UNITED STATES COAST GUARD ACADEMY

Naval Architecture and Marine Engineering

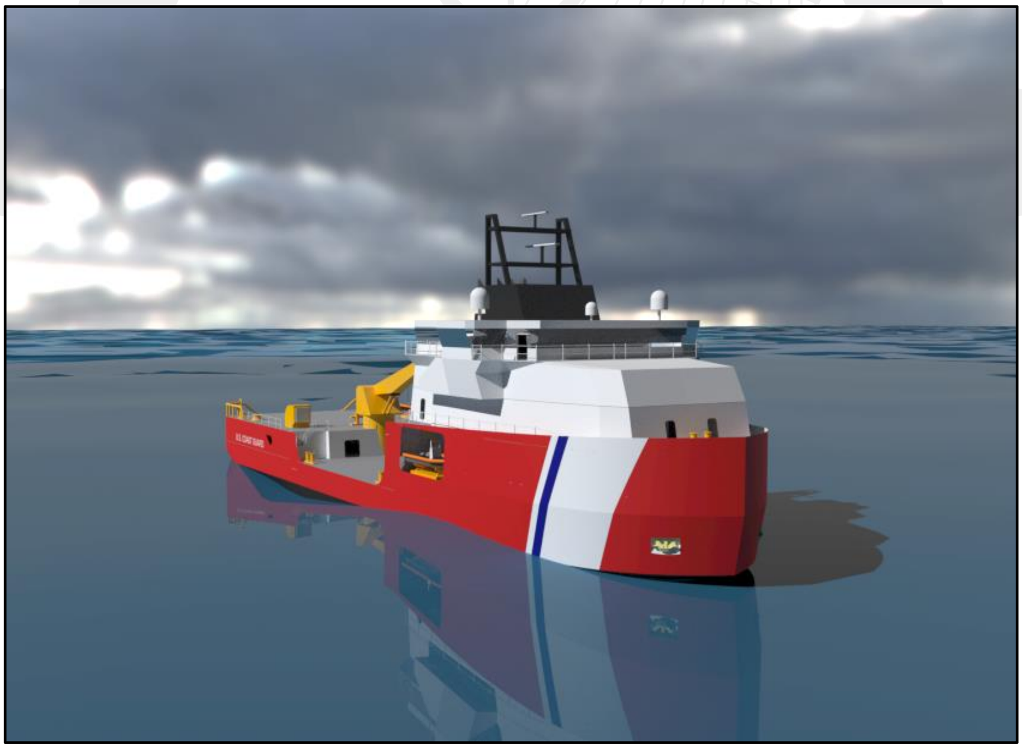
James A. Lisnyk Student Design Competition

May 2024

Khione Horizon Architects LTD.

The Maritime Transportation Cutter

A Heavy Great Lakes Icebreaker for the U.S. Coast Guard



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Faculty Advisor Statement

By this statement, I certify that the work done for this design competition was completed by the student team members.

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Dr. DeNucci

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ABBREVIATIONS

Abbreviation	Meaning	Abbreviation	Meaning
ABS	American Bureau of Shipping	LCG	Longitudinal Center of Gravity
AFFF	Aqueous Film Forming Foam	LOA	Length Overall
AMR	Auxiliary Machinery Room	LWL	Length Waterline
ATON	Aids to Navigation	MBL	Molded Baseline
BHP	Brake Horsepower	MDG	Main Diesel Generator
BOA	Beam Overall	MMR	Main Machinery Room
C_b	Block Coefficient	MSD	Marine Sanitation Device
CL	Centerline	MTC	Maritime Transportation Cutter
C_p	Prismatic Coefficient	OSV	Offshore Supply Vessel
D&C	Design and Construction	OTH	Over The Horizon
DCC	Damage Control Central	PODAC	Product Oriented Design & Construction
DOMICE	Domestic Icebreaking	PSD	Principles of Ship Design
DPC	Design Practices and Criteria	PWCS	Ports, Waterways, and Coastal Security
DWL	Design Waterline	ROV	Remote Operated Vehicle
EAR	Expanded Area Ratio	SAR	Search and Rescue
ECR	Engine Control Room	SFOC	Specific Fuel Oil Consumption
EHP	Effective Horsepower	SLA	Service Life Allowance
EOSL	End of Service Life	SPD	Ship Propulsion Design
EPA	Environmental Protection Agency	STBD	Starboard
EPLA	Electric Power Load Analysis	SWBS	Ship Work Breakdown Structure
ESS	Energy Storage Solution	TCG	Transverse Center of Gravity
HPU	Hydraulic Power Unit	TWTB	Transverse Watertight Bulkhead
I/B	Icebreaking	UIB	Ultimate Icebreaking Bow
ICU	Intensive Care Unit	USCG	United States Coast Guard
KG	Keel to Center of Gravity	VCG	Vertical Cener of Gravity
KHA	Khione Horizon Architects	VFD	Variable Frequency Drive
KPP	Key Performance Parameter	WQSB	Watch Quarter Station Bill

Maritime Transportation Cutter
Summary
Khione Horizon Architects LTD.

This report describes a year of design work for a new heavy Great Lakes icebreaker to complement the current heavy icebreaker, USCGC MACKINAW, on the Great Lakes. The scope of this design iteration includes the following:

- Research into the need for a new Great Lakes icebreaker
- Develop needs statement and requirements
- Development of a guiding design philosophy
- Performed a market analysis
- Development of a novel hull design
- Powering estimation from resistance predictions
- Performed a Electric Power Load Analysis
- and propulsion plant choices
- Tow tank resistance validation
- General arrangements and crewing
- Weight estimates
- Initial structure calculations
- Intact and damage stability analyses
- Seakeeping predictions
- Crewing
- Cost estimates

Table 1. Principal Characteristics

Length overall (ft)	285
Length between perpendiculars (ft)	270
Beam (ft)	70
Draft (ft)	18
C_b	0.59
C_p	0.62
Displacement (LT)	5,580
Design cruise speed (Knots)	10
Design icebreaking speed (Knots at 24-in of ice)	8
Flank Speed (Knots)	15
Installed power (kW)	9,260
Officer complement	10
Enlisted complement	36

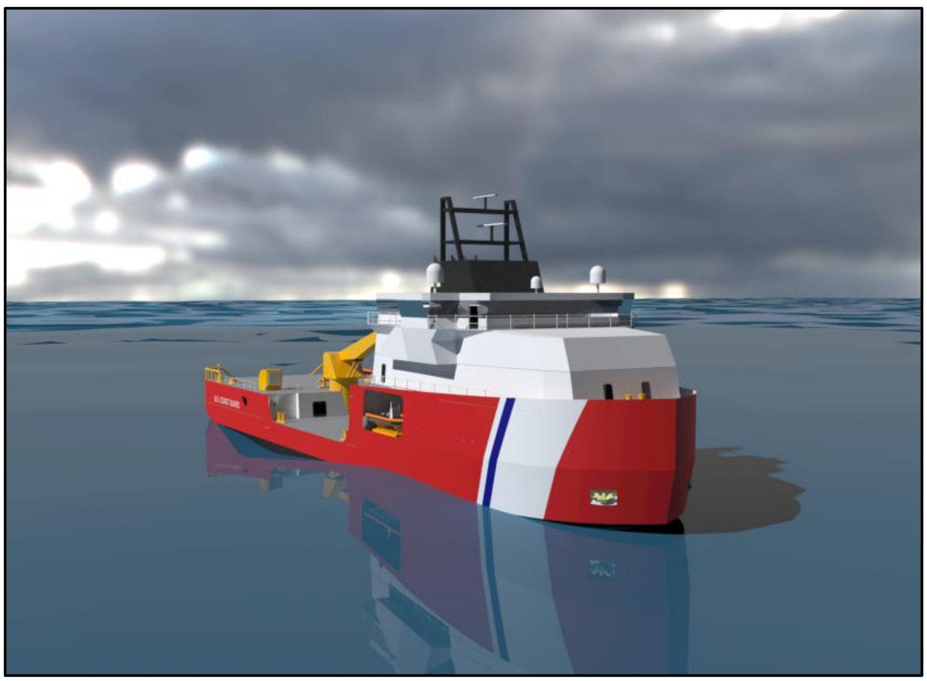

Figure 1. Render of The Maritime Transportation Cutter

Maritime Transportation Cutter
Design Report
Khione Horizon Architects LTD.

In response to insufficient redundancy in heavy ice breaking capabilities and the degradation of the US Coast Guard's ice breaking fleet in the Great Lakes, Khione Horizon Architects designed a new, multipurpose, heavy icebreaking vessel, the MTC, to fill vital gaps and provide unmatched capabilities to the Coast Guard's District 9 cutter fleet. Compared to its parent ship, the USCGC MACKINAW, the MTC notably has a larger displacement, wider beam, a more efficient ice breaking hull form, and a larger and more efficient, hybrid power plant, thereby making it capable of breaking more ice and doing additional Coast Guard missions more efficiently. Similarly to its parent ship, it has two azimuthing thrusters and a bow thruster which greatly improve maneuverability. When not breaking ice, the MTC is well suited for ATON operations, boasting high stability, a large buoy deck, and a telescoping crane. Furthermore, mission flexibility is a key focus of this design, featuring a significant payload capacity, and large cargo holds and deck space for modular containers to augment the base capabilities and make it the highly adaptable kind of asset that the Coast Guard needs. While the MTC is a Great Lakes icebreaker, this asset is not restricted to District 9. The MTC is an immensely capable platform with high mission flexibility and wide applicability, making the MTC an excellent class of vessel for the Great Lakes as well as Northern US ports as political focus continues to shift to polar security.

INTRODUCTION
Khione Horizon Architect's MTC (illustrated in Figure 1) responds to the unique challenge of both heavy ice breaking and conducting ATON on the Great Lakes. "Heavy ice breaking" in the Great Lakes poses uniquely specific challenges compared to ocean-going ice breakers. First, freshwater ice has a flexural strength approximately double that of seasonal saltwater ice, which effectively requires twice the icebreaking capability than that of saltwater ships. Second, fresh water weighs less than salt water and therefore ships need to displace more water to achieve the same level of buoyancy as a saltwater ship. Third, the shallower depth of the Great Lakes means that ice forms more quickly and ships need a shallower draft. Finally, the locks that connect the Lakes restrict the beam and draft of vessels. Consequently, vessels in the Great Lakes must displace more water yet are restricted in their beam and draft, all while breaking ice twice the strength of their ocean-going counterparts.

KHA's MTC exceeds all these requirements, featuring an integrated hybrid biodiesel-electric power plant capable of producing an output of over 12.3 MW (16,500 hp) continuously. This means that, via its two ABB Azipods and single bow thruster, MTC is designed to continuously break 3 feet of ice at over 9.5 knots. KHA's MTC also features a UIB and W-stern to improve icebreaking efficiency, a 5,000 ft^2 buoy deck to improve ATON operations, a fantail with over 3,300 ft^2 of deck space to better accommodate a flexible mission set. Finally, KHA implemented modular capabilities via modular containers, enabling that mission flexibility. This design report explores the major components of the MTC, explains KHA's design philosophy, and discusses how the philosophy guided a multitude of design decisions which make the MTC such a capable asset.

BACKGROUND
Currently, the USCGC MACKINAW is the only US asset in the Great Lakes capable of heavy ice breaking, while Canadian ice breakers are leaving the Great Lakes to support their northern seaports (Lake). Additionally, a rising upkeep cost and degradation of the WYTL (small harbor tugs) and WTGB (ice breaking tugs) fleets resulted in a loss of $1 billion and 5,800 jobs in the U.S. economy in 2014 due to insufficient icebreaking capability on the Great Lakes, for example. Another $1 billion and 5,000 jobs were lost in 2018 due to the same reason (Lake Carriers Association).

KHA designed the MTC to fill this gap. The MTC is a heavy icebreaker that is more capable than the current heavy icebreaker, USCGC MACKINAW, and will work in conjunction with the USCGC MACKINAW to complete the U.S. Coast Guard's icebreaking mission. To support this endeavor, the U.S. Senate passed the 2023 National Defense Authorization Act which allocated $350 million to the development and acquisition of a new heavy Great Lakes' icebreaker. Additionally, the bill also funds the combining of the Davis and Sabin locks to create a single more capable lock that can move larger vessels. A final accomplishment of the bill is that it codifies the Coast Guard's mission of ice breaking in a statute as a government responsibility. This means it is the U.S. Government's job to create and maintain the shipping lanes to facilitate and keep commerce alive (Ellison).

PHILOSOPHY
KHA's design philosophy recognizes the reality of Coast Guard operations, prioritizing the functionality and flexibility of the cutter. The criteria are ranked in order of priority in Table 2, with 1 being the highest priority.

Table 2. Philosophy criteria

Criteria	Priority	Description
Function	1	Critical mission requirements, as prescribed in the National Defense Authorization Act.
Mission Flexibility	2	Capable of performing almost every mission in the Coast Guard. The real "pickup truck" of the fleet
Service Life	3	Optimizing functionality and reliability in the current and future fleet
Environmental	4	Reduce environmental impact through hybrid capabilities.
Artistic Value and Pride	5	Inspire pride and appreciation for American ingenuity, quality, and service.

Function is KHA's highest priority because, above all else, the essential purpose of this design is to produce a vessel capable of performing all its required duties. Next is mission flexibility so that the MTC can adapt to changing mission sets. Along with the multi-mission capabilities, the vessel will be a long-term investment as service life is a priority in the design. A service life of 30 years with the possibility of a service life extension in the future is to be expected to align with the US*CGC* MACKINAW. In accordance with the CG mission of marine environmental protection, the environmental impacts are the focus of the next criteria. As the Great Lakes continue to be a strict environmental zone, the vessel should have hybrid capabilities to make as small of an environmental footprint as possible. The final criterion was artistic value and pride. The vessel should not only function well but project a positive image on the U.S. Coast Guard, which will aid to the fleet wide mission to increase retainment and recruitment. The American public should feel proud of the vessel as it embodies their nation and values.

NEEDS, MISSIONS, AND REQUIREMENTS

Needs Statement

The MTC is a multi-mission heavy CG icebreaker with modular capabilities to supplement the USCG MACKINAW and smaller icebreaking tugs in the Great Lakes area. The MTC will assist the marine transportation system through Ice Operations, Aids to Navigation, and Ports, Waterways, and Coastal Security. While congress authorized funding specifically for a heavy domestic ice breaker, KHA recognizes that the greater concern for the CG are the gaps in light and medium ice breaking, which means the MTC will be optimized for medium and light icebreaking, while still retaining the capability to break heavy ice. Since the vessel will also need to perform ATON, Search and Rescue, Law Enforcement, and any other CG mission, the MTC will be a highly flexible platform boasting a large working deck, a significant payload capacity, and the ability to provide power to modular systems housed in standard 20 TEU containers stored on deck. This modular capability enables the ship to equip itself more effectively for a range of missions to support the local marine industries and communities. This provides the USCG with a platform to transport supplies, assets, personnel, perform salvage operations, ROV operations, scientific missions, extend its own endurance, and all else the USCG may need to adapt to changing missions.

The Missions and Owners Requirements

The MTC will conduct the DOMICE mission and will supplement additional icebreaking capability to the maritime transportation industry in the Great Lakes area. Ice Operations include the ability to provide direct assistance to other vessels, escort vessels, establish and maintain tracks, flood-relief response, and exigent community service requests. The secondary missions of the MTC are Aids to Navigation, Ports, Waterways, and Coastal Security, and Search and Rescue. To accomplish ATON missions the MTC must be able to place and remove buoys, position check buoys, and service fixed ATON. To conduct PWCS the MTC must be able to conduct boardings and provide deterrence from terrorist attacks. To accomplish SAR, the MTC must be able to tow vessels, coordinate on-scene assets, locate people in the water, and extract people from the water. In addition to these missions the MTC must be able to effectively communicate with surrounding vessels using both data and voice and operate in the varying weather conditions to include severe winters.

The modular capability means the MTC can onload modular units in the form of 20-foot containers to readily adapt to mission needs. For example, if there is a large Coast Guard response to disaster relief, the MTC can carry containerized JP-5 tanks, containerized fuel pumps and purifiers, containerized living quarters, a containerized ICU, as well as containers of medical supplies, food, and disaster response supplies, therefore making the MTC a mobile refueling station and medical drop-off point for helicopters responding to disasters. Likewise, if there is a need for a longer patrol in the Great Lakes, the crew can load grey, black, and potable water tanks, and containers with food and essential supplies. Moreover, the MTC can carry containers with dive lockers for dive operations, ROV operation and maintenance equipment, and additional berthing spaces.

Key Performance Parameters

The Key Performance Parameters in Table 3 were built with a focus on medium icebreaking with the capability to, at minimum, break heavy ice 36 inches thick at a speed of 3 kts. KHA will also ensure that the MTC will fit through the Welland canal by adhering to the canal's dimensions in Table 3. KHA chose not to design a sustained speed of 17kts due to the power demand increase from 15kt, so 15kts is the flank speed being used. The installed endurance of the MTC will meet the 21-day requirement however as stated before the modular capabilities allow for additional stores to be onloaded for longer patrols. All ATON KPPs will be met and exceeded to maximize this capability.

Table 3. KPPs of the MTC

Attribute	Description	Threshold	Objective
Dimension	Transit	Welland Canal	
	Ice channel width	60 ft	75 ft
	EOSL draft	18 ft	16 ft
	Air draft	116.5ft	
Speed	Sustained speed	15kts	17 kts
Endurance	Food, water, waste, stores	21 days	45 days
	Fuel	20 days	30 days
Icebreaking	Level icebreaking (3kts)	36 in	40 in
ATON	Buoy crane and deck capability	9x35 buoy (4,575 lbs.) concrete sinker 20,000 lbs. 180 ft 1¾ in chain	
	Storage capability	Eight 6x20 Two 8x26 One 9x35 Ten concrete sinkers (8,500 lbs. each) 1¾ in chain (23,500 lbs.)	
	Unobstructed Deck space	3,000 ft^2	4,000 ft^2 6 Containers

The KPPs along with the operating profile in Figure 2 build the framework for this design. The operating profile shows the prioritization of the missions and helps to size the power plant.

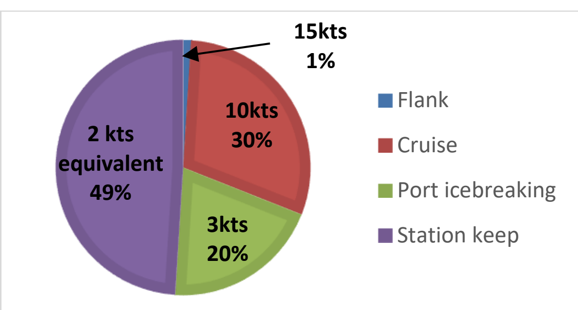

Figure 2. Operating Profile

MARKET ANALYSIS

KHA performed a market analysis to identify design lanes in which to establish principal dimensions. The MTC will be an icebreaker that can conduct ATON, along with other Coast Guard related sub-missions. A market analysis would ensure that the vessel has principal dimensions that make sense for the missions in accordance with successful ships. To do this, KHA compared relationships between principal dimensions of ships with similar mission statements to understand where the MTC should land. Using the KPPs, KHA plotted the MTC on these graphs and the principal dimensions were found. The principal dimensions are found in Table 4 on the next page.

KHA gathered data from 21 vessels with ice breaking capabilities, ATON capabilities, and those capable of both. See Appendix A for the market analysis study with plots and design lanes, with chosen principal dimensions. KHA chose three "parent hulls," which are vessels that have attributes that could add the most value to the MTC. These are USCGC MACKINAW, CCGS SIR WILLIAM ALEXANDER, and the ice breaking vessel OB. Using features from each of these three vessels, KHA designed a more ice capable ship than the USCGC MACKINAW and SIR WILLIAM ALEXANDER, and more mission flexible than the OB. The resultant MTC complements the USCGC MACKINAW by providing new functionality and redundancy to the Great Lakes cutter fleet.

SHIP PARTICULARS AND LINES

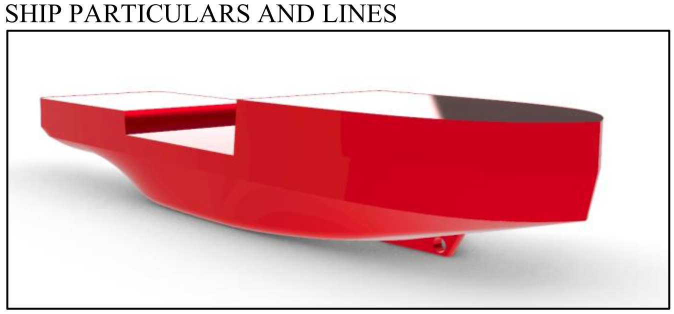

Figure 3. MTC preliminary hull choice

Figure 3 illustrates KHA's proposed preliminary hull form and the following subsections detail the geometry and associated required EHP from resistance predictions and propeller selection. Appendix B includes the lines drawing for the MTC.

Hull Geometry

The MTC hull has a LOA of 285 ft and a BOA of 70 ft. It features an Ultimate Icebreaking Bow with stem and buttocks angles near 15 degrees, a W-stern with buttocks angles ranging from 22 degrees to 15 degrees along the geometry, and an ice knife at the bow. The vessel has no parallel mid body, improving maneuverability. Near midships the MTC has near zero deadrise, which dampens rolling. This proposed hull features the following dimensions as compared to those derived from the market analysis of similar ships, in Table 4.

Table 4. Actual MTC Dimensions vs Similar Ships

Dimension	Actual principal characteristics	Target principal characteristics
LOA (ft)	285	280
BOA (ft)	70	68
Depth (ft)	38	
Draft (ft)	18	18
LWL (ft)	270	270
BWL (ft)	70	
Cb	0.59	.66
Cp	0.62	
Displacement FL (LT)_	5,580	6200

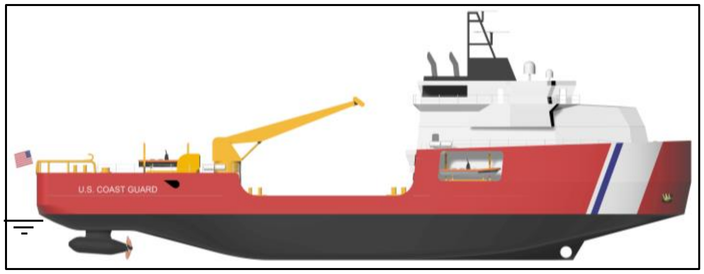

Figure 4. STBD profile view

Importantly, the hydrodynamically optimized hull below the waterline extends two feet above the waterline where it ends in a hard chine, which is illustrated in Figure 4. The hard chine does not affect general hydrodynamics as it is above the water line but reduces construction cost. The chine is sharpest at the bow where the shallow buttock angles of the UIB cut to steep angles which keep the overhang of the bow to a minimum. The increase of LOA compared to similar ships is to account for those shallow buttock angles of the UIB which, since the icebreaking bow shape must extend a few feet above the waterline, increases overhang. Thus, the increased LOA accounts for the smaller LWL resulting from the bow design, thereby putting the MTC's final LWL closer to that of similar ship dimensions. The larger BWL scales for the increase in LOA and widens the ice channel while not exceeding the Welland canal limits.

The MTC has a W-stern (illustrated in Figure 5) to improve efficiency of astern ice breaking and to improve maneuverability in ice. This geometry enables the MTC to break out ports and clear rivers. Operationally, the MTC will first break ice in a circle around the entrapped vessel then back down towards the vessel's bow and use its azimuthing thrusters to flush out the ice ahead of the entrapped vessel. This evolution requires maneuverability and astern operations. River ice breaking and river flushing require that the MTC operate in restricted waters, in some cases where there is insufficient room to come about. Consequently, the MTC must be able to operate efficiently and comfortably astern and in confined waters.

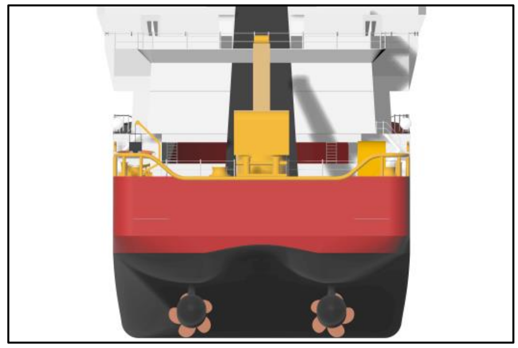
Figure 5. Stern body view

The difference between the block coefficients is a result of selecting a displacement nearer to the upper design lane during the similar ships analysis, but creating a hull with an UIB, W stern, and no parallel midbody. This is because the UIB and W-stern both significantly reduce the displaced volume in their regions, and the absence of a parallel midbody reduces the overall block coefficient. The bow, stern, and midbody shapes are prioritized because these shapes are more applicable to the mission design focuses of: Level Ice, Ridge/Rubble Ice, Maneuverability, Escort Operations, Ice Management, Brash ice, and Endurance (Tingstad).

Buoy Deck Placement

Departing from the standard arrangement found on most USCG buoy tenders, KHA designed the MTC to have its pilothouse forward of the buoy deck, illustrated in Figure 6. This arrangement considerably improves the flexibility and safety of the MTC because it increases functional deck space both on the buoy deck and on the fantail, the buoy deck is more protected from the elements, and the buoy deck and crane experience less motion. This is the result of more effectively utilizing the natural structure of a vessel.

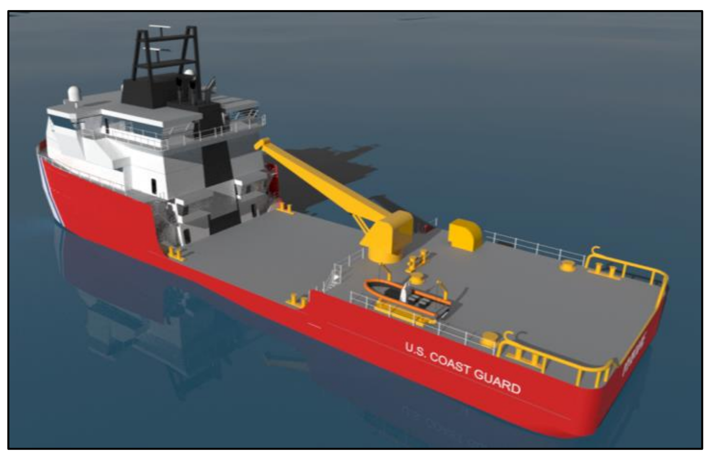

Figure 6. Perspective view of buoy deck and fantail.

This layout provides more deck space, which means more room for modular containers, increasing flexibility. More deck space also reduces how much the deck hatches need to be opened. The protection offered by the forward superstructure and reduced motions near midship also improves safety of ATON evolutions.

Lastly, the deck space aft improves the safety of helicopter operations, not including landing, by reducing the number of obstacles and enabling the helicopter to approach from astern. Beyond ATON operations, the towing bit can be placed forward of the azimuthing drives which significantly improves maneuverability and stability while towing.

One concern relayed to KHA about the aft buoy deck is often because the Conning Officer and CO will be unable to keep eyes forward and watch the buoy deck simultaneously. The same view of having forward lookout and of the buoy deck is achieved on the MTC through the bridge wings that extend past the beam, allowing clear sightlines on buoy approaches. Since the ship is not moving during buoy operations, the ship can be controlled from the aft facing crane shacks, effectively the same as the aft pilothouse.

POWERING ESTIMATION

Figure 7 describes a simplified concept map used to determine the necessary installed BHP for sizing the gensets. This process finds the resistance of the bare hull with NAVCAD and confirms using model testing, and then adds predictions for still air and appendage resistances to get the EHP required for overcoming resistance. An icebreaking check is then done to check whether icebreaking resistance will be a limiting factor. An in-depth electric power load analysis using a parent vessel will determine the EHP required for running equipment as part of the integrated powerplant. With appropriate margins and efficiencies applied the minimum required installed BHP is found.

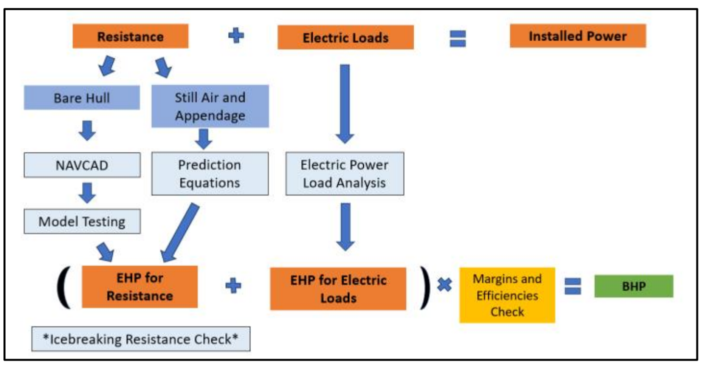

Figure 7. Powering concept map

EHP for Resistance

Before using NAVCAD a 10% service life allowance margin and 8% D&C margin was applied to the lightship displacement which gave KHA the EOSL displacement for the resistance prediction (Molland). Using the EOSL displacement, KHA used two different methods in NAVCAD, Holtrop and Fung CRTS. These methods contained parent vessels with similar hull characteristics as the MTC. Next, Molland prediction equations were used to calculate both the still air and appendage resistances.

To determine the icebreaking resistance of the MTC, and whether it will be a limiting factor or not, KHA used the "US method" which is a propulsion-oriented analysis. This analysis results are not fully accurate with only four seagoing hull forms in the method. However, KHA compared resistance predictions with the "Canadian method" which provided reassurance. Furthermore, the four hull forms in the analysis were not optimized icebreaking hull forms like the MTC, meaning the MTC will likely see much less resistance for a given speed and ice thickness than the estimate because the bow design is optimized for icebreaking. Through the lens of looking for order of magnitude, the MTC's ice breaking resistance at 3 kts in 36 inches of ice will most likely be in the range of 6,600 HP. Margins and efficiencies will be discussed more later, but after applying appropriate margins and efficiencies the predicted resistance for icebreaking will be less than that of flank speed. This is depicted in Figure 12, which also summarizes the aspects of the EHP required for overcoming resistance.

Tow Tank testing was used to validate the bare hull resistance of the MTC predicted by NAVCAD. KHA built a 50:1 scale model of the MTC, limited by the dimensions of the USCGA's tow tank. A CNC machine was used to cut the model and was then hand sanded and painted, shown in Figure 8. Hama strips were added to the model as well to reflect the actual turbulent flow, shown in Figure 9. The model was then tested under the *Froude Hypothesis.* This hypothesis assumes that the total resistance is comprised of frictional and residuary and that residuary is comprised of only wave making. Using this hypothesis the model speeds and resistances could be related to the full-size ship speeds and resistances.

The model was ballasted to the EOSL waterline, shown in Figure 10, and the force block was calibrated for this draft. The force block is what converts the resistance of the model in the tank to a voltage that can be directly related to a resistance in lbs. Nine full size ship speeds were tested, from 2kts to 17kts. 17kts is above the flank speed of 15kts to show the graph's trend. Each speed was tested three times so that an average could be taken, and outliers could be removed.

Figure 8. Perspective view of model MTC

Figure 9. Hama strips on MTC bow

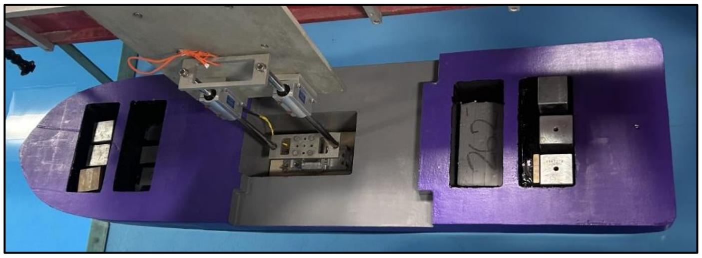

Figure 10. Ballasting of model

Although extensive steps were taken to minimize uncertainty, there are still some sources of error. First was the construction of the MTC. After the margins on the CNC machine, the greatest uncertainties came from the hand sanding, epoxying, and painting. This process could have altered the hull geometry which has the potential to exacerbate blemishes. There was also some uncertainty in the calibration, with an R^2 of 0.99, though this is negligible. The final uncertainty to note comes from the selection of usable data from each test. As the carriage moves faster, less data points are taken because the model gets to the end of the tow tank in less time.

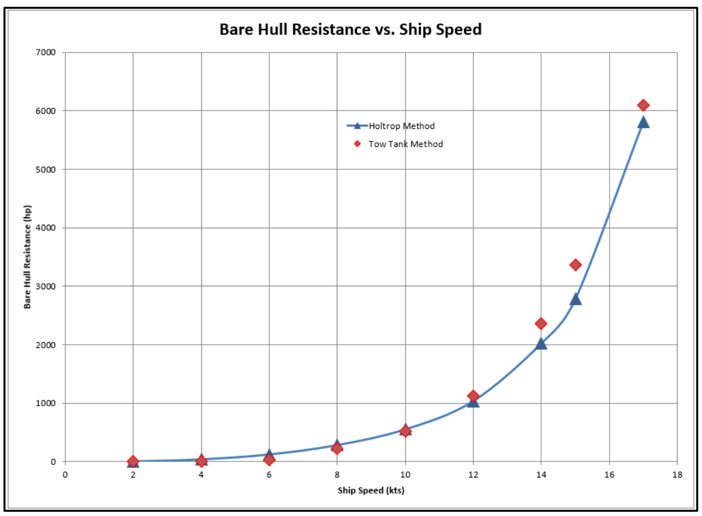

Figure 11. Tow tank data compared with Holtrop

Figure 11 compares NAVCAD's Holtrop method to the model testing. At 15kts, the model testing resistance was higher which could be from greater uncertainties but could also indicate a higher resistance from the hull geometry. This is reasonable since Holtrop does not include ships with UIB's or ships with relatively low L/B ratios. KHA moved forward with power prediction using the higher model test data and applied an additional 10% D&C and 30% SLA margins for EHP. Table 5 shows the summary of the resistance prediction.

Table 5. Summary of resistance predictions

Resistance Source	Flank (15kts) Resistance (lbs.)
Bare Hull (Model Test)	73,500
Still Air	4,040
Appendage	12,300
Powering D&C and SLA	2,300
Margins	
Total	128,500
Total (EHP)	5,890 HP

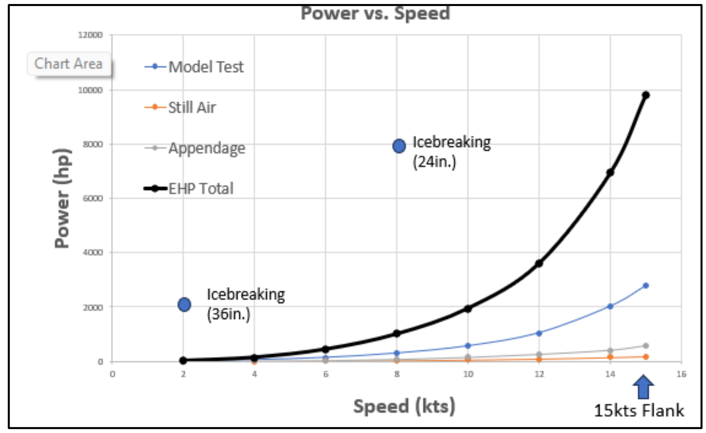

Figure 12. Applied margins and efficiencies

Propeller Selection

The limiting factor for the diameter of the propeller was the distance from the hull to the MBL with a 17% (of the diameter) clearance. This clearance maximizes apparent flow velocity and reduces vibrations. KHA optimized the propellers for efficient, higher speed (10 kts), medium ice breaking (24 in of ice) while retaining the capability to break heavy ice at slower speeds at slightly lower efficiency. Controllable pitch propellers were considered but ultimately with podded propulsors it is not necessary. The size of the propeller will impact the size of podded propulsor needed. Fortunately, the hull design allows for the two podded propulsors with propellers to rotate 360°. At this operating point, the MTC will need approximately 8,690 EHP. Table 6 has the input that was used in NAVCAD to produce the propeller.

Table 6. Variable used

Ship Speed	10 kts
RPMs	111 RPM
Diameter (D)	10.75 ft
Wake Fraction (w)	0.2
Thrust Deduction Factor (t)	0.23
Hub Depth (h)	13 ft
EHP	8,690 HP
P/D	1.1
Expanded Blade Area (A_E)	46.5 ft^2
k	0.12
Advance Velocity (V_A)	8 kts
Number of Propellers (Z)	2
Density (ρgh)	0.47 psia
Vapor Pressure (P_v)	0.34 psia
Atmospheric Pressure (P_0)	14.7 psia
Thrust (T)	46,600 lb

The NAVCAD process was iterative, in that three, four, and five bladed propeller characteristics were found and compared using initial EAR values as inputs. Pitch to Diameter ratios were also varied to find the most efficient propeller. KHA had to focus on keeping the cavitation below 5% at flank speed while maintaining efficiency at the cruising and icebreaking speed of 10 knots.

The Burrill diagram, which compares dimensionless numbers thrust loading coefficients (τ_c) and local cavitation number ($\sigma_{(0.7R)}$, was used to approximate the amount of cavitation on a prospective propeller area. Figure 13 shows the Burrill cavitation prediction plot. Appendix C has a larger plot of the Burrill cavitation curve.

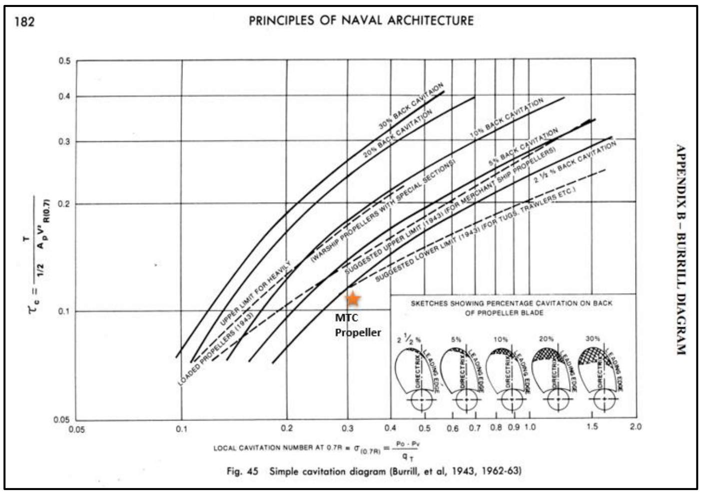

Figure 13. Burrill cavitation

The final propeller design has a cavitation value of 3.8% at flank speed (15kts) and 0% cavitation and an open water efficiency of 62% at the cruising speed (10kts). Table 7 shows the final propeller characteristics produced by NAVCAD. Figure 14 shows the KT, KQ, η_o vs Advance Coefficient plot. Appendix C shows a larger plot of the propeller characteristics. Figure 15 depicts the model of the designed propeller.

Table 7. NAVCAD propeller characteristics

Propeller Series	B Series
Diameter	10.75 ft
Number of Blades	5
Pitch to diameter ratio (P/D)	1.1
EAR	0.9
η_o at 10 kts	62.1%
Max % back cavitation (flank)	3.8%

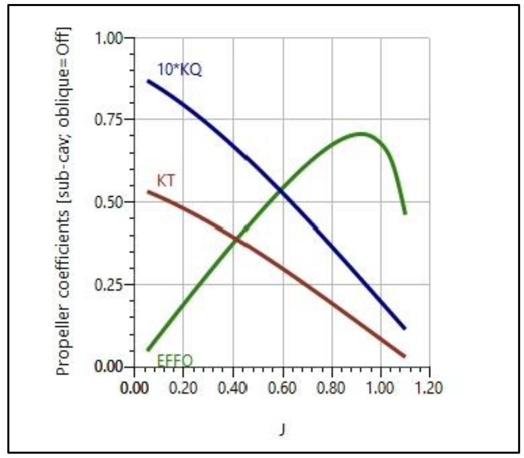

Figure 14. KT, KQ, Ƞo vs Advance Coefficient plot

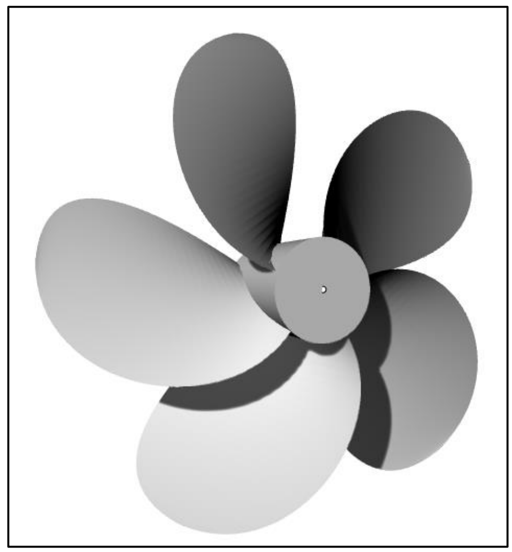
Figure 15. Model of propeller

EHP for Electric Loads

The MTC will have an integrated propulsion plant, which requires that the service loads must be estimated to appropriately size the generators. This is because the generators will provide power to both the service loads and propulsion through a BUS. To estimate the electric draw of the service loads, a modified SWBS ratiocination method was used. USCGC MACKINAW is the parent vessel for this ratiocination due to its information being readily available. This modified ratiocination used weight ratios between the MTC and USCGC MACKINAW to estimate the power for the MTC from specific systems known power requirements. KHA chose four operating conditions before conducting the ratiocination for both Summer and Winter. The four operating conditions for winter are cruising, emergency, station keeping, and icebreaking at design speed. The four operating conditions for summer are the same except for icebreaking which was replaced by the at anchor operating condition. The power factors for individual components were altered to best align with the expected usage which will differ from the parent vessel. Tables 8 and 9 show a summary of the EPLA predictions.

Table 8. Winter EPLA Summary

	Cruising (KW)	Emergency (KW)	Station Keep. (KW)	I/B @ design (KW)
SWBS 200 - Propulsion	350.7	35.8	349.7	399.2
SWBS 300 - Electric Plant	64.4	108.3	88.1	109.6
SWBS 400 - Command & Control	20.3	17.6	17.6	20.1
SWBS 500 - Auxiliary Systems	1,034.9	292.3	869.3	958.5
SWBS 600 - Outfit	188.6	13.9	102.9	226.1
Winter Subtotal	1,659.0	467.8	1,427.6	1,713.6
Design Margin - 10%	165.9	46.8	142.8	171.4
Service Life Margin - 30%	49.8	14.0	42.8	51.4
Winter Total with Margins	1,874.7	528.6	1613.2	1,936.3
Propulsive Load	2,690.8	14.7	14.7	6,273.7
Total Load	4,565.5	543.3	1,627.8	8,210.0
Percent Gen Loading is in unis of (kW used/CSR)*100				
% Generator Loading 1 Gen Online	111%	13%	40%	200%
% Generator Loading 2 Gens Online	55%	7%	20%	100%
% Generator Loading 3 Gens Online	37%	4%	13%	67%

Table 9. Summer EPLA Summary

	Cruising	Emergency	Station Keep.	Anchor
SWBS 200 - Propulsion	366.1	34.6	360.8	23.8
SWBS 300 - Electric Plant	61.2	108.3	117.6	70.9
SWBS 400 - Command & Control	17.9	17.6	20.7	13.9
SWBS 500 - Auxiliary Systems	534.2	282.9	595.7	416.1
SWBS 600 - Outfit	40.0	15.5	40.1	39.1
Summer Subtotal	1,019.5	458.9	1,135.0	563.7
Design Margin - 10%	101.9	45.9	113.5	56.4
Service Life Margin - 30%	30.6	13.8	34.0	16.9
Summer Total with Margins	1,152.0	518.6	1,282.5	637.0
Propulsive Load	2,690.8	14.7	14.7	14.7
Total Load	3,842.9	533.2	1,297.2	651.7
Percent Gen Loading is in unis of (kW used/CSR)*100				
% Generator Loading 1 Gen Online	93%	13%	32%	16%
% Generator Loading 2 Gens Online	47%	6%	16%	8%
% Generator Loading 3 Gens Online	31%	4%	11%	5%

Margins, Efficiencies, and Total Required EHP

Table 10 shows the calculations to find the minimum required brake power that was used to size the MDGs, which is consistent with the concept map from Figure7. The open water efficiency is for the flank speed of 15kts of the chosen propeller.

Table 10. Summary of Efficiencies and Margins

Power	**HP**	**Margin Applied (reference)**	
PE (Full Load, No Margins)	3,920	None	
PE (FL, w/ disp. D&C and SLA)		D&C for EOSL (DeNucci)	8%
	4,730	SLA for EOSL (DeNucci)	10%
PE (FL, w/ disp. And EHP D&C and SLA)	5,260	D&C for EHP (Molland)	10%
	5,890	SLA for EHP (Molland)	30%
Power	**HP**	**Efficiency Applied**	
P Thrust	6,130	η_H (Molland)	96%
P Delivered		η_o (Molland)	57%
	8,760	η_R (Molland)	100%
P shaft	8,760	η_s (Molland)	99.5%
P Brake (Integrated propulsion Plant)		$\eta_{electric\ Transmission}$	90.0%
		>$\eta_{distribution\ Cables}$ (Woud)	99.5%
		>$\eta_{Static\ Converters}$ (Woud)	99%
		>η_{Motors} (Woud)	92%
	9,640	>$\eta_{Transformers}$ (Woud)	99%
Power	**HP**	**Margin Applied**	
P Brake (with EPLA Service Loads)	11,940	None	
P Brake (With Service Loads & Margins)		D&C for EPLA (DeNucci)	10%
	12,240	SLA for EPLA (DeNucci)	30%
Power	**kW**	N/A	
Total Required Minimum P Brake	9,260	None	

Table 10 adds together the EHP required for overcoming resistance as well as the EHP for systems in the MTC's integrated power plant. The prime movers were then selected using the final value of 9,260kW.

POWER PLANT ARRANGEMENTS

The propulsion plant configuration of the MTC is a crucial decision for the development of the design going forward because it enables the missions of MTC. Choosing the plant encompasses the type of fuel, fuel storage method, prime mover, the transmission, and the propulsor. Of the countless possibilities for the engineering plant, KHA narrowed down to four configurations, largely dictated by the operational requirements of ice breaking and the operational area of the Great Lakes. KHA determined that, because of the ice breaking mission and shock loads associated with a propeller churning, an electric drive is the logical choice. While a mechanical drive is possible, the system would require a carefully tuned clutch to protect the reduction gears and prime movers from sudden changes in load. An electric drive, on the other hand, is less affected by shock loads.

There are many fuel sources that, given the right circumstances, would be a great option, considering the need for reduced emissions in the Great Lakes. Despite initially considering nuclear power, it became abundantly clear that incorporating a nuclear vessel into the Coast Guard on the Great Lakes was not a feasible option. LNG was also considered, but a lack of current and planned infrastructure supporting LNG eliminated that as an option. On the other hand, biodiesel is already widely used on the Great Lakes, and frequent stops in port present the potential for rechargeable batteries. Thus, KHA determined that the most sensible power sources to consider for the MTC are diesel or biodiesel electric plants, possibly with the addition of Lithium-Ion battery banks to peak-shave, load-level, and power station keeping or harbor transits.

Considering the principal dimensions of the MTC, the most logical prime mover type is medium-speed diesel engines. To provide the cutter with the necessary maneuverability to operate in harbors without tug assistance, station keep during ATON operations, and improve ice lane clearing ability through obliquely directed prop wash, KHA determined that L drives, Z drives, or podded propulsors are the ideal propulsion methods. Ultimately, KHA decided to align with the Coast Guard's adoption of podded propulsors with either one or two bow thrusters.

The following four power plant configurations were considered by KHA:

- Integrated Hybrid Diesel Electric
- Integrated Hybrid Biodiesel Electric
- Integrated Biodiesel and Diesel Electric
- Segregated Diesel Electric

To down select, the team used the scoring matrix in Table 11, which was created using KHA's design philosophy to help finalize a plant configuration.

Table 11. Criteria ranking for the four configurations

	Engineering Plant				
	1	2	3	4	Importance
Cost	2.5	2	2.5	3	3
Service Life	2.5	3	2.5	2	6
Maintenance	2.5	2.3	2.5	2.7	5
Training	2.7	2.3	2	3	2
Environmentals	3	3.5	2	1.5	4
Space	2	2	3	3	1
Health and Safety	2.25	2.25	2.75	2.75	8
Flexibility	2.6	3	2.4	2	7
avg score	20.88542	21.19792	20.46875	20.78125	36

The following is the final configuration for the MTC:

Integrated Hybrid Biodiesel Electric

- Energy Source: Biodiesel
- Storage Method: Biodiesel tanks, battery banks
- Power Generation: 03 Medium Speed Biodiesel/ Diesel Generator Sets
- Transmission Type: Variable Frequency Drive (VFD)
- Propulsor: 02 Azimuthing podded propulsors and 01 bow thruster.

The fully integrated power plant enables the MDGs to be located further forward in the vessel and placed with better maintenance envelopes. The MDGs can then be selected using 9,259kW as the baseline required power. KHA determined that, because of the lack of ice breaking assets on the Great Lakes, the MTC must have significant redundancy in its power plant to ensure that it can always complete its mission. Thus, KHA chose Main Diesel Generators (MDGs) such that the MTC can operate at design cruising and design icebreaking on two of three generators. Moreover, this incorporates a substantial margin for electric power load growth for rapidly advancing technologies, and sufficient power to support modular capabilities such as powering refrigerated containers of emergency medical supplies. Furthermore, with respect to KHA's importance placed on environmental considerations, the MTC's gensets will run on B100 biodiesel. This grade of biofuel is a common product of the great lakes and already in use by many great lakes' vessels such as NOAA vessels and Canada Steamship Lines (NOAA, CSL).

Generator Selections & Trade Offs

KHA compiled a list of various generators in multiple configurations across three separate companies: CAT, Anglo Belgian Company, and Wartsila. KHA had the option to use either three or four gensets but chose a three genset configuration due to the increased thermodynamic efficiencies of using larger gensets. Many prospective engines did not meet the EPA Tier 3 standards for category 2 engines of less than 2.4 g/kW-hr of NO_X, or four smaller gens would be needed. After an extensive comparison of twelve gensets across the three companies, KHA selected the Wartsila 9L32 and 8V31. The 9L32 is slightly lighter while producing more power than the 8V31, while ultimately being slightly less efficient. Ultimately the 9L32 was chosen because of space savings, general high efficiency, and weight. Table 12 gives general specifications for the 9L32. Figure 16 shows the plant operating map with this generator. See Appendix D for the full genset study.

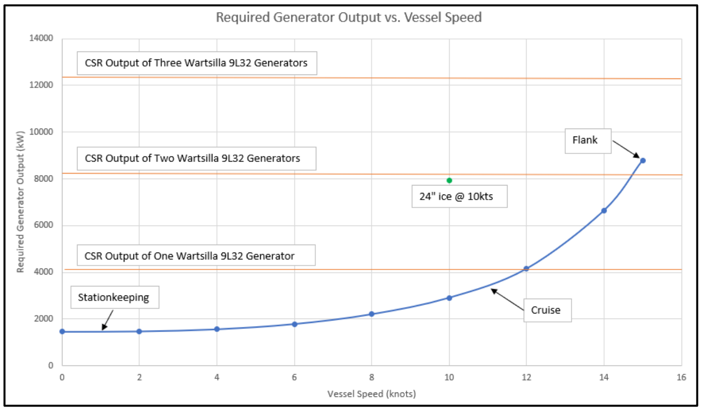

Figure 16. Plant operating map

To supplement the main generators as well as provide necessary redundancy an auxiliary generator was chosen. Using the ratio of the MTCs plant power to the parent vessel (USCGC MACKINAW), and the parent vessels E-gen size, the MTCs auxiliary generator should have a CSR of 1044 kW. To limit the number of different types of parts from different manufactures KHA decided to use Wartsila for the auxiliary generator as well. KHA chose the Wartsila 6L20. See Table 13 for a summary of the 6L20 Specifications.

Table 12. Wartsila 9L32 specifications

Rated Power (kW)	Speed at 60Hz (RPM)	MCR of 3 Gens	CSR of 3 Gens	Fuel Consumption at 85% load (g/kWh)
4,840	750	14,500	12,300	174

Table 13. Wartsila 6L20 specifications

Rated Power (kW)	Speed at 60Hz (RPM)	CSR (kW)	Fuel Consumption at 85% load (g/kWh)
1,260	750	1,070	187

Installed Battery Banks

In determining marine battery bank manufacturers and sizing, KHA settled on the Energy Storage Solution (PODAS) systems made by Corvus Energy, specifically their ESS “Orca Energy” which is designed for applications requiring high energy and high-power output such as offshore vessels and tugs (*Corvus*).

For the MTC to enter or leave port entirely under battery power, KHA predicted that the MTC would need to operate at an average speed of 6 knots for around 3 hours. Additionally, to have the power needed for evasive maneuvers to avoid collisions or allisions, the batteries must be able to provide full power, or around 12 MW, which is equivalent to flank speed. Based on the volumetric densities, this meant that the MTC will have around 2420 cubic feet or 6030 kWh of Corvus Energy Orca ESSs. Thus, the MTC will be able to operate for 3 hours at 6 kts, with the capacity to produce up to 18 MW on demand. This is more than enough for the MTC to comfortably enter and leave port under battery power only.

However, batteries are expensive and 6030 kWh of Orca ESSs costs in the range of $3 million. Fortunately, the MTC does not need enough battery power to transit in and out of port on batteries alone to benefit from the efficiency improvements peak shaving and load level. A battery bank capable of a peak discharge rate of 12 MW would cost in the range of $2 million. Thus, part of the eventual price prediction will be a cost-benefit analysis to determine reasonable battery sizing.

Main Propulsor Selection

ABB Azipod VI were selected as the propulsor. This was determined to be the most suitable propulsor of the options currently on the market due to size and power density as well as known success on icebreakers. It comes with 6 to 17 MW of AC power, which is well within the required 8.8 MW outlined in Table 10 (*Azipod*®). The propeller is mounted directly onto the motor, which allows for a lack of complex gears and shafts (*Azipod*®). The ABB Azipods illustrated in Figure 17.


Figure 17. ABB Azipod

Hybrid Power Plant Layout

The one-line diagram in Appendix E illustrates the power distribution system of power throughout the ship. It was constructed through analyzing the machinery chosen as well as referencing USCGC MACKINAW’s one line drawing and adding batteries. The MTC has an integrated power plant, and the one-line drawing reflects this. When the power goes from the generator to either a battery, propulsion unit, or the ship service switchboard. From the ship service switchboard, it can go to the rest of the vessel to power the auxiliary loads. When connected to shore power, the power can go throughout the vessel, or it can charge the batteries.

The power plant is configured with redundancies so if a generator or bus goes out of commission, there are enough redundancies to ensure that the MTC remains operational. Having multiple buses and paths provides various options for the operator to ensure power reaches essential systems in case of a bus or MDG failure or casualty. The main trade off with this is cost. More buses and generators will cost more; however, it will be worth it to keep the MTC in service. Additionally, the E-Gen chosen is powerful enough to power all the vital loads in addition to some house loads. Furthermore, the MTC's battery bank provides an additional level of redundancy. Although they are one of the more costly components of the power plant, the upside cannot be overlooked. The basic layout of the hybrid plant can be seen in Figure 18.

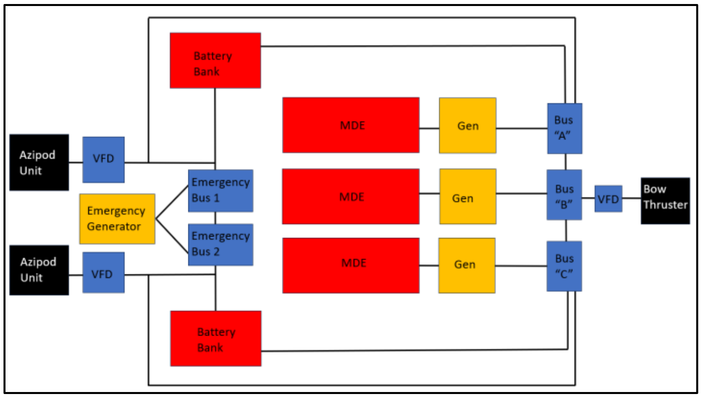

Figure 18. Simplified one-line diagram

INTERIOR ARRANGEMENTS

With the final hull design and power plant chosen, the next steps were placing the transverse watertight bulkheads, decks, general arrangements, and tanks. The position of the watertight bulkheads is heavily dictated by regulations to make the vessel survive damaged conditions. General and machinery arrangements were designed in accordance with the design philosophy. The remaining space is filled with tankage, which helps dictate the mission capabilities.

Subdivision Bulkhead Placement

The goal in flooding survivability is to allow any two adjacent watertight compartments to flood without submerging the margin line. This is a two-compartment standard. Regulations define the margin line, which is an imaginary line that provides a margin of error for when the deck edge is submerged, and the risk of down flooding is increased substantially. A floodable length curve was produced in GHS to prove that the bulkhead placements meet the two-compartment standard outlined in the regulations. The floodable length curve can be found in Figure 19 and in Appendix F. The green, blue, and red lines each signify a different permeability, or the percentage of a space that is taken up by physical contents, such as cargo and scantlings. The MTC passes a 2-compartment floodable length standard with 95% permeability, as seen by the tops of the carats being below the red line.

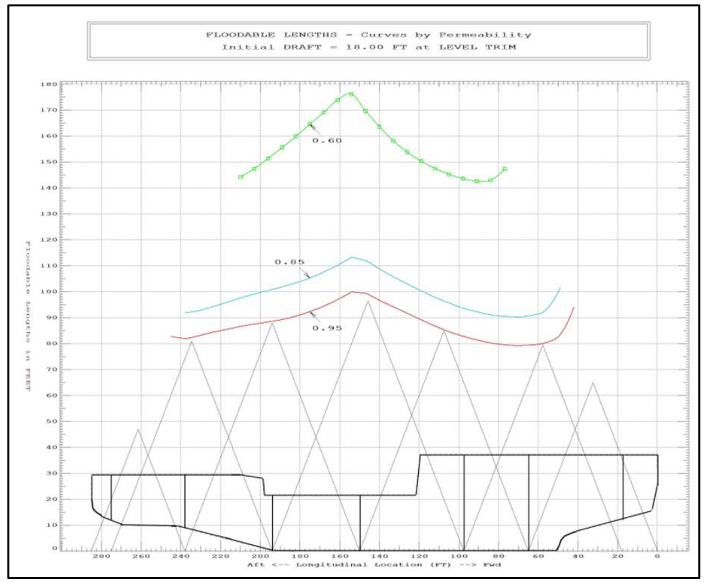

Figure 19. Floodable length curve

Table 14 shows the required placement of specific bulkheads from DPC-079-1 and DDS-079-1(2003) are shown and compared to the TWTBs in the MTC. The bulkhead placements that had high priority were the collision and the aft peak bulkheads. The collision bulkhead serves to limit flooding in a collision situation where the vessel is taking on water, and it should be located about 5% abaft of the forward perpendicular.

Table 14. Coast Guard Floodable Length Requirements

	MTC Value	Required value	USCG Reference
Margin Line	3in below	3in below	DPC-079-1 Section 8.4.10
Collision and Aft Peak Bulkheads	18 ft	14.25 ft	DDS-079-1(2003), Section 2.2.11
Minimum Spacing	37 ft	18.35 ft	DPC-079-1 Section 8.4.2.1
Volume Permeability	0.95	0.85	DPC-079-1 Section 3.2.6
Subdivision Standard	2	2	DPC-079-1 Section 8.4.2

The engine room compartment is placed so it lies halfway under the superstructure and the deck. This compartment was placed here to make the engine more accessible to remove from the engine room and to have the stacks be routed adjacent to the superstructure. In the inboard profile the superstructure is not aligned with a bulkhead, however, this discrepancy is intentional because that space for engine room exhaust and ventilation. That side of the superstructure is not structural. This is a common theme on offshore support vessels of similar design. For stiffness, there will be a supportive frame in this area, and increased structure to reduce stress concentrations.

This choice will optimize space for other components of the MTC. The total number of watertight transverse bulkheads will be seven.

Deck and Bulkhead Placement

The main deck was placed in such a way to be flush with the buoy deck. The MTC features a standard deck height of ten feet above the main deck and eleven-foot decks below the main deck to account for the larger number of pipes and wiring in the machinery spaces. Consequently, the decks are numbered from low to high as 5, 4, 3, 2, Main (or 1), 01, 02, 03, 04, and 05.

To validate the volume of the engine room, KHA used the Wartsila 9L32 Generator Set's dimensions. For bulkhead placement, the 9L32 has an overall length of 34.5 feet which fits comfortably within the 52.5 feet length of the engine room space, giving maintenance envelopes of nine feet fore and aft of each genset. Additionally, the width of the Main Machinery Room (MMR) is approximately 66 feet and the width of a 9L32 is 9.5 feet, giving maintenance envelopes of seven feet between each generator set and the bulkheads. The 9L32 has an overall height of 13.2 feet which requires that the engine room span two decks, a common feature for larger ships.

Crewing

To begin determining the necessary crew size, KHA referenced the USCGs Manpower Analysis Process. This process of functional decomposition begins by looking at the mission of the ship and breaks it down into tasks which either the crew or a ship's system are assigned to. This process was tackled by analyzing the special mission evolutions that the ship will be engaged in as determined by the mission of the ship. The MTC, as a Coast Guard icebreaker and buoy tender, will have those respective evolutions as well as others such as Search and Rescue and General Emergency. KHA developed the crewing around the most personnel intensive evolution, General Emergency, and built a WQSB, shown in Appendix G. Additional considerations for the crew include Special Sea Detail and Mooring Stations and ATON. Figure 20 illustrates the crew breakdown, which was made from the development of the WQSB. The crew breakdown accounted for the Coast Guard's minimum 67-hour work week underway (COMDTINST M5312.11A). This 67-hour work week is illustrated in combination with other aspects of underway life in the 81-hours of work, per person, per week pie chart in Figure 21. This work week ensures that when building a crewing requirement, a manageable schedule and rotation are built which provides safety by mitigating the potential to overwork the crew. There is not a specified WQSB for ATON buoy operations because it will likely rotate often, however it would include multiple safeties, crane operators, and deck force on the buoy deck. Between four departments the MTC will have ten divisions, and a total crew of 46.

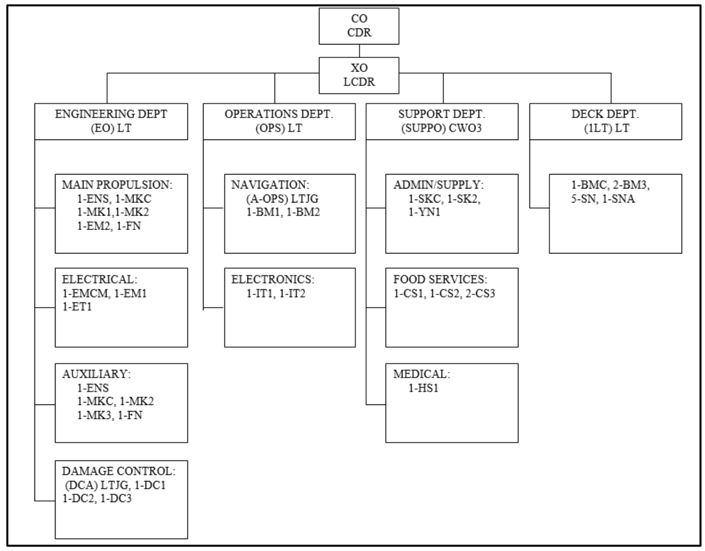

Figure 20. Crewing requirement

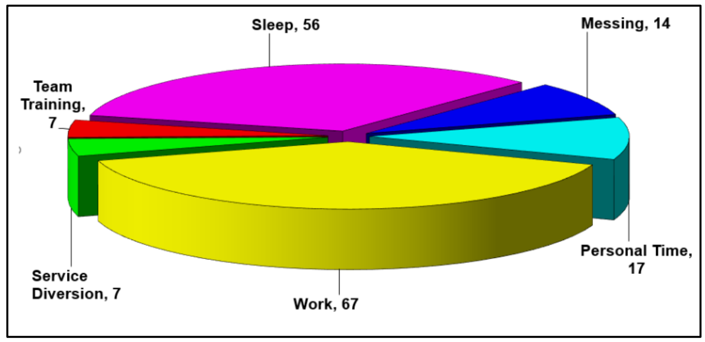

Figure 21. 81-hour work week underway

The estimated crewing cost for the MTC is shown in Table 15, with calculations in Appendix H. Through automation, the design of the MTC minimizes the size of the crew needed to manage and perform all functions of the MTC. Consequently, the total crew is only 46 members, which is smaller than the crew on USCGC MACKINAW, and therefore reduces the personnel cost.

Table 15. Cost estimation by amount of fiscal quarters

Number of Fiscal Quarters	Cost
1	$133,000
2	$266,793
3	$400,190
4	$533,000

General Arrangements

The priorities of KHA are function, mission flexibility, service life, environmental, and artistic value and pride, which are evident in the general arrangements design. In the interest of function, KHA placed trimming tanks in the MTC's bow and stern to ease the process of trimming for optimal ice breaking, and KHA designed the buoy deck to be 67% larger than required for easier ATON operations improving function. KHA built in flexibility to the MTC through an open fantail and two holds for ATON and modular container storage. In addition, KHA included two small boats, one for LE and SAR, and one for aiding ATON operations. Relatedly, the forward OTH small boat is recessed into the side of the hull and protected behind a weather tight door, and the aft ATON boat can be lowered into the aft hold for the winter, reducing exposure to the sea and ice for both boats, easing maintenance, and thereby improving service life. Environmentally, KHA selected a hybrid power plant which can improve efficiency up to 20% and included designs such as freezer access through the reefer to reduce heat loss. Lastly, KHA took pride in the artistic value of the MTC, giving it gentle bow flare and attractive lines, making it a beautiful vessel, sure to draw looks from mariners and citizens alike.

General Arrangement Regulations follow United States Coast Guard TS - 640 Living and Berthing Spaces. TS – 640 requires that there shall be no more than six accommodations per berthing area, to include rack and personal stowage. It also requires that berths shall not be used to pass from one space to another. The MTC has no more than four accommodations to a berth. The commanding officer of a cutter with an endurance greater than 15 days must have their own berthing space that has a desk and their own cabin. Table 16 and 17 show area requirements for berths and lounges respectively. In addition to having a gross net area requirement, there are also requirements for the needed furniture in berthing areas per person. Each accommodation should have enough personal stowage which includes lockers, drawers, and wardrobes.

Table 16. USCG berthing regulations from TS-640

Space	KHA [ft^2]	TS-640 [ft^2]
Commanding Officer's Stateroom	211	>=100 *for cutters with endurance>15 days
Commanding Officer's Cabin	275	>= 200
Commanding Officer's Head	45	>= 38
Executive Officer Head	46	>= 31
Engineering Officer Head	45	>= 31
Officer Double	177-228	>=135

Table 17. Lounge facilities

Personnel Type	MTC [ft^2]	TS-640
Officers	404	5ft^2/officer accommodation >=150 ft^2
CPO	379	5ft^2/CPO accommodation >=100 ft^2
Crew	565	4ft^2/crew accommodation

Superstructure Design: In determining topside structure, KHA decided to maximize work deck space, accepting the tradeoff of reduced superstructure area. To optimize enclosed area in the superstructure, KHA extended the superstructure forward on the forecastle, leaving only enough space for a bit and capstan on the forecastle weather deck. KHA created an anchor handling room below the forecastle weather deck to protect the anchoring equipment from icing during the winter, and to shelter the crew during anchoring evolutions.

The aft end of the superstructure is aligned with the stacks from the engine room which run up along the center of the superstructure including the bridge. This enables the bridge to be a "360º bridge" meaning it provides unobstructed views in all directions. Relatedly, in the interest of lines of sight, KHA designed several geometric features of the superstructure, specifically around the bridge, to improve visibility. For example, the aft sloping surfaces abaft of the bridge wings are to give the bridge crew clear lines of sight of the beam along the buoy deck. Lastly, the overhang of the bridge wings over the weather deck walkways provides the crew unobstructed view and access over the rail along the entire length of the ship. This is beneficial for mooring evolutions, ATON operations, and in emergencies such as MOB situations.

Deck Arrangements

05 Deck (Appendix I, drawing 1) is the area above the bridge. The only components in this area are the exhaust stack and mission critical electrical components including but not limited to radio antennas, transponders, navigation lights, etc. An external ladder adjacent to the port and starboard bridge wings will give access to this deck.

04 Deck (Appendix I, drawing 1) is the bridge. The bridge is equipped with external walkways that have line of sight on the buoy deck for supervision, and walkways in front of the bridge to accommodate cleaning the windows and superstructure, or to provide bridge crews some redundancy via an alternative means of keeping eyes forward if the defrosting equipment for the bridge windows fails.

03 Deck (Appendix I, drawing 1) consists of officer berthing, an officer laundry room, the Radio Room/ET Shop, an internal communications space, and a secure space. The specific regulations referenced and followed regarding the berthing spaces are explained in Table 16.

02 Deck (Appendix I, drawing 2) consists of enlisted berthing, a cardio room, small locker rooms, a sauna, enlisted laundry room, and surge berthing. The CPO stateroom's regulations can be found in Table 16.

01 Deck (Appendix I, drawing 2) consists of the small boat and adjacent staging area, lounge spaces, stores, workspaces, a second laundry room, two fan rooms, and a head. The lounge spaces exceed the minimum space allotment regulations in Table 17. Most of the ship's administrative work will be completed on this deck. The ship's office, main training room, and the quarterdeck are located on this deck. The operations completed on this deck will occur in the two crane shacks, the small boat area, and the enclosed anchor handling space in the foremost compartment. The small boat, an OTH, is accessed either through the small boat staging room which connects to a walkway adjacent to the pontoon of the small boat, allowing crew to load into the boat while it is cradled. The armory is deliberately placed close to the small boat to streamline small boat operations. It is also centralized for protection if the vessel were to take damage. Moving aft, the fantail has three capstans and two bitts for mooring and an "H" bitt for towing similar to tugboats, and four more 25-man life rafts. The second small boat is located here on another set of dual point davits. This small boat will be a more robust small boat for ATON operations.

The Main Deck (Appendix I, drawing 3) consists of a section forward of the buoy deck and a section aft of the buoy deck. The forward section contains the anchor windless machinery room, dry and general stores, freezer, reefer, mess deck, wardroom, the galley and scullery, and sickbay. The dry food stores, reefer, freezer, and galley are on the main deck so that food and supplies can be easily loaded via a daisy chain without the need to go up or down a deck. The main deck also has dumpsters.

Aft of the 5,000 square foot buoy deck are the hazmat lockers, deck gear lockers, emergency generator, ATON shop, aft hold/gym, and storage. The aft hold is sized so that it can be loaded with modular 20-foot shipping containers via a deck hatch.

2nd Deck (Appendix I, drawing 3) contains most of the MTC's machinery spaces, housing the upper level of the MMR, podded propulsor mounts, batteries, and related support systems, as well as the Main Hold and some tankage. In the bow beyond the collision bulkhead is the chain locker. Just aft of the collision bulkhead is potable water and a designated pump room. The ECR, Repair 2, and DCC are located two transverse watertight bulkheads forward of the MMR such that they are outside the secondary damage control boundary in the case of a fire in the MMR. Aft of ECR and DCC and forward of MMR is the Main Switchboard Room (MSR) and the MK and EM shop.

Passageways aft are located outboard of MMR along the skin of the ship so that the crew does not have to enter MMR to transit aft beneath the buoy deck. Aft of the Main Hold is the Battery Room, the Battery Ventilation Room, and Repair 3. Aft steering contains the ABB Azipod control units, the VFDs, and the aft hold deck hatch HPU.

3rd Deck (Appendix I, drawing 4) includes the AMR, Bow Thruster space, the bottom decks of MMR the Main Hold, and a large amount of tankage. To separate the deck of the battery room from fuel oil tankage, there is a deck three feet below the 2nd Deck named the 3-half deck to provide a buffer. This buffer zone is filled with other tankage to utilize the space. Below the buffer zone is all fuel oil.

4th and 5th Deck (Appendix I, drawing 5) is all tankage and is split by a double bottom. This double bottom allows the MTC to have no fuel oil against the skin of the ship. The space below the MMR has no fuel oil in it and only has Dirty Oil tanks. The bottom of the Main Hold was also raised three feet to hold more fuel oil.

Tankage is heavily dependent on the mission capabilities of the vessel as well as dictating the mission effectiveness of the vessel. Tankage also comprises a significant amount of internal volume. To estimate the minimum required volumes of tankage, KHA used a combination of parent ship benchmarking and approximated consumption values.

The predicted average power during winter operations is 3,970 kW, from the EPLA. Using the SFOC of the Wartsila 9L32, the average consumption rate is 208 gal/hr, requiring 105,000 gallons of fuel to operate for 21 days straight.

It is important to note that the SFOC provided for the Wartsila 9L32 is for peak efficiency which equates to the MTC's CSR rating for each gen set. Thus, since the operating conditions are not precisely at CSR, the actual SFOC will be higher, thereby requiring more tankage. However, the MTC's battery banks counteract this by load leveling and peak shaving, significantly increasing the efficiency of the power plant in many conditions. Moreover, carrying sufficient fuel for 21 days without being resupplied, a long time for Great Lakes operations, provides a sizeable level of redundancy as well.

The final clean ballast capacity for the MTC was 160,000 gallons weighing 592 LT. This achieved the MTC's ballast goal of 144,000 gallons which was calculated using the Principle of Ship Design Course Readers approximation of 67% volume of fuel oil. With the final capacity of clean ballast, the final volume of fuel oil approximation was 150% (DeNucci). This means that the MTC has surplus ballast for the stability requirement which further benefits the stability and loading requirements that the MTC can withstand. Additionally, this provides extra ballast weight to keep the MTC at design draft, heel, and trim when not carrying a full cargo capacity of buoys, sinkers, and module containers.

Potable, grey, and black water target volumes in Table 18 were designed using common usage rates for each. (*Fundamentals of Ship Design*) from PSD gave a value of 55 gallons of potable water per person per day. EPA's *Graywater Discharges from Vessels* gave 41 gallons of grey water per person per. The USCG has standards for Marine Sanitation Devices (MSD). USCG's *Capacity of The MSD* gave 8 gallons of black water per person per day using the vacuum pump system. The target volumes are calculated with an endurance of 21 days and crew size of 41.

The size of Lube Oil, Dirty Oil, Hydraulic Oil, and Oily Water tanks were more difficult to determine. Ideally, these values would be calculated based on requirements for installed machinery and associated maintenance. Without sufficient information from vendors the values were benchmarked from USCGC MACKINAW because of the similar machinery requirements. KHA used GHS to find the actual volumes of the tanks. Table 18 reports the summary of the minimum required tankages and the actual designed tankage volumes. Detailed tank arrangements for the capacity plan can be found in Appendix J.

Table 18. Summary of tankage volumes

Tank	Minimum (gal)	Actual Usable (gal)
B100	200,000	214,000
Grey	38,700	50,000
Black	1,640	10,200
Potable	47,400	69,500
Clean Ballast	144,000	160,000
L/O	1,240	2,110
Dirty Oil	1,990	2,600
H/O	751	786
Oily Water	645	1,300

Liquid Loading

A ships' loading changes drastically while underway and in port because of the inherent need to use fuel. This constant change in the vessels loading causes changes in list, trim, and overall stability through KG changes. To ensure the MTC is safe during operations, a burn sequence/liquid loading table was created, as seen in Table 19. As tanks get emptied, ballast is needed to keep the vessel at a constant draft for icebreaking and ATON operations. At each stage as fuel is burned off, ballast is added to compensate for the loss of displacement and to maintain appropriate trim and list. Additionally, it is important to note that the prime movers burn fuel only from the service tanks. For example, in step 2, fuel from fuel tanks 5 and 6 is moved into the service tanks five times until fuel tanks 5 and 6 are each at 10% capacity.

Table 19. Burn sequence

Step	Tanks	Trim	List	GM
Full Load	Load Potable Water & Fuel, Hydraulic Oil, Lube Oil, & 4 Ballast Tanks: 9, 10, 23 & 24	Fwd 0.13°	Stbd 0.01°	15.19
1	Burn Fuel Service Tanks, Load Ballast Tanks 3 & 4	Aft 0.08°	0.00°	15.58
2	Burn Fuel in Tanks 5 & 6	Aft 0.01°	Stbd 0.01°	15.15
3	Burn Fuel in Tanks 7 & 8	Fwd 0.12°	Stbd 0.01°	14.30
4	Burn Fuel in Tanks 3 & 4	Fwd 0.19°	Stbd 0.01°	14.11
5	Burn Fuel in Tanks 1 & 2, Load Ballast Tanks 2, 3, 5, & 6	Fwd 0.17°	Stbd 0.01°	13.98

AUXILIARY SYSTEMS AND EQUIPMENT

Marine vessels require various auxiliary systems to operate safely, such as HVAC, firefighting, refrigeration, and machinery cooling systems. These all must be compliant with the regulations set forth in the U.S. Code of Federal Regulations Title 46, Chapter 1, Subchapter F, Part 58-Main and Auxiliary Machinery and Related Systems (CFR 46). Two of the largest auxiliary loads are HVAC and firefighting, as seen in the EPLA in Table 8 and Table 9.

The power estimate for the auxiliary systems is much greater in the winter than the summer because of HVAC loads, specifically heating. Although the MTC will be equipped with air conditioning, the mild summers on the Great Lakes would not require the MTC to use as much power to cool the vessel in the summer as it would to heat the vessel in the harsh winters. The final part of HVAC, ventilation, will be needed year-round on the battery space, machinery spaces, and various tanks, as outlined in CFR 46.

The firefighting systems require significant power to minimize casualties. Fire suppression systems must be able to be activated remotely from the bridge and the engineering control room, and then be effective enough to either extinguish the fire or give the crew enough time to set up fire boundaries and attack the fire with the fire main. Firefighting tools that do not require power should also be utilized, such as handheld extinguishers (CO2, PKP, AFFF) and smoke curtains. The MTC will also be built with Class A fire divisions that are in accordance with SOLAS Ch. II-2, Regulation 9 to help mitigate casualties due to fire.

Mission-Related Systems and Equipment

Two of the main mission-related systems on the MTC are the crane and the small-boat davits. The specific crane will be determined in a later iteration of the design spiral, however it will have to rotate 360° and be able to lift the largest of the Great Lakes buoys. The power requirements to operate a crane of this size are included in the EPLA. The power requirement of the two dual point davits are also included in the EPLA, although much smaller than the crane. The Coast Guard uses these dual point davits on the current seagoing buoy tenders, along with the MTC's parent ship, USCGC Mackinaw. This means the crew will likely include members that are qualified to operate them before they are assigned to the MTC.

STRUCTURE AND STABILITY

Weights and Centers

To determine the overall stability, KHA conducted a thorough weight estimation of the MTC. KHA employed a ratiocination method using SWBS data found from the parent ship USCGC MACKINAW to determine the weight values for the MTC. Through these calculations, KHA determined an initial verification of the vessel's displacement and an estimate of the ship's centers of weight, (VGC, LCG, and TCG). Table 20 summarizes the SWBS weight analysis results.

Table 20. Summary of MTC weights and centers SWBS

Group	Displacement (LT)	KG (ft)	LCG (ft)	TCG (ft)
100	2,290	26.0	127	0.0
200	495	11.1	198	0.1
300	286	24.8	172	0.2
400	16.2	52.4	143	-0.1
500	438	28.6	142	-0.3
600	389	32.1	124	0.3
700	4.5	52.6	56	0.0
Lightship	3,910	25.1	141	0.0
Margins	4,460	29.1	141	0.0
Variable	1,120	13.2	139	0.4
Full Load	5,580	22	140	0.01

Loading Conditions

KHA used full load and minimum operating conditions that are defined in DPC-079. Table 21 summarizes the MTCs loading conditions in accordance with these definitions.

Table 21. Summary of loading conditions

Item	**Full Load Condition**	**Minimum Operating Condition**
Crew and Effects	Full	Full
Provisions, General stores, Ammunition	Full	1/3
F/O Service	95%	50%
F/O Storage	95%	33%
F/O Overflow	Empty	Empty
L/O, H/O	95%	33%
Oily Waste, D/O	25%	50%
Clean Ballast	As needed to maintain 18ft Draft and less than 0.5° trim	As needed to maintain 18ft Draft and less than 0.5° trim
Potable Water	100%	66%
Grey Water	25%	50%
Black Water	25%	50%

Intact Stability

Per DPC-079, the MTC must adhere to several stability criteria tests in accordance with vessels LBP less than 300 ft, to include beam winds with rolling, beam winds with rolling and icing, high speed turns, passenger crowding, heavy weight over the side, and towline pull. KHA decided that these were all appropriate vessel stability criteria to adhere too because of the broad mission statement of the MTC. The MTC doubles as both a heavy icebreaker and buoy tender, necessitating that the heavy weight over the side criteria is met because of buoy operations.

The MTC will be conducting towing operations as a Coast Guard vessel, so it is important to ensure that the towline pull criteria is met as well. The MTC passes all stability criteria at the loading conditions defined.

A max KG curve was built from these tests, each test producing its own max KG curve. Figure 22 shows the most conservative estimates, meaning that any KG value below the curve will pass all the intact stability tests. Figure 22 indicates that the MTC is safely loaded at both full load and minimum operating conditions as defined. Figure 24 shows the MTC at lightship condition, which displaces 4,462 LT. The KG is 29.1ft above the keel, which is below the maximum KG of 36ft determined for this displacement in Figure 22. Figure 23 shows the MTC at lightship load condition, which displaces 5,403 LT. It trims forward 0.06° and is heeled 0.01° to starboard. The KG is 26.4ft above the keel, which is below the maximum KG of 35.2ft determined for this displacement in Figure 22. Figure 24 shows the MTC at full load condition, which displaces 5,580 LT. It trims forward 0.46° and is heeled 0.15° to starboard. The KG is 22.1ft above the keel, which is below the maximum KG of 35.0ft determined for this displacement in Figure 22. At both lightship and full load, the vessel is well below the max KG curve, which shows the vessel is stable at these operating points.

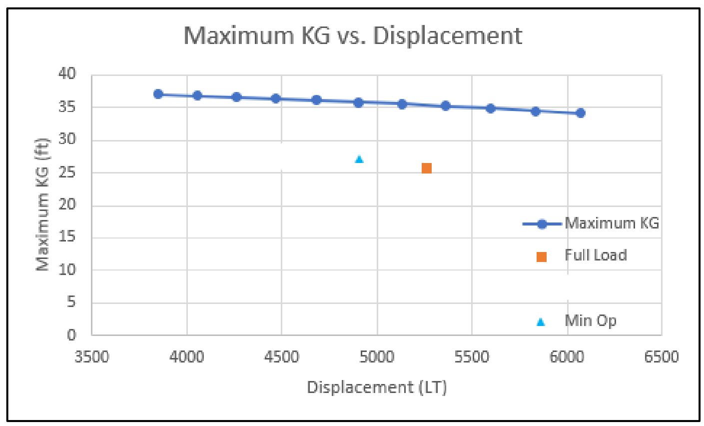

Figure 22. Max KG curve

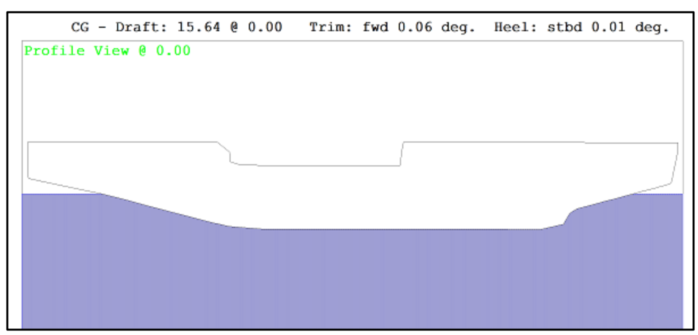

Figure 23. Profile view of MTC at lightship

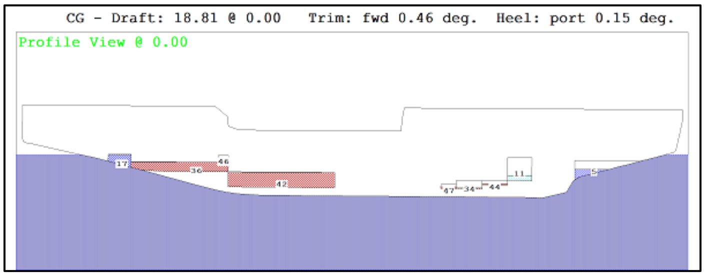

Figure 24. Profile view of MTC at full load

Longitudinal Strength

A longitudinal strength analysis was completed to get a better understanding of the structure that will be needed by the MTC. The point loads for the SWBS groups in Table 20 were transformed into distributed loads, in Table 22. The loading conditions for full load and minimum operation were then applied to the vessel in GHS. The loading curve, buoyancy, shear, and moment diagrams were developed with the loading conditions described. KHA used these longitudinal strength values in conjunction with applicable ABS rules for Building and Classing Marine Vessels to develop a minimum section modulus and minimum moment of inertia for the MTC.

The ships buoyancy curve was used to determine the distribution of SWBS W100 by distributing 2/3 of the weight of using the rectangular method, and 1/3 of the weight with the trapezoidal method over the buoyancy curve. This was because an in-depth plate and girder analysis is not available for this preliminary design. Figure 25 shows the distribution of W100.

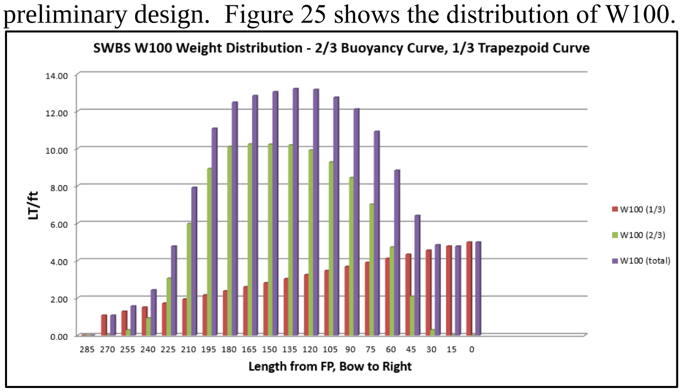

Figure 25. SWBS W100 distribution

The second step was distributing SWBS groups W200-W700. By inspection of the Rhino file, the W200-W700 groups were binned appropriately to align LCG's of individual subgroups and take into consideration large components like the podded propulsors, gensets, and tanks. Figure 26 shows the distribution of weight for the MTC. Table 22 shows a summary of the distribution of weight.

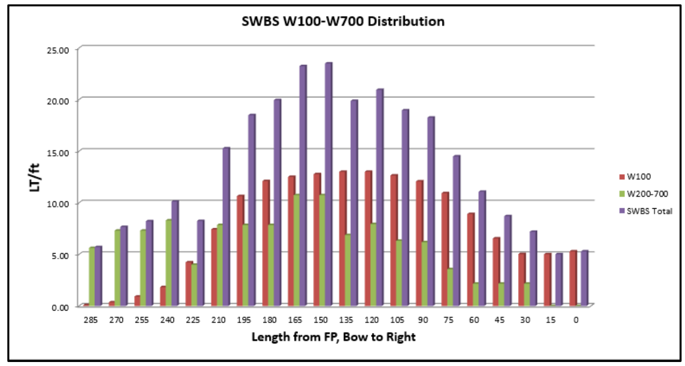

Figure 26. Lightship distributed weights plot

Table 22. Lightship distributed weights summary

Bins (Frames)	SWBS 100 (LT/bin)	SWBS 200-700 (LT/bin)	Light Ship Total (LT/bin)
1 (0-15)	5.0	0	5.0
2 (15-30)	4.8	0.0	4.8
3 (30-45)	4.8	2.2	7.0
4 (45-60)	6.4	2.2	8.6
5(60-75)	8.8	2.2	11.0
6 (75-90)	10.9	3.6	14.5
7 (90-105)	12.1	6.2	18.3
8 (105-120)	12.7	6.3	19.0
9 (120-135)	13.1	6.9	20.0
10 (135-150)	13.2	6.9	20.1
11 (150-165)	13.0	10.7	23.8
12 (165-180)	12.8	10.7	23.5
13 (180-195)	12.5	7.8	20.3
14 (195-210)	11.1	7.8	18.9
15 (210-225)	7.9	7.8	15.8
16 (225-240)	4.8	4.0	8.8
17 (240-255)	2.4	8.3	10.7
18 (255-270)	1.6	7.3	8.9
19 (270-285)	1.1	7.3	8.4
Total (LT)	2398	1707	4104

GHS was then used to find the VCG and LCG of the two loading conditions defined. Table 23 shows the results of the shear and moment calculations. These values can be applied with ABS regulations to build a minimum midship structure.

Table 23. Loading condition summaries from GHS

Item	Full Load Condition	Minimum Operating Condition	Lightship
Displacement (LT)	5,582	5,403	4,104
VCG	22.1	21.4	25.1
LCG	140.8	141.5	140.5

ABS rules for Building and Classing Marine Vessels include regression equations to best calculate a vessel's longitudinal strength characteristics. Since ABS does not have an equation for the maximum still-water bending moment, GHS was used with all the weights for the two loading conditions to find the maximum still water bending moment, shown in Table 24. This value is then added to the wave bending moment found with equations 1 (sagging) and 2 (hogging) to find the maximum bending moment (American). The variables ABS are defined in Table 25.

Table 24. Maximum bending moments

Hogging Still Water bending moment (LT-ft)	37,581	39,542

(Eq. 1) $$M_{ws} = -k_1 C_1 L^2 B(C_b + 0.7) \times 10^{-3}$$

(Eq. 2) $$M_{wh} = +k_2 C_1 L^2 B C_b \times 10^{-3}$$

Table 25. Table of variables for ABS equations

M_{sw}	Stillwater moment
M_{ws}	Wave bending moment (sag)
M_{wh}	Wave bending moment (hog)
k_1	1.026 (from ABS for >200ft ship)
k_2	1.772 (from ABS for >200ft ship)
C_1	7.569 (from ABS for 285ft ship)
L	285ft (from Rhino file)
B	70ft (from Rhino file)
C_b	0.593 (From Rhino file)

The hull girder minimum section modulus and minimum moment of inertia amidships for the vessel are also calculated using equations from ABS rules. These are equations 3 and 4 (American). The calculated values are shown in Table 26. These minimum values were compared against the actual midship structure to ensure compliance with ABS.

(Eq. 3) $$SM = M_t / f_p$$

(Eq. 4) $$I = (L \times SM)/33.3$$

(Eq. 5) $$Mt = Mw + Msw$$

Table 26. Longitudinal strength values

Msw (FL hog) =	37,581.0	LTf-ft
Msw (min op hog) =	39,542.0	LTf-ft
Mws=	-57,091.6	LTf-ft
Mwh=	45,221.5	LTf-ft
M_t h=	84,763.5	LTf-ft
M_t s=	-17,549.6	LTf-ft
SMmin=	8,012.9	in^2-ft
SMmin=	7,481.3	in^2-ft
MOImin=	64,029.4	in^2-ft^2

Midship Section

KHA designed the midships structure to PC4 standard, with the plan to also earn the notation of "Icebreaker." The PC4 description is for "Year-round operation in thick first-year ice which may include old ice inclusions" (*American*). This ruleset provides equations and ice loading condition factors that enable designers to calculate minimum shell plate thickness.

PC4 defers to general structural requirements for all vessels defined in Part 3 of the ABS ruleset. Therefore, part 3 of ABS was used to determine wave sheer and moments, minimum section moduli for the entire ship and individual hull girders, sheer strake thickness, deep tank thickness, and minimum deck plate thickness. In conjunction with the still water shear and moment calculated via GHS, this enabled KHA to select appropriate, commercially available steel plates for shell and deck plating and ST beams for hull girders. Finally, by adjusting frame and stiffener spacing, KHA designed a midships section with a minimum factor of safety (FOS) of 1.7.

To achieve the ABS Icebreaker notation, KHA will need to submit detailed plans of various ice loading scenarios and additional structural analysis. This will happen in subsequent iterations of the design spiral.

Finding the Section Modulus began with knowing what material properties to design for. KHA first determined the grade of steel for the hull plating and structure, then calculated minimum shell plating thicknesses based on the ABS PC4 standard. ABS specifies what grades of steel are necessary depending on temperatures in which the vessel is intended to operate, as well as the general thickness of the steel. KHA chose AH36 steel because it is common in ship building yards and more inexpensive than alternatives.

The plate thickness calculations for the PC4 standard consider various factors such as the angle of the frames relative to the shell plating at the location of analysis, multiple failure methods, and the intended polar class standard. Additionally, these calculations subdivide the shell plating into eleven different sections. Table 27 shows the results of the ABS PC4 calculations for minimum shell plating thicknesses for the MTC.

Table 27. ABS PC4 calculations for minimum shell thicknesses and closest applicable standard plate thicknesses selected.

Location	Subdivision	t_{min} (in)	Standard thickness
Bow	All	1.05	17/16
Bow intermediate	Ice belt	0.318	3/8
	Lower	0.272	5/16
	Bottom	0.239	1/4

Midbody	Ice belt	0.256	5/16
	Lower	0.230	¼
	Bottom	0.200	¼
Stern intermediate	Ice belt	0.318	3/8
	Lower	0.272	5/16
	Bottom	0.240	¼
Stern	All	0.337	3/8

Plate thickness because of deep tanks needs to be considered next because of the high pressure-head from a relatively tall forecastle where the tank vents will be located. The forecastle is about 50 feet above the baseline and using this pressure-head in the ABS equations, KHA calculated that the plates forming the deep tanks need a thickness of 7/16ths of an inch. Next, the sheer strake thickness was increased from 5/16 inch to ½ inch because the height of the neutral axis for section modulus was low and the sheer stress had the lowest factor of safety. Finally, ABS equations were used to calculate minimum plate thicknesses for the main deck and effective lower decks. All three equations KHA used resulted in 5/16th inch plates. The buoy deck thickness will likely be increased in subsequent iterations to account for point loads, drops, and increased wear. Final steel thicknesses are displayed in Table 28.

Table 28. Actual plate thicknesses selected

Location	Thickness (inch)
Deck	5/16
Sheer Strake	1/2
Ice Belt	3/8
Lowers	5/16
Bilge	7/16
Bottom	7/16
Deep Tanks	7/16

ABS likewise provides equations to calculate the minimum required section modulus of hull girders, therefore accounting for secondary stress. ABS dictated a minimum hull girder section modulus of 3.06 cubic inches, which KHA then used to locate appropriate T beams. KHA selected the ST 6x15.9 beam which has a section modulus of 3.31 cubic inches. KHA used 24 inches as the starting point for longitudinal spacing. The ST beam shape is illustrated in Figure 27, and the dimensions for ST 6x15.9 beams are in Table 29.

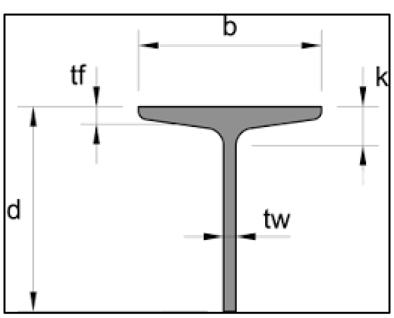

Figure 27. ST beam shape.

Table 29. Dimensions for the ST 6x15.9 beam selected for hull girders.

Beams used:	ST6x15.9	
Depth	6	in
Stem thickness	0.35	in
Flange width	5	in
Flange thickness	0.544	in
Area	4.68	In^2
I	14.9	in^4
SM	3.31	in^3

The Section Modulus used the maximum bending moment from Table 26, which is a hogging moment of 84,800 LT*ft. Since the maximum bending moment is a hogging moment, this means that the deck will be in tension, which is ideal since this is the preferred type of stress for steel. This bending moment drove the design of the midship section, and ultimately it exceeded the ABS minimum by 69% at the deck and 155% at the keel. See Appendix K for the midship section.

Secondary, Tertiary, and Shear Stress were next. The secondary stresses at the bottom of the vessel and on the buoy deck was, in both cases, minimal for individual hull girders. For analyzing stress on the buoy deck, KHA looked at the scenario of a 4'x4' 18,000 lb. sinker sitting on deck. Ultimately, the stress at the bottom of the MTC due to head pressure was found to be greater. Following secondary stress, KHA analyzed tertiary stress on the bottom plating with a head pressure of 18 feet. Since the max deflection of 0.1 inches is less than 75% of the 7/16" thick steel plate, Muckle's Large Deflection Theory was not necessary. The final FOS for the Von Mises stress was 4.6. From the initial midship section the sheer stress buckling FOS was significantly low at 0.15. This was rectified by decreasing the frame spacing and increasing the side shell plating from the ABS minimum of ¼ in to 5/16 in., raising the FOS to an acceptable 1.7.

Damage Stability

This damage stability assessment uses DPC-079 as a reference for what qualifies as passable for damage conditions, building on the previously assessed intact stability. KHA subjected the MTC to several damage conditions (defined later through DPC-079) and tested those conditions against specific stability criteria using GHS. Each damage condition was performed at both full load and minimum operating loading profiles. According to DPC-079 8.4.2.1.2.1, the standard for the MTC is that it meets a two-compartment standard. This means that any two adjacent compartments can be flooded, and the vessel will meet the ensuing damage stability criteria. Furthermore, KHA will assume decks and platforms as ruptured due to the adverse effect of flooding, as seen in DPC-079 8.4.2.1.2.3. The MTC does not have longitudinal watertight bulkheads, which increases the transverse extent of damage but reduces asymmetrical flooding, as seen in DPC-079 8.4.1.2.2. The MTC will follow the limitations outlined in DPC-079 8.3.1.1.1 to meet damage stability requirements, while enduring asymmetric damage.

DPC-079 8.3.1.1.1 outlines five criteria that the MTC must pass to be considered satisfactory. The first criterion is that the initial heel angle after damage does not exceed 15 degrees. The second criterion is that the ratio of the righting energy to the heeling energy of rough seas and beam winds does not exceed 1.4, with the magnitude of the rollback angle determined from DPC-079 8.4.8, Equation 1; and the wind magnitude from Equation 2, from DPC-079 6.1.2. The third criterion is that the maximum value of the righting arm minus the value of the wind heeling arm shall be greater than 0.25ft. Fourth, that the margin line shall not be submerged at static lists. And fifth, that the righting area on the righting arm curve meets or exceeds the required area from Equation 3 from DPC-079 8.3.1.1.1. See Table 30 for the required criteria and Appendix M for the calculations.

Eq 1. $\Theta_R = Co\Delta^7 + C1\Delta^6 + C2\Delta^5 + C3\Delta^4 + C4\Delta^3 + C5\Delta^2 + C6\Delta + C7$

Eq 2. $V = Co + C1*\Delta + C2*\Delta2 + C3*\Delta3$

Eq 3. $A1 = a\Delta^7 + b\Delta^6 + c\Delta^5 + d\Delta^4 + e\Delta^3 + f\Delta^2 + g\Delta + h$

Table 30. Summary of required calculations

Criteria	Value
Eq 1. Req. Rollback Angle (Θ_R) =	10.6 deg
Eq 2. Wind Velocity (V) =	34 kts
Eq 3. Required Area (A1) =	3.24

To begin using GHS to analyze damage stability the preliminary ship geometry must be converted from Rhino 7 to a GHS geometry file. Previously, KHA built a geometry file to analyze tank loadings and longitudinal strength of the vessel. This early-stage geometry file did not include any compartments other than tankage and voids with permeabilities of 0.89 (0.99 from structure and 0.90 usable). After building the rest of the compartments through inspection of the general arrangement, the next step is to assign appropriate permeabilities by referencing DPC-079 3.2.6.1. See Appendix M for the permeabilities.

The downflooding points (DF) are chosen in accordance with chapter 2 of DPC-079, Watertight Envelope. KHA assumes that all buoy deck cargo and access hatches are watertight. KHA will also ensure that the emergency generator exhaust port will be made to meet Grade A shock so it will not be considered a DF point. All intakes are DF points, as well as two access hatches on the fantail that will be considered a DF point.

After running both full load and minimum operating conditions with appropriate compartment permeabilities and assumed DF points against the damage stability criteria in GHS, it was found that the MTC passed all criteria listed above to a two-compartment standard. See Appendix N for a summary of all specific results of the analysis.

Worst Case Condition

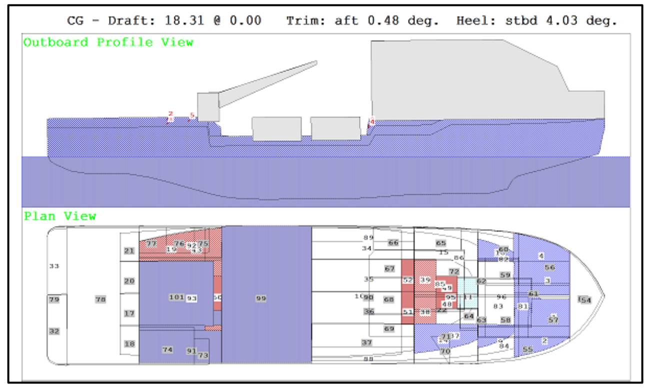

Figure 28. Damage condition 5 at full load

The worst damage condition found has the two adjacent watertight subdivisions including several ballast tanks, multiple large fuel oil tanks, hydraulic oil tank, a large main hold, and the battery bank, along with connecting passageways. Illustrated in Figure 28, this damage condition is at full load, which means there are buoys on deck and in the main hold. Several damage conditions have similar lists or worse trims, but this damage case is worse for several other factors. At this damage condition the fuel oil tanks have leaked out and flooded, and the battery bank is submerged partially below the waterline. This could imply fuel getting to the battery banks and if there was a discharge from the batteries the combination could spell disaster. These combinations of compartments make this condition much worse than any other because of the risk of total loss of control and a battery fire. During future design iterations the distribution of fuel oil throughout the ship will be revisited along with a more in-depth analysis on battery fire safety. In a positive light, the rather large beam of this vessel results in a wind heeling moment values being rather negligible. Testing from the minimum 34kts to 80kts the vessel barely heeled, making this an incredibly stable platform.

Seakeeping

Conducting a seakeeping performance assessment on the MTC is important to ensure that the MTC will be able to perform its assigned missions. Extreme sea states can prevent small boats from being launched, helicopters from landing, and compromise the whole comfort of those onboard the ship. GHS was used to compute seakeeping analysis by testing the six ship motions as well as slamming and motion sickness. To produce accurate results from GHS, the correct wave spectrum had to be included. The Join North Sea Wave Project (JONSWAP) wave spectrum was used because it is for waters with geographic boundaries which causes a limited fetch, just like the Great Lakes (*Principles of Naval Architecture).*

The very broad concept of seakeeping is systematically broken down into two different categories: transit mission and operability. For operability KHA will be looking at small boat operations as the most complex evolution that will be conducted while making way. Analysis is also conducted on station keeping because much of the operating profile includes servicing ATON. Criteria based on the six degrees of freedom (roll, pitch, yaw, heave, sway, and surge), deck wetness, and the Marine Sickness Incidence (MSI) index. The deck wetness metric measures the number of times the deck gets water on it within an hour. The MSI index is a measure of the percentage of passengers who would likely experience motion sickness during a three-hour exposure period. The motions are chosen for the transit mission and operability along with appropriate sea states and speeds in accordance with the USCGs seakeeping standards in Fundamentals of Ship Design, shown in Table 31. These criteria, sea states, and mission speeds will be analyzed with specific headings in mind. For the analysis, all headings from 000° to 180° are tested and then mirrored on graphs because the vessel is symmetrical down the centerline.

Table 31. Transit mission and operability CG limits

	Transit	Small boat
Speeds (kts)	8, 10, 12, 14	8
Roll (deg)	4	4
Pitch (deg)	1.5	1.5
Vertical Accel (Gs)	0.2 (pilot house, ECC)	0.2 (small boat)
Transverse Accel (Gs)	0.1 (pilot house, ECC)	0.2 (small boat)
Deck Wetness (occ/hr)	30	n/a
Slamming (occ/hr)	20	n/a
Sway at stern (ft)	n/a	4.9
MSI index	< 30%	< 30%

GHS is then used to test these limits at specific points on our ship. These critical points are locations where mission capability can be significantly diminished if the motions are poor. The critical points chosen for analysis are the bridge, boat stations 1 and 2, ECC, the buoy deck, and the fantail.

The polar graphs in the following Figures display a pass (green dot) or a fail (red circle) for all of the speeds and headings tested. In calm conditions of 2 ft seas, the expected typical operating condition, the MTC passes all DPC-079 requirements. In 12-foot seas, a condition which is not conducive to buoy tending operations nor possible when ice breaking, the tradeoffs of the hull form, as expected, become more apparent. Figure 29 shows that the vessel will roll to 15 degrees in 12ft seas, which is relatively mild though still failing. This shows the roll dampening effects of the wide beam and tight bilge radius. The UIB leads to significant slamming when heading into the seas, depicted in Figure 30 by the red circles indicating it does not meet the DPC-079 slamming criteria. In all though, the MTC performs very well and with good ship handling the crew can remain operational during even heavy sea states.

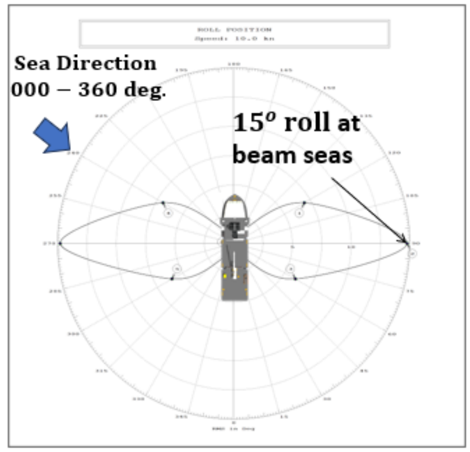

Figure 29. Roll degrees for 10 kts (12ft seas)

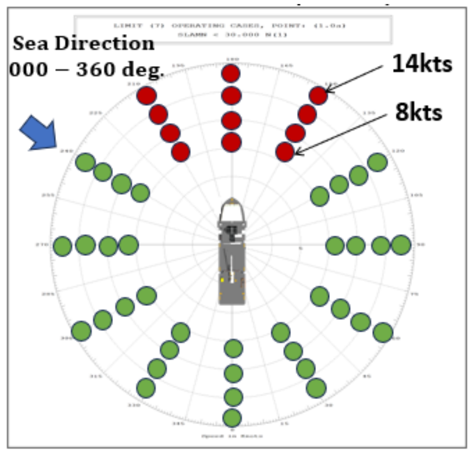

Figure 30. Slamming (12ft seas)

COST ANALYSIS

At the beginning of this project KHA conducted a Product-Oriented Design & Construction Cost (PODAC) Model to estimate the feasibility of the ship. It is a weight-based cost estimate intended for slow, heavy vessels, which lends itself well to the MTC. In addition to being built for larger ships, the model has a ship complexity factor which considers that the MTC is a USCG Icebreaker. The analysis is built on cost estimates from 1997 and uses the average inflation (CPI Bank of Minneapolis) since then to calculate modern costs. Follow-on ship costs are found using a learning curve factor of 85%, which is normal for shipbuilding according to Glosten Associates. A summary of the inputs and the cost estimate is included in Table 32.

Table 32. PODAC summary

Inputs	Value
Ship Factor	4.5
Displacement (LT)	5436
Speed (knots)	16
Years since 1997	27
Assumed US Inflation Rate	2.50%
Present Lead Ship Cost	$ 335,000,000
Assumed Learning Curve	85%

Slope	
Follow on Ship Cost	$ 286,000,000

The SWBS Acquisition cost analysis uses parametric labor and material factors based on the most recent labor and material rates from CG-459, and a weight margin of 12.5% (National).

These parametric labor and material factors are then applied to the different SWBS groups and sub-groups. For group 100, the steel hull and steel superstructure comprise most of the cost with some relegated to the power plant foundations and mast. Group 200 is broken down into the cost of the MDG's, intakes, exhausts, propulsors, and miscellaneous. The MDG's and propulsor weights are pulled directly from their manufacturers. Group 300 is the most expensive component group because it is comprised of sensitive electronics which have the highest labor rates and material costs. Group 400 is also expensive being comprised of the C4ISR systems. Groups 500-700 were not broken down past the group level due to the reduced complexity. The subtotal for the weight groups totals $275M. Groups 800 and 900 for integration/engineering and ship assembly/support systems total an additional $183M. These groups are a factor of the cost of materials and historical manhours (Glosten). The subtotal for construction totaled $458M.

Having conducted both analyses, KHA deemed the SWBS Acquisition cost estimates to be more accurate. It deals with current data, while the PODAC estimates deal with data from 1997. PODAC also uses the total displacement, while SWBS Acquisition compartmentalizes everything. Some drawbacks of the SWBS method like not taking different fabrication methods, shipyard skill, etc., and only using group weight does not lend the estimation well for novel ship designs. Without reaching out to contractors for bids, this is the best estimate.

RISK ASSESSMENT

With designing a new class of vessel comes tradeoffs and acceptance risk. For example, KHA wanted to ensure the gensets could be easily accessible and overhauled through the buoy deck if need be. The added risk that was accepted is that the aftermost bulkhead of the superstructure does not continue down through the main deck. This creates a concentration of stress at the junction of the superstructure and the buoy deck. A deeper technical analysis of the stresses in that corner should be conducted, however there is likely a need for additional structure in the main machinery space.

The LOA also raises issues when it comes to the cost of production. Shortening the MTC to the length of one of the parent vessels, USCGC Mackinaw (240 ft) greatly brings down the cost. Though, the MTC's length is driven by its beam, so the beam would likely have to come in if the length is shortened, which would mean a smaller ice channel for the ships on the Great Lakes. The possibility of having a much lower L/B ratio is also an option and should be researched more.

FUTURE ITERATIONS

Since the MTC is an icebreaker, resistance calculations are more difficult due to the variability of the densities and thicknesses of the possible ice that it will encounter. Although KHA was able to use regression models to predict the icebreaking resistance, model testing through ice would provide more accurate data moving forward.

CONCLUSION

KHA's MTC is a highly capable, flexible, and robust asset which will provide unmatched contributions to the Coast Guard missions in District 9. With an LOA of 285ft, BOA of 70ft, and draft of 18ft, the MTC breaks heavier ice and a wider channel than the USCGC MACKINAW and does so more efficiently with a UIB and hybrid biodiesel-electric power plant. Moreover, the MTC's 5,000 ft^2 buoy deck, 3,300 ft^2 fantail, and Main and Aft Holds enable it to execute ATON operations more safely and efficiently. These also allow the vessel to take on modular containers which turn the MTC into a modular asset, ready to adapt to any mission, and truly living up to the Coast Guard's motto, *Semper Paratus* (always ready).

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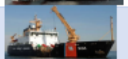
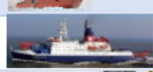
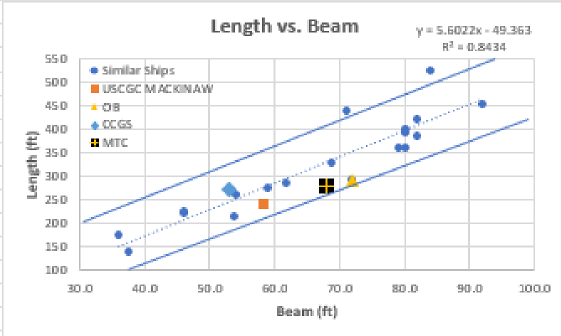
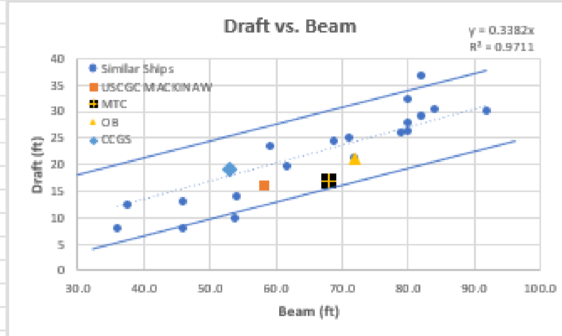
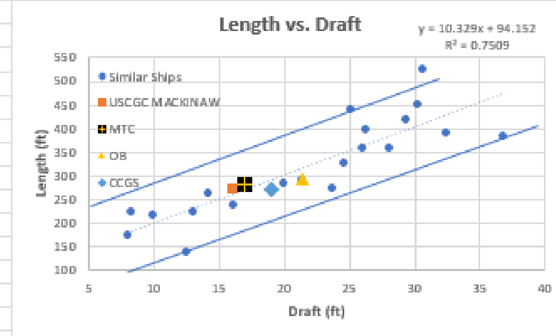
Appendix A.1 – Market Research

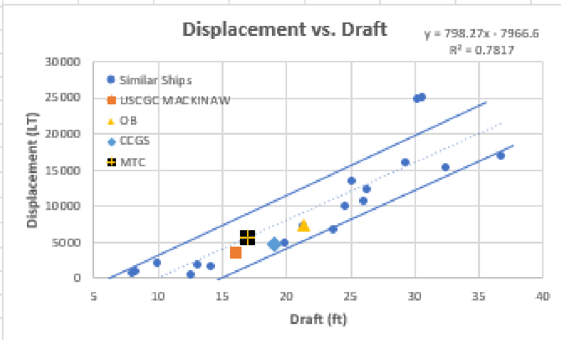
Name	Type	Image	LOA (ft)	L/B	(ft)	Depth (ft)	Draft (ft)	Disp. (LT)	Slender	Power (hp)	C_B (Calculated)	I/B	Crew	Country	Type	Max Speed	Cruising	Endurance	ion	Why?	The link
Sanaborg and Serkeborg	IMSV		224	4.87	45.9	16.7	8.2	990	6.8	5230	0.411	.6m at 4kts	8	Netherlands		12.5				Icebreaking, Large working deck	https://www.conoship.com/portfolio-item/36t-ice-breaking-multi-purpose-support-vessel/
Bay Class (140)	Ice Breaking Tug		140	3.73	37.5		12.5	662	4.9	2500	0.353		17	US	2xFairbanks-Morse diesel electric	14.7	12	4000 nm @ 12 kts		Great Lakes Icebreaker	140-foot bay-class tugboat > United States Coast Guard > Assets (uscg.mil)
OSD-IMT	AHTS ice breaker		263	4.86	54.1	18.0	14.1	1824	6.5	6600	0.318	27.5 in	34			13			Ice class 1A	Ice Breaking capabilities	engineering.com/wp-content/uploads/2022/01/Factsheet_Shallow_Draft_Ice_Class_AHTS_80m.pdf
Vidar Viking/CCGS Captain Molly Kool	AHTS ice breaker		275	4.65	59.1	27.9	23.6	6872	4.4	1797	0.628	1m at 3kts	19	Canada	Geared Diesel (2x Controllable Pitch, 2 generators, 1 emergency generator)	16	11	11000nm/42 days		Icebreaking,similar in length	CCGS Captain Molly Kool - Wikipedia
SEACOR Maya	**Hybrid** OSV		286	4.63	61.7	24.3	19.9	5073	5.0	10192	0.506	N/A		Mexico	4x Cummins QSK60-D(M), 4x 480 VAC	14.3			OSV	Hybrid Icebreaker	Vessel (seacormarine.com)
USCGC Mackinaw	Buoy tender/ice breaker		240	4.10	58.4		16	3500	4.8	9119	0.547	.81m at 3kts	55	US	3x Caterpillar 3612 Turbocharged V-12	15	9	4000 nm @ 12 kts, 9000 nm @9 kts		Our vessel's capabilities are based off of this vessel	CGC MACKINAW (uscg.mil)
Juniper Class (225)	Buoy Tender		225	4.89	46.0		13	2000	5.4	3100	0.520		48	US	2x3100 hp Cats	15	12	6000 nm @ 12 kts		Coast Guard Buoy Tender, operates on the Great Lakes	225-foot Juniper class > United States Coast Guard > Display (uscg.mil)
Keeper Class (175)	Buoy Tender		175	4.86	36.0		8	850	5.6	2000	0.590		24	US	2xCat 3508 DITA	12	10	2000 nm @ 10 kts		Coast Guard Buoy Tender	175-foot Keeper class > United States Coast Guard > Display (uscg.mil)
CCGS Sir William Alexander	Light Icebreaker/ buoy tender		272	5.13	53.0		19	4662	4.9	7040	0.596	no data	26	Canada	3xALCO diesel, 2xfixed pitch, bow thruster	16	10	120 days/6,500 NM	CASPPR Arctic Class 2	Light Ice Breaker on the Great Lakes	CCGS Sir William Alexander - Wikipedia
ASRV Nuyina	Icebreaking Research Vessel		526	6.26	84.0	93.2	30.5	25,097	5.4	35671	0.652	1.65m at 3kts	32	Australia	Diesel Electric (2 Diesel Engines 19,200 kW each and 4 generators 7,400 kW each)/ 2 shafts to CPPs	16	12		Lloyd's Register of Shipping	Icebreaking	https://www.damen.com/vessels/research-and-science-vessels/antarctic-supply-research-vessel
USCGC Healy	Medium Ice breaker		420	5.12	82		29.25	16000	5.0	46350	0.556	4.5ft @ 3 kts	85	US	4 x Sulzer 12ZAV40S	17	14			Heavy Coast Guard Icebreaker	United States Coast Guard > Our Organization > Area Cutters > CGC Healy > Ship (uscg.mil)
Aiviq	Icebreaking OSV		360	4.50	80	34	28			21760		1m @ 5kts	28	US	4xDiesel, 2CPP, 3xbow thruster	15			ABS A3	Superstructure, aft deck	Aiviq - Wikipedia
CCGS Louis S. St-Laurent	Heavy Icebreaker		392	4.90	80	53.48	32.4	15324	4.8	27010	0.528		44	Canada	Diesel Electric AC/DC (5x krupp mak, 3 shafts,)	18	15	28000 nm/205 days		Icebreaking	Vessel - CCG Fleet (dfo-mpo.gc.ca)
Shirase	Ice Breaking Research Vessel		453	4.93	91.9	47.6	30.2	25,000	4.7	30000	0.697	1.5m	170	Japan	Diesel Electric	19				Icebreaking	AGB Shirase Class (globalsecurity.org)
Polaris	Medium Ice breaker		360	4.56	79.0		26	10788	4.9	25479	0.511	6ft at 3.5 kts	16	Finland	2x Wartsila 9L34DF, 2x Wartsila 12V34DF, 3 azipods (2x6.5MW, 1x 6MW)	17		10 Days on LNG, 20 days on diesel	Polar class 4	Icebreaking, same company designed Mackinaw	POLARIS | Aker Arctic
S.A. Agulhas	polar supply and research		440	6.20	71.0	34.6	25.1	13471	5.6	12070	0.601	3.3ft at 5 kts	45	South Africa	4x Wartsila 6L32	16	14		Polar Class 5	Icebreaking and ATON capabilities	The Vessel - Endurance22
OB	Port icebreaker		293	4.07	71.9	34.4	21.3	7356	4.6	16092	0.574	4.9 ft @ 2 kts	19	Russia	3x 4880 kW Gensets, 4x 3000 kW azimuth thrusters	15		30 days	Polar Class 3	Similar mission, same company designed Mackinaw	OB | Aker Arctic
Mangystau	Shallow draft icebreaking tug		217	4.02	53.8	14.4	9.84252	2182	5.1	6437	0.666	2 ft @ ? kts		Romania	4x high speed Caterpillar 3512 C turbocharged gen sets, 3x 1600 kW azimuthing thrusters				Ice class 1A Super	Shallow draft, icebreaking	MANGYSTAU | Aker Arctic
ALEKSANDR SANNIKOV_AI	Icebreaking Support Vessel		399	4.99	80.1		26.2467	12453	5.2	28832	0.520	6.56 ft @ 2 kts		Russia	4x 27MW gen sets, 1x 1.2MW harbor gen set, 3 azipods (2x 7.5MW, 1x 6.5MW)	16			Polar Class 2	Icebreaking	https://akerarctic.fi/en/reference/aleksandr-sannikov/
RV Polarstern	Research Icebreaker		386	4.71	82.0		36.7	17026	4.5	18940	0.513	4.5 ft 11 in @ 5	44	Germany		16	10.5	75		Icebreaking	Polarstern - MOSAiC Expedition (mosaic-expedition.org)
SCF Sakhalin	Icebreaking platform supply and standby vessel		327.8	4.77	68.7	36.1	24.6	9980	4.6	23334	0.631	4.9 ft @ 2 kts	40	Russia	3x Wartsila 8L38B 5.8MW gen sets, 2 ABB Azipod VI1600 6.5MW, 2x 1.1MW bow thrusters	16.7	15		DNV ICE-10, RS Icebreaker 6	Icebreaking, large working deck aft	https://en.wikipedia.org/wiki/SCF_Sakhalin

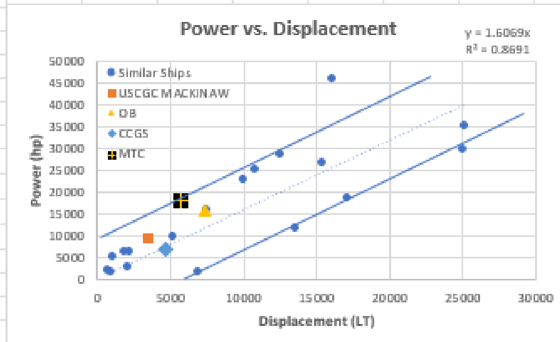
Appendix A.2-Market Research Plots

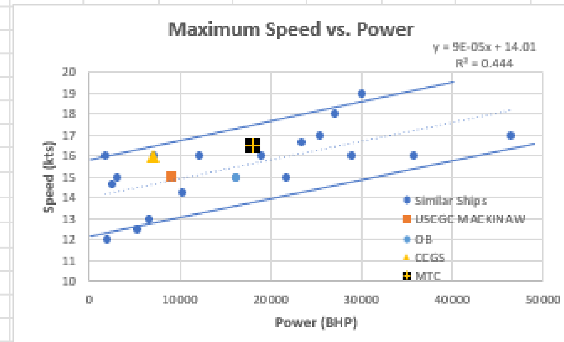


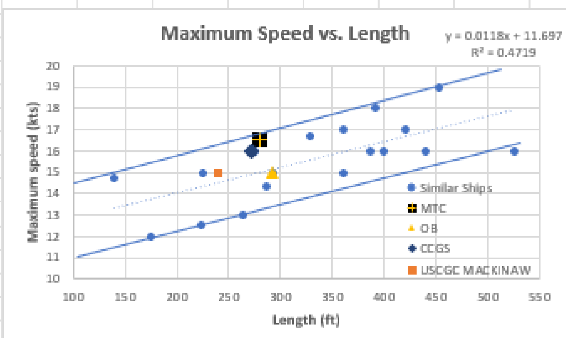


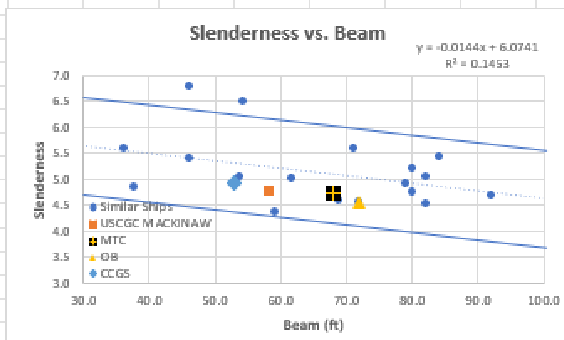






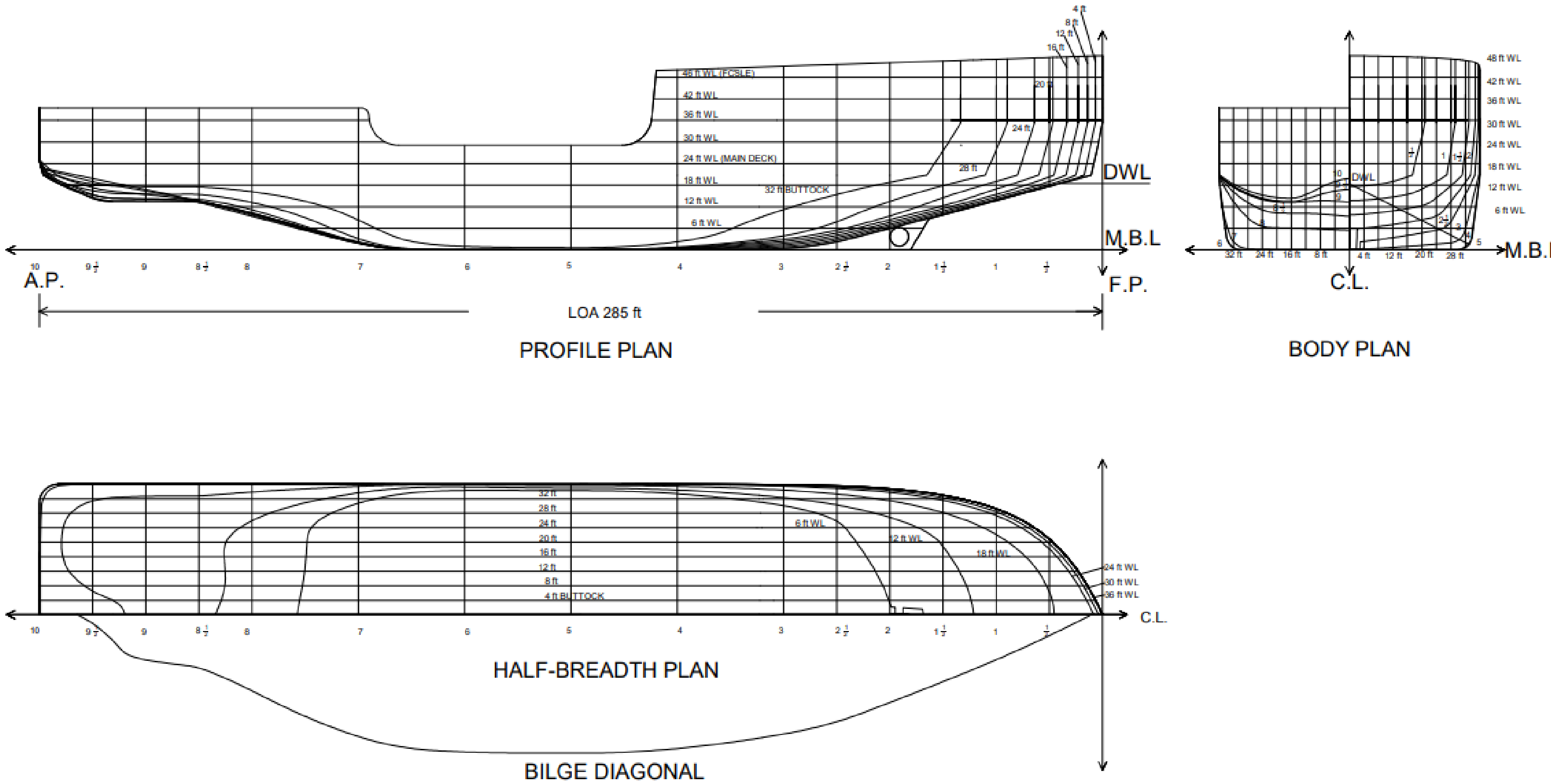






Note: This is a progressive model on what dimensions helped determine what dimensions. For example, the length was driven by the beam, and the draft was driven by the length.

Appendix B – Lines Drawing



Principal Characteristics	
LOA = 285 ft	BOA = 70 ft
D = 52 ft	T = 18 ft
Lwl = 270 ft	Bwl = 70 ft
Cb = 0.593	Cp = 0.616
Displacement = 5749 LT	S = 21563 ft^2

Maritime Transportation Cutter		
Khione Horion Architechts		
12/10/2023	1	SHEET 1 OF 1
feet	1:518	

Appendix C.1- Burrill Diagram

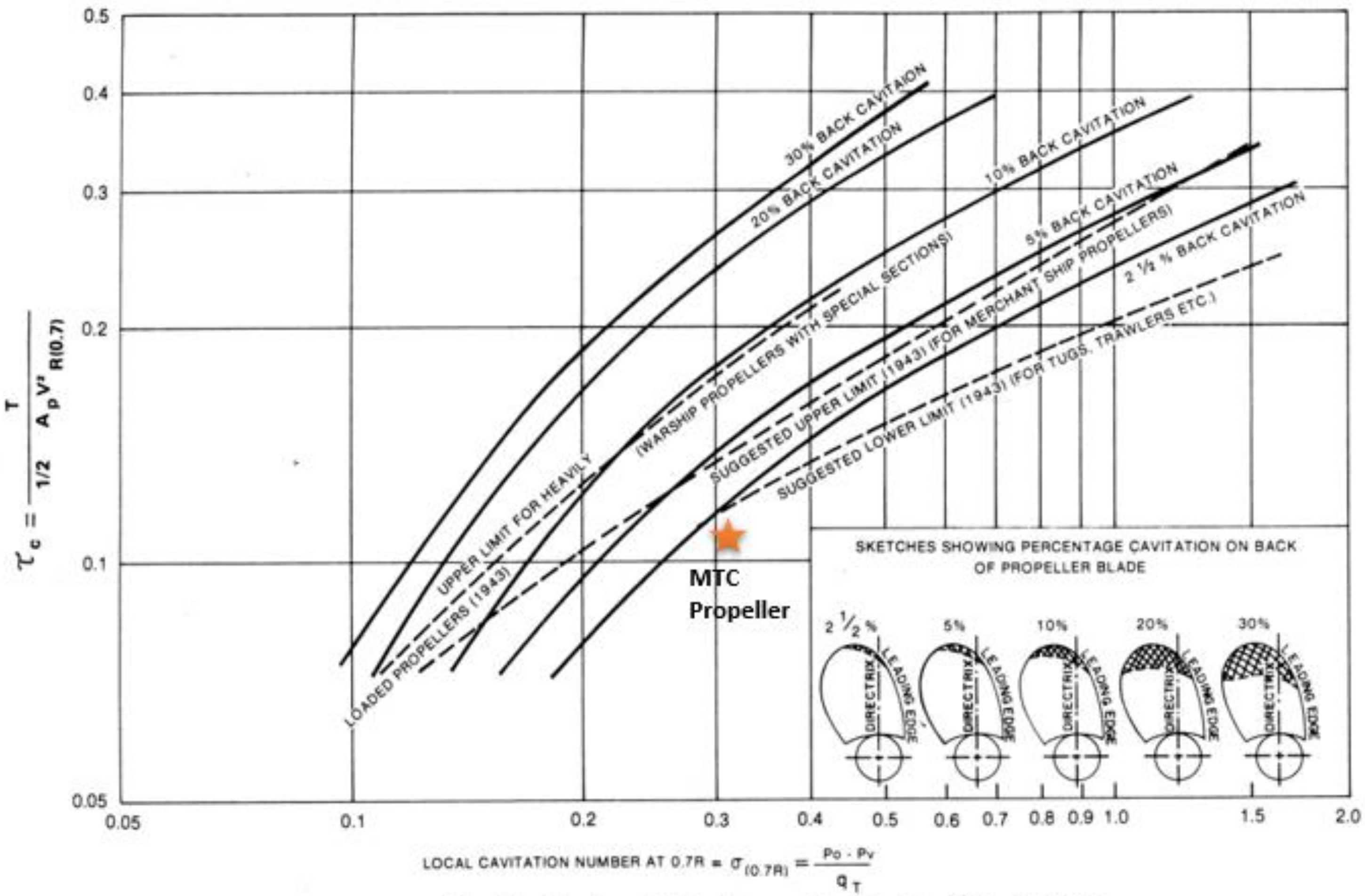
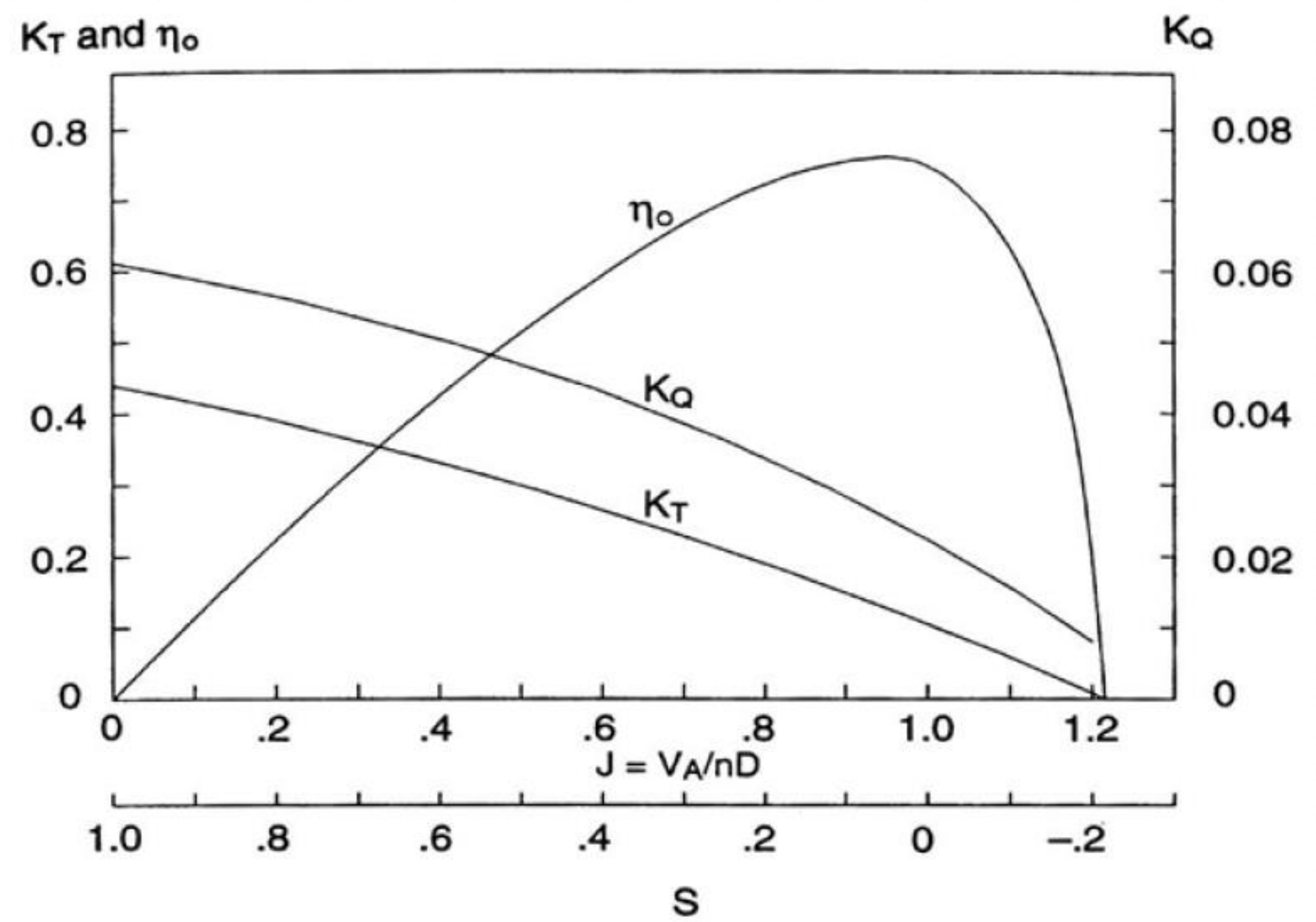


Fig. 45 Simple cavitation diagram (Burrill, et al, 1943, 1962-63)

APPENDIX B – BURRILL DIAGRAM

Appendix C.2 - KT, KQ, η_o vs Advance Coefficient plot



Appendix D – Genset and Emergency Genset Comparison

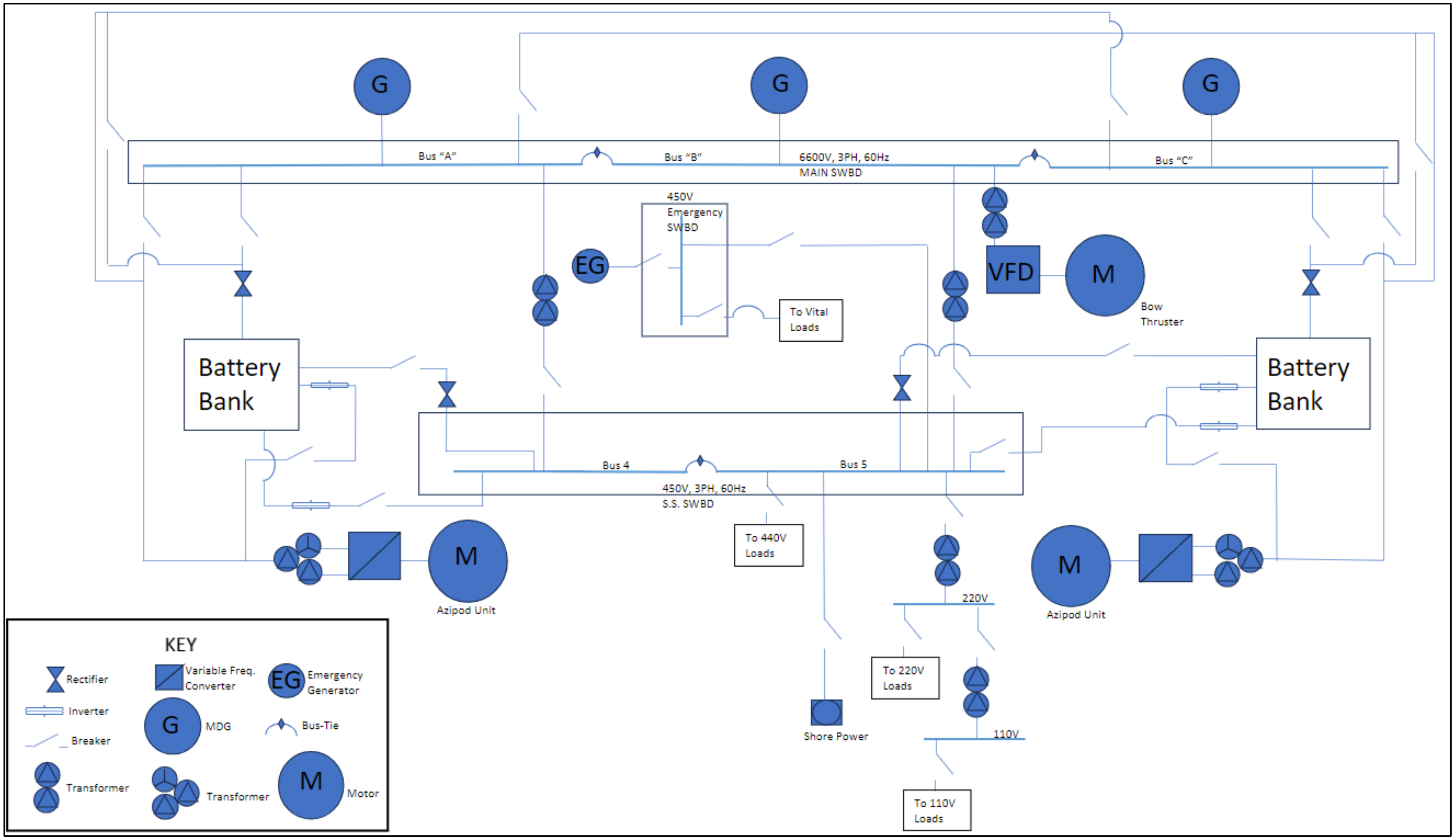
Company	Genset	Rated Gen Power (kW)	Speed (60hz) (RPM)	# of gens	Total power (n-1 gens) (kW)	Total Power (all gens) (kW)	CSR on n-1 gens (85%) (kW)	CSR on all gens (85%) (kW)	CSR speed (90%) (RPM)	Manufacturer Gen eff.	Fuel Consump (85%) (g/kWh)	Claimed Regulation Compliance	Confirmed Regulation Compliance	L (ft)	W (ft)	H (ft)	Mass (LT)
Wartsilla	6L34DF	2772	720	4	8316	11088	7068.6	9425	648	96%			Y	29	8	8	56
MAN	8L27/38	2535	720	4	7605	10140	6464.25	8619	648	96%	181	IMO II/III**	Y	28	6	13	57
MTU	16V 4000 M35S	2560	1800	4	7680	10240	6528	8704	1620			IMO II/III**	Y	19	6	7	21
Wartsila	8V31	4530	720	3	9060	13590	7701	11552	648	96%	167.7	IMO II/III**	Y	31	12	16	96
Wartsila	**9L32**	**4840**	**720**	**3**	**9680**	**14520**	**8228**	**12342**	**648**	**96%**	**174**	**IMO II/III****	**Y**	**34**	**9**	**13**	**85**
Wartsila	16V26	4990	900	3	9980	14970	8483	12725	810	96%	185.8	IMO II/III**	Y	32	9	12	69
Wartsila	10V31	5665	720	3	11330	16995	9630.5	14446	648	96%	167.7	IMO II/III**	Y	33	12	16	107
Cat	C280-12	3640	900	3	7280	10920	6188	9282	810			IMO II, EPA 2	Y	26	6	13	37
ABC	16DZC	3536	900	3	7072	10608	6011.2	9016.8	810	96%		UIC II, Euro IIIA, Euro IIIB	Y	27	5	10	43
Wartsila	9L26	2810	900	4	8430	11240	7165.5	9554	810	96%		IMO II/III	Y	28	8	10	50
ABC	12DZC	2292	1000	4	6876	9168	5844.6	7792.8	900			IMO II/III	Y	22	6	10	34

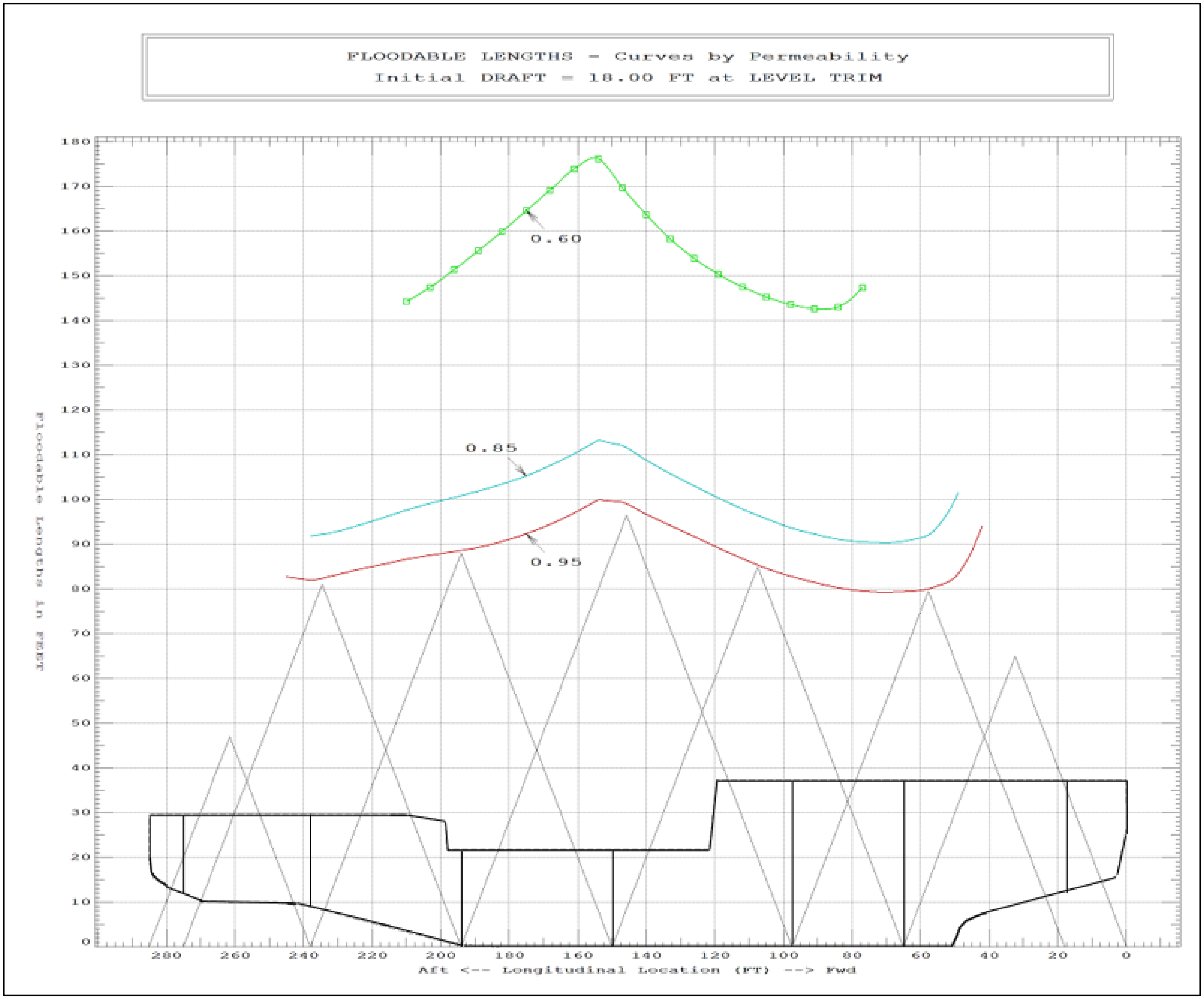
Note: The cells in green signify that the genset would supply enough power to the MTC, while the red cells signify that there would not be enough power to effectively accomplish the missions. The final choice is in bold (Wartsila 9L32).

Company	Gen	MCR	speed	CSR	L (mm)	W (mm)	H (mm)	Mass (tonnes)	L (ft)	W (ft)	H (ft)	mass (LT)
Wartsila	8L20	1405	60	1194.25	6030	2070	1800	20.7	19.8	6.8	5.9	18.5
Wartsila	**6L20**	**1255**	**60**	**1066.75**	5325	2070	1800	16.8	17.5	6.8	5.9	15.0
Wartsila	16V14	1155	60	981.75	4600	1540	1600	7.5	15.1	5.1	5.2	6.7

Note: KHA used ratiocination to estimate the required E-Gen size and chose to go with Wartsila to maintain continuity among machinery parts. The final choice is in bold (Wartsila 6L20).

Appendix E – One-Line Diagram




FLOODABLE LENGTHS - Curves by Permeability
Initial DRAFT = 18.00 FT at LEVEL TRIM
0.60
0.85
0.95
Floodable Lengths in FEET
Aft <-- Longitudinal Location (FT) --> Fwd

GENERAL EMERGENCY

BRIDGE		ECC	MEDICAL	DCTT/RRT	MRT
COMMAND	**SAFETY**	**EOW**	**BDS**	XO (LCDR)	EO (LT)
CO (CDR)	XO (LCDR)	MK1	HS1	EO (LT)	EMCM
OOD/JOOD	**LOOKOUT**	**JE**	YN1	OPS (LT)	MP MKC
LTJG 1	SN 5	MK2	BM2	AOPS (LT)	AUX MKC
ENS 1		**PHONE TALKER**	SN 1	AEO (LTJG 2)	
		CS1	SN 2	BOSN (CWO3)	
		PLOTTER			
		SK2			

REPAIR LOCKER					
DCA	LTJG 1	***PHONE TALKER***	SKC	**INVESTIGATORS**	**RPE**
RPL	DC1	***PLOTTER***	BM1 1	EM2 1	EM1
OSL	DC2	***AFFF OPERATOR***	MK1	ET2	

ATTACK TEAM 1		BOUNDARYMEN	P100	*ANCHOR DETAIL	AS DIR
ATL	DC3	SN 5	ET1	BOSN	SNA 1
NOZZLEMAN	BM3	BM3	CS2	BMC	CS3 2
HOSEMAN	SN 4	BM2	MK3		
PLUGMAN	ENS 2	CS3 1			

ATTACK TEAM 2	
ATL	MK2
NOZZLEMAN	FN 1
HOSEMAN	FN 2
PLUGMAN	SN3

4 QTR AMOUNT

AFC-01	Direct REC	$3,389,352
	Indirect REC	$114,463
	TOTAL	$3,503,815
AFC-08	Direct REC	$0
	Indirect REC	$0
	TOTAL	$0
AFC-20	REC	$148,609
	REC Savings	$0
	NR	$264,193
	TOTAL	$412,801
AFC-30	Distributed REC	$130,181
	ANACI/SSBI REC	$62,887
	ANACI/SSBI NR	$61,085
	TOTAL	$254,153
AFC-34	REC	$33,238
AFC-36	FTS REC	$65,202
	IRM REC	$28,291
	TOTAL	$93,494
AFC-56	REC	$97,794
	NR	$101,416
	TOTAL	$199,209
AFC-57	REC	$533,587

3 QTR AMOUNT

AFC-01	Direct REC	$2,542,014
	Indirect REC	$85,848
	TOTAL	$2,627,861
AFC-08	Direct REC	$0
	Indirect REC	$0
	TOTAL	$0
AFC-20	REC	$148,609
	REC Savings	$0
	NR	$264,193
	TOTAL	$412,801
AFC-30	Distributed REC	$97,636
	ANACI/SSBI REC	$62,887
	ANACI/SSBI NR	$61,085
	TOTAL	$221,608
AFC-34	REC	$24,929
AFC-36	FTS REC	$48,902
	IRM REC	$21,218
	TOTAL	$70,120
AFC-56	REC	$73,345
	NR	$101,416
	TOTAL	$174,761
AFC-57	REC	$400,190

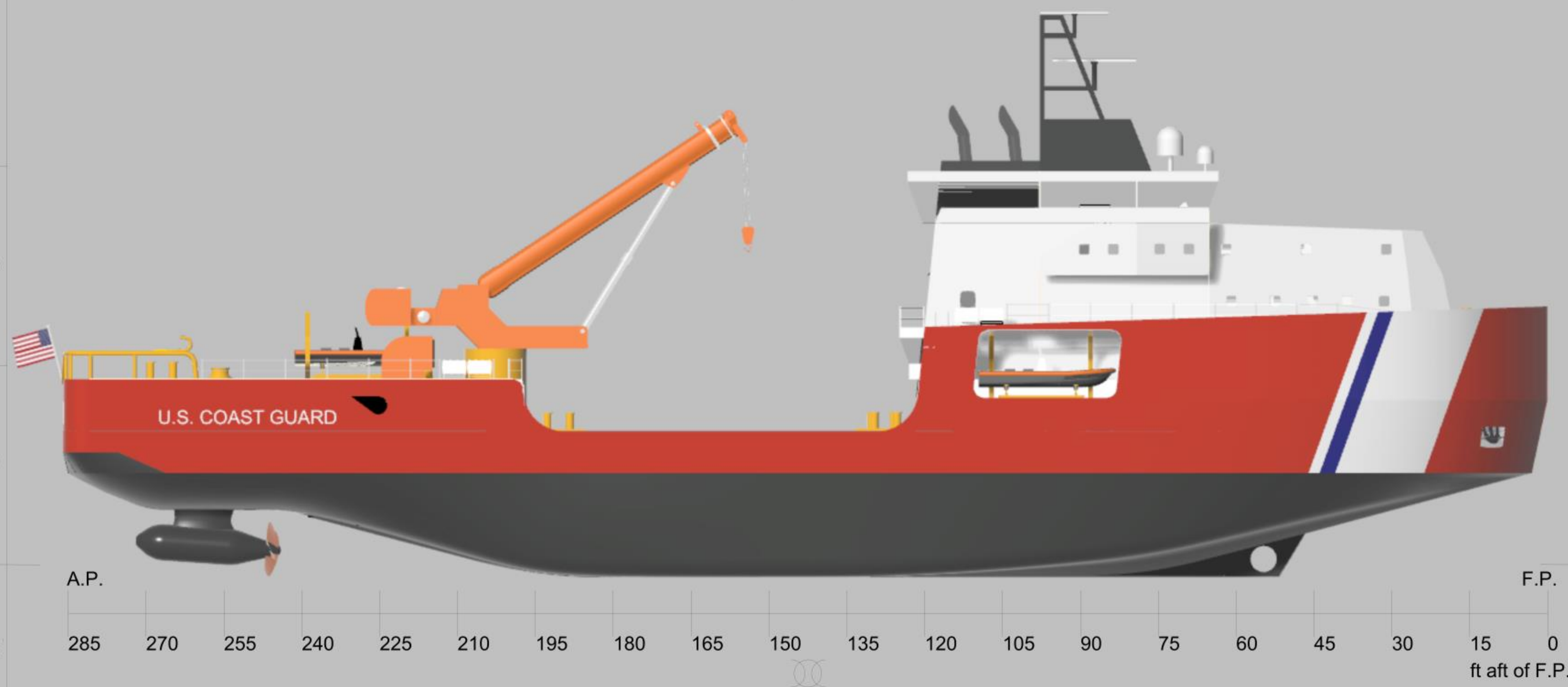
2 QTR AMOUNT

AFC-01	Direct REC	$1,694,676
	Indirect REC	$57,232
	TOTAL	$1,751,908
AFC-08	Direct REC	$0
	Indirect REC	$0
	TOTAL	$0
AFC-20	REC	$148,609
	REC Savings	$0
	NR	$264,193
	TOTAL	$412,801
AFC-30	Distributed REC	$65,090
	ANACI/SSBI REC	$62,887
	ANACI/SSBI NR	$61,085
	TOTAL	$189,063
AFC-34	REC	$16,619
AFC-36	FTS REC	$32,601
	IRM REC	$14,146
	TOTAL	$46,747
AFC-56	REC	$48,897
	NR	$101,416
	TOTAL	$150,313
AFC-57	REC	$266,793

1 QTR AMOUNT

AFC-01	Direct REC	$847,338
	Indirect REC	$28,616
	TOTAL	$875,954
AFC-08	Direct REC	$0
	Indirect REC	$0
	TOTAL	$0
AFC-20	REC	$148,609
	REC Savings	$0
	NR	$264,193
	TOTAL	$412,801
AFC-30	Distributed REC	$32,545
	ANACI/SSBI REC	$62,887
	ANACI/SSBI NR	$61,085
	TOTAL	$156,518
AFC-34	REC	$8,310
AFC-36	FTS REC	$16,301
	IRM REC	$7,073
	TOTAL	$23,373
AFC-56	REC	$24,448
	NR	$101,416
	TOTAL	$125,864
AFC-57	REC	$133,397

Appendix I.1 – General Arrangements



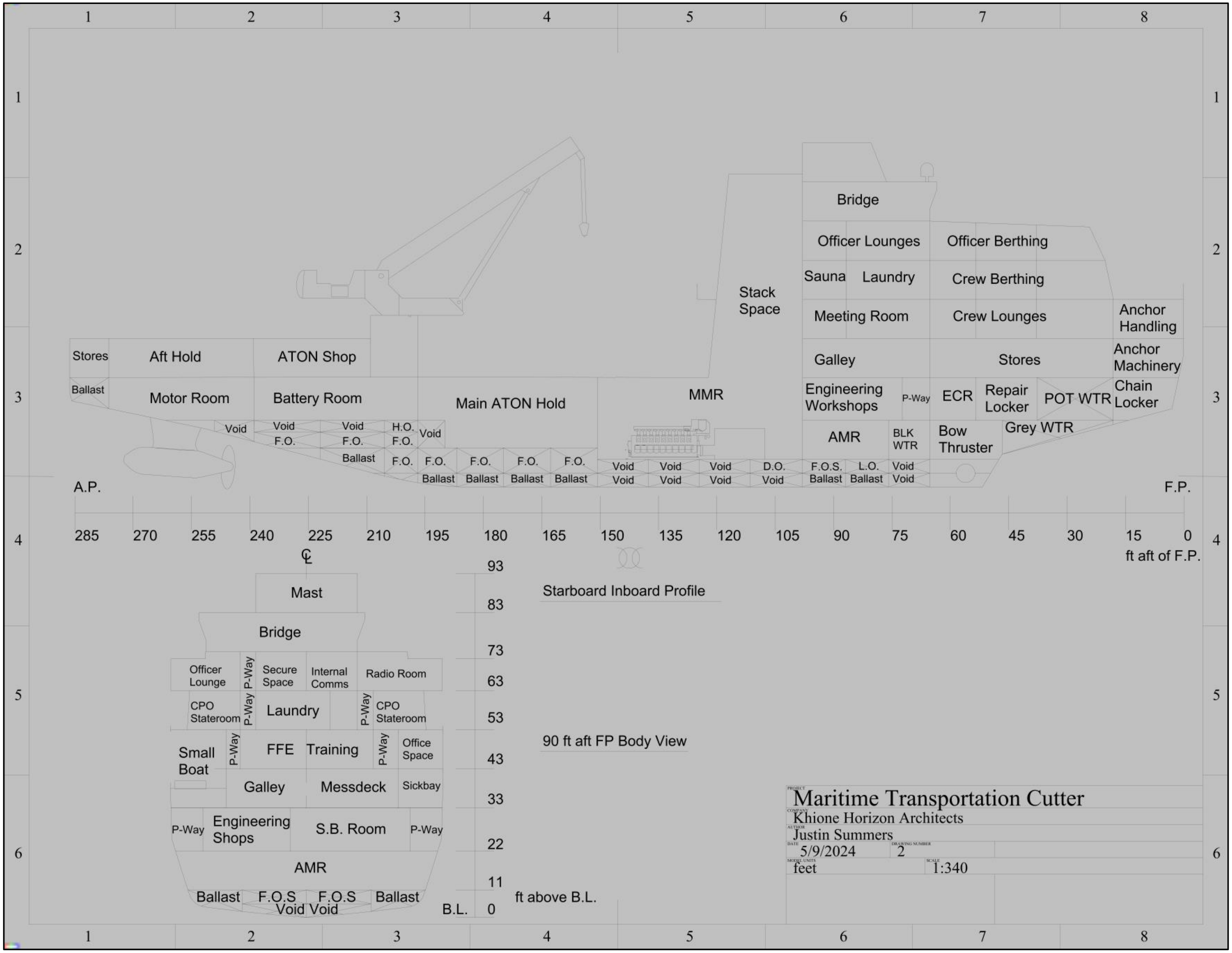
Starboard Outboard Profile

Abbreviations	
AMR	Auxiliary Machinery Room
A.P.	Aft Perpendicular
ATON	Aids to Navigation
CPO	Chief Petty Officer
DCC	Damage Control Assistant
ECR	Engine Control Room
FFE	Fire Fighting Equipment
F.O.	Fuel Oil
F.O.S.	Fuel Oil Service tank
F.P.	Forward Perpendicular
G/H	Gearhead
L.O.	Lubricating Oil
LR	Locker Room
MMR	Main Machinery Room
SR	Stateroom

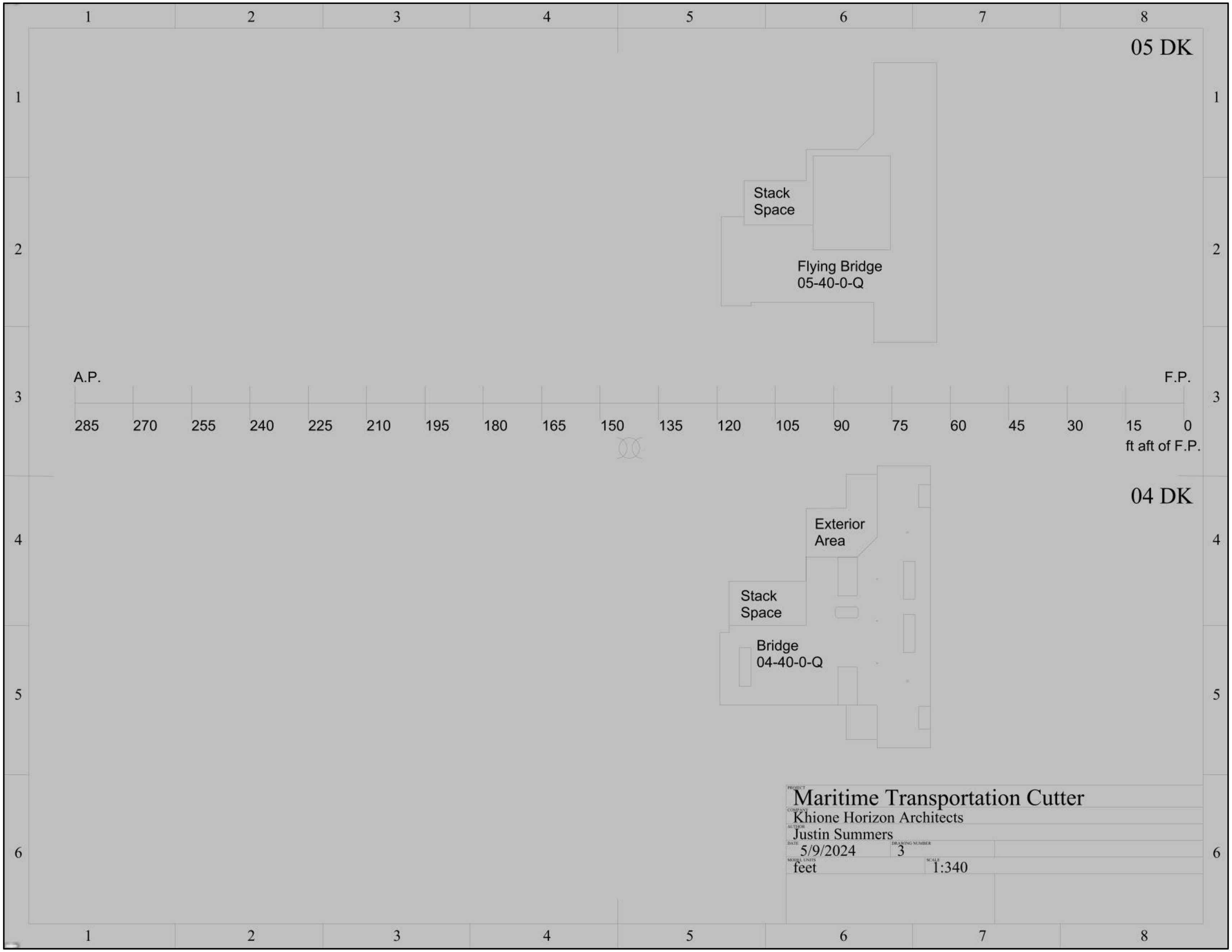
Principal Characteristics
LOA = 285 ft
Depth = 52 ft
LWL = 270 ft
Cb = 0.59
Displacement = 5,520 LT
BOA = 70 ft
Draft = 18 ft
BWL= 70 ft
Cp = 0.62
S = 21,500 ft^2

PROJECT	Maritime Transportation Cutter
COMPANY	Khione Horizon Architects
AUTHOR	Justin Summers
DATE	5/9/2024
DRAWING NUMBER	1
MODEL UNITS	feet
SCALE	1:340

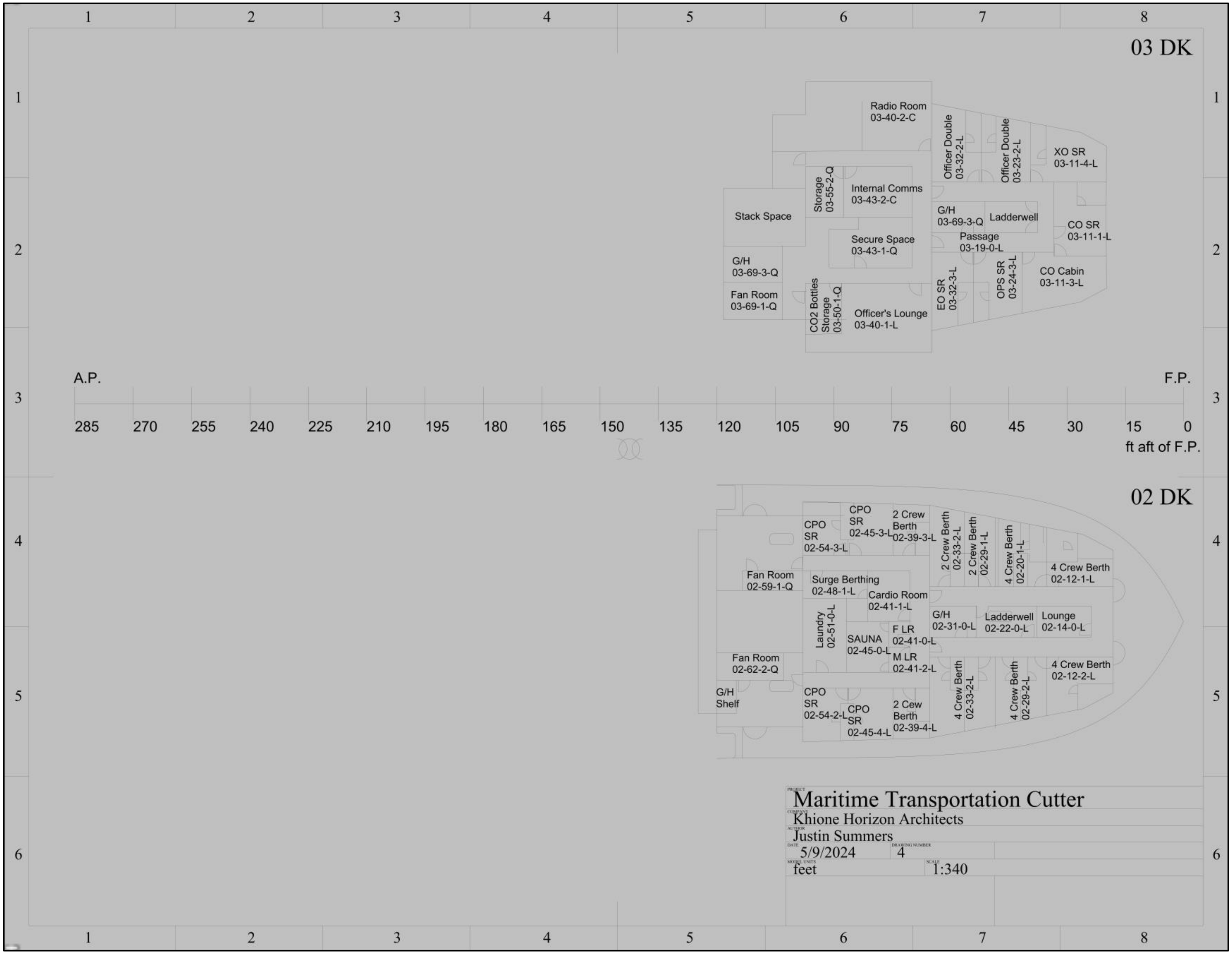
Appendix I.2 – General Arrangement

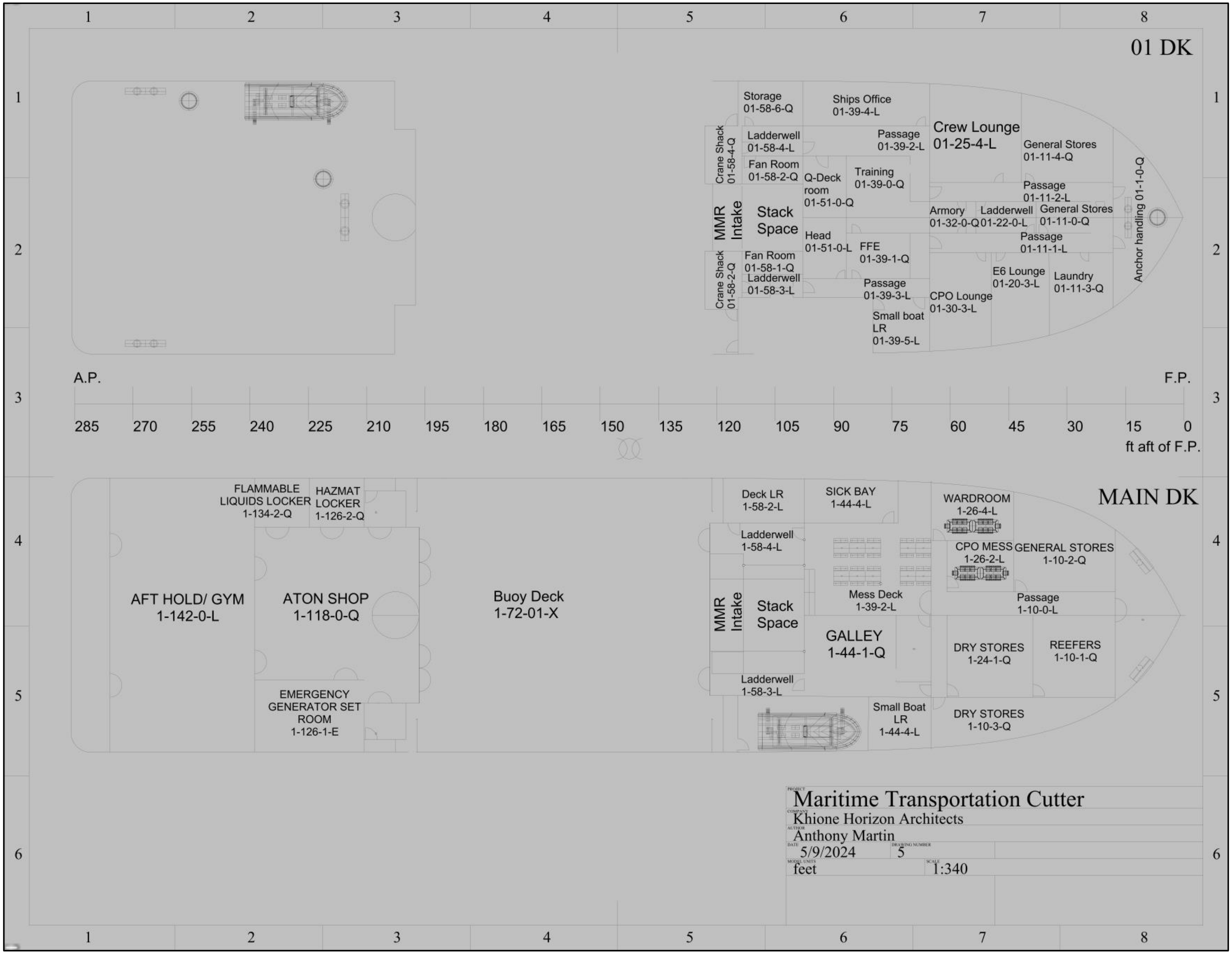


Appendix I.3 – General Arrangements

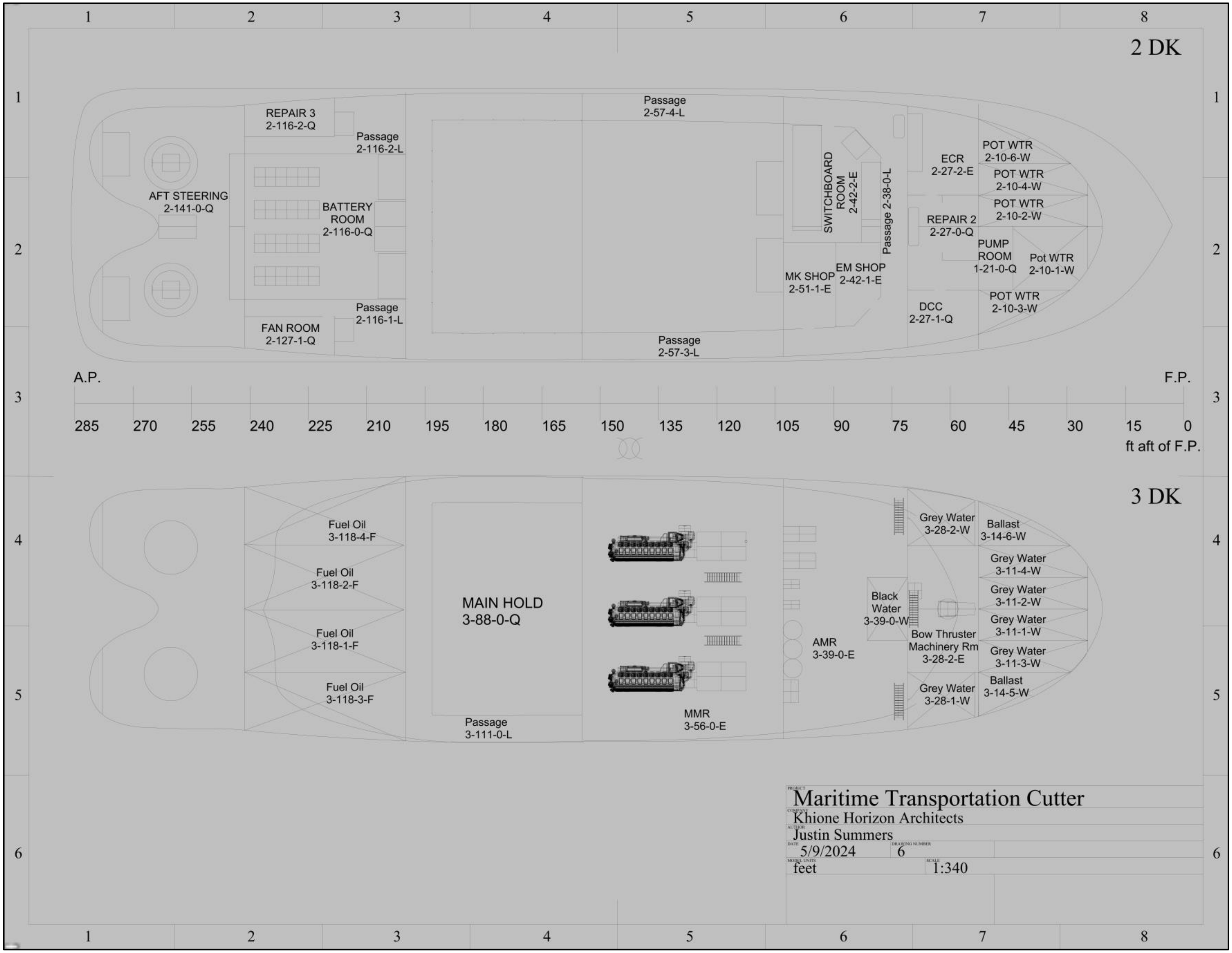


Appendix I.4 – General Arrangements

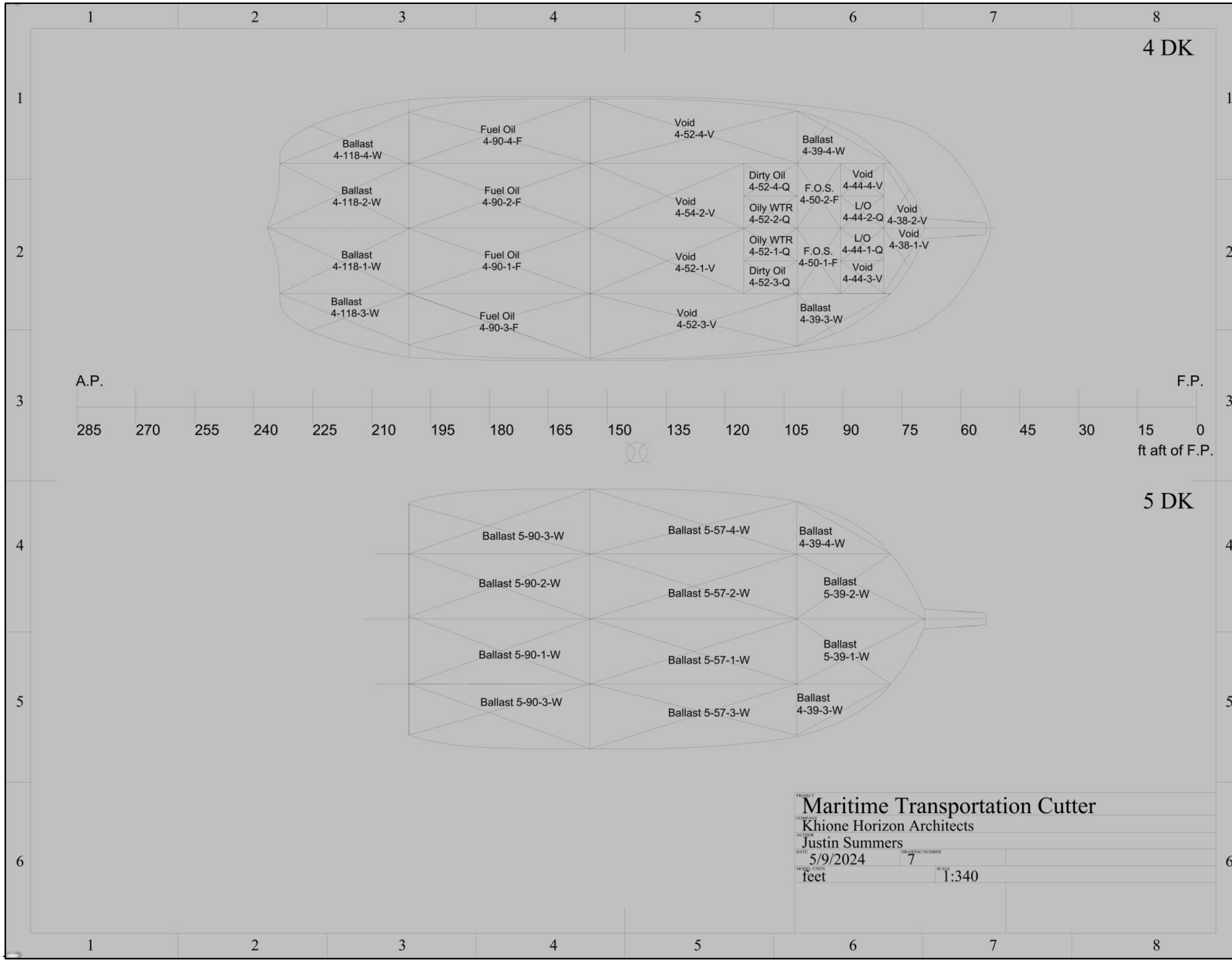



01 DK
Storage 01-58-6-Q
Ships Office 01-39-4-L
Crew Lounge 01-25-4-L
Crane Shack 01-58-4-Q
Ladderwell 01-58-4-L
Passage 01-39-2-L
General Stores 01-11-4-Q
Fan Room 01-58-2-Q
Q-Deck room 01-51-0-Q
Training 01-39-0-Q
Passage 01-11-2-L
MMR Intake
Stack Space
Armory 01-32-0-Q
Ladderwell 01-22-0-L
General Stores 01-11-0-Q
Anchor handling 01-1-0-Q
Head 01-51-0-L
Passage 01-11-1-L
FFE 01-39-1-Q
Crane Shack 01-58-2-Q
Fan Room 01-58-1-Q
Ladderwell 01-58-3-L
E6 Lounge 01-20-3-L
Laundry 01-11-3-Q
Passage 01-39-3-L
CPO Lounge 01-30-3-L
Small boat LR 01-39-5-L
A.P.
F.P.
285 270 255 240 225 210 195 180 165 150 135 120 105 90 75 60 45 30 15 0
ft aft of F.P.
MAIN DK
FLAMMABLE LIQUIDS LOCKER 1-134-2-Q
HAZMAT LOCKER 1-126-2-Q
Deck LR 1-58-2-L
SICK BAY 1-44-4-L
WARDROOM 1-26-4-L
Ladderwell 1-58-4-L
CPO MESS 1-26-2-L
GENERAL STORES 1-10-2-Q
AFT HOLD/ GYM 1-142-0-L
ATON SHOP 1-118-0-Q
Buoy Deck 1-72-01-X
MMR Intake
Stack Space
Mess Deck 1-39-2-L
Passage 1-10-0-L
GALLEY 1-44-1-Q
DRY STORES 1-24-1-Q
REEFERS 1-10-1-Q
EMERGENCY GENERATOR SET ROOM 1-126-1-E
Ladderwell 1-58-3-L
Small Boat LR 1-44-4-L
DRY STORES 1-10-3-Q
Maritime Transportation Cutter
Khione Horizon Architects
Anthony Martin
5/9/2024
5
feet
1:340

Appendix I.6 – General Arrangements



Appendix I.7 – General Arrangements

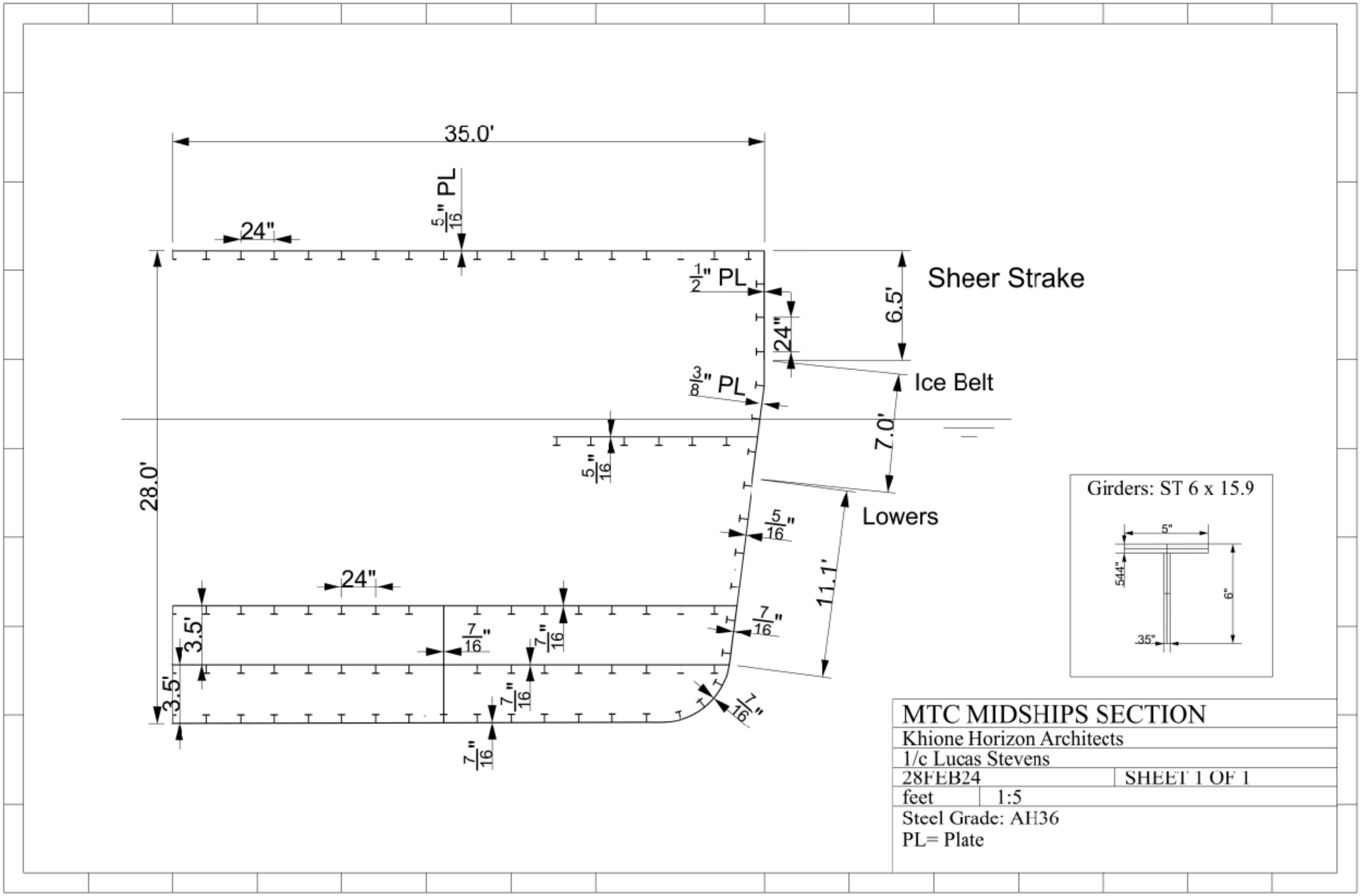


Appendix J – Capacity Plan

Contents	Capacity (Gal)	Weight (LT)	LCG	TCG	VCG
Ballast (fw)					
4-111-1-T	15638	58.26	208.31	8.03	7.4
4-111-2-T	15628	58.22	208.3	8.04	7.4
3-8-1-T	20267	11.52	40	19.89	15.04
3-8-2-T	20266	11.52	40	19.89	15.04
2-120-3-T	10229	38.11	220.49	24.18	15.55
2-120-4-T	10231	38.12	220.49	24.18	15.55
2-140-3-T	3350	12.48	242.76	22.19	15.18
2-140-1-T	4455	16.6	242.62	8.44	14.93
2-140-2-T	4457	16.61	242.62	8.45	14.93
2-140-4-T	3039	11.32	242.76	22.19	15.18
4-38-3-T	3984	14.84	78.27	21.6	5.56
4-38-4-T	3981	14.83	78.26	21.59	5.56
4-111-3-T	10320	38.45	206.11	22.51	7.44
4-111-4-T	10321	38.45	206.12	22.51	7.44
5-45-2-T	6032	22.47	87.4	7.13	2.15
5-45-1-T	6000	22.35	87.39	7.13	2.16
5-91-3-T	10459	38.97	177.4	23.73	1.93
5-91-1-T	12223	45.54	178.18	8.21	1.85
5-91-2-T	12323	45.91	178.26	8.23	1.84
5-91-4-T	10534	39.25	177.45	23.71	1.92
2-165-1-T	19134	71.32	279.46	17.27	23.62
2-165-2-T	19142	71.32	279.46	17.24	23.62
SUM	**232013**	**736.46**			
Potable Water					
2-19-3-W	20267	75.51	40.14	18.9	22.66
2-19-4-W	20266	75.5	40.4	18.9	22.66
3-11-1-W	7228.9	26.93	36.11	4.03	14.18
3-11-2-W	7228.4	26.93	36.11	4.03	14.18
SUM	**54990.3**	**204.87**			
Grey Water					
3-11-3-W	5755	21.44	37.12	12.11	14.5
3-11-4-W	5755	21.44	37.12	12.11	14.5
2-11-2-W	25614	95.43	25.62	12.22	22.71
2-11-1-W	25615	95.43	25.62	12.22	22.71
SUM	**62739**	**233.74**			

Sewage					
3-28-3-Q	11501	43.92	57.34	21.82	13.13
SUM	**11501**	**43.92**			
Fuel Oil					
4-50-1-F	4241	13.75	92	8.24	5.25
4-50-2-F	4241	13.75	92	8.24	5.25
3-118-1-F	12786	41.44	210.81	8.04	12.13
3-118-2-F	12786	41.44	210.81	8.04	12.13
3-118-3-F	7031.1	22.98	207.13	22.32	12.22
3-118-4-F	7091.1	22.98	207.13	22.32	12.22
4-90-3-F	21263	68.92	173.81	23.14	8.06
4-90-4-F	21263	68.92	173.81	23.14	8.06
4-90-1-F	32936	106.76	173	8.24	6.75
4-90-2-F	32936	106.76	173	8.24	6.75
SUM	**156574.2**	**507.7**			
H/O					
2-118-0-Q	836.6	2.88	198.13	0	16.16
SUM	**836.6**				
L/O					
4-45-1-Q	1060.9	3.65	81	4.12	6.12
4-45-2-Q	1060.9	3.65	81	4.13	6.12
SUM	**2121.8**				
D/O					
4-52-1-Q	1951	7.45	100.87	9.62	4.96
4-52-2-Q	1951	7.45	100.87	9.62	4.96
SUM	**3902**				
Oily Water					
4-52-0-Q	1302	4.97	100.88	0	6.13
SUM	**1302**				

Appendix K – Midship Section



Appendix L – Structure Calculations

Material			AH36 Steel
Material Yield	51000	psi	
Modulus of Elasticity	29007548	psi	
Poisson's Ratio	0.29		
Allowable FOS	2		
Material Allowable	25500	psi	

Stillwater Values (From GHS)		
Stillwater Shear	-720.8	LT
Stillwater Moment	54856	LT*ft

ABS Wave Shear Calculations		
Positive Shear	549.0567	LT
Negative Shear	-437.7096	LT

ABS Wave Moment Calculations		
Hogging Calculation	45755.3	LT*ft
Sagging Calculation	-57400.7	LT*ft

Total Bending Moment		
Total Hogging Moment	100611.3	LT*ft
Total Sagging Moment	-2544.7	LT*ft

Structural Calculations

ABS Minimum Plating Thickness		
Bottom Plating Thickness	0.3941	in
Side Shell Plating Thickness	0.2302	in
Deck Plating Thickness	0.280722	in

Actual Plating Thickness			
			Pass/Fail:
Bottom Plating	0.4375	in	
Side Shell Plating	0.3125	in	
Deck Plating	0.3125	in	

Plating Dimensions		
Bottom Plating Short Side (a)	24	in
Bottom Plating Long Side (b)	40	in
Side Plating Short Side (a)	24	in
Side Plating Long Side (b)	40	in

Section Modulus					
ABS Minimum Required Section Modulus	8056	ft*in^2	Pass/Fail:	96672	
Calculated Deck Section Modulus	13583	in^2*ft	1.68608315	162997	in^3
Calculated Keel Section Modulus	20577	in^2*ft	2.55420052	246919.7	in^3

Moment of Inertia			
ABS Hull Girder Moment of Inertia	68950	in^2*ft^2	Pass/Fail:
Calculated Moment of Inertia	229095	in^2*ft^2	

Maximum Total Bending Moment (See ABS)		
Maximum Bending Moment	102586	LT*ft

Primary Bending Stress		
Deck Bending Stress	7.552444	LT/in^2
Keel Bending Stress	4.985532	LT/in^2

Ship Values			
Depth	28	ft	**Height of Deck
Midship Beam (1/2 Ship)	35	ft	
Distance from Bilge Chine to CL	31.8	ft	

Bottom Pressure Head	18	ft

Frame		
Stiffener Flange Width		in
Stiffener Flange Thickness		in
Stiffener Web Height		in
Stiffener Web Thickness		in
ABS Minimum Section Modulus		in^2*ft
Calculated Section Modulus (Top)	-0.03	in^2*ft
Calculated Section Modulus (Bottom)	0.03	in^2*ft

Longitudinal				
Stiffener Flange Width	5	in	0.41666667	0.208333
Stiffener Flange Thickness	0.544	in	0.04533333	0.022667
Stiffener Web Height	6	in	0.5	0.25
Stiffener Web Thickness	0.35	in	0.02916667	0.014583
ABS Minimum Section Modulus	0.255	in^2*ft		
Calculated Section Modulus (Top)	-1.17	in^2*ft		
Calculated Section Modulus (Bottom)	0.53	in^2*ft		

Stiffener Spacing (s)	2	ft	*Spacing b/t Longitudinals
Distance b/t Supports (l)	3.333333	ft	*Spacing b/t Frames

High Speed Vessels Only

ABS Design Pressures		
Bottom Pressure		psi
Side Structure Pressure		psi

ABS Slamming Induced Bending Moment		
Slamming Bending Moment		LT*ft

Shear Buckling FOS	1.748944

Stresses		
Primary Top	7.552444	psi
Primary Bottom	4.985532	psi
Secondary	0.00136	psi
Tertiary Longitudinal	6,937	psi
Tertiary Transverse	12,867	psi
Shear at Deck	-4160.37	psi
Shear at Bilge	-2495.26	psi
Von Mises Deck	7205.983	psi
Von Mises Bilge	11962.66	psi

Global Hull Girder Section Modulus and Bending Stress Spreadsheet

Units (USCS/SI)	USCS	(USCS, SI)
Height of Deck	336	in

Plating (Major Components) (one-half of ship)

Component	# of items	Width	Thickness	Angle (0 or 90)	Total Area (a)	Height wrt BL (h)	1st Moment (ah)	2nd Moment (ah^2)	Local Moment (i)
		in	in	deg	in^2	in	in^3	in^4	in^4
Main Deck (Buoy deck)	1	420	0.3125	0	131.25	336	44100	14817600	1.068115234
Freeboard above chine	1	78	0.5	90	39	288	11232	3234816	19773
Ice belt	1	84.48	0.375	82.74	31.68	204	6462.72	1318394.88	18540.44934
Lowers	1	133.08	0.3125	82.74	41.5875	105.24	4376.6685	460600.5929	60397.02824
					0		0	0	0
Bottom	1	348.36	0.3125	0.13	108.8625	0.36	39.1905	14.10858	6.553457103
2 Deck walkways	1	145.32	0.3125	0	45.4125	204	9264.15	1889886.6	0.369567871
3 Deck	1	400.08	0.3125	0	125.025	84	10502.1	882176.4	1.017456055
4 Deck	1	394.68	0.3125	0	123.3375	42	5180.175	217567.35	1.003723145
3 Deck tank long'l bulkhds	1.5	42	0.3125	90	13.125	63	826.875	52093.125	2894.0625
4 Deck tank long'l bulkhds	1.5	41.64	0.3125	90	13.0125	21.24	276.3855	5870.42802	2820.279803
					Sum	672.2925	92260.2645	22879019.48	104434.8322

Longitudinals (Small Components) (One-Half of Ship)

Component	# of items	Area	Total Area (a)	Height wrt BL (h)	1st Moment (ah)	2nd Moment (ah^2)
		in^2	in^2	in	in^3	in^4
Main deck	17.5	4.68	81.90	331.2	27125	8983893
Walkways	6.0	4.68	28.08	199.2	5594	1114232
3 Deck	15.5	4.68	72.54	79.2	5745	455017
4 Deck	15.5	4.68	72.54	37.2	2698	100384
Bilge	13.5	4.68	63.18	5.2	326	1682
Sheer strake	3.0	4.68	14.04	288.0	4044	1164534
Ice belt	3.0	4.68	14.04	216.8	3044	660155
Lowers	6.0	4.68	28.08	109.7	3080	337794
Chine	3.0	4.68	14.04	17.0	239	4077
	Sum		388.44		51895.5	12821767.8

Curved Plating

Component	# of items	Width	Thickness	Height of Plate (h)	k^2	Total Area (a)	Height wrt BL (y)	1st Moment (ay)	Local Moment (i) (ak^2)
		in	in			in^2	in	in^3	in^4
Blige radius	1	67.44	0.3125	12.96	13.9968	21.075	18	379.35	294.98256
					Sum	21.075		379.35	294.98256

	Total Area (a)	1st Moment (ah)
Total Sum	1081.81	144535.10

Total 2nd Moment (ah^2)	Local Moment (i)
35700787.3	104729.8148

Half-Ship Values

h_{NA}	133.6051977	in
1/2 I_{ZZ}	35805517.1	in^4
A x h^2_{NA}	19310641.26	in^4
1/2 I	16494875.9	in^4
% ht of NA abv BL	40%	

Full Ship Values

Area	2163.615	in^2
Moment of Inertia (I)	32989751.74	in^4
Deck Section Modulus (Z)	162997.0304	in^3
Keel Section Modulus (Z)	246919.6731	in^3

Secondary Stress

Combined Longitudinal Stiffener and Plate

Member	Length (in)	Thickness (in)	Area (in^2)	y-bar (in)	Product (in^3)	2nd Product (in^4)	Local i (in^4)
Stiffener Flange	5	0.544	2.720	6.710	18.250	122.447	0.067
Stiffener Web	6	0.35	2.100	3.438	7.219	24.814	6.300
Cut out	0	0					
Plating	1.111111111	0.4375	0.486	0.219	0.106	0.023	0.008
		Sums =	5.306		25.575	147.285	6.375

Area =	5.306	in^2	Height =	6.9815	in
Height of NA =	4.820	in	SM Top =	-14.06	in^3
2nd Moment about NA =	30.39	in^4	SM Bottom =	6.31	in^3
Radius of Gyration=	2.393	in			

Transverse Frame

Member	Length (in)	Thickness (in)	Area (in^2)	y-bar (in)	Product (in^3)	2nd Product (in^4)	Local i (in^4)
Stiffener Flange	0	0	0.000	0.438	0.000	0.000	0.000
Stiffener Web	0	0	0.000	0.438	0.000	0.000	0.000
Cut out	0	0					
Plating	12	0.4375	5.250	0.219	1.148	0.251	0.084
		Sums =	5.250		1.148	0.251	0.084

Area =	5.250	in^2	Height =	0.4375	in
Height of NA =	0.219	in	SM Top =	-0.38	in^3
2nd Moment about NA =	0.08	in^4	SM Bottom =	0.38	in^3
Radius of Gyration=	0.126	in			

Hydrostatic Moment	wl^2/12	
l	0.277777778	in
s	0.166666667	in
p	8	psi
w	1.333333333	lb/in
m	0.008573388	lb*in
Stress at Top of Stiffener	-0.000609788	psi
Stress at Bottom of Stiffener	0.001359697	psi

Loading from sinker	7.8125	psi

Simply Supported Plates (Tertiary Stress)

pg. 115 of Timoshenko

Plate location	**bottom**	
Pressure head	**18**	ft
Material	**AH36**	

Loads		
Pressure =	8.00	psi

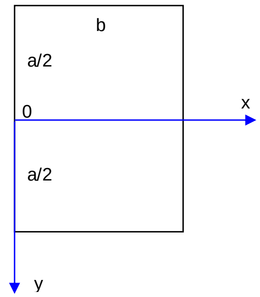
Geometry		
Thickness =	0.438	inches
Short Side, b =	24	inches
Long Side, a =	40	inches
a =	1.6666667	

Calculated Values		
D =	221,012	in^2-lbs

Material Properties		
E =	29007548	psi
n =	0.29	

Analysis Location		
x =	12	in
y =	0	in

Results at Analysis Location		
Deflection =	**0.10409**	inches
Short Dir. Stress =	**12,867**	psi
Long Dir. Stress =	**6,937**	psi
Von Mises Stress=	**11154**	psi



Deflection due to uniform load on a simply supported plate Timoshenko, pg 116, Eqn. (139)

m	1	3	5	7	9	11
a_m	2.61799388	7.8539816	13.089969	18.325957	23.5619449	28.797933
Hyperbolic Term	0.66691608	0.9961747	0.9999688	0.9999998	1	1
$1/m^5$	1	0.0041152	0.00032	5.95E-05	1.6935E-05	6.209E-06
sin mpx/b	1	-1	1	-1	1	-1
	0.66691608	-0.0040995	0.00032	-5.95E-05	1.6935E-05	-6.209E-06

w_1 = 0.10408802

a	b	b_1
0.00866726	0.089076	0.0480:

Moment at the analysis location in the short side direction Timoshenko, pg 117, Eqns. (k & l)

m	1	3	5	7	9	11
a_m	2.61799388	7.8539816	13.089969	18.325957	23.5619449	28.797933
A_m	-0.0043538	-2.058E-07	-1.3E-10	-1.738E-13	-3.31E-16	-7.782E-19
B_m	0.00094847	2.088E-08	8.641E-12	8.55E-15	1.295E-17	2.527E-20
sin mpx/b	1	-1	1	-1	1	-1
mpy/b	0	0	0	0	0	0
S terms	-0.0051286	2.005E-06	-3.44E-09	8.858E-12	-2.767E-14	9.666E-17
M_x"	-165.53777					
M_x'	576					

M_x = 410.462234 in-lbs 0.089076

Moment at the analysis location in the long side direction Timoshenko, pg 117, Eqns. (k & l)

m	1	3	5	7	9	11
a_m	2.61799388	7.8539816	13.089969	18.325957	23.5619449	28.797933
A_m	-0.0043538	-2.058E-07	-1.3E-10	-1.738E-13	-3.31E-16	-7.782E-19
B_m	0.00094847	2.088E-08	8.641E-12	8.55E-15	1.295E-17	2.527E-20
sin mpx/b	1	-1	1	-1	1	-1
mpy/b	0	0	0	0	0	0
S terms	-0.001682	1.323E-06	-2.65E-09	7.335E-12	-2.386E-14	8.555E-17
M_y"	54.2695071					
M_y'	167.04					

M_y = 221.309507 in-lbs 0.0480272

Shear Stress Equations	
Shear Stress at Deck Edge	
-4160.374201	psi
Shear Stress at Bilge Chine	
-2495.258071	psi
Shear Stress at Neutral Axis	
-5162.800527	psi

Shear Stress Buckling		
b/a	1.66667	
Ks	5.1	
E	2.9E+07	psi
t	0.3125	in
b	40	in
Critical Shear Buckling Stress	9029.45	psi
FOS	1.74894	

Appendix M - Required Damage Stability Calculations

A1=	aΔ^7+bΔ^6+cΔ^5+dΔ^4+eΔ^3+fΔ^2+gΔ+h		ΘR=	CoΔ^7+C1Δ^6+C2Δ^5+C3Δ^4+C4Δ^3+C5Δ^2+C6Δ+C7	
Δ=	5444	LT	Δ=	5444	LT
Required Area A1=	3.238	ft-deg	Rollback ΘR=	10.568	
constants	a	-6.8351E-32	constants	C0	-1.67E-32
	b	1.68E-26		C1	5.50E-27
	c	-1.71E-21		C2	-7.42E-22
	d	9.26E-17		C3	5.31E-17
	e	-2.90E-12		C4	-2.20E-12
	f	5.34E-08		C5	5.45E-08
	g	-5.73E-04		C6	-8.62E-04
	h	5.17E+00		C7	13.9601
V=	C0 + C1*Δ + C2*Δ2 + C3*Δ3				
Δ=	5444	LT			
Damage Wind Velocity=	34.0	kts			
constants	C0	30			
	C1	7.83E-04			
	C2	-8.86E-09			
	C3	5.99E-14			

Appendix N – Compartment Permeabilities

Type of Compartment	**Full Load**	**Minimum Operating**
Habitability and living Spaces	0.95	0.95
Command and control, offices	0.95	0.95
Shops	0.90	0.90
Pump rooms	0.90	0.90
Auxiliary machinery	0.85	0.85
Stores and provisions	0.80-0.90	0.95
Refrigerated spaces	0.80	0.90
Voids	0.98	0.98
Handling rooms	0.80	0.95
Cargo	0.60-0.80	0.95
Chain locker	0.65	0.65
Diesel machinery plant	0.85	0.85

Appendix O – Summary of Damage Stability Results

		Full Load													
Stability Criteria	Min/Max	DC1		DC2		DC3		DC4		DC5		DC6		DC7	
Absolute Angle at Equ0 (no moments)	<15.00deg	0.55	p	0.49	p	1.43	p	3.88	p	4.03	p	2.43	p	0.24	p
Res. Ratio from -10.6 deg to abs 45 or floo	>1.400	14.468	p	12.513	p	9.766	p	7.197	p	7.553	p	8.035	p	10.612	p
Res. Area from Equ. To abs 45 deg or floo	>3.24 ft-deg	248.64	p	192.5	p	155.09	p	126.91	p	124.9	p	128.42	p	167.82	p
Righting arm at MaxRA	>0.25 ft	8.14	p	6.26	p	6.14	p	7.37	p	7.19	p	7.06	p	7.49	p
Angle from Equ to Dk/margin immersion	>0.00deg	17.22	p	13.02	p	5.07	p	3.71	p	8.33	p	9.17	p	15.26	p

		Minimum Operating													
Stability Criteria	Min/Max	DC1		DC2		DC3		DC4		DC5		DC6		DC7	
Absolute Angle at Equ0 (no moments)	<15.00deg	0.42	p	0.34	p	1.14	p	4.53	p	3.78	p	0.65	p	0.07	p
Res. Ratio from -10.6 deg to abs 45 or floo	>1.400	13.912	p	12.423	p	10.49	p	6.866	p	7.971	p	10.179	p	11.844	p
Res. Area from Equ. To abs 45 deg or floo	>3.24 ft-deg	257.43	p	201.32	p	173.92	p	128.51	p	138.72	p	169.86	p	194.37	p
Righting arm at MaxRA	>0.25 ft	8.4	p	6.5	p	6.72	p	7.8	p	7.82	p	7.85	p	8.09	p
Angle from Equ to Dk/margin immersion	>0.00deg	17.83	p	13.99	p	6.52	p	3.55	p	8.94	p	12.51	p	16.5	p