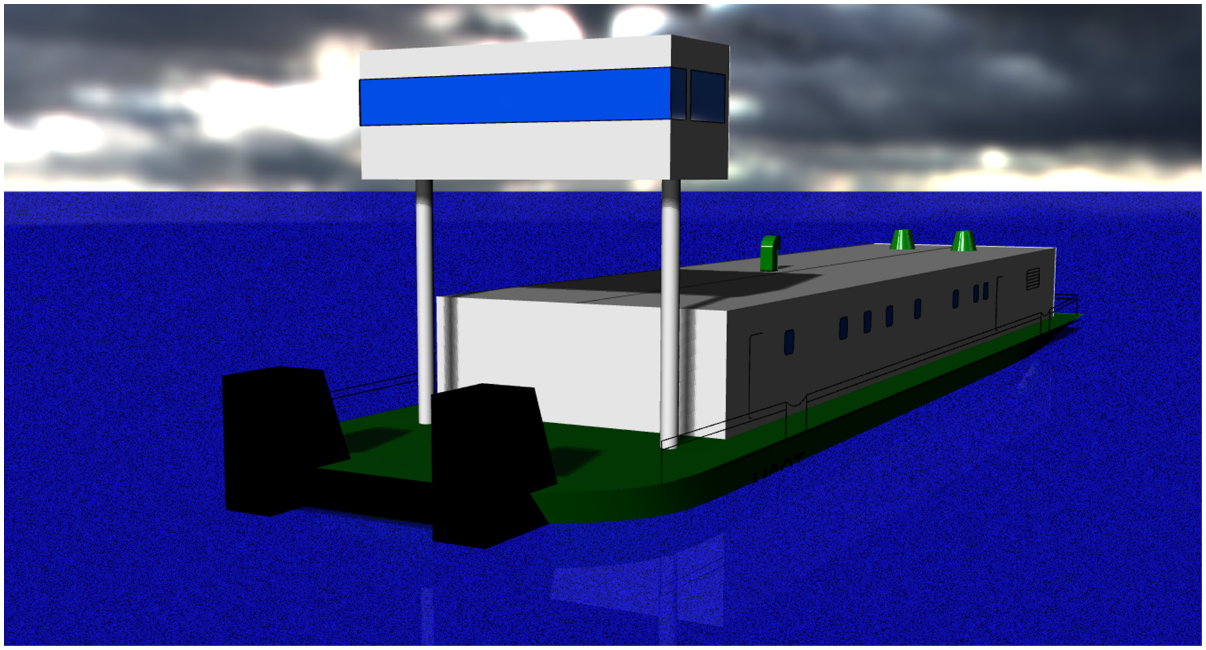
NORTHERN INLAND TOWING VESSEL

UNITED STATES COAST GUARD ACADEMY

Naval Architecture and Marine Engineering



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Northern Inland Towing Vessel Concept Design

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Abstract: Make Money, Get Towed, guided by the design philosophy of accessibility, high habitability, and resource efficiency, designed an inland towing vessel capable of pushing large barge trains, accessing the northern most ports, complying with new CFR standards, providing superior living conditions for a mixed gender crew, and reducing the environmental impact on the towing industry. The conceptual hull design is 150 feet in length, 35 feet in beam, and has a draft between 8.3 and 9.0 feet. The design has a jacking bridge, reduced bow rake, and parallel mid body. The vessel has a gym, lounge, entertainment center, and premium staterooms. Using ratiocination, the end of life light ship displacement is calculated to be 624 LT and full displacement to be 873 LT. It will be able to push 36 barges at 8 knots, and 40 barges at 5 knots with the two Wartsila 9L26 engines, as well cruise without a tow with the one Cummins QSM 11 engine. The kort nozzled propeller is 7 feet in diameter with five blades. From an electric plant load analysis, the electric plant is designated as two Caterpillar C4.4 ACERT generators and one Caterpillar C7.1 generator. The design passes all initial and damage stability requirements found within 46 CFR Subchapter M, according to analysis from General Hydrostatics software. A seakeeping analysis confirms that the vessel exceeds seakeeping levels typically required on the inland rivers. A longitudinal weight distribution is created and used to determine a maximum bending moment of 8511 LTf-ft when combined with wave loads. ABS rules for Vessels Operating on Inland Rivers is followed to create the midship section longitudinal structure, which has a lowest factor of safety of 1.6. Required crew size onboard is determined to be 4 members in compliance with the Marine Safety Manual, at an annual cost of $277,000. Construction cost is estimated using the PODAC model, with the lead ship costing $12 million to construct. Annual operating costs accounting for construction financing is estimated to be $8 million for the first 10 years of operation. Potential annual profit if maximum barge loads are used range from $11 million on northern rivers and $14 million on lower rivers. This conceptual hull design will make definitely make future owners money, and get many people's cargo towed throughout the inland rivers of the United States.

INTRODUCTION

The Inland Waterways and Western Rivers (IWWR) accounts for billions of dollars of economic revenue. Towboats are pushing approximately 763 million tons of cargo every year up and down the river system, including agricultural products, natural resources, and industrial materials. Commercial shipping solely in the upper Mississippi River, which is defined as the river system north of Cairo, IL [1], generates nearly $675 million annually.

The current towboat industry is drastically outdated in their practices, regulations, and designs. Most companies have fleets that are not standardized because each ship is tailored for one specific task. The inland towboat fleet has also been recently introduced to a new Code of Federal Regulations (CFR), to which all towboats will be subject. 46 CFR Subchapter M was published in 2016. In July 2019, 25% of every company's fleet will be required to meet all Subchapter M standards and have a Certificate of Inspection issued by the US Coast Guard [2]. As this gradual implementation of new regulations is set to be complete by 2027, there is immediate impact on the aging, commercial towboat fleet operating in the IWWR.

The design team, Make Money Get Towed (M$GT), designed a vessel that meets the demands of the towboat industry by providing the ability to complete multiple missions and complying with Subchapter M standards. This conceptual hull design (CHD) will help future owners capture more of the economic opportunity available in the IWWR. With this unique design, the CHD will possess the geographic flexibility to access waterways as far north as Hastings, MN, while also having the towing capability to push large barge trains in the lower sections of the IWWR.

MISSION ANALYSIS

The CHD has three primary missions that align with the design team's design philosophy, which was used throughout the design process to guide M$GT's decision making. The first mission is to transport cargo barges to the northern most portions of the IWWR. The CHD must be able to safely navigate low bridges, locks, and shallow waters in order to give the owners the ability to reach northern ports with barges, and to become more profitable. The CHD must have sufficient propulsion capacity to push barge trains against downstream currents. It must be able to securely attach to and maneuver with barge trains. Accessibility is the first component of the design philosophy, and it is critical in assisting the owner to meet their primary goal of making money.

The second mission is to provide maximum crew comfort 365 days a year through a wide area of operation (AOR) that often includes extreme summer and winter weather. It is mission critical to be able to accommodate mixed gender crews and have access to exercise, recreation, entertainment, and office/conference space. The well-being of the crew is critical to mission success. High Habitability standards is the second design component.

The third mission is to be environmentally conscious, mostly through a focus on high fuel efficiency. The CHD has a low resistance hull shape that will reduce drag and consequently, lower the vessel's specific fuel consumption. The propulsion plant meets the horsepower requirement and maximizes the efficiency of power transfer from main propulsion to the propellers. Resource Efficiency, the ability to sustainably use resources to minimize environmental impact in the life span of the ship, is the third design component.

SIMILAR SHIPS

M$GT conducted market research of inland towboats to form the CHD's principal characteristics and hull design. Ship characteristic data from 29 different vessels was collected and dimensionless coefficients were compared to other ships, allowing the examination of crucial dimensions such as length, beam, draft, Froude number, height, and horsepower. From all the similar ships analyzed, three ships were designated as parent hulls: *ALICE I. HOOKER* [3], *CODY BOYD* [4], and the *J. C. THOMAS* [5]. The parent hulls were selected based primarily on their operating area, jacking bridge, and principal dimensions, respectively. Preliminary research into the northern routes of the IWWR showed that locks are the primary limiting factor for vessel traffic in the CHD's AOR. Breadth, or beam, was the most important principal characteristic as it governed the CHD's degree of accessibility through narrow locks with tows alongside. A design beam of 35 feet will provide enough space in the locks to tow one barge on each side with 5 feet of total clearance [6][7]. The CHD was also limited by the height of the bridges in the northern IWWR. Based on the similar ships analysis, M$GT determined to set the total, maximum height of the CHD to 36 feet. The CHD was then given a hydraulically powered, jacking bridge that raises to 36 feet and lowers to 14 feet to allow the operator to see over the barge train and also mitigate the height challenges in the operating area. M$GT also decided to set the draft of the CHD to no more than 9 feet out of shallow draft concerns, especially while transiting through locks.

Table 1 (below) summarizes the principal characteristics determined by the design team for the northern inland towboat CHD.

Table 1. Principal Characteristics

Length (ft)	150
Beam (ft)	35
Draft (ft)	8.3-9
Block Coeff.	0.66
Height Extended	45
Height Collapsed	25
Displacement (LT)	864
Fn	0.231

HULL GEOMETRY

The similar ships analysis revealed that the typical towing vessel has a moderately large bow rake. However, research shows that a smaller bow rake of 50°, shown in Figure 1, will increase efficiency through the water by 9-15% [8]. The typical sea state for the IWWR does not warrant flare in the bow design to absorb plunging. The bow has medium softness to the forefoot curvature. The CHD hull gets full quickly, creating a stubbyness to the bow that is a common characteristic on pushboats. Figure 2 shows the 7.9 feet of transom clearance that was provided to allow for maximum propeller diameter necessary to push 40 barges. Additionally the transom cut-out slope provided increased propeller flow, increasing hull efficiency and thrust. The flat sides of the midbody allow more contact, and thus more control, with barges being towed alongside. The fullness of the midbody helps provide the underwater volume necessary to achieve the required displacement, while also having minimum draft. Also, the bilge radius is rounded to provide increased water flow towards the propellers.

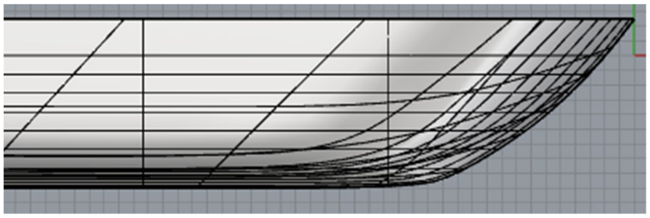

Figure 1. Reduced Bow Rake of CHD

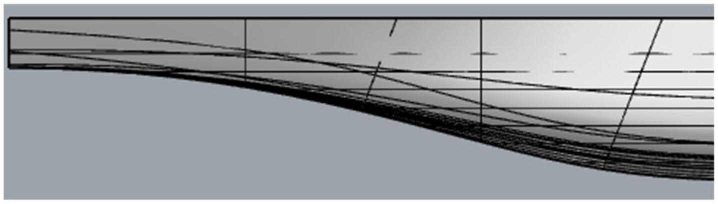

Figure 2. Transom Cutoff of CHD

RESISTANCE & TOWTANK

In order to predict an effective horsepower (EHP) for the hull, NAVCAD was utilized to predict vessel resistance. The Holtrop and Andersen methods were chosen based on matching ship characteristics with the CHD. Shallow channel and air resistance components were also accounted for using the Landweber and Taylor prediction methods, respectively. Barge train resistance was the primary resistance contributor. NAVCAD provides a special prediction analysis for barge trains. An open water efficiency of 60%, shaft efficiency of 99%, and gearbox efficiency of 95% were used in efficiency calculations [9]. The EHP calculated for a 40 barge tow at 10 knots was 10,000 hp, nearly double what is installed upon similar ships. The resistance was reevaluated for different barge train configurations. Figure 3 shows the resistance and BHP curve for a 6x6 barge train, which with an EHP of 3300 hp at 10 knots better aligned with expected values.

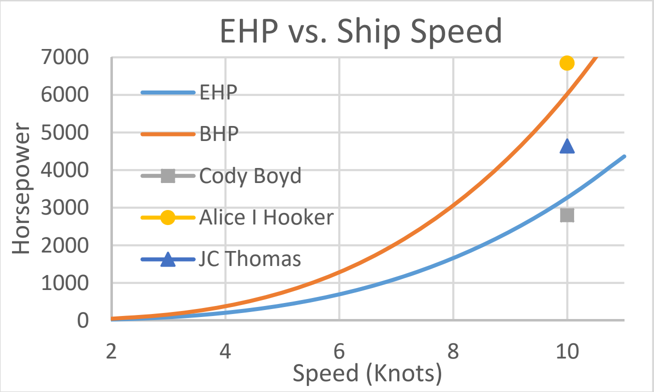

Figure 3. BHP curve w.r.t. EHP for 36 barges

A tow tank test was conducted in order to validate NAVCAD resistance predictions. A model was created with a scaling factor of 30:1. An additional model of a 40 barge train was created with a scaling factor of 140:1. After reviewing testing results, M$GT determined that due to size limitations of the available towing facilities, the models were not large enough to create realistic turbulent flow along the hull. The results ranged in values 200-2000% higher than predicted. These values were deemed inaccurate based on professional correspondences and not used for further design. The accepted EHP value was 3500 HP at 10 knots for 36 barges. M$GT concluded that the CHD would only be able to push 40 barges at 5 knots with this EHP. This was a necessary compromise to support the CHD's small size needed to access the northern routes of the IWWR.

PROPULSION PLANT ANALYSIS

A cost benefit analysis of different propulsion plants was conducted. Research focused on high speed vs. low speed diesel engines, geared reduction vs. electric motors, and straight shaft vs. azimuthing propulsion. The design team quantified these tradeoffs by prioritizing design philosophy and required missions. Two highly weighted factors of the decision matrix were power and environment/efficiency. Power was critical to completing the towboat's mission of pushing barges into the upper river system, aligning with design philosophy component of accessibility. Environment/efficiency aligned with the design philosophy component of resource efficiency. A medium speed diesel engine with azimuthing Z drive was chosen based on this analysis. This propulsion plant will have a higher acquisition cost but a lower lifetime cost, and will ultimately be more profitable in the long run. It also provided superior maneuverability with less input power versus a similarly sized straight shaft vessel, increasing speed through narrow river bends and locks [10]. M$GT decided that a medium speed diesel engine with azimuthing propulsor most aligned with the design philosophy and would best facilitate meeting operational goals.

PRIME MOVER SELECTION

After selecting a propulsion plant for the CHD, M$GT conducted research analysis on prime movers that would effectively meet the EHP requirement, even after accounting for efficiency losses through shafting and the propeller. Total transmission efficiency was calculated to be at 77%, while additional 8% design and 10% wave margins were applied. For all potential engines reviewed, the Continuous Service Rating (CSR) and minimum RPM values were assumed to be 90% and 33% of the MCR RPM value, respectively. The minimum BHP necessary to meet EHP with efficiency losses and margins was 6463 hp.

M$GT selected two Wartsila 9L26 engines. Up to 4105 BHP can be produced at 1000 RPM [11]. With both engines running at MCR, the maximum BHP possible is approximately 8200 hp. An operation box for the Wartsila 9L26 was plotted with the ships resistance. The profile, portrayed in Figure 4, shows both an operating box for a single and dual Wartsila combinations.

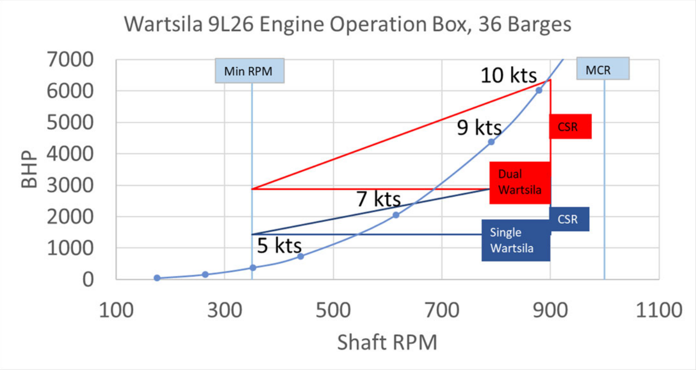

Figure 4. Wartsila 9L26 Engine Operational Box

To ensure optimal efficiency, M$GT considered using a single engine while not conducting barge tows. At 11 knots without barges, a BHP of only 1400 hp was required, which is less than the minimum BHP produced by a single Wartsila engine. A secondary, smaller engine was chosen to operate in the lower horsepower operational range. Figure 5 (below) shows the secondary engine characteristics. M$GT selected a Cummins QSM 11 [12].

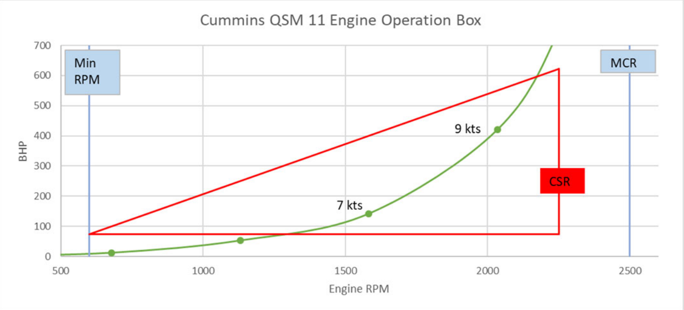

Figure 5. Cummins QSM 11 Engine Operational Box

PROPULSOR SELECTION

Propeller Prediction

M$GT selected a kort nozzle propeller with a diameter of 7 feet, exceeding the minimum required propeller diameter of 4.82 feet for the vessel [13]. The minimum diameter did not meet the thrust mission requirements, and failed to maximize the design propeller clearance of 7.66 feet. The Harvald wake fraction equation and the Holtrop thrust deduction regression equation were used to predict the wake fraction to be 0.20 and thrust deduction fraction to be 0.09, respectively [9]. An initial estimate of the expanded area ratio (EAR) of 1.206 was calculated using Keller's equation [14]. High thrust operations, like towing, typically require a high EAR. The thrust was calculated using the thrust reduction factor, a speed of 8 knots, and a 70°F based vapor pressure. The EAR was predicted to be 1.21.

Table 2. Keller's EAR Prediction

Diameter (in) "D"	84
k	0.1
Vapor Pressure (psia) "pv"	0.615
Static Pressure (psia) "po"	14.7
Thrust (lb) "T"	39269
Number of Blades "Z"	5
EAR	1.2063

Propeller Optimization

Several propellers were created using PROPCAD. The B series of propellers at a design speed of 8 knots was used for propeller analysis. The efficiency, rotational speed, and percent cavitation varied based on the geometry of the blades. Eight fixed pitch propeller variations were analyzed for comparison. The 5 blade, 7 foot diameter propeller with an EAR of 1.05 was selected because of the efficiency, back cavitation, and propeller cost.

Table 3. Selected Propeller Characteristics

Design Speed (kts)	8
Series	B
Number of Blades	5
Diameter (ft)	7
P/D	0.837
EAR	1.05
Cavitation	14%

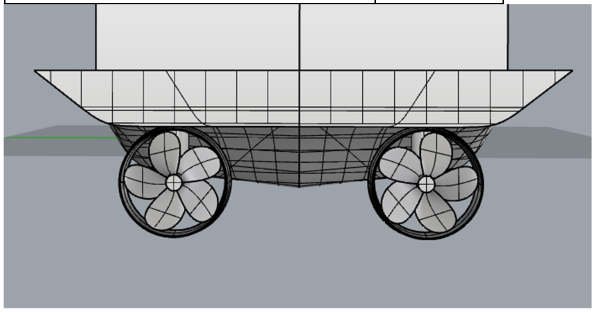

Figure 6. Stern View with Propellers.

Hull Natural Frequencies

The Campbell Diagram, shown in Figure 7, was used to check for aligning shaft vibrations and blade passage vibrations with the natural horizontal and vertical vibrations of the CHD. The initial natural vertical vibration, calculated from Burrill's 1935 formula [15], was used to find the remaining horizontal and vertical vibrations and ±5% ranges (Table 4). The two operating conditions for the propeller are 325 rpm for 8 knots and 408 rpm for 10 knots, which both fall outside of the 5% range of the ship frequencies.

Table 4. Natural Hull Vibrations

NV Table (CPM)	
NV2	170.82
NV3	379.21
NV4	589.31
NH2	234.02
NH3	547.60
NH4	889.26

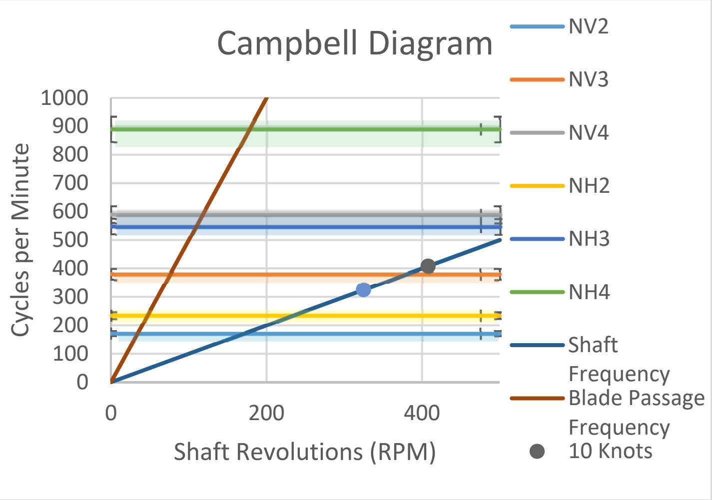

Figure 7. Campbell Diagram

ELECTRIC PLANT DESIGN

After completing the design of the propulsion line, M$GT used a load analysis to determine an electric plant suitable for the CHD's size and operational requirements. The electric plant load analysis focused on four operating conditions: pierside, maneuver, cruise, and emergency. The pierside condition included all items required to house the crew as well as prepare the vessel for getting underway. The maneuver condition was defined as the time the CHD is actively transiting with a tow and thus requires a higher degree of maneuverability. The difference between the maneuver and cruise conditions is the cruise does not have a tow, which does not affect the electric load, but only the engine power required. The emergency condition only included the loads essential to maintaining control of the vessel in the IWWR. The operating conditions were analyzed in both the extreme summer and winter weather conditions, because of the diverse range within the AOR. The winter loads included HVAC loads for heating, bridge window heaters, and space heaters.

The EPLA created a minimum and maximum operating requirement, including a design and service life margin of 8%, for each of the operating conditions for the different seasons. The maximum electric load was 168 kW for maneuvering and cruising in the winter months. The minimum electric load was 61 kW for emergency summer. The range of electric loads was the determining factor for selecting the (1) Caterpillar C7.1 and (2) Caterpillar C4.4 ACERT generators. The CAT C7.1 is rated for 100 to 200 kW and the CAT C4.4 ACERT is rated for 51 to 105 kW. Both generators are EPA Tier 3 [16, 17]. The generators are able to provide redundancy for all conditions. The C7.1 generator will be able to handle the entire load for the pierside winter, maneuver summer and winter, and cruise summer and winter conditions because of the higher loads. In order to handle the pierside summer, emergency summer, and winter conditions, one C4.4 ACERT will be required for the lower loads. The second C4.4 ACERT generator provides redundancy for the first C4.4 ACERT operating in emergency situations. If the C7.1 generator fails, then the two C4.4 ACERT generators will be able to run in parallel to cover any operating condition. Table 5 shows the different generator operating combinations at the analyzed conditions. Each condition has two generator combinations.

Table 5. Electric Plant Operational Redundancy

	C7.1	C4.4 ACERT	Two C4.4 ACERT
Pier side winter	X		X
Pier side summer		X	X
Maneuver winter	X		X
Maneuver summer	X		X
Cruise winter	X		X
Cruise summer	X		X
Emergency winter		X	X
Emergency summer		X	X

BULKHEAD PLACEMENT

Subchapter M does not include requirements pertaining to subdivision standards for towing vessels. However, M$GT designed the CHD to meet subdivision standards prescribed in 46 CFR 171 for Vessels Carrying Passengers to deliver a superior level of safety for all persons onboard. Applicable terms and boundaries for the factor of subdivision, collision bulkhead, bulkhead spacing, and compartment permeabilities can be found in [18]. Permeabilities of 60% and 85% were used for cargo and machinery spaces, respectively [19]. GHS was used to place bulkheads and create the floodable length curve. M$GT ensured each compartment fell below its applicable floodable length curve and also met all CFR limits using a highly iterative process. In order to create a more functional design, M$GT pushed the limits of the CFR criteria and floodable length curve, making the compartments as large as possible. Bulkhead spacing and factor of subdivision restrictions heavily impacted the ability to house large machinery and easily navigate the CHD. M$GT conducted a one compartment stability test in order to provide a higher level of survivability. After individually flooding each compartment, M$GT ensured the margin line, a fictitious line placed three inches below the CHD's uppermost watertight deck, was not submerged. If a compartment failed by submerging the margin line, the spacing between the respective bulkheads was decreased until it passed. Eventually, the margin line was not submerged after the flooding of any compartment and the CHD passed a one compartment standard.

Despite the challenges presented by the standards provided in 46 CFR 171, M$GT successfully created bulkhead locations that satisfied all subdivision requirements for Vessels Carrying Passengers and facilitated a functional inland towboat design. The CHD's watertight bulkheads were placed at frames 12, 22, 36.5, 51, 65.5, 95, 110, and 128. In the next design spiral, M$GT would consider opting not to design the CHD in accordance with the criteria outlined in 46 CFR 171, as inland towboats are not required to meet subdivision standards under Subchapter M.

GENERAL ARRANGEMENTS

The design philosophies of Accessibility, Habitability, and Resource Efficiency acted as guiding principles for deciding the function and contents of all compartments. First, the design team decided which compartments would serve as main machinery spaces. Berthing areas were then sized to meet ABS habitability requirements. The CHD has four machinery spaces. Two of the machinery spaces contain solely the hydraulic power unit for the bridge and the Heating, Ventilation, Air Conditioning Unit and Refrigeration Unit. Due to the CHD having mechanically driven Z-Drives, the main engine room is aft most on the main deck, directly above the transom cutout. This space will house the twin Wartsila 9L26 engines, the Cummins QSM 11 engine, the Caterpillar C7.1 generator, reduction gear, and Z-drive housing. A transverse bulkhead was removed in the space to allow for the machinery to fit. This requires structural support, but does not impact the intact stability or floodable length. An auxiliary machinery room is located on the 1 deck at amidships that will house the two Caterpillar C4.1 generators and other auxiliary equipment. The fuel for the machinery and other tanks are located primarily forward in wing tanks. Initially, the fuel tanks were conservatively estimated for general arrangements with a 14 day nonstop operational schedule. The tank locations were driven by stability requirements and functionality with surrounding equipment. In order to counteract the weight of the engine room on the aft section of the main deck, a trimming water system was included in the bow of the CHD.

Berthing areas were then sized to meet ABS requirements in "Crew Habitability on Ships." Satisfying the high Habitability design philosophy, M$GT choose to meet HAB++ standards, which is the most stringent habitability level for accommodation areas, whole-body vibration, noise, lighting, and indoor climate. In the first design spiral, the design team focused on the accommodation areas, as seen in Table 6.

Table 6. Habitability ++ Accommodations

Space	CHD (ft^2)	Required (ft^2)
Double Staterooms (4)	86	80.5
Double Stateroom	103	80.5
Single Staterooms (2)	121.5	80.5
Passenger Stateroom	122	102.5
Sanitary Free Spaces	27.8	12

The double and single person staterooms all exceeded the HAB++ standard for a non-passenger vessel under 3000 tons. The CHD's passageways, doors, lounge, stairwell entrance platforms, and all stairwells, except one, met the HAB++. The one non-HAB++ stairwell met the next highest habitability standard, HAB+. The messdeck, galley, and laundry all met the highest requirements set for each space. The general arrangements were impacted through every step of the design spiral. It was critical for the CHD, following the design philosophy, to have functionality for machinery and personnel spaces, as well as high habitability standards.

WEIGHT AND VCG ESTIMATION

Designing the general arrangements allowed M$GT to apply individual weights and locations to the previously determined lightship displacement. Unknown weights were estimated by ratiocination and verified by similar ships [20]. Ratiocination is the scaling of a preexisting ship's weight and center of gravity to form the new vessels weight, longitudinal center of gravity (LCG), and vertical center of gravity (VCG). The scaling process was conducted for individual groups in the vessel's Ship Service Breakdown Structure (SWBS). Using a known weight from a parent vessel, the scaling is used with ratios between the parent and new ship characteristics such as length, draft, BHP, etc.

The 86 foot T/V Shorty Baird was the primary source for parent weights for SWBS 400-600. For SWBS 100 group, structures, ratiocination predicted a weight of over 600LT, a large over estimate when compared with similar ships. M$GT decided to proportion the structural weight of the more similarly sized 154 foot USCG Fast Response Cutter [21], resulting in a more reasonable structural weight of 160LT. With prime movers and generators already chosen, their known weights were used in lieu of ratiocination. Due to the placement of the heavy engines 80% aft of the length overall, lead ballast was placed at the bow to maintain an even trim. SWBS groups were combined to obtain lightship weight and VCG, to which were applied margins such as building and service life allowances for a total margins of 20.7% on weight and 11% on VCG. The Final Lightship weight, VCG, and LCG were 696 LT, 10.6 feet, and 76 feet aft FP, respectively.

Weight analysis was completely concurrently with general arrangement, as well as tankage, allowing tanks to be designed and placed to improve vessel stability of the vessel. Variable loads of the vessel primarily consisted of fuel, potable water, and sewage, sized for an endurance of 14 days. Using the CHD's operational profile, depicted in Figure 16, in conjunction with the average specific fuel consumption for each engine and generator, the required weight of fuel was determined to be 126 LT. Lube oil tanks were sized to be 3.7 LT based on similar ships. Required potable water was based on 55 gals per day for each of the 12 crew and 2 passengers for a total 48 LT. The weight of food per passenger per day was conservatively assumed to be 9lb, for a total of 1.6 LT.

Table 7. SWBS Weights and centers

ESWBS	Description	Weight	KG	LCG
SWBS 100	Structures	160.00	7.1	67.6
SWBS 200	Propulsion	126.81	11.1	122.3
SWBS 300	Electrical	9.47	11.9	79.6
SWBS 400	Control	3.69	19.7	31.3
SWBS 500	Aux	92.78	10.1	51.7
SWBS 600	Utilities	184.28	10.2	53.7
Full Loads	Variable Loads	181.90	6.1	53.1

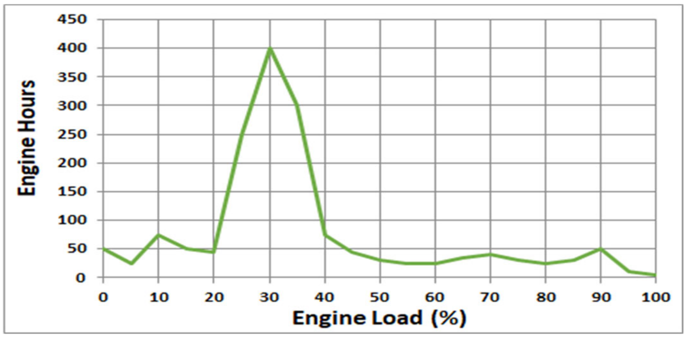

Figure 8. Operational Profile for CHD

At full load the CHD's total weight was 873 LT, 13 LT greater than the design displacement.

LIQUID LOADING

While solidifying general arrangements, M$GT simultaneously sized and place tanks in the CHD. Liquid loading instructions, outlining how to safely load tanks in order to maintain stability from departure to arrival condition, were also created. The following tanks were included in the CHD: fuel storage, fuel service, fuel overflow, lube oil, dirty oil, sewage, grey water, potable water, and trim water.

The operational profile and the specific fuel consumption of the Wartsila 9L26 main diesel engines were used to calculate the majority of diesel fuel required for 14 days, with 14 people onboard, and engines operating 24 hours a day. Next, M$GT used similar ships and other references to estimate the required volume for the lube oil, dirty oil, sewage, grey water, and potable water tanks. Lastly, the amount of ballast onboard the CHD was determined solely based on stability needs. GHS was used to add tanks in the CHD and to analyze the stability effects of loading and unloading each tank. It was important to incorporate as much weight as low and as forward as possible to counteract the propulsion plant located in the aft portion of the superstructure.

Consequently, M$GT included 67 LT of permanent lead ballast, located in the port and starboard corners of the bow, in the CHD. Furthermore, the CHD was designed with a trim water system, consisting of one forward and two aft trim water tanks. The two aft trim water tanks are only two feet high, essentially contained in the bilge, and separated by a watertight bulkhead. This system will allow future operations to pump water between the trim water tanks to maintain safe loading conditions at all times. M$GT also strategically created long, narrow tanks between each watertight bulkhead to decrease the free surface effect (FSE) of each tank. Table 8 and Figure 9 below exhibit the type, capacity, and location of each tank added to the CHD.

Table 8.Tank Description and Total Volume

Description	Gallons
DIESEL	44,046
LUBE OIL	2,300
SEWAGE	5,613
GREY WATER	5,613
POTABLE	13,114
TRIM WATER	8,398

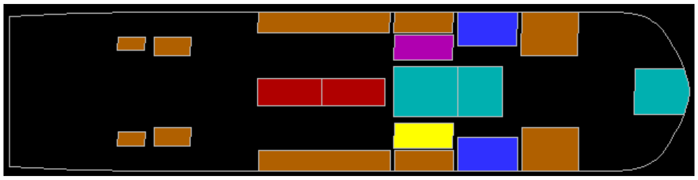

Figure 9. Plan View of Tanks

Starting from the departure condition and ending at the arrival (minimum operating) condition, detailed liquid loading instructions were created. Following these instructions will be necessary to maintain adequate stability throughout all loading conditions. Specifically, the loading instructions were designed to ensure the CHD maintained a trim of no more than 1ft/100ft (0.57 degrees) and a heel of no more than 0.5 degrees.

INITIAL STABILITY

After determining a valid lightship condition for the CHD, M$GT conducted an initial stability analysis.

CFR Requirements

The CHD is subject to 46 CFR 170.173(e) based on Subchapter M for towing vessels. The CFR provided stability criteria pertaining to the CHD's righting energy – its tendency to resist heeling and return to a point of equilibrium. The criteria is three-fold. First, the absolute downflooding angle must be greater than 15 degrees. Second, the righting area (ft-deg) from 0 degrees of heel to the angle of heel, either associated with the maximum righting arm or downflooding (whichever is less), must be greater than 10 ft-deg. Lastly, the righting area (ft-deg) from 0 degrees of heel to either 40 degrees of heel or the downflooding angle (whichever is less), must be greater than 10 ft-deg. The CHD is also subject to 46 CFR 170.170, which mandates a minimum metacentric height (GM) value depending on the area of operation. GM is a commonly used indicator of a vessel's initial stability. During this analysis, the CHD's GM was observed while wind pressure was applied to the sail area of the vessel. M$GT used the wind pressure value for protected waters, which is applicable to the CHD but easily met. M$GT also tested the CHD's GM against the wind pressure for Great Lakes winter service, which is equivalent to the exposed routes criteria and is the most stringent within the CFR.

Testing

M$GT designated the generator exhaust, engine intake, and engine exhaust as downflooding points for the analysis. GHS was used to test the CHD against all initial stability criteria outlined in 46 CFR 170.173(e) and 46 CFR 170.170. The CHD was tested at four different loading conditions – Departure, Intermediate (fuel forward), and Intermediate (fuel aft), and Arrival – based on proposed loading conditions set forth in Table 3 of [22]. The Departure loading condition consisted of all fuel and clean consumables, including potable water and lube oil, at full capacity. All dirty consumables, including dirty oil, sewage, and grey water, were at 10% load. The Intermediate Aft condition included 50% of the fuel load in the aft most fuel tanks. All clean consumable and dirty consumable tanks were filled to 50% capacity. The Intermediate Forward condition contained 50% of the fuel load in the forward most fuel tanks. All clean consumables and dirty consumable tanks were filled to 50% capacity. The Arrival condition consisted of 10% total fuel load in the forward most fuel tanks. The diesel oil service tanks were partially filled to supply the diesel engines at this stage of the vessels transit. Dirty consumables were filled to 90% and clean consumables are left at 10%.

Results

Table 9. Righting Energy Results

	Departure	Arrival	Fuel Fwd	Fuel Aft
Flood Angle > 15°	23.07	26.84	24.17	22.52
RA > 10 ft-deg	10.66	21.65	16.07	16.02
RA > 10 ft-deg	23.30	39.66	29.98	27.63
Pass/Fail	**Pass**	**Pass**	**Pass**	**Pass**

Summarized in Table 9, the CHD passed the 46 CFR 170.173(e) initial stability criteria at each loading condition.

Table 10. GM Results

	Departure	Arrival	Fuel Fwd	Fuel Aft
Required GM	1.17	1.44	1.41	1.40
Actual GM	9.89	9.98	10.22	10.46
Pass/Fail	**Pass**	**Pass**	**Pass**	**Pass**

Table 10 above shows the results of the CHD being tested against the Great Lakes winter weather criteria outlined in 46 CFR 170.170 after passing the weather criteria for protected routes. The CHD passed at all conditions.

DAMAGE STABILITY

M$GT also conducted a damage stability analysis. While Subchapter M does not contain any damage stability requirements for towing vessels, M$GT decided it was important to test the limits of the design's survivability and to ensure maximum safety for the crew. The CHD was tested against the damage stability criteria presented in 46 CFR 174.207 for Offshore Supply Vessels (OSV's), which experience some of the harshest sea states and thus are required to pass proportionally more stringent criteria. This analysis also included a two compartment standard due to the longitudinal extent of the damage simulated in this analysis (14.5 feet), while the CHD is not even subject to a one compartment standard under Subchapter M. A total of 8 damage cases were created and simulated using GHS. The CHD was tested by these 8 damage cases at two loading condition – Departure and Arrival – for a total of 16 damage scenarios. Compartment permeabilities were set in accordance with [23]. The results yielded multiple damage cases, in which the downflooding points were submerged and/or the CHD failed to meet all the damage stability criteria outlined in 46 CFR 174.207. However, after M$GT revised the analysis to only include a one compartment standard, the CHD passed all criteria in all damage scenarios. M$GT concluded that the CHD's survivability exceeded any damage scenarios typically found in the IWWR. The CHD was tested against damage stability criteria prescribed for OSV's operating in exposed waters and demonstrated a considerably higher level of survivability than required by Subchapter M.

SEAKEEPING

Criteria

M$GT conducted a seakeeping analysis in order to test the CHD against the TLR and better understand its seakeeping limits. The MARINTEK ShipX program was used to test the performance of the CHD against many different criteria including natural ship motions, such as roll & pitch, and other factors like the probability of motion sickness and the effects of equipment moving or toppling on deck. M$GT used a variety of sea states throughout the analysis to prove that the CHD met the minimum requirements as well as to explore its operational limits [24]. The CHD was tested against two different scenarios: transit mission and station keeping. Table 11 below summarizes the criteria for the transit mission.

Table 11. Transit Mission Criteria

Speed (Cruise)	10 knots
Sea State	SS2/SS3
Roll	3 degrees
Pitch	2 degrees
Motion Sickness Probability	30% for 3 hours
Heave (Pilot House)	0.4g (3.92 deg/s^2)
Pitch (Pilot House)	0.4g (3.92 deg/s^2)
Roll (Pilot House)	0.2g (1.96 deg/s^2)
Green Water (Fore Deck)	30 occ/hr
Slamming (Keel Station 3)	20 occ/hr

The CHD was first tested assuming SS2 (Hs = 0.5m) and a cruise speed of 10 knots. The CHD was also tested assuming SS3 (Hs = 1m) to better visualize the seakeeping limits during a basic transit mission, even though the CHD will probably never face environmental conditions more severe than SS2 in the IWWR. M$GT also tested the CHD from a more operational perspective, simulating station keeping while awaiting barge train hook up. Furthermore, this second scenario involved more severe criteria in order to test the seakeeping limits of the CHD. Table 12 below summarizes the criteria used for station keeping.

Table 12. Station Keeping Criteria

Speed (Station Keeping)	0 knots
Sea State	SS2/SS4
Roll	15 degrees
Pitch	10 degrees
MSI% (Forward Areas)	50% for 3 hours
MII (Pilot House)	3 MII's/min
Deck Wetness (Fore Deck)	40 occ/hr
Moving Equipment (Fore Deck)	15 events/hr

The CHD was first tested assuming SS2 (Hs = 0.5m) and a speed of 0 knots. The CHD was also tested assuming SS4 (Hs = 1.5m). Again, while this sea state will almost never be found on the IWWR, SS4 was used to better understand the seakeeping limits of the CHD.

Results

For each scenario, the results were depicted in a polar plot, which includes 360 degrees of relative bearings to the vessel and axes that display significant wave height in meters. The plots, each with a different symbol and color, represent where each criterion is limited by the significant wave height at a relative bearing. For example, Figure 10 below shows the polar plot produced by the transit mission criteria at SS3.

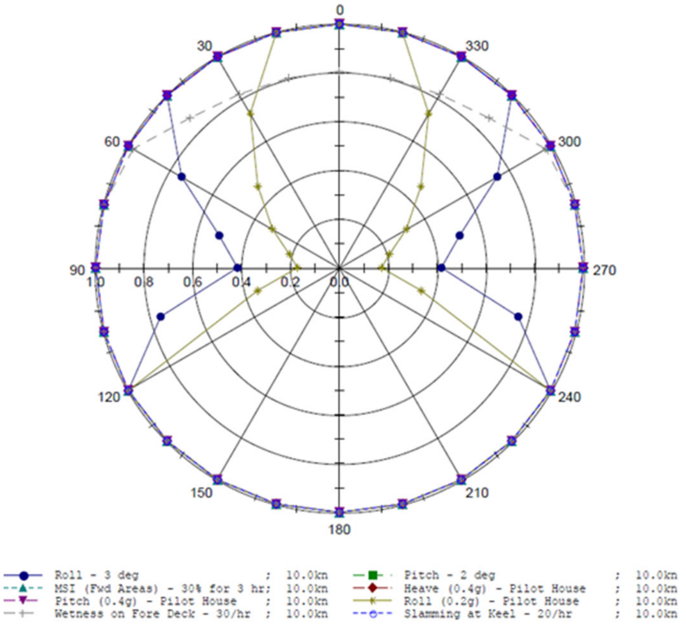

Figure 10. Transit Mission (SS3) Polar Plot

Based on Figure 10, it is evident that the most limiting criteria included a transverse acceleration (roll) of 0.2g at the pilot house with waves coming off the beam. Consequently, any wave off the beam with an Hs greater than 0.175m would cause the CHD to fail seakeeping limits defined in ShipX software. Green water on the fore deck was also limiting factor with waves coming from 0 to 060 or 300 to 0. Based on the results of the seakeeping analysis, the CHD was most affected by waves coming off the beam. However, due to the CHD operating in the IWWR, it is highly unlikely that it will encounter beam waves of concerning height. Overall, the CHD passed all requirements and displayed a superior level of seakeeping and crew comfot.

LONGITUDINAL STRENGTH & STRUCTURE

The weight profile of the CHD was distributed longitudinally, with SWBS 100 group following the accepted procedure employed by Hughes and PNA VOL 1 (1939) [25]. Combined load, shear, and moment diagram were created, with maximum still-water hogging moments of 2664 LTf-ft and 3205 LTf-ft obtained for departure and arrival conditions, respectfully. “ABS rules for Vessels Under 90 meters” were then applied to determine hogging and sagging wave moments, for a maximum combined moment of 8511 LTf-ft. Using this, the required section modulus of the midship section was calculated from “ABS Rules for Steel Vessels for Service on Rivers and Intracoastal Waterways” and determined to be 664 ft-in^2.

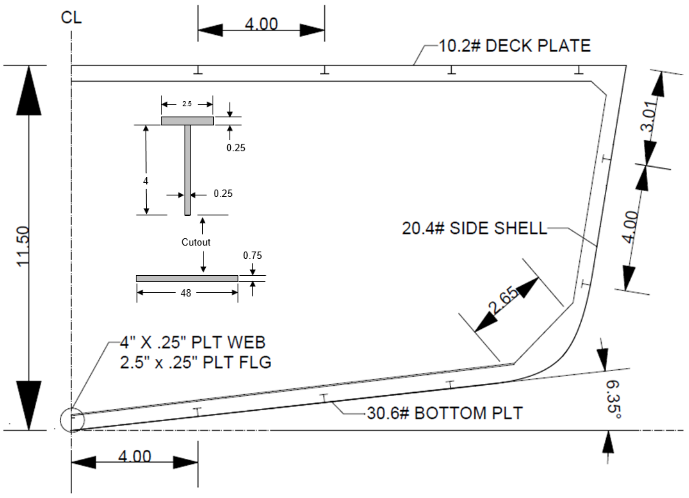

Figure 11. Midship Structure

When designing the midship section, the shell plating itself far exceeded the minimum required by ABS. Longitudinal stiffeners were added to reduce the needed thickness of the hull and save on weight. The midship section designed has a minimum section modulus of 2898ft-in^2. A36 steel was chosen as the design material due to its relatively low cost. Primary, secondary, and tertiary stress was analyzed to ensure adequate factors of safety (FOS) existed on all structural components. Critical buckling stress on all stiffeners and plate deflection were also checked. The minimum FOS on yield was 1.3 at the main deck. The lowest critical buckling stress had a 1.5 FOS over yield stress, meaning the material would yield before it would buckle.

Table 13. Vessel Factor of Saftey

Stress (type/location)	**Stress (psi)**	**FOS**
Stillwater deck stress	23036	1.5
Stillwater bottom stress	13500	2.5
Hogging deck stress	25857	1.3
Hogging bottom stress	15123	2.2
Sagging deck stress	10229	3.3
Sagging bottom stress	6132	5.5
Critical Buckling Stress	54000	1.5

CREWING

Based on applicable Coast Guard regulations in the Marine Safety Manual (MSM), a four person crew with potential for two persons in addition to crew was determined as the minimum for the CHD [26]. The design will be crewed by one master, one chief engineer, one able seaman, and one unlicensed deckhand. The MSM B.2.e.1 states that a chief engineer is not required on towboats under 46 CFR Subchapter M operating on inland service. However, the description of inland waters excludes Western Rivers. Therefore, the credentialing for the engineer responsible for the propulsion plant is based on a vessel-specific assessment from the USCG Officer in Charge, Marine Inspection. In order to have a conservative crew cost estimation, M$GT will have a chief engineer. The limited engineering personnel will require maintenance of machinery to be conducted in port, potentially with an engineering detachment crew. The CHD is authorized to operate with a two-watch system, and the deck department can be reduced to consist of 50% able seaman. The CHD will operate with one able seaman and one unlicensed deckhand. The deck department will do general deck work, but primarily focused on managing the barge train during transit, connecting, and disconnecting. A total crew cost is estimated to be $277,004, as outlined in Table 14 below. While the required crew minimum is four members, the operational minimum will have to be analyzed by the companies depending on watch rotation and maintenance scheduling.

Table 14. Annual Crew Cost

Estimated Yearly Cost	
Master	$90,835.00
Chief Engineer	$85,928.00
Able Seamen	$63,241.00
Unlicensed	$37,000.00
Total	**$277,004**

COST ESTIMATION

With the completion of the design, M$GT conducted a final cost analysis for construction and operations, as well as potential profit. The Product-Oriented Design and Construction Cost Model (PODAC) [27] was used for estimating the construction cost of the vessel. This model provides a concept design level weight based cost estimate that takes into consideration the particular shape factor of different vessel types. The lead ship cost for the vessel was estimated to be $12,000,000, which concurs with a separate prediction determined by the Army Corps of Engineers. A learning curve slope of 90% was assumed. For a fleet of 20 towboats, the average construction cost was determined to be $8,256,000, as shown in Figure 12.

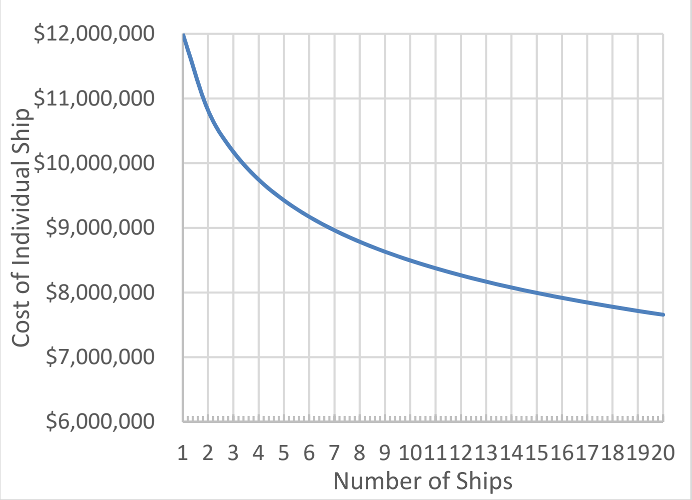

Figure 12. PODAC Cost Estimation

The annual operational cost estimate included crew, fuel, and maintenance cost. Capital costs repayment for the lead ship construction were also included assuming 20% equity and a 7% interest rate over a 10 year payback. Total annual cost was $6,000,000. The profit analysis included research on average barge rates for the various western river systems [28]. For service on the Illinois River, which has the highest barge rate of $19.7 per LT, a yearly average of 7 barges per trip must be pushed to break even, with a profit of $3.30 million for 10 barges and $10.72 million for 17 barges, the maximum that can fit through the lower portions of the locking systems. For the lower Mississippi river with a lower barge rate of $10.88 per LT, an average of 12.5 barges must be pushed annually to break even, with a profit of $4.41 million for 20 barges and $13.77 million for a full 36 barges.

CONCLUSION

The Make Money, Get Towed design team has completed the first trip around the design spiral for the northern variant of an inland towboat. The conceptual hull design is 150 feet in length and 35 feet in beam with a draft of 8.3-9.0 feet. The end of life weight is 873 LT at full displacement and 624 LT at lightship. The design has two, 7 foot in diameter, five bladed propellers that are powered by two Wartsila 9L26 engines for towing and a Cummins QSM 11 engine for cruising. The CHD is capable of pushing 36 barges at 8 knots, and 40 barges at 5 knots. It has a two C4.4 ACERT generators and one C7.1 generator capable of handling all electric loads with redundancy. The general arrangements meet the highest habitability standards and the CHD even includes a gym, lounge, entertainment center, and premium staterooms. Regarding initial and damage stability, the CHD meets all, and even exceeds some, 46 CFR Subchapters M requirements. The CHD exceeds the seakeeping requirements typically required in the inland rivers. The CHD's midship section has a minimum FOS of 1.5 and complies with ABS standards. A minimally manned crew was selected to adequately maintain the watch rotation in accordance with the MSM and to optimize cost. The lead ship cost is estimated to be $12 million, with an annual operating cost of $6 million during its first 10 years of service. Depending on the operating area, the first vessel in the fleet will be able to make a yearly profit between $10 million and $14 million, accomplishing the ultimate mission to Make Money, Get Towed.

WAY FORWARD

The design team will conduct further research on having a diesel electric propulsion plant. This would definitely address the wide range of propulsion needs, as well as electric loads, and reduce the various types of engines on board. Switching propulsion plants would have a large impact on the propulsion aspects of the design, electric plant, general arrangements, and stability. In future design spirals, the design team will adjust for having a reduced crew. This will directly impact general arrangements and allow for the increase in available space to be more appropriately used.

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