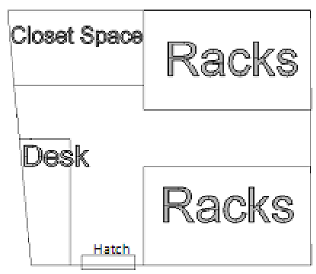


Figure 80-Typical Officer Berthing

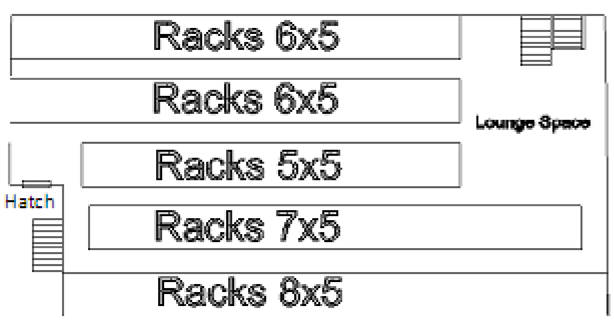


Figure 81-Typical Enlisted Berthing

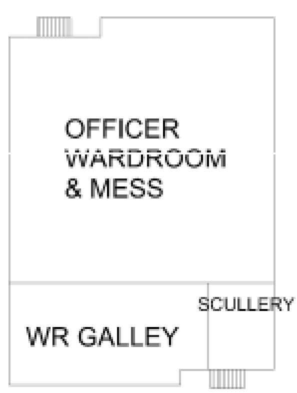


Figure 82-Typical Officer Mess

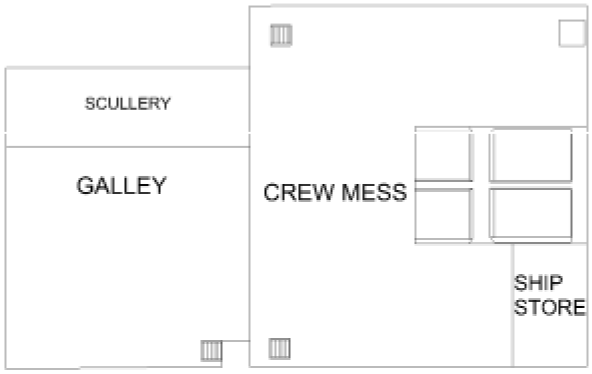


Figure 83-Typical Enlisted Mess

4.7.5 External Arrangements

Minimizing Radar Cross Section (RCS) is a major consideration in the design of the ship. All sides starting at three meters above the waterline are flared at a negative ten degree angle to offer a good RCS signature. An advanced enclosed mast structure is located at the top of the deckhouse to conceal various antennas and other arrays. Triple tubes which are normally mounted on deck are now mounted internally and fire through door openings in the hull. Conventional ship anchors were replaced by anchors similar to those found onboard submarines which tuck up into the hull, in the mooring spaces fore and aft.

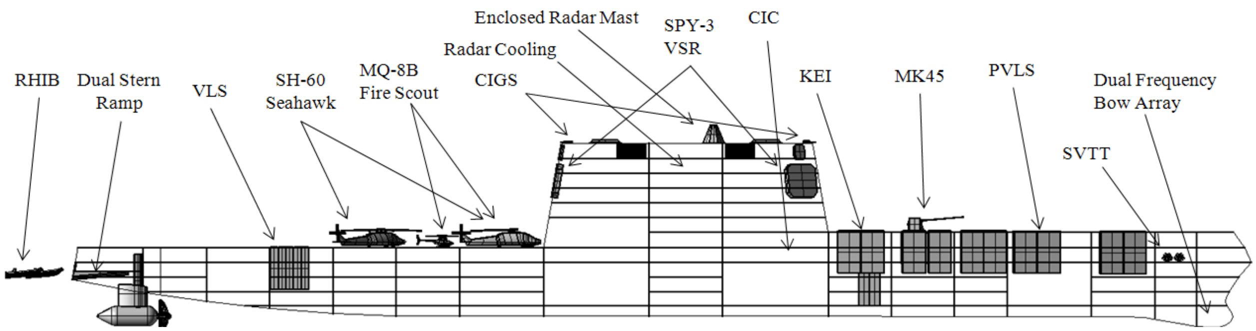


Figure 84-Profile of Combat Mission Systems

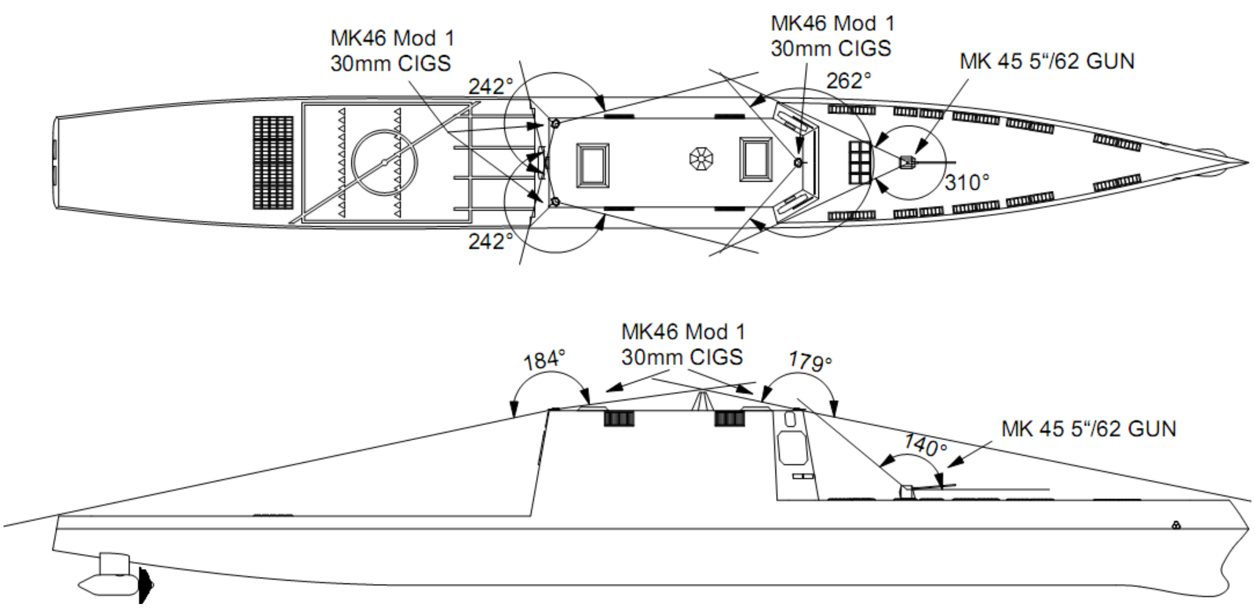


Figure 85-Arcs of Fire for MK45 5" Gun and 30mm CIGS

The dual stern ramp for the seven meter RHIBs is enclosed to reduce RCS. Three CIGS are located on top of the deckhouse, and provide 360° protection. SPY-3/VSR+++ have three locations on the sides of the deckhouse, also to provide 360° protection. The MK-45 gun located in front of the deckhouse allow for protection out of range of the CIGS. CGX/BMD is equipped with 80 cells MK-57 PVLS located along the bow. 80 cells MK-57 VLS cells are located behind the helo hangar and flight deck. Figure 84 shows a profile view of the combat mission systems and Figure 85 shows profile and plan coverage zone covered by the gun systems located on the CG(X).

4.8 Weights and Loading

4.8.1 Weights

Ship weights are grouped by SWBS. Some weights are obtained from manufacturer information. ASSET parametrics and the ship synthesis model were used when this information was unavailable. The VCGs and LCGs of the weights are determined from the general ship and machinery arrangements. These values are used to calculate mass moments and the lightship centers of gravity. A summary of lightship weights and centers of gravity by SWBS group is listed in Table 47. The weights spreadsheet is provided in Appendix G.

Table 47 - Lightship Weight Summary

SWBS Group	Weight (MT)	VCG (m-Abv BL)	LCG (m-Aft FP)
100	9430.10	8.23	112.70
200	1861.06	5.07	140.33
300	1039.2	9.25	116.33
400	1202.10	17.08	67.88
500	2207.20	11.99	121.94
600	1553.50	7.61	101.03
700	848.50	10.92	107.31
Margin	1814.17	9.08	112.64
Total (LS)	19955.83	9.08	112.64

4.8.2 Loading Conditions

As defined in DDS 079-1, the Full Load condition includes the lightship weights and LCG plus the full allowance of variable loads and cargo. This includes all liquid tankage at 95% capacity, ammunition, ship's force, provisions for endurance, and other miscellaneous cargoes. The Minimum Operating (MinOps) condition corresponds to a condition after some time at sea. Provisions, stores, ammunition, and fuel are considered to have one third of full capacity. Ballast tanks are filled to adjust trim appropriately. A summary of the weights for the Full Load condition is provided in Table 48. A summary for the Minimum Operating condition is provided in Table 49.

Table 48 - Weight Summary: Full Load Condition

Item	Weight (MT)	VCG (m-BL)	LCG (m-FP)
Lightship w/ Margin	18141.66	9.08	112.64
Ships Force	51.10	11.47	104.20
Total Weapons Loads	438.3	12.44	113.71
Aircraft	14.1	14.29	127.00
Provisions	53.5	8.40	119.72
General Stores	12.0	9.51	119.72
Diesel Fuel Marine	3767.00	2.45	118.30
JP-5	50.00	8.81	134.00
Lubricating Oil	23.00	1.55	105.16
SW Ballast	0.00	0.00	0.00
Fresh Water	154.00	3.38	105.00
Total	24518.83	8.09	113.53

Table 49 - Weight Summary: Minop Condition

Item	Weight (MT)	VCG (m-BL)	LCG (m-FP)
Lightship	18141.66	9.08	112.64
Ships Force	51.10	11.47	104.20
Total Weapons Loads	144.64	12.44	113.71
Aircraft	14.10	14.29	127.00
Provisions	17.66	8.40	119.72
General Stores	3.96	9.51	119.72
Diesel Fuel Marine	1308.00	1.51	118.10
JP-5	17.00	7.95	134.00
Lubricating Oil	8.00	1.23	105.21
SW Ballast	843.00	4.74	104.70
Fresh Water	103.00	2.92	105.00
Total	22466.28	8.48	112.65

Table 50 - Minop Trim and Stability Summary

Item	Weight MT	VCG m	LCG m-MS	TCG m-CL	FSMom m-MT
Light Ship	20,528	10.220	112.500A	0	----
Constant	0	0	0	0	0
Lube Oil	8	1.227	105.212A	0.243P	8
Fresh Water	103	2.921	105.000A	0	75
SW Ballast	843	4.842	104.704A	0	1,993
Fuel (JP5)	17	7.954	134.000A	----	59
Comp. Fuel/Ballast	0	0	0	0	0
Fuel (DFM)	1,322	1.513	118.112A	0	9,013
Waste Oil	16	1.572	105.253A	0.486S	17
Sewage	15	1.522	115.234A	0	14
Displacement	22,998	9.975	111.533A	0.001S	1,993

Stability Calculation			Trim Calculation		
KMt	11.761	m	LCF Draft	7.205	m
VCG	9.432	m	LCB (even keel)	112.503A	m-MS
GMt (Solid)	2.329	m	LCF	122.369A	m-MS
FSc	0..406	m	MT1cm	609	m-MT/cm
GMt (Corrected)	1.922	m	Trim	0.063	m-A
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from tables			Tank calcs from tables		

Drafts			Strength Calculations		
Draft at A.P.	7.170	m	Bending Moment	47,003H	m-MT
Draft at M.S.	7.201	m	Shear	-968	MT
Draft at F.P.	7.233	m			
Draft at Aft Marks	7.169	m			
Draft at Mid Marks	7.201	m			
Draft at Fwd Marks	7.232	m			

4.9 Hydrostatics and Stability

The hydrostatic properties of the CGX/BMD hullform were analyzed using the HECSALV software suite. First the section geometry was imported from RHINO into the HECSALV Ship Project Editor. Tankage and lightship distribution were established in the Ship Project Editor and bulkheads were arranged early on to set the floodable length curve. Once the ship's loads were balanced, the intact stability and damaged stability were analyzed in HECSALV and the Damaged Stability Module. The initial hydrostatics was calculated at a number of drafts, and the curves of form were also calculated. Intact stability was calculated in accordance with the U.S. Navy Design Sheet DDS 079-1. The damaged conditions were calculated for a number of possible scenarios with damage of 15% LWL or greater, then the three worst scenarios were modeled with the DDS 079-1 criteria for stability.

4.9.1 Intact Stability

In each condition, trim, stability and righting arm data were calculated. All conditions were assessed using DDS 079-1 stability standards for beam winds with rolling. There are two criteria which must be fulfilled in order to have satisfactory intact stability: (1) the magnitude of the heeling arm at the intersection of the righting arm and wind heel arm curves must be less than six-tenths of the maximum GZ, and (2) the area under the righting arm curve and above the heeling arm curve (A1) must be greater than 1.4 times the area under the heeling arm curve and above the righting arm curve (A2).

Table 51 - Full Load Trim and Stability Summary

Item	Weight MT	VCG m	LCG m-MS	TCG m-CL	FSMom m-MT	
Light Ship	20,528	10.220	112.500A	0.000	----	
Constant	0	0.000	113.540A	0.000	0	
Lube Oil	24	1.572	105.159A	0.259P	0	
Fresh Water	154	3.375	105.000A	0.000	----	
SW Ballast	0	----	----	----	----	
Fuel (JP5)	52	8.875	134.000A	0.000	0	
Comp. Fuel/Ballast	0	----	----	----	----	
Fuel (DFM)	3,807	2.351	117.292A	0.000P	5,930	
Waste Oil	0	----	----	----	----	
Misc. Weights	550	11.954	113.863A	0.000	0	
Displacement	25,115	8.933	113.298A	0.000P	5,930	
Stability Calculation			**Trim Calculation**			
KMt	11.630	m	LCF Draft		7.682	m
VCG	8.847	m	LCB (even keel)		113.347A	m-FP
GMt (Solid)	2.783	m	LCF		122.490A	m-FP
FSc	0.236	m	MT1cm		624	m-MT/cm
GMt (Corrected)	2.547	m	Trim		0.064	m-A
			List		0.0P	deg
Specific Gravity	1.0250					
Hull calcs from tables			Tank calcs from tables			
Drafts			**Strength Calculations**			
Draft at F.P.	7.927	m	Bending Moment		14,963	m-MT
Draft at M.S.	7.955	m	Shear Force		734	MT
Draft at A.P.	7.982	m				
Draft at Aft Marks	7.927	m				
Draft at Mid Marks	7.954	m				
Draft at Fwd Marks	7.981	m				

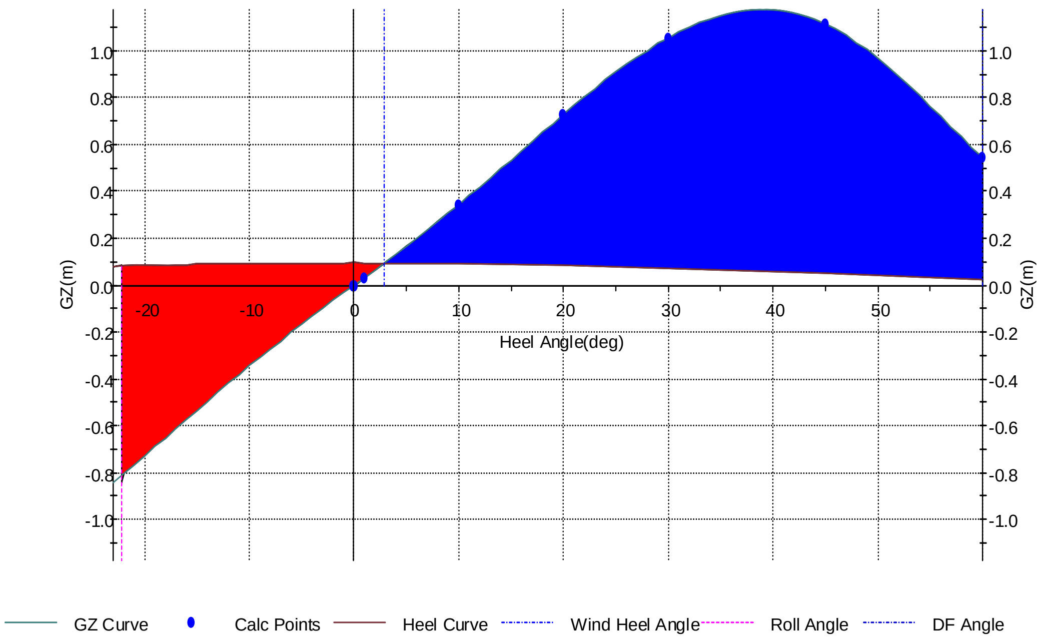


Figure 86-MinOps Righting Arm Curve

Table 52 - Righting Arm (GZ) and Heeling Arm Data for Minop Condition

Beam Wind with Rolling Stability Evaluation (per US Navy DDS079-1)			
Displacement	22,998 MT	Angle at Maximum GZ	39.1 deg
GMt (corrected)	1.922 m	Wind Heeling Arm Lw	0.095 m
Mean Draft	7.201 m	Angle at Intercept	
Projected Sail Area	1,729.29 m2	Wind Heel Angle	2.8 deg
Vertical Arm	11.058 m	Maximum GZ	1.175 m
Wind Pressure Factor	.0035	Righting Area A1	0.74 m-rad
Wind Pressure	0.02 bar	Capsizing Area A2	0.19 m-rad
Wind Velocity	100 kts	Heeling Arm at 0 deg	0..095 m
Roll Back Angle	25 deg		

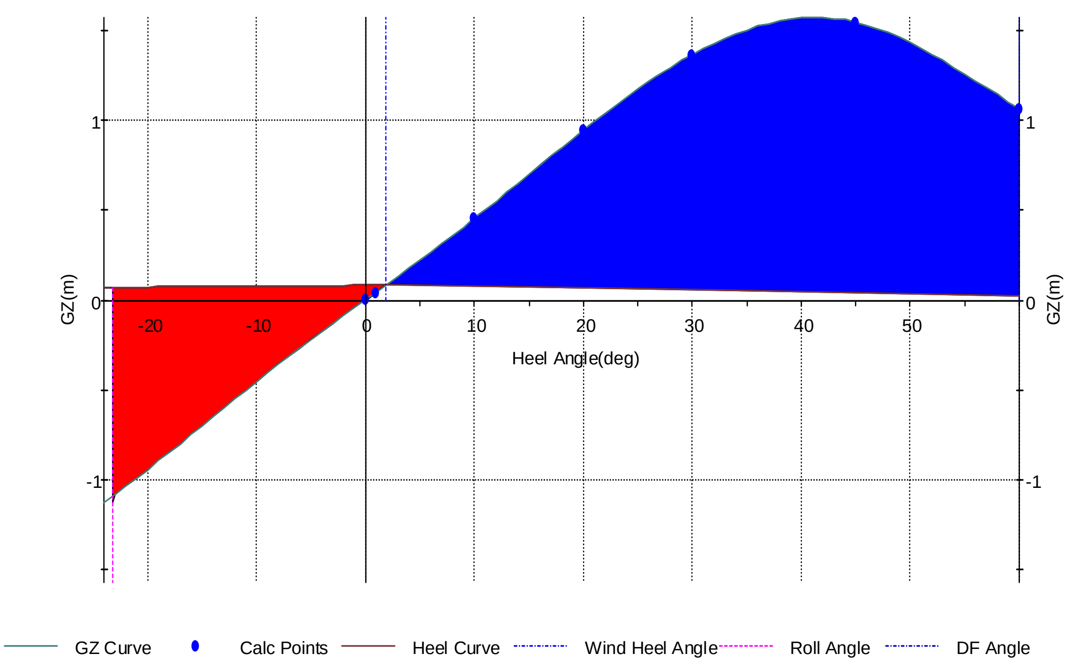


Figure 87-Full Load Righting Arm Curve

In this case, both criteria are met. (1) The maximum heeling arm ratio is 0.08, well below the limit of 0.6, and (2) the area A1 is greater than 0.26, which is 1.4 times the area A2. The intact stability is satisfactory in the MinOps condition.

Table 53 - Righting Arm (GZ) and Heeling Arm Data for Full Load Condition

Beam Wind with Rolling Stability Evaluation (per US Navy DDS079-1)			
Displacement	25,115 MT	Angle at Maximum GZ	41.3 deg
GMt (corrected)	2.547 m	Wind Heeling Arm Lw	0..081 m
Mean Draft	7.95 m	Angle at Intercept	
Projected Sail Area	1,584 m2	Wind Heel Angle	1.8 deg
Vertical Arm	11.396 m	Maximum GZ	1.57 m
Wind Pressure Factor	.0035	Righting Area A1	1.05 m-rad
Wind Pressure	0.02 bar	Capsizing Area A2	0.25 m-rad
Wind Velocity	100 kts	Heeling Arm at 0 deg	0.081 m
Roll Back Angle	25		

In the Full Load condition both DDS 079-1 criteria are met. (1) The maximum heeling arm ratio is 0.05, well below the limit of 0.6, and (2) the area A1 is greater than 0.34, which is 1.4 times the area A2. The intact stability is satisfactory in the Full Load condition.

4.9.2 Damage Stability

To assess the vulnerability of CGX/BMD to damage, twenty-six individual damage cases were modeled in the HECSALV Damaged Stability Module. These cases involved three and four compartment flooding to the waterline determined by the creating damage scenarios with a 15% LWL damage event on the starboard side. Since the ship is largely symmetrical in loading and tankage, it was safe to consider only damage to the starboard side. The DDS 079-1 criteria for righting arm and area ratio as discussed before is applied here as well.

Table 54 - Full Load Damage Results

	Intact	Damage 26 (trim 10.189A m)	Damage 20 (heel 8.5 S deg)
Draft AP (m)	7.710	14.124	9.325
Draft FP (m)	7.646	3.797	10.712
Trim on LBP (m)	0.064A	10.189A	1.387F
Total Weight (MT)	25,115	25,115	25,115
Static Heel (deg)	0	0	8.5
GM_t (upright) (m)	2.544	1.770	2.140
Maximum GZ	1.570	0.74	0.764
Maximum GZ Angle	41.5	39.2	39.9

Damage Case 20 in Figure 88 through Figure 90 was considered as a limiting state for extreme heel. The damage length in this scenario is 34m, which is just above the 15% LWL damage criteria. The aft diesel wing tank is also flooded in consideration of the damage potentially occurring further aft and as a worst case scenario. In the full load condition the weight of the fuel cargo on the port side helps to offset the lost of buoyancy on the starboard side. This can be seen in the sectional view in Figure 89. This case was a driving factor to boost the power in the auxiliary machinery spaces in the event of a large damage event at amidships.

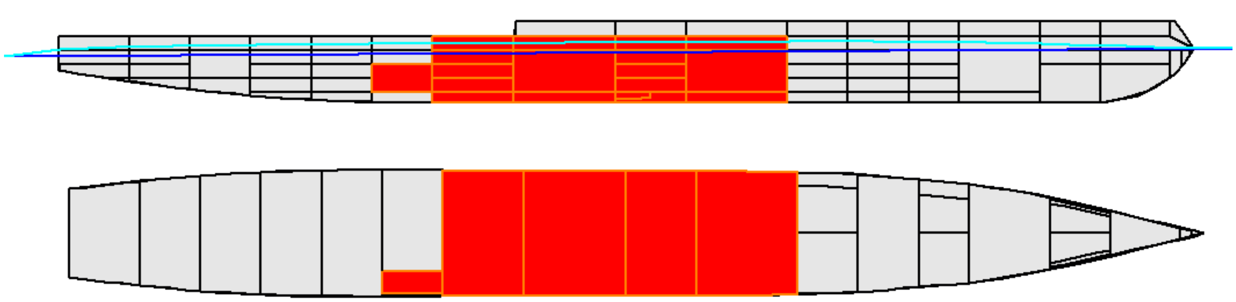


Figure 88 - Damage Case 20 – Four compartment flooding extreme aft case

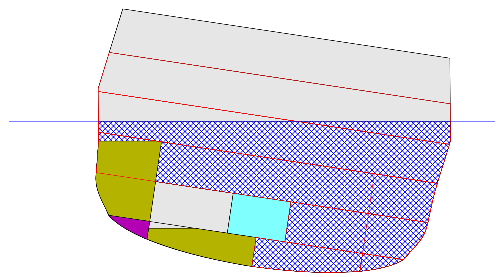


Figure 89 - Damage Case 20 – Sectional View of Starboard Flooding Amidships

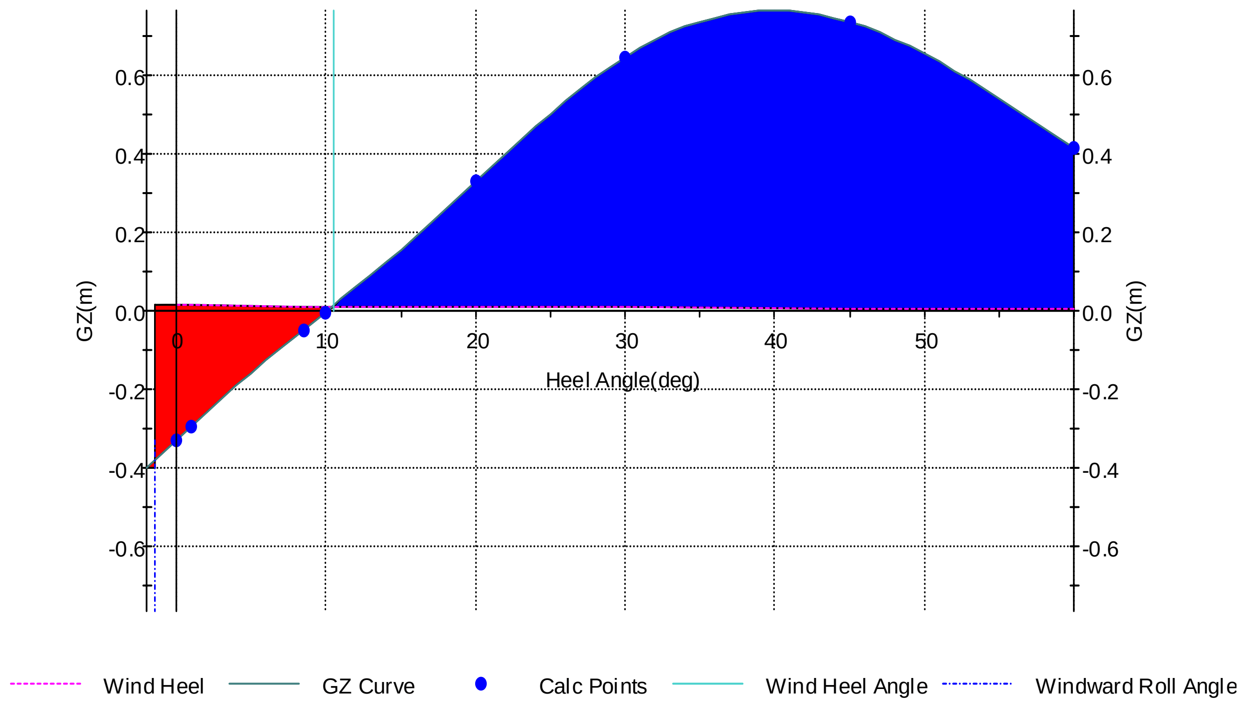


Figure 90 - Damage Case 20 – Full Load Righting Arm Curve

Damage Case 26 in Figure 91 and Figure 92 represents a 24m damage length along the aft starboard side, and is the limiting case for trim. The margin line is submerged by 1.5 m at the transom. This case shows an extreme vulnerability to aft damage. Considering the propulsion pods and AMR2 are located in this damage region, the effects of an attack here would deal a major blow to ship capability. This issue should be examined more in depth in the next cycle of the design spiral. The equilibrium condition after damage might be affected by neglecting the added buoyancy of the pods in stability calculations.

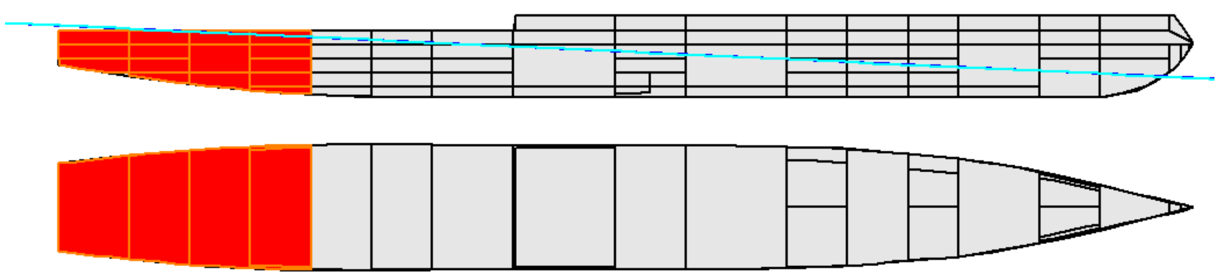


Figure 91 - Damage Case 26 – Four compartment flooding extreme aft case.

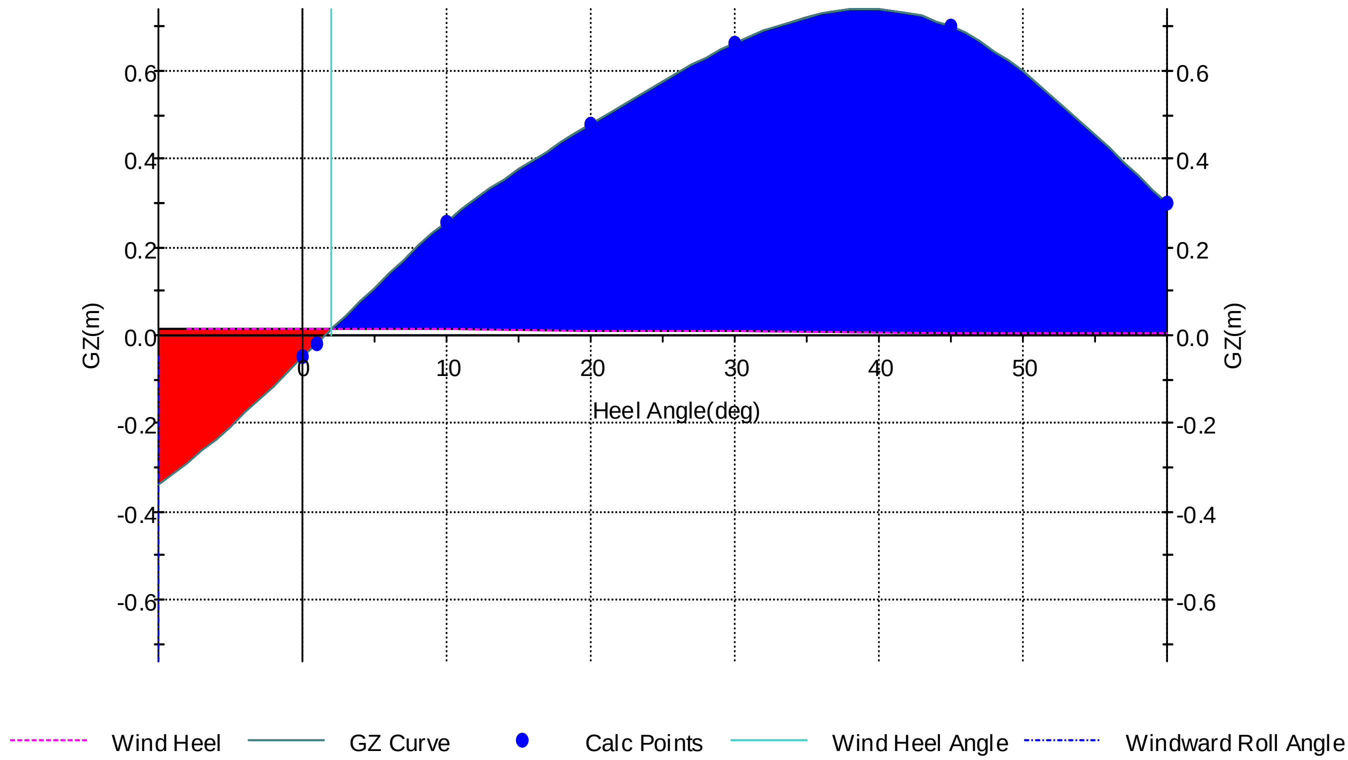


Figure 92 - Damage Case 26 - Full Load Righting Arm Curve

4.10 Cost and Risk Analysis

4.10.1 Cost and Producibility

As part of the multi-objective optimization performed at the end of concept exploration (see sections 3.4.3, 3.5, and 3.6), cost was estimated for both lead and follow ship using parametric mathematical models. These models use, primarily, the rough estimates for weight (by SWBS group) determined by other parametric math models to estimate the basic cost of construction. Other factors considered included endurance range, brake horsepower, propulsion system type, and engine type. Estimates for shipbuilder profit, government costs and change orders, and a variety of other capital-consuming aspects were added to this cost to come up with the final cost estimates.

In concept development, many of the assumptions and estimates on which the cost estimate was based were changed, or re-calculated as firm numbers presented themselves or as the design changed. Therefore, a new estimation of cost is in order at the end of concept development.

4.10.2 Risk Analysis

In Concept Development, changes were made to the design that affected the Overall Measure of Risk for the ship. The key technology changes made are the selection of permanent magnet motors (PMMs) for the pods and PEM fuel cells as emergency power generators. The motors were changed to PMMs because the pods, with induction motors, were determined to be too large and heavy, presenting structural and survivability dangers. The fuel cells were added as emergency generators in place of small diesel generators in the AMRs to increase survivability. The fuel cells provide enough power to drive the propellers in the event of flooding damage to both MMRs, while the small diesels did not.

It was determined that the change in motors would cause a change in overall risk, due to the uncertainty of the technology being available, but the addition of fuel cells would not increase risk, because they don't replace the large CAT 3616 diesels as SGPMs, they only supplement them. After recalculation, OMOR was found to have increased from 0.171 to 0.286. This is a moderate increase, but overall the design remains a low-risk option.

Table 55 - Cost Comparison

Characteristic	Concept Baseline	Final Concept Design
Design Variables		
Hull Structure Material	Steel	Steel
Deck House Material	Composite	Composite
Hull Form	Monohull – Flared	Monohull –Flared
Sustained Speed	20.0 knots	20.0
Endurance Speed	32.2 knots	32.9
Endurance Range	8158.7 nm	8007 nm
Propulsion and Power	2 Shaft FPP	2 Shaft FPP
	IPS	IPS
	4xMT30	4xMT30
	2xCAT 3616	2xCAT 3616
BHP	52.0 MW	103.0 MW
Fuel Volume	4652 m3	4720 m3
Weights (MT)		
Lightship Weight	18245.1	18141.66
Full Load Displacement	24938.8	24518.83
100 (hull structures)	9455.7	9430.10
200 (propulsion plant)	1938.7	1861.06
300 (electrical)	1039.2	1039.20
400 (command and surveillance)	1202.2	1202.10
500 (auxiliary)	2207.4	2207.20
600 (outfit)	1553.4	1553.50
700 (armament)	848.5	848.50
Internal communications		
Ordinance Loads Weight		
Operating and support		
Number of Officer Crew	31	
Number of Enlisted Crew	421	
Total Crew	452	452
Fuel Usage (Gal./Yr.)		
Service Life (Years)	35	35
Cost Elements		
Number of Ships to be Built	18	18
Shipbuilder		$1.03 Bil
Government Furnished Equipment (a)		$2.599 Bil
Other Costs		$105.128 Mil
Follow Ship Acquisition Cost	$3.630 Bil	$3.676 Bil

5 Conclusions and Future Work

5.1 Assessment

Table 56 compares the CDD KPPs to the performance of baseline designs.

Table 56 - Compliance with Operational Requirements

Technical Performance Measure	CDD KPP (Threshold)	Original Goal	Concept BL	Final Concept BL
Endurance Range (nm)	8000 nm	8000 nm	8000 nm	8007 nm
Sustained Speed (knots)	32.2 knots	32.2 knots	32.2 knots	32.7 knots
Endurance Speed (knots)	20 knots	20 knots	20 knots	20 knots
Stores Duration (days)	50	50	50	50
Collective Protection System	full	full	full	full
Crew Size	452	452	452	388
RCS (m^3)	14100	14100	14100	14100
Maximum Draft (m)	7.58 m	7.58 m	7.58 m	7.9 m
Vulnerability (Hull Material)	Steel	Steel	Steel	Steel
Ballast/fuel system	Clean, separate ballast tanks	Clean, separate ballast tanks	Clean, separate ballast tanks	Clean, separate ballast tanks

5.2 Future Work

There are a number of concerns and issues that should be addressed in future design spirals. Vulnerability is a major concern in this design, and efforts have been made to minimize them. However, in future designs, some steps to minimize vulnerability should be assessed. Sympathetic vibrations of the hull due to long slender hull girder should be investigated. Alternative propulsor arrangements should be assessed. Pods located close together present a vulnerable target. Viability of a secondary Forward Propulsion Unit (FPU) should be investigated.

The need for sustained speed on the order of 33 knots should be reevaluated. For this ship's mission, it may not need the ability to travel at carrier speed.

The ability of the ZEDS system to carry the amperage demanded of it at the specified voltage should be investigated. The voltage currently in the design may not be high enough. Also, the electromagnetic interference of communications and radars should be investigated.

Fuel cells take a long time to power on. In a battle situation, all power generators would be powered on for safety, but if the ship were to take unexpected damage to both MMRs and the fuel cells in the AMRs were not powered on, the ship would be temporarily without power. Because of this, changing the fuel cells to a secondary power generation role and the CAT 3616 diesels to an emergency role should be investigated. This may have an impact on arrangements, because if the large CAT 3616 diesels are placed in the AMRs, additional inlet/exhaust stacks might be needed on deck. This would also affect radar cross-section.

The ship structures weight as estimated seems high (9430 MT). This weight should probably be on the order of 8000 MT. This should be revisited in future work.

Arrangements could be adjusted in future work. The size of the ship in terms of length, depth, and deckhouse volume could possibly be reduced. Also, as many VLS cells aft of the deckhouse as possible could be placed in a peripheral arrangement, and the remaining cells could be placed forward, so that two helicopter landing pads could be placed aft, making use of all the deck area aft. To accomplish this, significant rearranging internally would be required.

5.3 Conclusions

The CGX/BMD design presented in this report represents a feasible, highly effective solution to the BMD capability gap presented by the ADM. The design is highly effective at its primary mission of BMD due to its very large DBR and missile outfit. The design also fits the vision of the future of the navy by incorporating IPS. With ample power generation and full IPS the ship is flexible for future growth. The ship also has multi-mission capability, incorporating LAMPS and boat ramps, and guns for fire support. CGX/BMD fulfills the projected needs for strategic ballistic missile defense of the homeland, with an innovative yet realistic design

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Appendix A – Initial Capabilities Document (ICD)

UNCLASSIFIED

INITIAL CAPABILITIES DOCUMENT

FOR A

Ballistic Missile Defense Cruiser (CGX/BMD)

1 PRIMARY JOINT FUNCTIONAL AREA

- Force and Homeland Protection

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

2 REQUIRED FORCE CAPABILITY(S)

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

3 CONCEPT OF OPERATIONS SUMMARY

Current Aegis ships are to be configured to intercept short and medium-range BM threats, but can not counter long-range intercontinental ballistic missiles that could target the US from China, North Korea and Iran. Current ships are also fully multi-mission ships. The radar and missile capabilities of the CGX/BMD are to be greater than the Navy's current Aegis ships. Some multi-mission capabilities may have to be sacrificed to control cost.

Potential strengths of CGX/BMD include the ability to conduct BMD operations from advantageous locations at sea that are inaccessible to ground-based systems, the ability to operate in forward locations in international waters without permission from foreign governments, and the ability to readily move to new maritime locations as needed. CGX/BMD could operate over the horizon from observers ashore, making it less visible and less provocative. CGX/BMD could readily move to respond to changing demands for BMD capabilities or to evade detection and targeting by enemy forces, and could do so without placing demands on other assets. Better locations might lie along a ballistic missile's potential flight path which can facilitate tracking and intercepting the attacking missile. Better locations would permit the CGX/BMD radar to view a ballistic missile from a different angle than other U.S. BMD sensors, which would allow CGX systems to track the attacking missile more effectively. If a potential adversary's ballistic missile launchers are relatively close to its coast, CGX/BMD could defend a large down-range territory against potential attack by ballistic missiles fired from those launchers. One to four BMD ships operating in the Sea of Japan could defend most or all of Japan against theater-range ballistic missiles (TBMs) fired from North Korea. CGX/BMD could be equipped with very fast interceptors (i.e., interceptors faster than those the Navy is currently deploying), and could intercept ballistic missiles fired from launchers during the missiles' boost phase of flight — the initial phase, during which the ballistic missiles' rocket engines are burning. A ballistic missile in the boost phase of flight is a relatively large, hot-burning target, is easier to intercept (in part because the missile is flying relatively slowly and is readily seen by radar), and the debris from a missile intercepted during its boost phase is more likely to fall on the adversary.

Potential limitations of a CGX/BMD include possible conflicts with performing other ship missions, and vulnerability to attack when operating in forward locations. Typical cruiser multi-mission capabilities and self-defense capabilities may have to be traded to control cost. CGX/BMD may require other surface combatant and submarine support to operate safely in high-risk environments. Conducting BMD operations may require CG(X) 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 CGX/BMD 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 CGX/BMD Concept of Operations.

CGX/BMD high-altitude long-range search and track radar will be much larger and more capable than current SPY-1B, 1D and 3 radars. It will be a mid-course fire-control radar designed to support long range BMD systems. Its principal functions are to detect and establish precise tracking information on ballistic missiles, discriminate missile warheads from decoys and debris, provide data for updating ground-based interceptors in flight, and assess the results of intercept attempts. It will be a large, powerful, phased-array radar operating in the X band, the frequency spectrum that is necessary for tracking missile warheads with high accuracy. It will have significant power and cooling requirements.

SM-3 Block IA missile is equipped with a kinetic (i.e., non-explosive) warhead designed to destroy a ballistic missile's warhead by colliding with it outside the atmosphere, during the enemy missile's midcourse phase of flight. It is intended to intercept SRBMs and MRBMs. An improved version, the Block IB, is to offer some capability for intercepting intermediate-range ballistic missiles (IRBMs). The Block IA and IB do not fly fast enough to offer a substantial capability for intercepting ICBMs. A faster-flying version of the SM-3, the Block II/IIA, is being developed. Block II/IIA is intended to give Aegis BMD ships a capability for intercepting certain ICBMs. The Block II version of the SM-3 will be available around 2013, and the Block IIA version in 2015. In contrast to the Block IA/1B version of the SM-3, which has a 21-inchdiameter booster stage but is 13.5 inches in diameter along the remainder of its length, the Block II/IIA version would have a 21-inch diameter along its entire length. The increase in diameter to a uniform 21 inches gives the missile a burnout velocity (a maximum velocity, reached at the time the propulsion stack burns out) that is 45% to 60% greater than that of the Block IA/IB version. The Block IIA version also includes an improved kinetic warhead. MDA states that the Block II/IIA version will "engage many [ballistic missile] targets that would outpace, fly over, or be beyond the engagement range" of earlier versions of the SM-3, and that the net result, when coupled with enhanced discrimination capability, is more types and ranges of engageable [ballistic missile] targets; with greater probability of kill, and a large increase in defended "footprint". Block II/IIA can be launched from Mk 57 VLS.

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

The Kinetic Energy Interceptor (KEI) is a potential ballistic missile interceptor that, although large, could be used as a sea-based interceptor. Compared to the SM-3, the KEI would be much larger (perhaps 40 inches in diameter and 36 feet in length) and would have a much higher burnout velocity. Because of its much higher burnout velocity, it might be possible to use a KEI to intercept ballistic missiles during the boost and early ascent phases of their flights. The KEI would require missile-launch tubes that are much larger than MK 57 VLS.

4 CAPABILITY GAP(S)

The overarching capability gap addressed by this ICD is to provide a robust sea-based terminal and/or boost phase ICBM defense platform:

Specific capability gaps and requirements in this ICBMD platform include:

Priority	Capability Description	Threshold Systems or metric	Goal Systems or metric
1	LRS&T Radar	SPY-3 X-band radar; S-Band VSR	Big!
2	BMD Missile Cell	SM-3/MK-57 VLS only	KEI and SM-3/MK-57 VLS
3	BMD Missile Capacity	96 SM-3	128 SM-3, 16 KEI

Priority	Capability Description	Threshold Systems or metric	Goal Systems or metric
4	BMD Platform Mobility	30knt, full SS4, 4000 nm, 60 days	35knt, full SS5, 6000 nm, 75 days
5	Platform Passive Susceptibility	DDG-51 signatures	DDG1000 signatures
6	Platform Vulnerability and Recoverability	AFSS	AFSS
7	Platform Self and Area Defense, Other Multi-Mission	CIGS, LAMPS haven, TSCE	1xAGS, IUSW, SOF and ASUW stern launch, Embarked LAMPS/AAV w/hangar, TSCE

5 THREAT AND OPERATIONAL ENVIRONMENT

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

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

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

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

6 FUNCTIONAL SOLUTION ANALYSIS SUMMARY

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

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

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

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

7 FINAL RECOMMENDATIONS

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

b. The secondary mission for this ship is CBG AAW and escort. The LPD-17 option does not support CBG requirements.

c. CG-52 ships do not have sufficient stability, margin or large object space to support robust BMD radar and missile requirements.

d. The options of a new CGX/BMD ship with limited multi-mission capability and new CGX/BMD ship with maximum DDG1000 commonality should both be explored and compared. A full range of multi-mission options should be considered from threshold to goal. Trade-offs and costs associated with such options as wave-piercing tumblehome hull form, IUSW and embarked LAMPS should be clearly identified and assessed.

e. The nuclear option should be studied separately and possibly as a separate acquisition.

Appendix B– Acquisition Decision Memorandum (ADM)

Virginia Tech
VIRGINIA POLYTECHNIC INSTITUTE
AND STATE UNIVERSITY

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

August 21, 2007

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

Subject: ACQUISITION DECISION MEMORANDUM FOR a Ballistic Missile Defense Cruiser

Ref: (a) Virginia Tech CGXBMD Initial Capabilities Document (ICD)

1. This memorandum authorizes concept exploration of two material alternatives proposed in Reference (a) to the Virginia Tech Naval Acquisition Board on 21 August 2007. Additional material and non-material alternatives supporting this ICD may be authorized in the future.

2. Concept exploration is authorized for a CG(X) Ballistic Missile Defense Cruiser consistent with the mission requirements and constraints specified in Reference (a), with particular emphasis on providing robust ICBM defense. Missile options should include SM-3 Block II/IIA, systems providing improved terminal phase capability, and systems providing boost phase capability (Kinetic Energy Interceptor). A range of increasingly powerful dual X/S-band radars should be considered beyond SPY-3 w/VSR. Ship options should range from a new CGX/BMD ship with limited multi-mission capability to a fully multi-mission ship with maximum DDG-1000 commonality. A full range of multi-mission options should be considered. Trade-offs and costs associated with such options as wave-piercing tumblehome hull form, IUSW and embarked LAMPS should be clearly identified and assessed. The design must minimize personnel vulnerability in combat through automation. Concepts shall include moderate to high-risk alternatives. Average follow-ship acquisition cost shall not exceed $3B (FY2012) with lead ship acquisition cost less than $4B. It is expected that 18 ships of this type will be built with IOC in 2018.

A.J. Brown
VT Acquisition Executive

Appendix C–Pairwise Comparison Results

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP1 - BMD

AAW Options	1.000
GMLS Options	.476
CCC Options	.235

Inconsistency = 0.08
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP1 - BMD
>AAW Options

AAW Option 1	1.000
AAW Option 2	.932
AAW Option 3	.676
AAW Option 4	.232

Inconsistency = 0.00609
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP1 - BMD
>GMLS Options

GMLS Option 1	1.000
GMLS Option 2	.611
GMLS Option 3	.492
GMLS Option 4	.397

Inconsistency = 0.00057
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP1 - BMD
>CCC Options

CCC Option 1	1.000
CCC Option 2	.588

Inconsistency = 0.
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP2 - AAW

AAW Options	1.000
GMLS Options	.476
CCC Options	.235

Inconsistency = 0.08
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP2 - AAW
>AAW Options

AAW Option 1	1.000
AAW Option 2	.913
AAW Option 3	.786
AAW Option 4	.640

Inconsistency = 0.00481
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP2 - AAW
>GMLS Options

GMLS Option 1	1.000
GMLS Option 2	.820
GMLS Option 3	.670
GMLS Option 4	.549

Inconsistency = 0.00156
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP2 - AAW
>CCC Options

CCC Option 1	1.000
CCC Option 2	.588

Inconsistency = 0.
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP3 - ASUW/NSFS

ASUW/NSFS Options	1.000
LAMPS Options	.938
CCC Options	.404

Inconsistency = 0.00096
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP3 - ASUW/NSFS
>ASUW/NSFS Options

ASUW/NSFS Option 1	1.000
ASUW/NSFS Option 2	.652
ASUW/NSFS Option 3	.284

Inconsistency = 0.02
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP3 - ASUW/NSFS
>LAMPS Options

LAMPS Option1	1.000
LAMPS Option 2	.603
LAMPS Option 3	.130

Inconsistency = 0.02
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP3 - ASUW/NSFS
>CCC Options

CCC Option 1	1.000
CCC Option 2	.588

Inconsistency = 0.
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP4 - ASW/MCM

ASW Options	1.000
LAMPS Options	.875
GMLS Options	.478
CCC Options	.155

Inconsistency = 0.00079
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP4 - ASW/MCM
>ASW Options

ASW Option 1	1.000
ASW Option 2	.952
ASW Option 3	.590
ASW Option 4	.247

Inconsistency = 0.00535
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP4 - ASW/MCM
>LAMPS Options

LAMPS Option1	1.000
LAMPS Option 2	.603
LAMPS Option 3	.130

Inconsistency = 0.02
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP4 - ASW/MCM
>GMLS Options

GMLS Option 1	1.000
GMLS Option 2	.820
GMLS Option 3	.670
GMLS Option 4	.549

Inconsistency = 0.00156
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP4 - ASW/MCM
>CCC Options

CCC Option 1	1.000
CCC Option 2	.588

Inconsistency = 0.
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Warfighting
>MOP5 - CCC/ISR

CCC Option 1	1.000
CCC Option 2	.310

Inconsistency = 0.
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Mobility
>MOP9 - Endurance Range

8000 nm	1.000
7500 nm	.900
7000 nm	.819
6500 nm	.567
6000 nm	.442
5500 nm	.295
5000 nm	.172

Inconsistency = 0.02

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Mobility
>MOP10 - Provisions Duration

75 days	1.000
70 days	.875
65 days	.616
60 days	.482

Inconsistency = 0.00531
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Mobility
>MOP11 - Seakeeping

40	1.000
38	.888
36	.709
34	.535
32	.423
30	.334

Inconsistency = 0.00329
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Survivability
>MOP12 - Vulnerability

DISTtype	1.000
Proptype	.994
PGM	.790

Inconsistency = 0.00368
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Survivability
>MOP12 - Vulnerability
>Proptype

FPP&SPU	1.000
2xFPP	.331
2xPods	.220

Inconsistency = 0.01
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Survivability
>MOP12 - Vulnerability
>PGM

3xGT	1.000
2xGT	.592

Inconsistency = 0.
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Survivability
>MOP12 - Vulnerability
>DISTtype

DC	1.000
AC	.441

Inconsistency = 0.
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Survivability
>MOP13 - NBC

full CPS	1.000
partial CPS	.845
no CPS	.214

Inconsistency = 0.00019
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Survivability
>MOP14 - RCS

11000 m3	1.000
12000 m3	.841
13000 m3	.664
14000 m3	.528
15000 m3	.392

Inconsistency = 0.0044
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Survivability
>MOP15 - Acoustic Signature

SPGM Fuel Cell	1.000
SPGM Gas Turbine	.165
SPGM Diesel	.095

Inconsistency = 0.04
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Survivability
>MOP16 - IR Signature

SPGM Fuel Cell	1.000
SPGM Diesel	.123
SPGM Gas Turbine	.094

Inconsistency = 0.01
with 0 missing judgments.

Priorities with respect to:
Goal: Maximize OMOE
>MISSION - BMD
>Survivability
>MOP17 - Magnetic Signature

Degaussing	1.000
No degaussing	.149

Inconsistency = 0.
with 0 missing judgments.

Appendix D–CDD

UNCLASSIFIED

CAPABILITY DEVELOPMENT DOCUMENT

FOR

BALLISTIC MISSILE DEFENSE CRUISER Variant #13 VT Team 2

1 Capability Discussion.

The Initial Capabilities Document (ICD) for this CCD was issued by the Virginia Tech Acquisition Authority on 21 August 2007. The range of military application for the functions in this ICD includes: force protection and awareness at sea; and protection of homeland and critical bases from the sea. Timeframe considered: 2015-2050. This extended timeframe demands flexibility in upgrade and capability over time.

Current Aegis ships are to be configured to intercept short and medium-range BM threats, but can not counter long-range intercontinental ballistic missiles that could target the US from China, North Korea and Iran. Current ships are also fully multi-mission ships. The radar and missile capabilities of the CGX/BMD are to be greater than the Navy's current Aegis ships. Some multi-mission capabilities have to be sacrificed to control cost.

Specific capability gaps resulting from insufficient BMD capabilities with adequate inherent core capabilities include: AAW/BMD; blue/green water ASW. Additional capabilities include mine countermeasures, ISR, ASUW, special operations.

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/VSR+++ DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved
2	BMD Missile Cell	SM-3/MK-57 VLS only	KEI and SM-3/MK-57 VLS
3	BMD Missile Capacity	96 SM-3	160 SM-3, 8 KEI
4	BMD Platform Mobility	30knt, full SS4, 4000 nm, 45 days	35knt, full SS5, 6000 nm, 75 days
5	Platform Passive Susceptibility	DDG-51 signatures	DDG1000 signatures
6	Platform Vulnerability and Recoverability	AFSS	AFSS
7	Platform Self and Area Defense, Other Multi-Mission	CIGS, LAMPS haven, TSCE	1xAGS, IUSW, SOF and ASUW stern launch, Embarked LAMPS/AAV w/hangar, TSCE

2 Analysis Summary.

An Acquisition Decision Memorandum issued on 21 August 2007 by the Virginia Tech Acquisition Authority directed Concept Exploration and Analysis of Alternatives (AoA) for a new Aegis-type ship with more capable core systems and modular systems similar to DDG-1000, with particular emphasis on providing robust ICBM defense. Required core capabilities are to project defense around friends, joint forces and critical bases of operations at sea.

The platforms must provide a sea-based layer of homeland defense, and provide persistent surveillance and reconnaissance. The platforms must operate within current logistics support capabilities. Inter-service and Allied C^4/I (inter-operability) must be considered.

Concept Exploration was conducted from 23 August 2007 through 5 December 2007. A Concept Design and Requirements Review was conducted on 23 January 2008. 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 design selected for Virginia Tech Team 2, and specified in this CDD, is the low risk design shown with an X in Figure 1. Selection of a point on the non-dominated frontier specifies requirements, technologies and the baseline design.

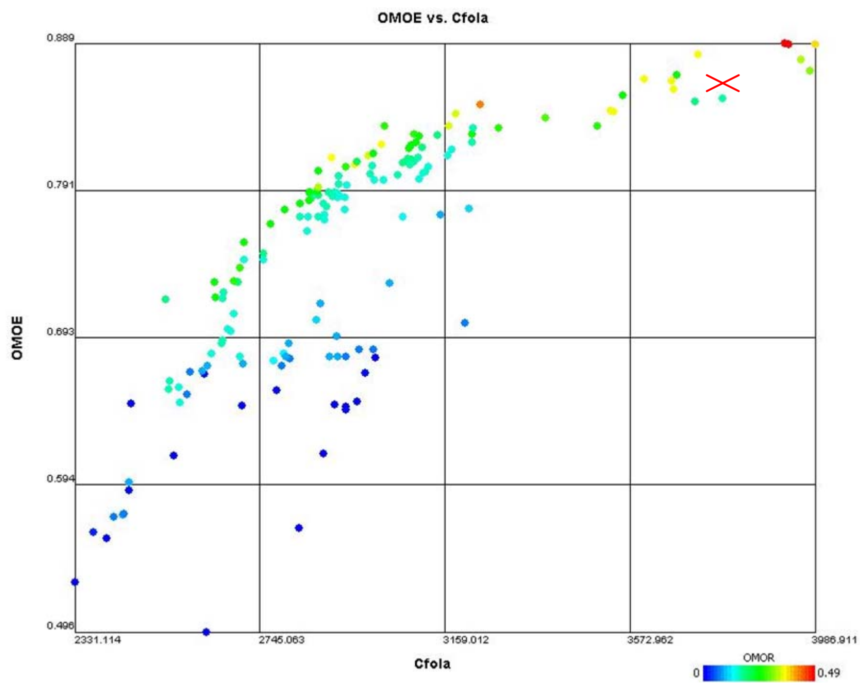

Figure 1 – CGX/BMD Non-Dominated Frontier

3 Concept of Operations Summary

The CGX concept of operations is based on the Initial Capabilities Document and the Acquisition Decision Memorandum for a Ballistic Missile Defense Cruiser that will have the ability to conduct BMD operations from advantageous locations at sea that are inaccessible to ground-based systems. It must have the ability to operate in forward locations in international waters and readily move to new maritime locations as needed. It must be able to operate over the horizon from observers ashore, and evade detection and targeting by enemy forces. It also must be able to move to locations that lie along a ballistic missile's potential flight path to facilitate tracking and intercepting the attacking missile, or move to locations to permit the CGX/BMD radar to view a ballistic missile from a different angle to allow the CGX systems to track the attacking missile more effectively.

CGX/BMD must be capable of defending a large down-range territory against potential attack by ballistic missiles. It will use very fast interceptors to intercept ballistic missiles fired from launchers during the boost phase and mid-flight. CGX/BMD must be equipped with high-altitude long-range search and track radar capable of detecting and establishing precise tracking information on ballistic missiles, discriminating missile warheads from decoys and debris, providing data for updating ground-based interceptors in flight, and assessing the results of intercept attempts.

CGX/BMD radar will be a large, powerful, phased-array radar operating in the X and S band frequencies. The X-band frequency is necessary for tracking missile warheads with high accuracy. To intercept the ballistic missile warheads in boost, early ascent, and mid-course of the flight, SM-3's and Kinetic Energy Interceptor's (KEIs) will be considered for the CGX/BMD weapons payload.

Additionally, the CGX/BMD will perform Carrier Battle Group (CBG) and Expeditionary Readiness Group (ERG) escort, providing area Anti-Air Warfare (AAW) defense and limited Anti-Submarine Warfare (ASW) and Anti-Surface Warfare (ASUW) defense in support of these units. The CGX/BMD will perform Tomahawk Land Attack Missile (TLAM) strikes in conjunction with the CBG, ERG, Surface Action Group (SAG) or operating independently.

Expected operations for CGX/BMD include:

- Ballistic Missile Defense
  - Provide Area AAW, ASW and ASUW defense
- Escort (CBG)
  - Provide Area AAW, ASW and ASUW defense
- Independent Ops
  - Provide Area AAW, ASW and ASUW
  - Provide ISR
  - Support UAVs, USVs and UUVs
  - Provide BMD
  - Provide MCM and additional ISR/ASW/ASUW
  - Support Special Operations
- Homeland Defense/Interdiction
  - Support AAW, ASW and ASUW
  - Provide surveillance and reconnaissance, support UAVs

4 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 – missiles. These include not only states, but also non-state groups interested in obtaining missiles with nuclear or other payloads. The spectrum encompasses the missile arsenals already in the hands of

Russia and China, as well as the emerging arsenals of a number of hostile states. The character of this threat has also changed. Unlike the Soviet Union, these newer missile possessors do not attempt to match U.S. systems, either in quality or in quantity. Instead, their missiles are designed to inflict major devastation without necessarily possessing the accuracy associated with the U.S. and Soviet nuclear arsenals of the Cold War.

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

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

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

Since many potentially unstable nations are located on or near geographically constrained (littoral) bodies of water, the tactical picture may be at smaller scales relative to open ocean warfare. Threats in such an environment include: (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 for BMD varies greatly depending on the most strategic and effective location necessary to counter a particular threat. It includes:

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

5 System Capabilities and Characteristics Required for the Current Development Increment.

Key Performance Parameter (KPP)	Development Threshold or Requirement

AAW/BMD/STK	SPY-3/VSR+++ DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA
ASUW/NSFS	1xMK45 5"/62 gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2x7m RHIB, MK46 Mod2 3x CIGS
ASW/MCM	Dual Frequency Bow Array, ISUW, NIXIE, 2xSVTT, mine-avoidance sonar
CCC	Enhanced CCC
LAMPS	2 x Embarked LAMPS w/Hangar, 2xVTUAV
SDS	SLQ-32(V) 3, SRBOC, NULKA, ESSM
GMLS	160 cells MK57, 8 cells KEI
Hull	Flare – 10 deg
Power and Propulsion	2 shaft, 2 pods FPP
Endurance Range (nm)	8000 nm
Sustained Speed (knots)	32.2 knots
Endurance Speed (knots)	20 knots
Stores Duration (days)	50
Collective Protection System	full
Crew Size	452
RCS (m^3)	14050
Maximum Draft (m)	7.58 m
Vulnerability (Hull Material)	Steel
Ballast/fuel system	Clean, separate ballast tanks
Degaussing System	No
McCreight Seakeeping Index	15.5

KG margin (m)	0.22m
Propulsion power margin (design)	10%
Propulsion power margin (fouling and seastate)	25% (0.8 MCR)
Electrical margins	5%
Net Weight margin (design and service)	10%

6 Program Affordability.

Average follow-ship acquisition cost shall not exceed $3.7B($FY2012) with a lead ship acquisition cost less than $5.3B. It is expected that 18 ships of this type will be built with IOC in 2018.

Appendix E–MEL

ITEM	QTY	NOMENCLATURE	DESCRIPTION	CAPACITY RATING
System: Main Engines and Transmission				
1	4	Gas Turbine, Main	MT30 Marine Turbine	36MW
2	2	EMR Eng	CAT 3616	5.1MW
3	4	SPGM	5 X 500kW Fuel Cell Module	2.5 MW 480 VAC at 60 Hz
4	4	Main Engine Exhaust Duct	MT30 Marine Turbine	153.8 kg/sec
5	4	Main Engine Inlet Duct	MT30 Marine Turbine	135 kg/sec
6	2	EMR Eng Inlet Duct	CAT 3616	7.5 kg/sec
7	2	EMR Eng Exhaust Duct	CAT 3616	17.3 kg/sec
8	2	ECS	Engineering Control Station	N/A
10	2	Console, Main Control	Main Propulsion	NA
System: Power Generation and Distribution				
11	4	PGM GEN	Power Generator Module	36000 kW, 4180 VAC, 3 phase, 60 Hz, 0.8 PF
12	2	EMR GEN	Fuel Cell	5060 kW, 4180 VAC, 3 phase, 60 Hz
13	2	SPGM GEN	Secondary Power Generation Module	500 kW
14	2	PMM	Brushless Permanent Magnet Motor Propulsion Motor Module	70MW
15	8	PCM4	PCM4-5000	4160 VAC to 1000 VDC
16	32	PCM1		1000 VDC to 375-800 VDC
17	32	PCM2		800 VDC to 450 VAC
18	2	Switchboard, Ships Service	Generator Control Power Distribution DC	-
19	2	EMR Switchboard	Generator Control Power Distribution AC	-
20	4	MMR and AMR ladders	Inclined ladders	
21	4	MMR and AMR escape trunks	Vertical ladders with fire tight doors at each level	
22	3	MN Machinery Space Fan	Supply	94762 m^3/hr
23	3	MN Machinery Space Fan	Exhaust	91644 m^3/hr
24	2	Aux Machinery Space Fan	Supply	61164 m^3/hr
25	2	Aux Machinery Space Fan	Exhaust	61164 m^3/hr
System: Salt Water Cooling				
26	8	Pump, Main Seawater Circ	Centrifugal, Vertical, Motor Driven	230 m^3/hr @ 2 bar
System: Lube Oil Service and Transfer				
27	4	Assembly, MGT Lube Oil Storage and Conditioning	Includes Oil Storage and Cooler	NA
28	4	Assembly, Lube Oil Storage and Conditioning	Includes Oil Storage and Cooler SEC ENG	NA
29	4	Purifier, Lube Oil	Centrifugal, Self Cleaning, Partial Discharge Type	1.1 m^3/hr
30	4	Pump, Lube Oil Transfer	Pos. Displacement, Horizontal, Motor Driven	4 m^3/hr @ 5 bar
System: Fuel Oil Service and Transfer				
31	4	Filter Separator, MGT Fuel	2-Stage, Static, 5 Micron	30 m^3/hr
32	4	Purifier, Fuel Oil GT	Self Cleaning, Centrifugal, Partial Discharge Type	7.0 m^3/hr
33	4	Pump, Fuel Trans	Gear, Motor Driven	45.4 m^3/h @ 5.2 bar
34	4	Fuel Oil Service Tanks		11.2 m^3 x 4 = 4 hrs
35	2	EMR Fuel Oil Service Tanks		5 m^3
System: Air Conditioning and Refrigeration				
36	4	Air Conditioning Plants	150 Ton, Centrifugal Units	150 ton
37	4	Pump, Chilled Water	Centrifugal, Horizontal, Motor Driven	128 m^3/hr @4.1 bar

38	4	Refrig Plants, Ships Service	R-134a	4.3 ton
39	6	Radar Cooling Units	150 Ton Radar	150 Ton
40	6	Pump, Coolant	Centrifugal, Horizontal, Motor Driven	128 m^3/hr @4.1 bar
System: Salt Water: Firemain, Bilge, Ballast				
41	8	Pump, Fire	Centrifugal, Horizontal, Motor Driven	454 m^3/hr @ 9 bar
42	4	Pump, Fire/Ballast	Centrifugal, Horizontal, Motor Driven	454 m^3/hr @ 9 bar
43	2	Pump, Bilge	Centrifugal, Horizontal, Motor Driven	227 m^3/hr @3.8 bar
44	2	Pump, Bilge/Ballast	Centrifugal, Horizontal, Motor Driven	227 m^3/hr @3.8 bar
45	5	Station, AFFF	Skid Mounted	227 m^3/hr @3.8 bar
System: Potable Water				
46	4	Distiller, Fresh Water	Distilling Unit	76 m^3/day (3.2 m^3/hr)
47	4	Brominator	Proportioning	1.5 m^3/hr
48	4	Brominator	Recirculation	5.7 m^3/hr
49	4	Pump, Potable Water	Centrifugal, Horizontal, Motor Driven	22.7 m^3/hr @ 4.8 bar
System: JP-5 Service and Transfer				
49	2	Pump, JP-5 Transfer	Rotary, Motor Driven	11.5 m^3/hr @ 4.1 bar
50	2	Pump, JP-5 Service	Rotary, Motor Driven	22.7 m^3/hr @ 7.6 bar
51	1	Pump, JP-5 Stripping	Rotary, Motor Driven	5.7 m^3/hr @ 3.4 bar
52	2	Filter/Separ., JP-5 Transfer	Static, Two Stage	17 m^3/hr
53	2	Filter/Separ., JP-5 Service	Static, Two Stage	22.7 m^3/hr
System: Compressed Air				
54	5	Receiver, Starting Air	Steel, Cylindrical	2.3 m^3
55	3	Compressor, MP Air	Reciprocating Motor Driven, Water Cooled	80 m^3/hr FADY @ 30 bar
56	2	Receiver, Ship Service Air	Steel, Cylindrical	1.7 m^3
57	2	Receiver, Control Air	Steel, Cylindrical	1 m^3
58	2	Compressor, Air, LP Ship Service	Reciprocating, Rotary Screw	8.6 bar @ 194 SCFM
59	2	Dryer, Air	Refrigerant Type	250 SCFM
System: Steering Gear Hydaulics				
60	2	Hydraulic Pump and Motor	Steering Gear	
61	1	Hydraulic Steering Ram	Steering Gear	
System: Environmental				
62	2	Pump, Oily Waste Transfer	Motor Driven	12.3 m^3/hr @ 7.6 bar
63	2	Separator, Oil/Water	Coalescer Plate Type	2.7 m^3/hr
64	2	Unit, Sewage Collection	Vacuum Collection Type w/ Pumps	28 m^3
65	2	Sewage Plant	Biological Type	225 people

Appendix F–SSCS

SSCS	GROUP	VOLUME M3	AREA M2	LOC	SD
1	MISSION SUPPORT	86.1	7570.6	T	0
			2573.5	D	
			4997	E	
1.1	COMMAND,COMMUNICATION+SURV	1696.3		D	0
			1572.2	E	
1.11	EXTERIOR COMMUNICATIONS		471.1	D	0
*1.111	RADIO		465.2	D	0
1.112	UNDERWATER SYSTEMS			E	0
1.113	VISUAL COM		5.9	D	0
1.12	SURVEILLANCE SYS		1143.3	D	0
			417.8	E	
*1.121	SURFACE SURV (RADAR)		1143.3	D	0
			1	E	
*1.122	UNDERWATER SURV (SONAR)		416.8	E	0
1.13	COMMAND+CONTROL		75.4	D	0
			948.4	E	
*1.131	COMBAT INFO CENTER		948.4	E	0
1.132	CONNING STATIONS		75.4	D	0
1.13201	PILOT HOUSE		68.3	D	0
1.13202	CHART ROOM		7.1	D	0
1.14	COUNTERMEASURES		6.5	D	0
			16	E	
*1.141	ELECTRONIC		6.5	D	0
*1.142	TORPEDO		16	E	0
1.143	MISSILE			E	0
1.15	INTERIOR COMMUNICATIONS		190	E	0
1.16	ENVIRONMENTAL CNTL SUP SYS			E	0
1.2	WEAPONS	24.1		D	0
			3155.8	E	
*1.21	GUNS		13.9	D	0
			115.8	E	
*1.211	BATTERIES		23.8	E	0
*1.22	MISSILES		10.1	D	0
			3040	E	
*1.221	LAUNCHERS		3040	E	0
1.23	ROCKETS			E	0
1.24	TORPEDOS			E	0
1.25	DEPTH CHARGES			E	0
1.26	MINES			E	0
1.27	MULT EJECT RACK STOW			E	0
1.28	WEAP MODULE STA & SERV INTER			E	0
1.3	AVIATION	86.1	806.6	D	0
			95.8	E	
1.31	AVIATION LAUNCH+RECOVERY		44.4	E	0
1.311	LAUNCHING+RECOVERY AREAS			E	0
1.31102	HELICOPTER LANDING AREA			E	0

SSCS	GROUP	VOLUME M3	AREA M2	LOC	SD
1.312	LAUNCHING+RECOVERY EQUIP		44.4	E	0
*1.3123	HELICOPTER RECOVERY		44.4	E	0
1.32	AVIATION CONTROL		20.4	D	0
1.321	FLIGHT CONTROL		9.3	D	0
1.3212	HELO FLIGHT CONTROL		9.3	D	0
1.321201	HELICOPTER CONTROL STATION		9.3	D	1
1.322	NAVIGATION		11.1	D	0
1.32202	TACAN EQUIP RM		11.1	D	1
1.323	OPERATIONS			E	0
1.33	AVIATION HANDLING			E	0
1.331	AIRCRAFT ELEVATORS			E	0
1.332	AIRCRAFT CRANE			E	0
1.334	GROUND SUPPORT EQUIPMENT			E	0
*1.34	AIRCRAFT STOWAGE		533.8	D	0
1.34002	HELICOPTER HANGAR			E	0
1.35	AVIATION ADMINISTRATION		8.4	E	0
1.353	AIR WING		8.4	E	0
1.35306	AVIATION OFFICE		8.4	E	1
*1.36	AVIATION MAINTENANCE		34.1	D	0
			17.6	E	
1.361	AIRFRAME SHOPS		5.9	E	0
1.36106	BATTERY SHOP		5.9	E	1
1.369	ORGANIZATIONAL LEVEL MAINTANENCE		11.6	E	0
1.36905	HELICOPTER SHOP		11.6	E	1
1.37	AIRCRAFT ORDINANCE		57.5	D	0
1.372	CONTROL			E	0
1.373	HANDLING			E	0
*1.374	STOWAGE		57.5	D	0
*1.38	AVIATION FUEL SYS	86.1	2.8	D	0
			4.1	E	
1.381	JP-5 SYSTEM		86.1	E	0
1.3811	JP-5 TRANSFER			E	0
1.3812	JP-5 HANDLING			E	0
1.3813	AVIATION FUEL		86.1	E	0
*1.39	AVIATION STORES		158.1	D	0
			21.4	E	
1.391	AVIATION CONSUMABLES		21.4	E	0
1.3911	SD STOREROOM		21.4	E	0
1.391102	AVIATION STORE RM		21.4	E	0
1.5	CARGO			E	0
1.5311	CARGO ELEVATORS			E	0
1.6	INTERMEDIATE MAINT FAC			E	0
1.7	FLAG FACILITIES	46.5		D	0
			114	E	
1.71	OPERATIONS			E	0
1.72	CONTROL		46.5	D	0
1.73	HANDLING			E	0
1.74	STOWAGE			E	0

SSCS	GROUP	VOLUME M3	AREA M2	LOC	SD
1.75	ADMIN		114	E	0
1.8	SPECIAL MISSIONS			E	0
*1.9	SM ARMS,PYRO+SALU BAT	59.2		E	0
1.91	SM ARMS (LOCKER)		7.9	E	0
1.92	PYROTECHNICS			E	0
1.93	SALUTING BAT (MAGAZINE)		3.7	E	0
1.94	ARMORY		19	E	0
1.95	SECURITY FORCE EQUIP		9.8	E	0
2	HUMAN SUPPORT	4222.8		T	0
			203.6	D	
			4019.2	E	
2.1	LIVING	203.6		D	0
			2738.6	E	
2.11	OFFICER LIVING		201.2	D	0
			312.8	E	
2.111	BERTHING		196.6	D	0
			274.8	E	
2.1111	SHIP OFFICER		196.6	D	0
			172.3 E		
*2.11111	COMMANDING OFFICER BERTHING		196.6	D	0
2.11111	COMMANDING OFFICER CABIN		36.5	D	1
2.11111	COMMANDING OFFICER STATEROOM		18.6	D	1
2.111121	EXECUTIVE OFFICER STATEROOM		13.9	E	1
2.111123	DEPARTMENT HEAD STATEROOM		58.1	E	5
2.11113	OFFICER STATEROOM (DBL)		100.3	E	8
2.1114	AVIATION OFFICER		37.6	E	0
2.11143	AIR OFFICER BERTHING		37.6	E	3
2.1115	FLAG OFFICER		64.8	E	0
2.11151	FLAG CABIN		36.5	E	1
2.11151	FLAG STATEROOM		18.6	E	1
2.11153	FLAG STAFF OFFICER STTRM		9.8	E	1
2.112	SANITARY		4.6	D	0
			38	E	
2.1121	SHIP OFFICER		4.6	D	0
			21.2	E	
2.11211	COMMANDING OFFICER BATH		4.6	D	1
2.11212	EXECUTIVE OFFICER BATH		2.8	E	1
2.11212	OFFICER BATH		2.1	E	2
2.11213	OFFICER WR, WC & SH		16.4	E	2
2.1124	AVIATION OFFICER		6.3	E	0
2.112403	AVIATION OFFICER BATH		6.3	E	3
2.1125	FLAG OFFICER		10.5	E	0
2.11251	FLAG OFFICER BATH		4.6	E	1
2.11253	FLAG STF OFF WR, WC & SH		5.9	E	1
*2.12	CPO LIVING		337.7	E	0
2.121	BERTHING		89.4	E	0
2.1211	SHIP CPO	53.7	E	2	

SSCS	GROUP	VOLUME M3	AREA M2	LOC	SD
2.1214	AVIATION CPO		20.4	E	1
2.1215	FLAG CPO		15.3	E	1
2.122	SANITARY		28.2	E	0
2.1221	SHIP CPO		15.7	E	2
2.1224	AVIATION CPO		6.7	E	1
2.1225	FLAG CPO		5.9	E	1
*2.13	CREW LIVING		1859.8	E	0
2.131	BERTHING		771	E	0
2.1311	SHIP CREW		747	E	0
2.131101	LIVING SPACE		747	E	16
2.1314	AVIATION ENLIST		24	E	1
2.132	SANITARY		146.9	E	0
2.1321	SHIP CREW		141	E	0
2.132101	SANITARY		141	E	16
2.1324	AVIATION ENLIST		5.9	E	1
2.133	RECREATION		35.9	E	0
2.13301	RECREATION ROOM		17.9	E	0
2.13302	LIBRARY		17.9	E	0
2.13306	CREW LOUNGE			E	0
2.14	GENERAL SANITARY FACILITIES		2.3	D	0
			10.2	E	
2.14001	LADIES RETIRING ROOM		5.6	E	1
2.14002	BRIDGE WASHRM & WC		2.3	D	1
2.14003	DECK WASHRM & WC		2.3	E	1
2.14004	ENGINEERING WR & WC		2.3	E	1
*2.15	SHIP RECREATION FAC		214.9	E	0
2.151	MUSIC		8.4	E	0
2.15101	ENTERTAINMENT EQUIP STRM		8.4	E	0
2.152	MOTION PIC FILM+EQUIP		1.9	E	0
2.15201	PROJECTION EQUIP RM		1.9	E	0
2.153	PHYSICAL FITNESS		5	E	0
2.15302	ATHLETIC GEAR STRM		5	E	0
2.154	TV ROOM			E	0
2.16	TRAINING		3.3	E	0
2.16002	RECOGNITION TRAINING LKR		3.3	E	0
2.2	COMMISSARY	776.7		E	0
2.21	FOOD SERVICE		375.3	E	0
2.211	OFFICER		62.7	E	0
2.21101	WARDROOM MESSRM & LOUNGE		62.7	E	0
*2.212	CPO		98.2	E	0
2.21201	CPO MESSROOM AND LOUNGE		69.7	E	0
*2.213	CREW		200	E	0
2.21301	1ST CLASS MESSROOM		25.6	E	0
2.21303	CREW MESSROOM		145.3	E	0
2.214	MESS MANAGEMENT SPLST		14.3	E	0
2.21401	MESS MNGMNT SPLST MESSRM		14.3	E	0
2.215	FLAG OFFICER			E	0
*2.22	COMMISSARY SERVICE SPACES		186.4	E	0

SSCS	GROUP	VOLUME M3	AREA M2	LOC	SD
2.221	FOOD PREPARATION SPACES		15	E	0
2.22104	BREAD ROOM			E	0
2.22105	VEGETABLE PREPARATION ROOM		11	E	0
2.22107	THAW ROOM		4	E	0
2.222	GALLEY		104.9	E	0
2.22201	COMMANDING OFFICER GALLEY		10.7	E	0
2.22202	WARD ROOM GALLEY		9.8	E	0
2.22203	CPO GALLEY		9.1	E	0
2.22204	CREW GALLEY		75.3	E	0
2.223	PANTRIES		7.6	E	0
2.22303	CPO PANTRY		7.6	E	0
2.224	SCULLERY		20.4	E	0
2.22403	CREW SCULLERY		20.4	E	0
2.225	GARBAGE DISPOSAL			E	0
2.226	PREPARED FOOD HANDLING			E	0
*2.23	FOOD STORAGE+ISSUE		215.1	E	0
2.231	CHILL PROVISIONS		27.3	E	0
2.232	FROZEN PROVISIONS		26.8	E	0
2.233	DRY PROVISIONS		57.5	E	0
2.234	ISSUE		8.6	E	0
2.23401	PROVISION ISSUE ROOM		8.6	E	0
2.3	MEDICAL+DENTAL (MEDICAL)	83.6		E	0
2.31	MEDICAL FACILITIES		50	E	0
2.31007	DIET PANTRY		6.7	E	0
2.3101	INTENSIVE CARE QUIET RM			E	0
2.31011	MEDICAL LINEN ISSUE RM			E	0
2.31012	MEDICAL TREATMENT ROOM		28	E	0
2.31023	MEDICAL UTILITY RM		5.2	E	0
2.31024	WARD		4.6	E	0
2.31025	WARD BATH		5.5	E	0
2.31027	MORGUE			E	0
2.33	BATTLE DRESSING		16.3	E	0
2.331	AUX BATTLE DRESSING		2.3	E	0
2.33101	FWD AUX BATTLE DRESS ST		2.3	E	0
2.33102	AFT AUX BATTLE DRESS ST			E	0
2.332	MAIN BATTLE DRESSING		13.9	E	0
2.33201	FWD BATTLE DRESSING STA		7	E	0
2.33203	AFT BATTLE DRESSING STA		7	E	0
2.34	MEDICAL & DENTAL STOWAGE		17.4	E	0
2.341	MEDICAL		17.4	E	0
2.34101	MEDICAL STOREROOM		6.2	E	2
2.34104	BATTLE DRESSING STRM		11.1	E	2
2.342	DENTAL			E	0
2.35	MEDICAL & DENTAL ADMIN			E	0
2.352	DENTAL ADMIN			E	0
2.4	GENERAL SERVICES	228.3		E	0
2.41	SHIP STORE FACILITIES		64.8	E	0
2.41001	SHIP STORE		26.9	E	0

SSCS	GROUP	VOLUME M3	AREA M2	LOC	SD
2.41005	VENDING MACHINE AREA			E	0
2.41006	SHIP STORE STORERM		37.9	E	0
*2.42	LAUNDRY FACILITIES		139.4	E	0
2.42001	LAUNDRY		84	E	0
2.42004	LAUNDRY STOREROOM			E	0
2.44	BARBER SERVICE		13.9	E	0
2.44002	BARBER SHOP		13.9	E	0
2.46	POSTAL SERVICE		10.2	E	0
2.46001	POST OFFICE		10.2	E	0
2.47	BRIG			E	0
2.48	RELIGIOUS			E	0
2.5	PERSONNEL STORES	46.3		E	0
2.51	BAGGAGE STOREROOMS		26.9	E	0
2.51001	OFFICER BAGGAGE STRM		5.8	E	0
2.51002	CPO BAGGAGE STRM		3.3	E	0
2.51003	CREW BAGGAGE STRM		17.9	E	0
2.52	MESSROOM STORES		11.2	E	0
2.52001	WARDROOM STOREROOM		2.9	E	0
2.52002	CPO STOREROOM		6.5	E	0
2.52003	COMMANDING OFFICER STRM		1.9	E	0
2.55	FOUL WEATHER GEAR		3.4	E	0
2.55001	FOUL WEATHER GEAR LOCKER		3.4	E	0
2.56	LINEN STOWAGE		2.2	E	0
2.57	FOLDING CHAIR STOREROOM		2.5	E	0
2.6	CBR PROTECTION	143.7		E	0
2.61	CBR DECON STATIONS		31.5	E	0
2.62	CBR DEFENSE EQUIPMENT		41.5	E	0
2.62001	CBR DEFENSE EQP STRMS		41.5	E	0
2.63	CPS AIRLOCKS		70.7	E	0
2.7	LIFESAVING EQUIPMENT	1.9		E	0
2.71	LIFEJACKET LOCKER		1.9	E	0
3	SHIP SUPPORT	6760.8	4757.5	T	0
			709.4	D	
			4048.2	E	
3.1	SHIP CNTL SYS(STEERING&DIVING)	144.9		E	0
3.11	STEERING GEAR		144.9	E	0
3.12	ROLL STABILIZATION			E	0
3.15	STEERING CONTROL			E	0
3.2	DAMAGE CONTROL	130.9		E	0
3.21	DAMAGE CNTRL CENTRAL			E	0
3.22	REPAIR STATIONS		73.6	E	0
3.25	FIRE FIGHTING		57.3	E	0
3.3	SHIP ADMINISTRATION	252.2		E	0
3.301	GENERAL SHIP		24.2	E	0
3.302	EXECUTIVE DEPT		55.5	E	0
3.303	ENGINEERING DEPT		34	E	0
3.304	SUPPLY DEPT		50.5	E	0
3.305	DECK DEPT		14.7	E	0

SSCS	GROUP	VOLUME M3	AREA M2	LOC	SD
3.306	OPERATIONS DEPT		73.4	E	0
3.307	WEAPONS DEPT			E	0
3.308	REACTOR DEPT			E	0
3.309	MARINES			E	0
3.31	SHIP PHOTO/PRINT SVCS			E	0
3.5	DECK AUXILIARIES		152.7	D	0
		237.2		E	
3.51	ANCHOR HANDLING		86.3	E	0
*3.52	LINE HANDLING		62	D	0
			101	E	
*3.53	TRANSFER-AT-SEA		74.7	D	0
			11.8	E	
*3.54	SHIP BOATS STOWAGE		16	D	0
			38	E	
*3.6	SHIP MAINTENANCE	272.7		E	0
3.61	ENGINEERING DEPT		195.9	E	0
3.611	AUX (FILTER CLEANING)		27.8	E	0
3.612	ELECTRICAL		65.6	E	0
3.613	MECH (GENERAL WK SHOP)		92.3	E	0
3.614	PROPULSION MAINTENANCE		10.2	E	0
3.62	OPERATIONS DEPT (ELECT SHOP)		152.3	E	0
3.63	WEAPONS DEPT (ORDINANCE SHOP)		15.3	E	0
3.64	DECK DEPT (CARPENTER SHOP)			E	0
*3.7	STOWAGE	921.2		E	0
3.71	SUPPLY DEPT		807.1	E	0
3.711	HAZARDOUS MATL (FLAM LIQ)		92.1	E	0
3.712	SPECIAL CLOTHING		15	E	0
3.713	GEN USE CONSUM+REPAIR PART		588.9	E	0
3.714	SHIP STORE STORES		23.4	E	0
3.715	STORES HANDLING		87.7	E	0
3.72	ENGINEERING DEPT		19.4	E	0
3.73	OPERATIONS DEPT		27	E	0
3.74	DECK DEPT (BOATSWAIN STORES)		239.3	E	0
3.75	WEAPONS DEPT		17.3	E	0
3.76	EXEC DEPT (MASTER-AT-ARMS STOR)		20	E	0
3.78	CLEANING GEAR STOWAGE		12.9	E	0
3.8	ACCESS	556.7		D	0
		2047		E	
3.82	INTERIOR		556.7	D	0
			2047	E	
3.821	NORMAL ACCESS		547.9	D	0
			2015.9	E	
3.822	ESCAPE ACCESS		8.8	D	0
			31.1	E	
3.9	TANKS	6760.8	42.2	E	0
3.91	SHIP PROP SYS TNKG		5935.5	E	0
3.911	SHIP ENDUR FUEL TNKG		5935.5	E	0
3.91101	ENDUR FUEL TANK	4651.6		E	0

SSCS	GROUP	VOLUME M3	AREA M2	LOC	SD
3.91104	FUEL OR BALLAST TANK		1283.9	E	0
3.914	FEEDWATER TNKG			E	0
3.92	BALLAST TNKG			E	0
3.93	FRESH WATER TNKG		69.9	E	0
3.94	POLLUTION CNTRL TNKG		42.2	E	0
3.941	SEWAGE TANKS		8.6	E	0
3.942	OILY WASTE TANKS		33.6	E	0
3.95	VOIDS		755.4	E	0
3.96	COFFERDAMS			E	0
3.97	CROSS FLOODING DUCTS			E	0
4	SHIP MACHINERY SYSTEM	1970.3		T	0
		875.3		D	
		1095		E	
4.1	PROPULSION SYSTEM	685.7		D	0
		312.4	E		
4.13	INTERNAL COMBUSTION		42.8	D	0
			64.4	E	
4.131	ENERGY GENERATION			E	0
4.132	COMBUSTION AIR		12.8	D	0
			4.1	E	
4.133	EXHAUST		30	D	0
			10.1	E	
4.134	CONTROL		50.2	E	0
4.14	GAS TURBINE		642.9	D	0
			248.1	E	
4.141	ENERGY GENERATION			E	0
4.142	COMBUSTION AIR		252.6	D	0
			63.2	E	
4.143	EXHAUST		390.3	D	0
			97.6	E	
4.144	CONTROL		87.3	E	0
4.17	AUX PROPULSION SYSTEMS			E	0
4.2	PROPULSOR & TRANSMISSION SYST			E	0
4.21	SCREW PROPELLER			E	0
4.21001	PROP SHAFT ALLEY			E	0
4.22	CYCLOIDAL PROPELLER ROOMS			E	0
4.23	WATERJET ROOMS			E	0
4.24	AIR FAN ROOMS			E	0
4.3	AUX MACHINERY	189.5		D	0
			782.6	E	
4.31	GENERAL (AUX MACH DELTA)		-897.9	E	0
4.32	A/C & REFRIGERATION		99.2	E	0
4.321	A/C (INCL VENT)		82.5	E	0
4.322	REFRIGERATION		16.7	E	0
4.33	ELECTRICAL		9.8	D	0
			1085.7	E	
4.331	POWER GENERATION		9.8	D	0
			37	E	

SSCS	GROUP	VOLUME M3	AREA M2	LOC	SD
4.3311	SHIP SERVICE PWR GEN		9.8	D	0
			37	E	
4.3313	BATTERIES			E	0
4.3314	400 HERTZ			E	0
*4.332	PWR DIST & CNTRL		1016.6	E	0
4.334	DEGAUSSING		32	E	0
4.34	POLLUTION CONTROL SYSTEMS		31.5	E	0
4.341	SEWAGE		21	E	0
4.342	TRASH		10.5	E	0
4.35	MECHANICAL SYSTEMS		50.5	E	0
4.36	VENTILATION SYSTEMS		179.8	D	0
			413.7	E	

Appendix G – Weights and Centers

SWBS	COMPONENT	WT-MT	VCG-m	Moment	LCG-m	Moment	TCG-m	Moment
	FULL LOAD WEIGHT + MARGIN	24518.83	8.09	198247.57	113.53	2783635.57	0.00	0.00
	MINOP WEIGHT AND MARGIN	22466.28	8.48	190409.38	112.65	2530736.26	0.00	0.00
	LIGHTSHIP WEIGHT + MARGIN	19955.83	9.08	181218.94	112.64	2247914.71	0.00	0.00
	LIGHTSHIP WEIGHT	18141.66	9.08	164744.49	112.64	2043558.83	0.00	0.00
	MARGIN	1814.17	9.08	16474.45	112.64	204355.88	0.00	0.00
100	HULL STRUCTURES	9430.10	8.23	77600.31	112.70	1062778.62	0.00	0.00
110	SHELL + SUPPORTS	3421.10	3.23	11050.15	110.54	378168.39		0.00
120	HULL STRUCTURAL BULKHDS	447.30	8.30	3712.59	108.65	48599.15		0.00
130	HULL DECKS	2243.40	13.86	31093.52	109.09	244732.51		0.00
140	HULL PLATFORMS/FLATS	658.00	6.06	3987.48	125.23	82401.34		0.00
150	DECK HOUSE STRUCTURE	423.50	25.06	10612.91	105.24	44569.14	0.00	0.00
160	SPECIAL STRUCTURES	791.90	6.29	4981.05	118.78	94061.88	0.00	0.00
170	MASTS+KINGPOSTS+SERV PLATFORM	1.00	33.85	33.85	99.73	99.73	0.00	0.00
180	FOUNDATIONS	1050.10	8.58	9009.86	119.87	125875.49	0.00	0.00
190	SPECIAL PURPOSE SYSTEMS	393.80	7.92	3118.90	112.42	44271.00	0.00	0.00
200	PROPULSION PLANT	1861.06	5.07	9437.80	140.33	261156.95	0.00	0.00
233	DIESEL ENGINES	70.50	4.20	296.10	98.38	6935.79		0.00
234	GAS TURBINES	184.10	4.44	817.40	99.56	18329.00		0.00
235	ELECTRIC PROPULSION	1035.56	1.07	1108.05	160.02	165710.31		0.00
243	SHAFTING	6.80	0.07	0.48	204.10	1387.88		0.00
244	SHAFT BEARINGS	46.70	0.07	3.27	205.30	9587.51		0.00
245	PROPULSORS	56.40	0.07	3.95	203.10	11454.84		0.00
250	SUPPORT SYSTEMS, UPTAKES	420.90	16.68	7020.61	101.90	42889.71		0.00
260	PROPUL SUP SYS- FUEL, LUBE OIL	11.40	4.88	55.63	98.02	1117.43		0.00
290	SPECIAL PURPOSE SYSTEMS	28.70	4.61	132.31	130.47	3744.49		0.00
300	ELECTRIC PLANT, GENERAL	1039.20	9.25	9610.84	116.33	120886.84	0.00	0.00
311	SHIP SERVICE POWER GENERATION	537.20	7.53	4045.12	109.44	58791.17		0.00
313	BATTERIES+SERVICE FACILITIES	2.00	9.94	19.88	109.44	218.88		0.00
320	POWER DISTRIBUTION SYS	381.10	10.65	4058.72	123.05	46894.36		0.00
330	LIGHTING SYSTEM	86.50	14.73	1274.15	116.38	10066.87		0.00
340	POWER GENERATION SUPPORT SYS	7.30	8.27	60.37	102.46	747.96		0.00
390	SPECIAL PURPOSE SYS	25.10	6.08	152.61	166.04	4167.60		0.00
400	COMMAND+SURVEILLANCE	1202.10	17.08	20535.12	67.88	81598.54	0.00	0.00
410	COMMAND+CONTROL SYS	91.00	10.31	938.21	21.46	1952.86		0.00
420	NAVIGATION SYS	32.40	24.23	785.05	89.65	2904.66		0.00
430	INTERIOR COMMUNICATIONS	99.30	12.69	1260.12	94.76	9409.67		0.00
440	EXTERIOR COMMUNICATIONS	106.00	26.51	2810.06	0.79	83.74		0.00
450	SURF SURVEILLANCE SYS (RADAR)	505.70	24.10	12187.37	97.00	49052.90		0.00
460	UNDERWATER SURVEILLANCE SYSTEMS	101.30	4.98	504.47	11.95	1210.54		0.00
470	COUNTERMEASURES	117.70	11.30	1330.01	89.94	10585.94		0.00
480	FIRE CONTROL SYS	11.30	13.24	149.61	110.85	1252.61		0.00
490	SPECIAL PURPOSE SYS	137.40	4.15	570.21	37.45	5145.63		0.00

500	AUXILIARY SYSTEMS, GENERAL	2207.20	11.99	26473.77	121.94	269139.01	0.00	0.00
510	CLIMATE CONTROL	587.30	13.21	7758.23	126.40	74234.72		0.00
520	SEA WATER SYSTEMS	272.30	9.38	2554.17	130.80	35616.84		0.00
530	FRESH WATER SYSTEMS	420.10	14.98	6293.10	105.50	44320.55		0.00
540	FUELS/LUBRICANTS,HANDLING+STORAGE	130.90	7.39	967.35	121.93	15960.64		0.00
550	AIR,GAS+MISC FLUID SYSTEM	255.70	10.39	2656.72	140.50	35925.85		0.00
570	UNDERWAY REPLENISHMENT SYSTEMS	63.00	12.23	770.49	145.60	9172.80		0.00
581	ANCHOR HANDLING+STOWAGE SYSTEMS	137.10	9.66	1324.39	31.20	4277.52		0.00
582	MOORING+TOWING SYSTEMS	33.20	15.41	511.61	108.50	3602.20		0.00
583	BOATS,HANDLING+STOWAGE SYSTEMS	29.60	16.91	500.54	216.60	6411.36		0.00
588	AIRCRAFT HANDLING, SERVICE, STOWAGE	26.00	16.10	418.60	122.60	3187.60		0.00
593	ENVIRONMENTAL POLLUTION CNTL SYS	28.60	5.57	159.30	121.93	3487.20		0.00
598	AUX SYSTEMS OPERATING FLUIDS	199.60	11.75	2345.30	150.50	30039.80		0.00
599	AUX SYSTEMS REPAIR PARTS+TOOLS	23.80	8.99	213.96	121.93	2901.93		0.00
600	OUTFIT+FURNISHING,GENERAL	1553.50	7.61	11823.91	101.03	156944.44	0.00	0.00
610	SHIP FITTINGS	32.70	2.78	90.91	122.51	4006.08		0.00
620	HULL COMPARTMENTATION	319.90	9.31	2978.27	106.35	34021.37		0.00
630	PRESERVATIVES+COVERINGS	650.30	7.02	4565.11	94.47	61433.84		0.00
640	LIVING SPACES	81.40	6.43	523.40	102.31	8328.03		0.00
650	SERVICE SPACES	33.60	7.18	241.25	103.59	3480.62		0.00
660	WORKING SPACES	194.30	8.04	1562.17	96.26	18703.32		0.00
670	STOWAGE SPACES	225.10	7.83	1762.53	110.85	24952.34		0.00
690	SPECIAL PURPOSE SYSTEMS	16.20	6.19	100.28	124.62	2018.84		0.00
700	ARMAMENT	848.50	10.92	9262.75	107.31	91054.44	0.00	0.00
710	GUNS+AMMUNITION	60.60	17.76	1076.26	138.19	8374.31		0.00
720	MISSLES+ROCKETS	749.20	10.36	7761.71	106.14	79520.09		0.00
750	TORPEDOES	2.70	11.60	31.32	14.80	39.96		0.00
760	SMALL ARMS+PYROTECHNICS	9.80	14.27	139.85	93.67	917.97		0.00
790	SPECIAL PURPOSE SYSTEMS	26.20	9.68	253.62	84.05	2202.11		0.00
	FULL LOAD CONDITION	WT-MT	VCG-m	Moment	LCG-m	Moment	TCG-m	Moment
F00	LOADS	4563.00	3.73	17028.63	117.41	535720.85	0.00	0.00
F10	SHIPS FORCE	51.10	11.47	586.12	104.20	5324.62	0.00	0.00
F21	SHIP AMMUNITION	438.30	12.44	5452.45	113.71	49839.09		0.00
F23	ORD DEL SYS (AIRCRAFT)	14.10	14.29	201.49	127.00	1790.70	0.00	0.00
F31	PROVISIONS+PERSONNEL STORES	53.50	8.40	449.40	119.72	6405.02	0.00	0.00
F32	GENERAL STORES	12.00	9.51	114.12	119.72	1436.64	0.00	0.00
F41	DIESEL FUEL MARINE	3767.00	2.45	9229.15	118.30	445636.10	0.00	0.00
F42	JP-5	50.00	8.81	440.50	134.00	6700.00	0.00	0.00
F46	LUBRICATING OIL	23.00	1.55	35.65	105.16	2418.68	0.00	0.00
F47	SEA WATER	0.00	0.00	0.00	0.00	0.00		0.00
F52	FRESH WATER	154.00	3.38	519.75	105.00	16170.00	0.00	0.00
	MINIMUM OPERATING CONDITION	WT-MT	VCG-m	Moment	LCG-m	Moment	TCG-m	Moment
F00	LOADS	2510.45	3.66	9190.44	112.66	282821.55	0.00	0.00

F10	SHIPS FORCE	51.10	11.47	586.12	104.20	5324.62	0.00	0.00
F21	SHIP AMMUNITION	144.64	12.44	1799.31	113.71	16446.90		0.00
F23	ORD DEL SYS (AIRCRAFT)	14.10	14.29	201.49	127.00	1790.70	0.00	0.00
F31	PROVISIONS+PERSONNEL STORES	17.66	8.40	148.30	119.72	2113.66	0.00	0.00
F32	GENERAL STORES	3.96	9.51	37.66	119.72	474.09	0.00	0.00
F41	DIESEL FUEL MARINE	1308.00	1.51	1975.08	118.10	154474.80	0.00	0.00
F42	JP-5	17.00	7.95	135.22	134.00	2278.00	0.00	0.00
F46	LUBRICATING OIL	8.00	1.23	9.84	105.21	841.68	0.00	0.00
F47	SEA WATER	843.00	4.74	3996.66	104.70	88262.10	0.00	0.00
F52	FRESH WATER	103.00	2.92	300.76	105.00	10815.00	0.00	0.00

Appendix H – Basic Resistance MathCAD file

Holtrop Resistance and Power

Units definition

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

Physical Parameters

Sea water properties: $\rho_{SW} := 1.9905\frac{slug}{ft^3}$ $\upsilon_{SW} := 1.28171 \cdot 10^{-5} \cdot \frac{ft^2}{sec}$

Air properties: $\rho_A := 0.0023817\frac{slug}{ft^3}$

Input

Principal characteristics: $LWL := 221.7\,m$ $B := 23.48\,m$ $D_{10} := 16\,m$ $T := 7.59\,m$ $C_P := .677$ $C_X := .87$

Margins: $PMF := 1.1$ $N_{fins} := 0$ $H_{DK} := 3 \cdot m$

$SON_{TYP} := 1$ $V_e := 20\,knt$ $C_A := .0004$ $N_P := 2$

Performance:

Process

$$S_{SD} := \begin{cases} 5 \cdot ft^2 & \text{if } SON_{TYP} = 0 \\ 80\,ft^2 & \text{if } SON_{TYP} = 1 \\ 1400\,ft^2 & \text{if } SON_{TYP} = 2 \end{cases} \qquad V_{SD} := \begin{cases} 5 \cdot m^3 & \text{if } SON_{TYP} = 0 \\ 19.1 \cdot m^3 & \text{if } SON_{TYP} = 1 \\ 163.4\,m^3 & \text{if } SON_{TYP} = 2 \end{cases}$$

$S_{SD} = 7.432\,m^2$

$V_{SD} = 1.91 \times 10^4\,L$

$C_B := C_P \cdot C_X$ $C_B = 0.589$

$V_{FL} := C_B \cdot LWL \cdot B \cdot T + V_{SD}$ $V_{FL} = 2.329 \times 10^7\,L$

$C_{BT} := \frac{B}{T}$ $C_V := \frac{V_{FL}}{LWL^3}$

TSS wetted surface coefficient:

$A_0 := 7.028 - 2.331 \cdot C_{BT} + 0.299\,C_{BT}^2$

$A_1 := -11 + 5.536\,C_{BT} - 0.704\,C_{BT}^2$

$A_2 := 6.913 - 3.419\,C_{BT} + 0.451 \cdot C_{BT}^2$

$C_{STSS} := A_0 + A_1 \cdot C_P + A_2 \cdot C_P^2$ $C_{STSS} = 2.563$

$S_{TSS} := C_{STSS} \cdot \sqrt{V_{FL} \cdot LWL}$ $S_{TSS} = 5825\,m^2$

$S := S_{TSS} + S_{SD}$ $S = 5832\,m^2$

$C_W := 0.278 + 0.836 \cdot C_P$ $C_w := C_W$

Pre-Process

$T_F := T$ $\quad C_M := C_X$ $\quad C_V := \frac{V_{FL}}{LWL^3}$ $\quad C_V = 2.137\times 10^{-3}$

$A_{BT} := \frac{S_{SD}}{6}$ $\quad A_{BT} = 1.239\cdot m^2$ (bulb section area at FP)

$h_B := \sqrt{\frac{A_{BT}}{\pi}}$ $\quad h_B = 0.628\,m$ (height of bulb center)

$A_T := \frac{B\cdot T\cdot C_X}{20}$ $\quad A_T = 7.752\,m^2$ (transom area)

$L_R := (1 - C_P)\cdot LWL$ $\quad L_R = 71.609\,m$ (Run length)

$$formfac := 1.03\cdot\left[.93 + \left(\frac{T}{LWL}\right)^{.22284}\cdot\left(\frac{B}{L_R}\right)^{.92497}\cdot(.95 - C_P)^{-.521448}\cdot(1 - C_P + .05)^{.6906}\right] + 2.7\cdot\frac{S_{SD}}{S} \qquad formfac = 1.134$$

Appendages drag coefficient:

$$C_{DAPP} := \left(-4\cdot 10^{-9}\cdot\frac{LWL^3}{ft^3} + 9\cdot 10^{-6}\cdot\frac{LWL^2}{ft^2} - 0.0081\cdot\frac{LWL}{ft} + 5.0717\right)\cdot\frac{hp\cdot 10^{-5}}{ft^2\cdot knt^3} \qquad C_{DAPP} = 4.977\times 10^{-6}\cdot\frac{hp}{ft^2\cdot\left(\frac{ft}{sec}\right)^3}$$

Estimate propeller size:

$C_{PROP} := \text{if}(N_P > 1, 1, 1.2)$ $\quad C_{PROP} = 1$ $\quad D_P := (0.64\cdot T + 0.013\cdot LWL)\cdot C_{PROP}$ $\quad D_P = 7.74\,m$

$i := 1..16$ $\quad V_i := (i-1)\cdot knt + V_e$

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

Viscous Drag

Coefficient of friction:

$R_{N_i} := LWL\cdot\frac{V_i}{\upsilon_{SW}}$ $\quad C_{F_i} := \frac{0.075}{(\log(R_{N_i}) - 2)^2}$ (ITTC)

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

Wave Making Drag

$Fn_i := \frac{V_i}{\sqrt{g\cdot LWL}}$

$c_3 := \frac{.56\cdot A_{BT}^{1.5}}{B\cdot T\cdot(.31\cdot\sqrt{A_{BT}} + T_F - h_B)}$ $\quad c_3 = 5.929\times 10^{-4}$ $\quad c_2 := \exp(-1.89\cdot\sqrt{c_3})$ $\quad c_2 = 0.955$

$c_5 := 1 - \frac{.8\cdot A_T}{B\cdot T\cdot C_M}$ $\quad c_5 = 0.96$

$$\lambda_R := \begin{cases} 1.446\cdot C_P - .03\cdot\frac{LWL}{B} & \text{if } \frac{LWL}{B} < 12 \\ 1.446\cdot C_P - .036 & \text{otherwise}\end{cases} \qquad \lambda_R = 0.696$$

$$c_{15} := \begin{cases} -1.69385 & \text{if } \dfrac{LWL^3}{V_{FL}} < 512. \\ 0.0 & \text{if } \dfrac{LWL^3}{V_{FL}} > 1726.91 \\ -1.69385 + \dfrac{\dfrac{LWL}{V_{FL}^{\frac{1}{3}}} - 8}{2.36} & \text{otherwise} \end{cases} \qquad c_{15} = -1.694$$

$$c_7 := \begin{cases} .229577\cdot\left(\dfrac{B}{LWL}\right)^{.33333} & \text{if } \dfrac{B}{LWL} < .11 \\ .5 - .0625\cdot\dfrac{LWL}{B} & \text{if } \dfrac{B}{LWL} > .25 \\ \dfrac{B}{LWL} & \text{otherwise} \end{cases} \qquad c_7 = 0.109$$

$$c_{16} := \begin{cases} 8.07981\cdot C_P - 13.8673\cdot C_P^2 + 6.984388\cdot C_P^3 & \text{if } C_P < .8 \\ 1.73014 - .7067\cdot C_P & \text{otherwise} \end{cases} \qquad c_{16} = 1.281$$

$$i_E := 1 + 89\cdot\exp\left[-\left(\frac{LWL}{B}\right)^{.80856}\cdot(1 - C_w)^{.30484}\cdot(1 - C_P)^{.6367}\cdot\left(\frac{L_R}{B}\right)^{.34574}\cdot\left(\frac{100\cdot V_{FL}}{LWL^3}\right)^{.16302}\right] \qquad i_E = 13.77$$

$$c_1 := 2223105\cdot c_7^{3.78613}\cdot\left(\frac{T}{B}\right)^{1.07961}\cdot(90 - i_E)^{-1.37565} \qquad c_1 = 0.379$$

$$m_1 := .0140407\cdot\frac{LWL}{T} - 1.75254\cdot\frac{V_{FL}^{\frac{1}{3}}}{LWL} - 4.79323\cdot\frac{B}{LWL} - c_{16} \qquad m_1 = -1.605$$

$$m_{4_i} := .4\cdot c_{15}\cdot\exp\left[-.034\cdot\left(Fn_i\right)^{-3.29}\right]$$

$$R_{w_i} := V_{FL}\cdot\rho_{SW}\cdot g\cdot c_1\cdot c_2\cdot c_5\cdot\exp\left[m_1\cdot\left(Fn_i\right)^{-.9} + m_{4_i}\cdot\cos\left[\frac{\lambda_R}{\left(Fn_i\right)^2}\right]\right]$$

$$P_B := \frac{.56\cdot A_{BT}^{.5}}{\left(T_F - 1.5\cdot h_B\right)} \qquad P_B = 0.094$$

$$Fni_i := \frac{V_i}{\sqrt{g\cdot\left(T_F - h_B - .25\cdot A_{BT}^{.5}\right) + .15\cdot\left(V_i\right)^2}} \qquad R_{B_i} := \frac{.11\cdot\exp\left(\dfrac{-3}{P_B^2}\right)\cdot\left(Fni_i\right)^3\cdot A_{BT}^{1.5}\cdot\rho_{SW}\cdot g}{1 + \left(Fni_i\right)^2}$$

$$FnT_i := \frac{V_i}{\sqrt{\dfrac{2\cdot g\cdot A_T}{B + B\cdot C_w}}} \qquad c_{6_i} := \begin{cases} .2\cdot\left(1 - .2\cdot FnT_i\right) & \text{if } FnT_i < 5 \\ 0. & \text{otherwise} \end{cases} \qquad R_{TR_i} := .5\cdot\rho_{SW}\cdot\left(V_i\right)^2\cdot A_T\cdot c_{6_i}$$

Bare Hull Resistance

$$R_{R_i} := \left(R_{w_i} + R_{B_i} + R_{TR_i} + R_{A_i}\right)$$

$$R_{T_i} := R_{V_i} + R_{R_i}$$

Ship Effective Horsepower

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

$$P_{Efins_i} := \begin{cases} 0 \cdot hp & \text{if } N_{fins} = 0 \\ 0.025 \cdot P_{EBH_i} & \text{otherwise} \end{cases}$$

$$P_{EAPP_i} := 1.23 \cdot LWL \cdot D_P \cdot C_{DAPP} \cdot \left(V_i\right)^3 + P_{Efins_i}$$

Air frontal area (+5% for masts, equip., etc): $A_W := 1.05 \cdot B \cdot \left(D_{10} - T + 3 \cdot H_{DK}\right)$ $A_W = 429.226\,m^2$

$C_{AA} := 0.7$ $P_{EAA_i} := \frac{1}{2} \cdot C_{AA} \cdot A_W \cdot \rho_A \cdot \left(V_i\right)^3$

Total effective horsepower: $P_{ET_i} := P_{EBH_i} + P_{EAPP_i} + P_{EAA_i}$ $EHP_i := PMF \cdot P_{ET_i}$

Appendix I – Prop Selection, Engine Match and Fuel Calculation MathCAD File

Units and Physical Constants

$knt \equiv 1.69 \cdot \frac{ft}{sec}$ $mile \equiv knt \cdot hr$ $lton \equiv 2240 \cdot lbf$ $nm := knt \cdot hr$ $kN := 1000 \cdot newton$ $RPM := \frac{1}{min}$

Sea water properties: $\rho_{SW} := 1.9905 \cdot \frac{slug}{ft^3}$ $\upsilon_{SW} := 1.2817 \cdot 10^{-5} \cdot \frac{ft^2}{sec}$ $\delta_F := 43.6 \cdot \frac{ft^3}{lton}$

Air properties: $\rho_A := 0.0023817 \cdot \frac{slug}{ft^3}$

Principal characteristics:

$T := 7.59 \cdot m$ $C_P := .677$ $C_X := .87$ $Draft := T$ $D_P := 6.14 \cdot m$ $D := D_P$

$KW_{24AVG} := 13531 \cdot kW$ $KW_{MFLM} := 28425kW$ $V_{F41} := 4651.6 \cdot m^3$

$V_e := 20 \cdot knt$ $V_S := 32.17 \cdot knt$ $C_B := C_P \cdot C_X$ $C_B = 0.589$ $z := 8m$

$PMF_e := 1.1$ $PMF_S := 1.25$ $N_P := 2$

$w := 2 \cdot C_B^{\,5} \cdot (1 - C_B) + .04$ $w = 0.098$ wake fraction

$t := .7 \cdot w + .06$ $t = 0.129$ thrust deduction fraction - prop changes pressure distribution around hull which effectively changes the resistance of towed hull

1. Maximize Propulsor Efficiency at Endurance Speed - input EHP from Resistance Calculation at Ve

$V := V_e$ $EHP := 17165 \cdot hp$ (total, hull)

$V_A := V \cdot (1 - w)$ $V_A = 18.035 \cdot knt$ speed of advance - average wake velocity seen by prop

$T := \frac{EHP}{V \cdot (1 - t) \cdot N_P}$ $T = 160301 \cdot lbf$ $T = 713.053 \cdot kN$ thrust/shaft

$\eta_H := \frac{1 - t}{1 - w}$ $\eta_H = 0.966$ hull efficiency = $EHP/(THP \cdot N_P) = R_T \cdot V/(T \cdot V_A \cdot N_P)$

$\eta_R := 1.0$ estimate   relative rotative efficiency - due to non-uniform flow into prop = DHPo/DHP

2. Determine the efficiency of an optimum standard propeller using the Wageningen B-screw series and the Propeller Optimization Program from the University of Michigan. The inputs for the program are:

Pitch Type = Fixed Pitch $Z := 5$ $EAR := 0.8$ $PtoD := 1.4$ $D = 6.14 \cdot m$ $T = 713.053 \cdot kN$

$V_e = 20 \cdot knt$ $w = 0.098$ $z = 8 \cdot m$

Output:

$D := 6.98 \cdot m$ $EAR := 0.8243$ $PtoD := 1.1871$ $n_{eSHAFT} := 82.66RPM$ $\eta_O := .765$ $\sigma := .6643$

$\eta_B := \eta_O \cdot \eta_R$ $\eta_B = 0.765$ prop efficiency behind ship = THP/DHP

$\eta_D := \eta_H \cdot \eta_B$ $\eta_D = 0.739$ quasi-propulsive efficiency

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

$\eta_P := \eta_S \cdot \eta_D$ $\eta_P = 0.739$ propulsive efficiency

$\eta_{gen} := .973$ generator efficiency

$\eta_{conv} := .955$ convertor efficiency

$\eta_{motor} := .957$ motor efficiency

$\eta_{elec} := \eta_{gen} \cdot \eta_{conv} \cdot \eta_{motor}$

$\eta_{elec} = 0.889$ electrical efficiency

$THP := \frac{EHP}{\eta_H \cdot N_P}$ $THP = 8883.158 \cdot hp$

$DHP := \frac{THP}{\eta_B}$ $DHP = 11611.971 \cdot hp$ $DHP_O := \eta_R \cdot DHP$ $DHP_O = 11612 \cdot hp$

$SHP := \frac{DHP}{\eta_S}$ $SHP = 11611.971 \cdot hp$ (per shaft)

$BHP_{ereq} := \frac{PMF_e \cdot SHP \cdot N_P}{\eta_{elec}}$ $BHP_{ereq} = 21422 \cdot kW$ (total ship)

3. Calculate "off-design" performance (η_O and n) and required BHP at sustained speed

$V := V_S$ $V = 32.17 \cdot knt$ $V := 32.17knt$ $EHP := 88316.8 \cdot hp$

$T := \frac{EHP}{V \cdot (1 - t) \cdot N_P}$ $T = 512759.629 \cdot lbf$ $T = 2280.868 \cdot kN$ $V_A := V \cdot (1 - w)$ $V_A = 29.009 \cdot knt$ (per shaft)

Determine the efficiency of the propeller at sustained speed (off-design):

$\eta_O := .755$ $n_{sSHAFT} := 138.69RPM$ $\sigma := .2392$ propeller cavitates

$THP := \frac{EHP}{\eta_H \cdot N_P}$ $THP = 45705.336 \cdot hp$

$\eta_B := \eta_O \cdot \eta_R$ $\eta_B = 0.755$ prop efficiency behind ship = THP/DHP

$\eta_D := \eta_H \cdot \eta_B$ $\eta_D = 0.729$ quasi-propulsive efficiency

$\eta_P := \eta_S \cdot \eta_D$ $\eta_P = 0.729$ propulsive efficiency

$DHP := \frac{THP}{\eta_B}$ $DHP = 60536.869 \cdot hp$ $DHP_O := \eta_R \cdot DHP$ $DHP_O = 60536.869 \cdot hp$

$SHP := \frac{DHP}{\eta_S}$ $SHP = 60536.869 \cdot hp$ (per shaft)

$BHP_{Sreq} := \frac{N_P \cdot PMF_S \cdot SHP}{\eta_{elec}}$ $BHP_{Sreq} = 126910.011 \cdot kW$ (total ship)

4. Calculate optimum engine operating characteristics - Electric Propulsion

input: $MCR_P := 35500 \cdot kW$ $MCR_S := 5100 \cdot kW$ $n_{eSHAFT} = 82.66 \cdot RPM$ $n_{sSHAFT} = 138.69 \cdot RPM$

Endurance Speed: input: $N_{eENGP} := 1$ $N_{eENGS} := 2$

$P_{eFracP} := .9$

$$P_{eP} := P_{eFracP} \cdot N_{eENGP} \cdot MCR_P = 31950 \cdot kW \qquad P_{eP} = 42845.656 \cdot hp$$

$$P_{eS} := BHP_{ereq} + \frac{KW_{24AVG}}{.8} - P_{eP} = 6385.974 \cdot kW \qquad P_{eS} = 8563.732 \cdot hp$$

$$P_{eFracS} := \frac{P_{eS}}{N_{eENGS} \cdot MCR_S} = 0.626$$

Sustained Speed: input: $N_{sENGP} := 4$ $N_{sENG.S} := 2$

$P_{sFracP} := .80$

$$P_{sP} := P_{sFracP} \cdot N_{sENGP} \cdot MCR_P = 113600 \cdot kW \qquad P_{sP} = 152340.109 \cdot hp$$

$$P_{sS} := BHP_{Sreq} + \frac{0.4KW_{MFLM}}{.8} - P_{sP} = 27522.511 \cdot kW \quad P_{sS} = 36908.296 \cdot hp$$

$$P_{sFracS} := \frac{P_{sS}}{N_{sENG.S} \cdot MCR_S} = 2.698$$

4a. Select engine RPM for minimum fuel consumption at endurance speed from the engine performance map. Estimate fuel consumption.

$n_{sPEopt} := 3600 \cdot RPM$ $n_{sPE} := n_{sPEopt}$

SFC data:

MT30

$$vx_P := \begin{pmatrix} .13 \\ .205 \\ .56 \\ .885 \\ 1 \end{pmatrix} \qquad vy_P := \begin{pmatrix} .77 \\ .62 \\ .465 \\ .36 \\ .345 \end{pmatrix} \cdot \frac{lb}{hp \cdot hr}$$

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$$vx_S := \begin{pmatrix} .18 \\ .53 \\ .86 \end{pmatrix} \qquad vy_S := \begin{pmatrix} .37 \\ .345 \\ .33 \end{pmatrix} \cdot \frac{lb}{hp \cdot hr}$$

Endurance

Speed:

$SFC_{eP} := interp(cspline(vx_P, vy_P), vx_P, vy_P, P_{eFracP}) = 0.356 \cdot \frac{lb}{hp \cdot hr}$ $\quad Fuelrate_{eP} := (P_{eP}) \cdot SFC_{eP} = 15260.22$

$SFC_{eS} := interp(cspline(vx_S, vy_S), vx_S, vy_S, P_{eFracS}) = 0.34 \cdot \frac{lb}{hp \cdot hr}$ $\quad Fuelrate_{eS} := (P_{eS}) \cdot SFC_{eS} = 2912.82 \cdot\cdot$

$Fuelrate_{e.TOT} := Fuelrate_{eP} + Fuelrate_{eS} = 8.243 \cdot \frac{tonne}{hr}$

Sustained Speed:

$.21 \frac{kg}{kW \cdot hr} = 0.345 \cdot \frac{lb}{hp \cdot hr}$

$SFC_{sP} := interp(cspline(vx_P, vy_P), vx_P, vy_P, P_{sFracP}) = 0.388 \cdot \frac{lb}{hp \cdot hr}$ $\quad Fuelrate_{sP} := (P_{sP}) \cdot SFC_{sP} = 59151.37$

$SFC_{sS} := interp(cspline(vx_S, vy_S), vx_S, vy_S, P_{sFracS}) = 0.01 \cdot \frac{lb}{hp \cdot hr}$ $\quad Fuelrate_{sS} := (P_{sS}) \cdot SFC_{sS} = 368.353 \cdot\cdot$

$Fuelrate_{sTOT} := Fuelrate_{sP} + Fuelrate_{sS} = 26.998 \cdot \frac{tonne}{hr}$

5. Endurance Fuel Calculation

Calculate the endurance range for the specified fuel tank volume and average 24 hour electric load.

$P_{eBAVG} := P_{e.P} + P_{e.S}$ $\quad P_{eBAVG} = 38308.008 \cdot kW$ $\quad V_e = 20 \cdot knt$

Correction for instrumentation inaccuracy and machinery design changes:

$$f_1 := \begin{cases} 1.04 & \text{if } P_{e.P} \le \frac{1}{3} \cdot MCR_P \\ 1.02 & \text{if } P_{e.P} \ge \frac{2}{3} \cdot MCR_P \\ 1.03 & \text{otherwise} \end{cases} \qquad f_1 = 1.02$$

Specified fuel rate: $FR_{SP} := f_1 \cdot SFC_{e.tot}$ $\quad FR_{SP} = 0.352 \cdot \frac{lbf}{hp \cdot hr}$

Average fuel rate allowing for plant deterioration over 2 years: $FR_{AVG} := 1.05 \cdot FR_{SP}$ $\quad FR_{AVG} = 11.882 \frac{ft}{s^2} \cdot \frac{lb}{hp \cdot hr}$

Tailpipe allowance: $TPA := 0.95$

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

$V_{F41} = 4651.6 \cdot m^3$ $\quad V_{orig} := V_{F41} = 4651.6 \cdot m^3$

$V_{F41} := 4720m^3$ $\quad diff := V_{F41} - V_{orig} = 68.4 \cdot m^3$

$W_{F41} := \frac{V_{F41}}{1.02 \cdot 1.05 \cdot \delta_F}$ $\quad E := \frac{W_{F41} \cdot V_e \cdot TPA}{P_{eBAVG} \cdot FR_{AVG}}$ $\quad E = 8007.473 \cdot nm$

Fuel Oil Service Tank Calculation:

$N_{servicetanks} := 2$

$V_{Servicetank} := \frac{FR_{AVG} \cdot 4hr \cdot P_{eBAVG} \cdot 1.02 \cdot 1.05 \cdot \delta_F}{N_{servicetanks}} = 22.399 \cdot m^3$

$boxdims := V_{Servicetank}^{\frac{1}{3}} = 2.819 \cdot m$

Appendix J – Simpliefied Cost Model MathCAD File

$Mdol := coul$

$Bdol := 1000 \cdot Mdol$

$lton := 2240 \cdot lb$

$Kdol := \frac{Mdol}{1000}$

$hp := \frac{33000 \cdot ft \cdot lb}{min}$

$dol := \frac{Kdol}{1000}$

SIMPLIFIED COST MODEL

FFSHI

1. Single Digit Weight Summary: $i1 := 100, 200 .. 700$

$W_{100} := 9306.362 \cdot lton$ $W_{400} := 1183.213 \cdot lton$ $W_{500} := 2172.537 \cdot lton$

$W_{200} := 1908.081 \cdot lton$ $W_{420} := 31.888 \cdot lton$ $W_{600} := 1528.866 \cdot lton$ $W_{F_{20}} := 445.550 \cdot lton$

$W_{300} := 1022.787 \cdot lton$ $W_{430} := 97.732 \cdot lton$ $W_{700} := 835.099 \cdot lton$ $W_{F_{23}} := 13.877 \cdot lton$ [helo]

Weight margin: $W_M := 1672.327 \cdot lton$

$N_{HELO} := 2$

$N_{VTUAV} := 2$

2. Additional charcteristics:

Lightship:

$W_{LS} := \sum_{i1} W_{i1} + W_M$ $W_{LS} = 1.963 \times 10^4 \cdot lton$ $tonne = 2.205 \times 10^3 \cdot lb$

Costed Military Payload: (helo and helo fuel weight not included)

$W_{MP} := \left[\left(W_{400} + W_{700}\right) - W_{420} - W_{430}\right] + W_{F_{20}} - W_{F_{23}}$ $W_{MP} = 2.32 \times 10^3 \cdot lton$

Installed Propulsion Power: $P_{SUM} := 95930 \cdot hp$

Manning: (crew + air detachment + staff)

Officers: $N_{C_1} := 31$ CPO's: $N_{C_2} := 35$ Enlisted: $N_{C_3} := 386$

Ship Service Life: $L_S := 35$ Initial Operational Capability: $Y_{IOC} := 2018$

Total Ship Acquisition: $N_S := 18$ Production Rate (per year): $R_P := 3$

3. Inflation:

Base Year: $Y_B := 2012$ $iy := 1 .. Y_B - 1981$

Average Inflation Rate (%): $R_I := 4$
(from 1981)

$F_I := \prod_{iy} \left(1 + \frac{R_I}{100}\right)$ $F_I = 3.373$

4. Lead Ship Cost:

a. Lead Ship Cost - Shipbuilder Portion:

SWBS costs: (See Enclosure 1 for K_N factors); includes escalation estimate

Structure $K_{N1} := \frac{.8 \cdot Mdol}{lton^{.772}}$ $C_{L_{100}} := .03395 \cdot F_I \cdot K_{N1} \cdot \left(W_{100}\right)^{.772}$ $C_{L_{100}} = 106.136 \cdot Mdol$

+ Propulsion $K_{N2} := \frac{1.43 \cdot Mdol}{hp^{.808}}$ $C_{L_{200}} := .00186 \cdot F_I \cdot K_{N2} \cdot P_{SUM}^{\ .808}$ $C_{L_{200}} = 95.127 \cdot Mdol$

+ Electric $K_{N3} := \frac{1.0 \cdot Mdol}{lton^{.91}}$ $C_{L_{300}} := .07505 \cdot F_I \cdot K_{N3} \cdot \left(W_{300}\right)^{.91}$ $C_{L_{300}} = 138.768 \cdot Mdol$

+ Command, Control, Surveillance

$$K_{N4} := \frac{1.06383 \cdot Mdol}{lton^{.617}} \quad C_{L_{400}} := .10857 \cdot F_I \cdot K_{N4} \cdot \left(W_{400}\right)^{.617} \qquad C_{L_{400}} = 30.669 \cdot Mdol$$

(less payload GFM cost)

+ Auxiliary

$$K_{N5} := \frac{1.0 \cdot Mdol}{lton^{.782}} \quad C_{L_{500}} := .09487 \cdot F_I \cdot K_{N5} \cdot \left(W_{500}\right)^{.782} \qquad C_{L_{500}} = 130.218 \cdot Mdol$$

+ Outfit

$$K_{N6} := \frac{1.0 \cdot Mdol}{lton^{.784}} \quad C_{L_{600}} := .09859 \cdot F_I \cdot K_{N6} \cdot \left(W_{600}\right)^{.784} \qquad C_{L_{600}} = 104.331 \cdot Mdol$$

+ Armament

$$K_{N7} := \frac{1.0 \cdot Mdol}{lton^{.987}} \quad C_{L_{700}} := .00838 \cdot F_I \cdot K_{N7} \cdot \left(W_{700}\right)^{.987} \qquad C_{L_{700}} = 21.629 \cdot Mdol$$

(Less payload GFM cost)

+ Margin Cost:

$$C_{LM} := \frac{W_M}{\left(W_{LS} - W_M\right)} \cdot \left(\sum_{i1} C_{L_{i1}}\right) \qquad C_{LM} = 58.381 \cdot Mdol$$

+ Integration/Engineering: (Lead ship includes detail design engineering and plans for class)

$$K_{N8} := \frac{10. \cdot Mdol}{Mdol^{1.099}} \quad C_{L_{800}} := .034 \cdot K_{N8} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{1.099} \qquad C_{L_{800}} = 444.715 \cdot Mdol$$

+ Ship Assembly and Support: (Lead ship includes all tooling, jigs, special facilities for class)

$$K_{N9} := \frac{2.0 \cdot Mdol}{(Mdol)^{.839}} \quad C_{L_{900}} := .135 \cdot K_{N9} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{.839} \qquad C_{L_{900}} = 64.661 \cdot Mdol$$

= Total Lead Ship Construction Cost: (BCC):

$$C_{LCC} := \sum_{i1} C_{L_{i1}} + C_{L_{800}} + C_{L_{900}} + C_{LM} \qquad C_{LCC} = 1.195 \times 10^3 \cdot Mdol$$

+ Profit:

$$F_P := .10 \qquad C_{LP} := F_P \cdot C_{LCC} \qquad C_{LP} = 119.463 \cdot Mdol$$

= Lead Ship Price:

$$P_L := C_{LCC} + C_{LP} \qquad P_L = 1.314 \times 10^3 \cdot Mdol$$

+ Change Orders:

$$C_{LCORD} := .12 \cdot P_L \qquad C_{LCORD} = 157.692 \cdot Mdol$$

= Total Shipbuilder Portion:

$$C_{SB} := P_L + C_{LCORD} \qquad C_{SB} = 1.472 \times 10^3 \cdot Mdol$$

b. Lead Ship Cost - Government Portion

Other support: $C_{LOTH} := .025 \cdot P_L$ $C_{LOTH} = 32.852 \cdot Mdol$

+ Program Manager's Growth: $C_{LPMG} := .1 \cdot P_L$ $C_{LPMG} = 131.41 \cdot Mdol$ $W_{MP} = 2.32 \times 10^3 \cdot lton$

+ Ordnance and Electrical GFE: (Military Payload GFE)

$$C_{LMPG} := \left(.319 \cdot \frac{Mdol}{lton} \cdot W_{MP} + N_{HELO} \cdot 18.71 \cdot Mdol + N_{VTUAV} \cdot 7.5 \cdot Mdol \right) \cdot F_I$$

$C_{LMPG} = 2.674 \times 10^3 \cdot Mdol$ (or incl actual cost if known)

+ HM&E GFE (boats, IC): $C_{LHMEG} := .02 \cdot P_L$ $C_{LHMEG} = 26.282 \cdot Mdol$

+ Outfittimg Cost : $C_{LOUT} := .04 \cdot P_L$ $C_{LOUT} = 52.564 \cdot Mdol$

= Total Government Portion:

$C_{LGOV} := C_{LOTH} + C_{LPMG} + C_{LMPG} + C_{LHMEG} + C_{LOUT}$ $C_{LGOV} = 2.917 \times 10^3 \cdot Mdol$

c. Total Lead Ship End Cost: (Must always be less than appropriation)

* Total End Cost:

$C_{LEND} := C_{SB} + C_{LGOV}$ $C_{LEND} = 4.388 \times 10^3 \cdot Mdol$

d. Total Lead Ship Acquisition Cost:

+ Post-Delivery Cost (PSA): $C_{LPDEL} := .05 \cdot P_L$ $C_{LPDEL} = 65.705 \cdot Mdol$

= Total Lead Ship Acquisition Cost: $C_{LA} := C_{LEND} + C_{LPDEL}$ $C_{LA} = 4.454 \times 10^3 \cdot Mdol$

5. Follow-Ship Cost:

Learning Rate/Factor: $R_L := .97$ $F := 2 \cdot R_L - 1$ $F = 0.94$ (f

a. Follow Ship Cost - Shipbuilder Portion

$C_{F_{i1}} := F \cdot C_{L_{i1}}$ $C_{FM} := F \cdot C_{LM}$ $C_{FM} = 54.878 \cdot Mdol$

$$\frac{C_{F_{i1}}}{Mdol} = \begin{pmatrix} 99.768 \\ 89.419 \\ 130.442 \\ 28.829 \\ 122.405 \\ 98.071 \\ 20.331 \end{pmatrix}$$

$$C_{F_{800}} := \frac{.104 \cdot Mdol}{Mdol^{1.099}} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM} \right)^{1.099} \qquad C_{F_{800}} = 136.031 \cdot Mdol$$

$C_{F_{900}} := F \cdot C_{L_{900}}$ $C_{F_{900}} = 60.782 \cdot Mdol$

Total Follow Ship Construction Cost: (BCC)

$$C_{FCC} := \sum_{i1} C_{F_{i1}} + C_{F_{800}} + C_{F_{900}} + C_{FM} \qquad C_{FCC} = 840.954 \cdot Mdol$$

+ Profit:

$F_P := .1$ $C_{FP} := F_P \cdot C_{FCC}$ $C_{FP} = 84.095 \cdot Mdol$

= Follow Ship Price:

$P_F := C_{FCC} + C_{FP}$ $P_F = 925.049 \cdot Mdol$

+ Change Orders:

$C_{FCORD} := .08 \cdot P_L$ $C_{FCORD} = 105.128 \cdot Mdol$

= Total Follow Ship Shipbuilder Portion:

$C_{FSB} := P_F + C_{FCORD}$ $C_{FSB} = 1.03 \times 10^3 \cdot Mdol$

b. Follow Ship Cost - Government Portion

Other support: $C_{FOTH} := .025 \cdot P_F$ $C_{FOTH} = 23.126 \cdot Mdol$

+ Program Manager's Growth: $C_{FPMG} := .05 \cdot P_F$

number of helo's: $N_{HELO} = 2$

+ Ordnance and Electrical GFE: (Military Payload GFE)

$$C_{FMPG} := \left(.3 \cdot \frac{Mdol}{lton} \cdot W_{MP} + 18.710 \cdot Mdol \cdot N_{HELO} \right) \cdot F_I$$

$C_{FMPG} = 2.474 \times 10^3 \cdot Mdol$

+ HM&E GFE (boats, IC): $C_{FHMEG} := .02 \cdot P_F$ $C_{FHMEG} = 18.501 \cdot Mdol$

+ Outfittimg Cost: $C_{FOUT} := .04 \cdot P_F$ $C_{FOUT} = 37.002 \cdot Mdol$

= Total Follow Ship Government Cost:

$$C_{FGOV} := C_{FOTH} + C_{FPMG} + C_{FMPG} + C_{FHMEG} + C_{FOUT} \qquad C_{FGOV} = 2.599 \times 10^3 \cdot Mdol$$

c. Total Follow Ship End Cost: (Must always be less than SCN appropriation)

* Total Follow Ship End Cost:

$$C_{FEND} := C_{FSB} + C_{FGOV} \qquad C_{FEND} = 3.629 \times 10^{3} \cdot Mdol$$

d. Total Follow Ship Acquisition Cost:

\+ Post-Delivery Cost (PSA): $C_{FPDEL} := .05 \cdot P_F$ $\qquad C_{FPDEL} = 46.252 \cdot Mdol$

= Total Follow Ship Acquisition Cost: $C_{FA} := C_{FEND} + C_{FPDEL}$ $\qquad C_{FA} = 3.676 \times 10^{3} \cdot Mdol$

AVERAGE SHIP ACQUISITION COST:

$$C_{AV} := \frac{\frac{C_{FA} - C_{FMPG}}{F} \cdot (N_S - 1)^{\frac{\ln(2 \cdot R_L)}{\ln(2)}} + (N_S - 1) \cdot C_{FMPG} + C_{LA}}{N_S}$$

$$C_{AV} = 3.65 \times 10^{3} \cdot Mdol$$

6. Life Cycle Cost:

a. Research and development

Ship design and development:

$$C_{SDD} := 1.1\cdot\left(.571\cdot\frac{C_{FSB}}{F} + .072\cdot C_{LMPG}\right) \qquad C_{SDD} = 900.105\cdot Mdol$$

+ Ship test and evaluation

$$C_{STE} := 1.2\cdot\left(.499\cdot\frac{C_{FSB}}{F} + .647\cdot C_{LMPG}\right) \qquad C_{STE} = 2.732\times 10^{3}\cdot Mdol$$

= Total Ship R&D Cost:

$$C_{RD} := C_{SDD} + C_{STE} \qquad C_{RD} = 3.632\times 10^{3}\cdot Mdol$$

b) Investment (less base facilities, unrep, etc)

Ship Expected Total Shipbuilding Program Cost:

$$C_{SPE} := C_{AV}\cdot N_S \qquad C_{SPE} = 65.7\cdot Bdol$$

+ Support Equipment (shore-based)

ship: $C_{SSE} := .15\cdot C_{SPE}$ $\qquad C_{SSE} = 9.855\cdot Bdol$

+ Spares and repair parts (shore supply)

ship: $C_{ISS} := .1\cdot C_{SPE}$ $\qquad C_{ISS} = 6.57\cdot Bdol$

= Total Investment Cost: $C_{INV} := C_{SPE} + C_{SSE} + C_{ISS}$

$$C_{INV} = 82.125\cdot Bdol$$

c) Operations and Support (total service life, base year dollars)

Personnel (Pay and Allowances)

$$C_{PAY} := F_I\cdot\left[.026184\cdot N_{C_1} + .01151\cdot\left(N_{C_2} + N_{C_3}\right)\right]\cdot N_S\cdot L_S\cdot Mdol \qquad C_{PAY} = 12.022\cdot Bdol$$

$$C_{TAD} := F_I\cdot\left(N_{C_1} + N_{C_2} + N_{C_3}\right)\cdot N_S\cdot L_S\cdot 2.6\cdot 10^{-6}\cdot Mdol \qquad C_{TAD} = 2.497\cdot Mdol$$

$$C_{PERS} := C_{PAY} + C_{TAD} \qquad C_{PERS} = 12.025\cdot Bdol$$

+ Operations:

Operating hours/year: $H := 2500\cdot hr$

$$C_{OPS} := N_S\cdot L_S\cdot\left[F_I\cdot Kdol\cdot\left[188. + 2.232\cdot\left(N_{C_1} + N_{C_2} + N_{C_3}\right) - \frac{H}{26.9\cdot hr}\right] + \frac{C_{AV}}{769.2} + \frac{C_{FMPG}}{196}\right]$$

$$C_{OPS} = 13.288\cdot Bdol$$

+ Maintenance

$$C_{MTC} := N_S\cdot L_S\cdot\left[F_I\cdot Kdol\cdot\left[2967 + 4.814\cdot\left(N_{C_1} + N_{C_2} + N_{C_3}\right) - \frac{H}{3.05\cdot hr}\right] + \frac{C_{AV}}{156.25}\right]$$

$$C_{MTC} = 23.904\cdot Bdol$$

+ Energy

Fuel Rate: $W := 3.0 \cdot \frac{\text{lton}}{\text{hr}}$ $C_{FUEL} := .9 \cdot \frac{\text{dol}}{\text{gal}}$

$$C_{EGY} := N_S \cdot L_S \cdot C_{FUEL} \cdot \frac{H}{6.8 \cdot \frac{\text{lb}}{\text{gal}}} \cdot W \qquad C_{EGY} = 1.401 \cdot \text{Bdol}$$

+ Replenishment Spares

$$C_{REP} := C_{ISS} \cdot \frac{L_S - 4}{4} \qquad C_{REP} = 50.917 \cdot \text{Bdol}$$

+ Major Support (COH, ROH):

$$C_{MSP} := N_S \cdot L_S \cdot \left[698. + 5.988 \cdot \left(N_{C_1} + N_{C_2} + N_{C_3}\right) - \frac{H}{10.36 \cdot \text{hr}}\right] \cdot \text{Kdol} \cdot F_I + .0022 \cdot C_{AV}$$

$$C_{MSP} = 6.73 \cdot \text{Bdol}$$

= Total Operation and Support Cost: $C_{OAS} := C_{PERS} + C_{OPS} + C_{MTC} + C_{EGY} + C_{REP} + C_{MSP}$

$$C_{OAS} = 108.266 \cdot \text{Bdol}$$

d. Residual Value:

$$RES := .5 \cdot C_{SPE} \cdot \left(1 - \frac{2}{L_S}\right)^{L_S} \qquad RES = 4.189 \cdot \text{Bdol}$$

e. Total Program

* Total Life Cycle Cost (Undiscounted): $C_{LIFE} := C_{RD} + C_{INV} + C_{OAS} - RES$

$$C_{LIFE} = 189.833 \cdot \text{Bdol}$$

7. Discounted Life Cycle Cost:

Discount Rate: $R_D := .1$

a. Discounted R&D:

Length of R&D Phase: $L_{RD} := 13$

end: $E_{RD} := Y_{IOC} + 2 - Y_B$ $E_{RD} = 8$ (normalized to base year)

start: $B_{RD} := E_{RD} - L_{RD} + 1$ $B_{RD} = -4$

$$F_{DRD} := \frac{\sum_{y = B_{RD}}^{E_{RD}} \frac{1}{(1 + R_D)^y}}{L_{RD}} \qquad F_{DRD} = 0.88$$

$$C_{DRD} := F_{DRD} \cdot C_{RD} \qquad C_{DRD} = 3.196 \times 10^3 \cdot \text{Mdol}$$

b. Discounted Investment:

start: $B_{INV} := E_{RD} + 1$

end: $E_{INV} := B_{INV} + \frac{N_S - 1}{R_P}$ $\quad E_{INV} = 14.667$

$L_{INV} := E_{INV} - B_{INV} + 1$ $\quad L_{INV} = 6.667$

$$F_{DINV} := \frac{\sum_{y = B_{INV}}^{E_{INV}} \frac{1}{(1 + R_D)^y}}{L_{INV}} \qquad F_{DINV} = ▪$$

$C_{DINV} := F_{DINV} \cdot C_{INV}$ $\quad C_{DINV} = ▪ \cdot Bdol$

c. Discounted O&S:

start: $B_{OAS} := E_{INV} + 1$ $\quad B_{OAS} = 15.667$

end: $E_{OAS} := B_{OAS} + L_S - 1$ $\quad E_{OAS} = 49.667$

$L_{OAS} := E_{OAS} - B_{OAS} + 1$ $\quad L_{OAS} = 35$

$$F_{DOAS} := \frac{\sum_{y = B_{OAS}}^{E_{OAS}} \frac{1}{(1 + R_D)^y}}{L_{OAS}} \qquad F_{DOAS} = ▪$$

$C_{DOAS} := F_{DOAS} \cdot C_{OAS}$ $\quad C_{DOAS} = ▪ \cdot Bdol$

d. Discounted Residual Value:

$$RES_D := RES \cdot \left(\frac{1}{1 + R_D}\right)^{E_{OAS}+1} \qquad RES_D = 33.49 \cdot Mdol$$

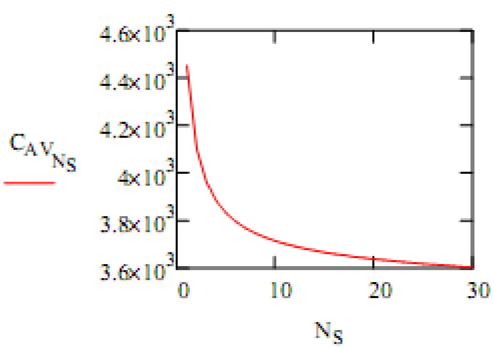
e. Total Discounted Life Cycle Cost:

$$C_{DLIFE} := C_{DRD} + C_{DINV} + C_{DOAS} - RES_D \qquad C_{DLIFE} = ▪ \cdot Bdol$$

LEARNING CURVE:

$N_S := 1 .. 30$

$$CAV_{N_S} := \frac{\frac{C_{FA} - C_{FMPG}}{F} \cdot (N_S - 1)^{\frac{\ln(2 \cdot R_L)}{\ln(2)}} + (N_S - 1) \cdot C_{FMPG} + C_{LA}}{N_S}$$



$C_{LA} = 4.454 \times 10^3 \cdot Mdol$

$C_{FA} = 3.676 \times 10^3 \cdot Mdol$