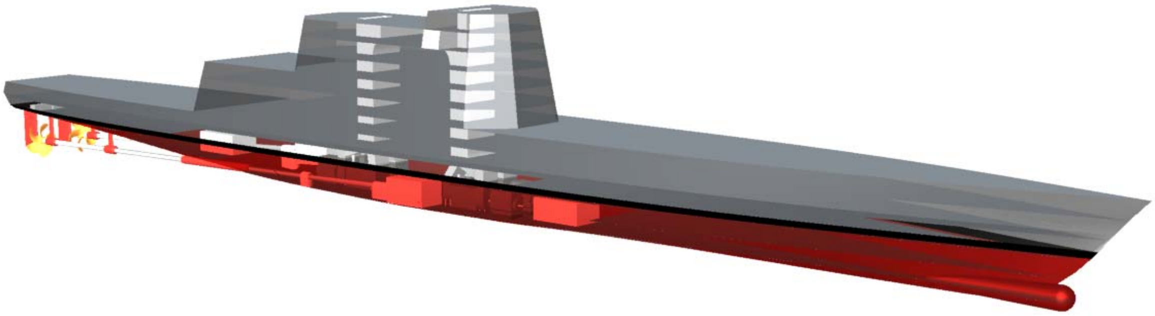
Virginia Tech
Aerospace & Ocean Engineering

Design Report
Modular Ballistic Missile Defense Cruiser (CGXmod)

VT Total Ship Systems Engineering



CGXmod Variant 91
Ocean Engineering Design Project
AOE 4065/4066
Fall 2008 – Spring 2009
Virginia Tech Team 1

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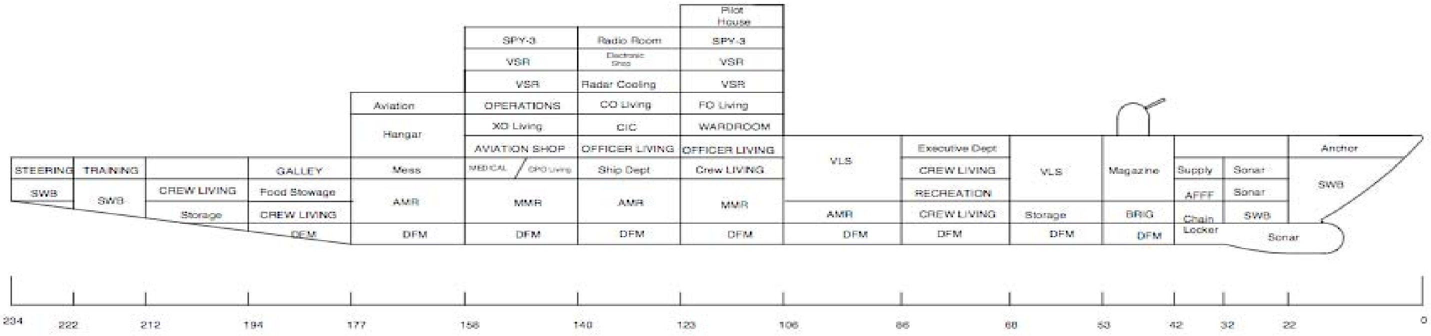
Executive Summary



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

The CGXmod requirement is based on the CGXmod Initial Capabilities Document (ICD) and the Virginia Tech CGXmod Acquisition Decision Memorandum (ADM), Appendices A and B. The ADM specified that the design must incorporate modularity concepts.

Concept Exploration through trade-off studies and design space exploration were accomplished using a Multi-Objective Genetic Optimization (MOGO) in Phoenix Integration's Model Center software after significant technology research, integration of proven concepts, and computer programming. Objective attributes for this optimization were cost, risk, and mission effectiveness. The product of this optimization is a series of cost-risk-effectiveness frontiers, which are used to select alternative baseline designs and define the Concept Development Document (CDD) based on the customer's preference for cost, risk, and effectiveness.

The initial baseline design slightly exceeded the maximum acquisition cost while allowing a measure of mission effectiveness of 90.8%, a measure that is only slightly improved upon in much higher cost alternatives, while providing a 28.5% level of risk, which falls in a moderate area of risk among the alternatives. It was chosen as it represented a knee in the non-dominated frontier while maintaining reasonable systems and a moderate degree of unproven technology and concepts. Modularity options in the C4I, machinery, habitability, sensor, and weapon areas represented some installed systems and proven concepts that have proven to be low risk, cost saving, and improved mission effective and readiness.

Further analysis included hull form development and analysis for intact and damage stability, structural finite element analysis, propulsion and power system development and arrangement, general and auxiliary arrangements, combat system definition and arrangement, seakeeping analysis, cost and producibility analysis, and risk analysis.

Final Baseline Design

Ship Characteristic	Value
LWL	226.7 m
Beam	23.7 m
Draft	7.93 m
D10	15.86 m
Cp	0.606
Cx	0.828
Cwp	0.784
Lightship weight	18779 MT
Full load weight	22356 MT
Sustained Speed	34 knots
Endurance Speed	20 knots
Sprint Range	6000 nm
Endurance Range	8875 nm
Propulsion and Power	4 x MT30, 2 x MC3.0 Fuel Cells, AC synchronous IPS, 2 x FPP
BHP	150 MW
Personnel	296
OMOE (Effectiveness)	0.908
OMOR (Risk)	0.285
Lead-ship Acquisition Cost	$2.6 Billion
Follow-ship Acquisition Cost	$2.1 Billion
Total Program Life-Cycle Cost	$100.5 Billion

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1 Introduction, Design Process and Plan

1.1 Introduction

This report describes the concept exploration and development of a Modular Ballistic Missile Defense Cruiser (CGXmod) for the United States Navy. The CGXmod requirement is based on the CGXmod Initial Capabilities Document (ICD) and the Virginia Tech CGXmod Acquisition Decision Memorandum (ADM), Appendices A and B. The concept design was completed in a two-semester ship design course at Virginia Tech with an emphasis on the following missions:

1. **Ballistic Missile Defense (BMD)** – independently detect, track, and intercept ballistic missiles that are a threat to United States interests.
2. **Carrier Strike Group (CSG)** – provide anti-air warfare capability to the strike group and protect the carrier from incoming threats.
3. **Surface Action Group (SAG)** – provide anti-air warfare capability to the surface action group and serve as a command platform for the group.

CGXmod will be the first platform specifically designed to counter the threat of Inter-Continental Ballistic Missiles (ICBMs) and will be expected to operate in forward positions over the horizon from observers in an effort to evade detection and targeting. CGXmod will be able to distinguish warheads from decoys and debris, track and intercept the missiles using SM-3 or better missiles, and provide an unparalleled level of upgradeability and reparability due to implemented modular options. The previous years' CGX designs from Virginia Tech were explored to find weaknesses and strengths, providing direction for this year's design. Modularity, surge cruise consideration, and enhanced radar/detection capabilities are key additions to past designs with more emphasis on analyzing and decreasing cost, analyzing the entire structure, providing the capability for quick and easy repairs, providing multi-mission capability and adaptability for the future, and allowing for faster production.

1.2 Design Philosophy, Process, and Plan

The design philosophy for this project is illustrated in Figure 1. We began the project with Concept Exploration where we considered a very broad range of technologies and ship characteristics. The process for Concept Exploration is shown in Figure 2. The broad design space was narrowed using a multi-objective genetic optimization (MOGO) considering cost, effectiveness and risk. At the completion of the MOGO, an initial baseline design was selected from the non-dominated designs identified by the optimization. Next a single-objective optimization was performed to refine initial baseline characteristics maximizing effectiveness with cost and risk as constraints. Finally a ROM feasibility study was performed using ASSET. In the Spring 2009, we began Concept Development following a much more traditional spiral-like process as shown in Figure 3. We were able to go once around this spiral in the time we had with a few small excursions resulting in our final baseline design.

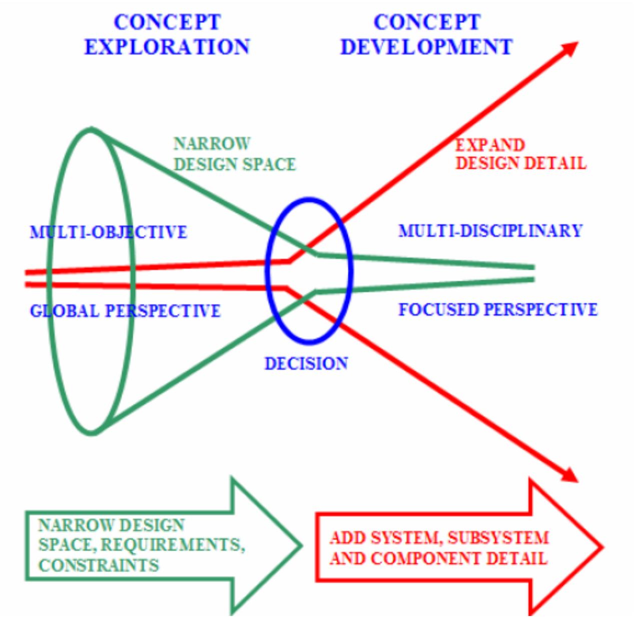


Figure 1: Design Philosophy [ ]

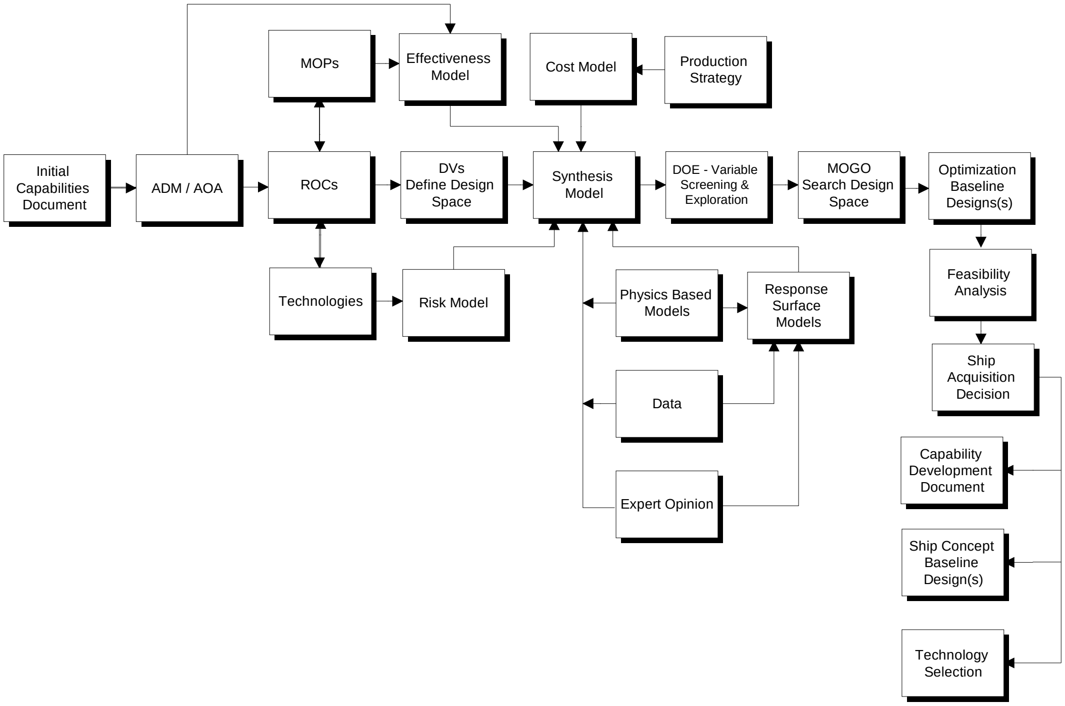


Figure 2: Concept Exploration Process [ ]

As shown in Figure 2, Concept Exploration is initiated by the Initial Capabilities Document and Acquisition Decision Memorandum, Appendices A and B. First, the ICD mission statement is refined by adding a concept of operations, mission scenarios, and specific Required Operational Capabilities (ROCs). Potential technologies are identified to provide these capabilities at various levels of performance. Data is gathered for these technologies and an Overall Measure of Risk (OMOR) metric and Risk Register are developed as metrics for technology risk. Design variable options and ranges are defined. Measures of Performance are developed and integrated into an Overall Measure of Effectiveness (OMOE). Next the Simplified Ship Synthesis Model (SSSM) is modified and updated to reflect the CGXmod design space and options. The weight-based cost model is modified and updated at the same time. After some preliminary variable screening and model verification, the MOGO is run and non-dominated designs in the design space are identified as a function of cost, effectiveness and risk. An initial concept baseline design is selected, refined and assessed. The products of Concept Exploration are the Initial Baseline Design, technology selection and the Concept Development Document (CDD).

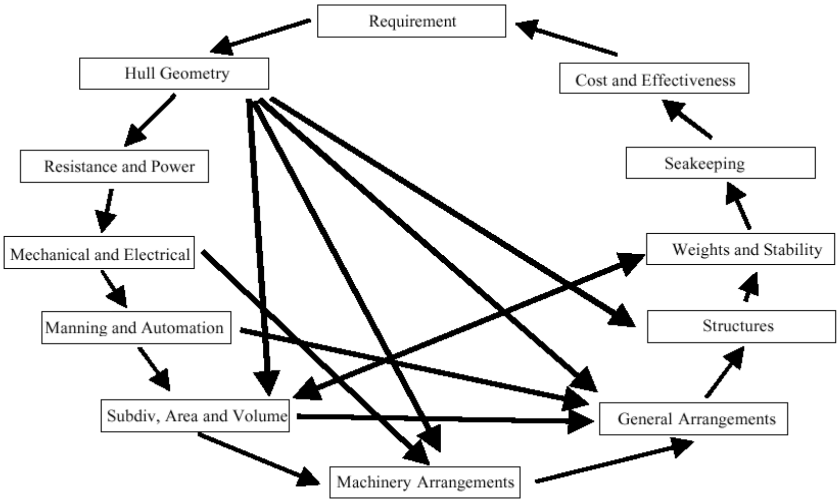


Figure 3: Concept Development Process [ ]

As shown in Figure 3, Concept Development followed a more traditional design spiral. After developing the 3D hull geometry and initial transverse subdivision (in Rhino), we were able to: refine subdivision considering floodable length and function; define tankage, subdivision and liquid loading; perform an initial check on intact stability and trim (in HECSALV); begin arrangements (in Rhino); and begin the structural design (in MAESTRO). The other processes shown in Figure 3 were mostly performed in the order indicated. The product of Concept Development was the Final Concept Baseline.

1.3 Work Breakdown

The CGXmod team consisted of six students from Virginia Tech with each student assigned specific areas of work according to his or her interests and skill sets as listed below:

Table 1: Group Work Breakdown

Name	Specialization
Billy Carver	Feasibility, Risk, Seakeeping, Modularity
Sarah Cibull	Effectiveness, Writer, Cost
Sean McCann	General Arrangements, Machinery Arrangements
Zachary Snyder	Hull Form, Structures, Combat Systems
Jason Price	Weights and Stability, Subdivision
Bryan Schmitt	Propulsion and Resistance, Electrical, Manning and Automation

Both team and individual work was critical through the process with team skills being apparent early in the design for research and initial considerations while individual skills became apparent later in the design. Maintaining configuration control was one of our most difficult concerns once we began specializing.

1.4 Resources

Table 2 shows computational and modeling tools used during this design. Each of these tools were used to check the other tools, as appropriate, while each tool provided unique properties and capabilities in the design process. We attempted to check all results with rough hand calculations where possible.

Table 2: Tools

Analysis	Software Package
Arrangement Drawings	Rhino3D, AutoCAD
Hull form Development	ASSET, Rhino3D, ORCA, ModelCenter
Hydrostatics	Rhino3D, HECSALV, ORCA, Rhino Marine
Resistance/Power	MathCAD
Ship Motions	PDStrip
Ship Synthesis Model	ModelCenter, ASSET
Structure Model	MAESTRO

2 Mission Definition

The CGXmod's mission requirements are based on the ICD and ADM with elaboration and clarification by customer.

2.1 Concept of Operations

Based on the CGXmod ICD and the ADM, the following Concept of Operations was developed. CGXmod will:

- Operate in forward locations in international waters and readily move to new maritime locations as needed;
- Operate over the horizon from observers ashore and evade detection and targeting by enemy forces;
- Move quickly to locations that lie along a ballistic missile's potential flight path to facilitate tracking and intercepting the attacking missile;
- Defend large, down-range territory against a potential attack by ballistic missiles in boost, early ascent, and mid-course phases of flight;
- Possess high-altitude, long-range search and track radar(s) capable of detecting and establishing precise tracking information on ballistic missiles, discriminate missile warheads from decoys and debris, provide data for ground-based and ship-based interceptors in flight, and assess the results of intercept attempts;
- Support SM-3 and future interceptor missiles/weapons;
- Integrate modularity into the ship and its systems;
- Use modularity for open system flexibility, upgradability, and ease of maintenance or repair;
- Support and operate with Carrier Strike Groups (CSGs);
- Function as Command Ship in Surface Action Groups (SAGs).

2.2 Projected Operational Environment (POE) and Threat

Based on the CGXmod ICD and the ADM, the POE and Threat for CGXmod include:

- Physical environment
  - Open ocean and littoral waters
    - Be able to survive sea states 1-9
    - Be able to maintain full operational capability through sea states 1-5
  - All weather capability in geographically constrained waters and open ocean
  - Manage complex and cluttered radar picture
- Threats
  - Littoral threats including small surface craft, diesel-electric submarines, land based air assets, mines, cruise missiles, and chemical/biological weapons
  - Open water threats including submarines and surface ships
  - Shallow crowded ports or operational areas
  - Major threats including the launch of long and short range ballistic missiles

2.3 Specific Operations and Missions

Mission types planned for CGXmod include:

- ▪ Independent Ballistic Missile Defense (BMD)
- ▪ Carrier Strike Group (CSG)
  - Provide AAW and support
- ▪ Surface Action Group (SAG)
  - Provide AAW and a command platform

Secondary missions for CGXmod could include:

- ▪ Providing disaster relief
  - Electrical services
  - Water services
  - Medical services
- ▪ Provide recon
- ▪ Future missions

Specific Modular Options for CGXmod include:

- Sensor/Radar
- Command and Control Center
- Weapons
    - Missile Module(s)
    - Gun Module(s)
    - Autonomous Vehicle Module(s)
- Machinery
    - Engine Module(s)
    - Auxiliary Systems-Pumps, Electrical, etc. Module(s)
- Modular compatibility/inter-operability with other Navy ships
- Integration/plug and play
- Extra system access to modular pieces as necessary

Modularity will be employed for efficient upgrades, faster maintenance, ease of production, decreased logistics support need, training, and multi-mission adaptability.

2.4 Mission Scenarios

Mission scenarios for the primary CGXmod missions are provided in Tables 3 through 5. Table 3 shows a Ballistic Missile Defense (BMD) scenario including missile warfare defense, anti-surface and anti-aircraft warfare defense in a typical 90 day scenario. Table 4 shows a Carrier Strike Group (CSG) scenario with anti-air warfare, with CGXmod supporting other vessels over a typical 90 day scenario. Table 5 shows a Surface Action Group (SAG) scenario where CGXmod provides anti-air warfare and a group command platform in a typical 75 day scenario.

Table 3: Ballistic Missile Defense 90 Day Scenario

DAY	MISSION DESCRIPTION
1 - 21	Leave from CONUS to Mediterranean
22 - 59	Intelligence, surveillance, and reconnaissance
33	Engage missile threat
40	Launch cruise missiles at land target
57	Join CSG and assist with ASW against diesel submarine threat
59 - 60	Port call for repairs through modularity and replenishment
60	Assist with in-port attack by several small boats and land-based missiles
61 - 89	Intelligence, surveillance, and reconnaissance
71	Detect tatical ballistic missile attack against ally; track, engage and destroy
70 - 72	Engage high speed boats using guns and harpoon missiles
75	Search and recovery of crew from damaged destroyer
76 - 80	Conduct missile defense against continued aggression
80 - 90	Return transit to home port
90+	Port call/Restricted availability

Table 4: Carrier Strike Group 90 Day Scenario

DAY	MISSION DESCRIPTION
1 - 21	Leave with CSG from CONUS to Persian Gulf
22 - 59	Intelligence, surveillance, and reconnaissance
33	Engage missile threat against CSG
40	Launch cruise missiles at land target
57	Assist with ASW against diesel submarine threat
59 - 60	Port call for repairs through modularity and replenishment
61	Assist with in-port attack by several small boats and land-based missiles
62 - 75	Rejoin CSG
65 - 89	Conduct AAW defense
70 - 72	Engage high speed boats using guns and anti-ship missiles
75	Search and recovery of crew from damaged destroyer
76 - 80	Conduct missile defense against continued aggression
80 - 90	Return transit to home port
90+	Port call/Restricted availability

Table 5: Surface Action Group 75 Day Scenario

DAY	MISSION DESCRIPTION
1 - 3	Transit with SAG 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 and provide AAW
11	Receive tasking for land strike
12	Cruise to 25 nm offshore
13	Embark special forces by helicopter; provide surveillance
14	Insert special forces by RIB, provide surveillance
15 - 25	Patrol grid for launch of BM
26	Detect tactical missile launch attack against ally; track, engage, and destroy
27 - 29	Cruise to new grid
30	Sustain damage from anti-ship missile; repair using plug and play modular components; regain full operational capability
31 - 44	Patrol grid
45 - 60	Port call for repairs and replenishment
61 - 68	Transit back to area of hostility
69	Detect ICBM launch against homeland; track, engage, and kill
70 - 71	Cruise to station, 35 nm offshore
72 - 74	Conduct recon with AAV
74	AAV detects terrorist activity
74	Intelligence indicates high-value target with terrorist cell; conduct land strike and kill target
75 - 77	Cruise back to forward base
77	Arrive at forward base

2.5 Required Operational Capabilities (ROCs)

In order to ensure completion of these expected missions, the capabilities listed below are required as defined by the U.S. Navy. Each of these capabilities can be related to the functional capabilities required for the ship, and thus must be implemented into its design and design considerations.

Table 6: List of Required Operational Capabilities (ROCs)

CAPABILITY	DESCRIPTION
AAW 1	Provide anti-air defense
AAW 1.1	Provide area anti-air defense
AAW 1.2	Support area anti-air defense
AAW 1.3	Provide unit anti-air self defense
AAW 2	Provide anti-air defense in cooperation with other forces
AAW 3	Provide Ballistic Missile Defense (BMD)
AAW 3.1	Provide Ballistic Missile Defense (BMD)
AAW 3.2	Support Ballistic Missile Defense (BMD)
AAW 3.3	Provide Theater Ballistic Missile Defense (BMD)
AAW 5	Provide passive and soft kill anti-air defense
AAW 6	Detect, identify, and track air targets
AAW 9	Engage airborne threats using surface-to-air armament
AMW 6	Conduct day and night helicopter, short/vertical vehicle, and airborne autonomous vehicle (AAV) take-off and landing operations
AMW 6.3	Conduct all-weather helicopter ops
AMW 6.4	Serve as a helicopter hangar
AMW 6.5	Serve as a helicopter haven
AMW 6.6	Conduct helicopter air refueling
AMW 12	Provide air control and coordination of air operations
ASU 1	Engage surface threats with anti-surface armaments
ASU 1.1	Engage surface ships at long range
ASU 1.2	Engage surface ships at medium range
ASU 1.3	Engage surface ships at close range
ASU 1.5	Engage surface ships with medium caliber gunfire
ASU 1.6	Engage surface ships with minor caliber gunfire
ASU 1.9	Engage surface ships with small arms gunfire
ASU 2	Engage surface ships in cooperation with other forces
ASU 4	Detect and track a surface target
ASU 4.1	Detect and track a surface target with radar
ASU 6	Disengage, evade, and avoid surface attack
ASW 1	Engage submarines
ASW 1.1	Engage submarines at long range
ASW 1.2	Engage submarines at medium range
ASW 1.3	Engage submarines at close range
ASW 4	Conduct airborne ASW/recon
ASW 5	Support airborne ASW/recon
ASW 7	Attack submarines with antisubmarine armament
ASW 7.6	Engage submarines with torpedoes
ASW 8	Disengage, evade, avoid, and deceive submarines
CCC 1	Provide command and control facilities
CCC 1.6	Provide a Helicopter Direction Center
CCC 2	Coordinate and control the operations of the task organization or functional force to carry out assigned missions
CCC 3	Provide own unit Command and Control
CCC 4	Maintain data link capability
CCC 6	Provide communications for own unit
CCC 9	Relay communications

CCC 21	Perform cooperative engagement
FSO 5	Conduct towing/search/salvage rescue operations
FSO 6	Conduct search and rescue operations
FSO 8	Conduct port control functions
FSO 9	Provide routine health care
FSO 10	Provide first aid assistance
FSO 11	Provide triage of casualties/patients
INT 1	Support/conduct intelligence collection
INT 2	Provide intelligence
INT 3	Conduct surveillance and reconnaissance
INT 8	Process surveillance and reconnaissance information
INT 9	Disseminate surveillance and reconnaissance information
INT 15	Provide intelligence support for non-combatant evacuation operation
MIW 4	Conduct mine avoidance
MIW 6	Conduct magnetic silencing (degaussing, deperming)
MIW 6.7	Maintain magnetic signature limits
MOB 1	Steam to design capacity in most fuel efficient manner
MOB 2	Support/provide aircraft for all-weather operations
MOB 3	Prevent and control damage
MOB 3.2	Counter and control nuclear, biological, and chemical contaminants and agents
MOB 5	Maneuver in formation
MOB 7	Perform seamanship, airmanship, and navigation tasks
MOB 10	Replenish at sea
MOB 12	Maintain health and well being of crew
MOB 13	Operate and sustain self as a forward deployed unit for an extended period of time during peace and war without shore-based support
MOB 16	Operate in day and night environments
MOB 17	Operate in heavy weather
MOB 18	Operate in full compliance of existing US and international pollution control laws and regulations
NCO 3	Provide upkeep and maintenance of own unit
NCO 19	Conduct maritime law enforcement operations
SEW 2	Conduct sensor and electronic counter measure operations
SEW 3	Conduct sensor and electric counter-counter measure operations
SEW 5	Conduct coordinated sensor and electronic warfare operations with other units
STW 3	Support/conduct multiple cruise missile strikes

3 Concept Exploration

3.1 Trade Studies, Technologies, Concepts, and Design Variables

Available technologies and the concepts necessary to provide required functional capabilities were identified and individually defined in terms of performance, cost, risk, and total ship impact (weight, area, volume, position, and 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. In many ways preparation for trade studies using this approach requires more work than performing a few trades by hand around a few baselines, but it allows a total ship design approach to these trades varying all design variables and their combined cost, effectiveness and risk in every assessment and ultimately considering only non-dominated concepts for selection. Technology and concept trade spaces and parameters are described in the following sections.

3.1.1 Hull Form Alternatives

To select alternative hull forms, a selection process using the transport factor methodology was used as shown in Figures 5 and 6.

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

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

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 5. Transport factor equations and variables

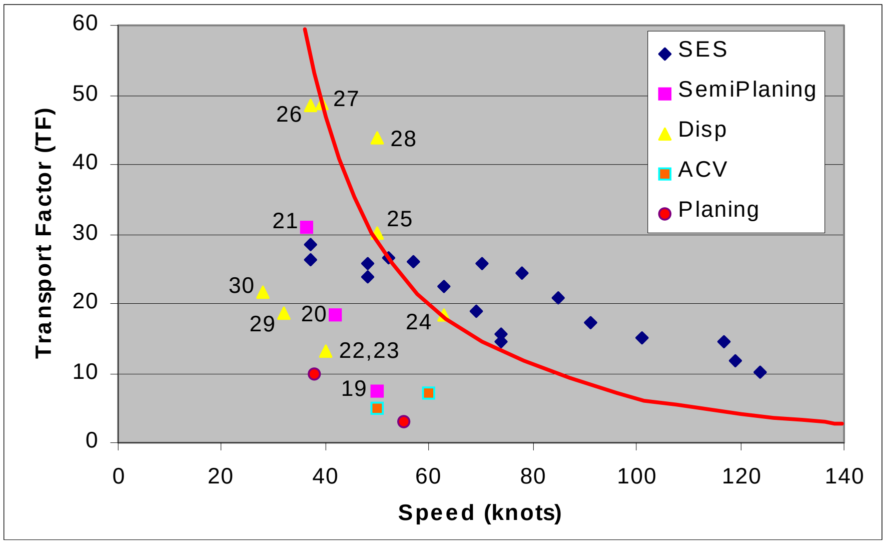


Figure 6: Transport factor verse speed for different hull types

Since the parameters of payload weight, required sustained speed, endurance speed, and range were known approximately and the design space limited these factors in order to achieve our missions and cost threshold, an approximate transport factor could be established. Based on cruiser sizes in the past and similarly sized ships, estimation of the transport factor for CGXmod suggests a displacement monohull. This option also provides structural efficiency, operational seakeeping performance, and a large interior volume while other options like a twin or tri-hull would add substantial risk due to lack of experience with the hulls and likely less arrangeable area for added hull weight. The Navy is investigating tumblehome hulls in an effort to reduce radar cross section while also providing more flat plate area production, thus cutting production costs as opposed to a curvy flared hull. Due to this, the hullform was considered. However, past performances of flared hulls, which are widely tested, indicate excellent seakeeping performance. Thus, to satisfy both requirements, a hybrid tumblehome/flare monohull was chosen.

3.1.2 Propulsion and Electrical Machinery Alternatives

An integrated power system (IPS) (Figure 7) was directed by the ADM and the customer including a range of technologies for both primary and secondary power generation modules (PGMs, SPGMs), propulsion motor modules (PMMs), power distribution and conversion. IPS offers greater flexibility in propulsion and ship service power arrangements, can reduce weight with fewer prime movers, increase power efficiency, and, along with zonal distribution, can provide greater survivability than conventional power systems.

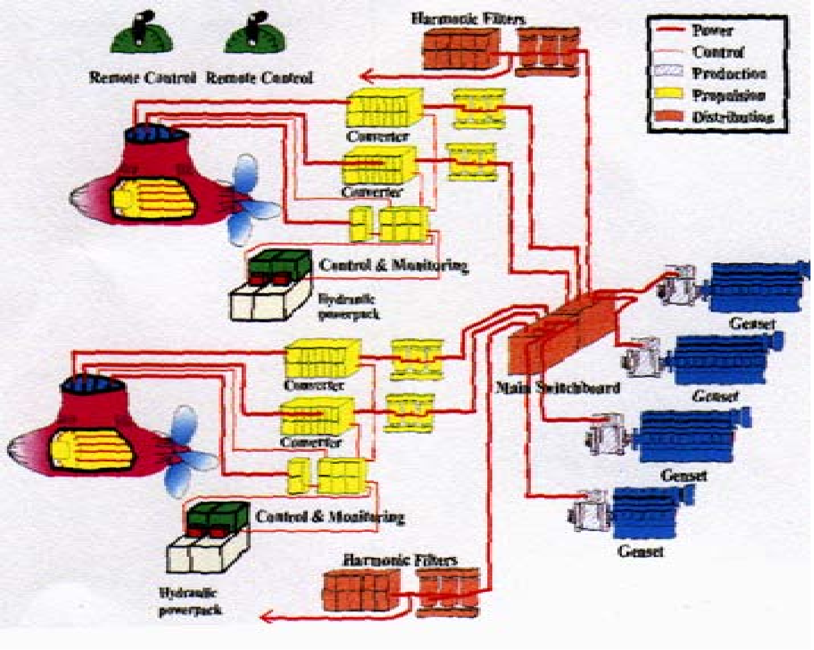


Figure 7: IPS Example

Both DC and AC zonal distribution systems are considered for power distribution, DC systems provide potential for better survivability characteristics and are more fault tolerant than AC systems.

Gas turbines offer fast start-up times, high power to weight ratios, and smaller sizes compared to diesels of equivalent power. The U.S. Navy has increasingly used gas turbines on their ships in both PGMs and SPGMs. SPGM options must provide greater fuel efficiency for lower power and speed operations. Thus, diesels with their lower specific fuel consumption are considered. Fuel cells, which show promise of even better performance than diesels are also considered even though they exhibit an increased risk due to their relatively early stage of development.

PMM options considered include two motor types: permanent magnet and advanced induction. Although the AIM is widely used and tested, the permanent magnet motor is currently being researched and models are being tested with results indicating improved performance, but at an increased cost and higher risk due to no large scale applications.

Three propulsor types were initially considered: fixed-pitch propulsors, controllable-pitch propulsors, and azimuthing pods. Pods, which have been considered in previous designs, would allow for flexible arrangements and excellent maneuvering due to rotational thrust vectoring, but would substantially increase required structure to support the moments and forces created with questionable vulnerability to UNDEX. Controllable pitch propellers offer an excellent alternative as blades can be rotated on their hub to vary pitch angle, allowing the most efficient pitch angle to be used and reversing to be a simple rotation of the blades. However, added components, increased drag due to large hubs, and limited area ratios increase acoustic signature, maintenance, cost, and risk at the loss of efficiency or the necessity for a lager blade diameter, and thus deeper draft. Fixed pitch propellers are, in comparison, simple. Their pitch angle and diameter are optimized for cruise speed with a slight decrease in efficiency at sprint speed. The lower machinery and maintenance requirements, along with an excellent history of survivability, make this option very attractive when combined with an IPS drive. Thus, to keep costs and risks down while maintaining effectiveness, and after reviewing the mission and mission scenarios which would not require the intense maneuverability provided by a pod, only fixed-pitch propellers were chosen for consideration in the CGXmod design.

Again, all of these choices were made in an effort to reduce the design space of CGXmod while providing reasonable engineering judgment.

3.1.2.1 Machinery Requirements

Based on the ADM and customer input, propulsion plant design requirements are summarized as follows:

General Requirements – The ship must have a minimum range of 5000 nautical miles at 20 knots; sustained speed must be achieved in full load, calm water, clean hull, and using no more than 80% MCR.

Sustained Speed and Propulsion Power – The ship must meet a minimum sustained speed of 30 knots with a goal sustained speed of 35 knots.

Ship Control and Machinery Plant Automation – The ship must comply with ABS ACCU requirements for periodically unattended machinery spaces; auxiliary systems, electric plant, and damage control systems will be continuously monitored from the command control center, main control console, and Chief Engineer's office. The systems will be controlled from the main control console and local controllers.

Propulsion Engine and Ship Service Generator Certification – All equipment should be Navy qualified and grade A shock certified while maintaining a low infrared signature; non-nuclear options only.

Table 7 is a summary of the final machinery alternatives considered for CGXmod.

Table 7: Machinery Plant Alternatives (Design Variables)

DV #	DV Name	Description	Design Space
10	PGM	Power Generation Module	Option 1) 3 x LM2500+, AC Synchronous, 4160 VAC
			Option 2) 3 x LM2500+, AC Synchronous, 13800 VAC
			Option 3) 4 x LM2500+, AC Synchronous, 4160 VAC
			Option 4) 4 x LM2500+, AC Synchronous, 13800 VAC
			Option 5) 2 x MT30, AC Synchronous, 4160 VAC
			Option 6) 2 x MT30, AC Synchronous, 13800 VAC
			Option 7) 3 x MT30, AC Synchronous, 4160 VAC
			Option 8) 3 x MT30, AC Synchronous, 13800 VAC
			Option 9) 4 x MT30, AC Synchronous, 4160 VAC
			Option 10) 4 x MT30, AC Synchronous, 13800 VAC
11	SPGM	Secondary Power Generation Module	Option 1) None
			Option 2) 2 x LM500G, Geared, AC Synchronous
			Option 3) 2 x CAT 3608 Diesels
			Option 4) 2 x PC 2.5/18 Diesels
			Option 5) 2 x MC3.0 Fuel Cells
			Option 6) 2 x MC4.0 Fuel Cells
			Option 7) 2 x PEM5.0 Fuel Cells
12	PROPtype	Propulsor Type	Option 1) 2 x Fixed Pitch Propellers
			Option 2) 2 x Fixed Pitch Propellers, 2 x SPU (3 MW each)
13	DISTtype	Power Distribution Type	Option 1) AC Zonal Electrical Distribution System
			Option 2) DC Zonal Electrical Distribution System
14	PMM	Propulsion Motor Module	Option 1) Advanced Induction Motor
			Option 2) Permanent Magnet Motor

3.1.3 Automation and Manning Parameters

The personnel needed to man a ship are, in most cases, the largest expense of a ship over its lifetime. Manning accounts for 60% of the Navy's budget, thus creating the opportunity to decrease costs if the efficiency of a crew can be increased, thus requiring less crew members. Technology such as automated systems and system monitoring, smarter coatings, and increased quality standards provides this ability and with a potential increase in effectiveness. Implementation of such technology, though, will come with an increased cost and risk as with any technology. Still, the Navy has begun to look for ways to reduce its manpower while increasing its ability through the implication of systems and concepts like:

- Faster computers and smarter software
- Large flat panel displays
- Expert systems
- More reliable, effective, and smarter sensors
- Corrosion and wear resistant coatings
- Better anti-fowling paints
- Synthetic bushings that do not require conventional lubrication or maintenance
- Increased individual watch standing ability through GPS, automated route planning, electronic charting and navigation (ECDIS), collision avoidance, and electronic log keeping
- Condition based maintenance
- Paperless ship concept

Finding the most effective balance for a ship, especially when taking into account a ship's future, can prove extremely difficult. To simplify matters in this Concept Exploration, a ship manning and automation factor was used, which represents reductions from conventional (current) manning levels to more automated systems. As detailed below, the crew size is determined from a manning factor (CMan), the percentage of crew onboard compared to a current expected crew size (where CMan = 1.0), along with various chosen systems, ship characteristics, and the degree of automation. The equations used were developed from a comprehensive analysis performed using current fleet analysis and expert opinion. Because this determination also design variables and outputs from other portions of the synthesis used for this design, which are also used in calculating cost, risk, performance, feasibility, etc., a balance between manning and automation can be found that will best suit the design for future operations.

PSYSM = propulsion option based from PGM selection
NT = total crew size
NO = number of officers
NE = number of enlisted
NA = additional accommodations
LWL = length of waterline

PGM.xx.## = power generation module option
Maint = maintenance or automation level
CMan = manning factor
ASW = anti-submarine option
ASUW = anti-surface option
CCC = C4I option

```
If ((PGM.GT.4.and.PGM.lt.9).or.(PGM.GT.16)) then
                    PSYSM=1
Elseif (PGM.lt.5.or.(PGM.gt.12.and.PGM.lt.17)) then
                    PSYSM=2
Else
                    PSYSM=3
END IF

NT = INT(360.-ASW*8.328125-(-6.0232*CMan+7.0174)*39.85031-
        Maint*7.703488+(LWL/161.24)*13.73633+ASW*Maint*3.203125 -Maint*CCC*1.676841*ASUW*CCC**2*.4738692-
        (LWL/161.26)*PSYSM**2*.2832031+
        (-6.0232*CMan+7.0174)**2*CCC*.2432359)

NOS = INT(.07*NT)
If (NOS .GT. 23) then
          NO=NOS
Else
          NO=23
END IF

NE=NT-NO
NA=INT(.1*NT)
```

Fugure XX: Manning Calculation

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

AAW system Alternatives are listed in Table 8. Anti-air warfare options for CGXmod include varying degrees of volume search radar capability with more plus signs (+) indicating a more capable system. Missile capacities are listed under Guided Missile Launching System (GMLS) options.

The SPY-3 and Volume Search radars (Figure 8) are integrated into the AEGIS combat system to create an envelope of horizon and over-horizon radar ability, collectively known as a Dual Band Radar (as the SPY-3 operates in the X-band and the VSR operates in the S-band frequencies). With 3-D capability, distance, speed, direction, and other pertinent target information is quickly gathered and distributed to the appropriate personal and systems through AEGIS.

The Infrared Search and Track sensors provide an additional ability to detect heat signatures on the horizon with an ability to adjust elevation.

The SLQ-32(R) antenna provides yet another set of eyes to help detect signatures and emitted radar while the MK36 Super Rapid Blooming Offboard Chaff system and NULKA missile decoy system provides defensive measures for the ship.

Table 8: AAW System Design Variable Options

DV #	DV Name	Description	Design Space
19	AAW	Anti-Air Warfare alternatives	Option 1) SPY-3/VSR +++ DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA
			Option 2) SPY-3/VSR ++ DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA
			Option 3) SPY-3/VSR + DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA
			Option 4) SPY-3/VSR (DDG-1000 3L) DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA

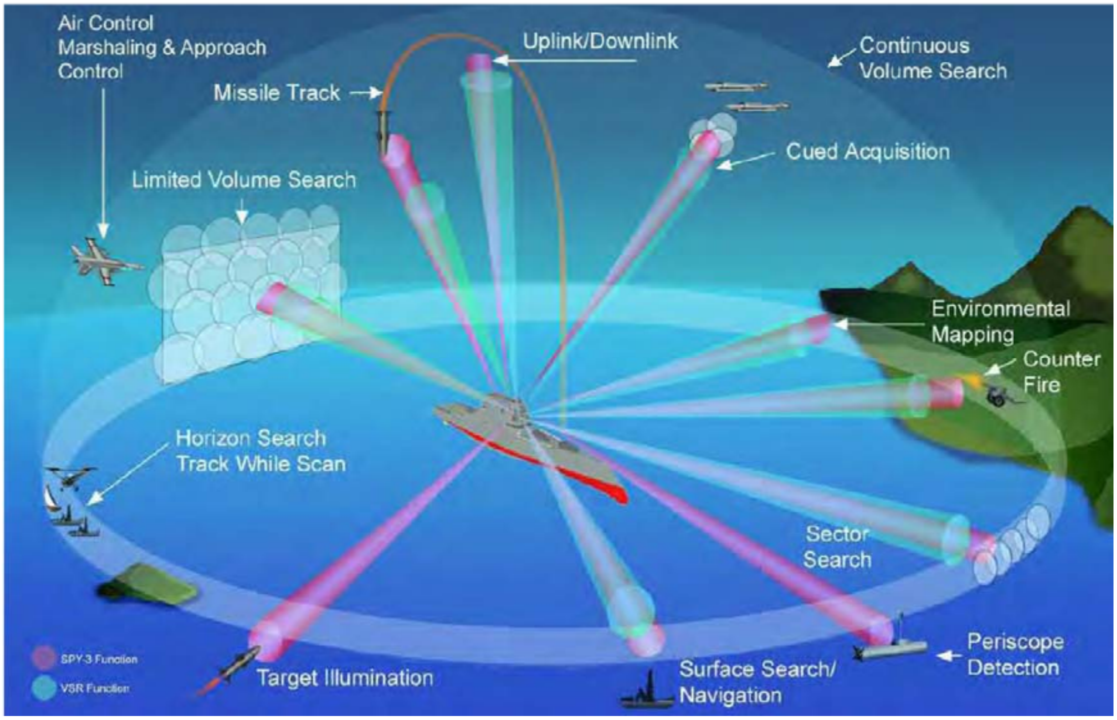


Figure 8: Depiction of Dual Band Radar Capabilities

3.1.4.2 **ASUW**

ASUW system alternatives are listed in Table 9. Naval guns are an effective and inexpensive means of anti-surface warfare and providing naval gunfire support. For CGXmod, three primary gun systems are considered along with smaller anti-surface weapons.

The 155m Advanced Gun System is planned for DDG-1000 and should provide a new era in naval guns through new munitions, automation, faster fire rates, and smart munition delivery. The MK45 5” gun has a proven track record and is currently the gun of choice for DDG-51s and CG-47s. Lastly, the MK110 57mm gun, which is currently installed on LCS-1, provides a 220 round per minute fire rate and 17 km range.

The SPS-73 provides a backup navigation and surface search capability, and the Thermal Imaging Sensory System and Forward Looking Infrared Radar provide short-range 2-D view of the battlefield along with information like bearing and speed of threats. Information is fed into the Gun Fire Control System, which is also tied into and part of the larger AEGIS system, to provide effective firing solutions.

The 7 meter Rigid Hull Inflatable Boats, small arms, and MK 46 Close-in Gun System provide close range security for CGXmod, while the RHIBs also provide an effective means for search and rescue and other potential short-range surface missions.

Table 9: ASUW/NSFS Design Variable Options

DV #	DV Name	Description	Design Space
20	ASUW / NSFS	Anti-Surface Warfare / Naval Surface Fire Support alternatives	Option 1) 1 x 155m AGS, SPS-73, Small Arms, TISS, FLIR, GFCS, 2 x 7m RHIB, MK46 Mod 1 2x CIGS
			Option 2) 1 x MK45 5"/62 Gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2 x 7m RHIB, MK46 Mod 1 2x CIGS
			Option 3) 1 x MK110 57mm Gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2 x 7m RHIB, MK46 Mod 1 2x CIGS

Figure 9: Thermal Imaging Sensor System (TISS)

Figure 10: Forward Looking Infared Radar (FLIR)

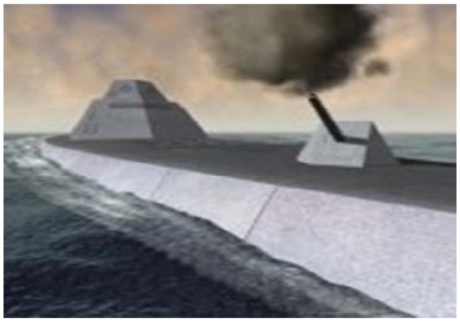


Figure 11: 155mm Advanced Gun System

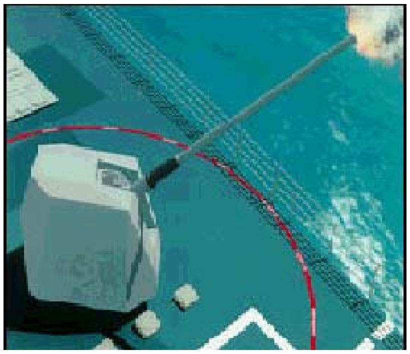


Figure 12: MK45 62 caliber

Figure 13: 7m RHIB

3.1.4.3 **ASW**

ASW system options are listed in Table 10. As the emerging threat of submarines escalates as diesel and AIP submarines provide a relatively cheap and effective means for foreign navies to combat the U.S. Navy's surface fleet, anti-submarine warfare continues to be important.

For Options 1 through 3, a ship sonar is installed on the bow, along with the Mine-Hunting Sonar. The Dual Frequency Array provides the most capable and most flexible system, while the SQS-53C provides moderate abilities, and the SQS-56 provides less abilities when compared to the SQS-53C. The Integrated Undersea Warfare system provides control and interpretation of signals from the bow mounted sonar and relays information to the AEGIS system.

The Tactical Towed Array System provides the ability to search for undersea contacts while maintaining distance from the ship self noise in an improved acoustic environment. The NIXIE towed decoy emits signals in an attempt to lure a hostile torpedo from the ship. Lastly, the Surface Vessel Torpedo Tubes provide a means to fire at undersea targets independent of LAMPS.

Table 10: ASW Design Variable Options

DV #	DV Name	Description	Design Space
21	ASW	Anti-Submarine Warfare alternatives	Option 1) Dual Frequency Bow Array, ISUW, NIXIE, 2 x SVTT, Mine-Hunting Sonar
			Option 2) SQS-53C, NIXIE, SQR-19 TACTAS, ISUW, 2 x SVTT, Mine-Hunting Sonar
			Option 3) SQS-56, NIXIE, ISUW, 2 x SVTT, Mine-Hunting Sonar
			Option 4) NIXIE, 2 x SVTT, Mine-Hunting Sonar

Figure 14: Render of NIXIE Decoy Array

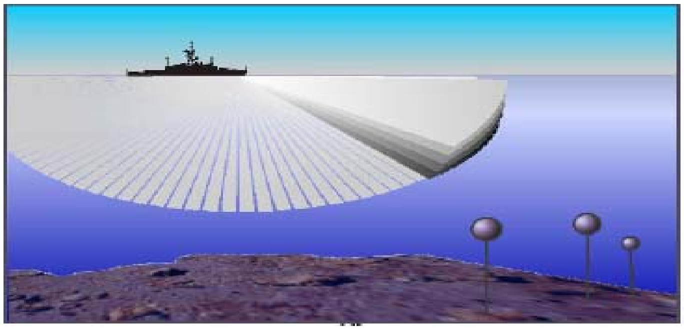


Figure 15: Mine hunting sonar searching for threats

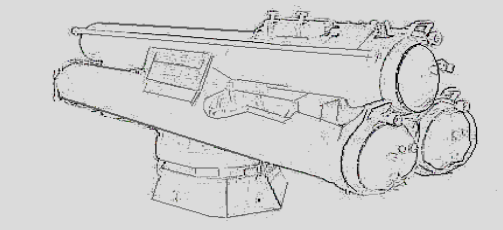


Figure 16: MK32 SVTT

3.1.4.4 C4I

Table 11 lists C4I system options. Command, control, communications, computers, and information systems (C4I) are an integral part of a ship at sea, especially a ship who's mission will require it to act as a control center for a battle group and as an individual for various missions.

For this design, two C4I systems and their components were considered. The basic version consists of a conventional install of present day ships, but with updated hardware, software, interface, etc. as required by the chosen systems of the design. The enhanced version expands on the basic system by providing additional service capabilities, thus providing increased effectiveness but at a greater expense.

Table 11: C4I Design Variable Options

DV #	DV Name	Description	Design Space
22	CCCCI	Command Control Communication Computer Intelligence alternatives	Option 1) Enhanced C4I
			Option 2) Basic C4I (CG 47)

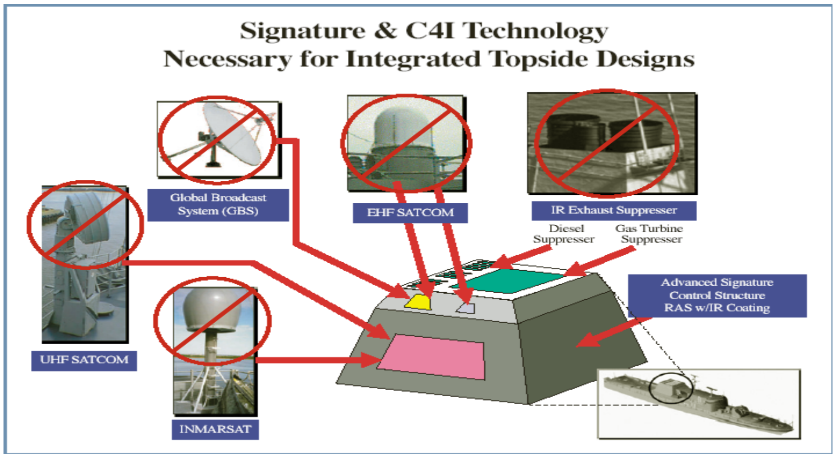


Figure 17: Example of a Multi-function Stack

3.1.4.5 GMLS

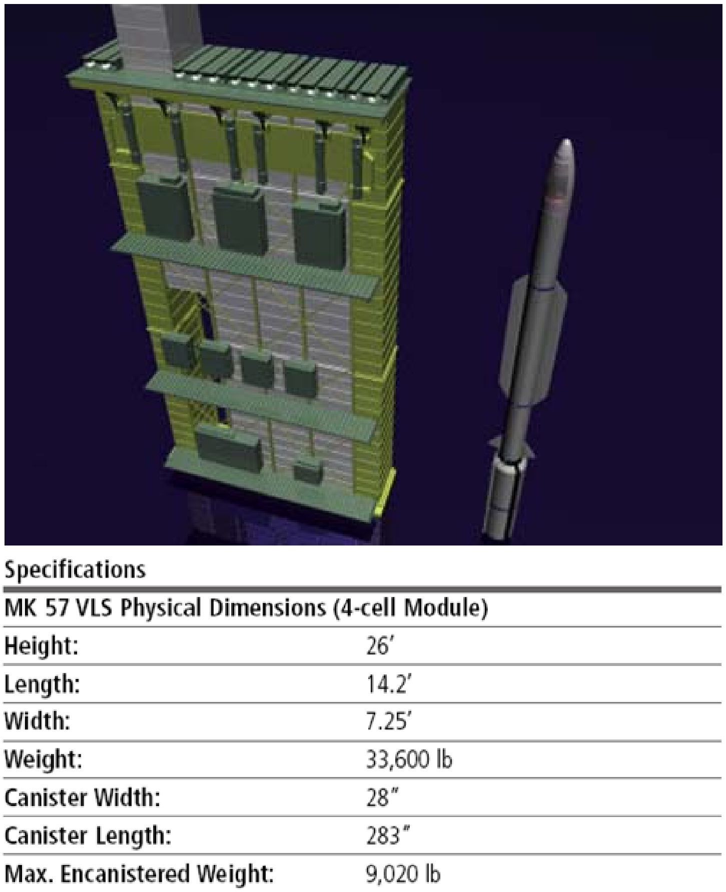
The Guided Missile Launching System (GMLS) is the primary means through which naval ships project firepower. Several types of missiles fit into the launch tubes supporting anti-submarine, anti-surface, anti-air and strike capabilities. GMLS options are listed in Table 12.

Only the MK57 VLS is considered for CGXmod. MK57 four-cell modules will be grouped into two separate batteries forward of the deckhouse to make the most of useable deck-space and to allow for structural adequacy. Although peripheral launch systems were also considered, their distributed locations and questions surrounding the survivability and producibility of this alternative increase their potential cost and risk.

Table 12: GMLS Design Variable Options

DV #	DV Name	Description	Design Space
24	GMLS	Guided Missile Launching System alternatives	Option 1) 192 cells, MK57 VLS
			Option 2) 160 cells, MK57 VLS
			Option 3) 144 cells, MK57 VLS
			Option 4) 128 cells, MK57 VLS

Figure 18: MK41 VLS Cluster



Specifications

MK 57 VLS Physical Dimensions (4-cell Module)	
Height:	26′
Length:	14.2′
Width:	7.25′
Weight:	33,600 lb
Canister Width:	28″
Canister Length:	283″
Max. Encanistered Weight:	9,020 lb

Figure 19: MK 57 Four-cell Module

3.1.4.6 LAMPS

To further increase mission effectiveness, capability, and adaptability, helicopters offer the potential to vastly expand a ship's capability. The U.S. Navy's Light Airborne Multi-Purpose System (LAMPS) is widely accepted and supported by the fleet and other defense services, making it a low cost, low risk, effective option for short, vertical operations. Like the GMLS, aviation options are able to perform multi-mission functions. Table 13 lists LAMPS design variable options.

The first two options provide a substantial increase in cost and effectiveness as the hanger addition and embarked helicopters add services and structure to the ship at the expense of added weight and usable volume. The last option provides basic services with a flight deck, basic aviation services, and basic maintenance/refuel capabilities. The inability to effectively embark a helicopter substantially decreases cost and effectiveness.

SH-60's can be equipped with multiple munitions and sensors to combat against ship, mine, torpedo, submarine, small boat, and ship threats while providing search and rescue, recon, security/protection, and various other capabilities to enhance ship effectiveness.

Table 13: LAMPS Design Variable Options

DV #	DV Name	Description	Design Space
23	LAMPS	LAMPS alternatives	Option 1) Embarked with Two SH-60s with Hangar
			Option 2) Embarked with Single SH-60 with Hangar
			Option 3) Helicopter haven (flight deck only)

Figure 20: SH-60 Seahawk in flight

3.1.4.7 Unmanned Vehicles

As is apparent by their widespread implementation, unmanned vehicles are important to the future in war fighting. The ability to project power or to gather intelligence without risking life has proved to be extremely valuable to all the services. The U.S. Navy has developed, tested, and is using several styles of vehicles with numerous capabilities under water, on the surface, and in the air. Although this design did not specifically explore using unmanned vehicles as part of its weapon systems, a modular ship will allow for easier implementation of such vehicles into its arsenal as the future will almost certainly require this design to support unmanned vehicles.

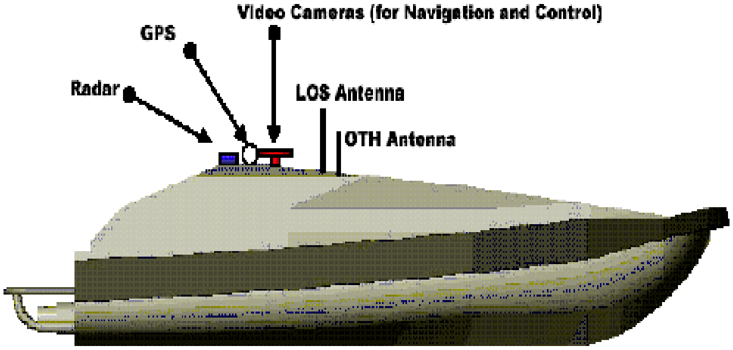


Figure 21: Spartan USV

Figure 21: VTAUV primed for take-off

3.1.4.8 Combat Systems Payload Summary

To ensure correct weights and loads for the various combat system components, and to allow flexibility in alternative options by allowing various system components to be selected, a spreadsheet or summary of available components is needed. Extensive research has allowed this data to be compiled over this year and past years with corrections being made to weights, loads, etc. as options are changed. A summary of the design's selected options are summarized in Table 14.

Table 14: Combat System Ship Synthesis Characteristics

NAME	DV	Weight (MT)	Hull Area (m2)	Deckhouse Area (m2)	Electric Load - Cruise (KW)	Electric Load - Battle (KW)
SPS-73 SURFACE SEARCH RADAR	ASUW	0.24	0	6.50	0.2	0.2
SMALL ARMS AND PYRO STOWAGE	ASUW	5.94	18.86	0	0	0
SMALL ARMS AMMO - 7.62MM + 50 CAL + PYRO	ASUW	4.17	0	0	0	0
THERMAL IMAGING SENSOR SYSTEM - TISS	ASUW	0.13	0	0	0	1
FLIR	ASUW	0.16	1	0	0	1.5
GFCS	ASUW	0.76	0	13.94	12.3	42.7
3 X 30MM CIGS GUN	ASUW	2.5	0	0	0	0
SWBS 187 2 X 30MM CIGS GUN FOUNDATION	ASUW	9	0	0	0	0
3 X CIGS SYSTEMS	ASUW	16.94	23.84	0	20	40
3 X CIGS HOIST EXTENTIONS	ASUW	0.89	0	0	0	0
3 X CIGS AMMO HOIST	ASUW	0.45	0	0	0	0
3 X CIGS CASE CAPTURE	ASUW	4.96	0	0	0	0
3 X 30MM CIGS GUN AMMO	ASUW	4.29	0	0	0	0
2 X 7M RHIB	ASUW	7	38.02	0	0	0
1X MK45 5IN/62 GUN	ASUW	37.39	26.48	0	36.6	50.2
MK45 5IN AMMO - 600 RDS	ASUW	33.63	65.5	0	0	0
MK45 5IN/62 GUN HY-80 ARMOR LEVEL II	ASUW	20.52	0	0	0	0
PVLS NON-STRUCTURE FRAG ARMOR 144 CELLS	GMLS	171	0	0	0	0
PVLS FOUNDATIONS 144 CELLS	GMLS	48.4	0	0	0	0
PVLS COOLING UNIT-VLS MAG 144 CELLS	GMLS	47.58	0	0	0	0
PVLS COOLING EQUIPMENT OP FLUIDS 144 CELLS	GMLS	21.98	0	0	0	0
PVLS 144 CELLS	GMLS	503.14	1520	0	579.68	579.68
PVLS MISSLE HANDLING	GMLS	0.25	0	0	0	0
PVLS LOADOUT 144 CELLS	GMLS	265.9	0	0	0	0
TOTAL SHIP COMPUTING ENVIR SYSTEM	CCC	73.38	763.6	0	435.68	435.68
ENHANCED RADIO/EXCOMM	CCC	51	0	265	227.89	228.19
TOMAHAWK WEAPON CONTROL SYSTEM	CCC	5.70	0	0	11.5	11.5
UNDERWATER COMMUNICATIONS	CCC	2.88	0	0	0	0
VISUAL & AUDIBLE SYSTEMS	CCC	0.32	0	0	0	0
SECURITY EQUIPMENT SYSTEMS	CCC	0.88	0	0	0	0
DUAL FREQUENCY BOW ARRAY STRUCTURE	ASW	22.5	0	0	0	0
DUAL FREQUENCY BOW ARRAY SONAR ELEX	ASW	26.73	104.2	0	94.3	94.3

DUAL FREQUENCY BOW ARRAY HULL DAMPING	ASW	10.1	0	0	0	0
MINEHUNTING SONAR	ASW	2.1	21	0	3.7	3.7
ISUW - INTEGRATED UNDERSEA WARFARE SYS	ASW	4.88	0	0	19.5	19.5
SQR-19 TACTAS	ASW	23.67	43.94	0	26.6	26.6
AN/SLQ-25 NIXIE	ASW	3.66	15.98	0	3	4.2
BATHYTHERMOGRAPH	ASW	2.63	0	0	0	0
TORPEDO DECOYS	ASW	5.09	46	0	2.4	2.4
C+S OPERATING FLUIDS	ASW	72.31	0	0	0	0
2X MK32 SVTT ON DECK	ASW	2.74	0	0	0.6	1.1
6 X MK46 LIGHTWEIGHT ASW TORPEDOES	ASW	1.38	0	0	0	0
VOLUME SEARCH RADAR [S BAND]- VSR+	AAW	256	0	393	2714	2714
GLYCOL WATER COOLING SYSTEM FOR VSR+	AAW	98.76	0	183	2300	2300
AN/SPY-3 MFR - MULTIPLE MODE RADAR	AAW	75.71	0	108.68	382.7	382.7
GLYCOL WATER COOLING SYSTEM SPY-3 MFR / EWS	AAW	22.92	0	25.14	300	300
AEGIS BMD 2014 COMBAT SYSTEM AND CIC	AAW	17.62	184.78	0	74.5	74.5
CIFF-SD	AAW	4.47	0	0	2.7	2.4
MK53 NULKA DECOY LAUNCHING SYSTEM - DLS	AAW	0.82	0	0	0	0
MK 36 SRBOC DECOY LAUNCHING SYSTEM - DLS	AAW	3.06	0	0	0	0
EWS - ACTIVE ECM - SLQ/32R	AAW	9.88	0	6.5	0.32	0.32
IRST - INFRARED SENSING & TRACKING	AAW	0	0	0	0	0
DUAL HELO/UAV DET - 2X SH60R HANGAR UPPER	LAMPS	0	0	266.9	0	0
DUAL HELO/UAV DET - 2X SH60R HANGAR LOWER	LAMPS	0	0	266.9	0	0
DUAL HELO/UAV DET - FUEL SYSTEM	LAMPS	21	0	2.77	0	0
DUAL HELO/UAV DET - HNDLG/SUPPORT/MAINT	LAMPS	0	0	34.1	0	0
DUAL HELO/UAV DET - RAST/RAST CONTROL	LAMPS	0	44.4	0	0	0
DUAL HELO/UAV DET-HANDLING/SERVICE/STOWAGE	LAMPS	26.04	0	0	0	0
DUAL HELO/UAV DET - MAGAZINE HANDLING	LAMPS	0.001	0	0	0	0
DUAL HELO/UAV DET - MAGAZINE 12-MK46 24-HELLFIRE 6-PENQUIN	LAMPS	0.001	0	57.46	0	0
DUAL HELO/UAV DET - VTUAV	LAMPS	3.47	0	0	0	0
DUAL HELO/UAV DET - 2X SH60R	LAMPS	10.66	0	0	0	0
DUAL HELO/UAV DET - SUPPORT/SPARES	LAMPS	0	0	158.08	0	0
SONOBOUY MAGAZINE STOWAGE - NONE IN PARENT	LAMPS	0.001	0	0	0	0
SONOBOUY MAGAZINE - 300 BUOYS - 88 MARKERS	LAMPS	0.001	0	10.12	0	0
SQQ-28 LAMPS MK III ELECTRONICS	LAMPS	3.52	0	0	5.3	5.5
LAMPS MKIII:AVIATION FUEL [JP-5]	LAMPS	65.43	0	0	0	0

3.1.5 Modularity

In an attempt to lower costs, improve performance, and to achieve a more flexible platform, modularity was specifically directed to be considered for CGXmod. The proven idea, as seen with the German MEKO design, has allowed for a nearly infinite combinations of mission and operational platforms while reducing cost, decreasing build time, and increasing flexibility. Due to varying definitions of modularity types, it is important to provide the definitions that this team used:

- Raft – entire deck or platform installed as a unit.
- Track - system of beams either welded or bolted to the deck for a particular mission area in a grid. Beams provide numerous attachment points by a bolted or locking mechanism. Mounts between the track and equipment are provided with ample mount configurations for all possible equipment in a mission space. Floor tiles lock directly into the track.
- Pallets - equipment or mission assemblies are pre-assembled and secured to a standardized pallet. Pallets are secured to the deck with bolts or other devices. The interfaces between pallet equipment and vessel are standardized to allow for changes, upgrades, or replacements to plug-and-play. A path for the pallet to be removed/installed should be provided in the vessel

- Component Modules - equipment is installed using conventional methods. Equipment is broken into modular sections with easily replaceable parts and standardized interfaces.
- Modular Spaces - standardized spaces that are pre-assembled with standardized interfaces for space and vessel connection. Spaces can contain a degree of modularity in them (as in re-configurable racks or shelves). Spaces are permanently secured to vessel.
- Conventional Install - equipment is installed with current methods.

Table 15: Modularity Design Variable Options

DV #	DV Name	Description	Design Space
25	C4IMOD	Computer Information Systems Compartment Modularity	Option 1) C4I Raft System
			Option 2) C4I Track System
			Option 3) Conventional Install
26	HMEMOD	Hull and Mechanical Spaces Modularity	Option 1) Mechanical Room Deck Rafts
			Option 2) HM&E Palletized
			Option 3) HM&E Component Modules
			Option 4) Conventional Install
27	HABMOD	Habitat/Living Quarters Modularity	Option 1) Habitat Track System
			Option 2) Modular Habitat Spaces
			Option 3) Conventional Install
28	WEAPMOD	Weapons Modularity	Option 1) Maximum Margin and Interface Connectivity
			Option 2) Minimum Margin and Interface Connectivity
			Option 3) Same/Similar Weapon Only Modularity
			Option 4) Conventional Install
29	SENSMOD	Sensor Systems Modularity	Option 1) Modular Sensors
			Option 2) Modular Mast
			Option 3) Conventional Install

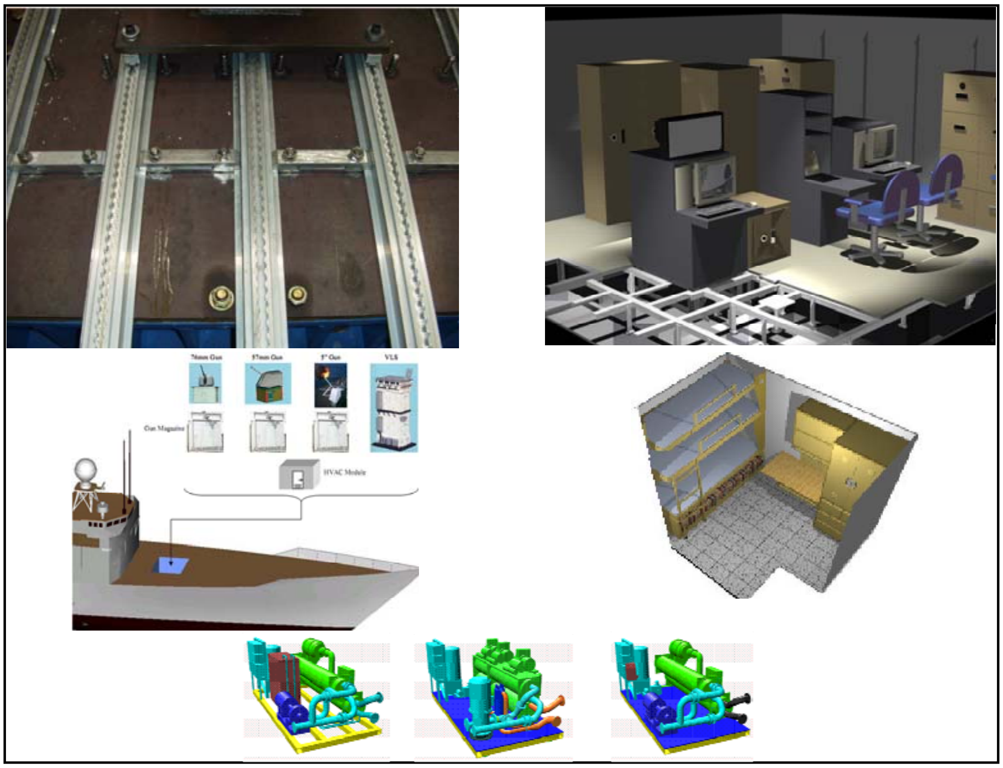


Figure 22: Modular Concepts (Provided by Gryphon Technologies)

In Weapons Interface Modularity the degree of standardized interface can include additional space/structure around the weapons install, and significant service margins. Sensor modularity may include a modular mast where the mast is reconfigurable and upgradable with emphasis on data, electrical, cooling, and structure. Modular sensors are secured to mast by bolts or other method and plug into standardized interfaces, using only the services they need.

To simplify the CGXmod modularity design and decision mechanism for concept exploration, the following general systems/spaces were chosen: weapon systems, sensory/mast system, C4I spaces, habitat/living spaces, and machinery spaces. Professional opinion was gathered from various members of Gryphon Technologies and faculty at Virginia Tech through the use of a pairwise comparison questionnaire that provided a performance assessment of modularity options. Estimated differences in weight, space, electrical loads, performance, effectiveness, cost and risk were incorporated into the synthesis, cost and risk models for the modularity options listed in Table 15. Figure 22 illustrates a number of these concepts.

3.2 CGXmod Design Space

In addition to technology options described in Section 3.1, hull and deckhouse characteristics (DVs 1 through 9), Provisions Duration, Collective Protection System, Degaussing System, and Manning factor (DVs 15 through 18) were also considered. Table 16 list all DVs considered in the CGXMod design.

Table 16: CGXmod Design Variables (DVs)

DV #	DV Name	Description	Design Space
1	LWL	Waterline Length	550 - 700 ft. (150-200m)
2	LtoB	Length to Beam ratio	7.9-9.9
3	LtoD	Length to Depth ratio	10.75-17.8
4	BtoT	Beam to Draft ratio	2.9-3.2
5	Cp	Prismatic coefficient	0.56 - 0.64
6	Cx	Maximum section coefficient	0.75 - 0.84
7	Crd	Raised deck coefficient	0.7 - 0.8
8	VD	Deckhouse volume	100,000-150,000 ft3 (2800-4250m3)
9	Cdhmat	Deckhouse material	1 = Steel, 2 = Aluminum, 3 = Advanced Composite
10	PGM	Power Generation Module	Option 1) 3 x LM2500+, AC Synchronous, 4160 VAC
			Option 2) 3 x LM2500+, AC Synchronous, 13800 VAC
			Option 3) 4 x LM2500+, AC Synchronous, 4160 VAC
			Option 4) 4 x LM2500+, AC Synchronous, 13800 VAC
			Option 5) 2 x MT30, AC Synchronous, 4160 VAC
			Option 6) 2 x MT30, AC Synchronous, 13800 VAC
			Option 7) 3 x MT30, AC Synchronous, 4160 VAC
			Option 8) 3 x MT30, AC Synchronous, 13800 VAC
			Option 9) 4 x MT30, AC Synchronous, 4160 VAC
			Option 10) 4 x MT30, AC Synchronous, 13800 VAC
11	SPGM	Secondary Power Generation Module	Option 1) None
			Option 2) 2 x LM500G, Geared, AC Synchronous
			Option 3) 2 x CAT 3608 Diesels
			Option 4) 2 x PC 2.5/18 Diesels
			Option 5) 2 x MC3.0 Fuel Cells
			Option 6) 2 x MC4.0 Fuel Cells
			Option 7) 2 x PEM5.0 Fuel Cells
12	PROPtype	Propulsor Type	Option 1) 2 x Fixed Pitch Propellers
			Option 2) 2 x Fixed Pitch Propellers, 2 x Surface Piercing Unit (3 MW each)
13	DISTtype	Power Distribution Type	Option 1) AC Zonal Electrical Distribution System
			Option 2) DC Zonal Electrical Distribution System
14	PMM	Propulsion Motor Module	Option 1) Advanced Induction Motor (AIM)
			Option 2) Permanent Magnet Motor (PMM)
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	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 / Naval Surface Fire Support alternatives	Option 1) 1 x 155m AGS, SPS-73, Small Arms, TISS, FLIR, GFCS, 2 x 7m RHIB, MK46 Mod 1 3x CIGS
			Option 2) 1 x MK45 5"/62 Gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2 x 7m RHIB, MK46 Mod 1 3x CIGS
			Option 3) 1 x MK110 57mm Gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2 x 7m RHIB, MK46 Mod 1 3x CIGS
21	ASW	Anti-Submarine Warfare alternatives	Option 1) Dual Frequency Bow Array, ISUW, NIXIE, 2 x SVTT, Mine-Hunting Sonar
			Option 2) SQS-53C, NIXIE, SQR-19 TACTAS, ISUW, 2 x SVTT, Mine-Hunting Sonar
			Option 3) SQS-56, NIXIE, ISUW, 2 x SVTT, Mine-Hunting Sonar
			Option 4) NIXIE, 2 x SVTT, Mine-Hunting Sonar
22	C4I	Command Control Communication Computer Intelligence alternatives	Option 1) Enhanced C4I
			Option 2) Basic C4I
23	LAMPS	LAMPS alternatives	Option 1) Embarked with Two LAMPS w/Hangar
			Option 2) Embarked with Single LAMPS w/Hangar
			Option 3) LAMPS haven (flight deck)
24	GMLS	Guided Missile Launching System alternatives	Option 1) 192 cells, MK57 variant
			Option 2) 160 cells, MK57 variant
			Option 3) 144 cells, MK57 variant
			Option 4) 128 cells, MK57 variant
25	C4IMOD	Computer Information Systems Compartment Modularity	Option 1) C4I Raft System
			Option 2) C4I Track System
			Option 3) Conventional Install
26	HMEMOD	Hull and Mechanical Spaces Modularity	Option 1) Mechanical Room Deck Rafts
			Option 2) HM&E Palletized
			Option 3) HM&E Component Modules
			Option 4) Conventional Install
27	HABMOD	Habitat/Living Quarters Modularity	Option 1) Habitat Track System
			Option 2) Modular Habitat Spaces
			Option 3) Conventional Install
28	WEAPMOD	Weapons Modularity	Option 1) Maximum Margin and Interface Connectivity
			Option 2) Minimum Margin and Interface Connectivity
			Option 3) Same/Similar Weapon Only Modularity
			Option 4) Conventional Install
29	SENSMOD	Sensor Systems Modularity	Option 1) Modular Sensors
			Option 2) Modular Mast
			Option 3) Conventional Install

3.3 Ship Synthesis Model

The ship synthesis model was integrated and run in Phoenix Integration's Model Center (MC). The MC model is comprised of different FORTRAN ship synthesis modules which were adapted and developed specifically for the CGXmod design from previous ship design modules. Each module receives variable input values from the Input module or from preceding modules, and runs the module's FORTRAN code to calculate output variable values for use by subsequent modules. Figure 23 shows the synthesis model in MC. The boxes represent modules, which proceed from top left to bottom right, and the arrows represent variables passed from module to module. Integrating the model in Model Center enables linking of the various multi-disciplinary ship synthesis modules, objective modules (cost, effectiveness and risk), a specific system and ship characteristics Input module, a Multi-Objective Genetic Optimizer (MOGO), and a Gradient Optimizer (GO). During optimization, the optimizer sends inputs values to the Input module for each design assessed in the design space, and receives outputs from the cost, risk, feasibility, and effectiveness modules. For the initial concept exploration, the MOGO searches the design space by selecting hundreds of designs for each of hundreds of generations, thus completing thousands of assessments, to identify non-dominated designs in a design space of millions of possible designs. After identifying the non-dominated designs, an initial baseline design is selected and improved using the GO.

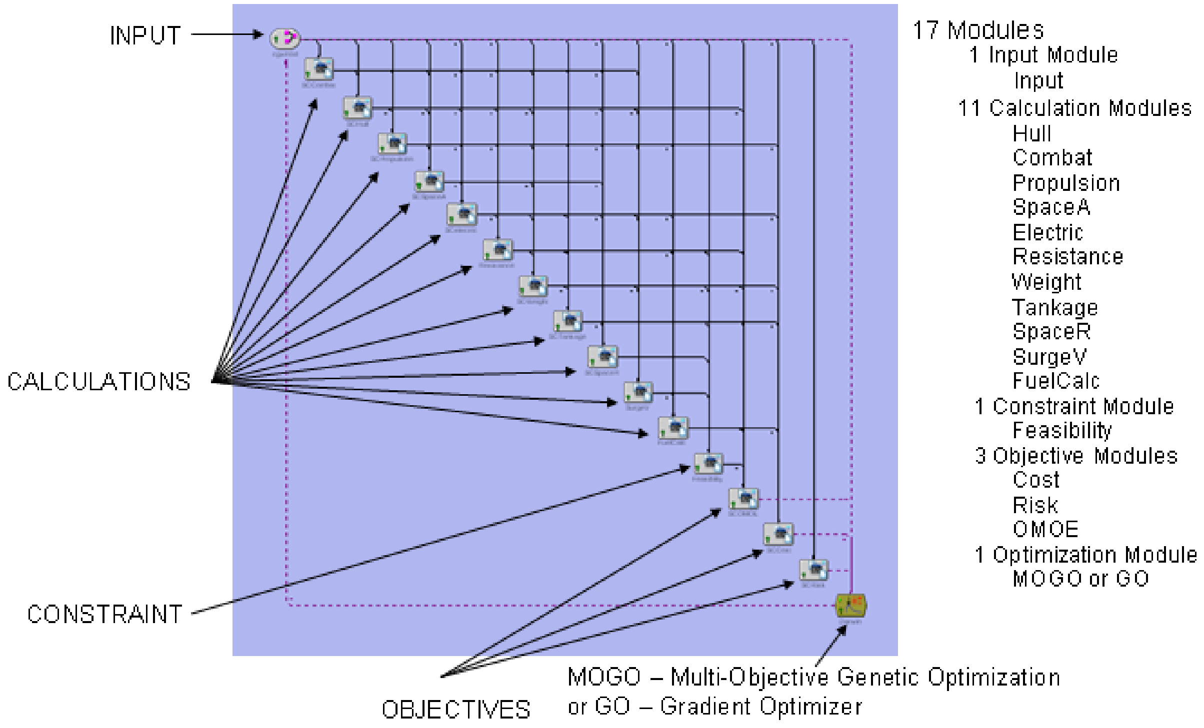


Figure 23 - Ship synthesis Model in Model Center

- **Input Module** – stores and provides design variable and design parameter values for use by the other modules. This module is also tied to the optimizer. During optimization runs, optimizer outputs provide new inputs for the Input Module.
- **Combat Systems Module** – inputs values for the discrete combat system options and extracts data for these options from the CS data spreadsheet. It calculates and sums combat system weights, vertical centers of gravity, deckhouse and hull area, and required electric power using this data.
- **Propulsion Systems Module** – inputs values for the discrete power and propulsion options and extracts data for these options from the Propulsion System data spreadsheet. It calculates required areas and volumes for machinery rooms and intake/exhaust stacks, propulsion systems weights and centers, and various efficiencies.
- **Hull Systems Module** – inputs LBP and various hull characteristic ratios, and calculates hull principal characteristics, hull volume, displacement, surface area and other coefficients.
- **Space Available Module** – calculates available volume and arrangeable area from hull characteristics and deckhouse volume. Calculates machinery room length and minimum height from propulsion system characteristics and required volume. Calculates freeboard forward and aft based on DDS079-2 requirements. Calculates minimum depth at midships based on heeling, structural and machinery requirements.
- **Electric System Module** – inputs combat system power requirements and calculates other ship service power requirements using regression-based equations. Calculates required manning using the response surface model described in Section 3.3.3.
- **Resistance Module** - uses Holtrop-Mennon residual resistance and ITTC ’57 frictional resistance models to calculate Effective Horsepower at endurance speed and sustained speed.

- **Weight & Stability Module** – inputs combat system and propulsion system weights. Calculates other system and load weights and centers using regression-based equations and adjusts weights for selected modularity options. Sums weights. Subtracts total weights less propulsion fuel from displacement to calculate propulsion fuel weight. Fuel weight is used in the Tankage Module to calculate endurance range which must satisfy the minimum threshold requirement for feasibility. This is the slack variable in the weight balance calculation. Calculates KG and BM, estimates KB, and calculates GM to assess initial stability.
- **Space-Required Module** – calculates requirements for volume and arrangeable area using inputs from other modules, habitability requirements and regression-based equations. Adjusts for selected modularity options.
- **Surge Module** – Calculates maximum sustained speed for transit to theater without refueling using DDS200-1 margins and procedures. Calculates required EHPs for speeds specified in the annual speed/time profile.
- **Fuel Calculation Module** – Calculates SFCs and fuel consumption for various engine configurations and part-loads required at speeds in the specified annual speed/time profile. Calculates the total annual fuel consumption barrels per year based on this profile.
- **Tankage Module** – calculates propulsion fuel tankage volume and other tankage using liquid load weights from the Weight Module. Calculates endurance range based on DDS200-1 margins and procedures. Calculates the number of refuelings required to transit to theater at sustained speed.
- **Feasibility Module** – compares available area, volume, electric power, stability, and performance to requirements and thresholds. All of these requirements must be satisfied for feasibility.
- **Cost Module** - uses complexity, modularity and producibility factors and weight based equations to estimate the cost of lead ship acquisition, follow ship acquisition, life cycle costs, and total ownership cost as described in Section 3.4.3.
- **Effectiveness Module** - The effectiveness module calculates OMOE as described in Section 3.4.1.
- **Risk Module** – Technology risk impacting performance, schedule, and cost is considered in this module as described in Section 3.4.2. Based on expert opinion, a risk register (Figure 28) is developed considering each design variable and its options including automation, and their potential risk. An Overall Measure of Risk (OMOR) metric is calculated.

3.4 Objective Attributes

3.4.1 Overall Measure of Effectiveness (OMOE)

Overall Measure of Effectiveness (OMOE) is a single overall figure of merit index from 0 to 1.0 calculated using Equation (1), where VOP_i represents Value of Performance functions for each Measure of Performance (MOP), normalized from zero to one and developed using expert opinion; and W_i are weighting factors also calculated using expert opinion. The OMOE describes CGXmod overall effectiveness in its required missions.

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

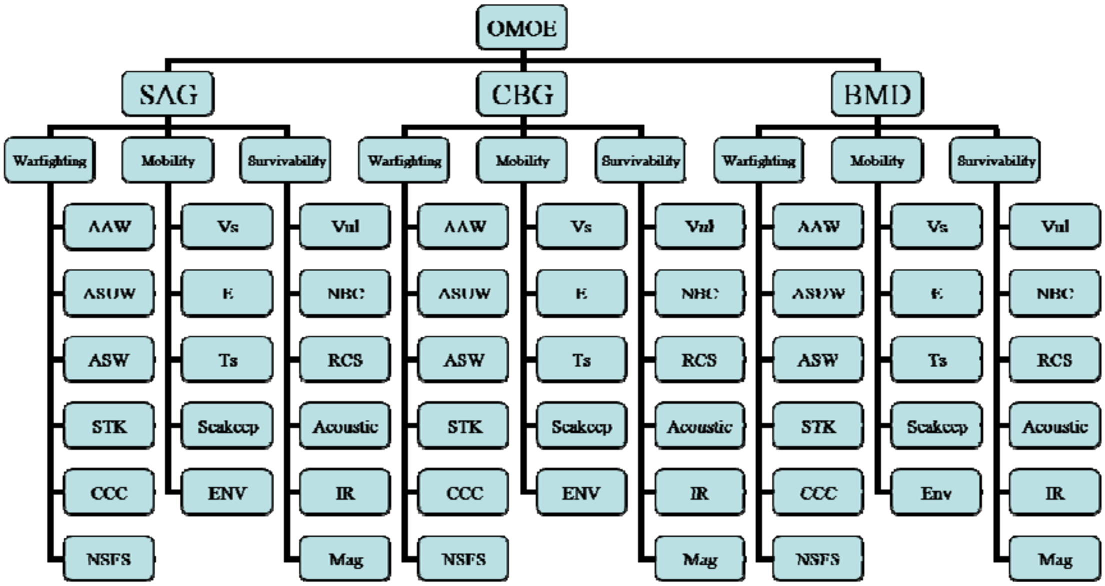


Figure 24: OMOE Hierarchy

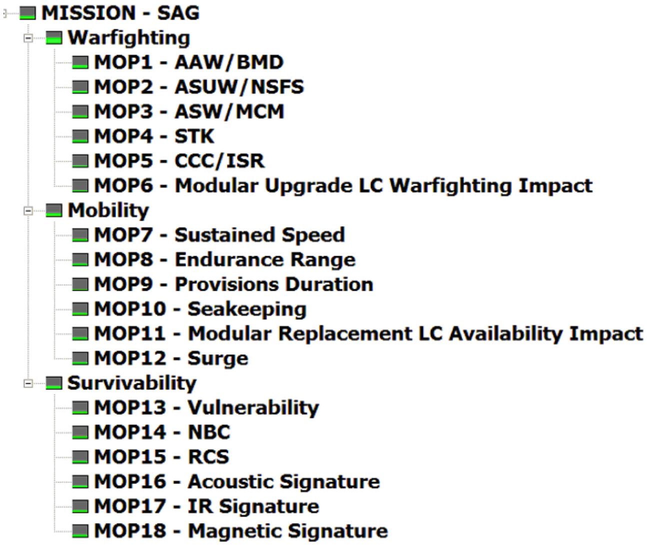
The OMOE metric should consider MOPs, defense policy and goals, threats, environment, missions, mission scenarios, and the force structure. Ideally the OMOE metric would be developed using simulation or master war-gaming models to estimate effectiveness in a series of probabilistic mission scenarios. However, this extensive modeling capability does not yet exist for practical applications, and effectiveness must be modeled using alternative methods. Possible alternatives are to use expert opinion, Multi-Attribute Utility Theory (MAUT), Analytical Hierarchy Process (AHP), Multi-Attribute Value Theory (MAVT), additive MAVT, or to blend these methods.

Table 14 - MOP Table

MOP #	MOP	Metric	Goal	Threshold
1	AAW / BMD	AAW Option	AAW = 1	AAW = 4
		GMLS Option	GMLS = 1	GMLS = 4
		C4I Option	C4I = 1	C4I = 2
2	ASW	ASW Option	ASW =1	ASW = 4
		LAMPS Option	LAMPS=1	LAMPS = 3
		C4I Option	C4I =1	C4I = 2
3	ASUW / NSFS	ASUW Option	ASUW=1	ASUW = 4
		LAMPS Option	LAMPS=1	LAMPS = 3
		C4I Option	C4I =1	C4I = 2
4	C4I	C4I Option	C4I=1	C4I = 2
5	STK	GMLS Option	GMLS=1	GMLS = 2
		C4I Option	C4I=1	C4I = 2
6	Sustained Speed	knt	Vs = 35knt	Vs = 30 knt
7	Endurance Range	nm	E = 8000 nm	E = 5000 nm
8	Provisions Duration	days	Ts = 75 days	Ts = 60 days
9	Seakeeping	McCreight Index	McC = 15	McC = 4
10	NBC	CPS Option	NCPS = 1	NCPS = 1
11	Radar Cross Section	m^3	VD = 11000 m^3	VD = 15000 m^3
12	Acoustic Signature	SPGM	SPGM = 5, 6, 7	SPGM = 1
13	IR Signature	SPGM	SPGM = 5, 6, 7	SPGM = 2
14	Magnetic Signature	Ndegaus	Ndegaus = 1	Ndegaus = 0
15	Modularity for Upgrade	C4I Option	C4I = 2	C4I = 3
		HM&E Option	HM&E = 1	HM&E = 4
		SENS Option	SENS = 1	SENS = 3
		HAB Option	HAB = 1	HAB = 2
		WEAP Option	WEAP = 1	WEAP = 4
16	Modularity for Replacement	C4I Option	C4I = 2	C4I = 3
		HM&E Option	HM&E = 1	HM&E = 4
		SENS Option	SENS = 1	SENS = 3
		HAB Option	HAB = 1	HAB = 3
		WEAP Option	WEAP = 1	WEAP = 4
17	Surge	knt	Vsur = 25 knt	Vsur = 20 knt
18	Vulnerability	Cdhmat	Cdhmat = 1	Cdhmat = 3

Our approach uses expert opinion to integrate these diverse inputs, and assess the value or utility of CGXmod MOPs for a given mission, force, threat, etc. This is accomplished using AHP and additive MAVT to calculate MOP weights and value functions, and assemble the OMOE function. The main advantage of using AHP is that it works well with quantitative and qualitative characteristics, and AHP provides feedback on consistency and sensitivity of the results.

The AHP process begins by identifying MOPs (Table 14), based on CGXmod ROCs and DVs, which are critical to CGXmod missions, with goal and threshold values for each. The MOPs are organized in a hierarchy, and pair wise comparison and AHP are used to calculate MOP weights and develop value (or utility) functions for each MOP, normalized with goal VOPs = 1.0 and threshold VOPs = 0.0. Figures 24 and 25 show the OMOE hierarchy and Figure 26 is an example of the questionnaires used for pairwise comparison. Figure 27 shows the resulting MOP weights.



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

- MOP1 - AAW/BMD
  - AAW Options
    - AAW Option 1
    - AAW Option 2
    - AAW Option 3
    - AAW Option 4
  - GMLS Options
    - GMLS Option 1
    - GMLS Option 2
    - GMLS Option 3
    - GMLS Option 4
  - CCC Options
    - CCC Option 1
    - CCC Option 2

Figure 25: Portion of OMOE Hierarchy with Individual Options Used in Pairwise Comparison

1	C4I Modularity Options	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	HM&E Modularity Options
2	C4I Modularity Options	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Habitability Modularity Options
3	C4I Modularity Options	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Weapons Modularity Options
4	C4I Modularity Options	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Sensors/Topside Modularity Options
5	HM&E Modularity Options	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Habitability Modularity Options
6	HM&E Modularity Options	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Weapons Modularity Options
7	HM&E Modularity Options	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Sensors/Topside Modularity Options
8	Habitability Modularity Options	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Weapons Modularity Options
9	Habitability Modularity Options	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Sensors/Topside Modularity Options
10	Weapons Modularity Options	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Sensors/Topside Modularity Options

Figure 26: Part of CGXmod pairwise questionnaire

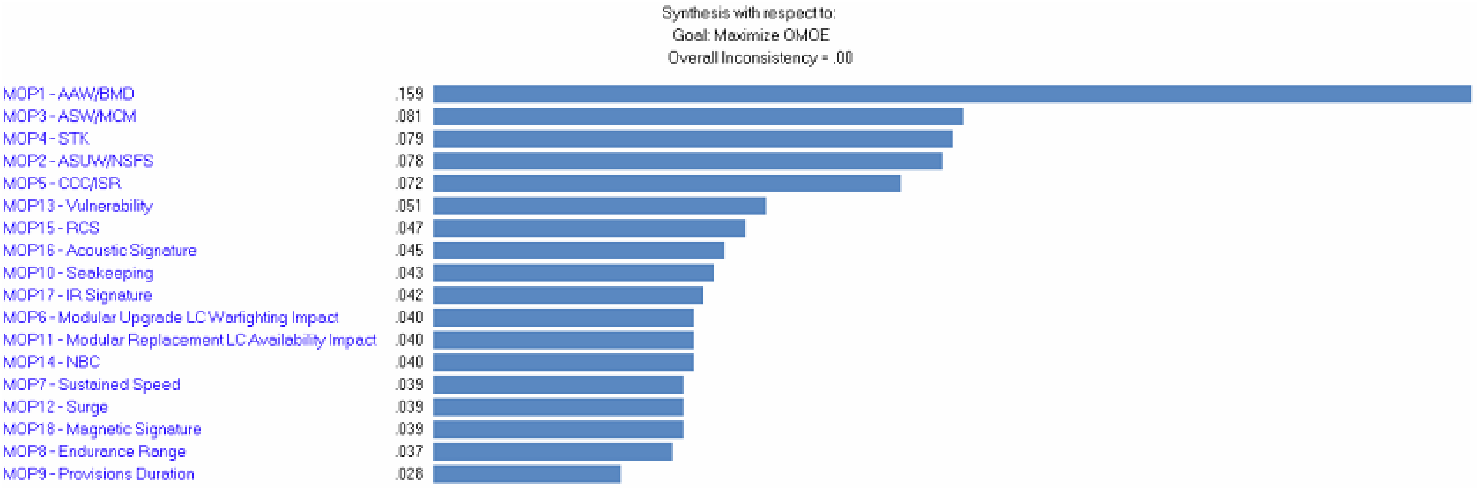


Figure 27: CGXmod MOP Weights

3.4.2 Overall Measure of Risk (OMOR)

There are three types of technology risk considered in this design: performance, cost, and schedule. Performance risks are any risks that may cause a decrease in ship performance. Cost risks are risks that will likely increase the cost to construct and operate the ship over the ships life. Schedule risks are risks that could increase the production time of a ship. The basic equation for risk is Equation (2). Here P_i is the probability that the risk event i will occur and C_i is the consequence of the risk event i.

$$R_i = P_i \cdot C_i \tag{2}$$

Risk events are identified for all Design Variable technology options. Estimates are made for P_i and C_i using Tables 15 and 16, and used to calculate risk for each event. These risk events are listed in a Risk Register, Figure 28.

Table 15 – Probability of Occurrence 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 3 - 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%

XXXXXX

Figure 28: CGXmod Risk Register

Finally, Equation (3) is used to calculate the overall measure of risk for CGXmod. The constants W_{perf}, W_{cost}, W_{sched} are the weighting factors of risks for performance, cost, and scheduling. The other variables, P and C, are the probably of occurrence and consequence of occurrence for each technology risk event identified in the Risk Register developed

$$OMOR = W_{perf} \frac{\sum_i P_i C_i}{\sum_i (P_i C_i)_{\max}} + W_{\mathrm{cost}} \frac{\sum_j P_j C_j}{\sum_j (P_j C_j)_{\max}} + W_{sched} \frac{\sum_k P_k C_k}{\sum_k (P_k C_k)_{\max}} \tag{3}$$

3.4.3 Cost

CGXmod costs are estimated using several inputs including SWBS group weights, total propulsive power, base year and inflation rate, annual fuel usage, manning, and rate of production. Adjustments are made to weight-based costs for system complexity, selected modularity options, and producibility. Estimated costs include: lead ship acquisition, follow-ship acquisition, and life-cycle cost. Acquisition cost is further broken down into government cost and shipbuilder cost as shown in Figure 29. Shipbuilder cost includes engineering and design, production support, and the physical construction of the ship. Government costs include government-furnished materials and outfitting the ship with auxiliary support systems and munitions.

Life-cycle costs include acquisition cost, fuel costs, intermediate maintenance, depot maintenance, upgrade, manning costs and expendables (Figure 30). All costs are discounted to the base year. For this project, the Base Year is 2013, with an average lead-ship inflation rate of 4%, an average follow-ship inflation rate of 3%, and a discount rate of 8%.

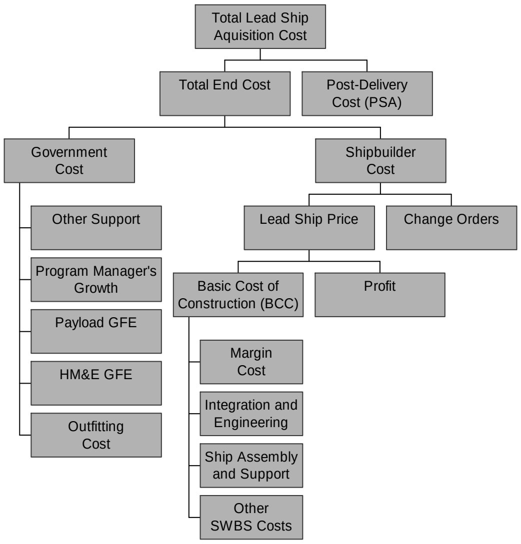


Figure 29: Naval Ship Acquisition Cost Components

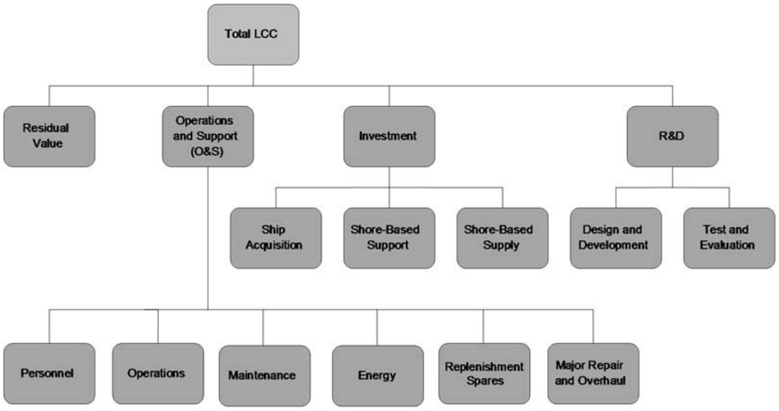


Figure 30: Naval Ship Life Cycle Cost Components

3.5 Multi-Objective Optimization

The Multi-Objective Genetic Optimization (MOGO) is executed in Model Center (MC) using the Darwin optimization plug-in as shown in Figure XXXX. The three objective attributes for this optimization are average follow ship acquisition cost, overall risk (OMOR) (technology performance, cost, and schedule risk), and overall effectiveness (OMOE). The objectives are developed as described in sections **Error! Reference source not found.**, 3.4.2 and **Error! Reference source not found.**. The optimization is constrained by the feasibility module outputs, and the design space is defined as in Table 16. In the first design generation, the optimizer defines 200 balanced ships at random from the design space using the MC ship synthesis model to balance each design and quantify feasibility, cost, effectiveness, and risk. Each of the designs in this generation is ranked according to its fitness or dominance in the three objectives compared to the other designs in the population. When infeasibility or niching (bunching-up) in the design space occurs, penalties are assigned to the corresponding design. The second design generation of the optimization process is randomly selected from the first design generation, with higher probabilities of selection assigned to higher-fitness designs. Twenty-five percent of this second design generation is selected for crossover or swapping of design variable values. An even smaller percentage of randomly selected design variable values are then mutated or replaced with a new value at random. This process is repeated up to 300 times, and as each generation of ship designs is selected, the ship designs spread out and converge on the non-dominated frontier. Each ship design on the non-dominated frontier provides the highest effectiveness for a given cost and risk relative to other ship designs in the design space. The “best” design is determined by the customer’s preference for effectiveness, cost, and risk.

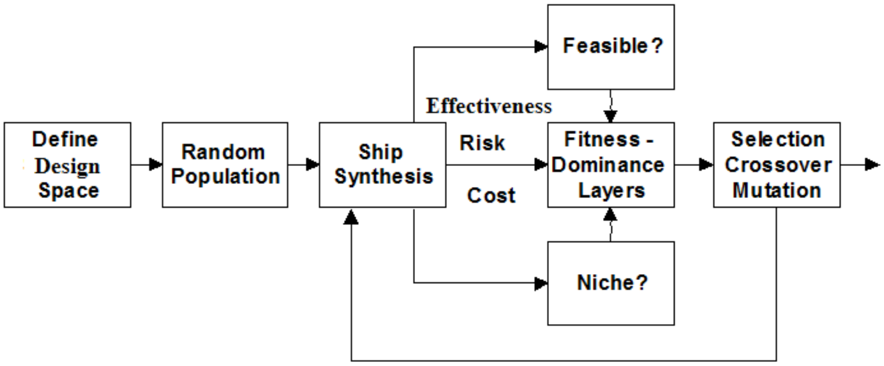


Figure XXXX – Multi-Objective Optimization (MOGO)

3.6 MOGO Results – Initial Baseline Design

The non-dominated optimization results from Model Center, based on total ownership cost, OMOE, and OMOR, are presented in Figure 31 and Figure 32. Figure 31 is a 3D representation of the non-dominated frontier (NDF) with total ownership cost in $M on the horizontal axis, OMOR and OMOE as labeled. The design selected as the CGXmod Initial Baseline Design is Variant #91 (circled in Figure 31), an obvious knee-in-the curve with high effectiveness, moderate risk, and moderate ownership cost. Variant #91 has an OMOE value of 0.907, an OMOR of 0.283, and a total ownership cost of $4.849 Billion. Figure 32 shows the NDF in 2D with total ownership cost on the horizontal axis, OMOE on the vertical axis and OMOR in color.

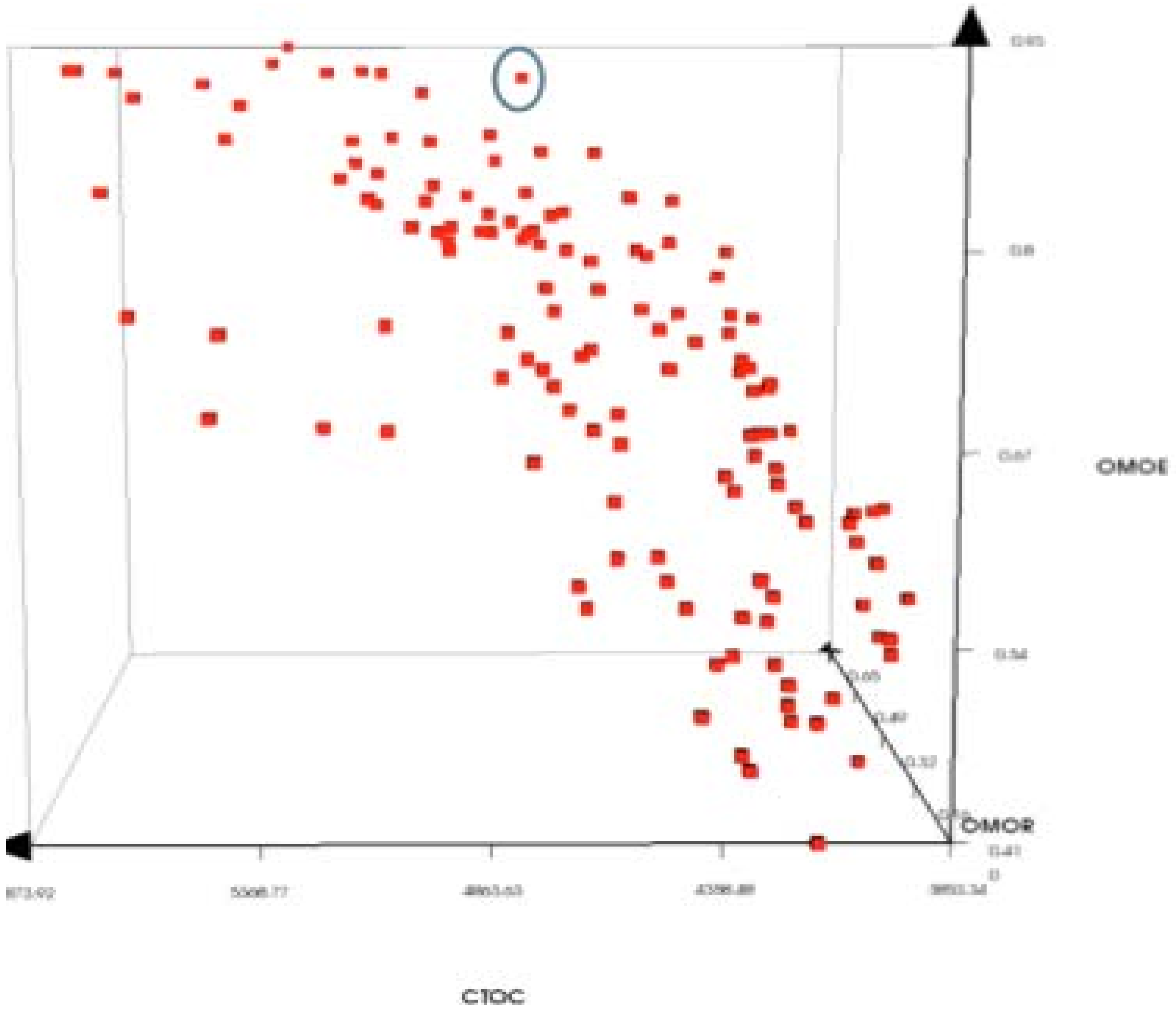


Figure 31: 3-D Representation of CGXmod Non-dominated Frontier (NDF)

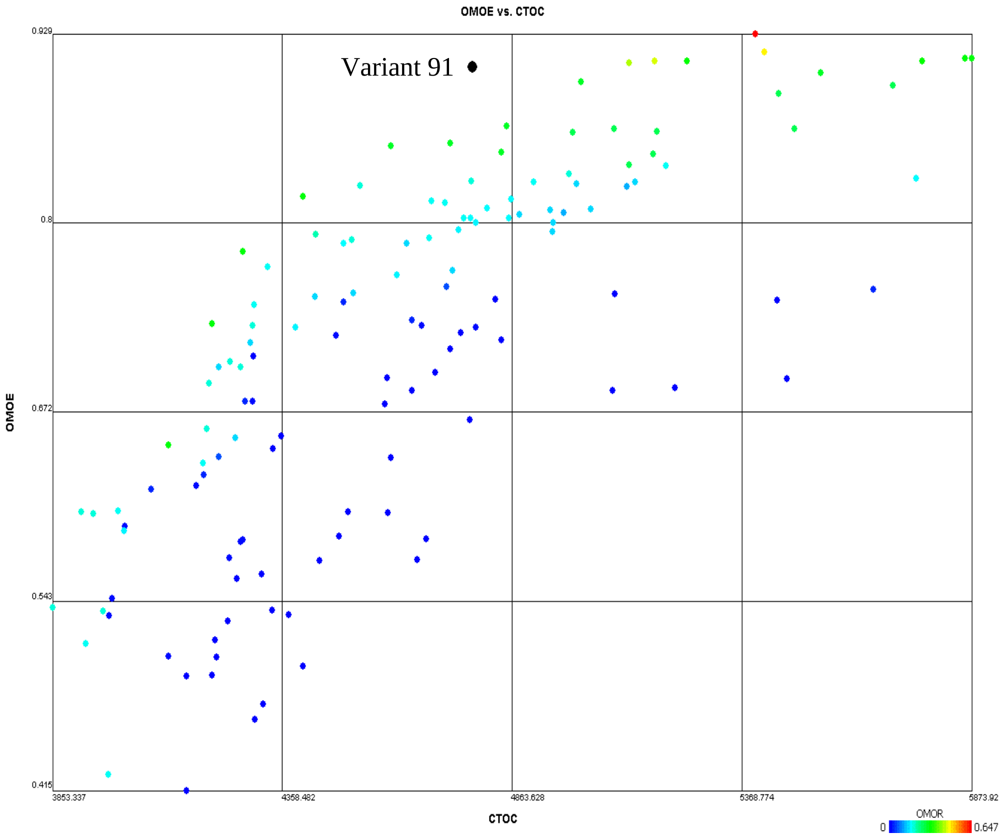


Figure 32: 2-D representation of NDF with OMOR in color

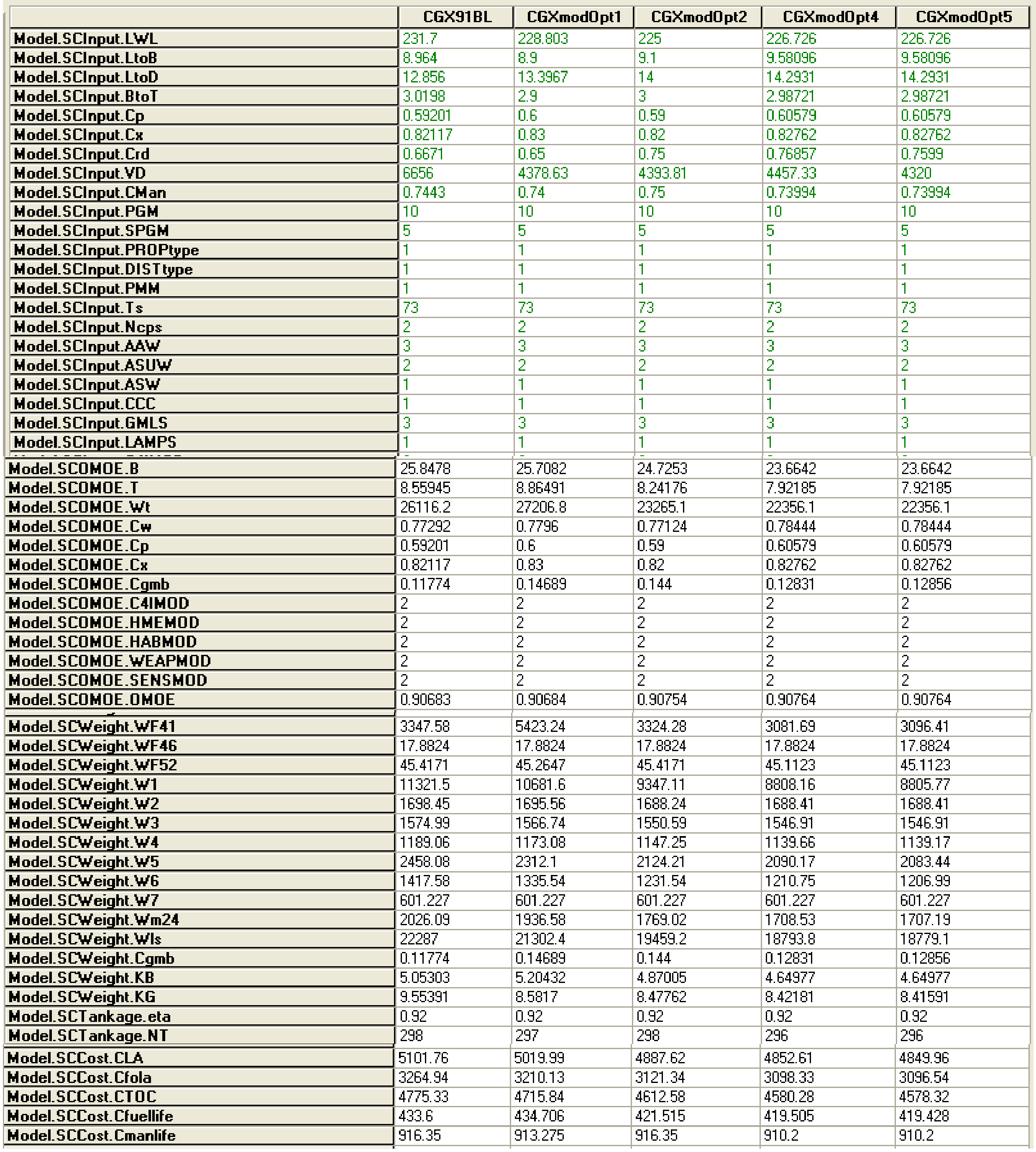
3.7 Gradient Optimizer – Improved Baseline Design

Next, with the Initial Baseline Design chosen, a single-objective gradient-based optimization was run, maximizing OMOE with cost and risk constraints equal to the baseline values, holding discrete system options at their baseline values, and varying only continuous design variables: hull principal characteristics, deckhouse volume and automation factor.

3.8 Improved Baseline Design – ASSET Feasibility Study

The Improved Baseline design characteristics were then entered into the NAVSEA's Advanced Surface Ship Evaluation Tool (ASSET) using the DDG-51 hull as a parent hull that would be scaled to correctly match the inputs. This tool would allow for more detailed calculations in resistance, structure, distributed loads of systems, fuel calculations, etc. while also allowing for primary machinery arrangement, bulkhead arrangement, deckhouse sizing, and other physical attributes. During its own synthesis process, ASSET and ModelCenter did not always agree, as in the case of resistance. For that particular case, MathCad and a resistive calculation code provided by Dr. Alan Brown was used to find that the ASSET numbers did not fully make sense (it is theorized that the amount of scaling, along with legacy coding in ASSET was not meant for such a large ship as CGXmod and thus found erroneous values). Other features, like the hullform and deckhouse, required tumblehoming and thus Rhio 3D was employed to revise the hull as the capability escaped both ModelCenter and ASSET. These examples provide a glance as the design team moved from their first semester of research and initial development into more detailed design.

Table XX – Gradient Optimization from Initial to Improved Baseline



	CGX91BL	CGXmodOpt1	CGXmodOpt2	CGXmodOpt4	CGXmodOpt5
Model.SCInput.LWL	231.7	228.803	225	226.726	226.726
Model.SCInput.LtoB	8.964	8.9	9.1	9.58096	9.58096
Model.SCInput.LtoD	12.856	13.3967	14	14.2931	14.2931
Model.SCInput.BtoT	3.0198	2.9	3	2.98721	2.98721
Model.SCInput.Cp	0.59201	0.6	0.59	0.60579	0.60579
Model.SCInput.Cx	0.82117	0.83	0.82	0.82762	0.82762
Model.SCInput.Crd	0.6671	0.65	0.75	0.76857	0.7599
Model.SCInput.VD	6656	4378.63	4393.81	4457.33	4320
Model.SCInput.CMan	0.7443	0.74	0.75	0.73994	0.73994
Model.SCInput.PGM	10	10	10	10	10
Model.SCInput.SPGM	5	5	5	5	5
Model.SCInput.PROPtype	1	1	1	1	1
Model.SCInput.DISTtype	1	1	1	1	1
Model.SCInput.PMM	1	1	1	1	1
Model.SCInput.Ts	73	73	73	73	73
Model.SCInput.Ncps	2	2	2	2	2
Model.SCInput.AAW	3	3	3	3	3
Model.SCInput.ASUW	2	2	2	2	2
Model.SCInput.ASW	1	1	1	1	1
Model.SCInput.CCC	1	1	1	1	1
Model.SCInput.GMLS	3	3	3	3	3
Model.SCInput.LAMPS	1	1	1	1	1
Model.SCOMOE.B	25.8478	25.7082	24.7253	23.6642	23.6642
Model.SCOMOE.T	8.55945	8.86491	8.24176	7.92185	7.92185
Model.SCOMOE.Wt	26116.2	27206.8	23265.1	22356.1	22356.1
Model.SCOMOE.Cw	0.77292	0.7796	0.77124	0.78444	0.78444
Model.SCOMOE.Cp	0.59201	0.6	0.59	0.60579	0.60579
Model.SCOMOE.Cx	0.82117	0.83	0.82	0.82762	0.82762
Model.SCOMOE.Cgmb	0.11774	0.14689	0.144	0.12831	0.12856
Model.SCOMOE.C4IMOD	2	2	2	2	2
Model.SCOMOE.HMEMOD	2	2	2	2	2
Model.SCOMOE.HABMOD	2	2	2	2	2
Model.SCOMOE.WEAPMOD	2	2	2	2	2
Model.SCOMOE.SENSMOD	2	2	2	2	2
Model.SCOMOE.OMOE	0.90683	0.90684	0.90754	0.90764	0.90764
Model.SCWeight.WF41	3347.58	5423.24	3324.28	3081.69	3096.41
Model.SCWeight.WF46	17.8824	17.8824	17.8824	17.8824	17.8824
Model.SCWeight.WF52	45.4171	45.2647	45.4171	45.1123	45.1123
Model.SCWeight.W1	11321.5	10681.6	9347.11	8808.16	8805.77
Model.SCWeight.W2	1698.45	1695.56	1688.24	1688.41	1688.41
Model.SCWeight.W3	1574.99	1566.74	1550.59	1546.91	1546.91
Model.SCWeight.W4	1189.06	1173.08	1147.25	1139.66	1139.17
Model.SCWeight.W5	2458.08	2312.1	2124.21	2090.17	2083.44
Model.SCWeight.W6	1417.58	1335.54	1231.54	1210.75	1206.99
Model.SCWeight.W7	601.227	601.227	601.227	601.227	601.227
Model.SCWeight.Wm24	2026.09	1936.58	1769.02	1708.53	1707.19
Model.SCWeight.Wls	22287	21302.4	19459.2	18793.8	18779.1
Model.SCWeight.Cgmb	0.11774	0.14689	0.144	0.12831	0.12856
Model.SCWeight.KB	5.05303	5.20432	4.87005	4.64977	4.64977
Model.SCWeight.KG	9.55391	8.5817	8.47762	8.42181	8.41591
Model.SCTankage.eta	0.92	0.92	0.92	0.92	0.92
Model.SCTankage.NT	298	297	298	296	296
Model.SCCost.CLA	5101.76	5019.99	4887.62	4852.61	4849.96
Model.SCCost.Cfola	3264.94	3210.13	3121.34	3098.33	3096.54
Model.SCCost.CTOC	4775.33	4715.84	4612.58	4580.28	4578.32
Model.SCCost.Cfuellife	433.6	434.706	421.515	419.505	419.428
Model.SCCost.Cmanlife	916.35	913.275	916.35	910.2	910.2

Table XXX – Comparison of Baseline Designs and ASSET Feasibility Results

Ship Characteristic	**Initial Baseline**	**Improved Baseline**	**ASSET Feasibility Study**
LWL		226.7 m	
Beam		23.7 m	
Draft		7.93 m	
D10		15.86 m	
Cp		0.606	
Cx		0.828	
Cwp		0.784	
W1			
W2			
W3			
W4			
W5			
W6			
W7			
Lightship weight w/ margin		18779 MT	
Full load weight		22356 MT	
Sustained Speed		34 knots	
Endurance Speed		20 knots	
Sprint Range		6000 nm	
Endurance Range		8875 nm	
Total BHP		150 MW	
Total Personnel		296	
OMOE (Effectiveness)		0.908	
OMOR (Risk)		0.285	
Initial Ship Acquisition Cost		$4.85 Billion	
Follow Ship Acquisition Cost		$3.09 Billion	
Life-Cycle Cost		$4.58 Billion	
Propulsion and Power	4 x MT30, 2 x MC3.0 Fuel Cells, AC synchronous IPS, 2 x FPP		
Power Generation	Option 10) 4 x MT30, AC Synchronous, 13800 VAC		
Secondary Power Generation	Option 5) 2 x MC3.0 Fuel Cells		
Propulsor Type	Option 1) 2 x Fixed Pitch Propellers		
Power Distribution Type	Option 1) AC Zonal Electrical Distribution System		
Propulsion Motor Module	Option 2) Permanent Magnet Motor (PMM)		
Anti-Air Warfare Option	Option 3) SPY-3/VSR + DBR, IRST, AEGIS BMD 2014 Combat System, CIFF-SD, SLQ/32(R) improved, MK36 SRBOC with NULKA		
Anti-Surface Warfare/Naval Fire Support Option	Option 2) 1 x MK45 5"/62 Gun, SPS-73, Small Arms, TISS, FLIR, GFCS, 2 x 7m RHIB, MK46 Mod 1 3x CIGS		
Anti-Submarine Warfare Alternative	Option 2) SQS-53C, NIXIE, SQR-19 TACTAS, ISUW, 2 x SVTT, Mine-Hunting Sonar		
C4I Option	Option 1) Enhanced C4I		
LAMPS Option	Option 1) Embarked with Two LAMPS w/Hangar		
GMLS Option	Option 3) 144 cells, MK57 variant		
C4I Modularity	Option 2) C4I Track System		
Hull and Mechanical Spaces Modularity	Option 2) HM&E Palletized		
Habitat/Living Spaces Modularity	Option 2) Modular Habitat Spaces		
Weapons Modularity	Option 2) Minimum Margin and Interface Connectivity		
Sensor Systems Modularity	Option 2) Modular Mast		

4 Concept Development

CGXmod Concept Development follows a more traditional design spiral as shown in Figure XX. In Concept Development the general 3D concepts for the hull, systems and arrangements are developed. These general concepts are refined in specific systems and subsystems that meet the CDD requirements. Design risk is reduced by this analysis and parametric equations used in Concept Exploration are validated. Starting with our Improved Baseline design we were able to go once around this spiral in the time we had with a few small excursions resulting in our Final Baseline design.

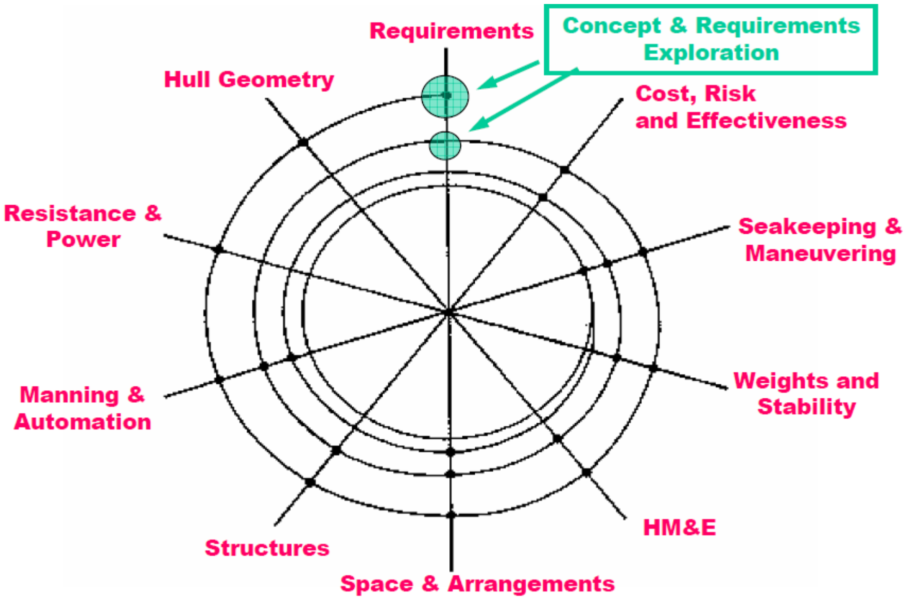


Figure 33: Concept Development Process

4.1 Preliminary Arrangement (Cartoon)

As a preliminary step in starting hull form geometry, deck house geometry, and arrangements, an arrangement cartoon was developed for areas supporting mission operations, propulsion, and other critical constrained functions. The preliminary cartoon is presented in Figure XX. The cartoon shows placement of major machinery and weapons systems as well as hullform shape.

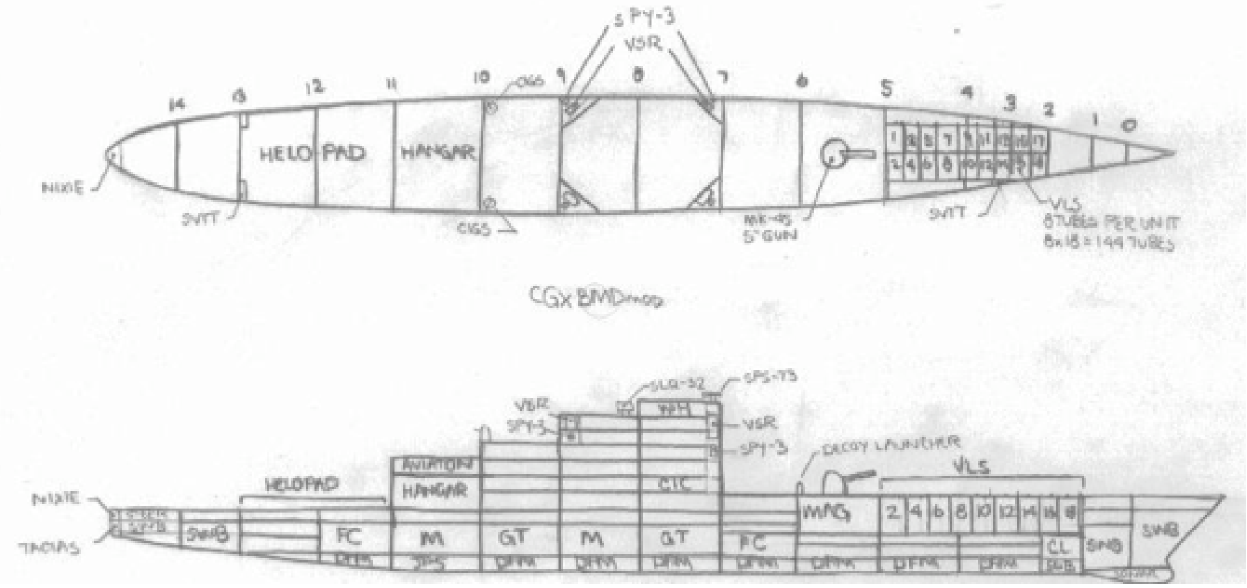


Figure 34: Preliminary Cartoon

4.2 Hull Form

4.2.1 Hullform

The CGXmod hullform is a hybrid tumblehome/flare design. A hybrid design is used to achieve desirable sea keeping characteristics while attempting to reduce radar cross-section. We used a DDG-51 hullform parent below the waterline with the CGXmod Improved Baseline principal characteristics, Table 16.

The ASSET Hull Geometry Module was used to create the initial hullform to the Improved Baseline principal characteristics, and this hullform was imported into the Rhino 3D modeling program. In Rhino, modifications were made to create the desired hybrid tumblehome/flare hull. The bow keeps its flare characteristics while the rest of the ship has a 10-degree tumblehome starting at a chine 3 meters above the design waterline. The tumblehome form continues into the deckhouse without discontinuity and around the back of the stern. A bulbous bow was also added to improve resistance characteristics and enclose the sonar transducers. The resulting hullform is shown in Figures 35 through Figure 37.

Table 16: CGXmod Improved Baseline Hullform Characteristics

Ship Characteristic	Value
LWL	226.7 m
Beam	23.7 m
Draft	7.93 m
D10	15.86 m
Cp	0.606
Cx	0.828
Cwp	0.784
Full Load Displacement	22356 MT

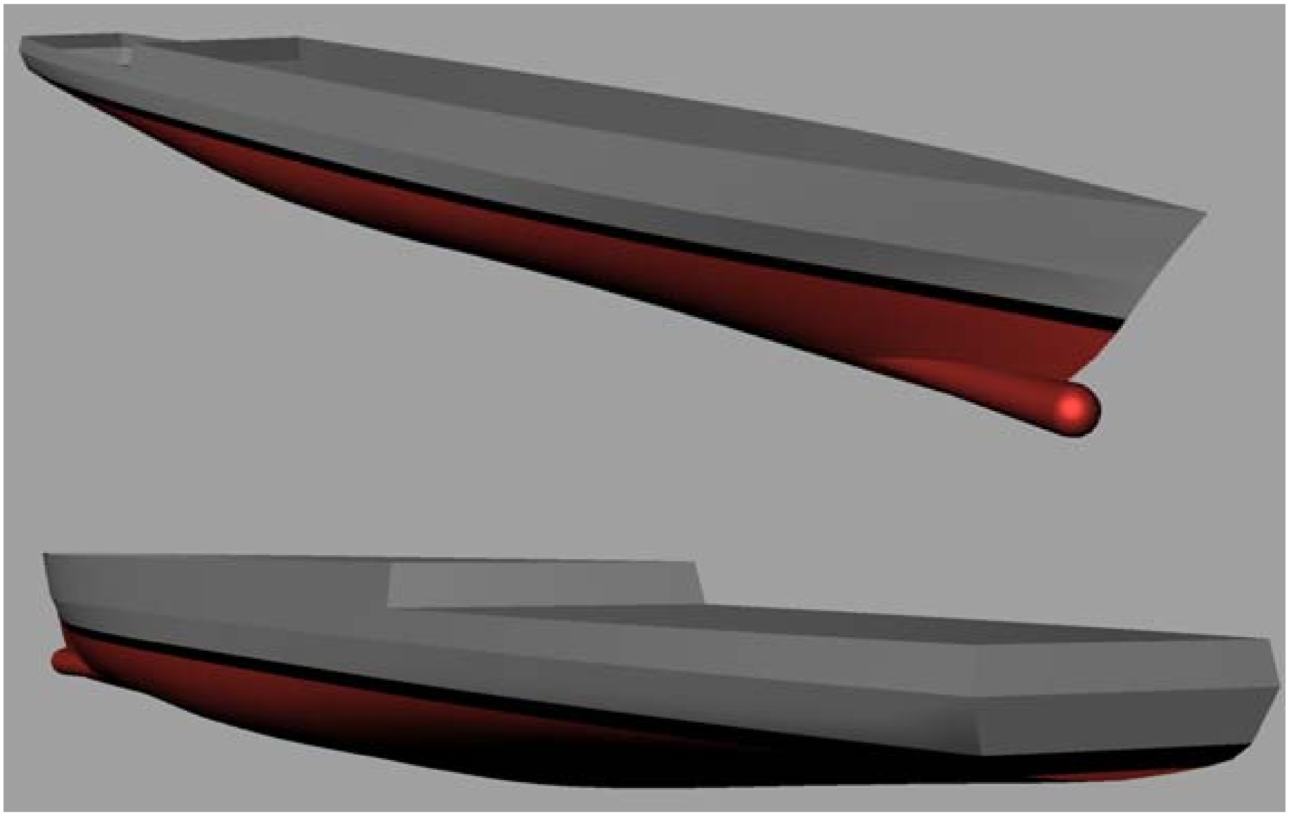


Figure 35: CGXmod Hullform

Figure 36: CGXmod Curves of Form

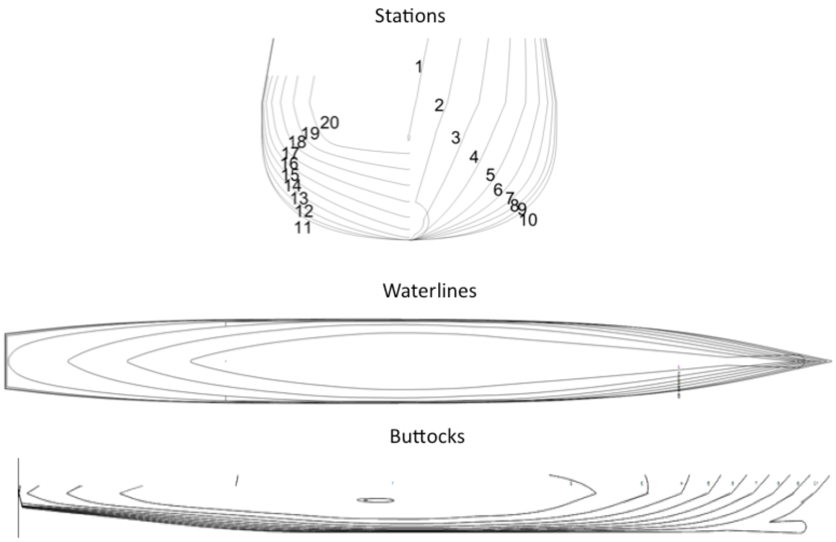


Figure 37 – Preliminary CGXmod Lines Drawing

4.2.2 Deck House

Figure 34 shows the preliminary deckhouse and Figure 38 shows the final CGXmod deckhouse. The highest level of the deckhouse contains the pilot house for visibility and control. Recent designs have moved the pilot house down to raise the radar arrays, but operator feedback indicates preference for the higher location.

The exhaust exits from the top of the deckhouse, while air is taken in along the sides of the highest continuous level. Alignment with MMRs? Hangar?

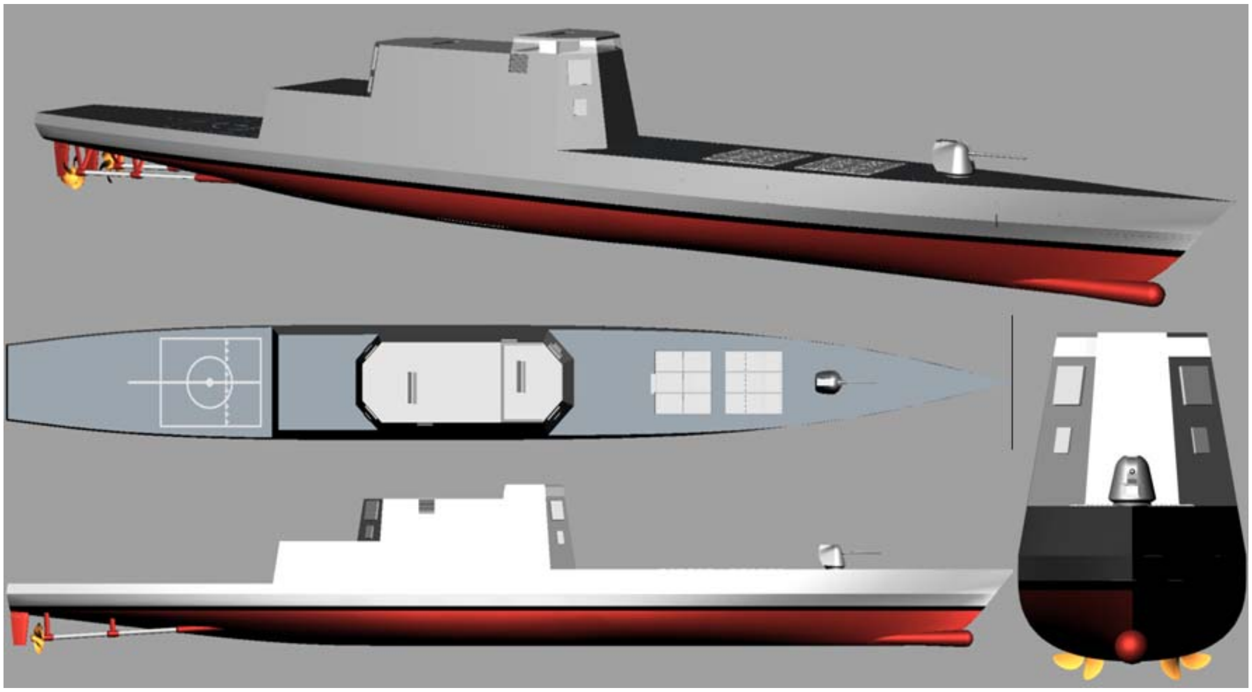


Figure 38– Deck House

4.3 Preliminary Subdivision, Tankage, Loads, Trim and Stability

Use your T17! It was good.

4.3.1 Transverse Subdivision

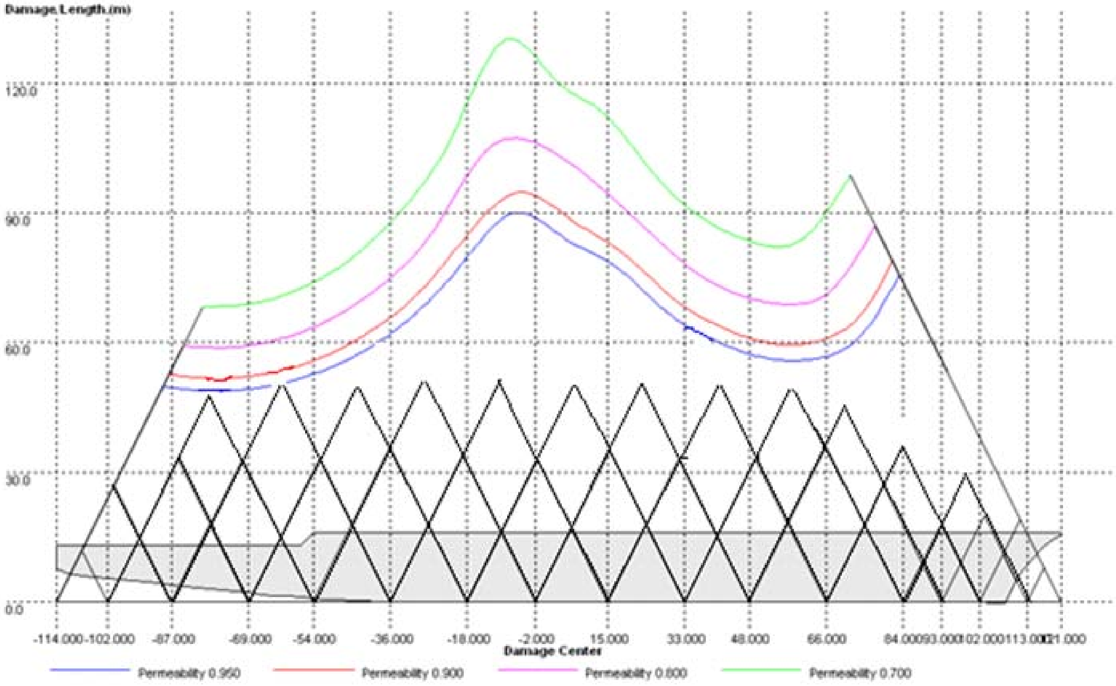


Figure 36: Floodable Length Curve

4.3.2 Tankage and Preliminary Load Conditions (Full Load and Minop)

Include loads, trim, intact stability –

4.4 Producibility and Ship Production

Use your T13! It was good.

4.5 Structural Design and Analysis

MAESTRO is a finite-element program used to analyze the structural effectiveness of ships. MAESTRO stands for **M**ETHOD for **A**NALYSIS, **E**VALUATION, and **STR**UCTURAL **O**PTIMIZATION. MAESTRO is a complete ship structural design system for the design of ocean structures. has rapid structural modeling, ship-based loading, finite element analysis, structural evaluation, optimization, fine mesh analysis, and natural frequency evaluation. The structural Design Process used with MAESTRO is shown in Figure 39.

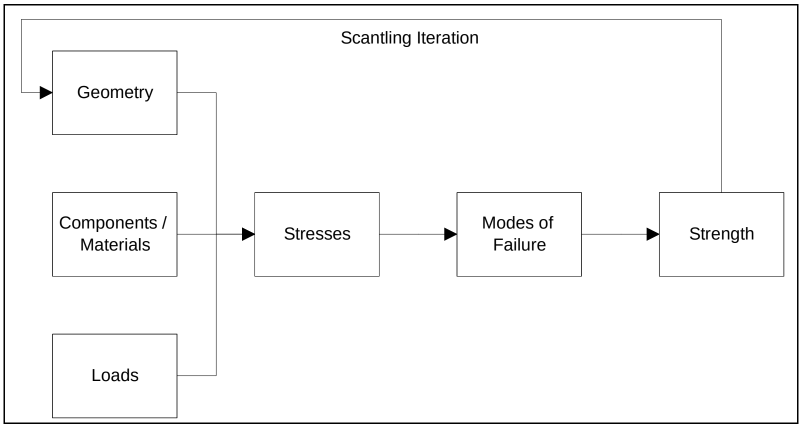


Figure 39 - Structural Design Process

4.5.1 Geometry, Components, and Materials

Initial scantlings and structural endpoint locations were taken from the ASSET structural model and input into MAESTRO to build the finite element model panel by panel with plating, stiffeners, frames and girders. The structure was built bow to stern using modules, 15 modules for the hull, and 3 for the deckhouse. The completed Finite Element model is shown in Figure 40. Material? – Add a table with material characteristics.

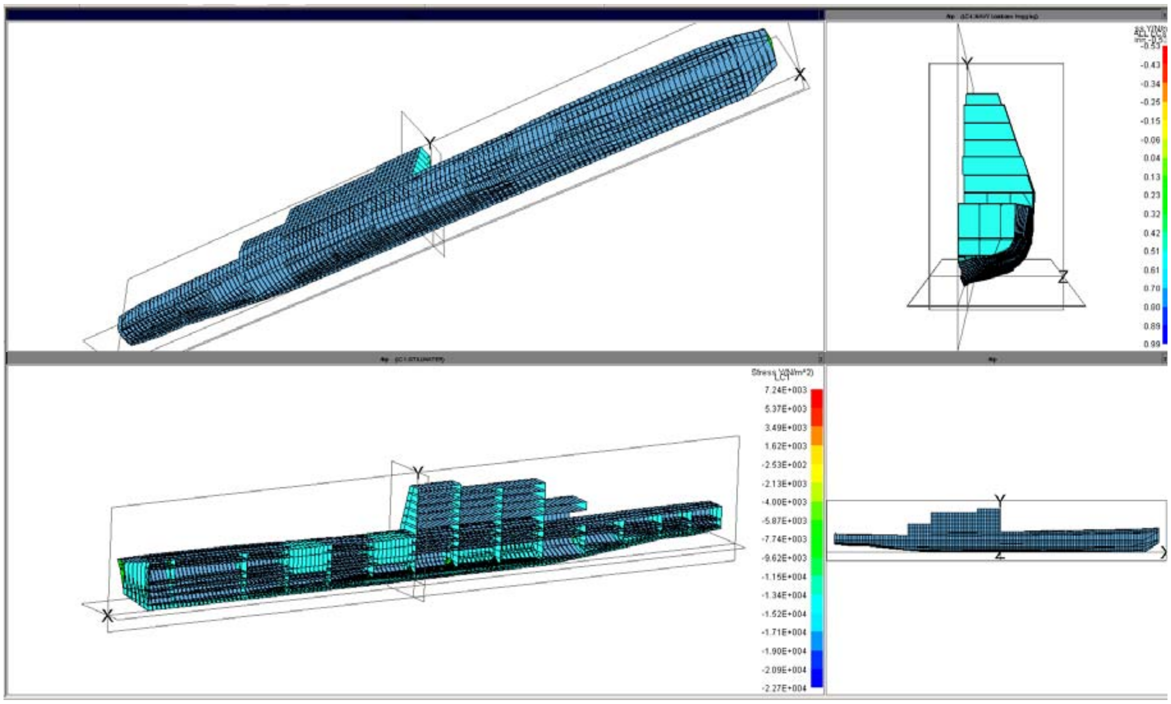


Figure 40: Completed Finite Element Model

The structural model has many details in it including girders, frames, and stiffeners. Figure 41 shows the skeletal structure of the model including the girders, frames, and stiffeners with bulkheads, VLS locations, and tanks shown as well.

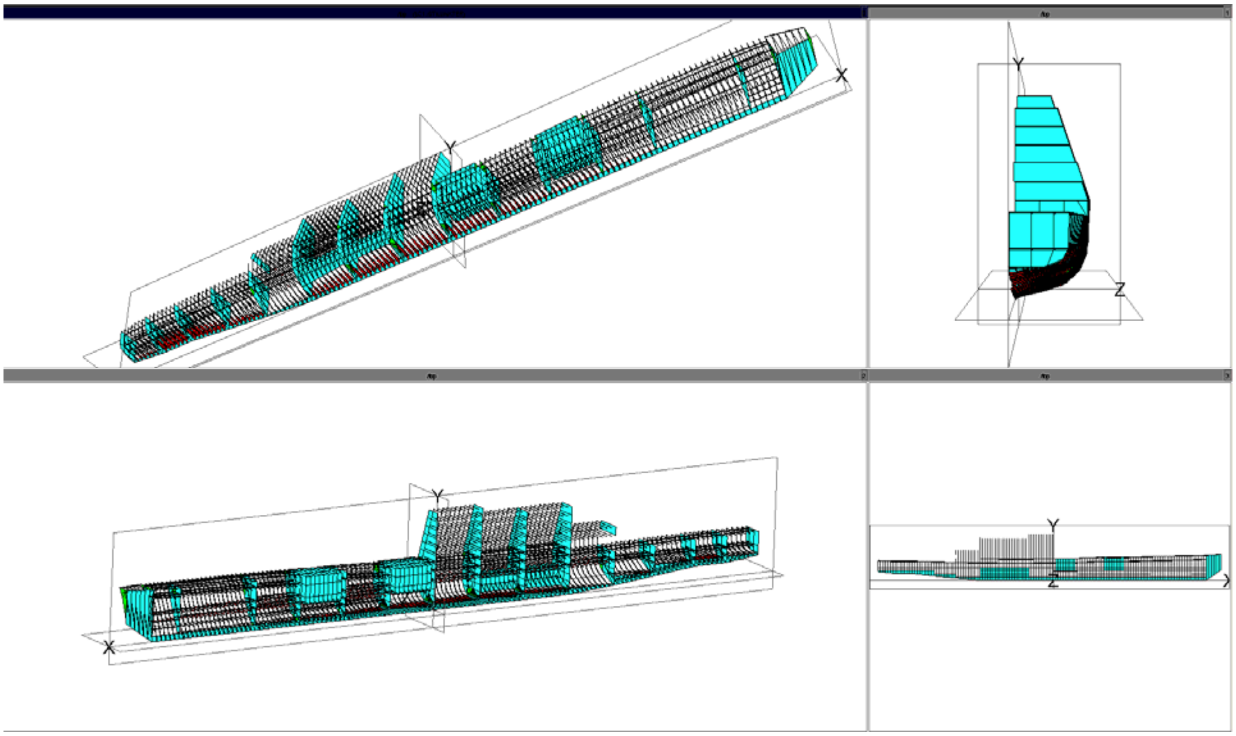


Figure 41: Skeletal Structure

Figure 42 shows all the different plate thicknesses used in the model, each color representing a different thickness.

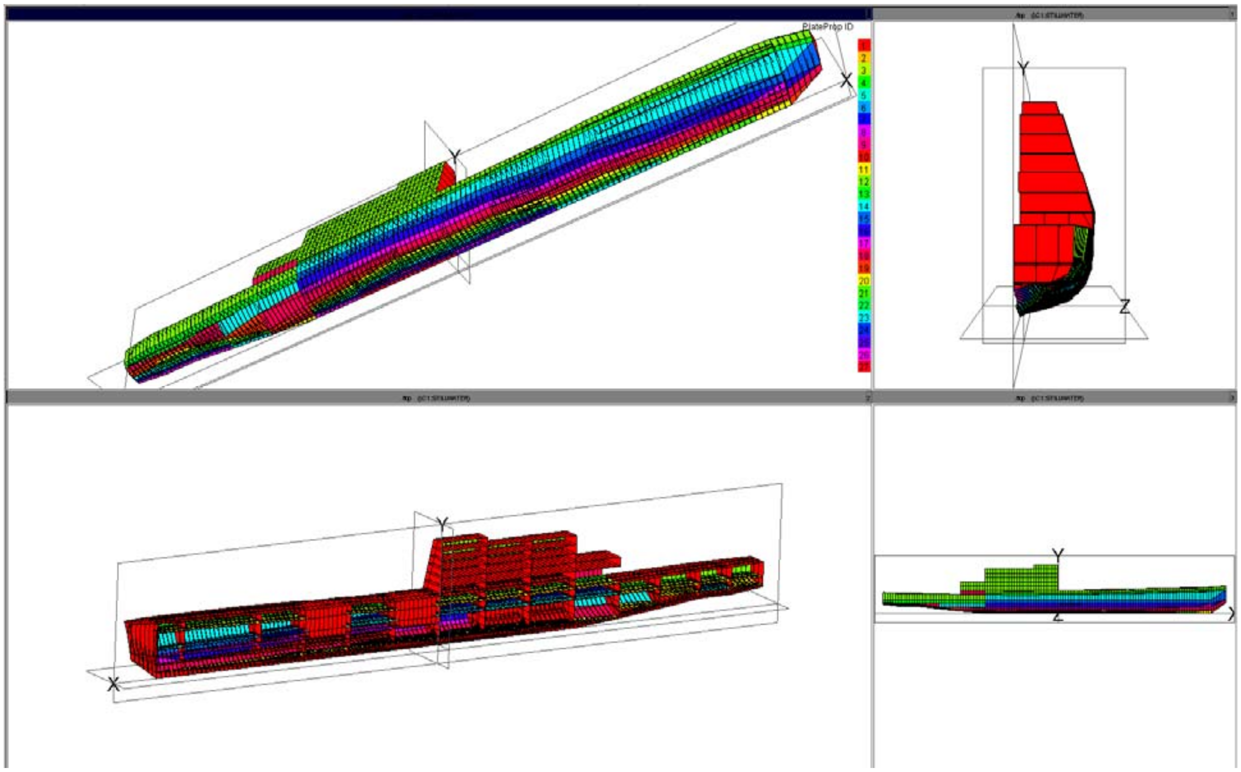


Figure 42: Plate thicknesses

4.5.2 Loads

The loads on the ship include tankage weights, VLS component weights, lightship weight (weight distribution curve from HECSALV), and wave loads. Load conditions were developed in HECSALV and transferred to MAESTRO. The tanks were created as volumes and entered as being 98% full. A table of these loads is shown in Table 16. The lightship weights are presented in Table 17.

Table 16: Volume Loads

Tank Name	% Full	Density (kg/m^3)	Volume (m^3)
Ballast Bow	0.98	1025	450
Ballast Stern 1	0.98	1025	10.8
Ballast Stern 2	0.98	1025	70.6
DFM1	0.98	880	72.8
DFM2	0.98	880	79.5
DFM3	0.98	880	101.2
DFM4	0.98	880	140.7
DFM5	0.98	880	182.5
DFM6	0.98	880	200.2
DFM7	0.98	880	194.3
DFM8	0.98	880	130.6
DFM9	0.98	880	44.8
JP5	0.98	925	127.4
DFM10	0.98	880	252.3
DFM11	0.98	880	121.4
DFM Wing 1	0.98	880	409.5
DFM wing 2	0.98	880	359.6
VLS 1	1	81.688	1469.4
VLS 2	1	81.866	1520.14

Table 17: Module Lightship Weights from HECSALV

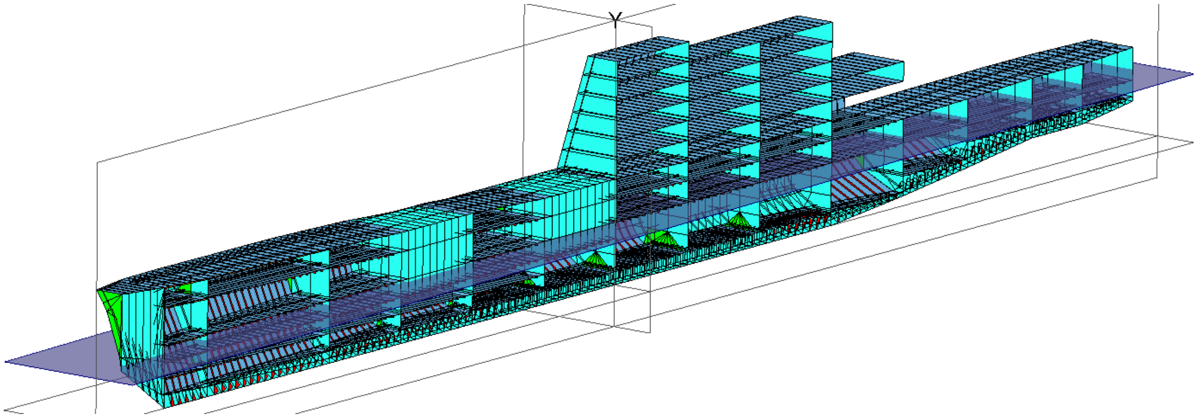
Module	Weight (kg)
1	110000
2	180000
3	250000
4	630000
5	810000
6	712000
7	900000
8	850000
9	800000
10	873000
11	810000
12	652000
13	675000

14	375000
15	165000
1	1646000
2	223348
Pilothouse	87196

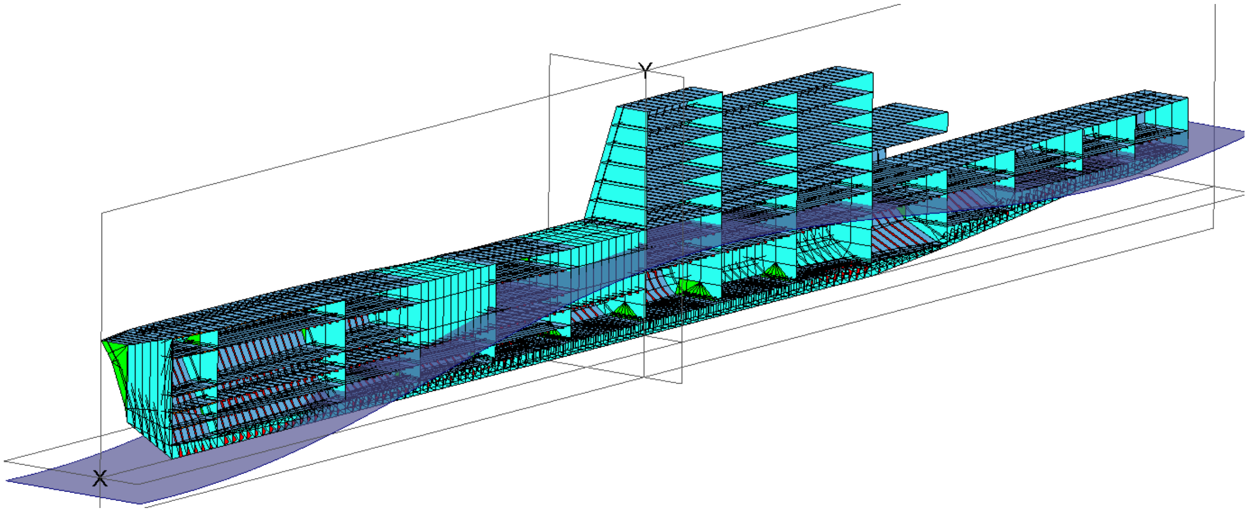
The final loading conditions are environmental, which includes stillwater, hogging, and sagging conditions. The wave amplitude on the conditions is roughly LBP/20 or about 5.5 m. The MAESTRO program uses a balancing algorithm to balance the model with emersion in the conditions. A picture of these loading conditions is shown in Figure 43.

Figure 43: Loading Conditions

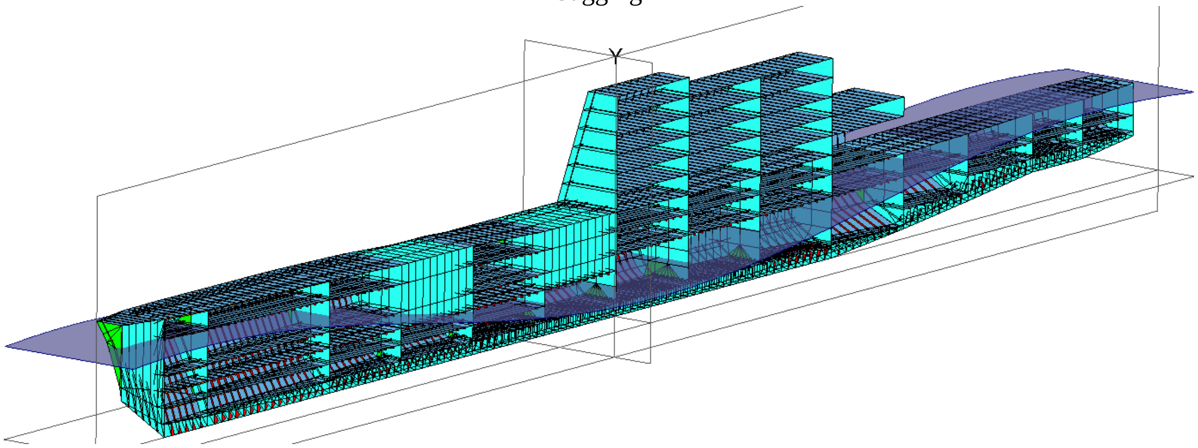
Still Water



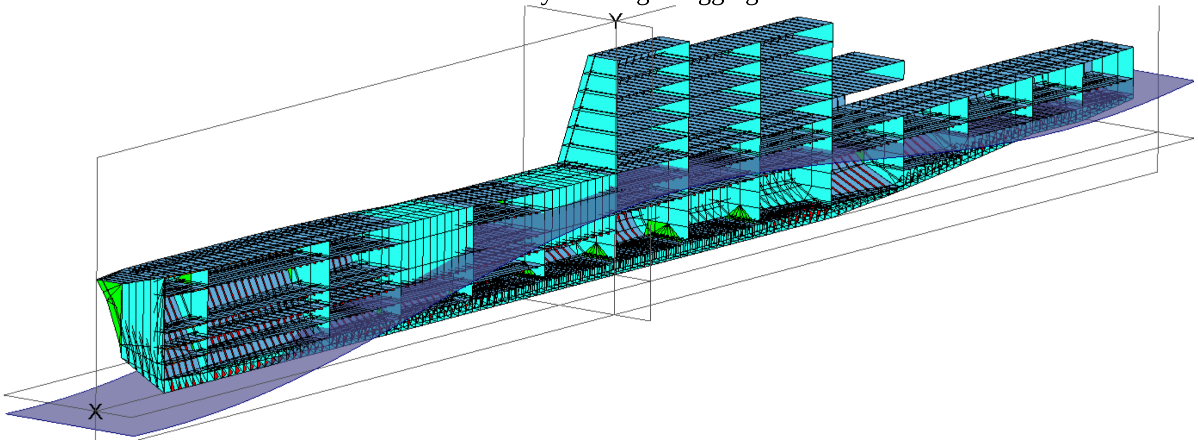
Hogging



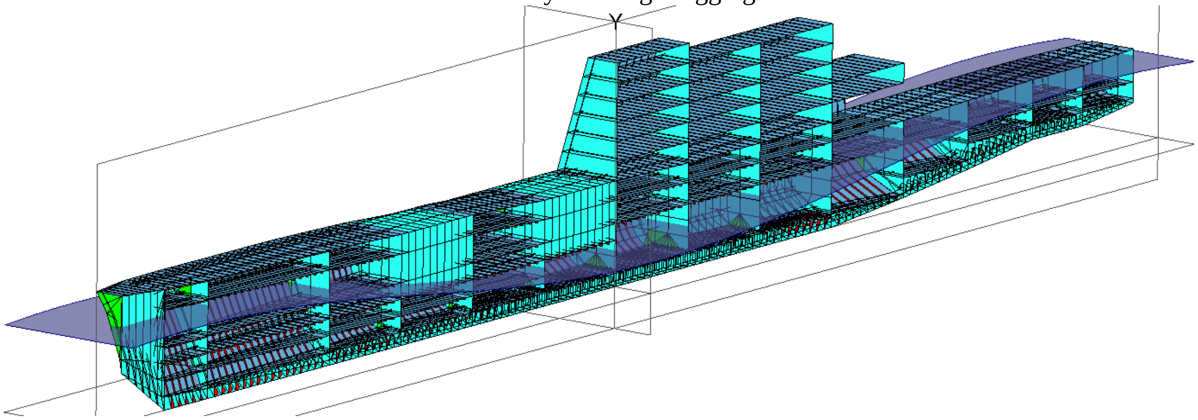
Sagging



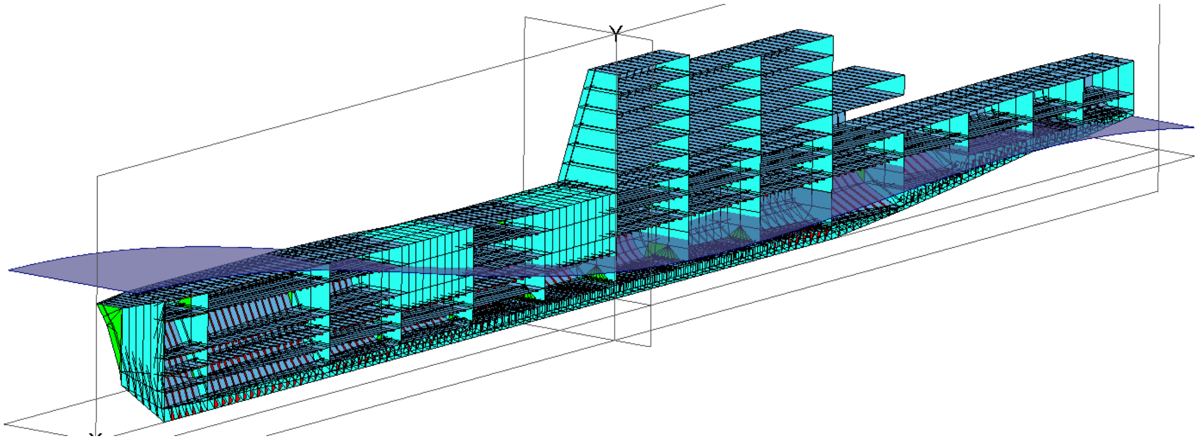
Navy Loading- Hogging



Navy Loading- Sagging

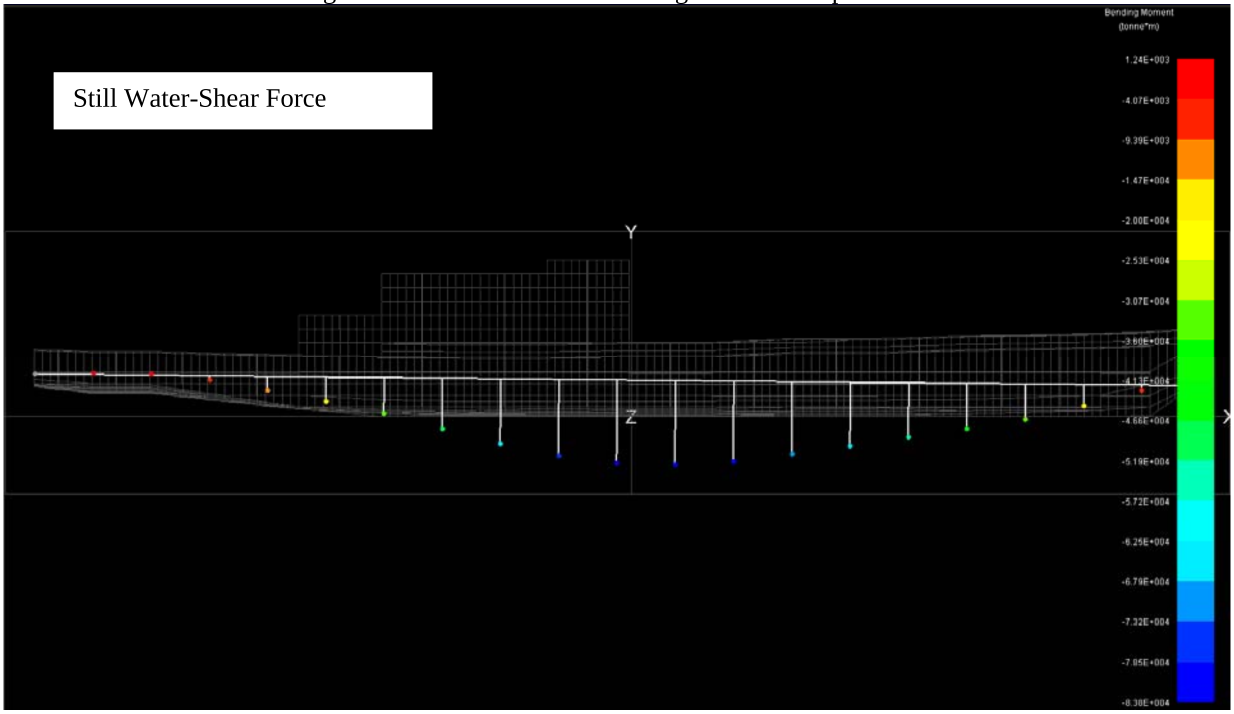


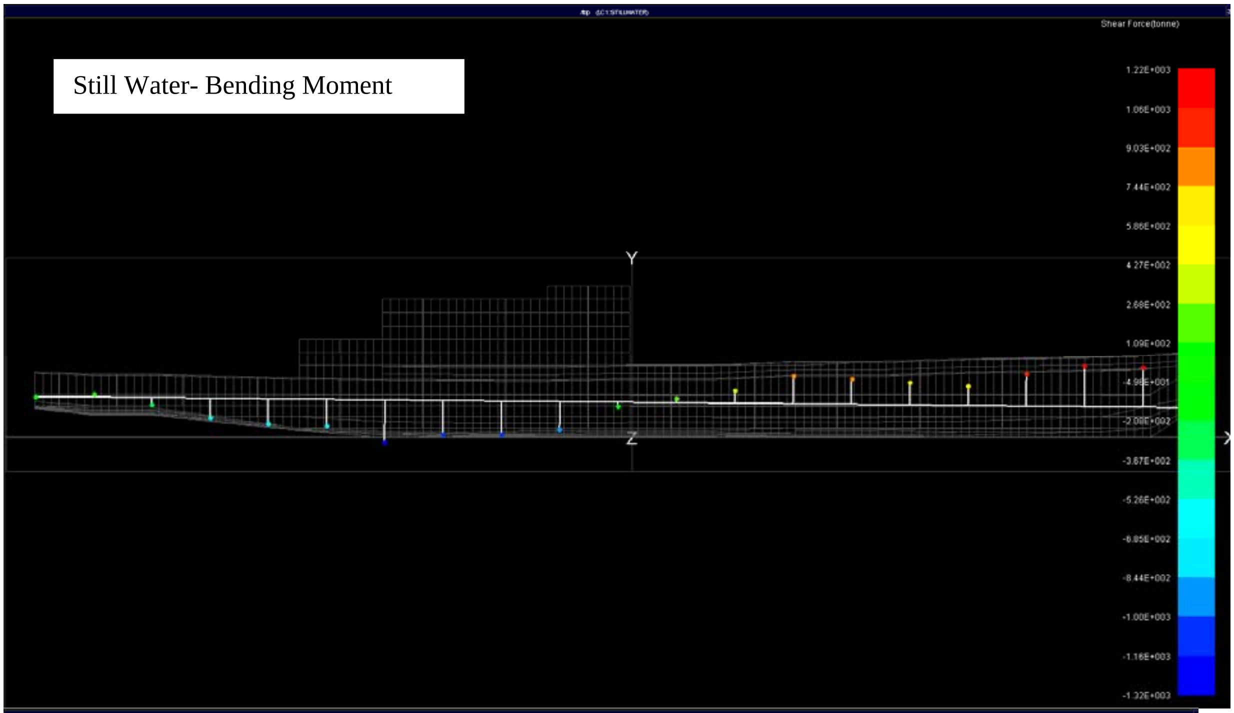
Navy Loading- Fore Deck
Immersion



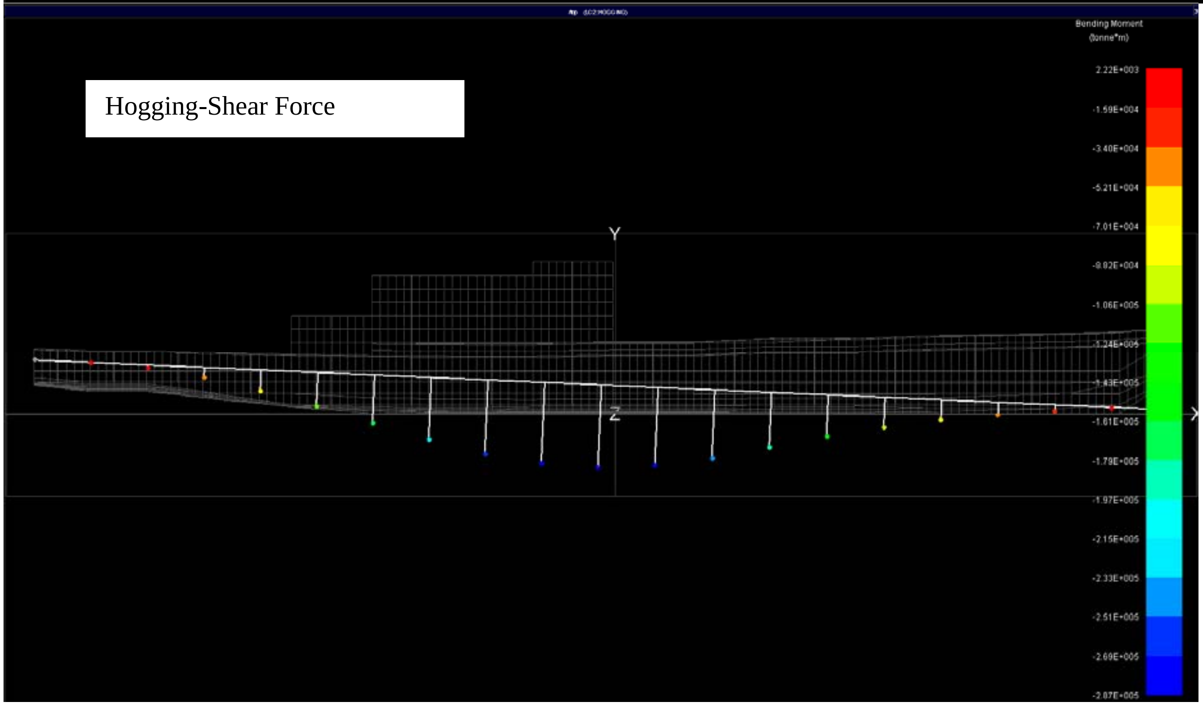
Under the loading conditions shear force and bending moment calculations can be produced. The can be seen in Figure 44.

Figure 44: Shear Force and Bending Moment Graph

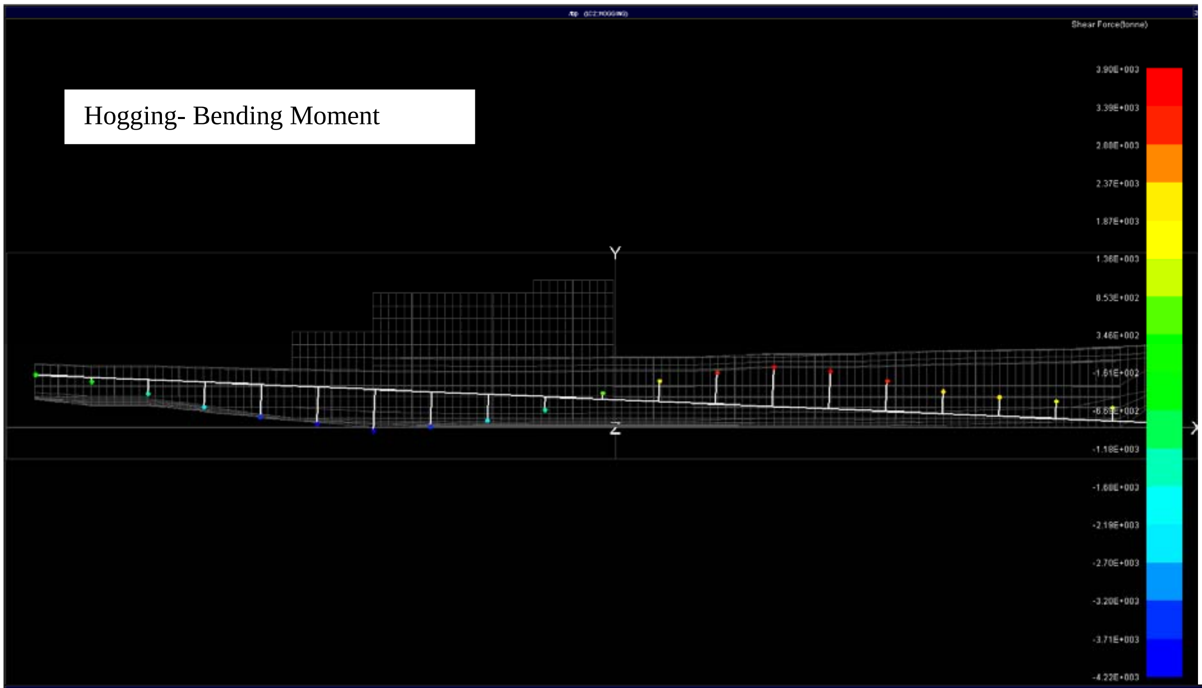


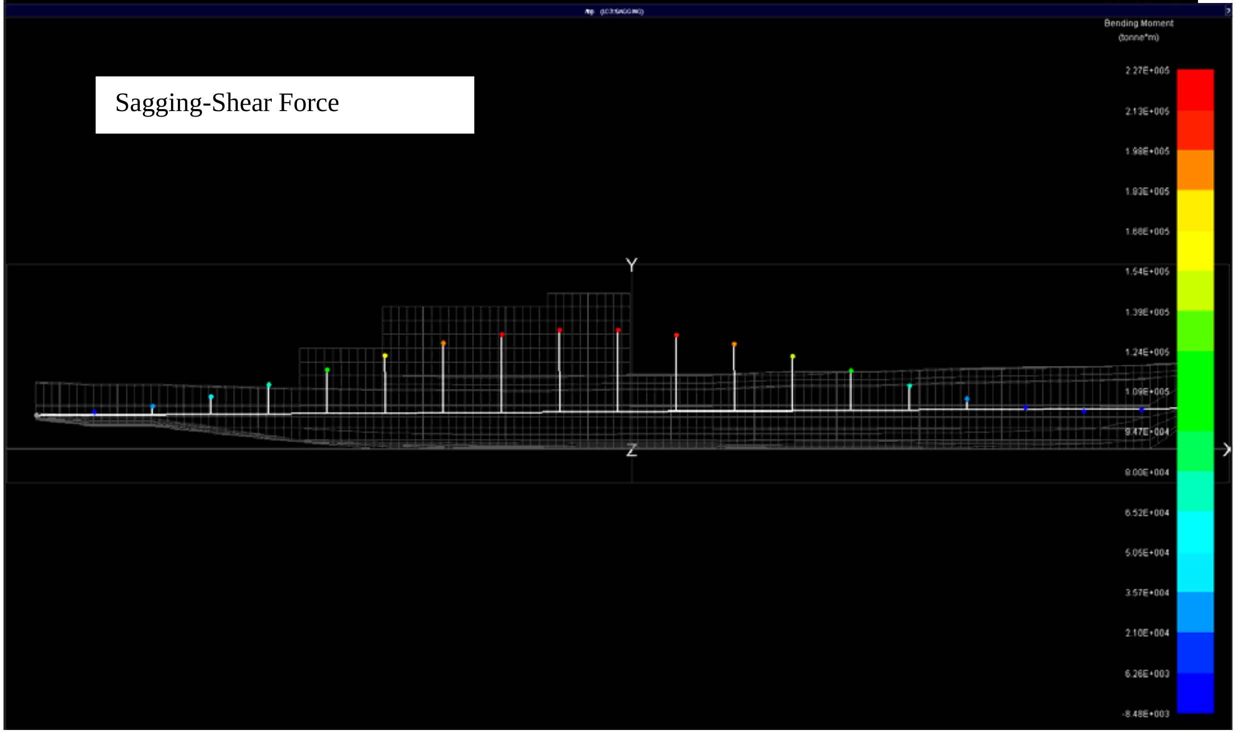


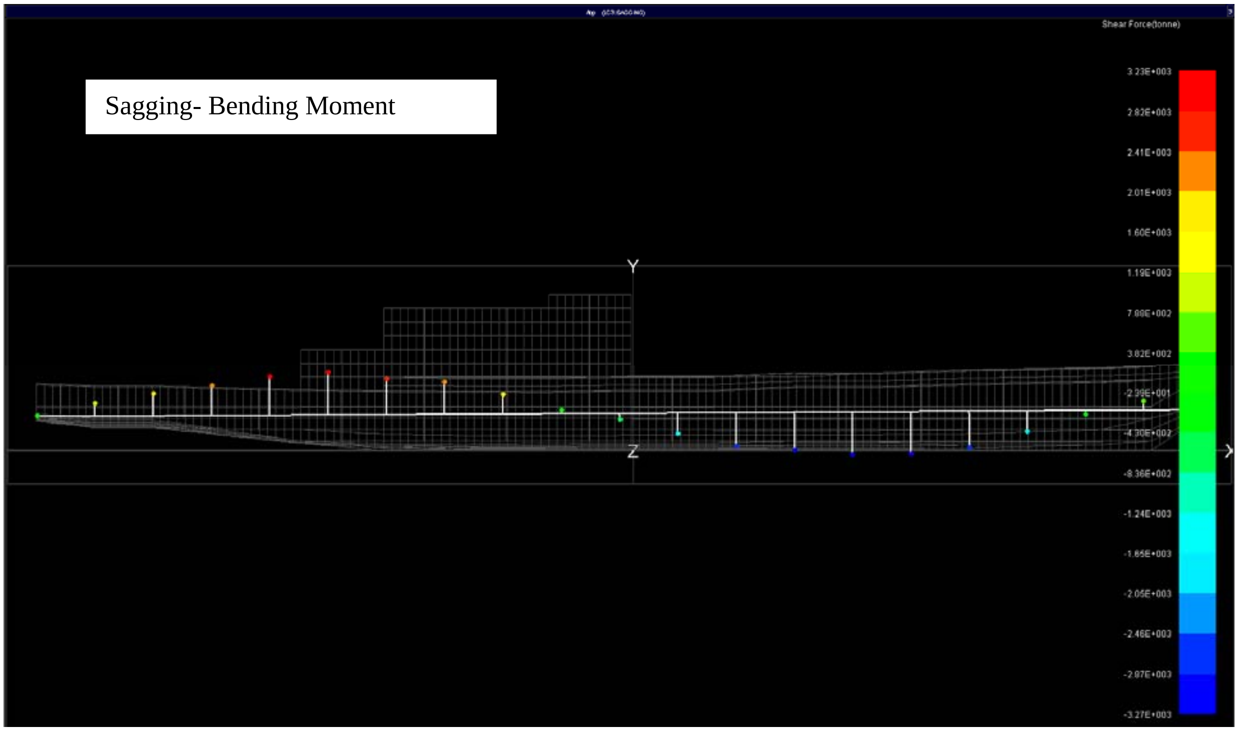
Still Water- Bending Moment



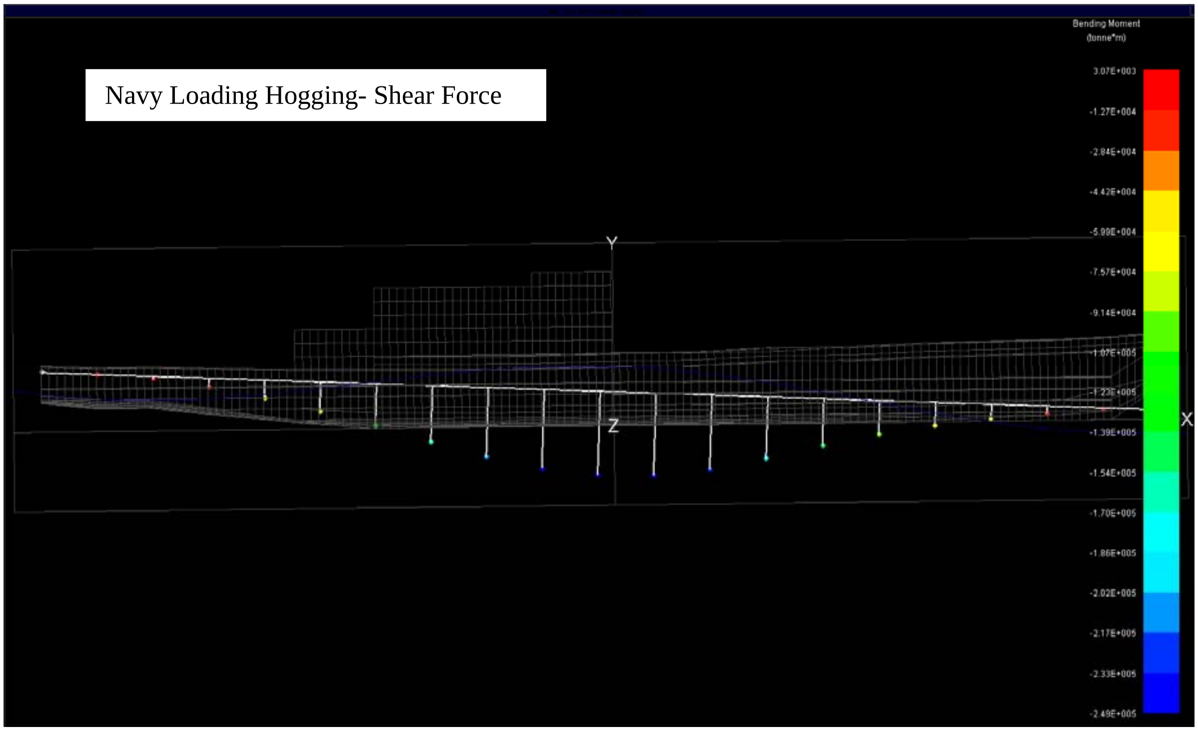
Hogging-Shear Force


Hogging- Bending Moment
Shear Force(tonne)
3.90E+003
3.39E+003
2.88E+003
2.37E+003
1.87E+003
1.36E+003
8.53E+002
3.46E+002
-1.61E+002
-6.68E+002
-1.18E+003
-1.68E+003
-2.19E+003
-2.70E+003
-3.20E+003
-3.71E+003
-4.22E+003
Y
Z

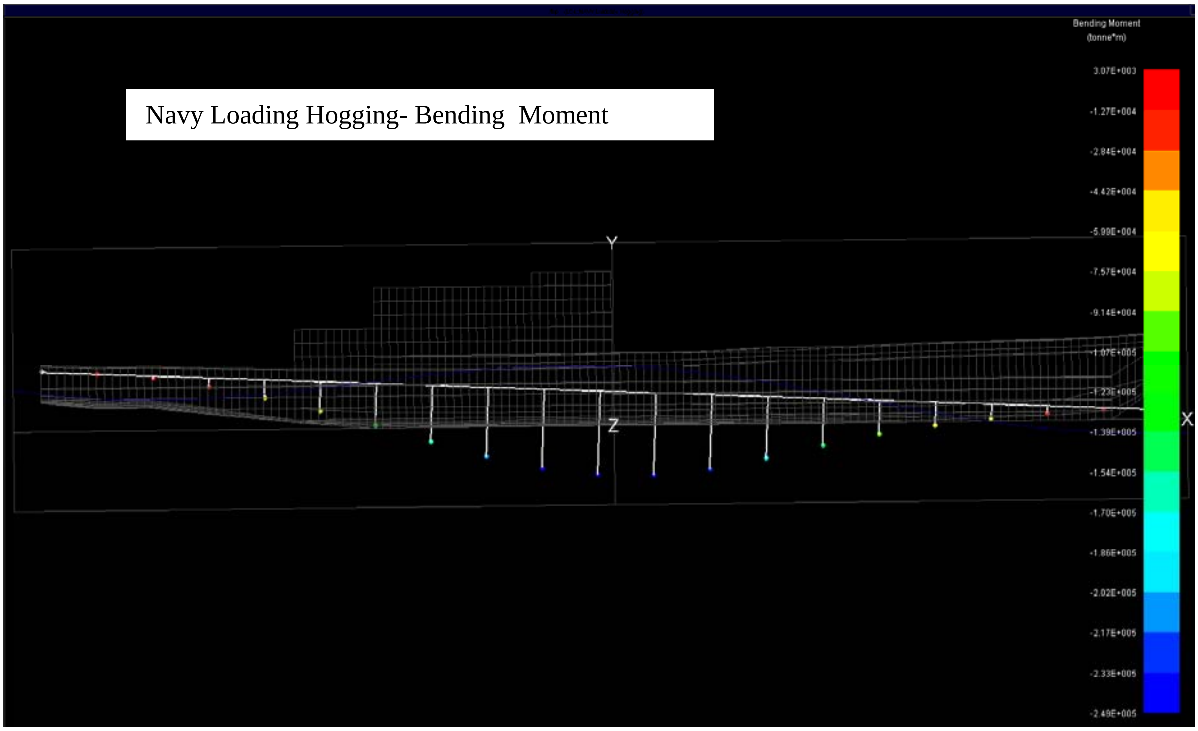

Sagging-Shear Force
Bending Moment
(tonne*m)
2.27E+005
2.13E+005
1.98E+005
1.83E+005
1.68E+005
1.54E+005
1.39E+005
1.24E+005
1.09E+005
9.47E+004
8.00E+004
6.52E+004
5.05E+004
3.57E+004
2.10E+004
6.26E+003
-8.48E+003
Y
Z

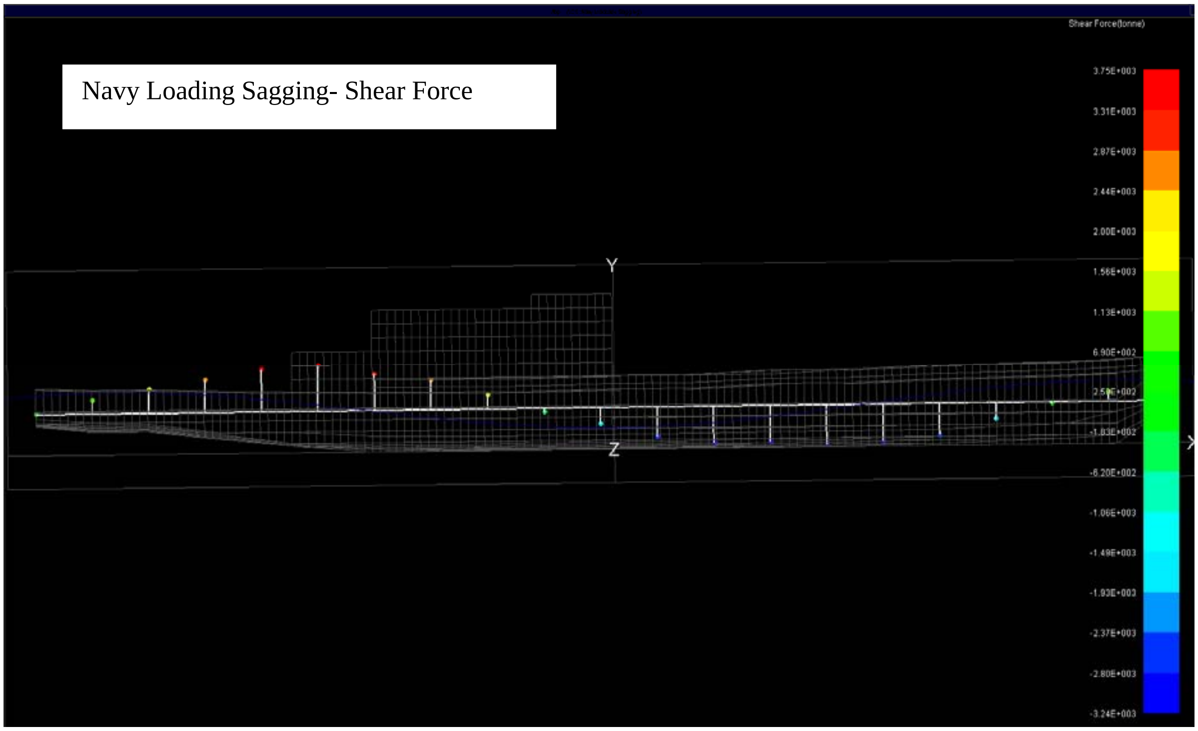


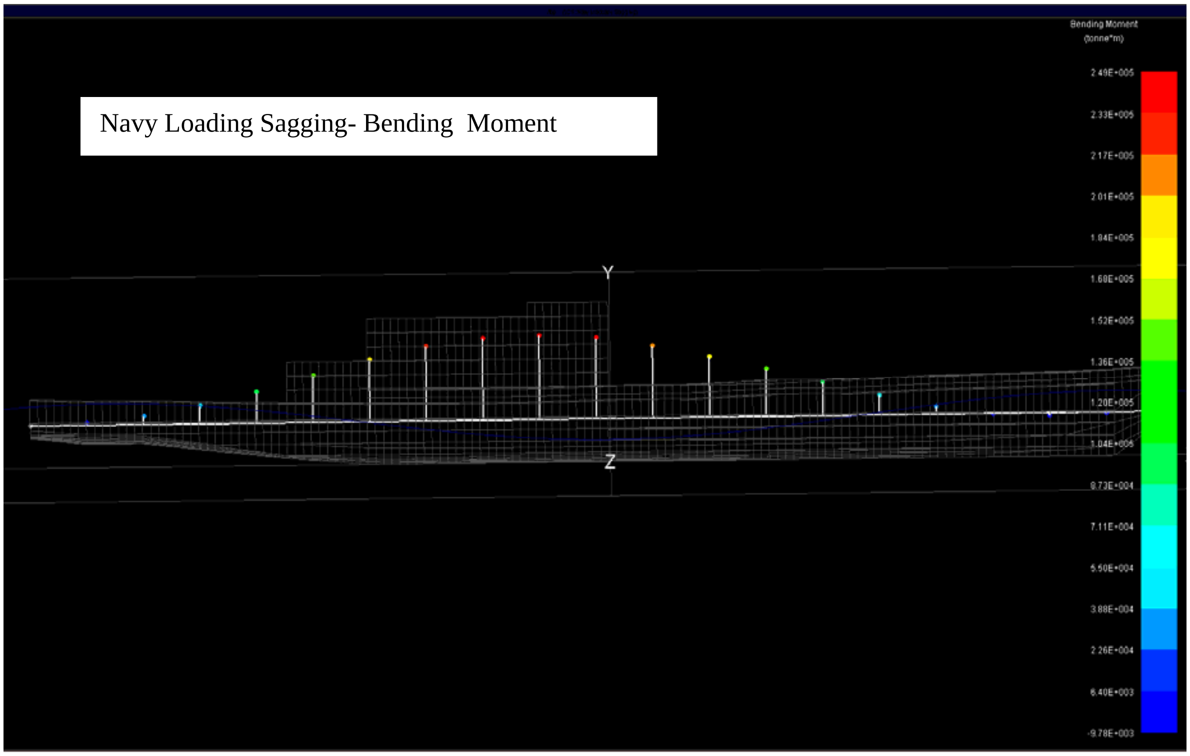
Sagging- Bending Moment



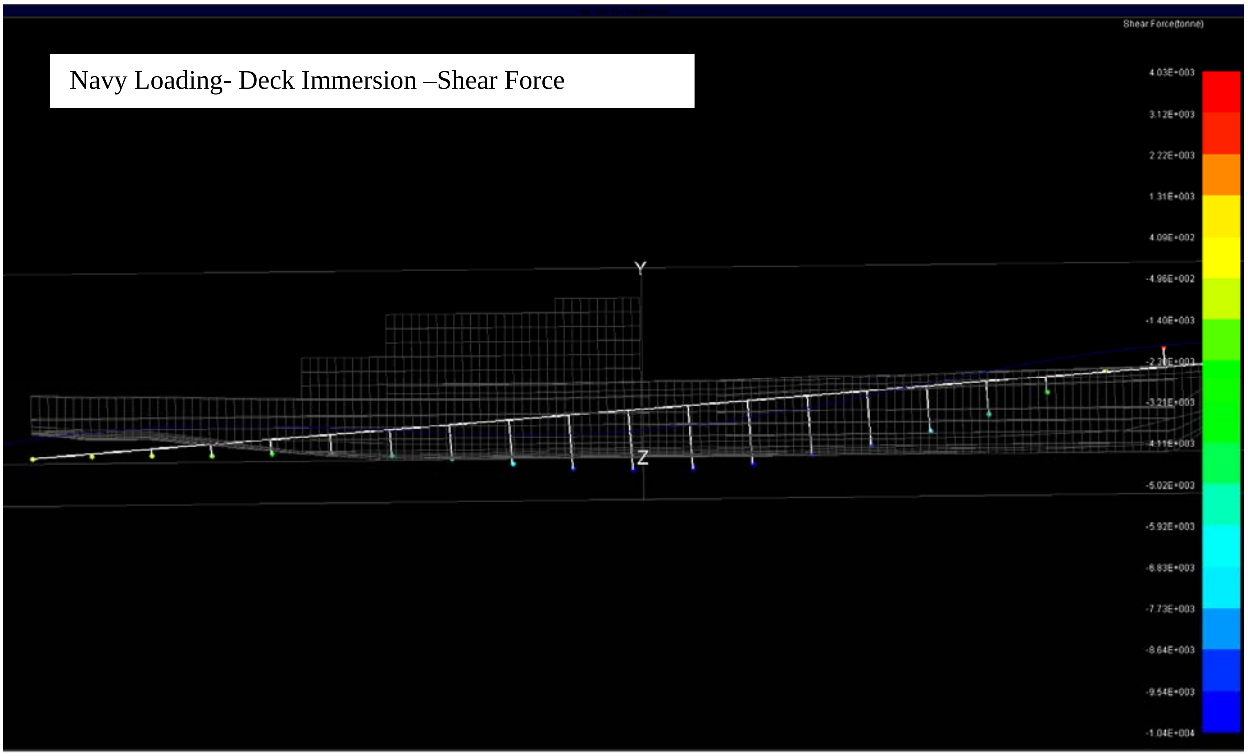
Navy Loading Hogging- Shear Force


Navy Loading Hogging- Bending Moment
Bending Moment (tonne*m)
3.07E+003
-1.27E+004
-2.84E+004
-4.42E+004
-5.99E+004
-7.57E+004
-9.14E+004
-1.07E+005
-1.23E+005
-1.39E+005
-1.54E+005
-1.70E+005
-1.86E+005
-2.02E+005
-2.17E+005
-2.33E+005
-2.49E+005
Y
Z
X

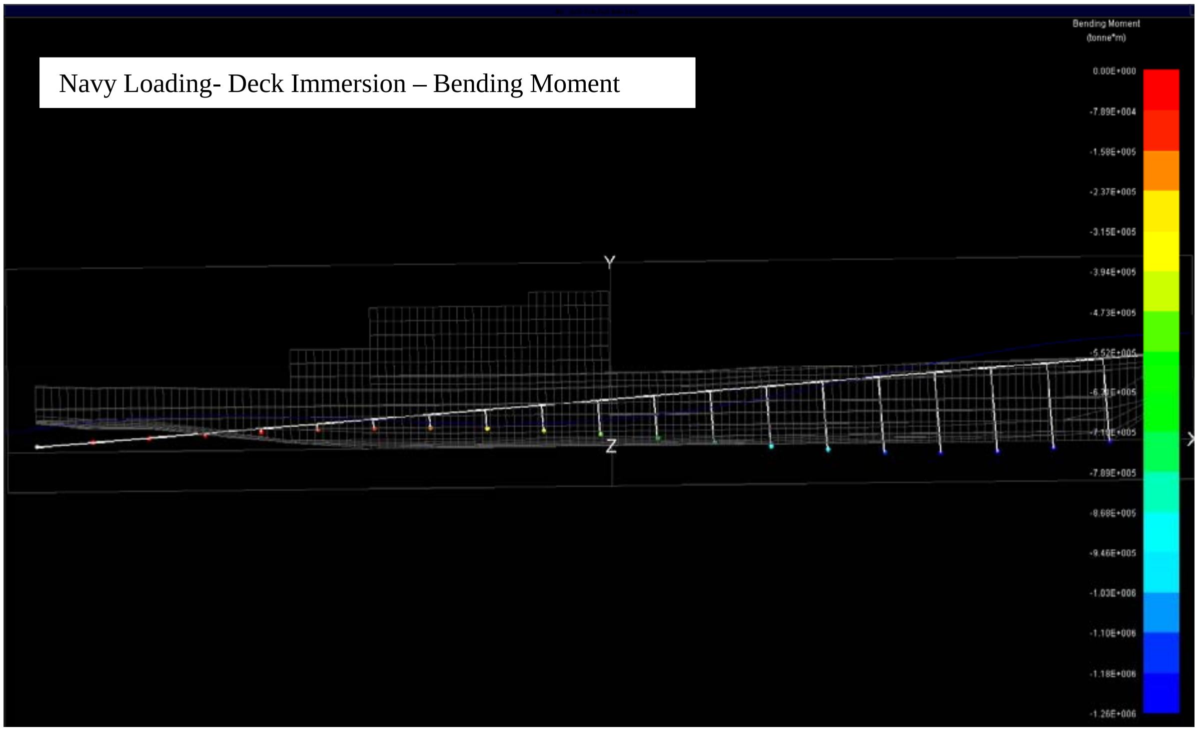

Navy Loading Sagging- Shear Force
Shear Force(tonne)
3.75E+003
3.31E+003
2.87E+003
2.44E+003
2.00E+003
1.56E+003
1.13E+003
6.90E+002
2.59E+002
-1.83E+002
-6.20E+002
-1.06E+003
-1.49E+003
-1.93E+003
-2.37E+003
-2.80E+003
-3.24E+003
Y
Z



Navy Loading Sagging- Bending Moment



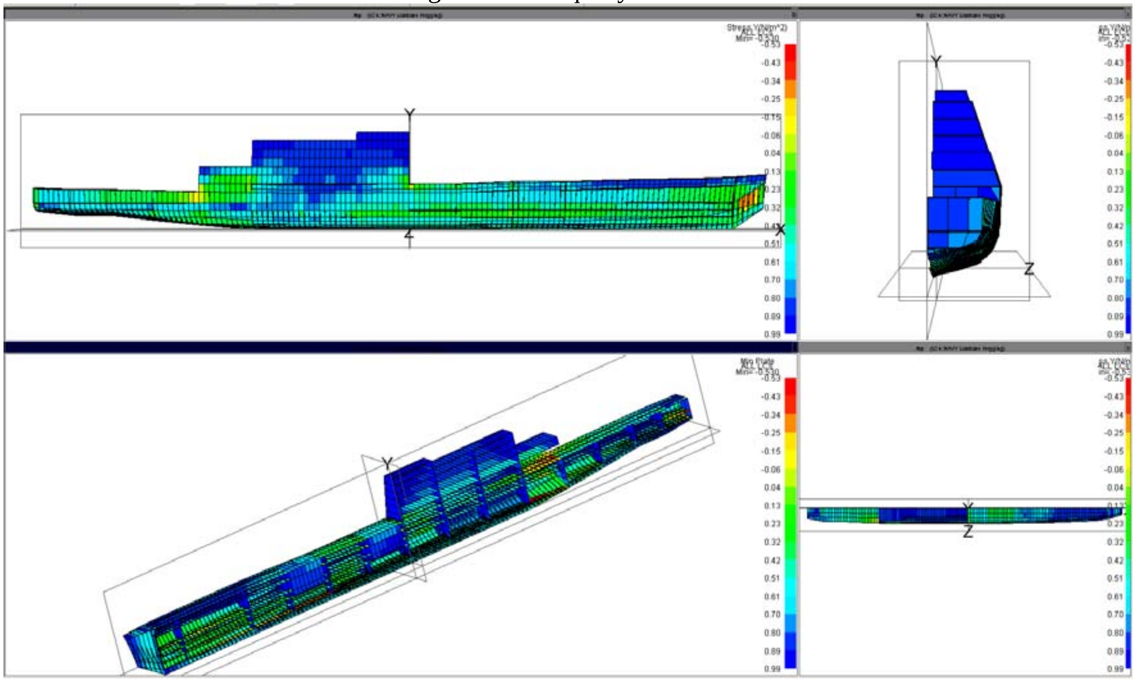
Navy Loading- Deck Immersion –Shear Force



4.3.3 Adequacy

The MAESTRO modeler has an installed adequacy algorithm. This function determines shows is a plate in a certain area will fail under the caused stresses. Areas that failed are then redesigned and entered until all the areas will not fail. Figure 45 shows the adequacy of the areas in all loading conditions.

Figure 45: Adequacy of Plates



4.6 Power and Propulsion

The propulsion system for CGXmod is an integrated power system (IPS). Four Rolls Royce MT-30 Gas Turbines and two fuel cells generate the power needed for propulsion ship service and emergency loads. Two permanent magnetic motors drive twin shafts with fixed pitch propellers.

4.6.1 Resistance

Basic resistance and effective power was calculated using the Holtrop-Mennon method. Viscous drag and wave making drag were included in the resistance calculation, as well as a basic estimation of the expected appendage drag and wind drag. Resistance and power was calculated for speeds ranging from 20 – 35 knots. At the endurance speed of 20 knots, the drag on the hull was 645 kN with a required effective horsepower of approximately 16,000 horsepower. At the sustained speed of 34 knots, the drag was 24500 kN with a required effective horsepower of approximately 102,500 horsepower. Resistance and power curves are shown below in Figures 46 and 47.

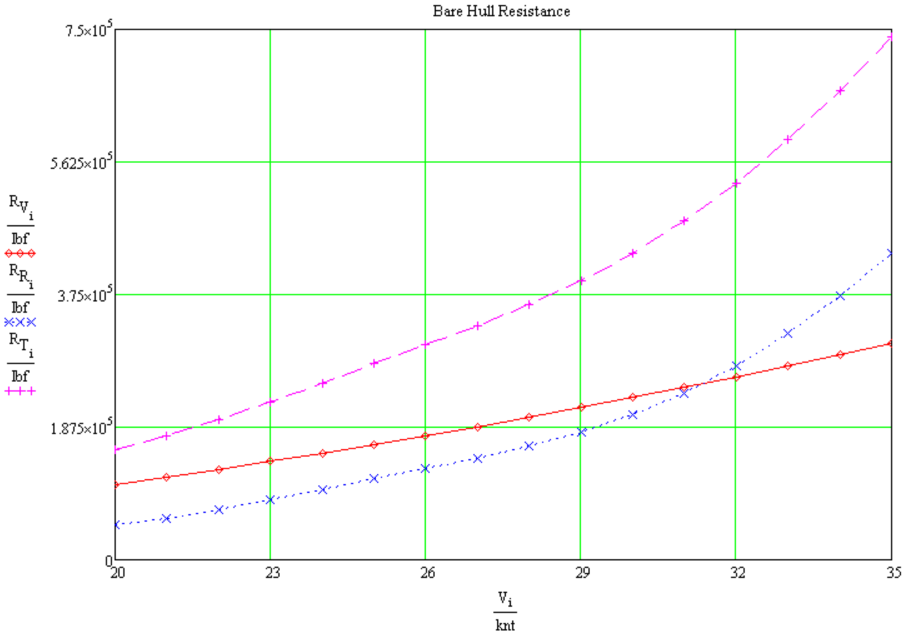


Figure 46: CGXmod bare hull resistance curve

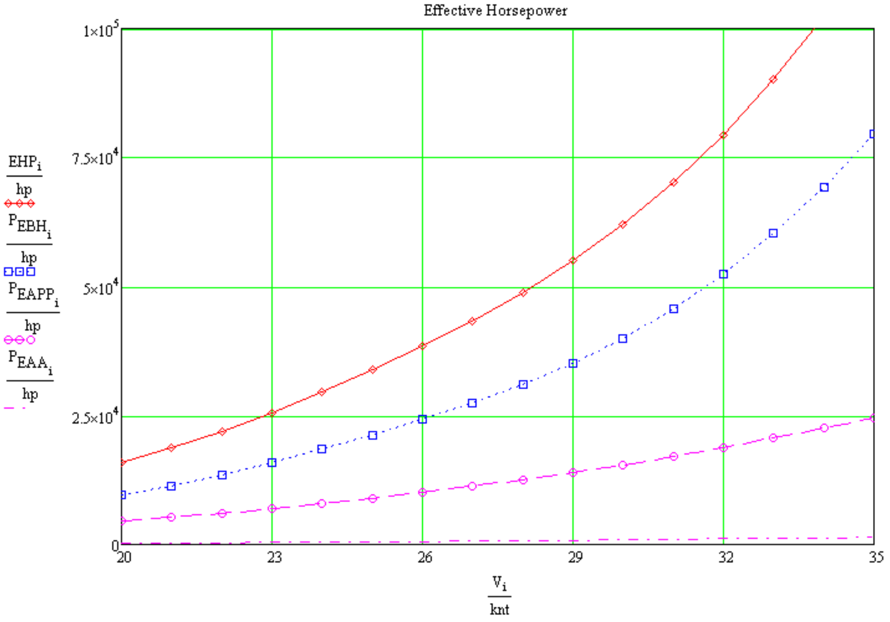


Figure 47: CGXmod effective horsepower curves

4.6.2 Propulsion

Each gas turbine is rated at 36 MW and each fuel cell is rated at 3 MW. This provides a total power of 150 MW. Both fuel cells are online at all times, and only one gas turbine is online at endurance speed. All four are online at sustained speed. The permanent magnetic motors are mounted at an elevation that requires a 2.5 and 3 degree shaft angle. There are two strut bearings per shaft outside the hull for support and stability. There are twin rudders and each has a maximum chord length of 4.2 meters.

The two propellers are fixed pitch, five bladed, Wageningen B-Series propellers optimized for efficiency at 20 knots. The propeller performance curves are shown in Figures 48 and 49. At 20 knots, the propellers have an open water efficiency of 0.775, and 0.764 at 34 knots. The propellers cavitate at 34 knots.

Figure XX shows the specific fuel consumption of the gas turbines and fuel cells. At endurance speed, a load fraction of 100% for the fuel cells and approximately 65% for the gas turbines, the SFC for the fuel cells and gas turbines are 0.395 and 0.405 respectively. At sustained speed, a load fraction of 100%, the SFC for the fuel cells are 0.365 and 0.440 for the gas turbines. To calculate the total specific fuel consumption, a power weighted average was used. This resulted in an SFC of 0.397 lb/hp-hr at 20knots and 0.437 at 34 knots.

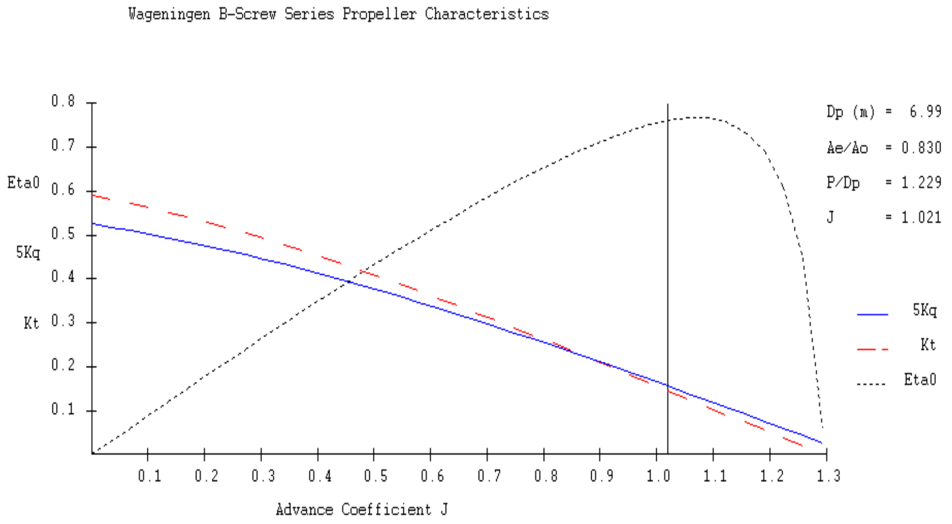


Figure 48: Endurance speed propeller characteristics

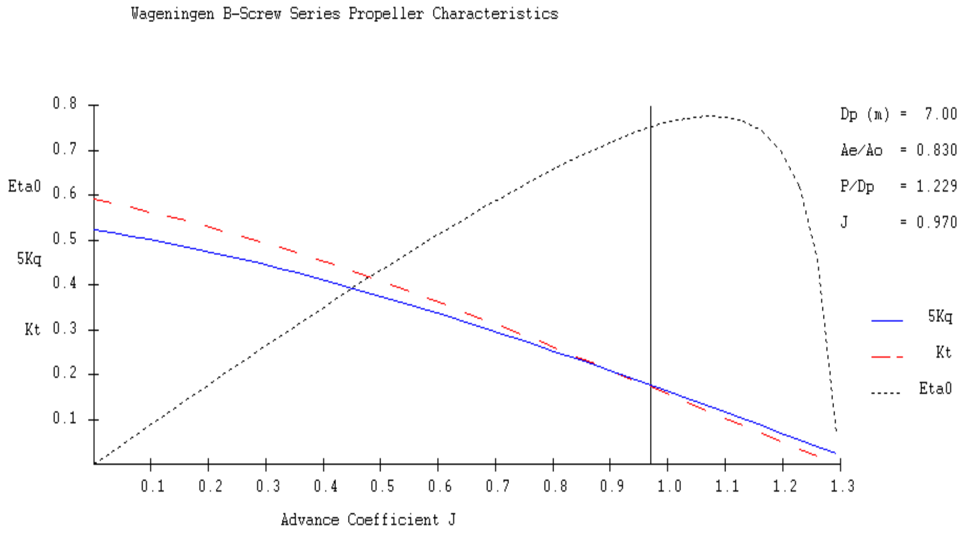


Figure 49: Sustained speed propeller characteristics

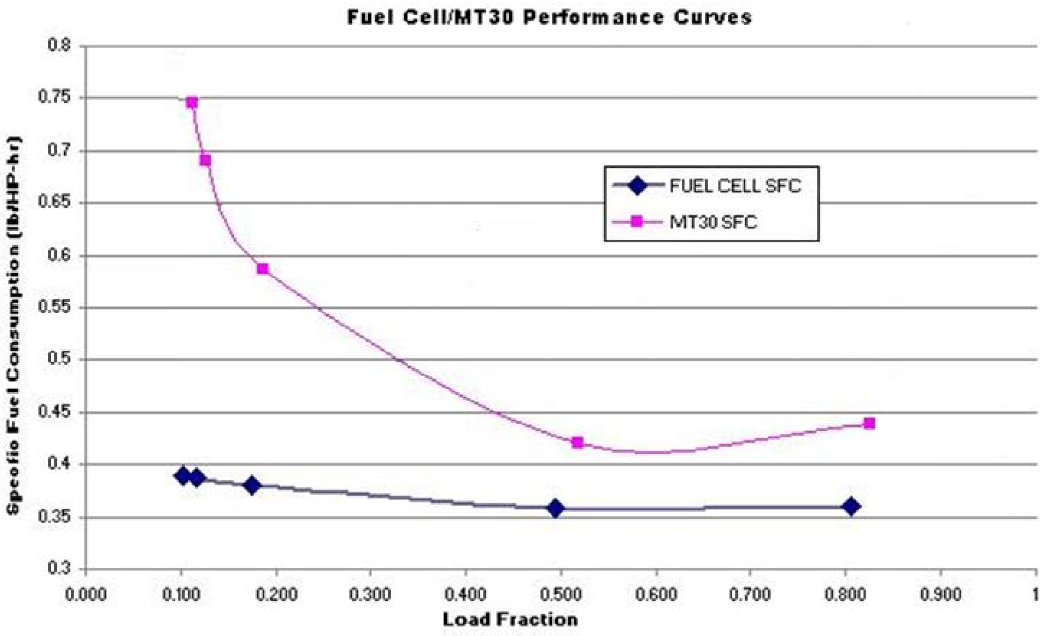


Figure 50: Engine performance curves

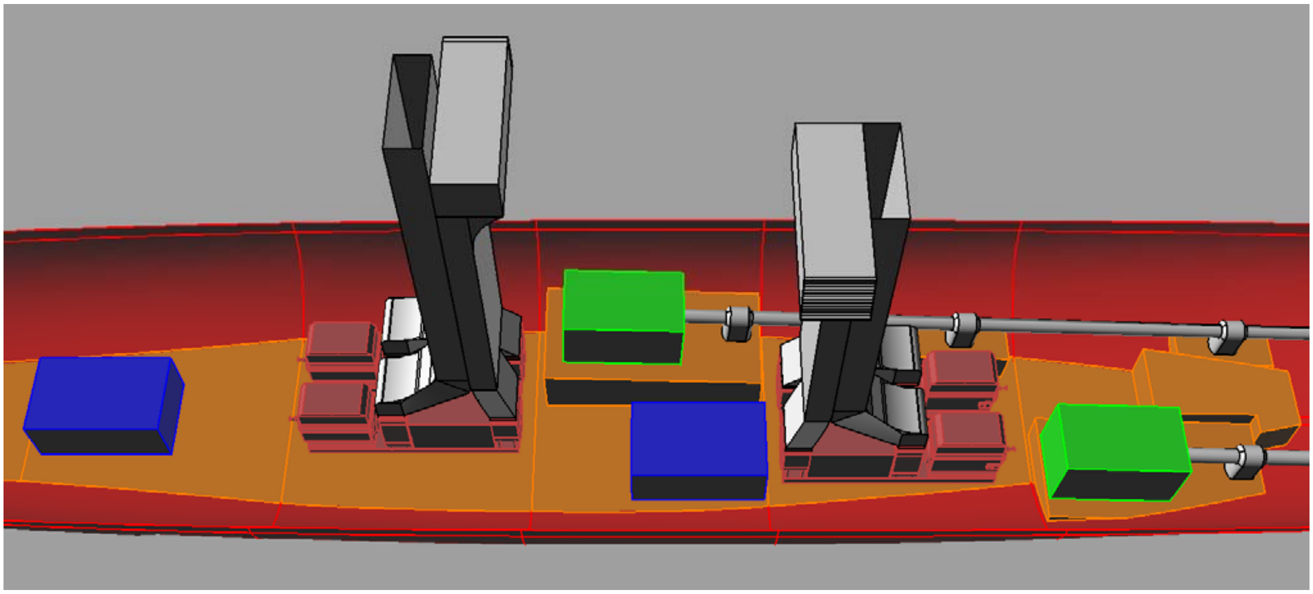


Figure 51: CGXmod propulsion system

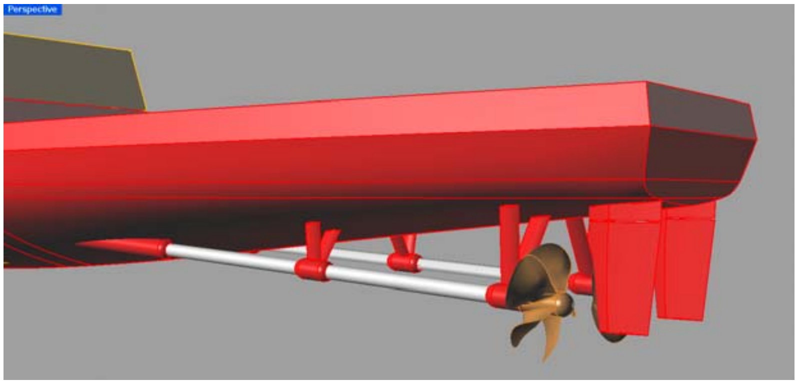


Figure 51: CGXmod props and shafts

4.6.3 Electric Load Analysis (ELA)

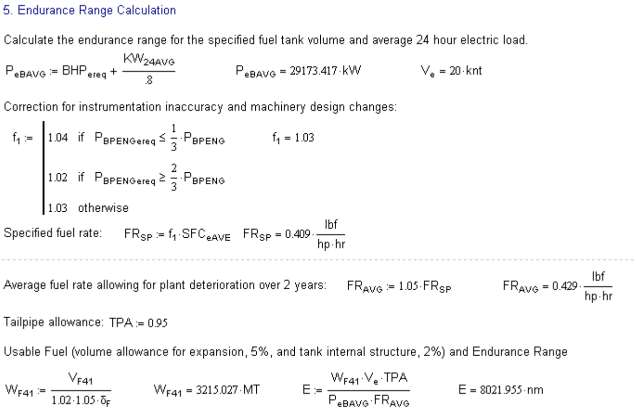
The Electric Load Analysis was done using ASSET to describe the electrical needs. The ELA describes all the necessary requirements used on the ship and gives a total summary of the equipment. Table XX presents the ELA.

Table 17 - Electric Load Analysis Summary

	SWBS	Description	Connected Load (kW)	Battle Power Factor	Battle (kW)	Cruise Power Factor	Cruise (kW)	Anchor Power Factor	Anchor (kW)	Port Power Factor	Port (kW)	Emergency Power Factor	Emergency (KW)
	100	Deck Machinery	560.0	0.0	0.0	0.0	0.0	0.4	224.0	0.0	0.0	0.0	0.0
	200	Propulsion	115,850.0		105,340.0		16,340.0		340.0		0.0		340.0
		Propulsion Direct	115,000.0		105,000.0		16,000.0		0.0		0.0		0.0
		Propulsion support	850.0	0.4	340.0	0.4	340.0	0.4	340.0	0.0	0.0	0.4	340.0
	300	Electric	960.0	0.6	576.0	0.6	576.0	0.5	480.0	0.4	384.0	0.4	384.0
	400	C4I	7,515.0		4,336.0		4,336.0		2,254.5		86.5		1,503.0
		Combat Systems	6,650.0	0.6	3,990.0	0.6	3,990.0	0.3	1,995.0	0.0	0.0	0.2	1,330.0
		Miscellaneous	865.0	0.4	346.0	0.4	346.0	0.3	259.5	0.1	86.5	0.2	173.0
	500	Auxiliary	8,007.5		4,680.2		4,328.2		3,497.8		2,384.0		1,385.2
	510	CPS	322.5	0.4	129.0	0.4	129.0	0.4	129.0	0.0	0.0	0.0	0.0
	510	HVAC	4,924.0	0.7	3,446.8	0.7	3,446.8	0.6	2,954.4	0.4	1,969.6	0.2	984.8
	520	Firemain	596.0	0.4	238.4	0.4	238.4	0.4	238.4	0.4	238.4	0.4	238.4
	540	Fuel Handling	1,760.0	0.4	704.0	0.2	352.0	0.1	176.0	0.1	176.0	0.0	0.0
	560	Ship Control (Steering)	405.0	0.4	162.0	0.4	162.0	0.0	0.0	0.0	0.0	0.4	162.0
	600	Services	220.0	0.4	88.0	0.8	176.0	0.4	88.0	0.4	88.0	0.1	22.0
	700	Weapons	1,200.0	0.6	720.0	0.5	600.0	0.5	600.0	0.0	0.0	0.1	120.0
		Total Required	134,312.5		115,740.2		26,356.2		7,484.3		2,942.5		3,754.2
		24 Hour Average			109,845.7		20,692.1		3,485.7		1,407.4		1,936.1
Number	**Generator**	**Rating (kW)**	**Average Connected (kW)**	**Online**	**Battle (kW)**	**Online**	**Cruise (kW)**	**Online**	**Anchor (kW)**	**Online**	**Port (kW)**	**Online**	**Emergency (KW)**
4	MT30	36,000	144,000	3	108,000	1	36,000	0	0	0	0	0	0
2	Fuel Cell	3,000	6,000	2	6,000	2	6,000	2	6,000	1	3,000	1	3,000
	Total	150,000	150,000		114,000		42,000		6,000		3,000		3,000

4.6.4 Fuel Calculation

A fuel calculation was performed for endurance range and sprint range in accordance with DDS 200-1. The electrical load used for endurance range calculation is total propulsion power plus 125% of the 24 hour average load. This is considered a maximum load that would be used during a transit at endurance speed. Plant deterioration and tank volume allowances were also included in the calculation. An endurance range of 8,022 nautical miles was calculated for CGXmod, and this is 33% over the required 6,000 nm range specified in the ORD. The endurance range calculations are show below in Figure XX. Fuel volume is approximately 4000 cubic meters.



5. Endurance Range Calculation

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

$P_{eBAVG} := BHP_{ereq} + \frac{KW_{24AVG}}{.8}$ $P_{eBAVG} = 29173.417 \cdot kW$ $V_e = 20 \cdot knt$

Correction for instrumentation inaccuracy and machinery design changes:

$$f_1 := \begin{vmatrix} 1.04 & \text{if} \quad P_{BPENGereq} \le \frac{1}{3} \cdot P_{BPENG} \\ 1.02 & \text{if} \quad P_{BPENGereq} \ge \frac{2}{3} \cdot P_{BPENG} \\ 1.03 & \text{otherwise} \end{vmatrix} \qquad f_1 = 1.03$$

Specified fuel rate: $FR_{SP} := f_1 \cdot SFC_{eAVE}$ $FR_{SP} = 0.409 \cdot \frac{lbf}{hp \cdot hr}$

Average fuel rate allowing for plant deterioration over 2 years: $FR_{AVG} := 1.05 \cdot FR_{SP}$ $FR_{AVG} = 0.429 \cdot \frac{lbf}{hp \cdot hr}$

Tailpipe allowance: $TPA := 0.95$

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

$W_{F41} := \frac{V_{F41}}{1.02 \cdot 1.05 \cdot \delta_F}$ $W_{F41} = 3215.027 \cdot MT$ $E := \frac{W_{F41} \cdot V_e \cdot TPA}{P_{eBAVG} \cdot FR_{AVG}}$ $E = 8021.955 \cdot nm$

Figure 52: Endurance fuel calculations

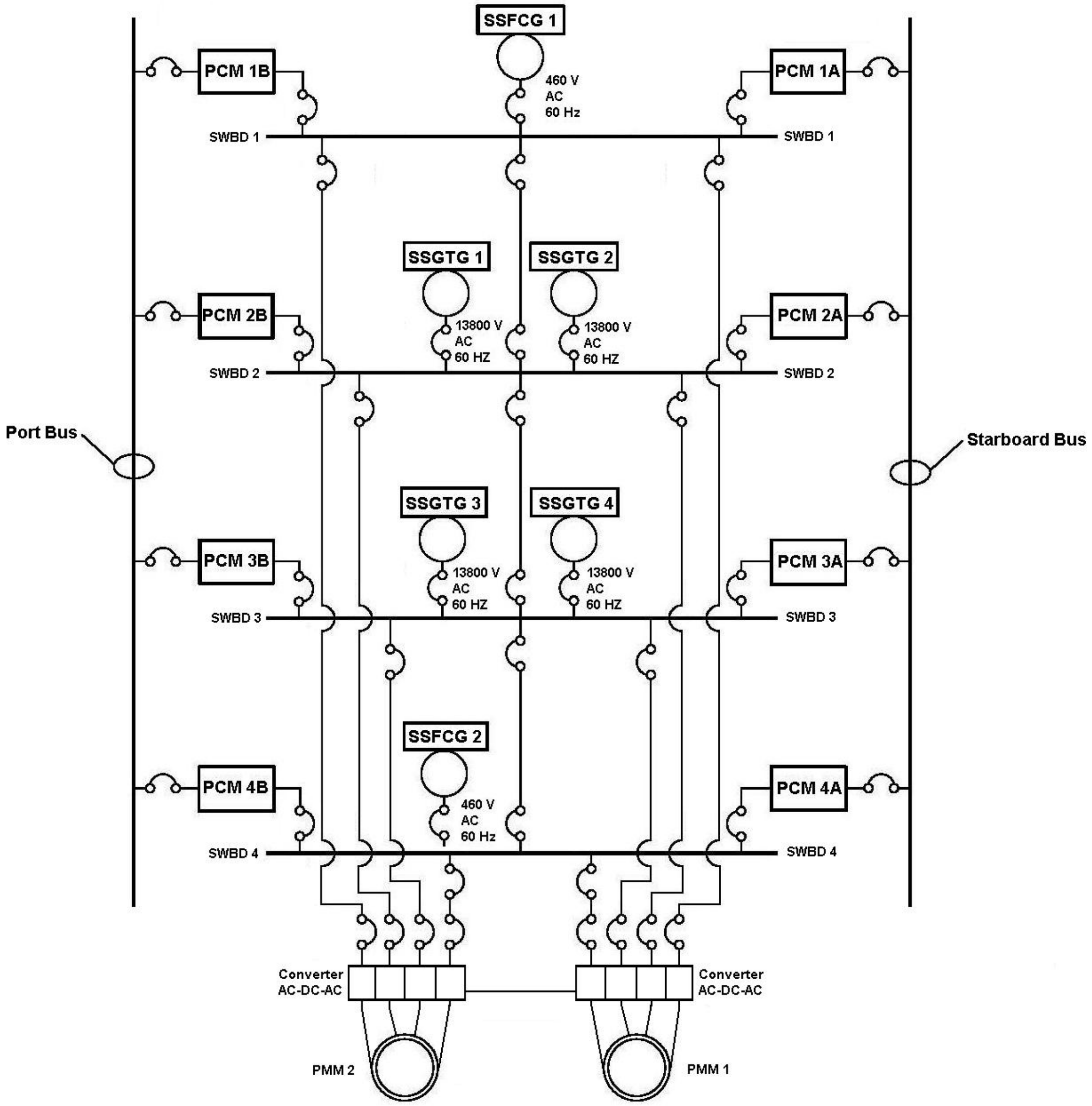
4.7 Mechanical and Electrical Systems

Mechanical and electrical systems are selected based on mission requirements, standard naval requirements for combat ships, and expert opinion. The Machinery Equipment List (MEL) of major mechanical and electrical systems includes quantities, dimensions, weights, and locations. The complete MEL is provided in Appendix D. Partial MELs are provided in Table XX. and Table XX. 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 4.9.2.

4.7.1 Integrated Power System (IPS)

An IPS was chosen for CGXmod because of the benefits that it provides of a conventional geared propulsion system. One benefit of an integrated power system allow for increased survivability because the gas turbines and fuel cells to be decoupled from the shafts and placed in another part of the ship. IPS also eliminates reduction gears, which in turn increases survivability because that is one less critical part that could break while underway. Decreased fuel consumption is another benefit of an IPS because the motors and propellers can each operate independently at their most fuel efficient conditions.

Figure 53 - One-Line Electrical Diagram



4.7.2 Service and Auxiliary Systems

The service and auxiliary systems are standard ones present on a ship. This includes air conditioning, sanitary, water, and pumps.

4.7.3 Ship Service Electrical Distribution

The Ship Service Electrical is part of the IPS. It is integrated as part of this.

4.8 Manning

CGXmod will have a crew of 296 sailors with accommodations for 326. A requirement of 23 officers that comprise of a commanding officer, executive officer, department heads, and division officers is necessary to lead and have responsibility for the vessel. 23 Chief Petty Officers are also required to oversee the smooth running of operations and 250 enlisted sailors will man and maintain the ship. With moderate automation, the size of the crew is considerably smaller than that of the current Ticonderoga class cruiser.

Table 18: Manning summary

Departments	Division	Officers	CPO	Enlisted	Department Totals
Executive/Admin	CO / XO	2	0	0	10
	Department Heads	4	0	0	
	Administration	0	1	3	
Operations	Communications	1	1	12	58
	Navigation and Control	1	1	13	
	Electronic Repair	1	1	12	
	CIC, EW, Intelligence	1	2	12	
Weapons	Air	3	1	13	91
	Boat and Vehicle	0	1	15	
	Deck	1	2	17	
	Ordnance / Gunnery	1	2	17	
	ASW / MCM	1	1	16	
Engineering	Main Propulsion	1	2	28	100
	Electrical / IC	1	1	17	
	Auxiliaries	1	2	22	
	Repair / DC	1	2	22	
Supply	Stores	1	1	7	37
	Material / Repair	1	1	12	
	Mess	1	1	12	
	Total Crew	23	23	250	296
	Accommodations	27	25	275	326

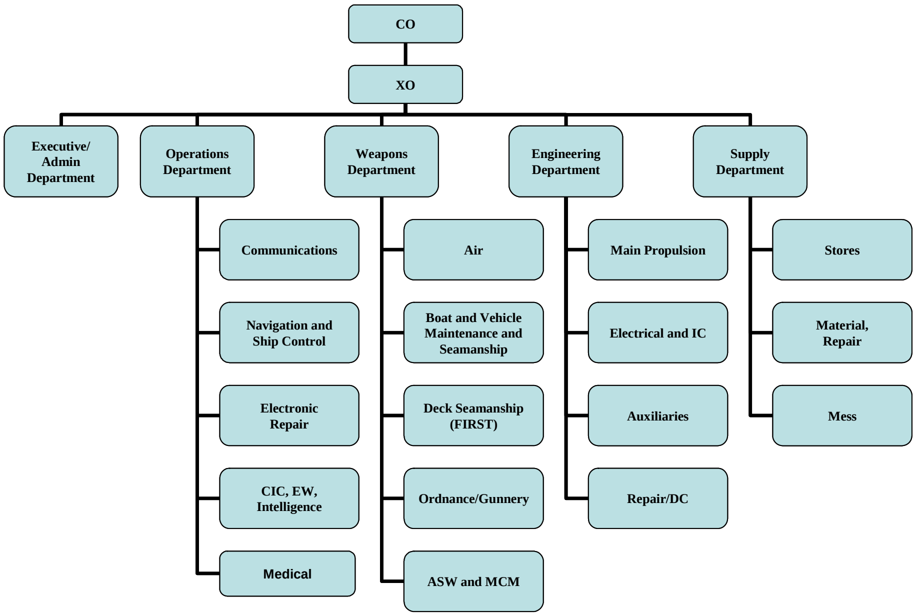


Figure 53: Manning organization

The crew is broken down into departments including operations, weapons, engineering, and supply, and further broken down into several divisions in each department. The commanding officer of a cruiser is a Navy Captain (O-6), the executive officer a Commander (O-5), department heads Lieutenants (O-3) and Lieutenant-Commanders (O-4), and division officers Ensigns (O-1) and Lieutenant, Junior Grades (O-2). The enlisted ranks are headed by a Command Master Chief (E-9) and Chief Petty Officers (E-7 and E-8) that are spread through the departments.

4.9 Space and Arrangements

HECSALV, Rhino and AutoCAD are used to generate and assess subdivision, arrangements and create 2D drawings. HECSALV is used for primary subdivision, tank arrangements and loading. AutoCAD 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 XX.

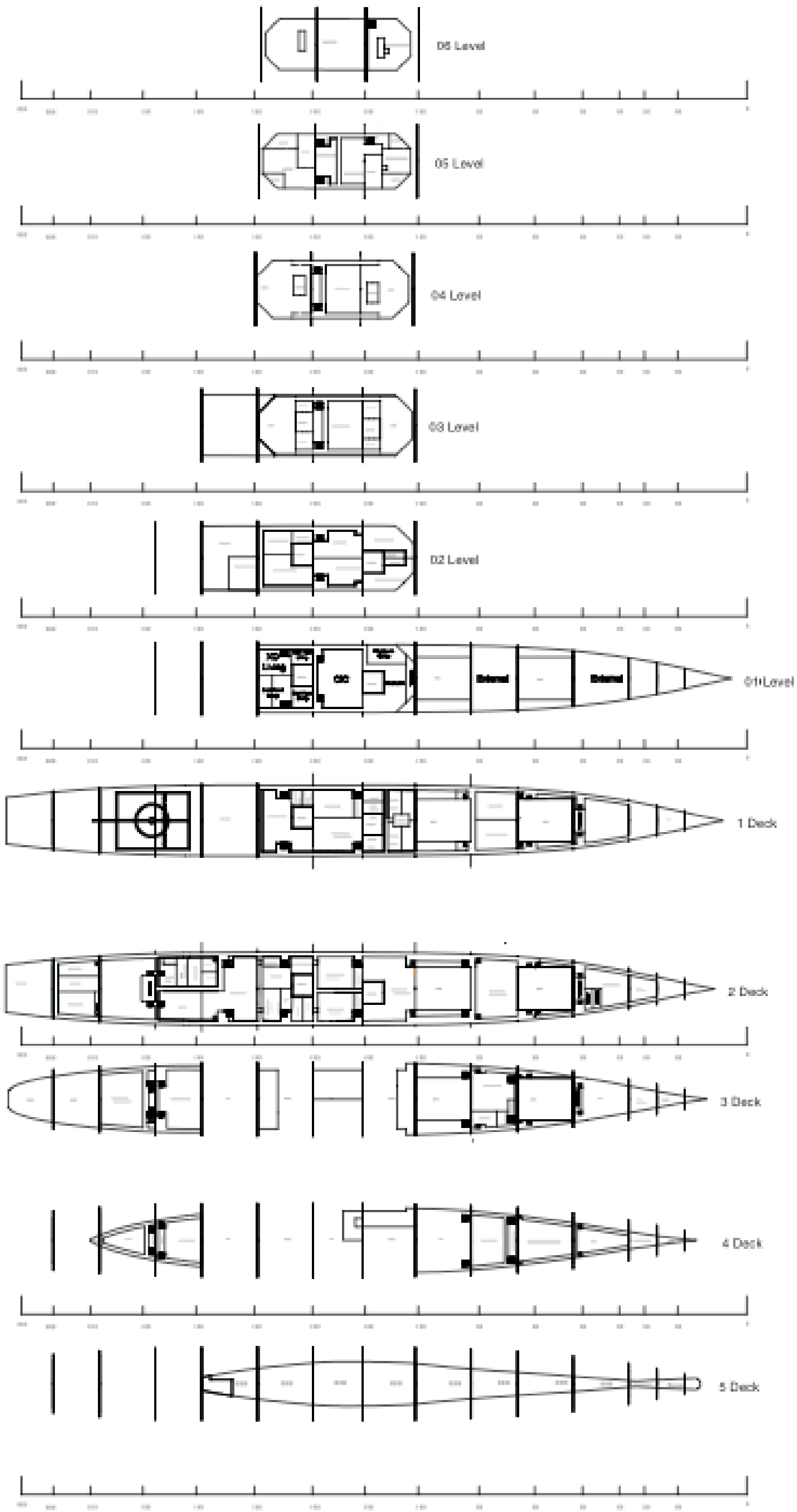


Figure 54. Various views of CGXmod arrangements

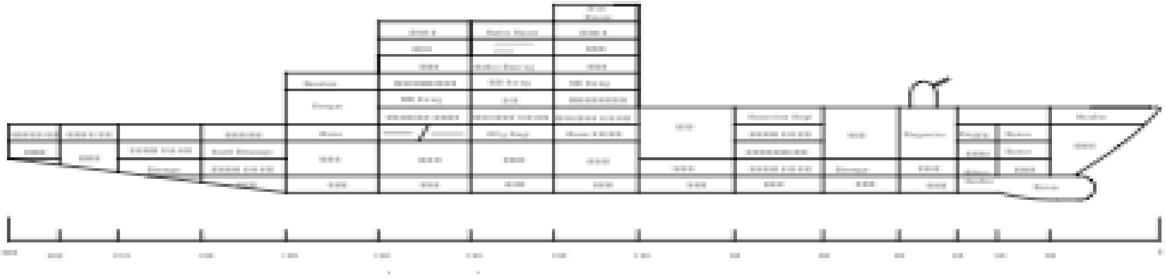


Figure 55 - Profile View Showing Arrangements

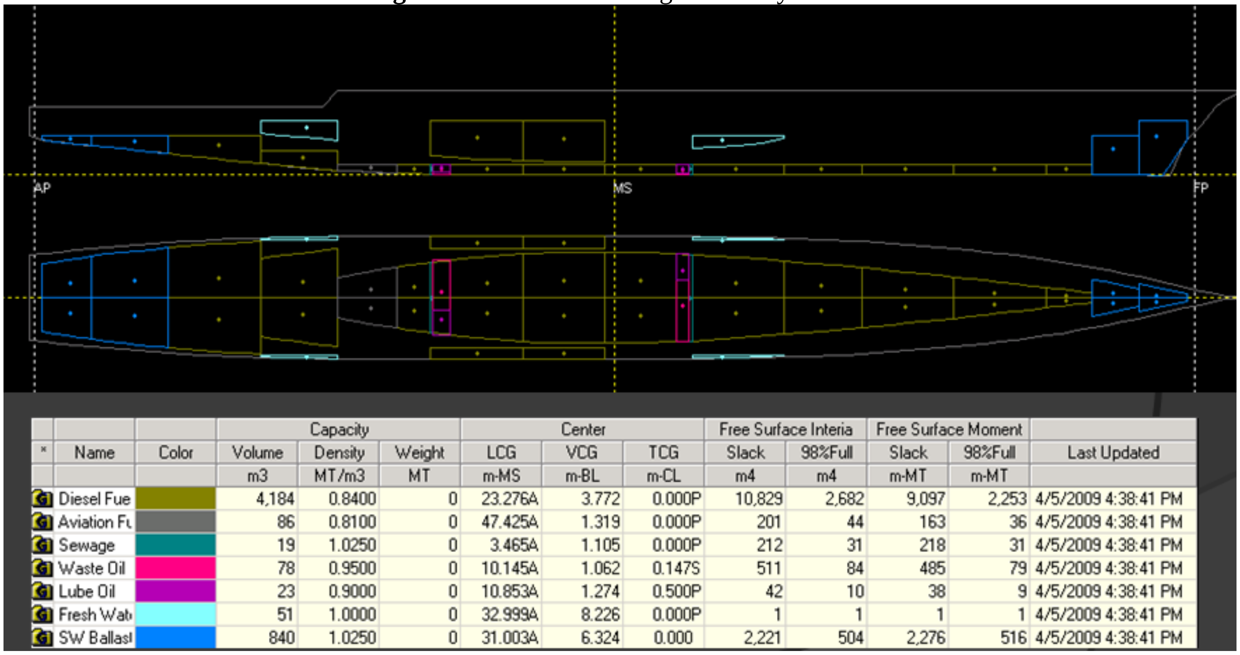
4.9.1 Volume

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 4.9.2 through 4.9.4. Table compares required versus actual tankage volume. Figure 54 shows a plan view of the ship showing only tank locations. The largest weight would come from DFM, so the majority of the diesel was placed in the inner bottom for stability, as well as in close proximity to the main engines. Salt water ballast was placed both fore and aft to best adjust trim. Fresh water is located as wing tanks somewhat higher in the hull separate from other tanks, and is found slightly below crew living spaces. Finally, Figure 54 contains a brief table including tank sizes and locations.

Table 18 – Required vs. Available Tankage Volume

Variable	Required	Final Concept Design
Waste Oil	70	78
Lube Oil	20	23
Potable Water	50	51
Sewage	15	19
Helicopter Fuel (JP5)	80	86
Clean Ballast	800	840
Propulsion Fuel (DFM)	4100	4184

Figure 54. CGXmod tankage summary

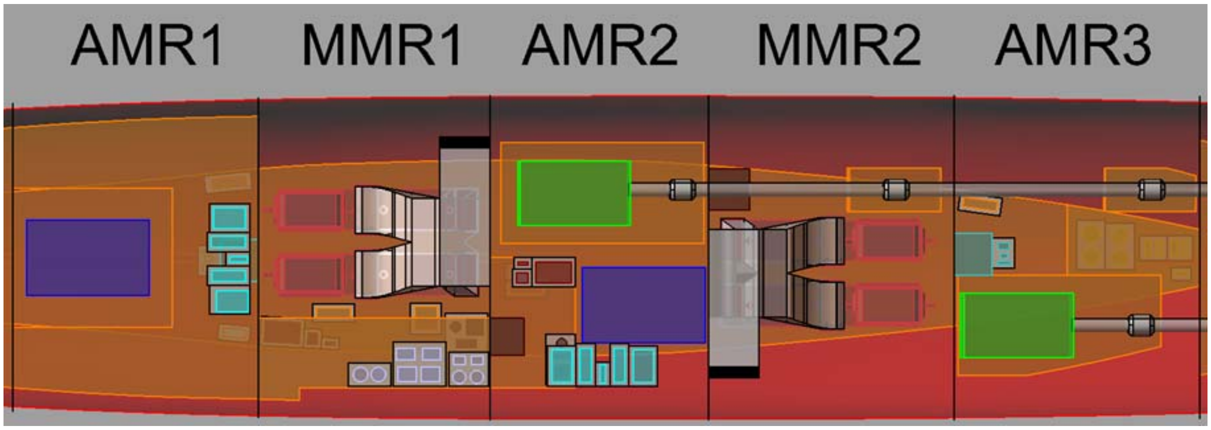


			Capacity			Center			Free Surface Interia		Free Surface Moment		
*	Name	Color	Volume	Density	Weight	LCG	VCG	TCG	Slack	98%Full	Slack	98%Full	Last Updated
			m3	MT/m3	MT	m-MS	m-BL	m-CL	m4	m4	m-MT	m-MT	
G	Diesel Fue	🟨	4,184	0.8400	0	23.276A	3.772	0.000P	10,829	2,682	9,097	2,253	4/5/2009 4:38:41 PM
G	Aviation Fu	⬛	86	0.8100	0	47.425A	1.319	0.000P	201	44	163	36	4/5/2009 4:38:41 PM
G	Sewage	🟩	19	1.0250	0	3.465A	1.105	0.000P	212	31	218	31	4/5/2009 4:38:41 PM
G	Waste Oil	🟥	78	0.9500	0	10.145A	1.062	0.147S	511	84	485	79	4/5/2009 4:38:41 PM
G	Lube Oil	🟪	23	0.9000	0	10.853A	1.274	0.500P	42	10	38	9	4/5/2009 4:38:41 PM
G	Fresh Wat	🟦	51	1.0000	0	32.999A	8.226	0.000P	1	1	1	1	4/5/2009 4:38:41 PM
G	SW Ballast	🟦	840	1.0250	0	31.003A	6.324	0.000	2,221	504	2,276	516	4/5/2009 4:38:41 PM

4.9.2 Main and Auxiliary Machinery Spaces and Machinery Arrangement

In CGXmod, there are three auxiliary machinery rooms (AMR) and two main machinery rooms (MMR). Both MMRs and AMR2 span the 5th, 4th, and 3rd decks. AMR1 and AMR3 span only the 5th and 4th decks. All of the auxiliary machinery is palletized for modularity based on the results of Concept Exploration and the Improved Baseline design.

In AMR1 there is a fuel cell, potable water plant, and a fire and bilge pump on the 5th deck, and one of the air conditioning plants on the 4th deck. In MMR1, two gas turbines take up most of the space on the 5th deck. There is also lube oil, fuel oil, a fire pump, and a ballast pump on the 5th deck. The compressed air equipment and machinery ocupy the 4th deck, and machinery control occupies the 3rd deck. In AMR2, the second fuel cell, starboard motor, and fuel service tank are located on the 5th deck as well as another bilge pump and ballast pump. The fuel service tank is sized for four hours at endurance speed, or 34 cubic meters of fuel. On the 4th deck there is lube oil and fuel oil equipment, and the second air conditioning plant is located on the 3rd deck. In MMR2, the remaining two gas turbines and a fuel service tank are located on the 5th deck. There is nothing else on the 5th or 4th decks because the starboard side shaft limits space. A machinery control space is located on the 3rd deck above the turbines. Last, AMR3 contains the port side motor, the second potable water plant and a fire pump. The JP-5 pump room is also located here between the shafts. This is an appropriate location because the JP-5 tanks are directly below, and the helicopter hangar is directly above. Layouts of the machinery rooms can be seen below in Figures XX- XX.



Equipment	Color	Equipment	Color
A/C & Fridge	L. Blue	JP-5	Yellow
Comp. Air	Purple	Lube Oil	L. Red
Sewage	Brown	Potable Water	D. Blue
Fuel Oil	D. Red	Fire/Salt Water	Orange

Figure 55. CGXmod machinery arrangements

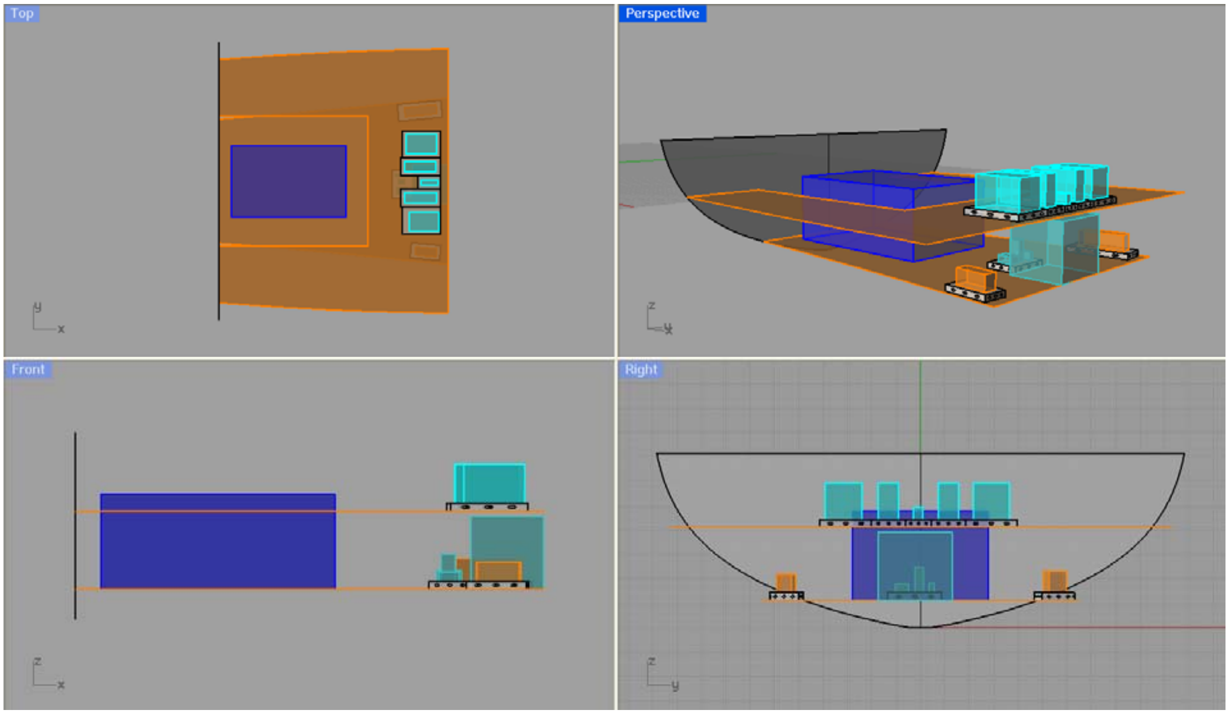


Figure 56. Auxiliary machinery room 1

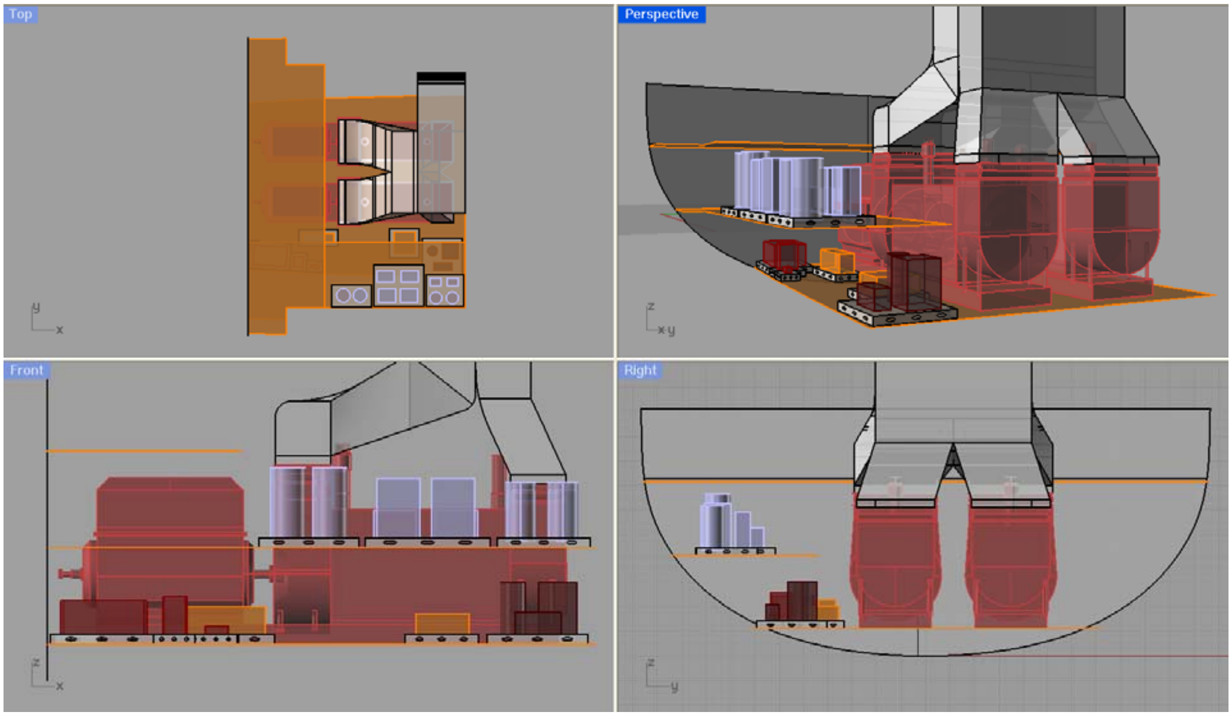


Figure 57. Main machinery room 1

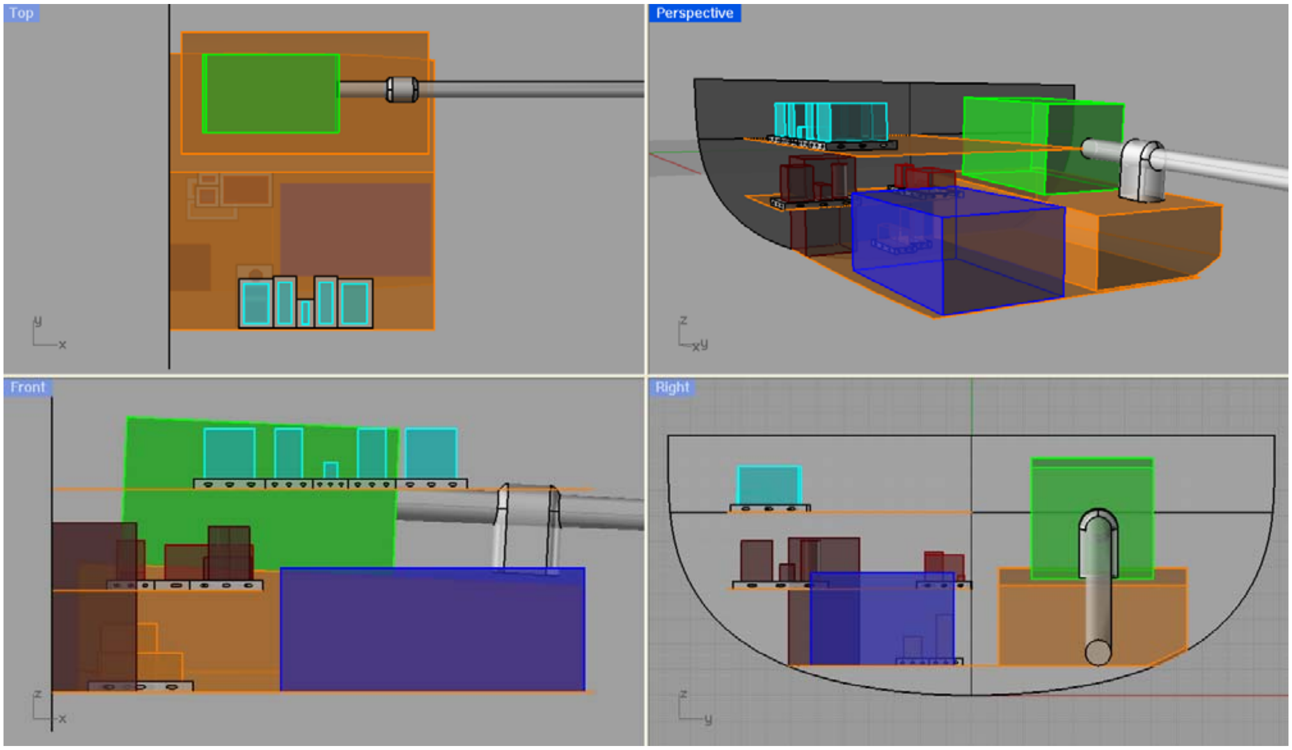


Figure 58. Auxiliary machinery room 2

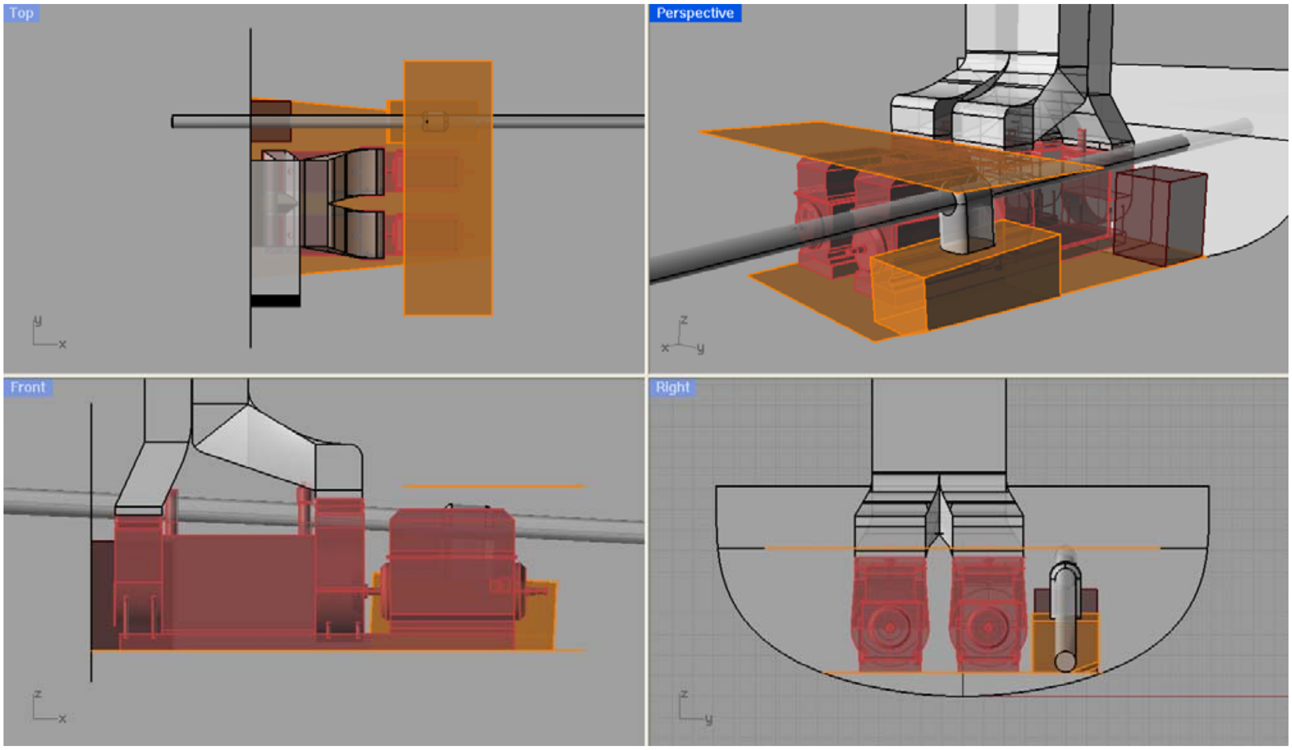


Figure 59. Main machinery room 2

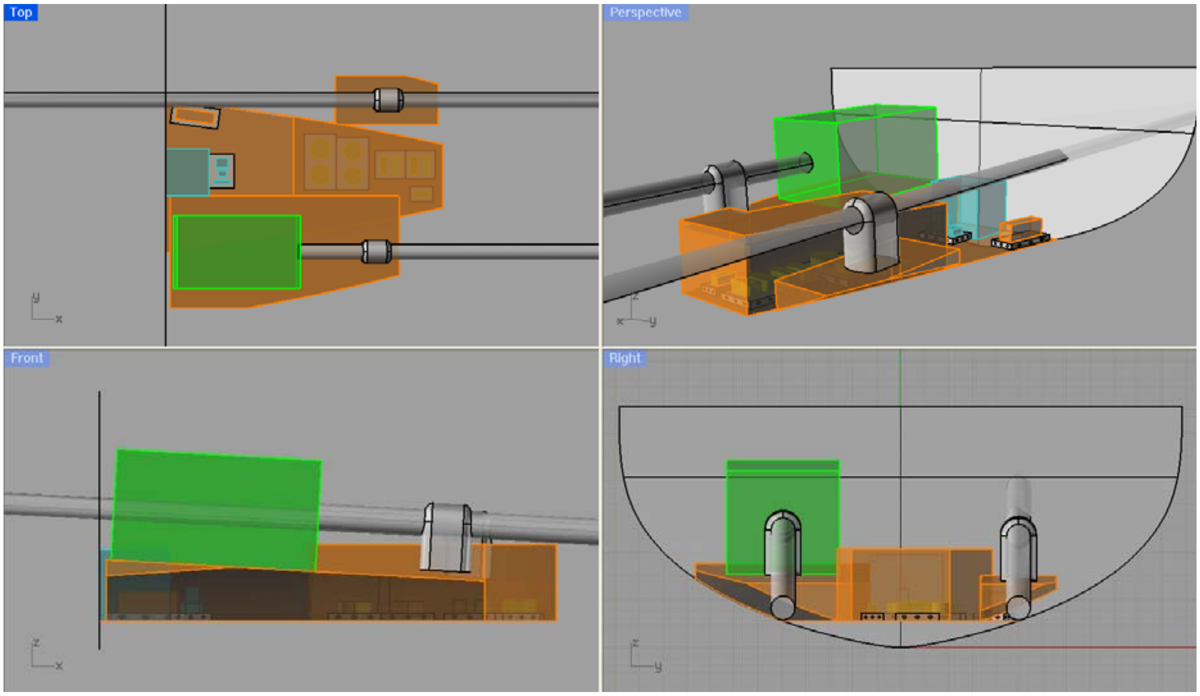


Figure 58. Auxiliary machinery room 3

4.9.3 Internal Arrangements

Figure 52 and 53 give the plan view and profile view of the ships arrangements. The hangar is located at the aft end of the deckhouse superstructure, and can fit two SH-60 helicopters. An aviation shop is directly adjacent to this. CPO and officer living spaces are also on this first deck. The second deck is the damage control deck (DCC), and contains several repair and firefighting stations fore, aft, and at midships, as well as medical facilities. Slightly behind midships is the crew mess and galley. This was put in this location to have the galley be adjacent to the mess, as well as having the food storage directly below the galley for ease of transport. This way, movements are optimized without taking up too much space for storage on the DCC. The second deck also contains the majority of the ships department offices. The first platform contains the food storage and the recreational facilities and laundry areas for the crew. The second platform contains the brig and some general storage spaces. There are crew living spaces fore and aft on both platforms.

4.9.4 Living Arrangements

Crew living and arrangements were estimated using the synthesis model and ASSET results to give baseline information and necessary areas. These areas were refined in the arrangements. Table 4 lists accommodation space for the crew. Figure XX shows the typical berthing and crew mess.

Table 4 - Accommodation Space

Item	Accommodation Quantity	Per Space	Number of Spaces	Area Each (m2)	Total Area (m2)
CO	1	1	1	37.3	37.3
XO	1	1	1	13.9	13.9
Flag Officer	1	1	1	15	15
Department Head	4	1	4	11.6	46.5
Other Officer	20	2	10	12.5	125.4
CPO	25	5	5	13.64	66.4
Enlisted	275	25	11	49.9	549
Officer Sanitary	28	7	4	7	27.9
CPO Sanitary	25	5	5	4	20.3
Enlisted Sanitary	275	25	11	9.3	102.3
Total			77		1004

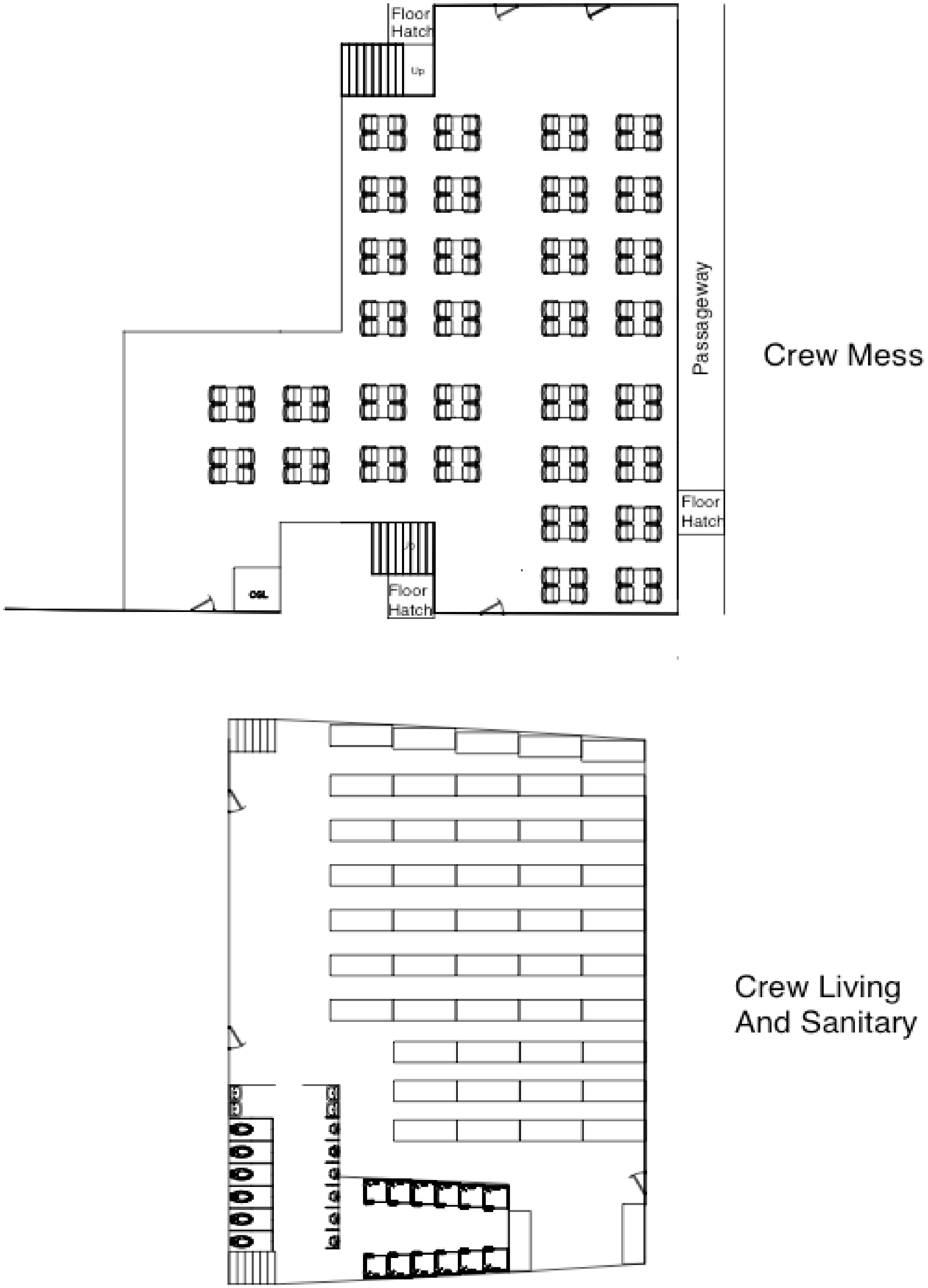


Figure 59: Typical Berthing and Mess Arrangements

4.9.5 External Arrangements

The primary weapons systems of CGXMod are the GMLS, VSR and SPY-3 radars. Figure 60 shows the radius of firing and the radius of effectiveness of the radars.

Figure 60. Weapon systems

4.10 Weights and Loading

4.10.1 Weights

Ship weights are grouped by SWBS. Final weights and centers are estimated using the ship synthesis model, ASSET, HECSALV and available data. A summary of lightship weights and centers for the Final Concept Baseline by SWBS group is listed in Table . Note that this represents a small increase from the previous Improved Concept Baseline.

Table 21 – Final Concept Baseline Lightship Weight Summary

SWBS	Weight	VCG (m-Abv	LCG (m-Aft
100	9816.9	9.28	118.79
200	2442.4	7.33	144.04
300	572.4	9.00	121.51
400	930.5	17.89	79.69
500	2276.8	10.93	139.42
600	1418.5	7.72	110.61
700	615.6	12.70	116.59
Margin	1807.3	11.00	113.35
Total (LS)	19877	10.00	122.66

4.10.2 Loading Conditions

As defined in DDS 079-1, the Full Load Condition consists of the full crew, ammunition loads, and stores. Fuels and other departure liquid loads (except Ballast) are filled to 95% of tank capacity. A summary of weights for the Full Load condition is provided in Table 22. Minimum Operating condition (MinOp) is described as the expected load condition after extended time at sea and is considered the least stable of loading conditions. A full crew complement is maintained, but fuels, ammunitions, and stores are depleted to one-third of full condition with ballast as required for stability. A summary for the Minimum Operating condition is provided in Table 23.

Table 22 - Weight Summary: Full Load Condition – Final Concept Baseline

Item	Weight(MT)	VCG (m-FP)	LCG (m-FP)
Lightship w/ Margin	19877	10.00	122.66
Ships Force	34	11.67	106.56
Total Weapons Loads	327	12.43	117.82
Aircraft	16	16.14	145.00
Provisions	39	8.56	122.43
General Stores	9	9.69	122.43
Diesel Fuel Marine	3260	3.69	136.26
JP-5	66	1.29	160.40
Lubricating Oil	20	1.24	123.85
SW Ballast	0	0.00	0.00
Fresh Water	51	8.22	145.99
Total	23682	9.12	116.78

Table 23 - Weight Summary: Minop Condition

Item	Weight(MT)	VCG (m-FP)	LCG (m-FP)
Lightship	19877	10.00	122.66
Ships Force	34	11.67	106.56
Total Weapons Loads	109	12.43	117.82
Aircraft	16	16.14	145.00
Provisions	13	8.56	122.43
General Stores	3	9.69	122.43
Diesel Fuel Marine	1170	2.61	135.88
JP-5	23	0.89	159.80
Lubricating Oil	7	0.828	123.83
SW Ballast	0	0.00	0.00
Fresh Water	34	7.84	145.95
Total	21270	9.57	114.71

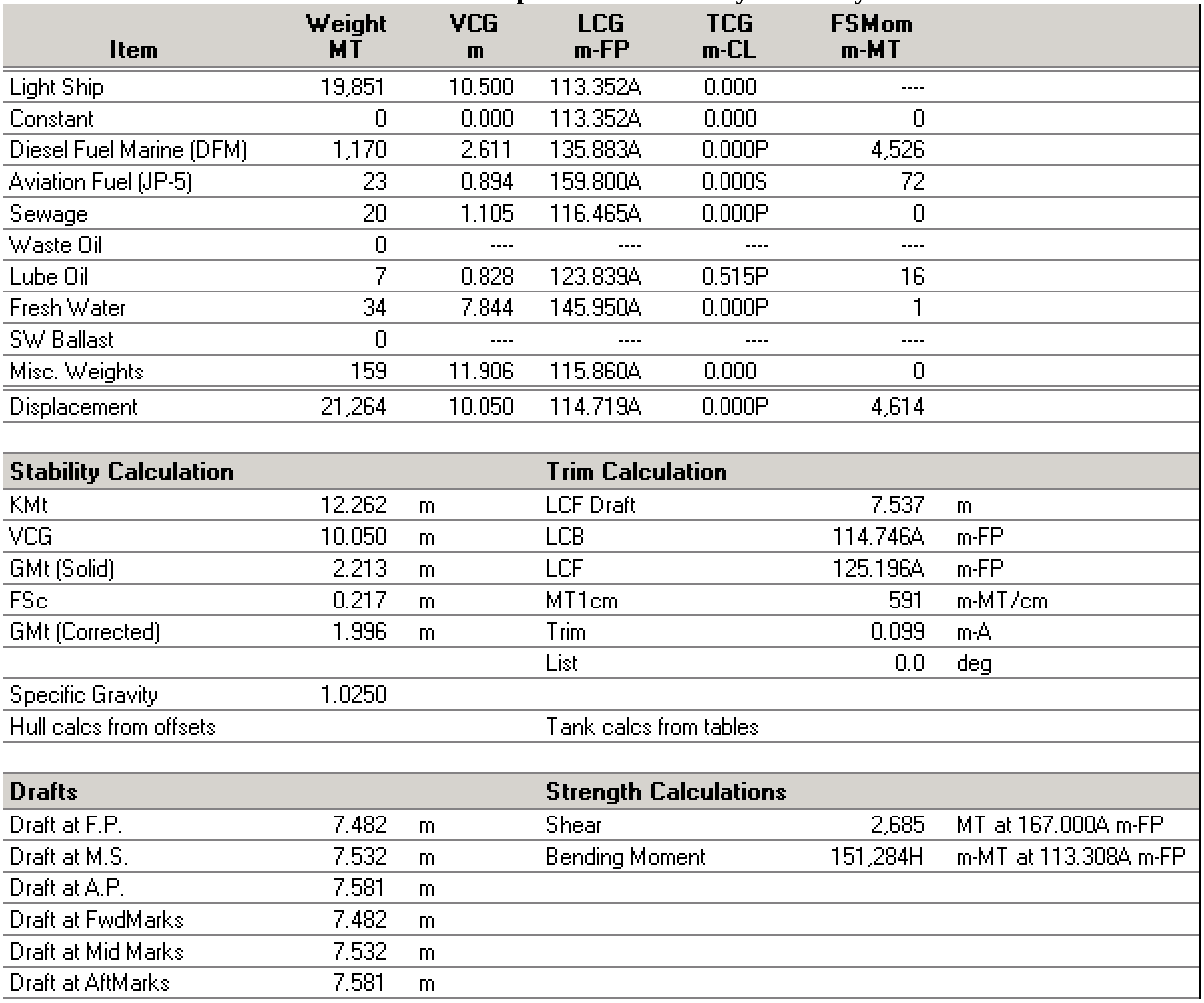
4.10.3 Hydrostatics and Stability – Final Concept Design

Hydrostatics and intact stability is determined in HECSALV in accordance with DDS 079-1 after the tankage, general arrangements, and loading conditions are established for the Final Baseline. An intact trim and stability summary, as well as a righting arm curve and strength summary are calculated using HECSALV. Damage stability is determined using HECSALV and the Herbert Engineering Damage Stability Program. An estimated damage length of 15% of LBP is assumed. A worst case scenario is determined for each loading condition with flooding.

4.10.3.1 Intact Stability

In each condition, trim, stability and righting arm data are calculated. All conditions are assessed using DDS 079-1 stability standards for beam winds with rolling. Intact trim and stability summaries as well as righting arm curves are developed in HECSALV. Both MinOp, shown in Table 24, and Full Load, shown in Table 25, stability summaries show a slight trim by the stern. Wind speed, reference draft, and projected sail area and center are input to determine righting arm curves. CGXmod has adequate stability with respect to transverse heel and roll motions, as seen in MinOp righting arm summary, Table 26, and in the Full Load righting arm summary, Table 27.

Table 24 - Minop Trim and Stability Summary

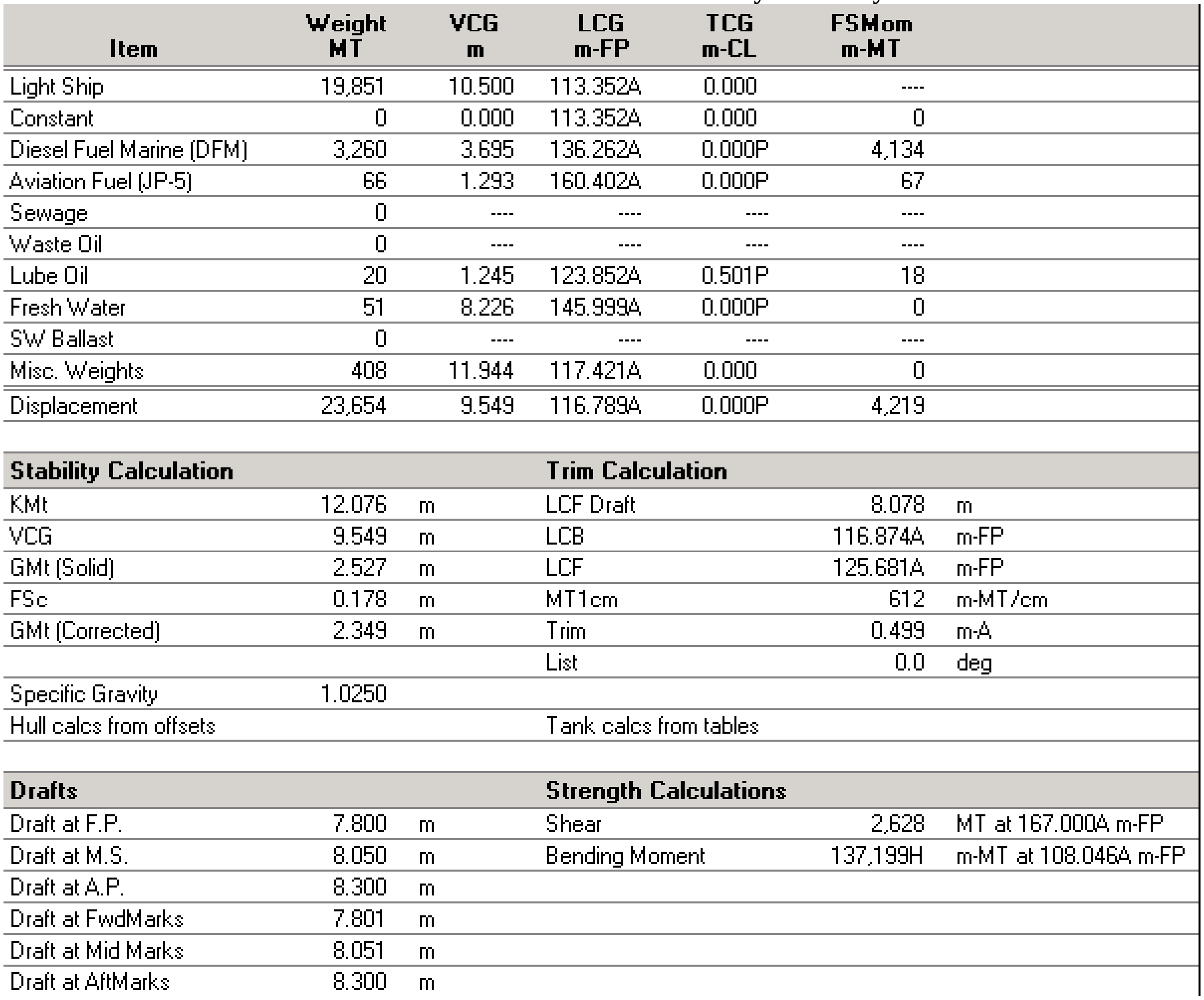


Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT
Light Ship	19,851	10.500	113.352A	0.000	----
Constant	0	0.000	113.352A	0.000	0
Diesel Fuel Marine (DFM)	1,170	2.611	135.883A	0.000P	4,526
Aviation Fuel (JP-5)	23	0.894	159.800A	0.000S	72
Sewage	20	1.105	116.465A	0.000P	0
Waste Oil	0	----	----	----	----
Lube Oil	7	0.828	123.839A	0.515P	16
Fresh Water	34	7.844	145.950A	0.000P	1
SW Ballast	0	----	----	----	----
Misc. Weights	159	11.906	115.860A	0.000	0
Displacement	21,264	10.050	114.719A	0.000P	4,614

Stability Calculation			Trim Calculation		
KMt	12.262	m	LCF Draft	7.537	m
VCG	10.050	m	LCB	114.746A	m-FP
GMt (Solid)	2.213	m	LCF	125.196A	m-FP
FSc	0.217	m	MT1cm	591	m-MT/cm
GMt (Corrected)	1.996	m	Trim	0.099	m-A
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		

Drafts			Strength Calculations		
Draft at F.P.	7.482	m	Shear	2,685	MT at 167.000A m-FP
Draft at M.S.	7.532	m	Bending Moment	151,284H	m-MT at 113.308A m-FP
Draft at A.P.	7.581	m			
Draft at FwdMarks	7.482	m			
Draft at Mid Marks	7.532	m			
Draft at AftMarks	7.581	m			

Table 25 - Full Load Trim and Stability Summary

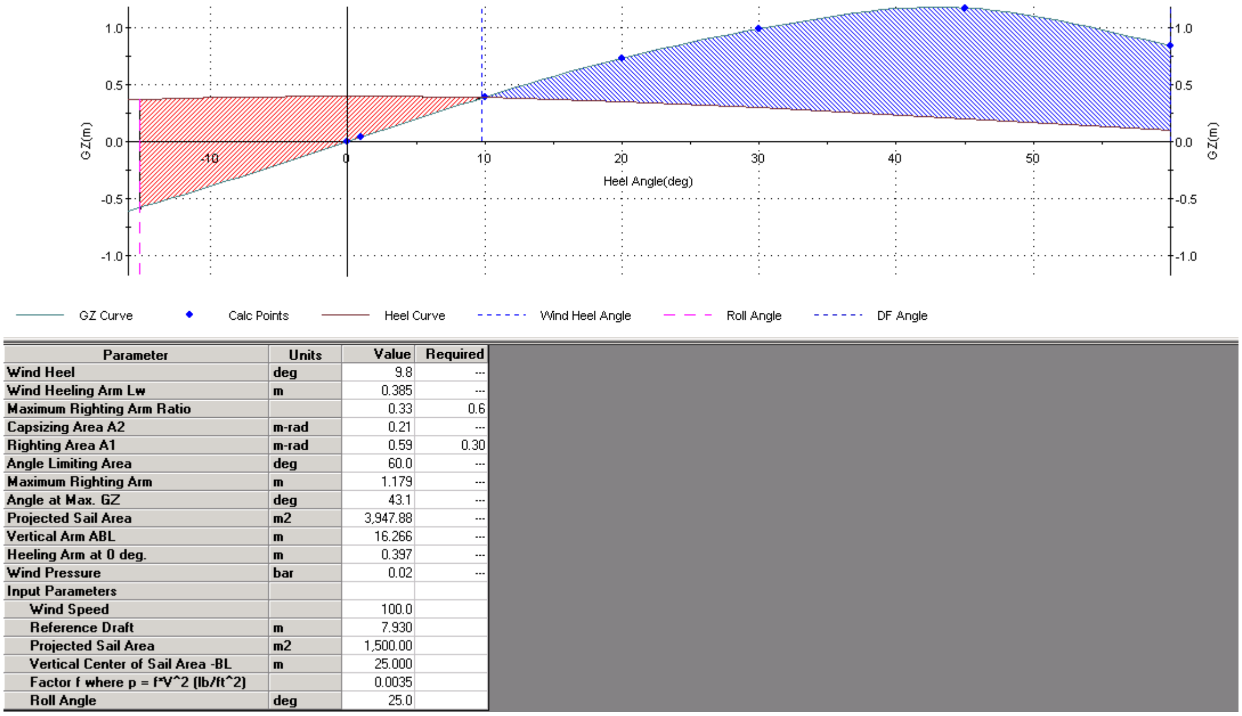


Item	Weight MT	VCG m	LCG m-FP	TCG m-CL	FSMom m-MT
Light Ship	19,851	10.500	113.352A	0.000	----
Constant	0	0.000	113.352A	0.000	0
Diesel Fuel Marine (DFM)	3,260	3.695	136.262A	0.000P	4,134
Aviation Fuel (JP-5)	66	1.293	160.402A	0.000P	67
Sewage	0	----	----	----	----
Waste Oil	0	----	----	----	----
Lube Oil	20	1.245	123.852A	0.501P	18
Fresh Water	51	8.226	145.999A	0.000P	0
SW Ballast	0	----	----	----	----
Misc. Weights	408	11.944	117.421A	0.000	0
Displacement	23,654	9.549	116.789A	0.000P	4,219

Stability Calculation			Trim Calculation		
KMt	12.076	m	LCF Draft	8.078	m
VCG	9.549	m	LCB	116.874A	m-FP
GMt (Solid)	2.527	m	LCF	125.681A	m-FP
FSc	0.178	m	MT1cm	612	m-MT/cm
GMt (Corrected)	2.349	m	Trim	0.499	m-A
			List	0.0	deg
Specific Gravity	1.0250				
Hull calcs from offsets			Tank calcs from tables		

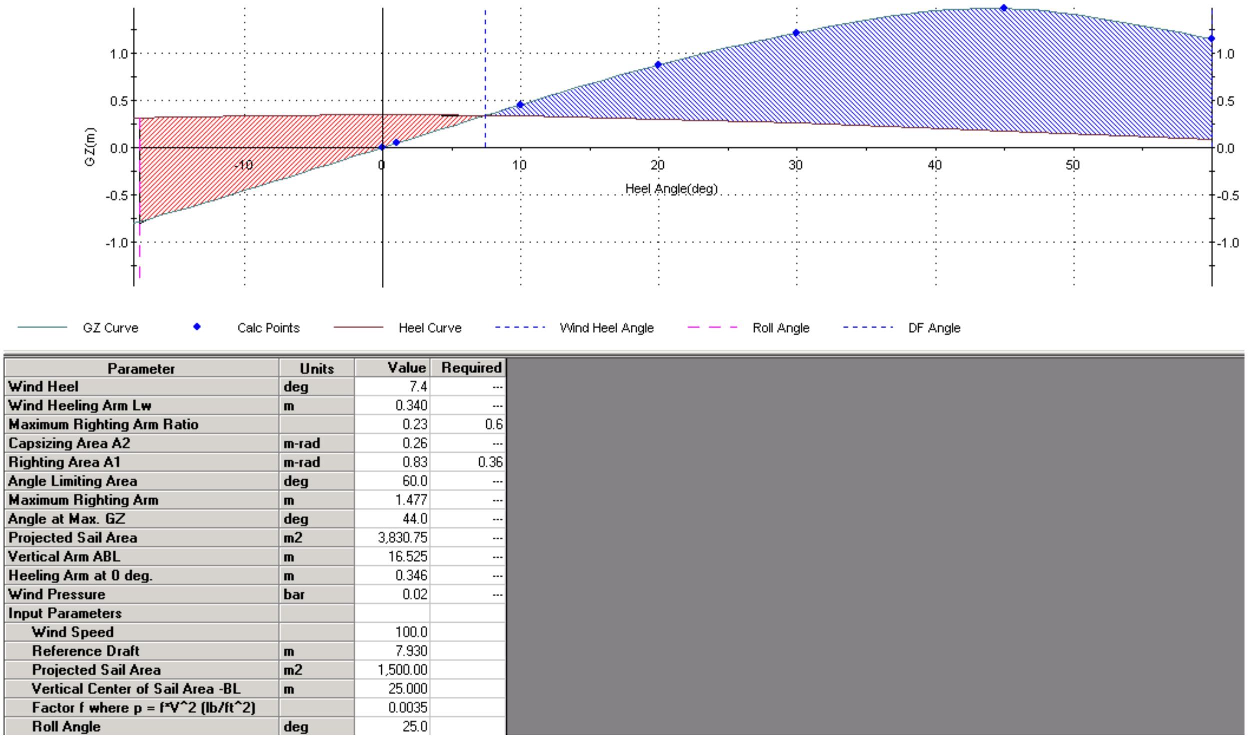
Drafts			Strength Calculations		
Draft at F.P.	7.800	m	Shear	2,628	MT at 167.000A m-FP
Draft at M.S.	8.050	m	Bending Moment	137,199H	m-MT at 108.046A m-FP
Draft at A.P.	8.300	m			
Draft at FwdMarks	7.801	m			
Draft at Mid Marks	8.051	m			
Draft at AftMarks	8.300	m			

Table 26 - Righting Arm (GZ) and Heeling Arm Data for Minop Condition



Parameter	Units	Value	Required
Wind Heel	deg	9.8	---
Wind Heeling Arm Lw	m	0.385	---
Maximum Righting Arm Ratio		0.33	0.6
Capsizing Area A2	m-rad	0.21	---
Righting Area A1	m-rad	0.59	0.30
Angle Limiting Area	deg	60.0	---
Maximum Righting Arm	m	1.179	---
Angle at Max. GZ	deg	43.1	---
Projected Sail Area	m2	3,947.88	---
Vertical Arm ABL	m	16.266	---
Heeling Arm at 0 deg.	m	0.397	---
Wind Pressure	bar	0.02	---
Input Parameters			
Wind Speed		100.0	
Reference Draft	m	7.930	
Projected Sail Area	m2	1,500.00	
Vertical Center of Sail Area -BL	m	25.000	
Factor f where p = f*V^2 (lb/ft^2)		0.0035	
Roll Angle	deg	25.0	

Table 27 - Righting Arm (GZ) and Heeling Arm Data for Full Load Condition



Parameter	Units	Value	Required
Wind Heel	deg	7.4	---
Wind Heeling Arm Lw	m	0.340	---
Maximum Righting Arm Ratio		0.23	0.6
Capsizing Area A2	m-rad	0.26	---
Righting Area A1	m-rad	0.83	0.36
Angle Limiting Area	deg	60.0	---
Maximum Righting Arm	m	1.477	---
Angle at Max. GZ	deg	44.0	---
Projected Sail Area	m2	3,830.75	---
Vertical Arm ABL	m	16.525	---
Heeling Arm at 0 deg.	m	0.346	---
Wind Pressure	bar	0.02	---
Input Parameters			
Wind Speed		100.0	
Reference Draft	m	7.930	
Projected Sail Area	m2	1,500.00	
Vertical Center of Sail Area -BL	m	25.000	
Factor f where p = f*V^2 (lb/ft^2)		0.0035	
Roll Angle	deg	25.0	

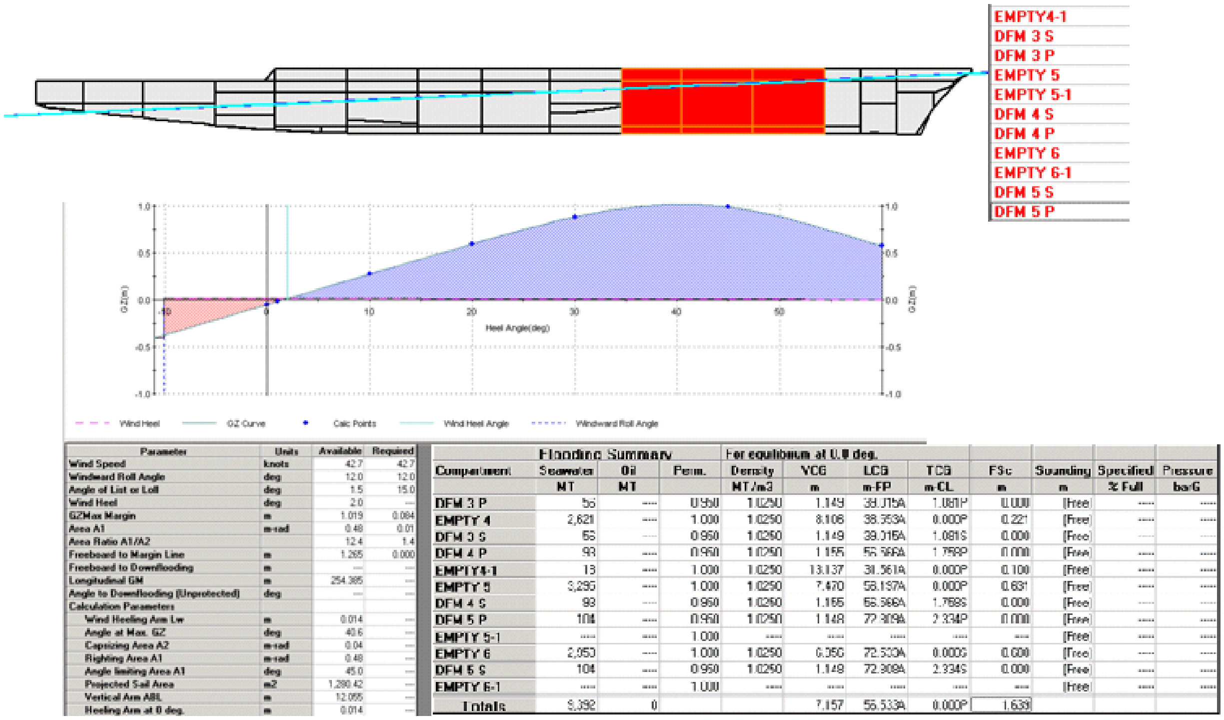
4.10.4 Damage Stability

In accordance with DDS 079-0, damage stability was determined. Damage cases were considered taking roughly 15% of LBP and damaging all compartments within range. 23 cases were created in HEC Damage Stability over the length of the ship, ranging from 2 to 3 compartments. Worse cases were determined from largest differential in trim and moved to HECSALV to estimate detailed impact of flooding.

As shown in Figure 61 and Table 28, the worst case for MinOp was a 3-compartment damage case towards the bow of the ship, leading to significant trim, but not exceeding the margin line. The worst case for Full Load was a 3-compartment damage case at the stern of the ship, shown in Figure 61 and Table 28, also acceptable.

Table 28 – Minop Worse-Case Damage Results

	Intact	Damage BH 6-42
Draft AP (m)	7.183 m	4.790 m
Draft FP (m)	7.453 m	14.613 m
Trim on LBP (m)	0.269A m	9.823F m
Total Weight (MT)	21,264 MT	29,616 MT
Static Heel (deg)	0.0 deg	0.0 deg
GM_t (upright) (m)	2.571 m	1.855 m
Maximum GZ	1.179 m	1.019 m



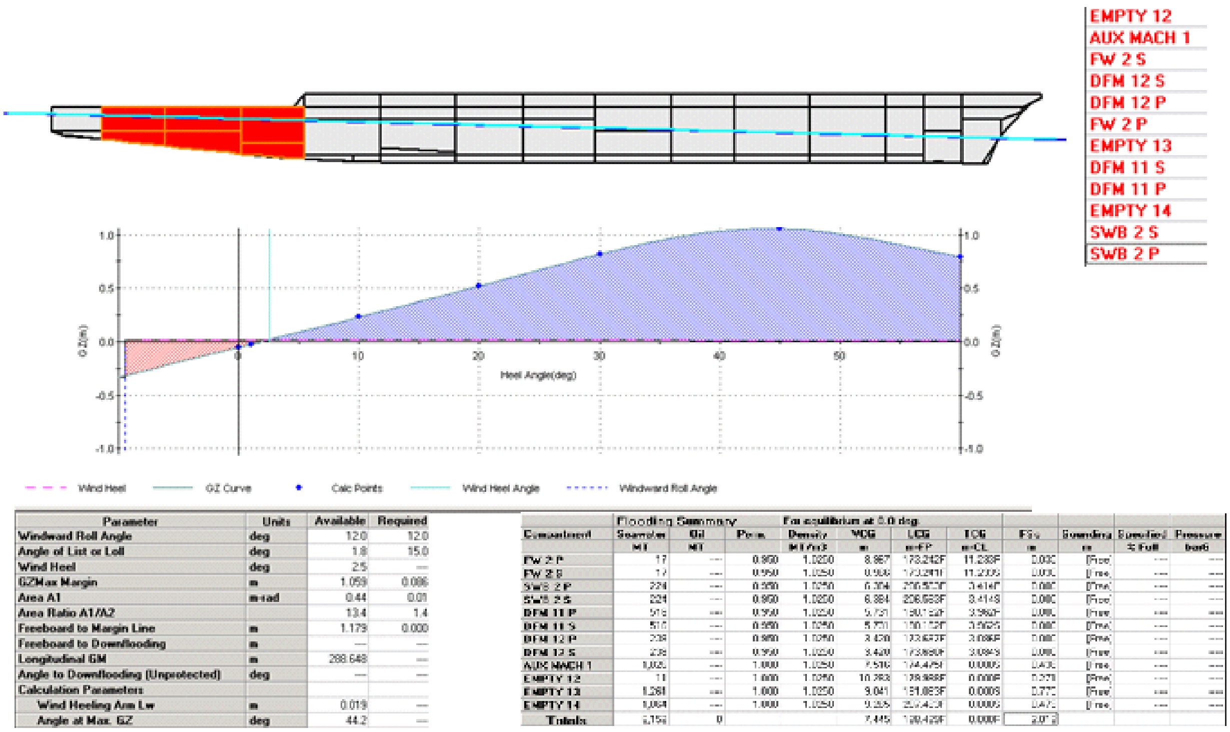
Parameter	Units	Available	Required
Wind Speed	knots	42.7	42.7
Windward Roll Angle	deg	12.0	12.0
Angle of List or Loll	deg	1.5	15.0
Wind Heel	deg	2.0	---
GZMax Margin	m	1.019	0.084
Area A1	m-rad	0.48	0.01
Area Ratio A1/A2		12.4	1.4
Freeboard to Margin Line	m	1.265	0.000
Freeboard to Downflooding	m	---	---
Longitudinal GM	m	254.385	---
Angle to Downflooding (Unprotected)	deg	---	---
Calculation Parameters			
Wind Heeling Arm Lw	m	0.014	---
Angle at Max. GZ	deg	40.6	---
Capsizing Area A2	m-rad	0.04	---
Righting Area A1	m-rad	0.48	---
Angle limiting Area A1	deg	45.0	---
Projected Sail Area	m2	1,280.42	---
Vertical Arm ABL	m	12.055	---
Heeling Arm at 0 deg.	m	0.014	---

	Flooding Summary			For equilibrium at 0.0 deg.							
Compartment	Seawater MT	Oil MT	Perm.	Density MT/m3	VCG m	LCG m-FP	TCG m-CL	FSc m	Sounding m	Specified % Full	Pressure bar/G
DFM 3 P	56	----	0.950	1.0250	1.149	39.015A	1.081P	0.000	(Free)	----	----
EMPTY 4	2,621	----	1.000	1.0250	8.106	38.353A	0.000P	0.221	(Free)	----	----
DFM 3 S	56	----	0.950	1.0250	1.149	39.015A	1.081S	0.000	(Free)	----	----
DFM 4 P	93	----	0.950	1.0250	1.155	55.966A	1.768P	0.000	(Free)	----	----
EMPTY4-1	13	----	1.000	1.0250	13.137	31.561A	0.000P	0.100	(Free)	----	----
EMPTY 5	3,295	----	1.000	1.0250	7.470	58.197A	0.000P	0.631	(Free)	----	----
DFM 4 S	93	----	0.950	1.0250	1.155	55.966A	1.768S	0.000	(Free)	----	----
DFM 5 P	104	----	0.950	1.0250	1.148	72.309A	2.334P	0.000	(Free)	----	----
EMPTY 5-1	----	----	1.000	----	----	----	----	----	(Free)	----	----
EMPTY 6	2,053	----	1.000	1.0250	6.356	72.530A	0.000S	0.000	(Free)	----	----
DFM 5 S	104	----	0.950	1.0250	1.149	72.309A	2.334S	0.000	(Free)	----	----
EMPTY 6-1	----	----	1.000	----	----	----	----	----	(Free)	----	----
Totals	8,392	0			7.157	56.533A	0.000P	1.639			

Figure 61 - Minop Worse-Case Damage Case

Table 28 - Full Load Worse-Case Damage Results

	Intact	Damage BH 6-42
Draft AP (m)	8.300 m	11.497 m
Draft FP (m)	7.800 m	5.779 m
Trim on LBP (m)	0.500A m	5.718A m
Total Weight (MT)	23,654 MT	27,725 MT
Static Heel (deg)	0.0	0.0
GM_t (upright) (m)	2.955 m	1.534 m
Maximum GZ	1.477 m	1.059 m
Maximum GZ Angle	44.0 deg	44.2 deg
GZ Pos. Range (deg)	7.0-60.0 deg	3.0-60.0 deg



Parameter	Units	Available	Required
Windward Roll Angle	deg	12.0	12.0
Angle of List or Loll	deg	1.8	15.0
Wind Heel	deg	2.5	---
GZMax Margin	m	1.059	0.086
Area A1	m-rad	0.44	0.01
Area Ratio A1/A2		13.4	1.4
Freeboard to Margin Line	m	1.179	0.000
Freeboard to Downflooding	m	---	---
Longitudinal GM	m	288.648	---
Angle to Downflooding (Unprotected)	deg	---	---
Calculation Parameters			
Wind Heeling Arm Lw	m	0.019	---
Angle at Max. GZ	deg	44.2	---

	Flooding Summary			For equilibrium at 0.0 deg.							
Compartment	Seawater MT	Oil MT	Perm.	Density MT/m3	VCG m	LCG m-FP	TCG m-CL	FSs m	Sounding m	Specified % Full	Pressure barG
FW 2 P	17	---	0.950	1.0250	8.967	173.242F	11.238F	0.000	[Free]	---	---
FW 2 S	17	---	0.950	1.0250	8.966	173.241F	11.220S	0.000	[Free]	---	---
SWB 2 P	224	---	0.950	1.0250	6.384	206.583F	3.414P	0.000	[Free]	---	---
SWB 2 S	224	---	0.950	1.0250	6.384	206.583F	3.414S	0.000	[Free]	---	---
DFM 11 P	516	---	0.950	1.0250	5.731	150.152F	3.562P	0.000	[Free]	---	---
DFM 11 S	516	---	0.950	1.0250	5.731	150.152F	3.562S	0.000	[Free]	---	---
DFM 12 P	238	---	0.950	1.0250	3.420	173.687F	3.086P	0.000	[Free]	---	---
DFM 12 S	238	---	0.950	1.0250	3.420	173.690F	3.084S	0.000	[Free]	---	---
AUX MACH 1	1,025	---	1.000	1.0250	7.510	144.475F	0.000S	0.430	[Free]	---	---
EMPTY 12	11	---	1.000	1.0250	10.283	128.988F	0.000F	0.271	[Free]	---	---
EMPTY 13	1,281	---	1.000	1.0250	9.041	151.083F	0.000S	0.772	[Free]	---	---
EMPTY 14	1,064	---	1.000	1.0250	9.235	257.423F	0.000S	0.475	[Free]	---	---
Totals	6,158	0			7.445	128.429F	0.000F	2.073			

Figure 62 - Full Load Worse-Case Damage Case

4.11 Seakeeping

Seakeeping is an important part of any ship design. Unfortunately this remains unfinished. This year a new program was used to calculate seakeeping, PDStrip, and it introduced many issues. PDStrip is a freeware seakeeping program that uses strip theory embedded in fortran code to calculate ship motions. It does not calculate them directly, and it requires much more additional processing to actually obtain the ship motion equations and values. Table 29 is the setup and the values that need to be found from PDStrip.

Table 29 - Limiting Motion Criteria (Significant Amplitude) and Results

Application	Roll	Pitch	Yaw	Longitudinal Acceleration	Transverse Acceleration	Vertical Acceleration	ORD Threshold SeaState	Sea State Achieved

4.12 Cost and Risk Analysis

4.12.1 Cost and Producibility

The cost for the CGXmod lead ship is estimated to be approximately $4.85 billion, a slight overrun from the $4 billion dollar goal price set at the beginning of the acquisition process. The lead ship cost is estimated to be $3.09 billion. Although this ship class has a high acquisition cost, total cost of the class is comparatively reduced because of the low life-cycle cost at $4.18 billion. The modularity designed into the ship drastically lowers lifecycle cost because the modular systems can be quickly changed or updated without time consuming design changes. The total cost for the CGXmod class is approximately $139 billion compared to $185 billion for last year's design.

The producibility is greatly increased for CGXmod over a traditionally built ship because of the modularity. The modular combat systems, habitability spaces and machinery equipment can be assembled quickly and efficiently on shore and then installed on the ship in one unit. The only factor decreasing the producibility of CGXmod is the bow. The top portion of the bow slopes from a flared hull to a ten degree slope at the deckhouse. This may be difficult to produce early in the ship class until the shipyard develops an efficient way to build it.

Table 30 - Cost Comparison

ENGINEERING INPUT	Concept Baseline	Final Concept Baseline
Hull Structure Material (select one)		
Steel	1	1
Aluminum	0	0
Composite	0	0
Deckhouse Material (select one)		
Steel	1	1
Aluminum	0	0
Composite	0	0
Hull Form (select one)		
Monohull	1	1
Catamaran	0	0
Trimaran	0	0
Plant Type (select one)		
Gas Turbine	1	1
Diesel	0	0
Diesel Electric	0	0
CODOG	0	0
CODAG	0	0
Power Plant (select one)		
Power Rating (in SHP)	102409	102409
Main Propulsion Type (select one)		
Fixed Pitch Propeller	1	1
Controllable Pitch Propeller	0	0
Waterjet	0	0
Weights (metric tons)		
100 (less deckhouse)	9280	9280
150 (deckhouse)	536	536
200 (less propeller)	2352	2352
245 (propeller)	90	90
300	572	572
400	930	930
500	2276	2276
600	1418	1418
700	615	615
Margin	1806	903
Lightship	19875	18972
Full Load Displacement	23654	22746
Operation and Support		
Complement		
Steaming Hrs Underway / Yr		
Fuel Usage (BBL / Yr)	132860	132860

Service Life (Yrs)	30	30
Cost Element	**Concept Baseline**	**Final Concept Baseline**
Shipbuilder	$1.065 B	$1.065 B
Government Furnished Equipment (a)	$1.603 B	$1.603 B
Other Costs	$47.826 M	$47.826 M
Operating and Support		
Personnel (Direct & Indirect)	$910.200 M	$910.200 M
Unit Level Consumption (Fuel, Supplies, Stores)	$14.101 M	$14.101 M
Maintenance & Support	$117.324 M	$117.324 M
Life Cycle Cost	$4.176 B	$4.176 B

LCC Threshold	**$4B**
Average Acquisition Cost	**$2.175B**
Average Acquisition Cost Threshold	**$3B**

4.12.2 Risk Analysis

The estimated overall measure of risk (OMOR) for CGXmod is 0.233. This is slightly higher than what would typically be accepted because the ship is using two fuel cells. Fuel cells are unproven technology on ships and there is an associated risk involved with installing them. However, this risk has been mitigated a little be leaving enough room for them to be replaced by diesels if need be. Inserting the diesels into the ship would essentially be a “plug-and-play” and no design changes would be necessary. Also contributing to the high OMOR are the new radars installed on ship. CGXmod is the first ship to use the SPY-3 and Volume Search Radar (VSR). The ship is basically a test platform to see how well the radars work as well as fixing any reliability issues that surface. Although modularity reduces the cost of CGXmod, it increases the risk. Modularity has never been successfully implemented on a U.S. Navy ship on a large scale before. Any issues regarding the reliability as well as survivability in high sea states will have to be addressed and corrected early on, so they can be fixed on later ships that are still in the shipyard.

5 Conclusions and Future Work

5.1 Assessment

The design was able to meet the goals set forth in the preliminary design.

Table 31 - Compliance with Concept Development Document Thresholds

MOP #	MOP	Metric	Goal	Threshold	Final Baseline Design
1	AAW / BMD	AAW Option	AAW = 1	AAW = 4	AAW = 1
		GMLS Option	GMLS = 1	GMLS = 4	GMLS = 1
		C4I Option	C4I = 1	C4I = 2	C4I = 1
2	ASW	ASW Option	ASW =1	ASW = 4	ASW =1
		LAMPS Option	LAMPS=1	LAMPS = 3	LAMPS=1
		C4I Option	C4I =1	C4I = 2	C4I =1
3	ASUW / NSFS	ASUW Option	ASUW=1	ASUW = 4	ASUW=1
		LAMPS Option	LAMPS=1	LAMPS = 3	LAMPS=1
		C4I Option	C4I =1	C4I = 2	C4I =1
4	C4I	C4I Option	C4I=1	C4I = 2	C4I=1
5	STK	GMLS Option	GMLS=1	GMLS = 2	GMLS=1
		C4I Option	C4I=1	C4I = 2	C4I=1
6	Sustained Speed	knt	Vs = 35knt	Vs = 30 knt	Vs = 35knt
7	Endurance Range	nm	E = 8000 nm	E = 5000 nm	E = 8000 nm
8	Provisions Duration	days	Ts = 75 days	Ts = 60 days	Ts = 75 days
9	Seakeeping	McCreight Index	McC = 15	McC = 4	McC = 15
10	NBC	CPS Option	NCPS = 1	NCPS = 1	NCPS = 1
11	RCS	m^3	VD = 11000 m^3	VD = 15000 m^3	VD = 11000 m^3
12	Acoustic Signature	SPGM	SPGM = 5, 6, 7	SPGM = 1	SPGM = 5, 6, 7
13	IR Signature	SPGM	SPGM = 5, 6, 7	SPGM = 2	SPGM = 5, 6, 7
14	Magnetic Signature	Ndegaus	Ndegaus = 1	Ndegaus = 0	Ndegaus = 1
15	Modularity for Upgrade	C4I Option	C4I = 2	C4I = 3	C4I = 2
		HM&E Option	HM&E = 1	HM&E = 4	HM&E = 1
		SENS Option	SENS = 1	SENS = 3	SENS = 1
		HAB Option	HAB = 1	HAB = 2	HAB = 1
		WEAP Option	WEAP = 1	WEAP = 4	WEAP = 1
16	Modularity for Replacement	C4I Option	C4I = 2	C4I = 3	C4I = 2
		HM&E Option	HM&E = 1	HM&E = 4	HM&E = 1

		SENS Option	SENS = 1	SENS = 3	SENS = 1
		HAB Option	HAB = 1	HAB = 3	HAB = 1
		WEAP Option	WEAP = 1	WEAP = 4	WEAP = 1
17	Surge	knt	Vsur = 25 knt	Vsur = 20 knt	Vsur = 25 knt
18	Vulnerability	Cdhmat	Cdhmat = 1	Cdhmat = 3	Cdhmat = 1

5.2 Future Work

In the future the design should be have more iterations of every calculation. This will help to reduce cost and increase effectiveness. This would include lighter structures and more mission effectiveness. Seakeeping is also future work. Seakeeping is an extensive process and because of software issues, the timeline ran out.

5.3 Conclusions

CGXMod is an effective design that incorporates modularity. The modularity will increase the life of the ship while decreasing the life-cycle cost. While the initial investment into the technologies to make the ship modular are much more expensive, the savings comes in as the age of the ship increases. The modularity allows for quick reconfigurations and re-outfitting for a more mission effective cruiser. This allows for a better cruiser to be part of the fleet.

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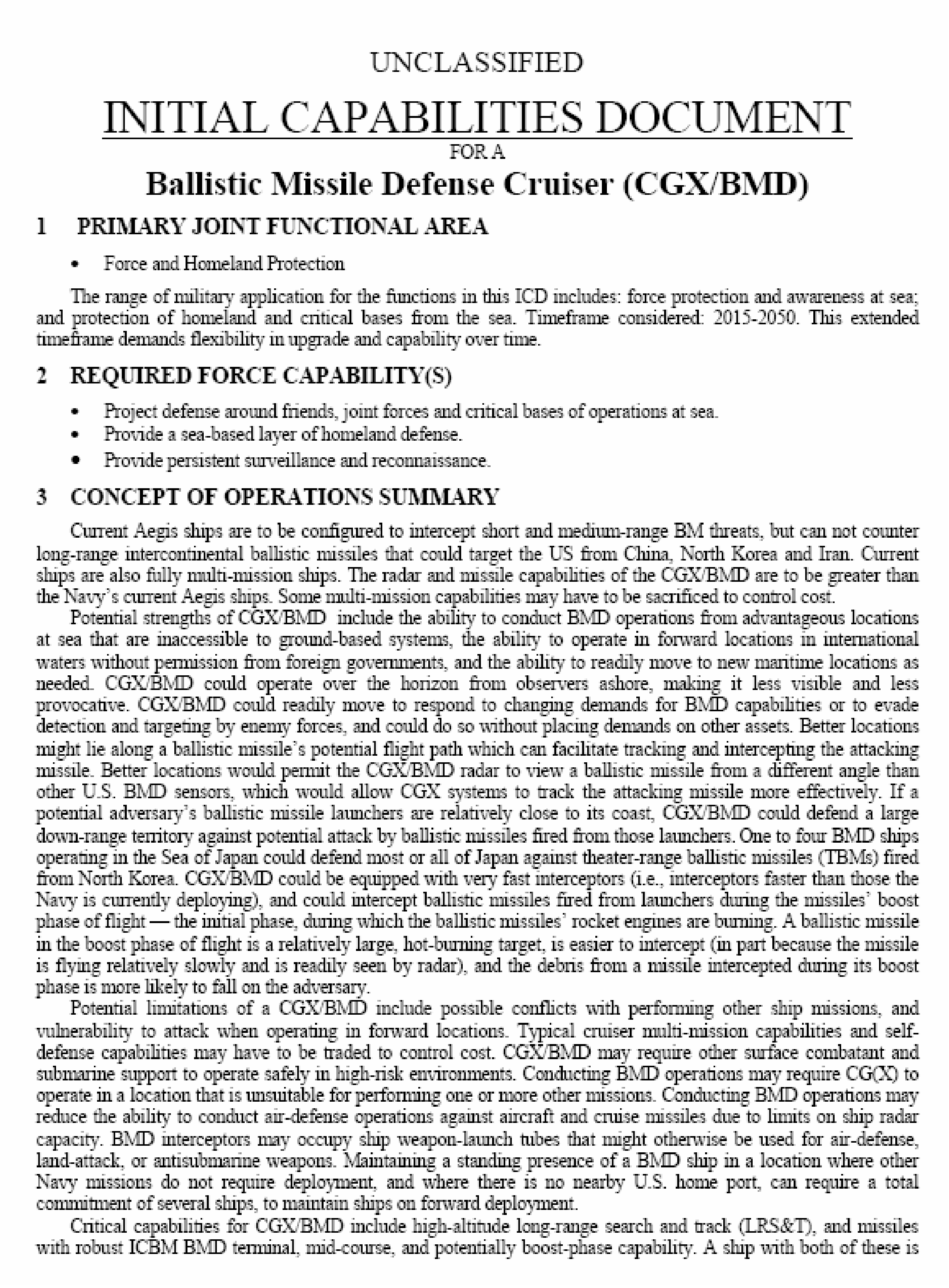
Appendix A – Initial Capabilities Document (ICD)



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.

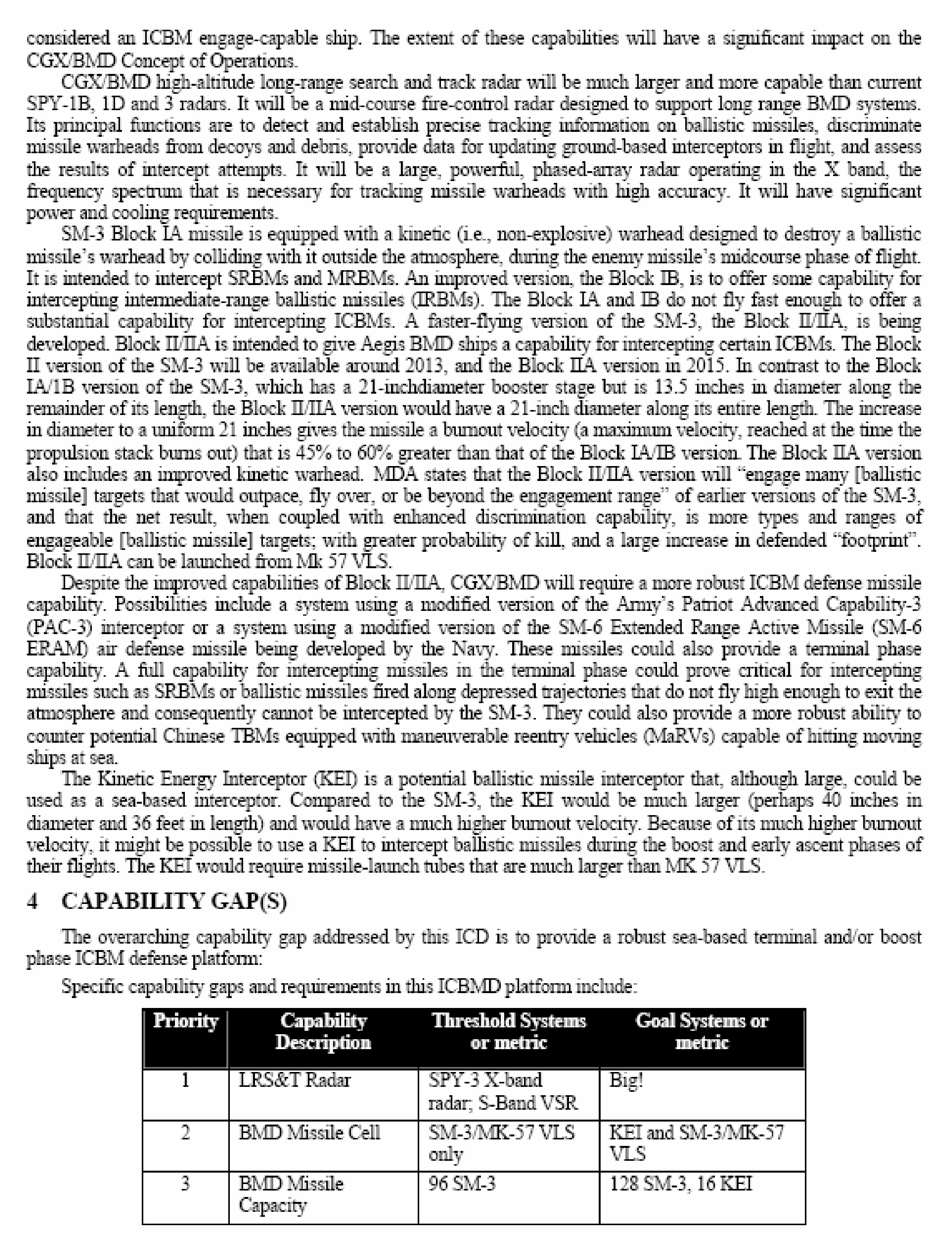
3 CONCEPT OF OPERATIONS SUMMARY

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

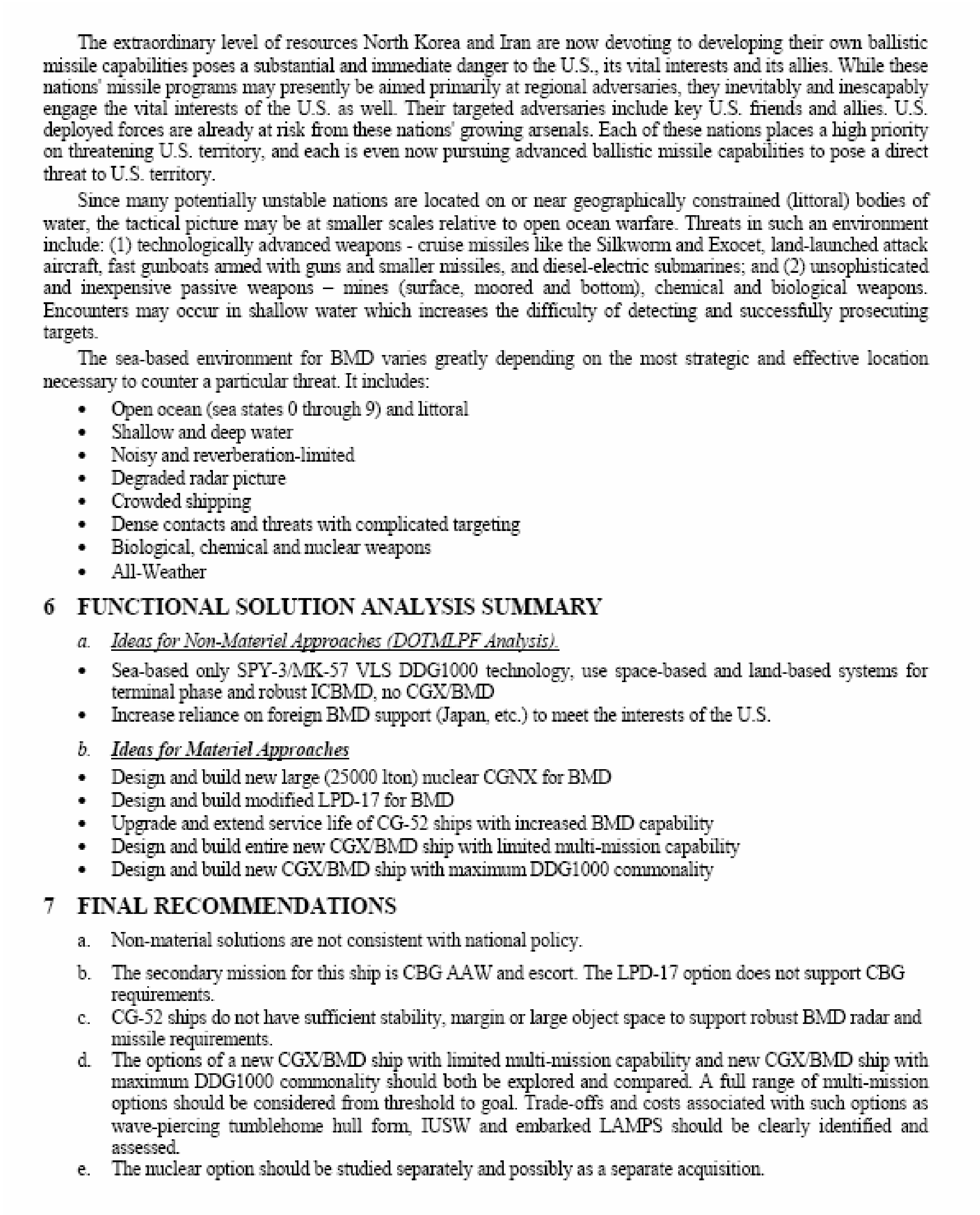
5 THREAT AND OPERATIONAL ENVIRONMENT

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.

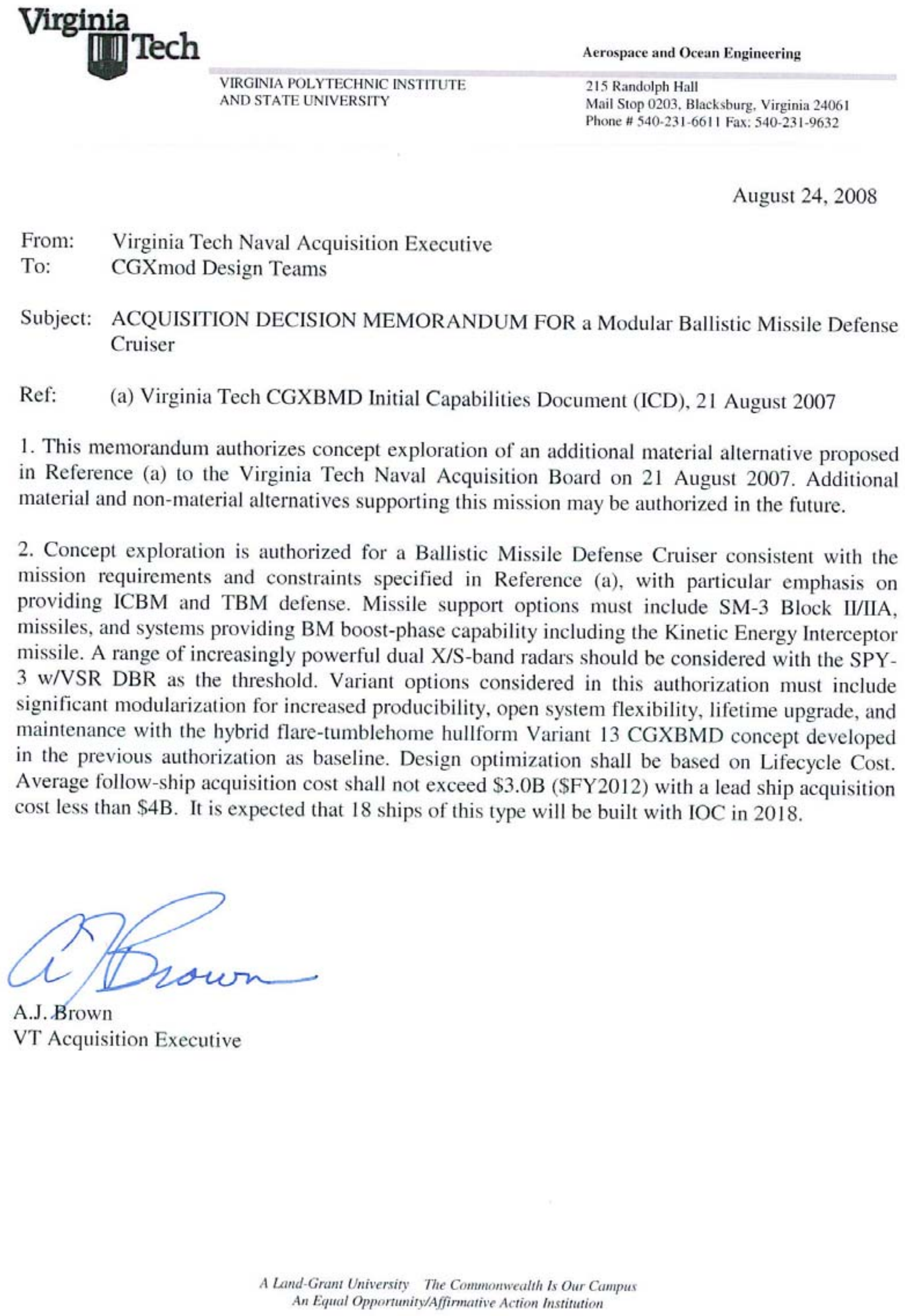
b. The secondary mission for this ship is CBG AAW and escort. The LPD-17 option does not support CBG requirements.

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)



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August 24, 2008

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

Subject: ACQUISITION DECISION MEMORANDUM FOR a Modular Ballistic Missile Defense Cruiser

Ref: (a) Virginia Tech CGXBMD Initial Capabilities Document (ICD), 21 August 2007

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

2. Concept exploration is authorized for a Ballistic Missile Defense Cruiser consistent with the mission requirements and constraints specified in Reference (a), with particular emphasis on providing ICBM and TBM defense. Missile support options must include SM-3 Block II/IIA, missiles, and systems providing BM boost-phase capability including the Kinetic Energy Interceptor missile. A range of increasingly powerful dual X/S-band radars should be considered with the SPY-3 w/VSR DBR as the threshold. Variant options considered in this authorization must include significant modularization for increased producibility, open system flexibility, lifetime upgrade, and maintenance with the hybrid flare-tumblehome hullform Variant 13 CGXBMD concept developed in the previous authorization as baseline. Design optimization shall be based on Lifecycle Cost. Average follow-ship acquisition cost shall not exceed $3.0B ($FY2012) with a lead ship acquisition cost less than $4B. It is expected that 18 ships of this type will be built with IOC in 2018.

A Brown

A.J. Brown
VT Acquisition Executive

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