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Optimization of Zero Emission Hydrogen Fuel Cell Ferry Design, With Comparisons to the SF-BREEZE

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Optimization of Zero Emission Hydrogen Fuel Cell Ferry Design, With Comparisons to the SF-BREEZE

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Abstract

Zero emission hydrogen fuel cell technology has the potential to drastically reduce total "well-to-waves" maritime emissions. Through realistic design studies of five commercially-relevant passenger vessels, this study examines the most cost-effective entry points in the US fleet for deploying today's available technology, and includes analysis of resulting well-to-waves emission profiles.

The results show that per-passenger mile vessel energy use is directly correlated to increased emissions, capital costs, and operating costs. As a consequence, low speed, large capacity vessels offer a cost-effective starting place today. Increases in vessel efficiency through such measures as hull design and light-weighting can have large impacts in reducing cost and emissions of these systems.

Overall this work showed all five vessel types to be feasible with today's hydrogen fuel cell technology and presents more options to fleets that are committed to reducing maritime emissions in cost effective ways.

ACKNOWLEDGMENTS

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The authors would like to thank Curt Leffers and Kurt Jankowski at Elliott Bay Design Group for their professionalism, adaptability, excitement, and technical excellence in performing the mapping study and producing vessel designs and accompanying analysis and assessments.

Thank you also to Ryan Sookhoo of Hydrogenics for many discussions on hydrogen fuel cell technology and costs, Joe Burgard of Red and White Fleet for insight into the passenger vessel industry, and to Andrew Martinez at the California Air Resources Board for his assistance with air pollution quantification methods.

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EXECUTIVE SUMMARY

The SF-BREEZE feasibility study[1] determined it is possible to build and operate a 35 knot, 150 passenger catamaran ferry powered by hydrogen fuel cells and producing zero emissions. The feasibility study also revealed that the performance requirements and design of that particular vessel led to higher vessel capital and operating cost, and to lifecycle GHG emissions that are more than two-times higher than a conventional diesel ferry when the hydrogen is produced from natural gas. It was recognized that these drawbacks may be mitigated on other vessel platforms with different designs, serving as better entry points for today's hydrogen and fuel cell technology.

Five vessels were chosen through examination of today's commercial passenger vessel fleet in the US, with each vessel chosen to represent a grouping of popular commercially-relevant vessel types while at the same time allowing interpolation between vessel types to achieve widest relevance of results. The vessels and notional routes were designed by Elliott Bay Design Group and consisted of:

1. 9-knot, double-ended, steel vehicle ferry for 100 passengers and 20 vehicles
2. 6-knot steel water taxi for 60 passengers
3. 24-knot aluminum catamaran ferry for 350 passengers
4. 12-knot steel tour/excursion vessel for 400 passengers
5. 12-knot, double-ended, steel vehicle ferry for 800 passengers and 64 vehicles

Elliott Bay produced all vessel designs which includes general arrangements with location of hydrogen tanks and fuel cells, explanation of design features needed to meet known regulatory requirements, weight estimate, speed and power curves, tonnage and stability assessments, route, energy use, and endurance calculations, and capital cost estimates.

The resulting vessel designs were evaluated for total and per-passenger mile energy use, greenhouse gas emissions, criteria pollutant emissions, capital cost, and powertrain+fuel operating cost. The energy use per passenger mile was shown to correlate directly to emissions and operating costs. The best vessels in terms of per passenger mile emissions and operating costs were the two vehicle ferries followed by the 400 passenger tour/excursion vessel. All of these are relatively low speed and power which cuts down on energy use, but can hold a significant number of passengers (and vehicles). Compared to the SF-BREEZE, the 100 passenger/22 vehicle ferry (the best performing vessel) reduced emissions by 91% and reduced fuel and powertrain maintenance costs by 87%.

The 350 passenger high-speed ferry has a high energy use per passenger and consequently a higher emissions and operating cost profile. This is not to say that high speed vessels should be avoided; the high speed serves a useful function and may be the only viable kind of vessel in some markets. Comparison of the 350 passenger 24 knot catamaran ferry to the 150 passenger 35 knot SF-BREEZE illustrates how increasing the passenger count while decreasing the speed can dramatically cut per passenger-mile energy, operating costs, and emissions by nearly 50%.

[1] Pratt, J.W. and L.E. Klebanoff, *Feasibility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry*. 2016, Sandia National Laboratories report SAND2016-9719.

The study also produced insight into well-to-waves emissions and costs of various hydrogen supply pathways. Pressurized, gaseous hydrogen at 350 bar was found to cost less than liquid hydrogen and have lower well-to-wave greenhouse gas emissions, but it has higher well-to-wave criteria pollutant emissions due to the abundant emissions associated with heavy-duty diesel delivery trucks. Volume of hydrogen consumption was shown to have a significant effect on expected hydrogen fuel cost with low daily usage (< 200 kg/day) increasing hydrogen cost by about 65% compared to high daily usage (> 600 kg/day). Renewable hydrogen is available and was estimated to cost approximately 1.75-times more than hydrogen produced from natural gas, but it eliminates all well-to-wave emissions other than those associated with trucking.

Overall this work built on the SF-BREEZE feasibility study to find other passenger vessels with more favorable cost and emissions profiles than the SF-BREEZE. All vessel types were shown to be feasible with today's hydrogen fuel cell technology and present more options to fleets that are committed to reducing maritime emissions in cost effective ways.

NOMENCLATURE

BOP	Balance of Plant
CFD	Computational Fluid Dynamics
CH2	Compressed hydrogen [at 350 bar]
EBDG	Elliott Bay Design Group
EU	European Union
GHG	Greenhouse Gas
IGF Code	International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
LCFS	Low Carbon Fuel Standard
LH_2	Liquid Hydrogen
LOA	Length Overall
M&R	Maintenance and Repair
MCR	Maximum Continuous Rating
MT	Metric Ton (1,000 kg)
NG	Natural Gas
pax	passenger
PM	Particulate Matter
ROG	Reactive Organic Gases
SMR	Steam Methane Reforming
SF-BREEZE	San Francisco Bay Renewable Energy Electric vessel with Zero Emissions
SV	Standard Vehicle
USCG	United States Coast Guard
VOC	Volatile Organic Compounds
WCPE	Weighted Criteria Pollutant Emission

1. INTRODUCTION AND BACKGROUND

It is becoming widely recognized that air emissions from marine vessels must be reduced to mitigate the effects on the environment. Large-percentage cuts are necessary in order to overcome expected high growth in the maritime shipping industry [1]. At the same time, the cost of utilizing traditional marine fossil fuels is expected to increase rapidly due to impending regulation [2] and the maritime industry is looking at alternative fuels as a way to mitigate increases in operating costs. Using domestically-produced renewable hydrogen as a fuel with fuel cells is a zero-emission pathway with the potential to meet both of these goals.

The SF-BREEZE feasibility study [3] determined it is possible to build and operate a 35 knot, 150 passenger catamaran ferry powered by hydrogen fuel cells and producing zero emissions. The 35 knot speed specification was deliberately chosen to set a high bar for feasibility. The feasibility study revealed that the high speed nature of the vessel combined with the weight of the zero emission power plant (fuel cells and hydrogen storage) leads to a large per-passenger power requirement relative to a conventional diesel ferry of similar size. This results in higher vessel capital cost, higher fuel cost, and higher maintenance and repair (M&R) cost of the power plant system due to the high per-unit cost of the fuel cells and hydrogen. It also leads to per-passenger lifecycle GHG emissions that are more than two-times higher than a conventional diesel ferry when the hydrogen is produced from natural gas. There is therefore a desire to optimize the vessel design to reduce emissions and cost.

Examination of the US ferry fleet performance characteristics (speed and passenger count) as shown in Figure 1 reveal that these initially-chosen performance specifications of the SF-BREEZE are not in the mainstream. The majority of ferries in the US operate in the 6-15 knot range. Passenger counts vary from very small (<25) to very large (> 1,000). This shows that there are many other commercially-relevant passenger vessels to which a hydrogen fuel cell powertrain can be applied with perhaps better emissions and cost characteristics than the SF-BREEZE.

One potential hindrance to examining larger vessels is that in the SF-BREEZE study the 150 passenger count was chosen to stay within US Coast Guard (USCG) Subchapter T regulations [4] under the rationale that the requirements would be easier to meet (compared to Subchapter K [5]) as a first step of introducing hydrogen in passenger vessels in the US. However, through the SF-BREEZE study it was determined that while the base Subchapter T regulations are more relaxed in their requirements, the addition of hydrogen fuel to the vessel required the application of many portions of the International Maritime Organization's *International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels* (IGF) code [6] in order to satisfy USCG standards. This combination of requirements (Subchapter T + IGF code) resulted in a vessel that would meet Subchapter K requirements with little additional effort. Therefore the same regulatory design philosophies used in the SF-BREEZE study could be applied to larger, Subchapter K vessels as well.

Considering all of the above, an effort was initiated to find the optimal entry point for today's hydrogen fuel cell technology on commercially-relevant passenger vessels with the goal of minimizing per-passenger emissions and costs.

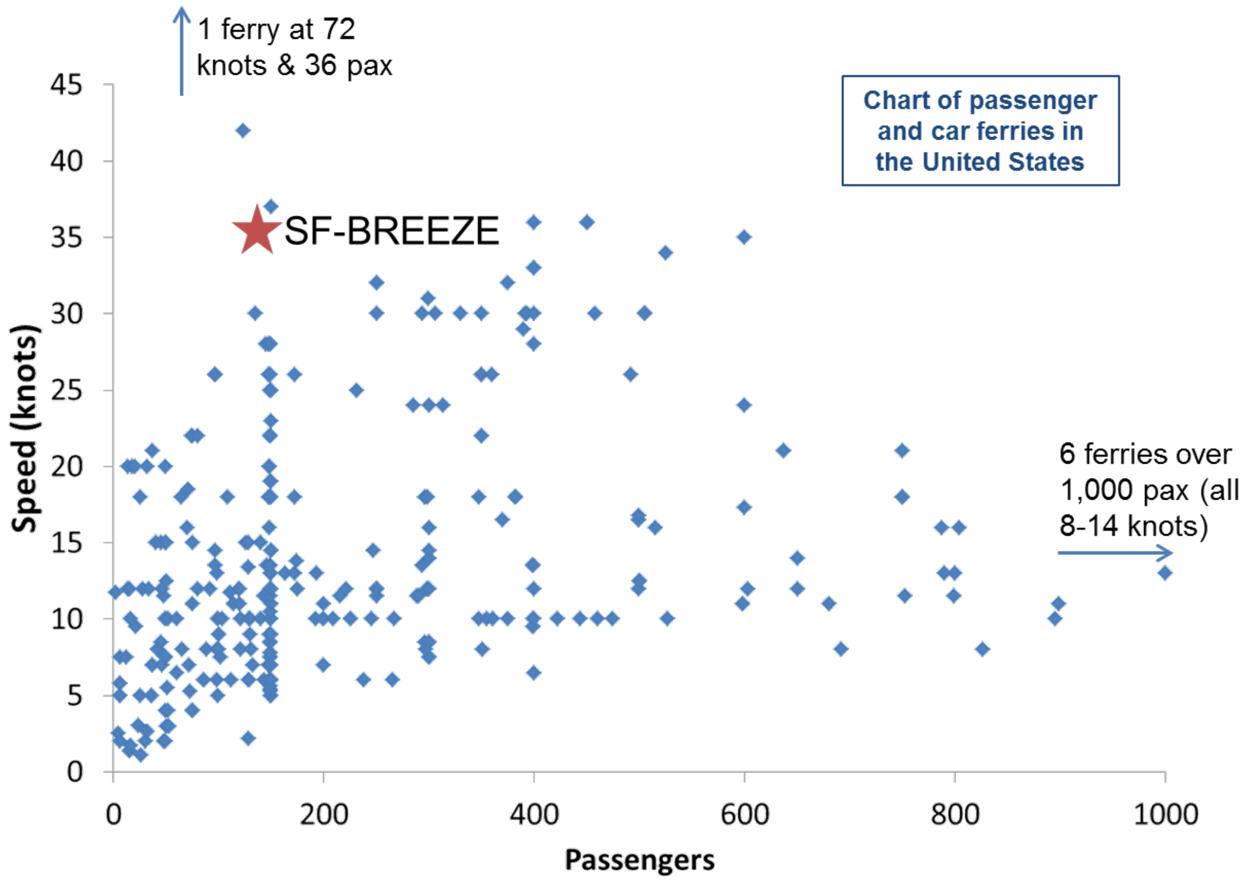


Figure 1: Speed/passenger profile of US passenger and vehicle ferries in 2014. Data from Ref. [7] excluding vessels that did not report passenger count or speed.

2. METHODS

This study determined optimal configurations of zero emission hydrogen fuel cell passenger vessels by finding the cost and emissions associated with a range of vessel speeds and capacities relevant to the US market. Accomplishing this required expertise in hydrogen fuel cell technology, the US maritime market, and in naval architecture to ensure relevancy and accuracy of the designs and resulting cost and emissions. The steps used are described in the following sections.

2.1. Vessel and Route Selection

The first step of the study was to determine which vessel types would be designed. The project scope and resources allowed for design of five different passenger vessels. In order to have maximum impact and relevance, it was important to select a set of vessels that can cover popular commercially-relevant vessel types while being broad enough to allow examination and interpolation of trends in the results to allow application to types not explicitly explored.

This was done by examining today's commercially relevant passenger vessels using data from the Bureau of Transportation Statistics about the US ferry fleet [7], focusing on dominant characteristics:

- Speed
- Subchapter
- Service type (Passenger only vs Passenger + Vehicle)
- Hull material

From the data five different vessel types were selected for design. Notional routes for each vessel type were identified by looking at the routes currently served by similar existing vessels in the US.

More detail on the vessel selection method is given in Elliott Bay's Mapping Study Results Memorandum, Appendix A.

2.2. Vessel Design and Refinement

Vessel design was done by the naval architect Elliott Bay Design Group, the same naval architect that designed the SF-BREEZE ferry and thus has existing knowledge of the nuances of hydrogen fuel cell vessel design. EBDG produced general arrangements, power requirements, and cost estimates for each vessel type with input where needed from equipment manufacturers and Sandia on the novel aspects (fuel cell and hydrogen storage). The designs considered placement of the fuel cell and hydrogen storage to maximize passenger count while taking into consideration weight distribution, stability, USCG regulations, etc. and, in a departure from the SF-BREEZE design, included placement of these items within the hull.

Rules and regulations of the classification and regulatory bodies as identified in the SF-BREEZE feasibility study were considered in forming the arrangements and designs were evaluated against these with any areas of known non-compliance identified along with proposed resolution. The bunkering process was assumed to be similar to that described in the SF-BREEZE feasibility study and any modifications necessary for a given design was identified.

The designs included defining approximate power requirements based on regression analysis. This information was used with notional, typical service routes to find energy requirements and endurance based on on-board energy storage capacity.

Detailed speed and power relationships were determined for four vessels in order to obtain better accuracy of the power requirement. This was done through a combination of CFD simulations and model testing (done previously for one of the hull forms). The fifth vessel was not selected for detailed speed and power analysis because it ranked last in both economics and emissions.

The last step of the vessel design portion performed by EBDG was to estimate the capital cost of each vessel. The base method used for this is typical for concept designs, using a parametric analysis with lightship weights including all material costs, and all engineering and build labor. The hydrogen storage and fuel cells were estimated separately and added to the total.

More detail on the vessel design methods is given in Elliott Bay's *SF-BREEZE Optimization Study*, Appendix B.

2.3. Air Emission Predictions

The hydrogen fuel cell vessels studied are all zero emission, having no emissions associated with the use of hydrogen on-board. However, there can be air emissions associated with producing and distributing any fuel, which are called pathway emissions. To get a complete understanding of the emissions impact of using hydrogen fuel cells it is important to consider both "pathway" and "use" emissions, and for maritime vessels we call this combination a "well-to-waves" analysis. This section discusses the method used to find the well-to-waves greenhouse gas (GHG) and criteria pollutant emissions of the five vessels.

Four paths of hydrogen supply were considered and well-to-waves emissions were calculated for each:

1. Hydrogen produced by reforming fossil natural gas and transporting and storing as a compressed gas at 350 bar. This will be called "*Fossil NG Compressed Gas*"
2. Hydrogen produced by reforming fossil natural gas, liquefied with typical grid-supplied electricity, and transporting and storing as a liquid, or "*Fossil NG* LH_2"
3. Hydrogen produced by 100% renewable electrolysis and transporting and storing as a compressed gas at 350 bar, or "*Renewable Compressed Gas*"
4. Hydrogen produced by 100% renewable electrolysis, liquefied with 100% renewable electricity and transporting and storing as a liquid, or "*Renewable* LH_2"

The general method was similar to that used in the SF-BREEZE report but had to be adapted primarily because the SF-BREEZE report did not consider gaseous hydrogen as a distribution or fuel storage option. The following sections describe how GHG and criteria pollutant well-to-wave emissions were calculated for each path.

2.3.1. GHG Emissions

Similar to the SF-BREEZE report, the work by Edwards et al. [8] was used to estimate hydrogen production and delivery (pathway) GHG emissions. A modified version of pathway GPCH3b from that work was used to estimate the GHG emissions of the *Fossil NG Compressed Gas* path. Pathway GPCH3b consists of the following steps:

1. Piped natural gas supply transported by pipeline
2. Natural gas distribution through high pressure trunk lines
3. Large central steam methane reforming
4. Hydrogen compression to 500 bar
5. Road transport 50 km to retail site in a 28 MT truck carrying 400 kg of hydrogen at 500 bar
6. Compression at the retail site to 880 bar

This pathway has associated GHG emissions of 108.2 gCO_{2eq}/MJ_{H2}.

The road trucking distance in Step 5 was changed from 50 km to 300 km to be consistent with the LH_2 pathways and to be more consistent with actual distances encountered in the U.S. from central reformers rather than in the EU, where the study was based. This increased the truck transport GHG emissions from 3.66 gCO_{2eq}/MJ_{H2} to 21.95 gCO_{2eq}/MJ_{H2}, an increase of 18.29 gCO_{2eq}/MJ_{H2}. A second modification was to remove Step 6 because 500 bar in the supply trailer is sufficient to fill the 350 bar tanks on the vessels without additional compression, decreasing the GHG emissions by 7.93 gCO_{2eq}/MJ_{H2}. The resulting pathway emissions are thus 118.46 gCO_{2eq}/MJ_{H2}.

The *Fossil NG LH_2* path was based on pathway CPLCHb which consists of the following steps:

1. Piped natural gas supply transported by pipeline
2. Natural gas distribution through high pressure trunk lines
3. Large central steam methane reforming
4. Hydrogen liquefaction
5. Road transport 300 km to retail site in a 24 MT truck carrying 3,500 kg of LH_2
6. Vaporization and compression at the retail site to 880 bar

This pathway has associated GHG emissions of 135.8 gCO_{2eq}/MJ_{H2}. Step 6 was removed because the LH_2 will be dispensed directly into the vessel. This decreased the GHG emission by 7.70 gCO_{2eq}/MJ_{H2} resulting in a pathway emission of 128.10 gCO_{2eq}/MJ_{H2}.

The only GHG emissions associated with the *Renewable Compressed Gas* and *Renewable LH_2* paths are those from the truck transportation from the production plant to the bunkering location. Reference [8] describes the truck contribution to GHG emissions only for LH_2 transport with a 24 MT truck carrying 3,500 kg of LH_2 a distance of 300 km. Two numbers were given (1.6 gCO_{2eq}/MJ_{H2} and 2.7 gCO_{2eq}/MJ_{H2}) using the same truck and distance parameters with no explanation given for the difference, so an average of those two (2.15 gCO_{2eq}/MJ_{H2}) was used. To calculate the GHG emissions for truck transport of 500 bar compressed gas, the 2.15 gCO_{2eq}/MJ_{H2} was proportionally modified by increasing the truck weight (28 MT for the compressed gas truck versus 24 MT for the LH_2 truck) and decreasing the amount of hydrogen carried per load (400 kg for the compressed gas truck versus 3,500 kg for the LH_2 truck). This resulted in 21.95 gCO_{2eq}/MJ_{H2}.

Table 1 through Table 4 summarize each path used in these GHG analyses.

Table 1: Steps and associated GHG emissions for the *Fossil NG Compressed Gas* pathway

Steps of the *Fossil NG Compressed Gas* Pathway	GHG Emissions (gCO_{2eq}/MJ_{H2})
Piped natural gas supply transported to the EU by pipeline	96.5
Natural gas distribution through high pressure trunk lines	
Large central steam methane reforming	
Hydrogen compression to 500 bar	
Road transport 300 km to retail site in a 28 MT truck carrying 400 kg of hydrogen at 500 bar	22.0
Total	**118.5**

Table 2: Steps and associated GHG emissions for the *Fossil NG LH_2* pathway

Steps of the *Fossil NG LH_2* Pathway	GHG Emissions (gCO_{2eq}/MJ_{H2})
Piped natural gas supply transported to the EU by pipeline	125.95
Natural gas distribution through high pressure trunk lines	
Large central steam methane reforming	
Hydrogen liquefaction	
Road transport 300 km to retail site in a 24 MT truck carrying 3,500 kg of LH_2	2.15
Total	**128.1**

Table 3: Steps and associated GHG emissions for the *Renewable Compressed Gas* pathway

Steps of the *Renewable Compressed Gas* Pathway	GHG Emissions (gCO_{2eq}/MJ_{H2})
Central electrolysis	0
Hydrogen compression to 500 bar	
Road transport 300 km to retail site in a 28 MT truck carrying 400 kg of hydrogen at 500 bar	22.0
Total	**22.0**

Table 4: Steps and associated GHG emissions for the *Renewable LH_2* pathway

Steps of the *Renewable LH_2* Pathway	GHG Emissions (gCO_{2eq}/MJ_{H2})
Central electrolysis	0
Hydrogen liquefaction	
Road transport 300 km to retail site in a 24 MT truck carrying 3,500 kg of LH_2	2.15
Total	**2.15**

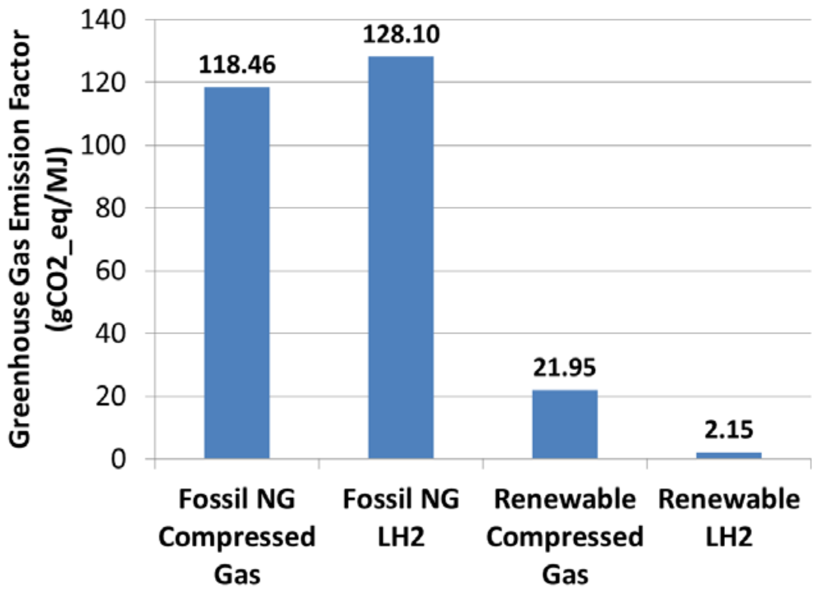


Figure 2: GHG emission factors used for the four hydrogen supply options.

Figure 2 summarizes the overall resulting GHG emissions factors used in this work. The *Renewable Compressed Gas* path has a higher GHG contribution than the *Renewable LH_2* path primarily because it takes nearly nine trucks to transport the same amount of hydrogen as a compressed gas compared to one truck of LH_2 and the GHG contributions of the trucks' diesel internal combustion engines are significant. Despite this large contribution to GHG emissions of compressed gas delivery, the *Fossil NG Compressed Gas* path has a lower overall GHG emission than the *Fossil NG LH_2* path. This is because the large amount of energy required for the liquefaction of hydrogen and its associated GHG emissions more than offsets any gain from more efficient trucking. (As the trucking distance gets longer the *Fossil NG Compressed Gas* emissions increase more than those from the *Fossil NG LH_2* path, so that at distances above about 450 km the total GHG emissions from the *Fossil NG Compressed Gas* path become greater than those from the *Fossil NG LH_2* path.)

2.3.2. Criteria Pollutant Emissions

Criteria pollutant emissions were estimated using the work of Unnasch and Pont [9], as was done for the SF-BREEZE report. The Unnasch and Pont work did not consider distributing the hydrogen as a compressed gas, only as LH_2. Also the Unnasch and Pont work did not explicitly provide emissions factors for the individual processes (e.g., production, compression, transport, etc.) that make up the path. Fortunately the work did provide sufficient other details about the processes that enabled estimating the process emissions, which then allowed determination of the overall emissions factors for the four hydrogen supply paths considered here.

The starting point was the Unnasch and Pont pathway "H2, NG SR, LH2, Ren Power" which is used to represent our *Fossil NG LH_2* path. This pathway has the following steps:

1. Natural gas extraction from North American fields
2. Transport via pipeline to central plants
3. Steam reformation at large central plants
4. Hydrogen liquefaction
5. Road transport 50 mi to fueling station in a truck carrying 3,700 kg of LH_2

6. Vaporization and compression at the fueling station using 100% renewable energy

The criteria pollutant emission factors for this path are 44.5 $gNOx/GJ_{H2}$, 1.1 $gPM10/GJ_{H2}$, and 3 $gVOC/GJ_{H2}$. The fact that Step 6 uses 100% renewable energy means that there is no contribution to emissions from that step, effectively eliminating it, so it is acceptable to use these emission factors as-is for our *Fossil NG LH_2* path where the LH_2 is dispensed directly into the vessel.

Breaking the emissions of this pathway into its components was necessary in order to adapt it to the three other paths used in this work. The Unnasch and Pont work did not provide a breakdown of emissions factors for each process but did provide information about the total energy use and energy use of each process. By changing the individual processes to match the desired paths used in this work, the proportion of energy used by each process can be used to determine the criteria pollutant emissions of each process and thus the total path emissions.

However, changes in overall pathway energy use do not necessarily lead to 1:1 proportional changes in criteria pollutant emissions because different processes in the pathway can have different emissions factors. The emissions factors for grid-supplied electricity used for liquefaction and compression are identical, and those for steam methane reformation are very close to those for grid supplied electricity (ref. emissions factors in Tables 3-16 and 5-2 from [9]). Trucking-related emissions factors are very different though, requiring use of an emissions "scaling factor" whenever the proportion of trucking energy in a pathway changed. For changes of the trucking energy proportion the following scaling factors were calculated based on the proportional difference between trucking emissions factors and the average of electricity generation and SMR emissions factors:

- NOx: 5.11
- PM10: 13.47
- VOC: 47.07

Whenever changes in trucking energy are made, the energy change is multiplied by these scaling factors to find the corresponding change in criteria pollutant emissions.

The following steps were used to adapt the criteria pollutant emissions given above for the "H2, NG SR, LH2, Ren Power" pathway to our *Fossil NG Compressed Gas* path:

1. Reduce the trucking distance in the pathway energy calculation from 100 mi to 50 mi to be consistent with the criteria pollutant emission factors given for the pathway. This reduced the trucking energy from 0.012 J/J_{H2} to 0.006 J/J_{H2} and the total pathway energy by from 1.53 J/J_{H2} to 1.524 J/J_{H2}, which can now be used as the baseline energy for criteria pollutant calculations.
2. Remove the energy *and* associated emissions of the 50 mi LH_2 trucking portion altogether. This reduced the criteria pollutant emission factors by 0.89 $gNOx/GJ_{H2}$, 0.06 $gPM10/GJ_{H2}$, and 0.56 $gVOC/GJ_{H2}$ when combining the 0.006 J/J_{H2} energy reduction with the scaling factors listed above, for new pathway totals of 43.6 $gNOx/GJ_{H2}$, 1.0 $gPM10/GJ_{H2}$, and 2.4 $gVOC/GJ_{H2}$.
3. Replace the liquefaction step with a gas compression step. This was done by taking the difference in electrical energy consumption from a path using liquefaction with a comparable path using gas compression to 420 bar ("Central NG SR, LH2 Truck" and

"Central NG SR, Mobile Fueler" from Table 3-14 of [9]). This decreased the pathway energy (still excluding trucking energy) to 1.23 J/J_{H2}. Because no trucking energy is included in the total, the criteria pollutant emissions can be scaled 1:1 resulting in emissions factors of 35.1 gNOx/GJ_{H2}, 0.84 gPM10/GJ_{H2}, and 2.0 gVOC/GJ_{H2}.

4. Add emissions associated with 50 mi gaseous hydrogen trucking. According to the numbers in Table 5-30 of Ref [9], trucking 50 mi with 240 kg of gaseous hydrogen consumes 15.8-times more energy per kilogram of hydrogen than trucking 50 mi with 3,700 kg of LH2. Thus the emission factors for 50 mi LH_2 trucking calculated above in Step 2 were multiplied by 15.8 to find the 50 mi gaseous trucking emissions factors of Added to the total pathway emission excluding trucking from Step 3 results in total pathway emissions factors of 49.2 gNOx/GJ_{H2}, 1.76 gPM10/GJ_{H2}, and 10.8 gVOC/GJ_{H2}.

The criteria pollutant emissions factors for our *Renewable Compressed Gas* path are simply those due to the gaseous trucking as determined in Step 4: 14.17 gNOx/GJ_{H2}, 0.92 gPM10/GJ_{H2}, and 8.80 gVOC/GJ_{H2}. Likewise the factors for our *Renewable LH_2* path are those due to the LH2 trucking determined in Step 2: 0.89 gNOx/GJ_{H2}, 0.06 gPM10/GJ_{H2}, and 0.56 gVOC/GJ_{H2}.

Table 5 through Table 8 summarize each path used in these criteria pollutant emission analyses.

Table 5: Steps and associated criteria pollutant emissions for the *Fossil NG Compressed Gas* pathway

Steps of the *Fossil NG Compressed Gas* Pathway	**Criteria Pollutant Emissions (g/GJ_{H2})**		
	NOx	**PM10**	**VOC**
Natural gas extraction from North American fields	35.06	0.84	1.96
Transport via pipeline to central plants			
Steam reformation at large central plants			
Hydrogen compression to 420 bar			
Road transport 50 mi to fueling station in a truck carrying 240 kg of compressed hydrogen at 420 bar	14.17	0.92	8.80
Total	**49.2**	**1.8**	**10.8**

Table 6: Steps and associated criteria pollutant emissions for the *Fossil NG LH_2* pathway

Steps of the *Fossil NG LH_2* Pathway	**Criteria Pollutant Emissions (g/GJ_{H2})**		
	NOx	**PM10**	**VOC**
Natural gas extraction from North American fields	43.61	1.04	2.44
Transport via pipeline to central plants			
Steam reformation at large central plants			
Hydrogen liquefaction			
Road transport 50 mi to fueling station in a truck carrying 3,700 kg of LH2	0.89	0.06	0.56
Total	**44.5**	**1.1**	**3**

Table 7: Steps and associated criteria pollutant emissions for the *Renewable Compressed Gas* pathway

Steps of the *Renewable Compressed Gas* Pathway	**Criteria Pollutant Emissions (g/GJ_{H2})**		
	NOx	**PM10**	**VOC**
Central electrolysis Hydrogen compression to 420 bar	0	0	0
Road transport 50 mi to fueling station in a truck carrying 240 kg of compressed hydrogen at 420 bar	14.17	0.92	8.80
Total	**14.2**	**0.9**	**8.8**

Table 8: Steps and associated criteria pollutant emissions for the *Renewable LH_2* pathway

Steps of the *Renewable LH_2* Pathway	**Criteria Pollutant Emissions (g/GJ_{H2})**		
	NOx	**PM10**	**VOC**
Central electrolysis Hydrogen liquefaction	0	0	0
Road transport 50 mi to fueling station in a truck carrying 3,700 kg of LH2	0.89	0.06	0.56
Total	**0.89**	**0.06**	**0.56**

Figure 3 summarizes the criteria pollutant emission factors used in this work. For both renewable pathways the entire contribution to emissions comes from the trucking portion. The large amount of criteria pollutants from trucking gaseous hydrogen explains the higher emissions of the *Fossil NG Compressed Gas* path compared to the *Fossil NG LH_2* path despite the higher energy consumption and GHG emissions of the latter. Even at the relatively short travel distances used here (50 mi) the criteria pollutant emissions from trucking gaseous hydrogen are more than that for trucking LH_2. As distance increases this difference will become even greater.

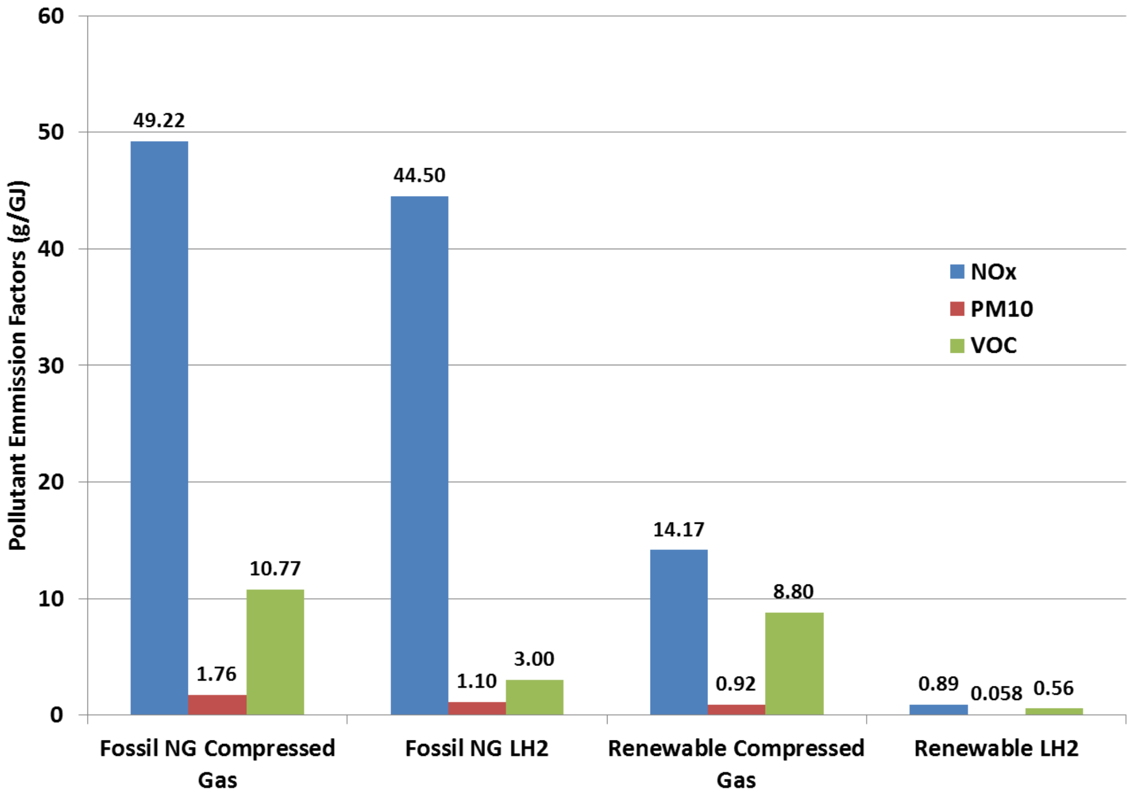


Figure 3: Criteria pollutant emission factors used for the four hydrogen supply options.

While the separation of criteria pollutants into their components (NOx, PM10, and VOC) is insightful, simplifying into a single pollutant parameter can be easier to understand especially when comparing multiple scenarios. The California Air Resources Board uses a weighting system which we can similarly apply and define here as the Weighted Criteria Pollutant Emission (WCPE) factor:

$$WCPE = NOx + VOC + 20*PM10$$

The factor of 20 placed on PM10 emissions reflects the higher health risk and higher cost to control it relative to either NOx or ROG[2] (VOC) emissions [11]. Figure 4 shows the resulting WCPE factors used in this work.

[2] The California Air Resources Board uses the term Reactive Organic Gases (ROG) to classify a list of reactive airborne chemicals while the US EPA uses the term Volatile Organic Compounds (VOC) for a very similar list. Because of the similarity the terms are used here interchangeably. Details about the two lists including differences between them can be found in Ref [10].

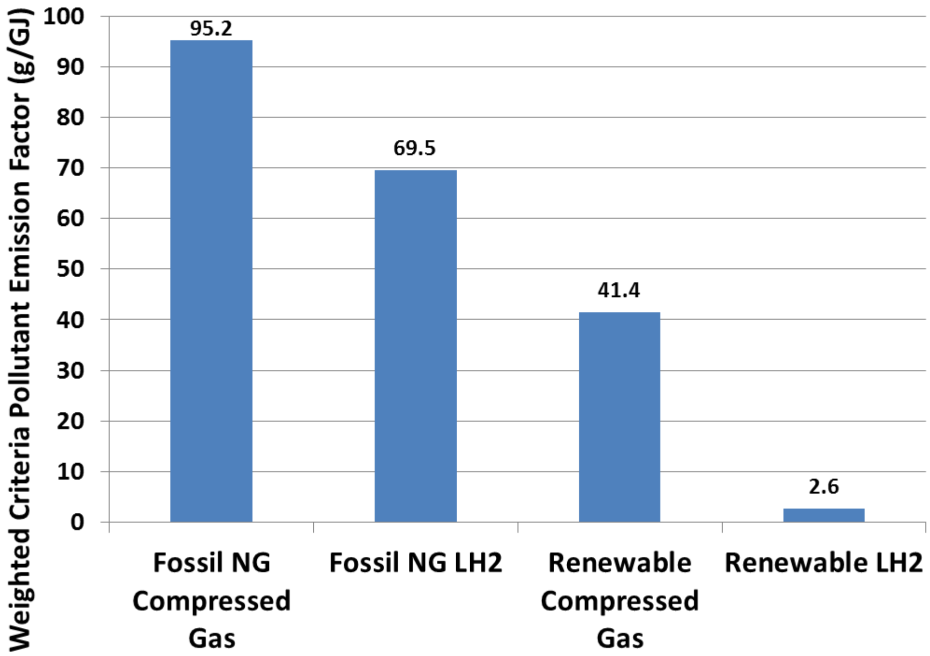


Figure 4: Weighted criteria pollutant emission (WCPE) factors for the four hydrogen supply options.

2.4. Cost Estimating

EBDG estimated vessel capital costs as described above and those estimates are included in Appendix B.

Operating costs for each vessel were estimated considering only the cost of fuel and powertrain maintenance; like the SF-BREEZE it does not include crew, general vessel maintenance, administration, etc. The operating profile is the same for all:

- 310 operating days per year
- 9 hours of operation per operating day

2.4.1. Hydrogen Fuel

Hydrogen fuel costs were estimated based on two baseline costs from the SF-BREEZE study:

- \$5.90/kg for Fossil NG LH_2 assuming 2,000 kg/day usage
- \$10.39/kg for Renewable LH_2 assuming 2,000 kg/day usage

These were adjusted for the compressed gas pathways and for different daily consumptions using information from Paster et al. [12] in the following ways:

- Liquid hydrogen was shown to have a 1.1x cost premium compared to gaseous hydrogen because of the additional cost of liquefaction so Fossil NG Compressed Gas was set to \$5.36/kg and Renewable Compressed Gas was set to \$9.45/kg for the 2,000 kg/day consumption level
- Cost increases with decreasing daily consumption. The increase is minor as consumption decreases from 2,000 kg/day to 1,000 kg day, but the cost of a daily consumption of 300 kg/day is about 1.1-times higher than that at 1,000 kg/day, and the cost of daily consumption of 100 kg/day is about 1.5-times higher than that at 300 kg/day.

Table 9: Cost of hydrogen for different supply pathways and daily consumption volumes

Pathway	Low volume (< 50-200 kg/day)	Medium volume (200-600 kg/day)	High volume (> 600 kg/day)
Fossil NG Compressed Gas	$8.85	$5.90	$5.36
Fossil NG LH_2	$9.74	$6.49	$5.90
Renewable Compressed Gas	$15.59	$10.39	$9.45
Renewable LH_2	$17.14	$11.43	$10.39

Table 1 summarizes the resulting hydrogen costs used in this work. Another recent study [13] independently estimated today's fossil natural gas produced compressed gas delivery costs of about $10/kg for 100 kg/day consumption and $6/kg for 300 kg/day consumption, both which match fairly well with the cost estimates ($8.85 and $5.90, respectively) using the method above.

In the SF-BREEZE report the hydrogen costs were further adjusted downward by applying Low Carbon Fuel Standard (LCFS) credits available in the California market. The value of these credits depend upon the renewable content of the fuel and the current market price for credits. Recently (2017) the credits have been trading at high prices. In the SF-BREEZE report a trading price of $120/MT was estimated to result in a credit of $0.65/kg for hydrogen produced from natural gas and a credit of $2.36/kg for 100% renewable hydrogen. These credits are not included in Table 9 and are not used in calculating the operating costs of the vessels but illustrate that the fuel costs can be reduced by around 10% for hydrogen produced from natural gas and around 20% for renewable hydrogen.

2.4.2. Powertrain Maintenance

Powertrain maintenance consists of three components: (1) fuel cell cost, which here only includes the refurbishment cost of the fuel cells after they reach their operating hour limit, (2) fuel cell balance of plant (BOP) costs which include periodic maintenance on fans, pumps, etc., and (3) power conditioning equipment costs which includes periodic maintenance on that equipment. Fuel cell stack refurbishment consists of replacement of the core fuel cell membranes after a certain amount of run time. The assumptions behind these costs are:

- 10,000 hr fuel cell refurbishment interval. Fuel cell companies are working towards a 15,000 hr run time refurbishment interval but 10,000 is an achievable goal today.
- 50% fuel cell operating time. Usually, about half of the time the fuel cells are not operated at full load, typically less than half load. So assume that, like SF-BREEZE, stacks can be placed on standby thus reducing hours per year on each stack by half. Different fuel cell brands handle "stand-by" differently so the manufacturer should be consulted to determine whether this is an appropriate assumption for a particular brand.
- $1,000/kW fuel cell refurbishment cost.
- 3% of fuel cell capital cost as yearly fuel cell BOP maintenance budget.
- 3% of power conditioning capital cost as a yearly power conditioning maintenance budget. Power conditioning equipment capital cost was estimated to be about $830/kW of fuel cell installed gross power. As the maritime industry trends more towards battery electric and diesel-electric powertrains, power conditioning equipment and maintenance practices become more standardized so these costs can be expected to rapidly decline in the near future.

Consolidating the above effects with the operating profile gives an estimated yearly powertrain maintenance budget of $230 per kW of installed fuel cell power. This is identical to the estimated yearly maintenance budget of a diesel generator as estimated from Table 25 of Ref. [14], showing that fuel cell system maintenance does not have a significant, if any, cost premium compared to diesel generator systems.

3. RESULTS AND DISCUSSION

This chapter presents a summary of Elliott Bay Design Group's Mapping Study and Vessel Designs in the first two sections, with the full text of Elliott Bay's work in Appendices A and B. Following these summaries the energy use of each vessel is determined. This feeds into the well-to-waves GHG and criteria pollutant emission profiles in the fourth section, and the capital and operating costs in the last section.

3.1. Mapping Study

The mapping study was performed by EBDG and is given in its entirety in Appendix A. Based on the trends discovered for the current US ferry fleet, the vessels shown in Table 10 were selected for design and analysis. Figure 5 graphically shows how analysis of these sample vessels covers much of the current fleet.

Table 10: Vessels selected for design and analysis based on the mapping study

Vessel	Subchapter	Passengers	Std. Vehicles	Speed	Hull
1	T	100	20	9 kts	Steel
2	T	60	-	6 kts	Steel
3	K	350	-	24 kts	Aluminum
4	K	400	-	12 kts	Steel
5	H	800	64	12 kts	Steel

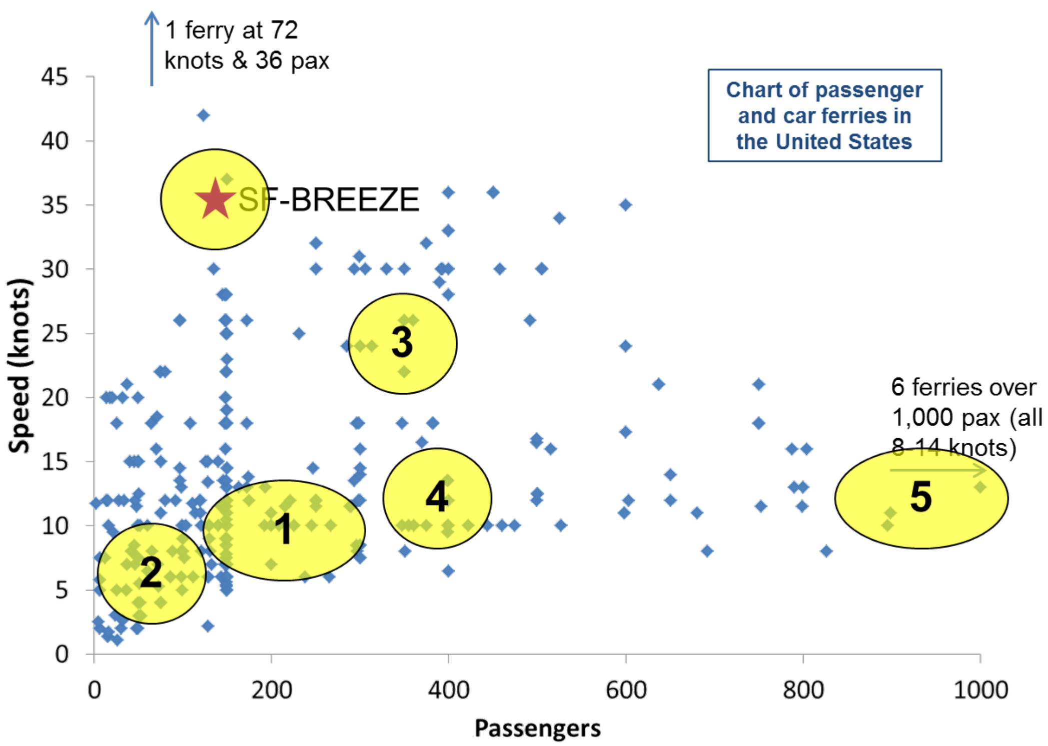


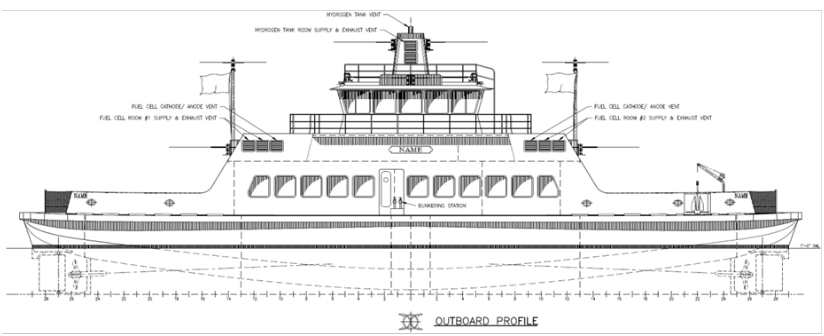
Figure 5: The speed and passenger characteristics of the five vessels to be analyzed in this study are over-laid on top of Figure 1 showing how they, along with the SF-BREEZE study, can be used to represent a large fraction of the current US passenger ferry fleet.

3.2. Vessel Designs

Elliott Bay Design Group performed all vessel designs using accepted naval architecture methods, ensuring that each design is realistic with acceptable operating and safety characteristics, and which meet all known regulatory requirements. Appendix B presents the vessel designs in their entirety, including:

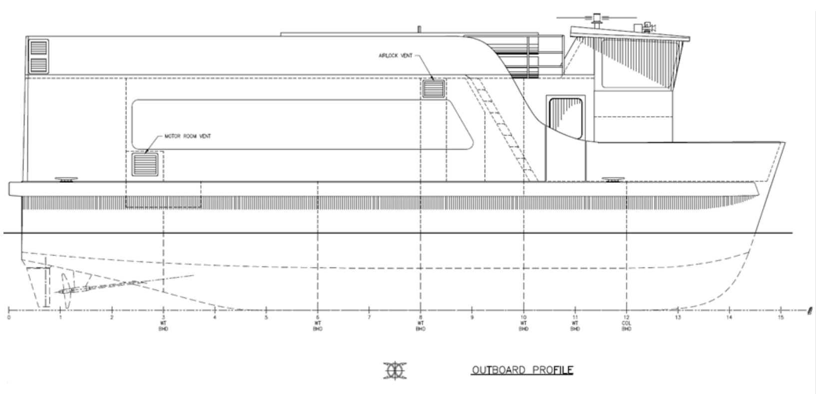
- General arrangements with location of hydrogen tanks and fuel cells
- Explanation of design features needed to meet known regulatory requirements
- Weights, including explanation of different margins used
- Speed and power, including rationale of applying different Maximum Continuous Rating (MCR) values for different vessels
- Tonnage and stability
- Route, energy use, and endurance
- Capital cost estimate

Figure 6 through Figure 10 reproduce the outboard profiles and selected vessel particulars from the appendix for easy reference, and the reader is encouraged to refer directly to the appendix for many more design and operating details. In addition, Figure 11 reproduces the outboard profile and particulars from the SF-BREEZE report [3] for that high-speed ferry, which will be used in the emissions and cost comparisons that follow.



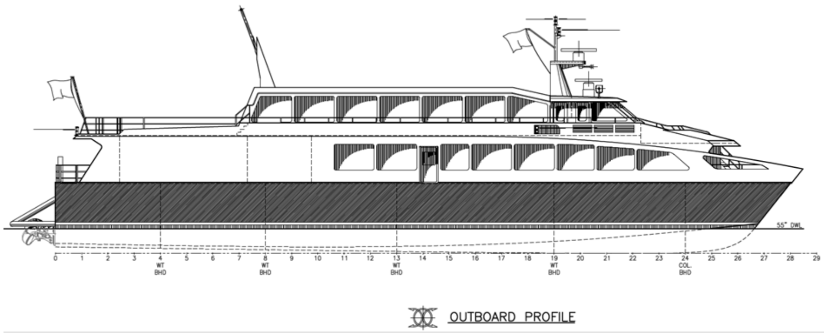
Vessel #1
Type: Double-ended car ferry
Capacity: 100 pax, 22 SV
LOA: 120 ft
Speed: 9 kts
Power: 240 kW
H2 capacity: 212 kg (liq)
Cost: $9.7M

Figure 6: Outboard profile and particulars of Vessel #1, a double-ended car ferry



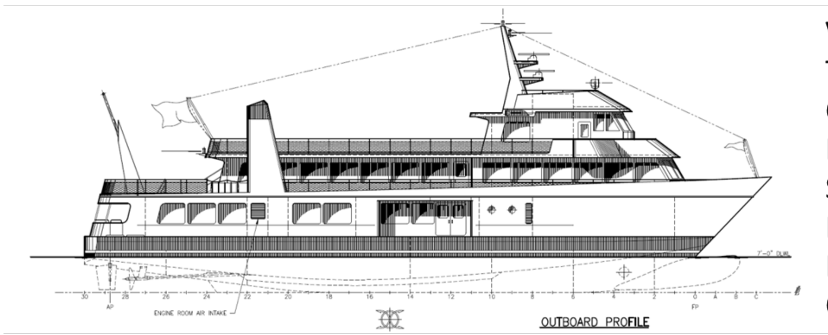
Vessel #2
Type: Water Taxi
Capacity: 60 pax
LOA: 60 ft
Speed: 6 kts
Power: 270 kW
H2 capacity: 95 kg (gas)
Cost: $3.5M

Figure 7: Outboard profile and particulars of Vessel #2, a water taxi



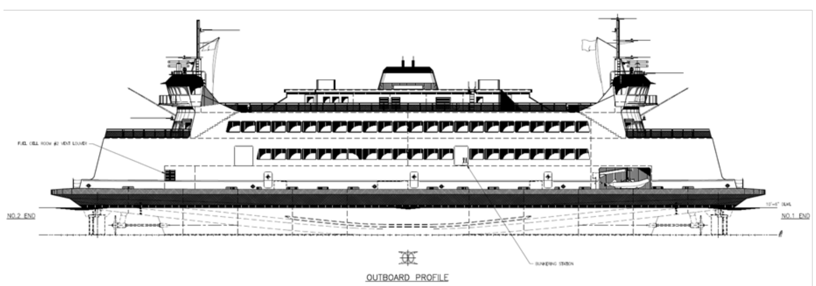
Vessel #3
Type: High Speed Catamaran
Capacity: 350 pax
LOA: 140 ft
Speed: 24 kts
Power: 4,200 kW
H2 capacity: 1,369 kg (liq)
Cost: $35.2M

Figure 8: Outboard profile and particulars of Vessel #3, a high speed catamaran.



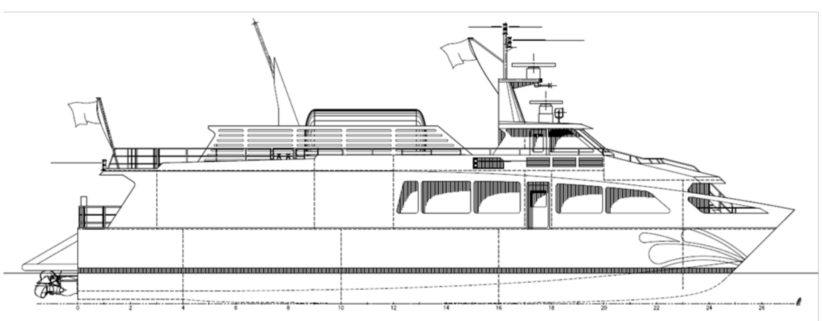
Vessel #4
Type: Excursion boat
Capacity: 400 pax
LOA: 135 ft
Speed: 12 kts
Power: 870 kW
H2 capacity: 776 kg (liq)
Cost: $15.3M

Figure 9: Outboard profile and particulars of Vessel #4, an excursion boat.



Vessel #5
Type: Double-ended car ferry
Capacity: 800 pax, 64 SV
LOA: 274 ft
Speed: 12 kts
Power: 2,045 kW
H2 capacity: 4,064 kg (liq)
Cost: $70.8M

Figure 10: Outboard profile and particulars of Vessel #5, a large double-ended car ferry.



SF-BREEZE
Type: High Speed Catamaran
Capacity: 150 pax
LOA: 109 ft
Speed: 35 kts
Power: 4,920 kW
H2 capacity: 1,200 kg (liq)
Cost: $26.4M

Figure 11: Outboard profile and particulars of the SF-BREEZE, a high-speed catamaran.

3.3. Energy Use

To estimate emissions and operating costs it is necessary to quantify the energy use of each vessel. However, because each vessel has different payload capacities and routes it is difficult to compare vessels in a meaningful way based on absolute energy consumption. Instead energy use is normalized to distance to account for differences in routes and daily usage, and normalized to the passenger-carrying capacity to account for differences in design capacities.

Differences in route distances and trip frequency were normalized by finding the energy use of a single trip and dividing by the trip distance. (Statute miles were used instead of nautical miles in order to allow easier comparisons of energy use with other methods of passenger transport such as cars, buses, and rail.) Routes are detailed in Appendix B and are also summarized here in Table 12 for convenience.

It is common to compare the efficiency of different transportation methods based on the energy needed per passenger. This is easily done by dividing the energy per trip by the passenger capacity and the result is shown in Figure 12. The excursion vessel has the lowest per passenger-mile energy use reflecting its larger passenger capacity (400) and slower speed (12 kts). The two car ferries follow. The high speed (24 kt) catamaran ferry has over double the energy use as the excursion vessel despite a similar size and passenger capacity (350 vs 400); this is because of the

Table 11: Summary of vessel routes. Distance, time, and energy use given for a single 1-way trip and includes time at the dock for loading/unloading passengers. Energy use includes auxiliary ("hotel") power demand. Refer to Appendix B for more detailed route information including a breakdown of route segments, speed, propulsion power, and auxiliary power.

Vessel	Route Type	Distance (mi)	Time (min)	Energy Use (MJ)
1. Sm. car ferry	Short island service	2.3	35.3	658 (82.2 kWh)
2. Water taxi	City waterway	2.3	26.3	513 (64.2 kWh)
3. Cat ferry	Long distance commuter	28.75	90	30,900 (3,860 kWh)
4. Excursion	Sightseeing cruise	23	180	12,300 (1,540 kWh)
5. Lg. car ferry	Commuter	8.05	87.5	15,600 (1,940 kWh)
SF-BREEZE	Long distance commuter	27.6	63.3	24,900 (3,110 kWh)

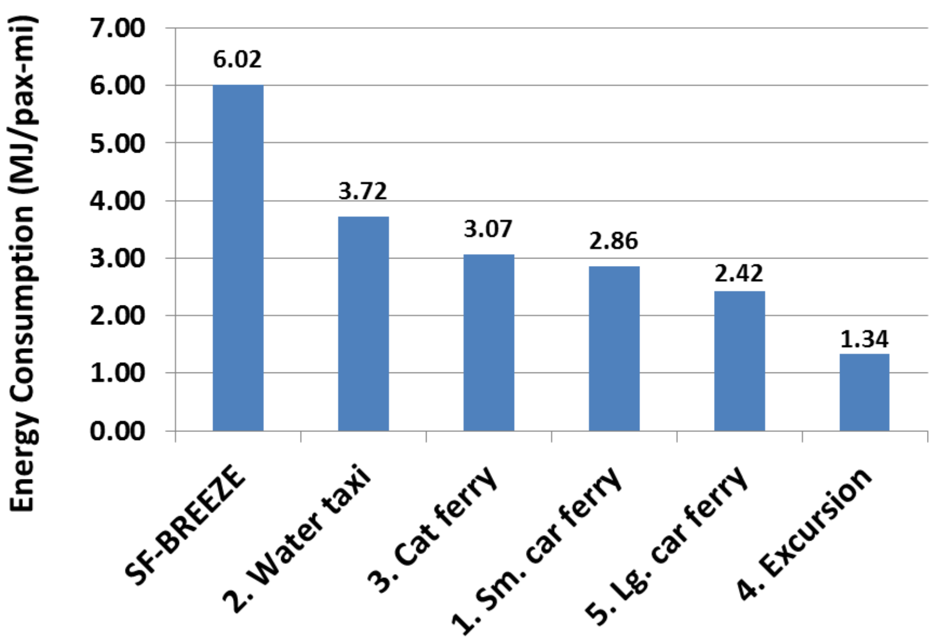


Figure 12: Per passenger-mile energy use of the five vessels in this study and the SF-BREEZE.

higher speed of the catamaran. Interestingly the slow water taxi has the second-highest per passenger-mile energy use of any vessel. This is primarily due to the low passenger count and that the design constraints result in an energy-inefficient hull and propeller design. The SF-BREEZE, with a high speed (35 kts) but relatively few passengers (150) has the highest per passenger-mile energy consumption.

While high speed vessels generally fare worse than low speed ones in terms of energy efficiency, this is not to say that high speed vessels should be avoided. High speed can be very useful and worth the efficiency penalty. In many areas high speed vessels are the only practical means of water transportation and can outperform other modes of passenger transportation in terms of energy use, cost, and convenience.

In this study normalizing by passenger capacity is complicated by the fact that two vessels carry vehicles in addition to passengers. Normalizing for passenger-carrying capacity alone does not account for the added utility of carrying vehicles, nor the additional energy demand of the vessel needed to move this payload around. In effect, these vessels are being penalized for their larger size, weight, and power to carry the vehicles without receiving a benefit for providing that service. Therefore, to make comparisons as fair as possible, vehicle payload was converted to an equivalent passenger payload. This was done based on the design standard weights of vehicles (4,000 lb) and passengers (185 lb) and resulted in each vehicle equivalent to 21.6 passengers in terms of weight. Table 11 gives the resulting equivalent passenger count for each vessel as used in the normalized energy and emissions results that follow.

Applying the per-equivalent passenger and per-mile normalizations to the per-trip energy use shown in Table 12 gives the new energy consumption of each vessel in terms of MJ/pax-mi. The results are shown in Figure 13. This time both vehicle ferries become the two most energy efficient options when accounting for their vehicle carrying utility.

All normalized results which follow use the vehicle equivalent passenger method as a way to account for the added utility of the vehicle ferries.

Table 12: List of passenger and standard vehicle carrying capacities of the five vessels and the SF-BREEZE, and resulting equivalent passengers as used in the normalization of energy and emissions results.

Vessel	Passengers	Std. Vehicles	Equivalent Passengers
1	100	22	576
2	60	-	60
3	350	-	350
4	400	-	400
5	800	64	2,184
SF-BREEZE	150	-	150

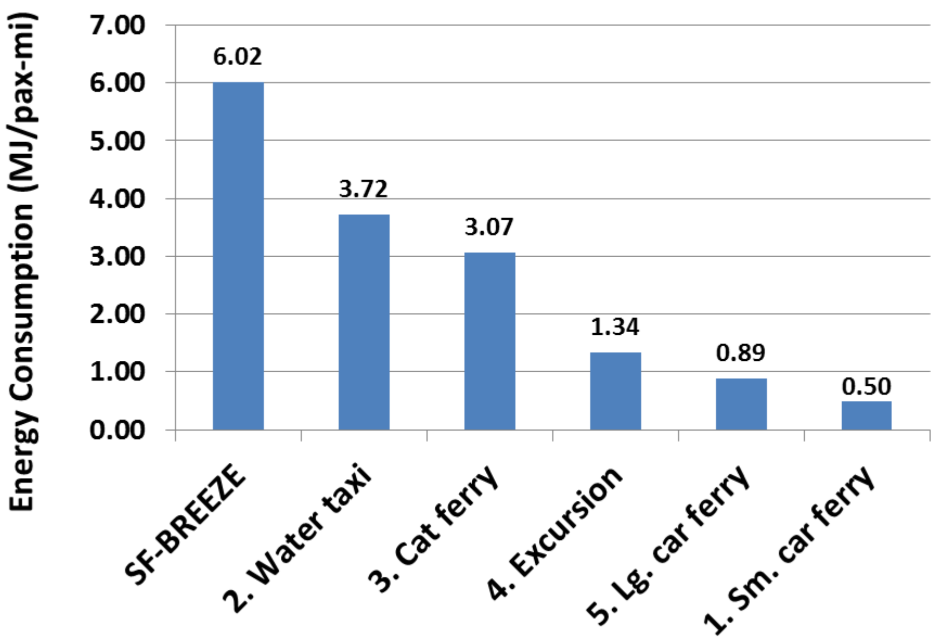


Figure 13: The per passenger-mile energy use results from Figure 12 re-calculated accounting for vehicle-carrying capacity of both vehicle ferries using a conversion factor of 21.6 passengers per vehicle, based on weight.

3.4. Well-to-Waves Emissions

The energy use results shown in Figure 13 were combined with the GHG and weighted criteria pollutant emission factors from Figure 2 and Figure 4, respectively, to produce normalized well-to-waves emission profiles for each vessel. The GHG results are shown in Figure 14. The vessel-by-vessel trend follows the energy use trend shown in Figure 13 as expected. Within each vessel type, the GHG emission trend of each form of hydrogen supply follows that shown in Figure 2 also as expected. Thus the total well-to-waves GHG emissions depend on both the GHG emissions from making the hydrogen as well as the energy efficiency of the vessel.

The chart also shows that whether or not the hydrogen is produced renewably has a larger effect on overall GHG emissions than vessel type and energy use. For example, the 24 knot catamaran ferry (vessel #3) with renewably-produced hydrogen can achieve similar GHG emissions as the small car ferry (vessel #1) with fossil-fuel produced hydrogen. While the combination of low energy use and renewably-produced hydrogen is ideal, this illustrates one way for high-energy consumption vessels to obtain low well-to-waves GHG emissions.

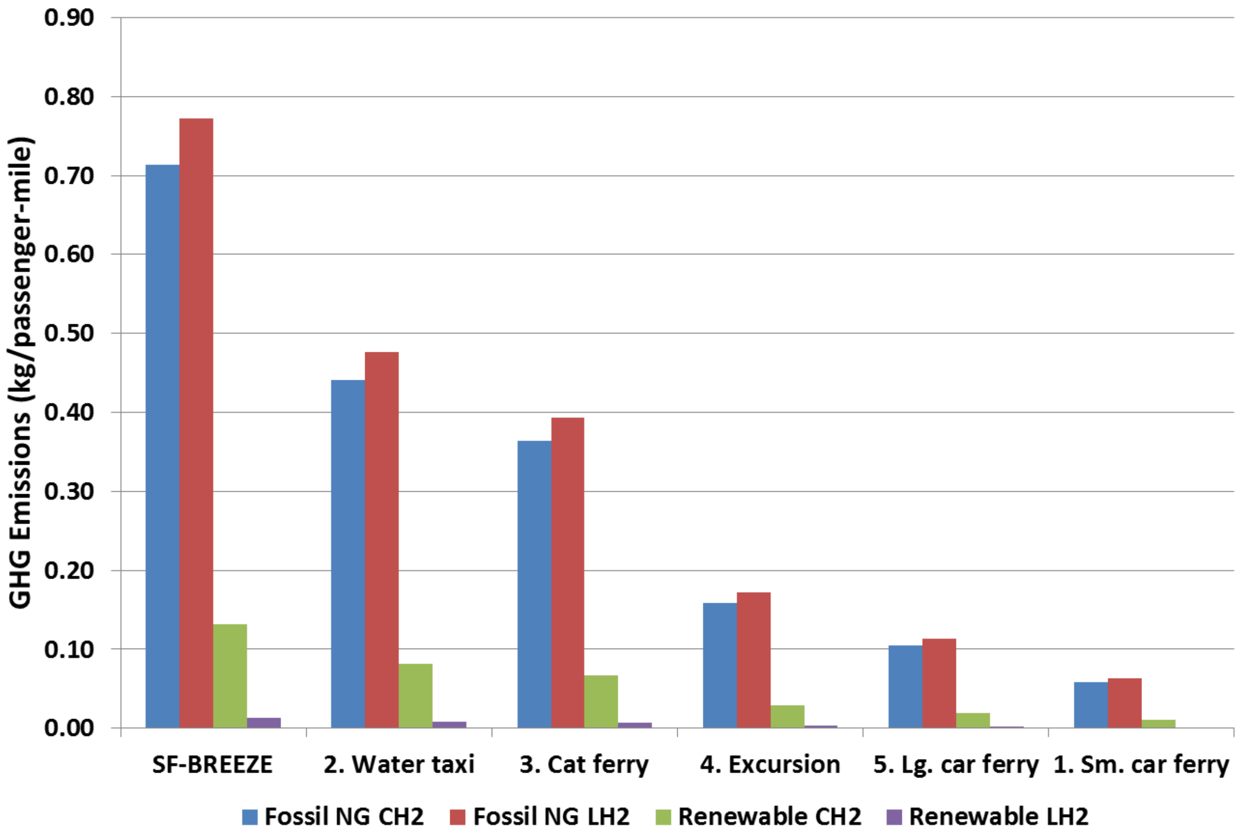


Figure 14: Normalized well-to-waves GHG emissions for the five vessels and four fuel options studied, and including the SF-BREEZE for comparison.

Figure 15 presents the normalized well-to-waves weighted criteria pollutant emissions (WCPE) for each vessel. As above, the trends follow the energy use and fuel WCPE factors from Figure 13 and Figure 4, respectively, showing that criteria pollutant emissions also depend on pollutants from making the hydrogen and the energy efficiency of the vessel. And similar to the GHG emissions, the chart illustrates how well-to-waves criteria pollutant emissions for less energy-efficient vessels can also be mitigated by using renewably-produced hydrogen.

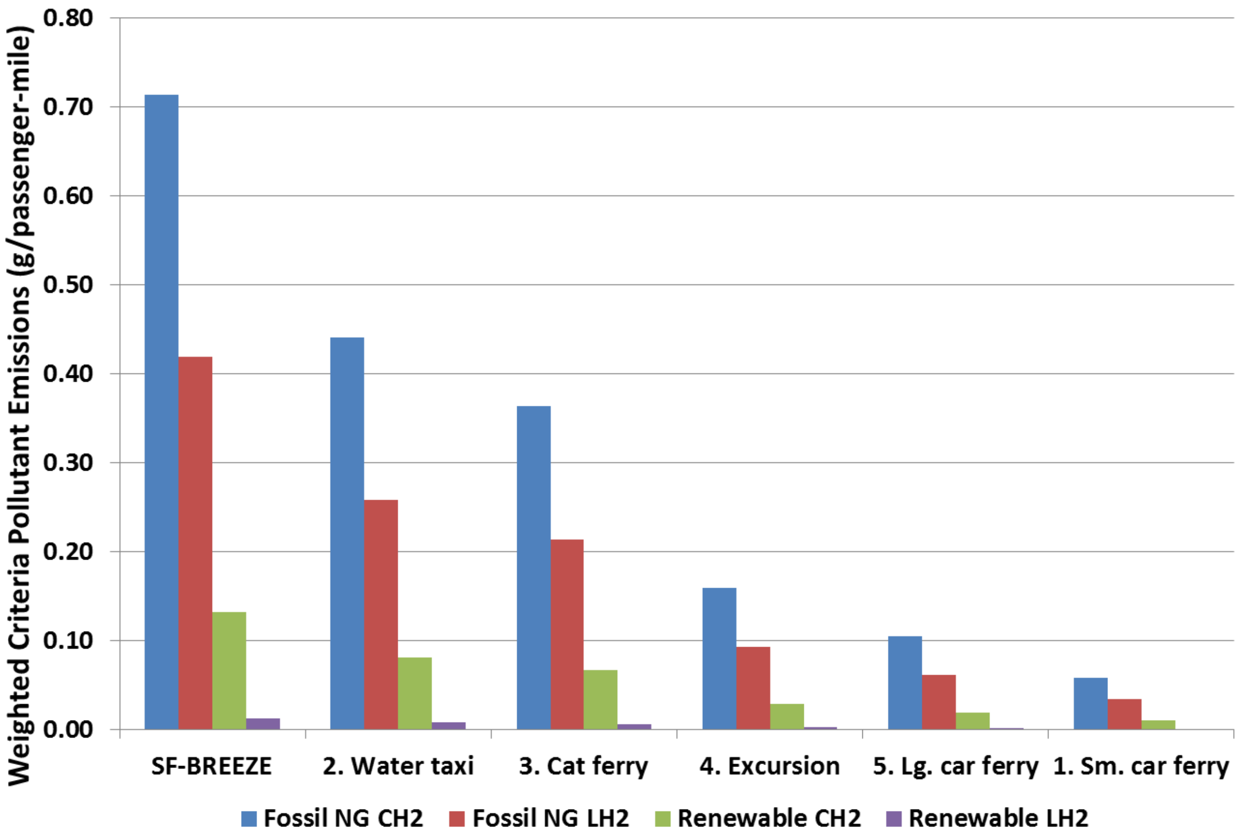


Figure 15: Normalized well-to-waves weighted criteria pollutant emissions for the five vessels and four fuel options studied, and including the SF-BREEZE for comparison.

3.5. Costs

Capital cost was estimated by Elliott Bay and the details of the estimates and assumptions are described in the appendices of Appendix B. Figure 16 and Figure 17 show the total estimated capital cost (with 10% contingency) and the capital cost per equivalent passenger (using the equivalent of 21.6 passengers per vehicle as discussed above), respectively, with the SF-BREEZE costs included for reference[3]. The figures distinguish between the capital cost of the hydrogen fuel cell powertrain system, and the rest of the vessel including non-powertrain balance of plant systems. The vessel with the lowest capital cost per passenger is the small car ferry, followed by the large car ferry and the excursion vessel. The high-speed SF-BREEZE and catamaran ferry are the highest capital cost per passenger. The water taxi has the lowest absolute cost but the third highest capital cost per passenger.

Figure 17 shows that the vessels with the lowest capital cost per passenger are the ones where the hydrogen fuel system cost is a smaller percentage of the total. However, the value of "all other costs (the red bars) is also shown to directly affect overall capital cost per passenger. This shows how high passenger counts can also help reduce capital cost per passenger.

[3] The capital costs shown here for the SF-BREEZE differ from those in the SF-BREEZE report because of adjustments made to provide an equal comparison. The labor rate was adjusted from $80/hr to $73/hr and the fuel cell cost was reduced from $2,500/kW to $2,200/kW.

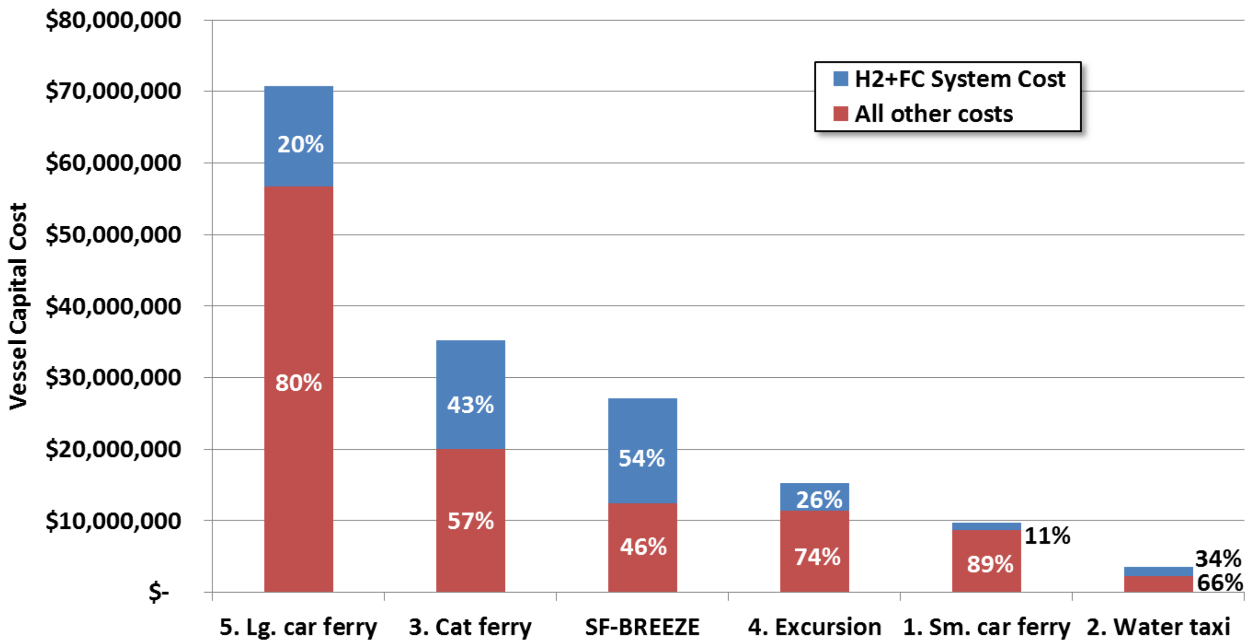


Figure 16: Capital costs of the five vessels studied and the SF-BREEZE. Percentages represent the contribution to cost from the different components: hydrogen fuel cell ("H2+FC") system costs and all other costs.

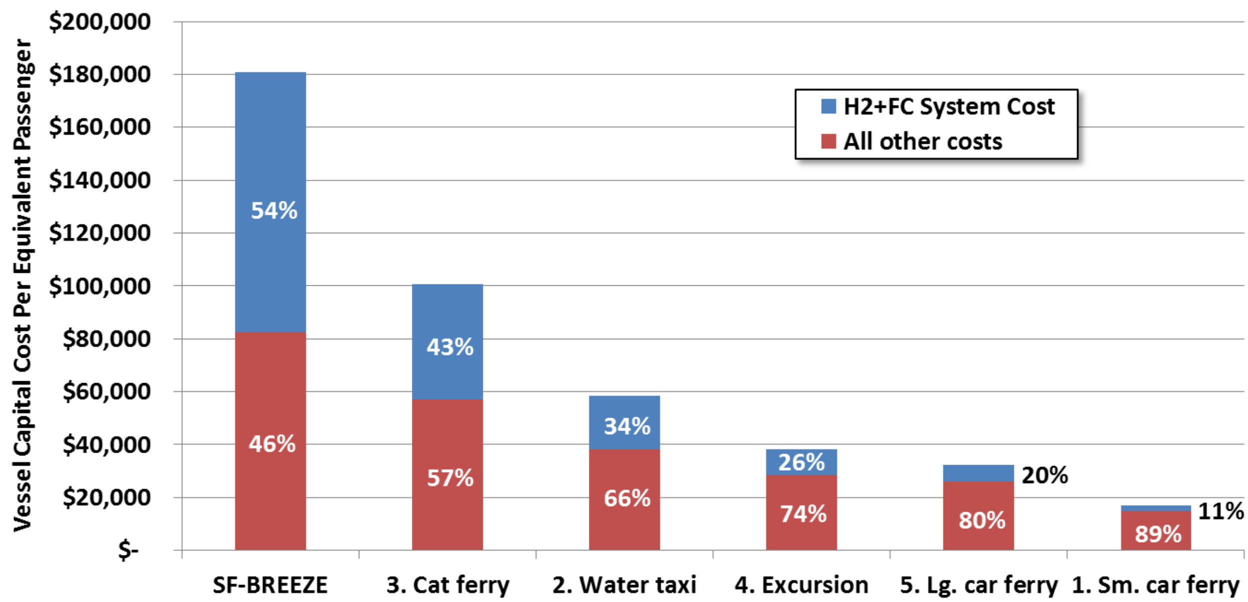


Figure 17: Per-passenger capital costs of the five vessels studied and the SF-BREEZE. Percentages represent the contribution to cost from the different components: hydrogen fuel cell ("H2+FC") system costs and all other costs.

Maintenance costs of the hydrogen fuel cell portion of the powertrain and hydrogen fuel costs for each vessel were estimated based on the methods and assumptions described in Section 2.4. Table 9 in that section showed that hydrogen fuel costs per kilogram vary depending on volume. Table 13 presents the daily consumption for each vessel and the corresponding fuel costs used in the fuel and maintenance costs that follow. As mentioned in Section 2.4.1, the fuel costs here do not include potential LCFS credits which could reduce the cost of natural gas hydrogen by about 10%, and 100% renewable hydrogen by up to 20%.

Table 13: Daily hydrogen consumption, hydrogen volume category, and hydrogen costs for each of the vessels in the study (categories and costs from Table 9).

Vessel	Daily Amount (kg)	Category	Fossil NG Comp. Gas	Fossil NG LH_2	Renew. Comp. Gas	Renew. LH_2
1. Sm. car ferry	84	Low	\$8.85	\$9.74	\$15.59	\$17.14
2. Water taxi	88	Low	\$8.85	\$9.74	\$15.59	\$17.14
3. Cat ferry	1,546	High	\$5.36	\$5.90	\$9.45	\$10.39
4. Excursion	309	Medium	\$5.90	\$6.49	\$10.39	\$11.43
5. Lg. car ferry	800	High	\$5.36	\$5.90	\$9.45	\$10.39
SF-BREEZE	1,772	High	\$5.36	\$5.90	\$9.45	\$10.39

Figure 18 and Figure 19 present the yearly and per passenger-mile powertrain maintenance and fuel costs, respectively, for the five vessels in this study and the SF-BREEZE. It makes sense that the yearly costs directly correlate to the higher powers. The larger powerplants have more maintenance and consume more fuel. The lower fuel cost due to high volume consumption is not sufficient to overcome this trend.

The per passenger-mile costs of each vessel follow the expected trend with the high-capacity vehicle ferries at the lowest cost. It is surprising that the per passenger mile cost of the water taxi is nearly as high as the SF-BREEZE. This is due to a relatively high fuel cost because of an inefficient hull design combined with low daily fuel volume, compounded by a small passenger capacity.

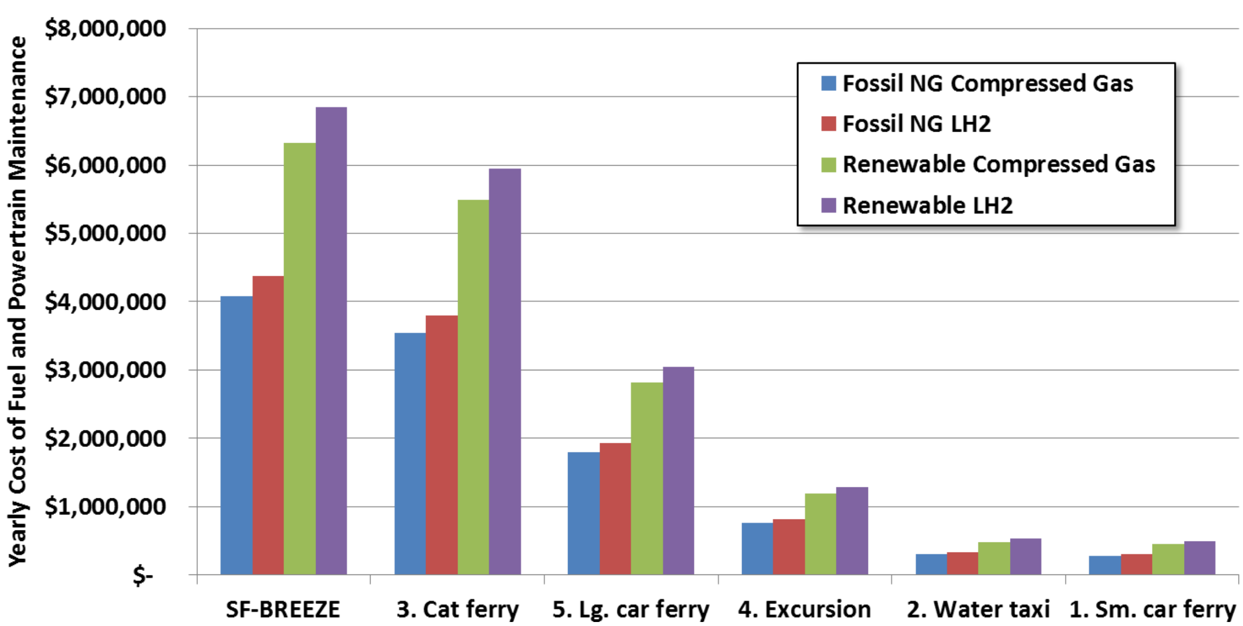


Figure 18: Yearly cost of fuel and powertrain maintenance.

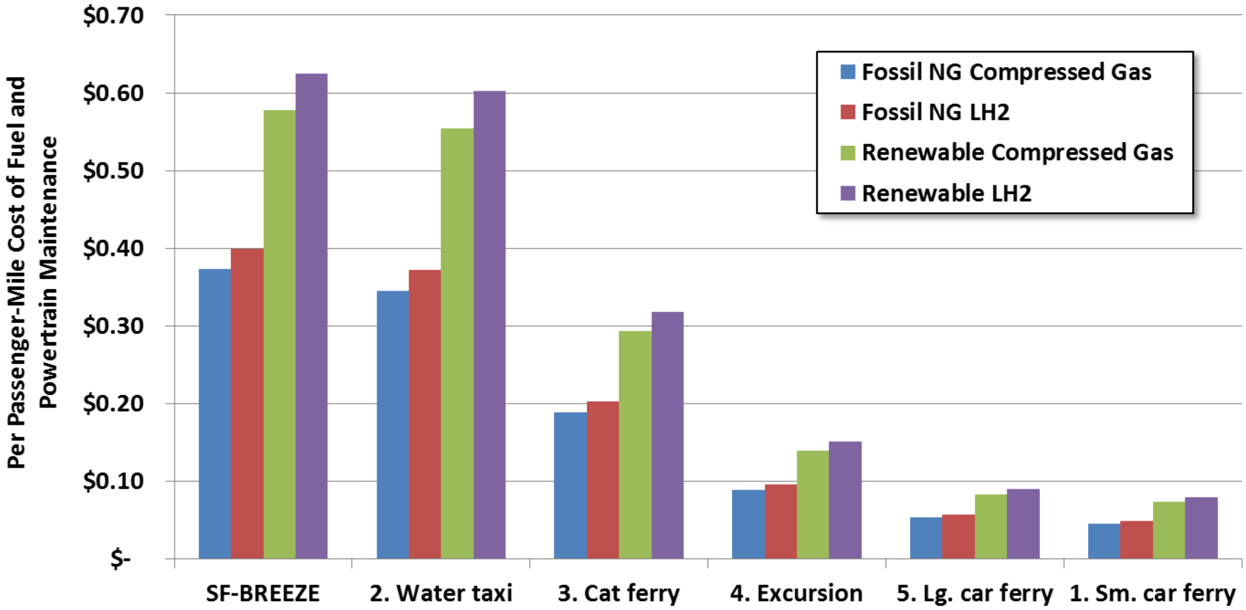


Figure 19:Yearly fuel and powertrain maintenance cost, per passenger mile.

Overall the capital and operating cost results closely follow the energy consumption results shown in Figure 12. This is expected because of the relatively high costs of the fuel cell powertrain and hydrogen fuel. The most cost-effective vessels are the two vehicle ferries, followed by the excursion vessel, the 350 passenger catamaran, the water taxi, and then the SF-BREEZE. However, a recommendation on the most profitable vessel(s) cannot be made unless passenger revenue is also considered: ticket fares may be able to be higher for the more expensive vessels reflecting their utility (high speed) which can work to offset the higher operating costs.

4. CONCLUSIONS AND RECOMMENDATIONS

Through examination of five passenger vessels, this study presents feasible options for commercially-relevant passenger vessels that can be powered solely by today's hydrogen fuel cell technology, with less emissions and lower cost than the SF-BREEZE. Besides information about the vessels themselves, the study provided insight into well-to-wave emission characteristics for various hydrogen sources and presented new insight into the projected cost of hydrogen in a marine application as well as hydrogen fuel cell powertrain maintenance costs.

Greenhouse gas and criteria pollutant calculations show how use of renewable hydrogen can drastically reduce total "well-to-waves" emissions when compared to using hydrogen made from natural gas. The calculations also revealed the significance of emissions from trucking the hydrogen from the production facility to the fueling dock, and how these are much higher for trucking gaseous hydrogen than for liquid hydrogen due to the lower amount of hydrogen carried by each gaseous transport truck. When the final usage on the vessel is gaseous hydrogen, possible mitigations for these trucking emissions could be on-site liquid storage with vaporization, or the installation of on-site hydrogen production via electrolysis or steam methane reforming. On-site production of liquid could also be considered but requires much more investment and has less of a benefit since LH_2 trucking is already quite efficient. Any of these methods will likely increase the overall fuel cost because of the additional investment of an on-site facility.

Per-kilogram hydrogen fuel costs were estimated for three daily volume scenarios based on available literature including the SF-BREEZE report. Both liquid hydrogen and 350 bar gaseous hydrogen delivery and storage scenarios were included, as well as both hydrogen obtained from natural gas and that obtained from 100% renewable energy. Low daily volume (< 200 kg/day) was shown to increase hydrogen cost by about 65% compared to high daily volume (> 600 kg/day). Renewable hydrogen is less known but is estimated to cost approximately 1.75-times the cost of natural gas-derived hydrogen. In California the Low Carbon Fuel Standard (LCFS) credits may reduce the cost premium of 100% renewable hydrogen closer to that of natural gas-derived hydrogen but there is still expected to be a cost premium in the near-term until renewable hydrogen supplies increase. In any case, liquid hydrogen is expected to cost about 10% more than gaseous hydrogen.

Yearly powertrain maintenance costs were estimated at $230 per kW of installed fuel cell power. This is comparable to diesel generator maintenance cost estimated in a separate study, showing that even at today's fuel cell prices, fuel cell system maintenance is expected to be on-par with conventional systems. With expected future decreases in fuel cells costs, the powertrain maintenance costs are expected to fall below that of an equivalent diesel engine based system.

Five new vessel designs were found which can be powered solely by hydrogen fuel cell power. The vessels included a 60 passenger, 60' water taxi, a 100 passenger + 22 vehicle, 120' double-ended car ferry; a 400 passenger, 135' excursion/tour boat; a 350 passenger, 140' high speed catamaran; and a 800 passenger + 64 vehicle, 274' double-ended car ferry. The vessels represent a large portion of the US passenger vessel fleet and show that hydrogen fuel cell technology can be practically considered for a wide variety of passenger vessels.

The energy use per passenger mile use of each vessel was estimated and was shown to correlate directly to per passenger mile emissions and operating costs. This trend was not affected by installed power and shows that it is the efficiency of the vessel in transporting people/cargo that is most important, not the size or power of the vessel. An example of this is the fact that the inefficient hull design of the 60 passenger, 6 knot, 270 kW water taxi led to higher per passenger mile operating costs and emissions than the 350 passenger, 24 knot, 4,200 kW catamaran ferry.

The best vessels in terms of per passenger mile emissions and operating costs were the two vehicle ferries followed by the 400 passenger tour/excursion vessel. All of these are relatively low speed and power which cuts down on energy use, but can hold a significant number of passengers (and vehicles). Compared to the SF-BREEZE, the 100 passenger/22 vehicle ferry (the best performing vessel) reduced emissions by 91% and reduced fuel and powertrain maintenance costs by 87%.

The fact that the 350 passenger high-speed ferry was the 4th best vessel in these categories reflects its high energy use. This is not to say that high speed vessels should be avoided; the high speed serves a useful function and may be the only viable kind of vessel in some markets. Comparison of the 350 passenger 24 knot catamaran ferry to the 150 passenger 35 knot SF-BREEZE illustrates how increasing the passenger count while decreasing the speed can dramatically cut per passenger-mile energy, operating costs, and emissions, by nearly 50%.

Overall this work built on the SF-BREEZE feasibility study to find other passenger vessels with more favorable cost and emissions profiles than the SF-BREEZE. All vessel types were shown to be feasible with today's hydrogen fuel cell technology and present more options to fleets that are committed to reducing maritime emissions in cost effective ways.

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APPENDIX A: MAPPING STUDY RESULTS

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MEMORANDUM

Vessel:	SF-BREEZE Optimization Study
Engineer:	Kurt Jankowski
Reference:	16128-070-0-
Date:	02/17/2017
Subject:	Mapping Study Results

PURPOSE

This memo summarizes the results of the SF-BREEZE optimization study mapping phase. The goal of the mapping phase is to evaluate the most relevant vessel parameters in order to short list five ferry types for evaluation in the following optimization phase. This memo provides an overview of ferry vessel statistics and provides justification for the five proposed vessel types.

FERRY STATISTICS

Data from the Bureau of Transportation Statistic Nation Census of Ferry Operators (NCFO) was used to evaluate the nationwide ferry fleet [1]. The database was last updated in 2014 and contains 499 vessels. Some information regarding passenger or vehicle capacities is missing from the database. For completeness, in many of these instances the capacities were added based on Elliott Bay Design Group's knowledge of the ferry vessels.

The database was first divided into three groups based on the 46 Code of Federal Regulations subchapter designation:

- Subchapter T: Vessels of less than 100 GT with fewer than 150 passengers
- Subchapter K: Vessels of less than 100 GT with greater than 150 passengers
- Subchapter H: Vessels of 100 GT or more

Note that Subchapter K vessels with overnight accommodations for fewer than 150 passengers were indistinguishable from Subchapter T vessels given the information provided in the database. Such vessels are included in Subchapter T below.

Figure 1 shows the breakdown of the total ferry fleet by subchapter. Subchapter T is the largest with 236 vessels or 47% of all ferries in the database. Subchapter K makes up 27% of the database with 135 vessels. Subchapter H is slightly smaller with 128 vessels for 26% of the database.

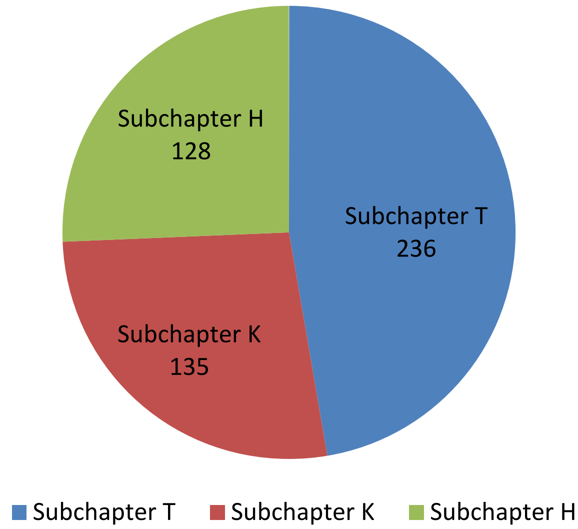

Figure 1: The total vessel database breakdown by subchapter

Subchapter T

The Subchapter T vessels were broken down further by service type and hull material as shown in the distributions below. Passenger only service is provided by 60% of the vessels, while 39% provide both vehicle and passenger service. Nearly half of all Subchapter T vessels are constructed in steel with an additional 33% in aluminum.

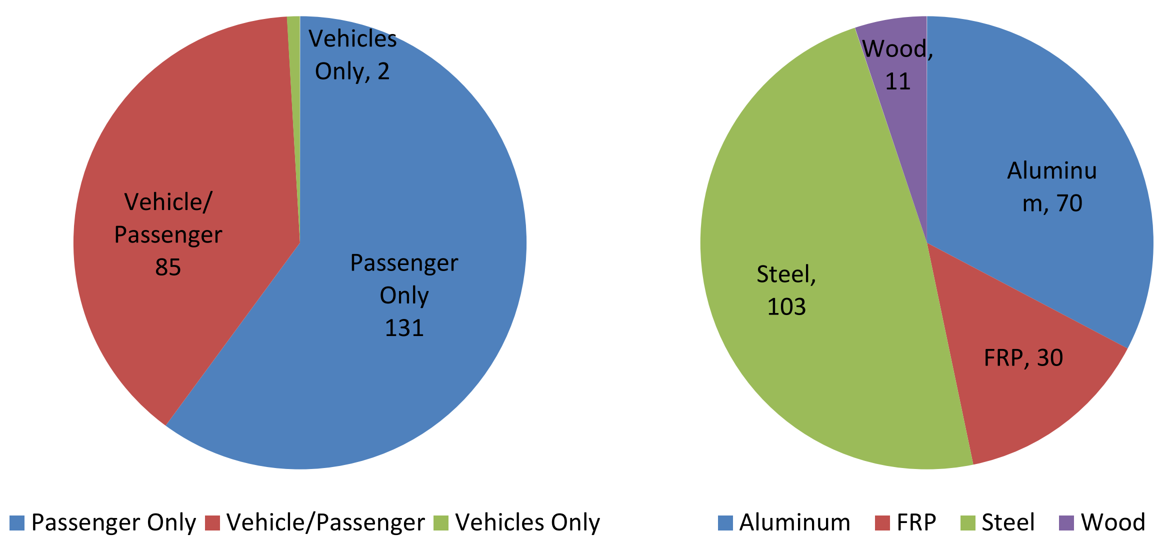

Figure 2: The distributions of service type and hull material of Subchapter T vessels

The distribution of typical speed is plotted in Figure 3. Some 53% of vessels operate at speeds of 10 knots or less, while only 20% of vessels operate at speeds greater than 20 knots.

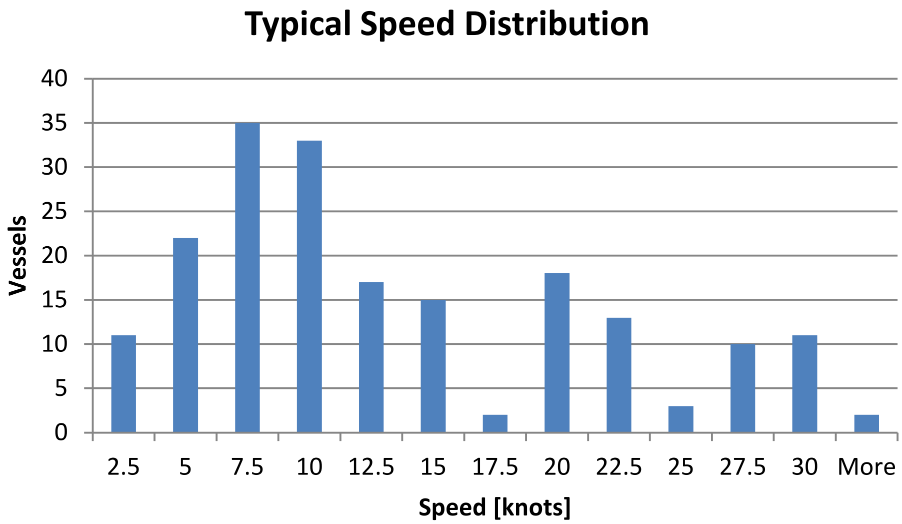

Figure 3: The distribution of typical operating speed for Subchapter T vessels

Subchapter K

The distributions of service type and hull material for Subchapter K vessels are shown in Figure 4. Passenger only service is provided by 81% of the vessels with nearly all other vessels providing both vehicle and passenger service. Aluminum hulls make up 61% of the Subchapter K fleet with most other vessels being made of steel.

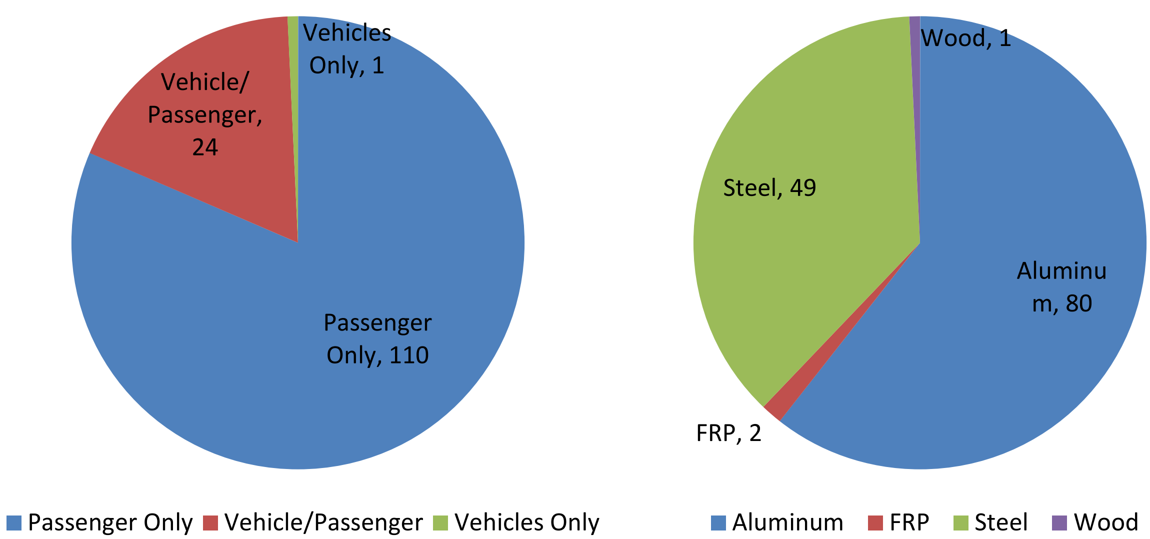

Figure 4: The distributions of service type and hull material of Subchapter K vessels

The distribution of typical speed is plotted in Figure 5. There is a wide range of speeds within the Subchapter K fleet with 40% of vessels operating at speed greater than 20 knots.

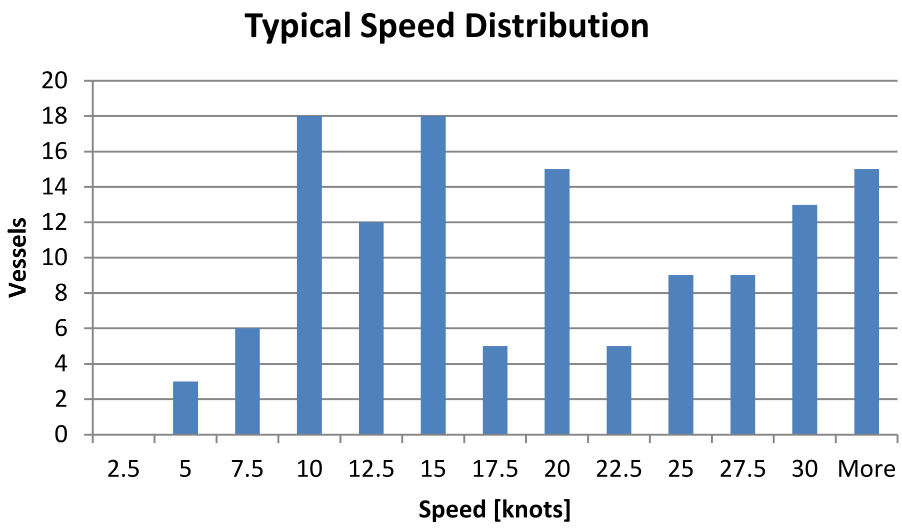

Figure 5: The distribution of typical operating speed for Subchapter K vessels

Subchapter H

A vast majority of Subchapter H vessels offer vehicle and passenger service and nearly all are constructed of steel as shown in the distributions in Figure 6. Only 9% of Subchapter H vessels offer passenger only service.

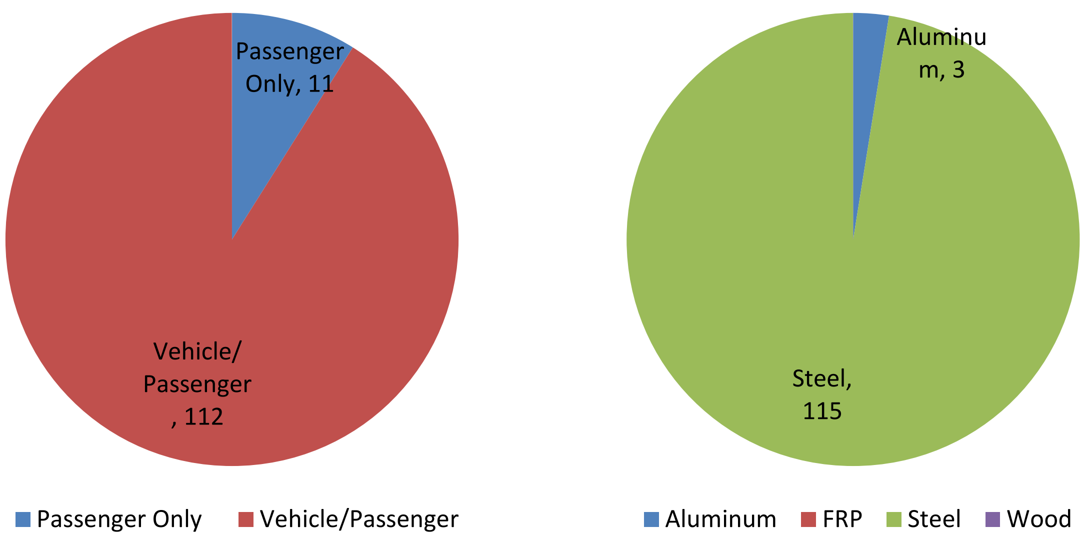

Figure 6: The distributions of service type and hull material of Subchapter H vessels

The typical speed distribution is plotted in Figure 7. It is clear that high speed Subchapter H vessels are very uncommon with 97% of all vessels operating at speeds of 20 knots or less.

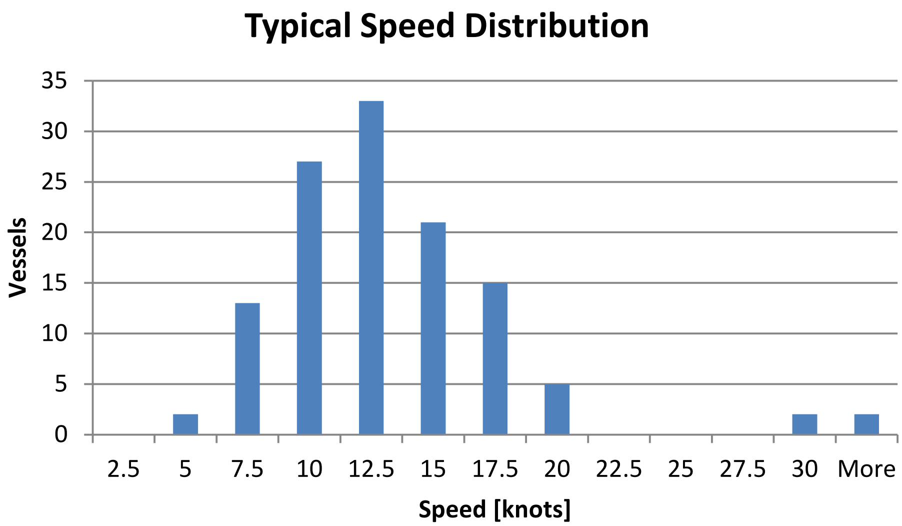

Figure 7: The distribution of typical operating speed for Subchapter H vessels

VESSEL DESCRIPTIONS

Based on the overall makeup of the nationwide ferry fleet, five vessel types are proposed for study during the optimization phase. These are outlined below with the configurations compared to the national ferry fleet trends. Note that "high speed" is considered greater than 20 knots for comparison purposes.

Vessel #1 - A Subchapter T vehicle/passenger ferry constructed of steel and operating at low speeds

The original SF-BREEZE Feasibility Study examined a high speed aluminum passenger ferry. This vessel is intended to capture the other prominent characteristics of the Subchapter T fleet.

Characteristic	Service Type	Hull Material	Speed
Configuration	Vehicle/Passenger	Steel	Low
Common % of Fleet	39%	48%	69%

Vessel #2 - A Subchapter T passenger ferry constructed of steel and operating at low speeds

This vessel description is intended to capture the "water taxi" type of small passenger vessel. The Subchapter T fleet was filtered to include only vessels up to 60 ft. in length providing passenger only service. There were 68 such vessels, indicating that this vessel description accounts for approximately 30% of the total Subchapter T fleet.

Characteristic	Service Type	Hull Material	Speed
Configuration	Passenger	Steel	Low
Common % of Fleet	60%	48%	69%

Vessel #3 - A Subchapter K passenger ferry constructed of aluminum and operating at high speeds

This vessel is intended to match the most common service type and hull material of a Subchapter K vessel as shown in the table below. The speed was selected from the hull material based on the plot in Figure 8. Here, the hull material is plotted against typical speed. It is clear from this plot that most aluminum vessels (hull material #1) operate in a higher speed range and that all steel vessels (hull material #8) operate at low speeds.

Characteristic	Service Type	Hull Material	Speed
Configuration	Passenger	Aluminum	High
Common % of Fleet	81%	61%	40%

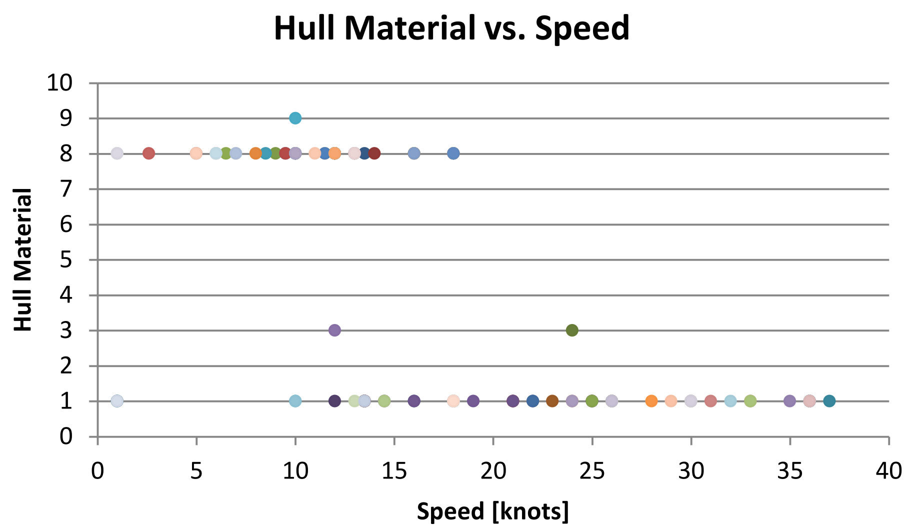

Figure 8: The hull material (1-Aluminum, 3-FRP, 8-Steel, 9-Wood) plotted with speed.

Vessel #4 - A Subchapter K passenger ferry constructed of steel and operating at low speeds

This vessel definition is intended to examine the more common low speed Subchapter K vessel. Steel was selected as the hull material as it is more common for low speed vessels as show in Figure 8. Vehicle service was not considered for this vessel as it is quite uncommon for a Subchapter K ferry.

Characteristic	Service Type	Hull Material	Speed
Configuration	Passenger	Steel	Low
Common % of Fleet	81%	37%	60%

Vessel #5 - A Subchapter H vehicle/passenger ferry constructed of steel and operating and low speeds.

This vessel type was selected to match the characteristics of more than 90% of the Subchapter H fleet.

Characteristic	Service Type	Hull Material	Speed
Configuration	Vehicle/Passenger	Steel	Low
Common % of Fleet	91%	97%	97%

VESSEL SPECIFICATIONS

After determining the five general vessel descriptions from the overall fleet characteristics, the NCFO data was analyzed in finer resolution to determine the vessel specifications. The specifications selected based on the data are:

- Passenger capacity
- Vehicle capacity
- Speed

All other vessel specifications such as vessel dimensions and power requirements will be determined in the following stages of this study.

Vessel #1

To determine the specifications of Vessel #1, the Subchapter T vessels were filtered to include only vessels which carried vehicles and had a hull constructed of steel. The vehicle capacity was considered first as it is likely to be the primary characteristic driving the vessel's design. The distribution of vehicle capacity is plotted in Figure 9. It can be seen that a majority of vessels have vehicle capacities of 30 standard vehicles (SV) or less, however there are several vessels with vehicle capacities up to 50 SV. The capacity for Vessel #1 was therefore selected to be 20 SV in order to study a vessel which was closer to the observed median capacity.

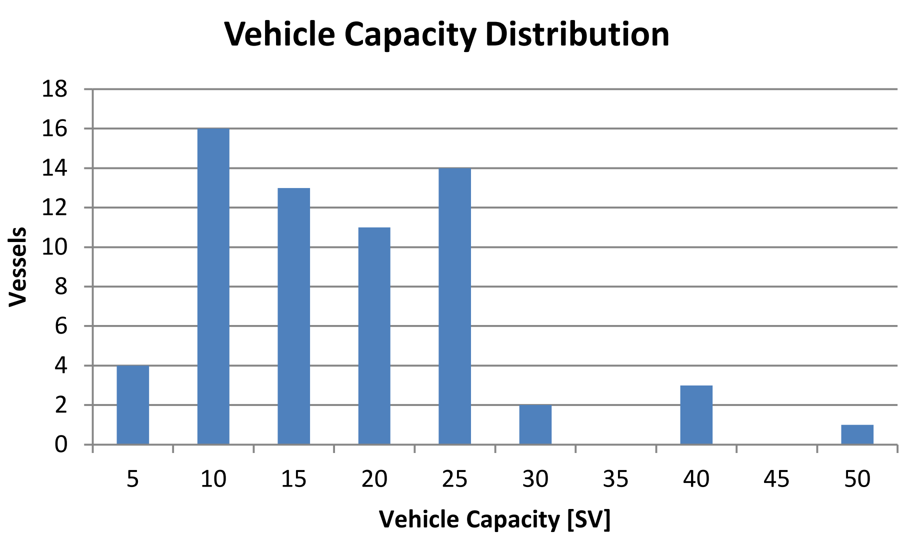

Figure 9: The distribution of vehicle capacity for the Vessel #1 subgroup

Once the vehicle capacity had been determined, the passenger capacity was analyzed. Figure 10 shows the passenger capacity plotted against the vehicle capacity. While there are some 149 passenger vessels across the full vehicle capacity range, there is a clear trend visible in the data. The passenger capacity was selected to be 100 passengers (PAX) based on this trend.

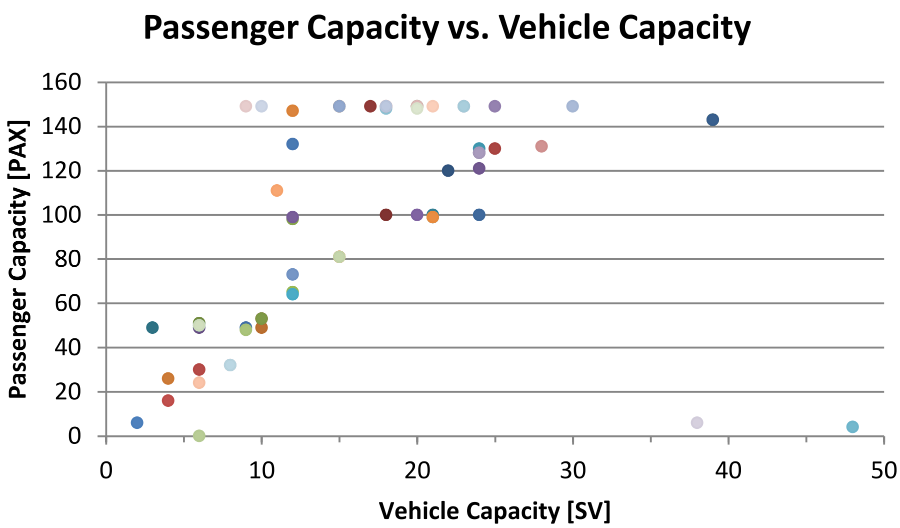

Figure 10: The correlation of passenger capacity to vehicle capacity for the Vessel #1 subgroup

Speed is plotted against vehicle capacity in Figure 11. The plot shows a cluster of vessels with approximate vehicle capacities in the range of 15 to 25 SV. A speed of 9 knots was chosen for the Vessel #1 specification in order to study a speed near the approximate center of this cluster.

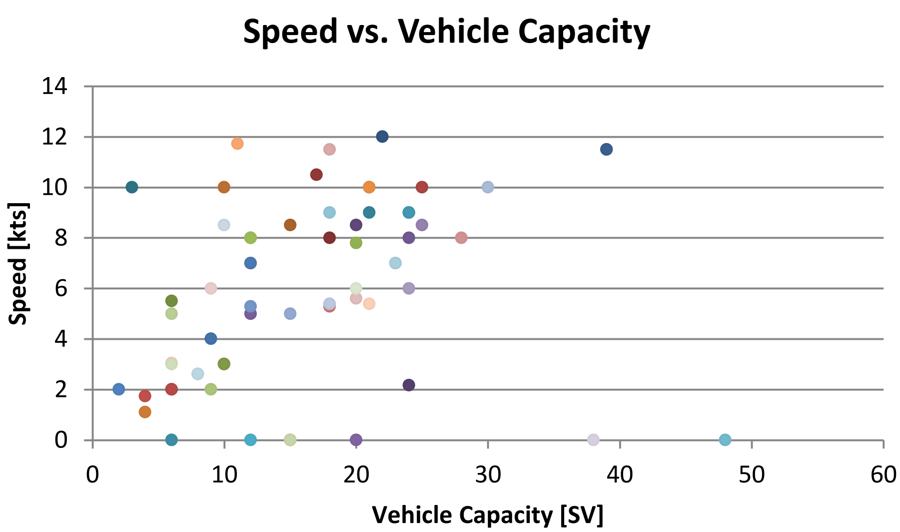

Figure 11: Speed plotted against vehicle capacity for subgroup #1

The specifications for Vessel #1 are summarized below.

Passenger Capacity	Vehicle Capacity	Speed
100 PAX	20 SV	9 kts

Vessel #2

As previously discussed, the database was filtered to include only Subchapter T vessels of 60 ft. or less in length providing passenger only service when determining the specifications of Vessel #2. Initially, the distribution of hull material was examined as shown in the pie chart in Figure 12. Steel was selected for the hull material as it accounts for nearly 50% of the vessels in this subgroup.

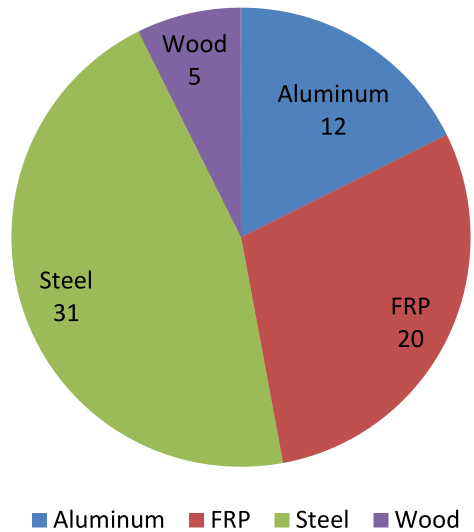

Figure 12: Hull material distribution of Vessel #2 subgroup

The passenger capacity distribution is plotted in Figure 13. The average passenger capacity of the subgroup was chosen for the specification as there are vessels spread across the full passenger capacity range of 2 to 149 passengers. The average was 58 PAX, which was rounded up to 60 PAX for simplicity. The selected passenger capacity also falls into the most populated distribution bucket, reinforcing the validity of the selection criteria.

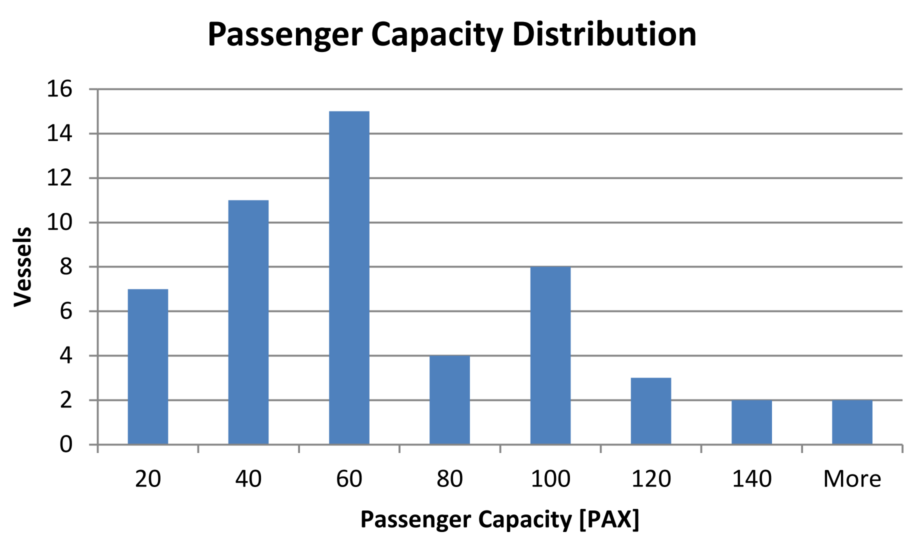

Figure 13: The distribution of passenger capacity for the Vessel #2 subgroup

The typical speed of Vessel #2 was next analyzed by looking for correlations in the data between speed and other parameters. As is clearly seen in Figure 14, the data shows no correlation between passenger count and typical operating speed. The hull material was then plotted against speed as shown in Figure 15. While there is a range of speeds for vessel constructed of aluminum and FRP, vessels with steel hulls do not have speeds exceeding 12 knots. Therefore, the speed of Vessel #2 was taken to be the average of all steel hulled vessels, or 6 knots. The associated distribution is plotted in Figure 16.

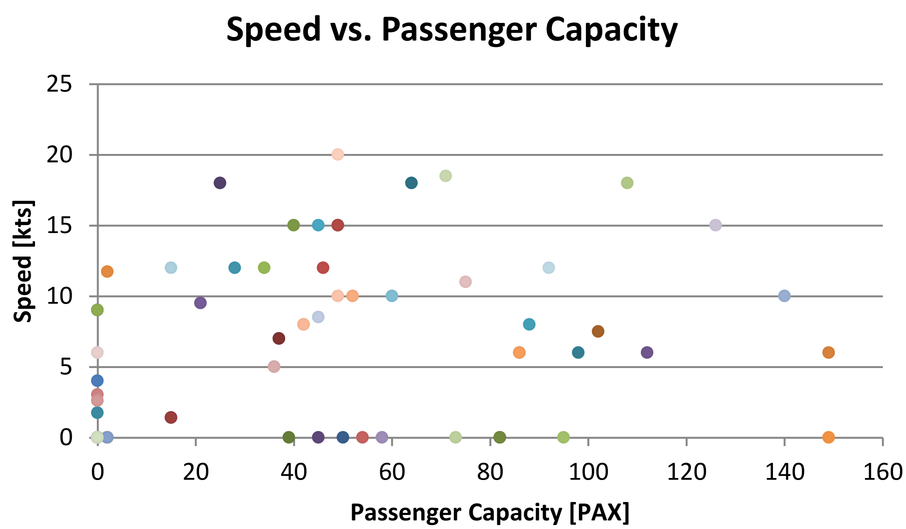

Figure 14: A plot of speed against passenger capacity indicating no correlation

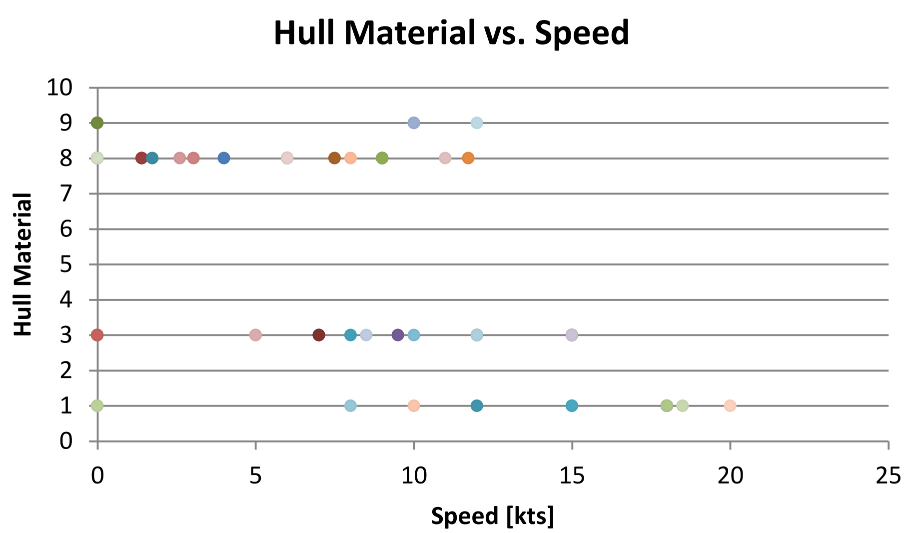

Figure 15: The hull material (1-Aluminum, 3-FRP, 8-Steel, 9-Wood) of the Vessel #2 subgroup plotted with speed

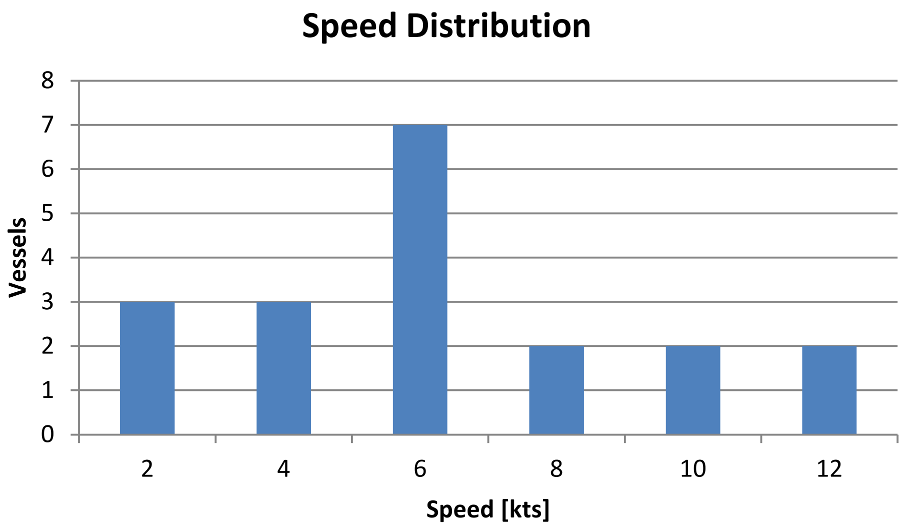

Figure 16: The Vessel #2 subgroup speed distribution

Vessel #2's specifications are summarized below.

Passenger Capacity	Vehicle Capacity	Speed
60 PAX	-	6 kts

Vessel #3

Vessel #3 specifications were determined from a list of vessels which included only Subchapter K vessels providing passenger only service and with a hull made of aluminum. The distribution of passenger capacity is plotted in Figure 17. There is a clear prominence for vessels with passenger capacities between 300 and 400 PAX. Therefore, the passenger capacity of 350 PAX was selected to be in this range and close to the calculated average of 344 PAX.

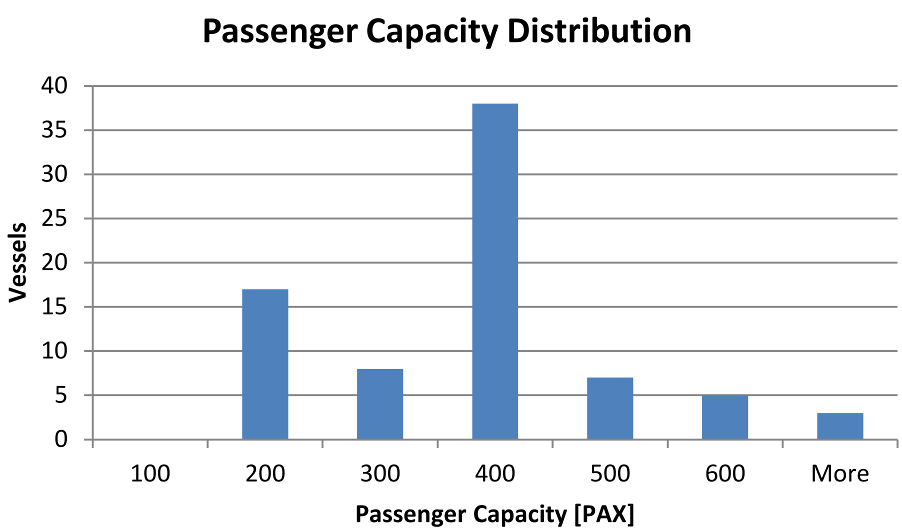

Figure 17: The passenger capacity distribution of the Vessel #3 subgroup

Similar to previous subgroups, no correlation was observed between passenger capacity and speed as shown in Figure 18. Therefore, Vessel #3's speed was selected to be the average speed of all vessels in the subgroup, 24 knots. The speed distribution is plotted in Figure 19.

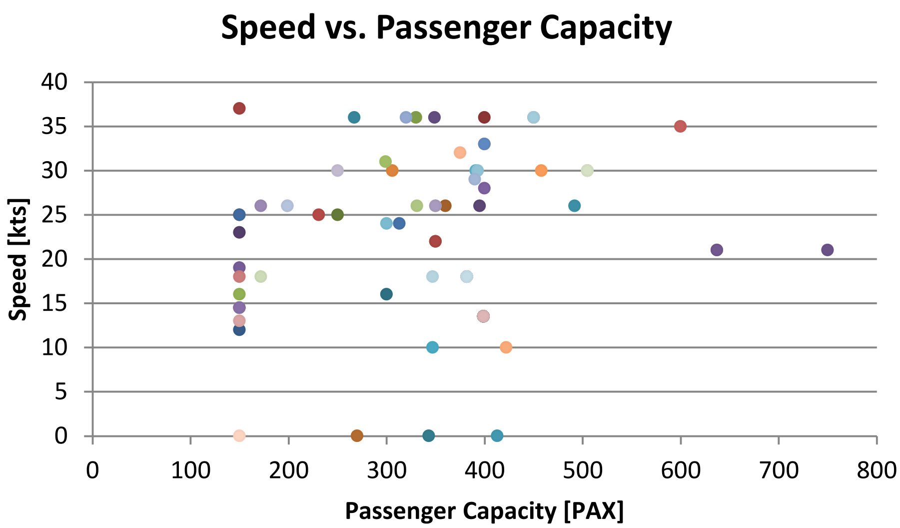

Figure 18: Speed plotted with passenger capacity for subgroup #3

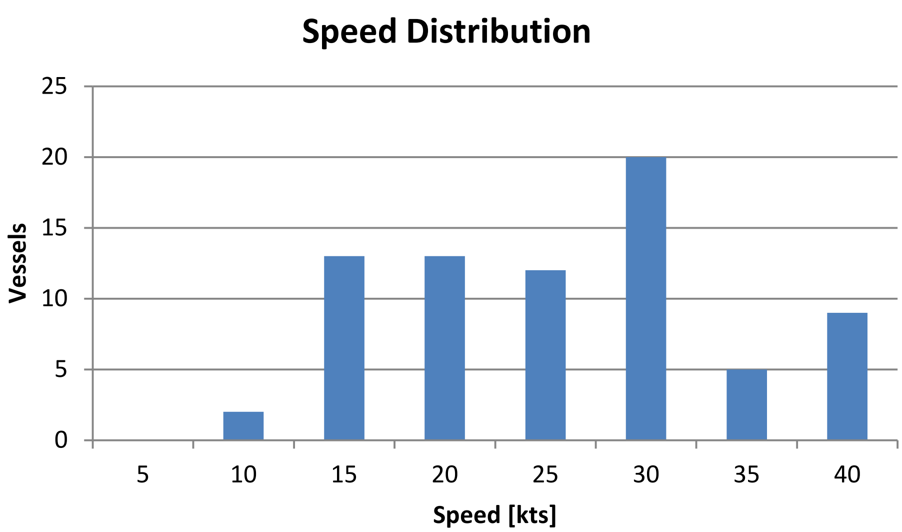

Figure 19: The speed distribution of the Vessel #3 subgroup

The specifications for Vessel #3 are summarized below.

Passenger Capacity	Vehicle Capacity	Speed
350 PAX	-	24 kts

Vessel #4

To determine the specifications of Vessel #4, the Subchapter K vessels were filtered to include only vessels made of steel and providing passenger only service. The passenger capacity distribution is plotted in Figure 20. Here, a majority of vessels have capacities in the range of 200 to 300 PAX, which is smaller than the Vessel #3 subgroup. However, the steel hulled vessels in the Vessel #4 subgroup include larger passenger capacities of more than 800 PAX. Therefore, the average capacity of 371 PAX was rounded up to 400 PAX for the Vessel #4 specification.

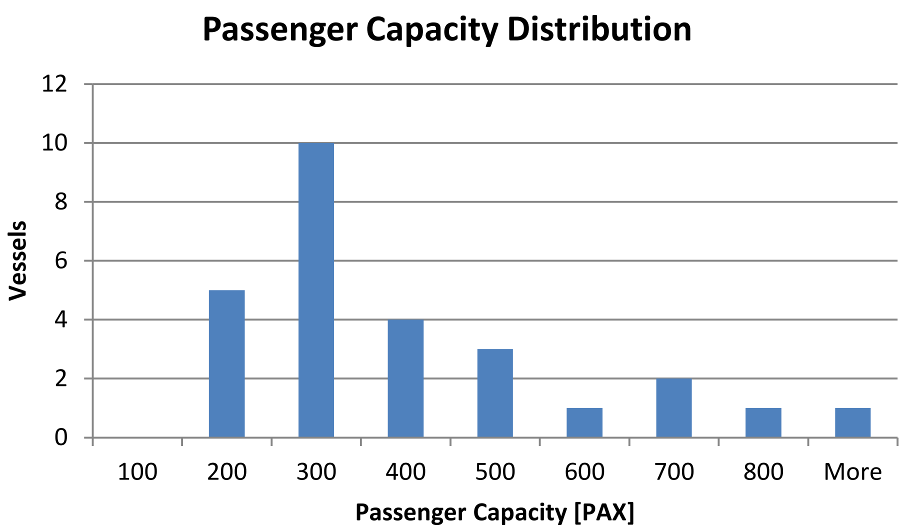

Figure 20: The Vessel #4 subgroup passenger capacity distribution

As with previous subgroups, no correlation was observed between passenger capacity and speed (see Figure 21). Therefore, the rounded up average seed of 12 knots was selected for the speed criteria. The speed distribution is plotted in Figure 22.

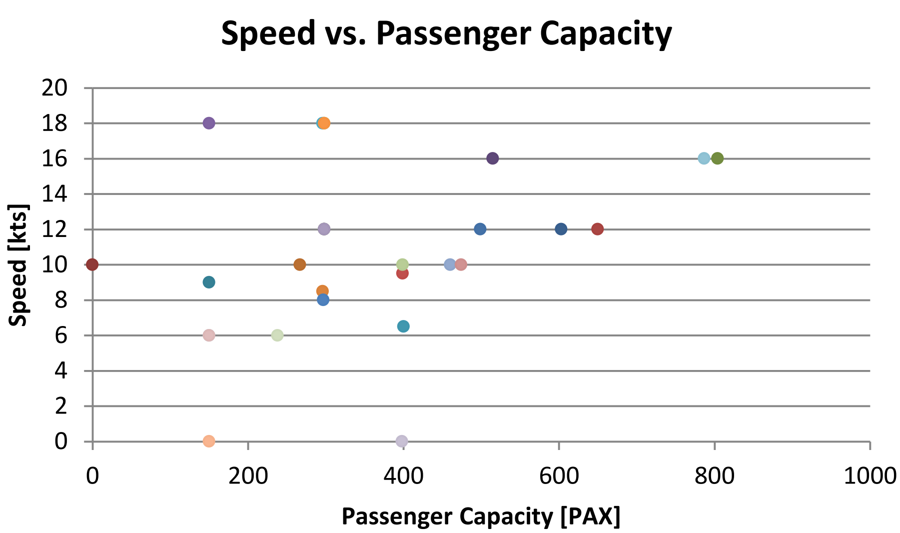

Figure 21: Speed plotted against passenger capacity for subgroup #4

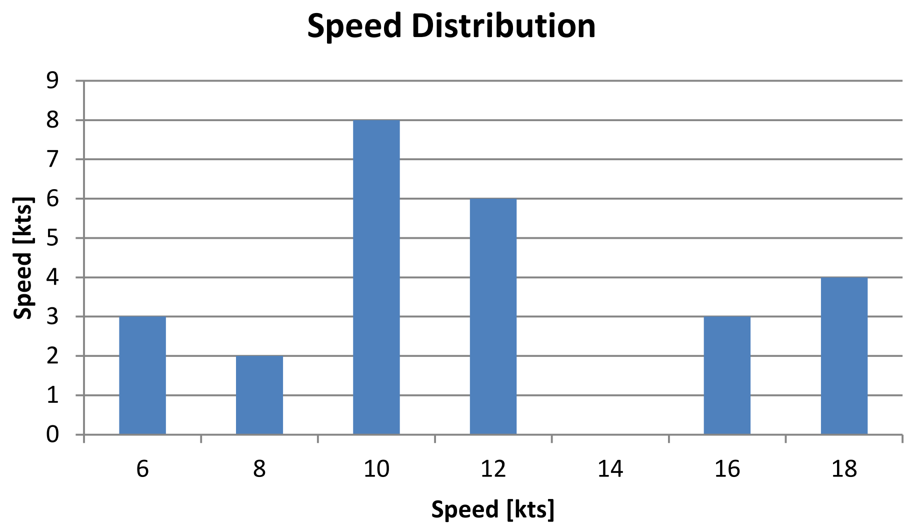

Figure 22: The speed distribution of subgroup #4

The Vessel #4 specifications are summarized below.

Passenger Capacity	Vehicle Capacity	Speed
400 PAX	-	12 kts

Vessel #5

To determine the specifications for Vessel #5, all passenger only vessels were removed from the Subchapter H dataset. The vehicle capacity was first considered by plotting the distribution shown in Figure 23. The vehicle capacity was selected to be the average capacity of 64 SV.

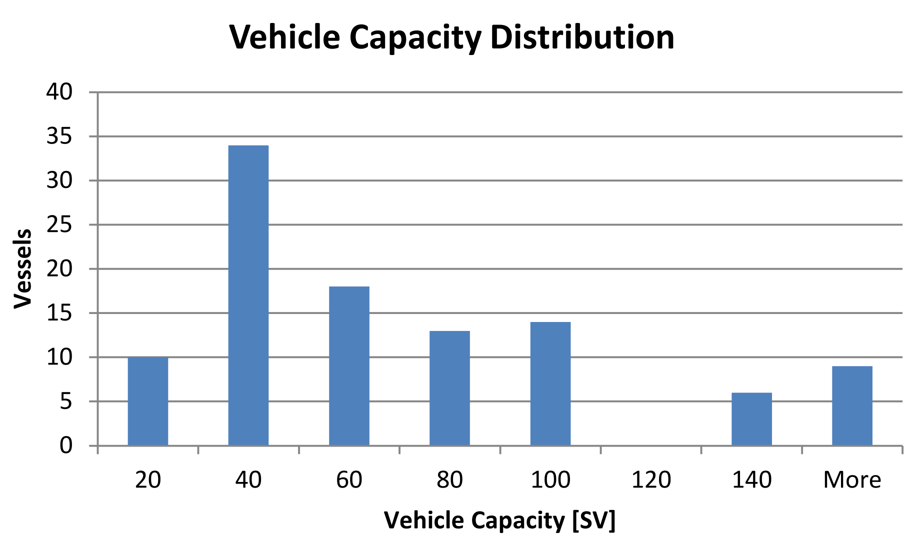

Figure 23: The Vessel #5 subgroup vehicle capacity distribution

A weak correlation between vehicle capacity and passenger capacity is evident in the data, as shown in Figure 24. Therefore, the passenger capacity was selected, like the vehicle capacity, by taking the average value of all vessels. The average value of 784 PAX was rounded up to 800 PAX for simplicity. The distribution of passenger capacity is plotted in Figure 25. A wide range of passenger capacities is observed of up to 4427 PAX.

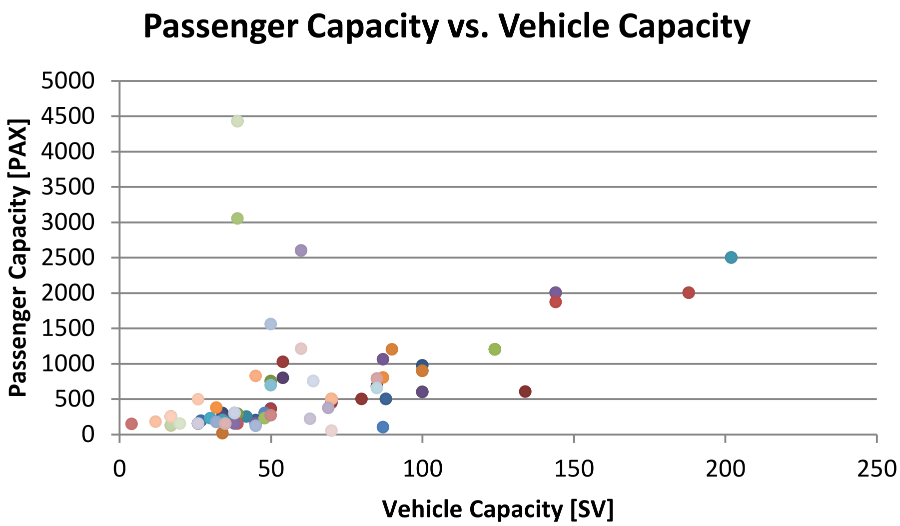

Figure 24: A plot of passenger capacity against vehicle capacity shows weak correlation

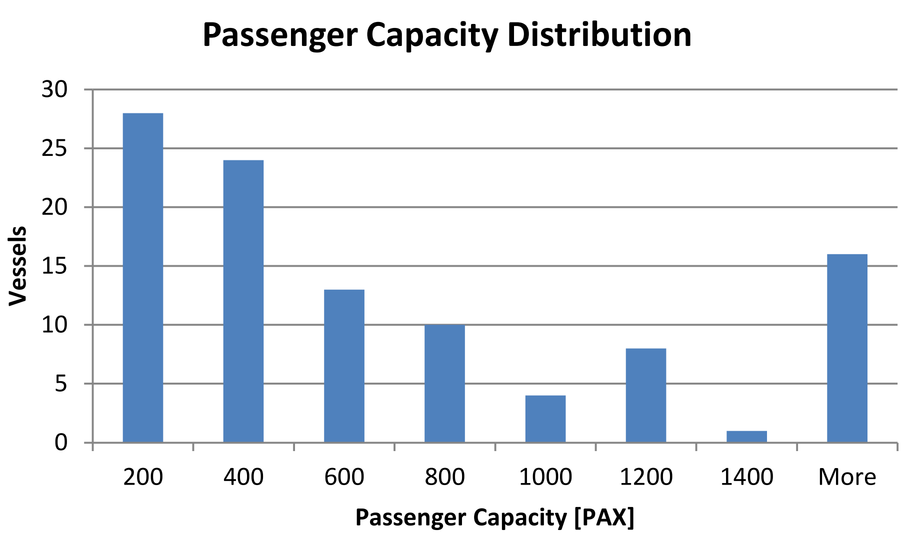

Figure 25: The distribution of passenger capacity

The correlation between vehicle capacity and speed is similarly weak as shown in Figure 26. However, there is noticeably better correlation compared to the speed and passenger capacity observed in subgroups #3 and #4. The speed distribution, plotted in Figure 27, shows a somewhat normal distribution. Therefore, the vessel speed specification was selected to be the average speed of 12 knots.

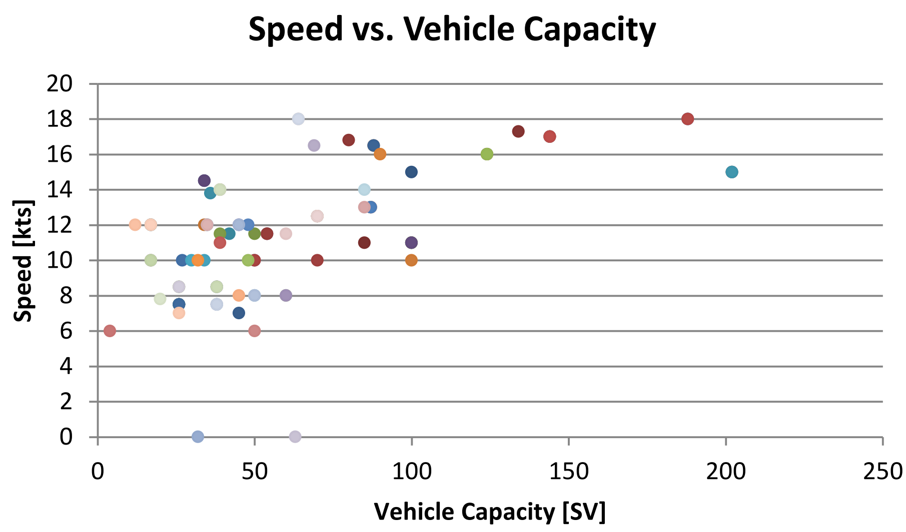

Figure 26: A plot of speed and vehicle capacity indicates a weak correlation

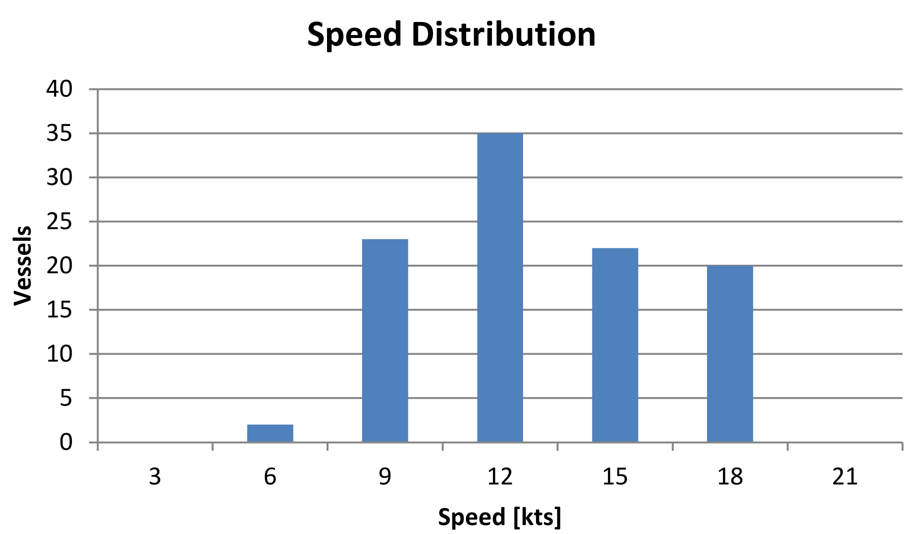

Figure 27: The Vessel #5 subgroup speed distribution

The specifications for Vessel #5 are summarize below.

Passenger Capacity	Vehicle Capacity	Speed
800 PAX	64 SV	12 kts

CONCLUSIONS

A summary of the proposed vessel specifications is provided in Table 1. These vessel types are intended to cover the range of vessel characteristics observed in the survey of the nationwide ferry fleet and to have design specifications that correspond to real world vessels.

Table 1: A summary of the proposed vessel types

Vessel	Subchapter	Passengers	Vehicles	Speed	Hull
1	T	100 PAX	20 SV	9 kts	Steel
2	T	60 PAX	-	6 kts	Steel
3	K	350 PAX	-	24 kts	Aluminum
4	K	400 PAX	-	12 kts	Steel
5	H	800 PAX	64 SV	12 kts	Steel

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APPENDIX B: SF-BREEZE OPTIMIZATION STUDY

SIGNED COPY ON FILE

SF-BREEZE OPTIMIZATION STUDY

Prepared for: Sandia National Laboratories • Livermore, CA

Ref: 16128-070-1 Rev. A December 1, 2017

Elliott Bay Design Group
Architectural & Engineering Services for the Marine Industry

PREPARED BY

Elliott Bay Design Group
5305 Shilshole Ave. NW, Ste. 100
Seattle, WA 98107

GENERAL NOTES

REVISIONS

REV	DESCRIPTION	DATE	APPROVED
-	Initial issue	09/14/17	KAJ
A	Revised fuel consumption calculations	12/01/17	KAJ 55055

TABLE OF CONTENTS

PAGE

1 PURPOSE

This report summarizes the concept designs of five ferry vessels which utilize hydrogen fuel cells to generate all required shipboard power. The performance requirements of the five vessels were developed from a mapping study in which data from the United States Bureau of Transportation Statistics National Census of Ferry Operators were analyzed. The results of this analysis are presented in Reference [1]. A design summary for each of the five ferry vessels is provided in the following sections of this report. Detailed calculations are provided in the appendices.

2 VESSEL #1

Vessel #1 is a Subchapter T double-ended ferry designed to carry 22 vehicles and 100 passengers. The design cruising speed of the steel-hulled vessel is 9 knots.

Table 1: Vessel #1 particulars

Particulars	
Length Overall	120 ft
Beam	46 ft
Depth	12 ft
Hullform	Double-ended
Passenger Capacity	100 PAX
Vehicle Capacity	22 SV
Cruising Speed	9 kts
Installed Power	240 kW
Fuel Cell Modules	8
Tank Volume	3,160 L water
Tank Capacity	212 kg

2.1 General Arrangements

2.1.1 Main Deck

The main deck arrangements for Vessel #1 are typical of a vehicle/passenger ferry of this size. The vessel has two passenger cabins separated by a crew space on the starboard side with pilothouse above. There are four unobstructed vehicles lanes with space for a total of 22 standard sized vehicles.

The bunkering station is located on the outboard starboard side of the vessel near midship. While it makes access more challenging, positioning the bunkering station here results in the superstructure blocking the hazardous zone from any passenger accessible spaces. Access to the bunkering station is then provided through a positive pressure airlock which passes entirely through the superstructure.

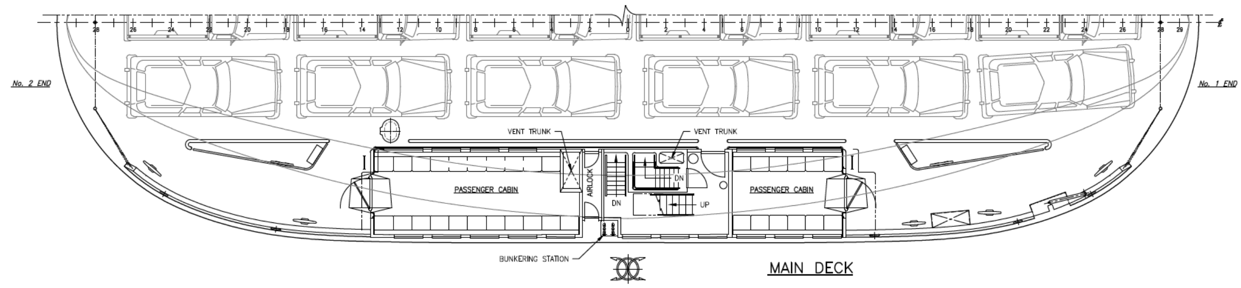

Figure 1: Vessel #1 main deck plan

2.1.2 Hold Arrangements

Due to the small vessel size, it was determined that all hydrogen equipment should be arranged below deck so as not to reduce the passenger or vehicle capacity compared to similarly sized, traditionally powered vessels. While this results in an efficient use of space, it poses challenges in providing access to below deck compartments which are considered hazardous zones. In order to eliminate the need to provide individual above deck access to each hazardous space, three air locks are used to separate the hydrogen tank room and fuel cell rooms from a single corridor space. The tank room is equipped with a single 835-gallon (water) cryogenic liquefied hydrogen (LH2) fuel tank and two vaporizers. Two independent fuel cell rooms house a total of 240 kW in Hydrogenics HyPM HD 30 modules.

A second stair is provided for accessing the non-hazardous below deck compartments. Two motor rooms house the electric propulsion motors, reduction gears, electrical switchboard and power conversion equipment. The vessel is driven at each end of the vessel by a 200 kW electric motor with reduction gear. The spaces outside the motor rooms are largely void spaces, with steering gear rooms at each end of the vessel.

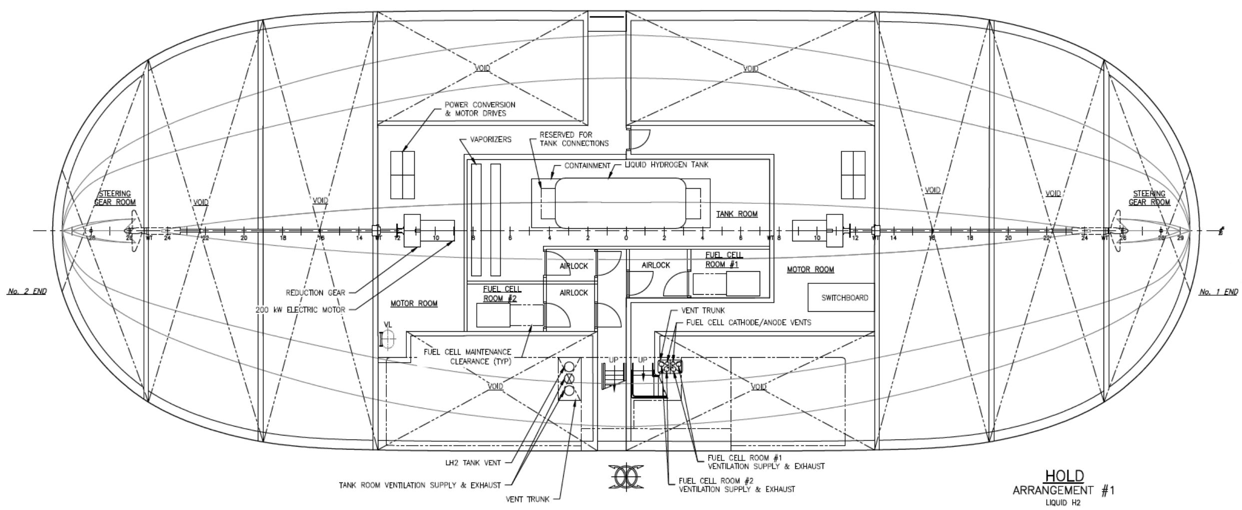

Figure 2: Vessel #1 hold plan

An alternative tank room arrangement is provided showing the use of a number of compressed hydrogen steel cylinders. Depending on the service requirements of the vessel, it may be feasible to simplify the hydrogen fuel system by utilizing compressed hydrogen rather than liquefied hydrogen. Note that the tank arrangement was developed only to determine the potential storage capacity of compressed hydrogen. The impact of the additional weight of the steel cylinders was not considered. Further analysis may show that composite cylinders provide a better overall solution, despite having a reduced total storage capacity.

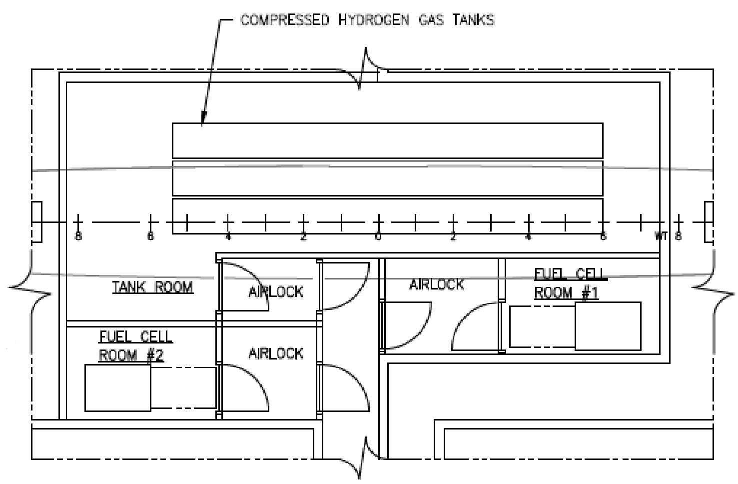

Figure 3: Alternative compressed hydrogen tank room

2.1.3 Outboard Profile

As with access to hazardous zones, the venting of hazardous spaces poses a challenge on a vessel of this size. It is difficult to position the vents where the hazardous zone around the outlets does not overlap any passenger accessible areas. Therefore the venting arrangement shown in the outboard profile below assumes that a gas dispersion analysis would show that all hydrogen gas would travel up from the ventilation louvers and would not reach the main deck.

Both the tank room and the tank are vented from the stack at midships above the pilothouse. The fuel cell rooms are ventilated from louvers at each end of the superstructure. The louvers are positioned at the extreme ends of the superstructure in order to keep the pilothouse outside of the hazardous zones created by these vents. It is also assumed that a dispersion analysis would indicate the pilothouse is not within the hazardous zones of the tank room ventilation louvers or tank vent. This allows the pilothouse to maintain immediate access to the exterior deck and ensures the navigation electronics are outside of a hazardous zone.

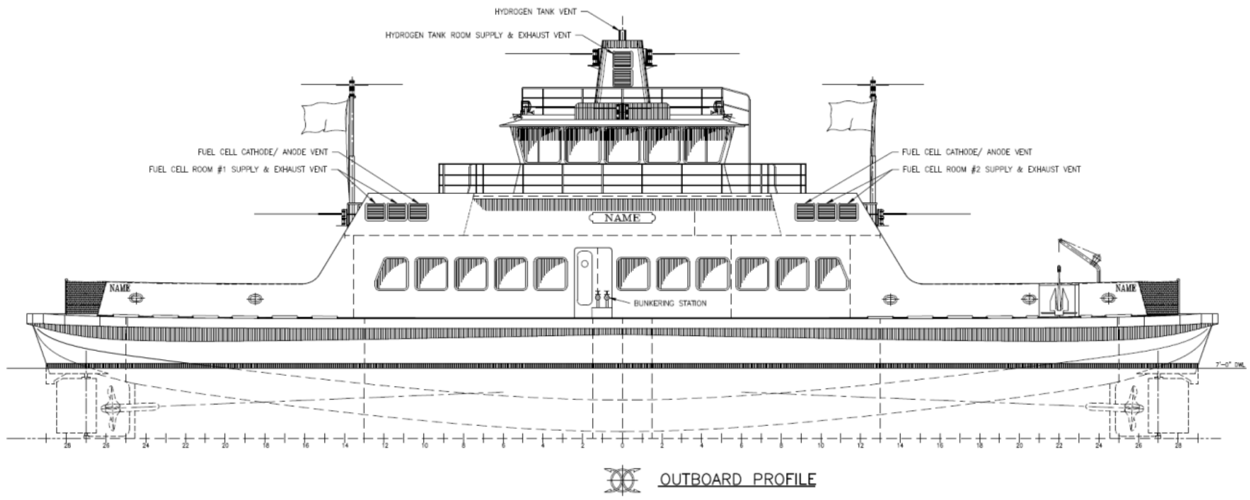

Figure 4: Vessel #1 outboard profile

2.1.4 LH2 Equipment

The fuel cell specifications are provided in Table 2. LH2 tank specifications are provided in Table 3. Compressed H2 tank specifications are given in Table 4.

Table 2: Fuel cell specifications

Characteristic	
Manufacturer	Hydrogenics
Model	HyPM HD30
Module Dimensions (LxWxH)	28.3 x 16 x 10.3 in
Module Weight	160 lbs
Modules/Rack	4
Rack Dimensions (LxWxH)	42.1 x 30 x 78.7 in
Rack Weight	1,764 lbs
Quantity of Racks	2
Total Modules	8
Total Weight	3,528 lbs

Table 3: LH2 Tank specifications

Characteristic	
Manufacturer	Linde
Model	Size 30 Cryogenic Tank
Tank Volume	3,160 L water
Tank Capacity	212 kg
Tank Dimensions (L x D)	13.6 x 5.2 ft
Tank Weight	5,732 lbs

Table 4: H2 Tank specifications

Characteristic	
Manufacturer	Fibatech
Model	ASME Pressure Vessel
Tank Volume	966 L water
Tank Capacity	24 kg
Tank Dimensions (L x D)	23.0 x 1.7 ft
Tank Weight	6,771 lbs
Quantity of Tanks	9
Total Volume	8,694 L water
Total Capacity	217 kg
Total Weight	60,939 kg

2.1.5 Regulatory Compliance

While the vessel design is at a concept level, all efforts were made to ensure the vessel is capable of meeting regulatory requirements of the United States Coast Guard (USCG), including the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code). The vessel generally complies with all regulatory rules considered. However, due to the vessel's small size, it was impractical to position the fuel cell rooms, tank rooms, and tank vent in accordance with IGF regulations on hazardous zones. Therefore, it is assumed that a gas dispersion analysis would demonstrate that hydrogen emitting from any of the previously mentioned vents would not reach the non-hazardous passenger areas on the main deck.

Additionally, based on the preliminary tonnage calculations the engine room tonnage deduction must be utilized to allow the vessel to measure at less than 100 gross registered tons (GRT). It is assumed that the motor rooms, shaft alleys, and fuel cell rooms all qualify to be included under the engine room deduction. This is explained in more detail in the tonnage section below.

2.2 Weights

The vessel's lightship weight and deadweight were calculated through a combination of parametric and itemized weight estimates. The lightship weight is the weight of the vessel itself, not including the weight of passengers, fuel, fresh water, or any other consumable or cargo loads. The deadweight is the combined weight of all passengers, consumable loads, or cargo loads. The full load condition is the sum of the lightship weight and the deadweight.

2.2.1 Lightship Weight

The lightship weight calculation was based on a detailed weight estimate of a similarly arranged vessel. The weights were divided into groups per the Ship Work Breakdown Structure (SWBS). The SWBS group categories are shown in Table 5.

Table 5: SWBS group numbers and descriptions

SWBS Group Number	Description
100	Structure
200	Machinery
300	Electrical
400	Electronics
500	Auxiliary Systems
600	Outfit

The base weight of each SWBS group was taken directly from the detailed estimate of the similar vessel. Equipment and systems which were not required on a hydrogen-powered ferry were then removed on a line item basis. Further, items required for the hydrogen power plant were added to the estimate. The weights of the LH2 system equipment were based on manufacturer specifications with the exception of the propulsion system electrical components (DC-DC converters, DC-AC inverters, filters, line reactors, etc.) which were scaled by installed power from the line item estimate of the SF-BREEZE [2]. For simplicity, all LH2 system weights were added to Group 200. A 5% margin was also added to Group 100 to account for the increase in below deck bulkheads required for the LH2 system. Table 6 lists the equipment which was added to and removed from the baseline weight estimate.

Table 6: Line item weights added to and removed from the baseline estimate

Weights Added	Weights Removed
• Electric Propulsion Motors • Propulsion System Electrical Components • Fuel Cell Racks • Vaporizers • LH2 Tank	• Main Propulsion Engines • Fuel Oil System • Exhaust System • Generators

In naval architecture it is typical to put margins on each weight category to account for items which are unknown or not included in the itemized weight estimate. Margins were used in this manner when completing the lightship weight estimate in accordance with standard naval architecture practice. The baseline weights included the centers of gravity from the similar vessel, and estimates of equipment locations were made for each line item weight. The overall center of gravity was estimated in order to verify vessel trim and stability.

The estimated lightship weight of the vessel is 243.8 LT. Table 7 shows the total weight broken down by SWBS group.

Table 7: Lightship weight estimate summary

SWBS Group	Description	Weight [LT]
100	Structure	197.0
200	Machinery	13.6
300	Electrical	4.2
400	Electronics	0.3
500	Auxiliary Systems	9.0
600	Outfit	19.7
	Total	**243.8**

2.2.2 Deadweight

The vessel's deadweight was calculated with an itemized estimate of all cargo and variable loads. Passengers were assigned a weight of 185 lbs in accordance with USCG regulation. Crew members were assigned a weight of 225 lbs. Vehicles were assumed to weigh 4,000 lbs. A water ballast weight of 10,000 lbs was included as it is common for vehicle ferries to use ballast to offset the trim effects of partial vehicle loads. A 5% service life margin was also included. The service life margin provides an allowance for weight growth over the life of the vessel and is commonly used in vessel design. The weight of LH2 was also included in the deadweight. The total deadweight was estimated to be 64.7 LT. Table 8 shows a summary of the deadweight calculation.

Table 8: Summary of deadweight for Vessel #1

Item	Weight [LT]
Crew and Effects	0.3
Passengers	8.3
Vehicles	39.3
Water Ballast	4.5
LH2	0.2
Service Life Margin	12.2
Total	**64.7**

2.2.3 Full Load Condition

Summing the lightship weight and the deadweight results in a full load displacement of 309 LT. The hullform was designed to displace 310 LT at the design load water line of 7 ft. The vertical center of gravity of the full load condition is estimated to be 9.5 ft above baseline.

2.2.4 Weight Reduction

Reducing the weight of the vessel is beneficial as it results in a reduction in required propulsion power. The deadweight cannot be readily reduced as this is primarily driven by the vessel's service requirements. Therefore, the vessel's lightship weight must be reduced. One method often considered for reducing the lightship weight is to construct the vessel's superstructure out of aluminum. While such an approach is feasible on this vessel, the vessel's superstructure is only a small portion (~10%) of the vessel's total structural weight. Therefore, the overall impact of an aluminum superstructure would be small on the total weight of the vessel.

To estimate the impact, it is assumed an aluminum structure weighs 70% of an equivalent steel structure. Therefore, the total weight reduction with an aluminum superstructure is approximately 6 LT, or 2.5% of the vessel's lightship weight. While this would provide for a small reduction in required propulsion power, the added cost of aluminum construction may outweigh the benefits.

2.3 Speed and Power

A speed and powering analysis was undertaken to estimate the required vessel propulsion power. Calculating the propulsion power accurately is an important part of the design process as it directly relates to the required quantity of fuel cell modules in the hydrogen power plant.

The analysis was completed in NavCAD 2016, a parametric regression based software which estimates the vessel's resistance and powering characteristics from previous vessels. The parameters required for the analysis were measured from the general arrangement and from a 3D model of the hullform created in Rhinoceros 3D.

The hull resistance was estimated at the 7.0 ft design load draft at even keel and in calm water. A 10% margin was added to the hull resistance for conservatism. Propeller characteristics were optimized in NavCAD based on a 54" propeller diameter. Figure 5 shows a plot of the required shaft power over the anticipated speed range. At the cruising speed of 9 knots, the vessel requires 121 kW of shaft power.

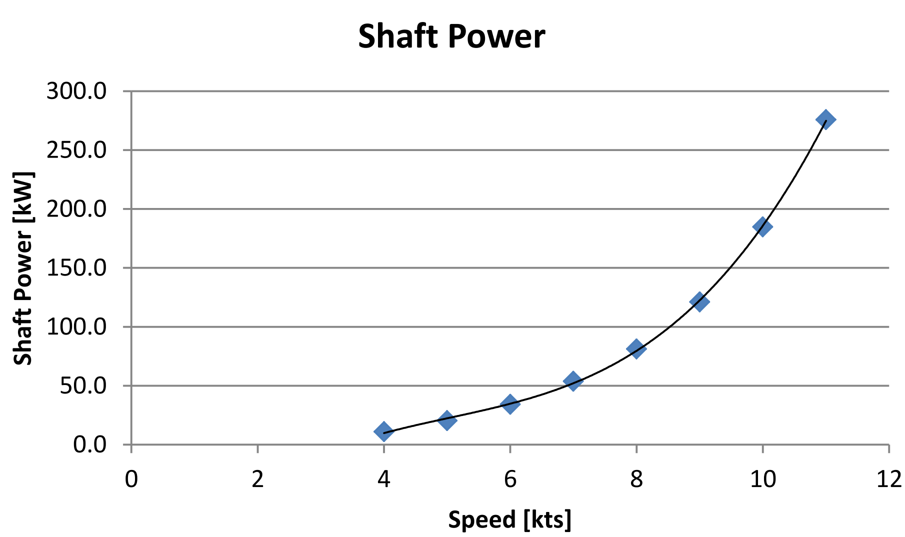

Figure 5: Required shaft power for Vessel #1

The power plant was sized assuming a vessel cruise condition at 85% of the maximum continuous rating (MCR). The assumed propulsion electrical system efficiencies are shown in Table 9. From these, the required brake power was calculated to be 160 kW.

Table 9: Propulsion electrical system efficiencies

Equipment	Efficiency
Electric Motor	96%
AC Inverter	97%
DC Converter	97%

In an electrically driven vessel, the power plant provides not only the propulsion power, but the power required for the hotel loads as well. To estimate the hotel loads, the electrical system of a vessel of similar capacity and arrangement was studied. The previous design used an 80 kW generator to account for the house loads. While the detailed loads analysis indicated this was oversized, it was decided that the full generator capacity would be included for conservatism.

Considering the propulsion system efficiencies and MCR requirements, and including the hotel loads requirements, the total required capacity of the hydrogen power plant was calculated to be 240 kW. This load is generated by two fuel cell racks, each containing four Hydrogenics HyPM HD 30 modules generating 30 kW of power.

One advantage of the electric propulsion system over a conventional diesel propulsion system is the ability to distribute power from a single source to both ends of the vessel. In a conventional diesel arrangement, both ends of the vessel would require engines large enough to power the boat. In the electrical propulsion arrangement, only the electric motors must be sized to meet the required propulsion power on each end. The power generation equipment can simply provide power to whichever end of the vessel is providing the driving thrust. This reduces the total amount of installed power compared to a conventional diesel arrangement.

2.3.1 CFD Analysis

After completion of the concept design, a computational fluid dynamics (CFD) analysis was performed in order to determine the vessel's resistance with greater accuracy. The CFD geometry was taken from a 3D model of the hullform created in Rhinoceros 3D. The CFD simulation mesh had 4.4 million elements and utilized a symmetry plane on the vessel's centerline to reduce the cell count. The vessel was allowed to heave and trim throughout the run. The transient simulation was run for a length of time sufficient to achieve a converged result. Figure 6 shows the wake at the cruising speed of 9 knots.

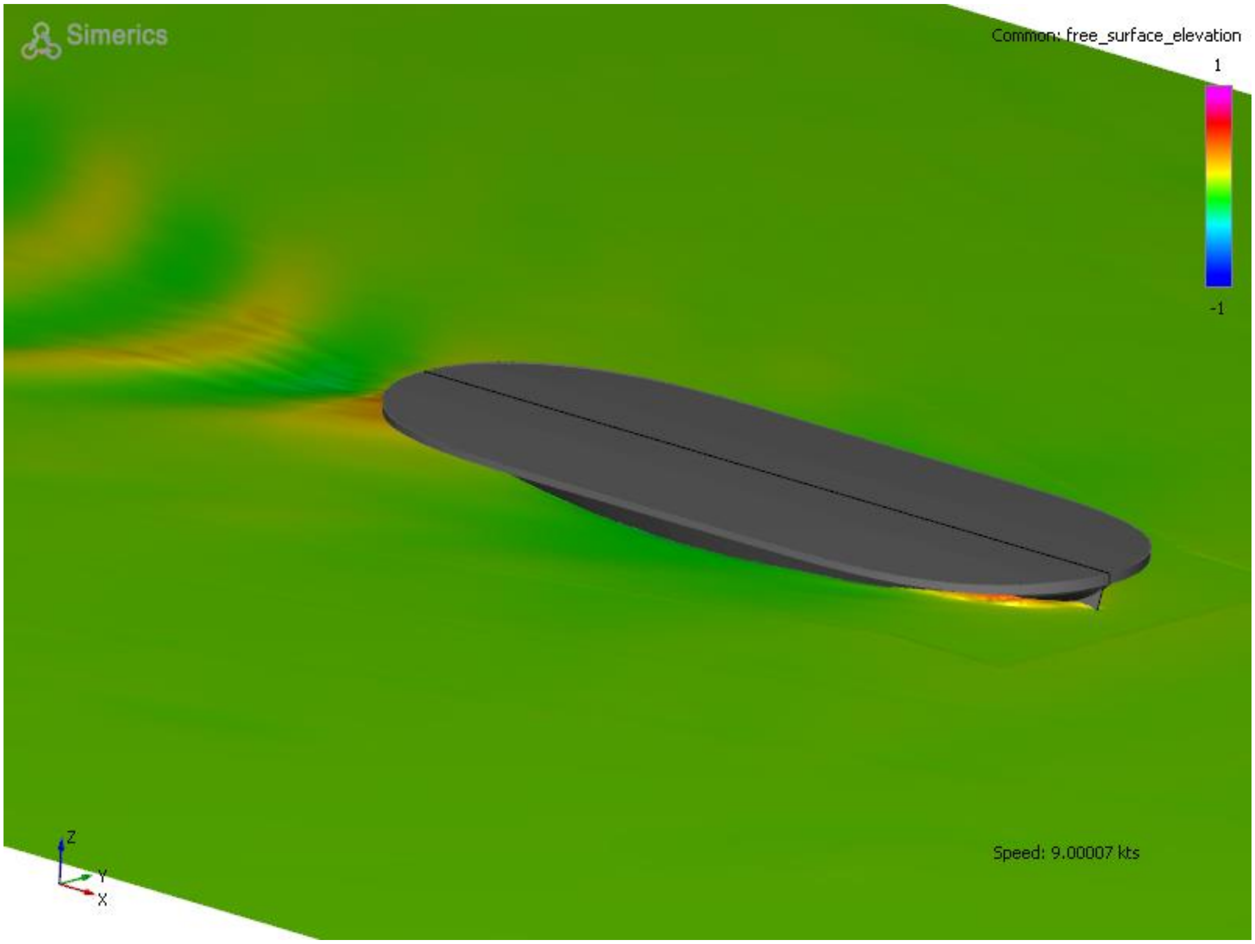

Figure 6: The vessel's wake at 9 knots

The CFD simulation indicated the vessel's resistance would be 5% greater than was predicted with the initial parametric analysis. It is unlikely that this small increase in resistance would result in additional fuel cell modules. The difference could likely be made up by reducing the conservative estimate of the house electric loads. This would result in the fuel consumption per trip decreasing by 0.2 kg. Alternatively, the vessel could be operated at 90% MCR. This results in a fuel consumption increase of 0.1 kg per trip. In either case, the vessel would still be required to bunker every two days (see Section 2.6 for additional details on the vessel's route and endurance).

2.4 Stability

A preliminary stability assessment was completed in order to confirm the feasibility of the vessel design. The preliminary assessment considered USCG subdivision and intact stability requirements for passenger vessels. The analysis was completed using General Hydrostatics (GHS) Version 15. The GHS model was created from the Rhinoceros model used in the speed and power analysis.

The maximum allowable vertical center of gravity (VCG) was calculated based on the following criteria:

- 46 CFR §170.170 Weather Criteria
- 46 CFR §170.173 Criterion for Vessels of Unusual Proportion and Form
- 46 CFR §171.050 Passenger Heel Requirements

Figure 7 shows a plot of all criteria over the expected trim and displacement range. For conservatism, it was assumed the vessel was operating on exposed waters. Calculations are provided in Appendix A. The full load VCG is estimated to be 9.5 ft indicating the concept vessel arrangements comply with intact stability criteria.

The subdivision requirements were verified with a floodable length curve at the vessel's full load draft. Per 46 CFR § 171.070, the floodable length analysis uses a two compartment standard of flooding for all of the vessel forward of the first main transverse watertight bulkhead aft of the collision bulkhead and a single compartment standard of flooding throughout the remainder of the vessel. Figure 8 shows the floodable length curve with 95% and 85% compartment permeabilities. In each case, the bulkhead arrangement passes the floodable length calculation.

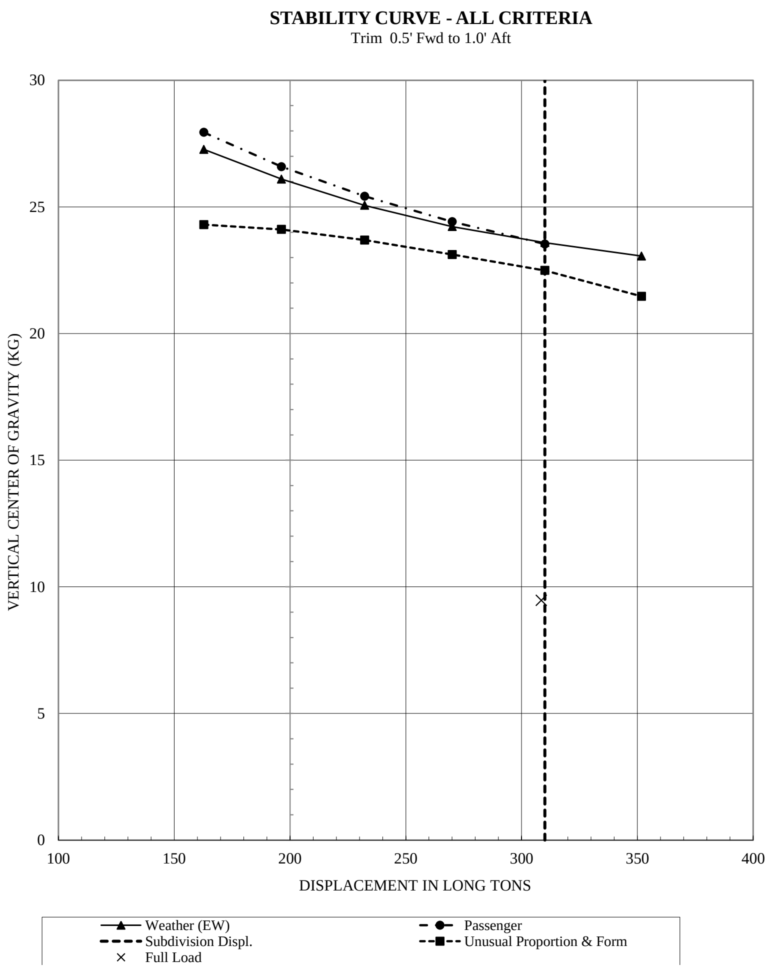

Figure 7: Maximum VCG curves for Vessel #1

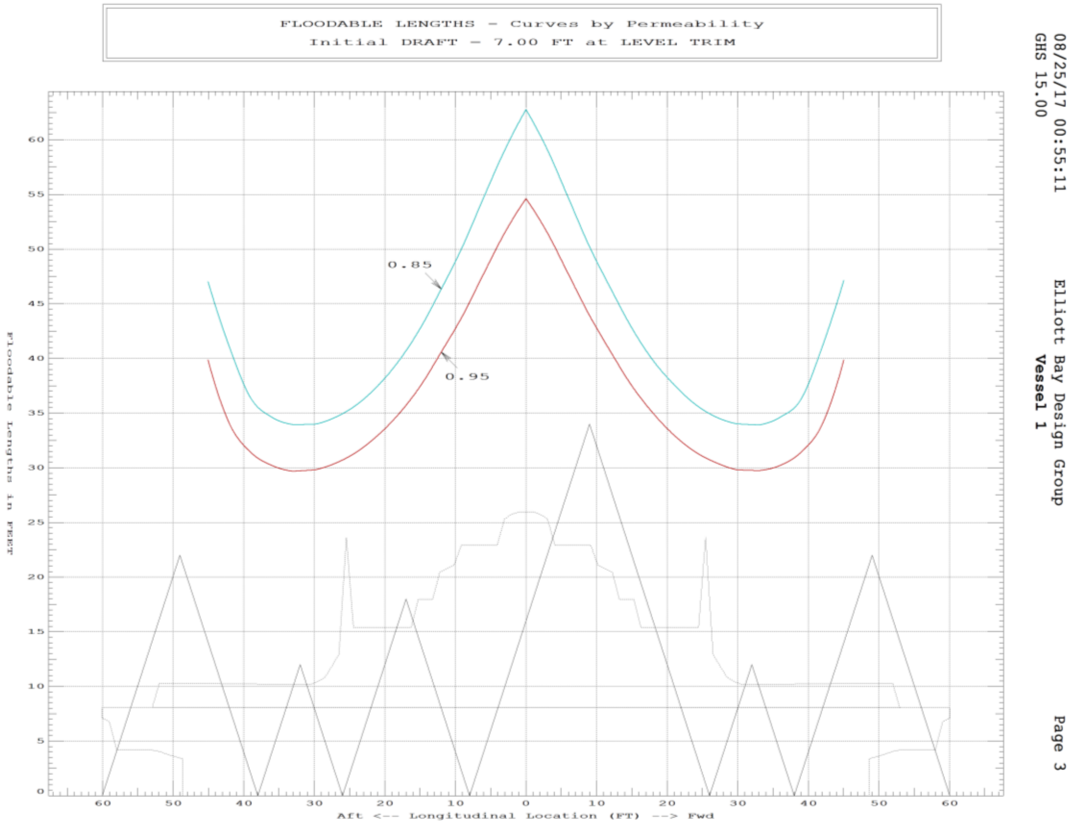

Figure 8: Floodable length curve for Vessel #1

2.5 Tonnage

An estimate of the vessel's GRT was completed to confirm the vessel would comply with the tonnage limitations of Subchapter T. The underdeck tonnage was measured with 10 stations over a tonnage length of 112 ft. The superstructure tonnage was estimated with block estimates of each space.

Due to the hydrogen equipment located below deck, the underdeck tonnage is high compared to a typical vessel of this size. Therefore, the engine room tonnage deduction must be utilized to allow the vessel to measure at less than 100 GRT. It is assumed that the motor rooms, shaft alleys, and fuel cell rooms all qualify to be included under the engine room deduction. These spaces account for 38% of the underdeck space. Therefore, 37% of the underdeck tonnage may be deducted.

With this methodology, the tonnage is estimated to be 88.86 GRT. Detailed calculations are included in Appendix A.

2.6 Route and Endurance

It is not uncommon for vessels of this size and capacity to be operated on short routes of one nautical mile or less. Several examples of such routes are provided in Table 10.

Table 10: Example routes for Vessel #1

Route	Distance (nm)	Vessel Capacity (SV)
Terminal Island - Fisher Island	1	22
Anacortes - Guemes Island	0.5	22
Gooseberry Point - Lummi Island	0.5	20

For conservatism, a notional 2.0 nautical mile one-way route was developed. It was assumed that a three-minute maneuvering period occurred at the start and end of the route but that the remainder of the route was spent at cruising speed. An 18 minute vehicle load/unload period was also included in the route profile. A small amount of propulsion power was included during the loading period as it is common for the vessel to push against the embarkation ramp or pilings during loading operations. A breakdown of the route and the estimate fuel consumption is shown below. The fuel consumption assumes a fuel cell efficiency of 45%.

Based on this notional route, the vessel is capable of completing 32 one-way trips before needing to refuel. Assuming the vessel completed 12 one-way trips per day, the vessel would need to bunker every two to three days when using either the 212 kg capacity liquid hydrogen tank or the 217 kg capacity gaseous hydrogen tanks. Note, however, that the endurance with compressed hydrogen does not account for the added weight of the tanks. The range may be reduced after more detailed analysis of such an arrangement.

Table 11: Notional route for Vessel #1

Speed (kts)	Distance (nm)	Time (min)	Propulsion Power (kW)	Hotel Load (kW)	Total Power (kW)	% Load of Installed Power	Total Energy (kW-hr)	Fuel Consumption (kg)
3	0.15	3.0	48	80	128	53%	6.4	0.4
9	1.70	11.3	135	80	215	90%	40.6	2.7
3	0.15	3.0	48	80	128	53%	6.4	0.4
0	0.00	18.0	16	80	96	40%	28.8	1.9
Total	**2.00**	**35.3**					**82.2**	**5.5**

2.7 Capital Cost Estimate

A parametric estimate of the capital cost of Vessel #1 was made. The estimate was based on the lightship weight of the vessel. Each SWBS group was assigned a material cost per ton and labor hours per ton factor based on previously constructed vessels. The estimate assumed a labor rate of $73 per hour which is an average between the typical rates for Pacific Northwest and Gulf Coast shipyards. A 10% margin was included for conservatism and 10% contingency was included to account for cost growth during the time between estimate completion and vessel delivery. This is a standard approach for estimating costs at the concept design stage. The cost of engineering and constructions services were assumed to be higher than for a traditionally power vessel due to the added complexity of the LH2 system.

The material cost of the hydrogen fuel cells and the cryogenic fuel tank were considered separate from the parametric weights based analysis. The cost of the fuel cells was assumed to be $2,200/kW. This cost was given by Hydrogenics as the upper range of expected fuel cell cost today based on a one-time order with ruggedization and marinization options. The lower range was given as $1,800/kW without the additional options. Since the fuel cells will be located in a controlled environment fuel cell room, the ruggedization and marinzation options may be unnecessary, according to Hydrogenics. The cost of the hydrogen tank was assumed to be $700 per kilogram of tank weight based on the original SF-BREEZE capital cost estimate. The cost of the additional components in the LH2 system was included in the estimated cost of Group 200.

The total capital cost to construct Vessel #1, including engineering and construction services, is estimated to be $9,700,000. Additional calculation details are provided in Appendix A.

3 VESSEL #2

Vessel #2 is a 61-passenger Subchapter T ferry. The steel-hulled boat is designed to have a cruising speed of 6 knots.

Table 12: Vessel #2 particulars

Particulars	
Length Overall	60 ft 4 in
Beam	18 ft
Depth	10 ft
Hullform	Single-ended
Passenger Capacity	61 PAX
Vehicle Capacity	-
Cruising Speed	6 kts
Installed Power	270 kW
Fuel Cell Modules	9
Tank Volume	3,816 L water
Tank Capacity	95 kg

3.1 General Arrangements

3.1.1 <u>Main Deck Arrangements</u>

Vessel #2 is designed in the style of a typical water taxi. Passenger embarkation is available from both sides of the vessel through doors just aft of the elevated pilothouse. There is a small passenger accessible open deck forward. Inside the passenger cabin there is available seating for 61 passenger including two wheel chairs. There is a bar and head aft and floor hatches for gaining access to below deck spaces. On the port side of the vessel there is a crew-only stair which leads to the upper deck.

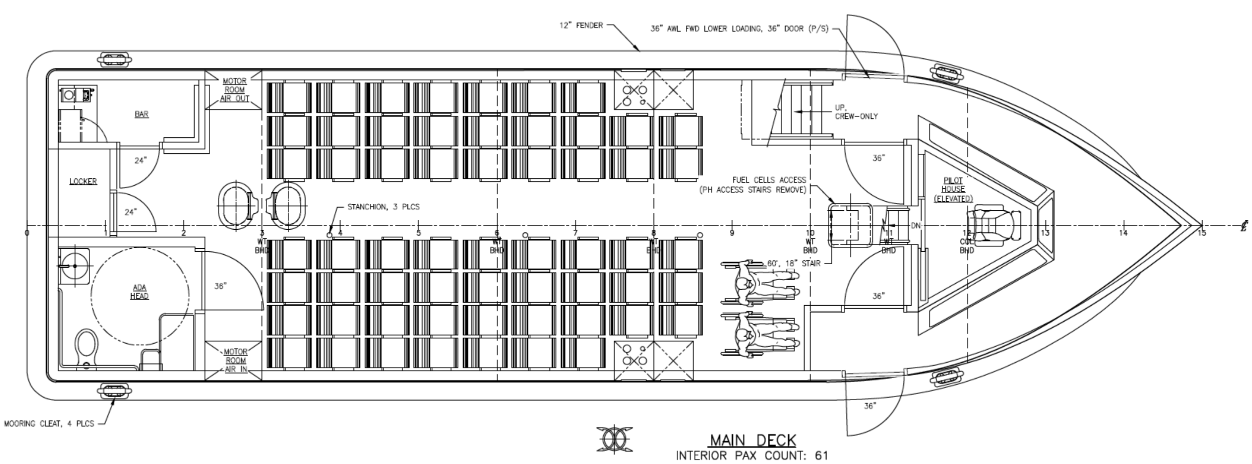

Figure 9: Vessel #2 main deck arrangement

3.1.2 Hold Arrangements

Hold compartments are accessed from deck hatches on the main deck leading to vertical ladders. There is a centerline hatch between Frames 10 and 11 which provides access to a void space. Separated on centerline, two airlocks isolate this void from the fuel cell rooms located between Frames 6 and 8. The fuel cell room ventilation follows a trunk to the upper deck where it is lead aft to louvers at the stern.

The motor room is directly aft of the fuel cell rooms. The space contains two motors which drive the propeller shafts directly. The after most compartment contains steering gear.

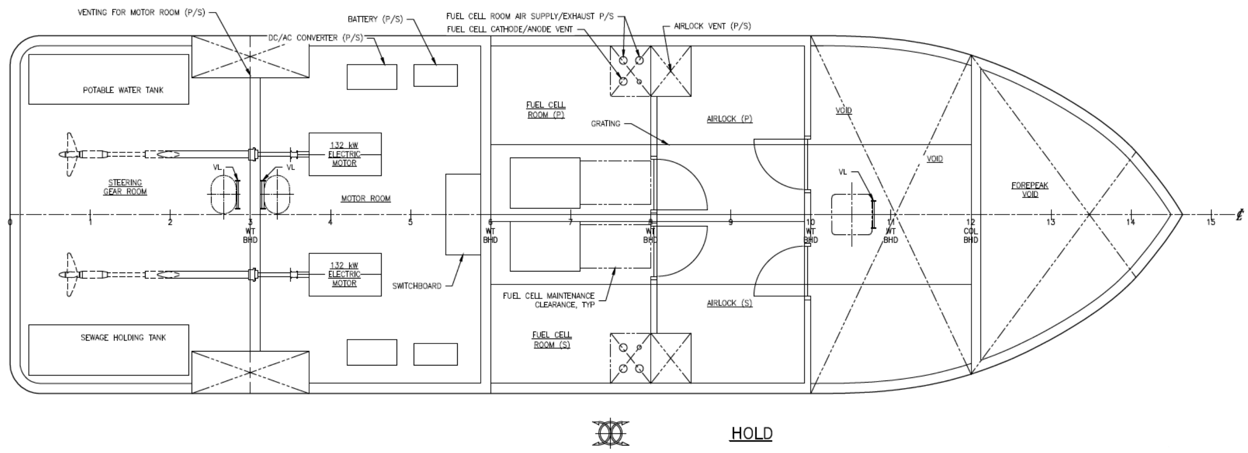

Figure 10: Vessel #2 hold arrangements

3.1.3 Upper Deck Arrangements

The upper deck is only accessible to crew members. There are 12 composite compressed gas cylinders with a total water volume of 3,816 liters which hold 95.4 kg of compressed hydrogen at 350 bar. The tanks are located on centerline and forward in order to prevent their hazardous zones from intersecting those of the fuel cell room ventilation louvers at the stern. It is assumed that a gas dispersion analysis would show that the hazardous zones around the tanks, tank vent, and ventilation louvers would not impact the passenger accessible areas of the vessel or the pilothouse.

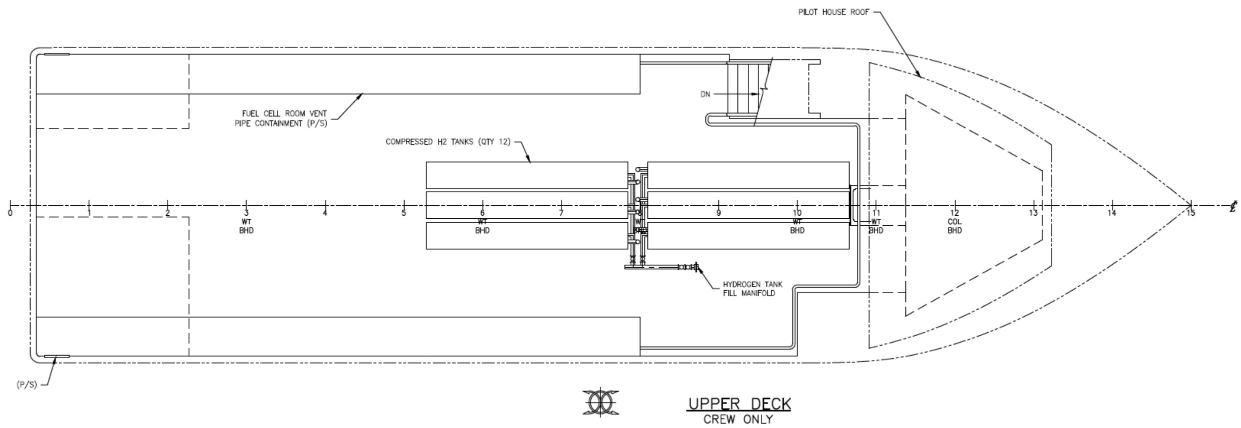

Figure 11: Vessel #2 upper deck arrangements

3.1.4 Outboard Profile

The outboard profile is shown in Figure 12. The fuel cell room ventilation can be seen on the upper deck at the stern of the vessel. The airlocks vents are located near midship just below the upper deck level. The motor rooms are vented at the main deck level near the stern.

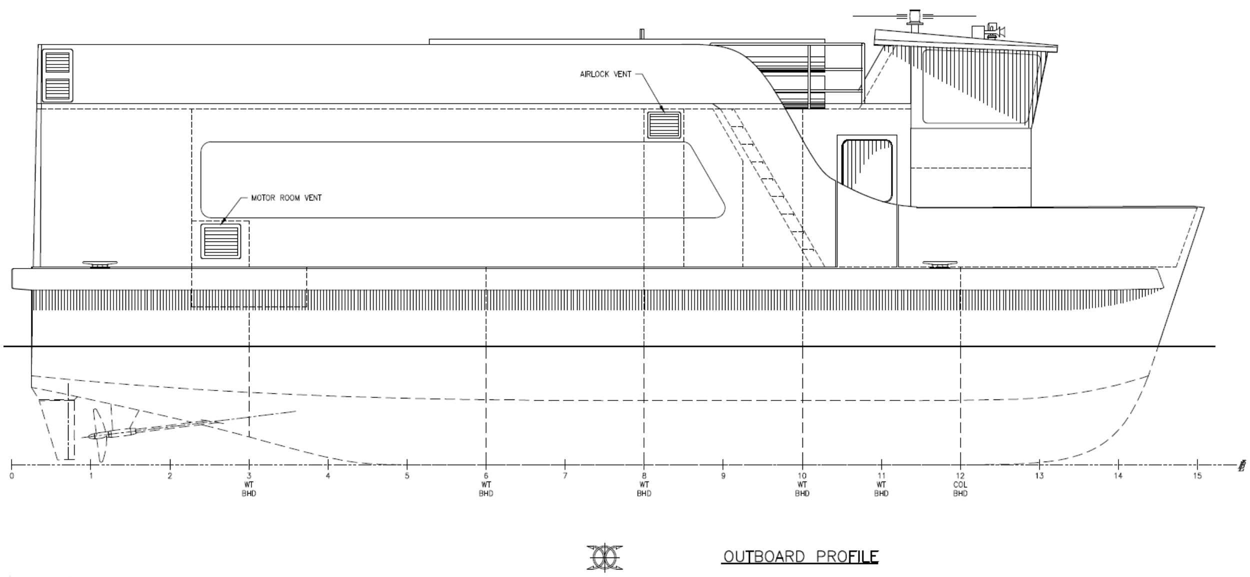

Figure 12: Vessel #2 outboard profile

3.1.5 H2 Equipment

The fuel cell specifications are provided in Table 13. The vessel contains two racks for a total weight of 3,528 lbs. H2 tank specifications are provided in Table 14.

Table 13: Fuel cell specifications

Characteristic	
Manufacturer	Hydrogenics
Model	HyPM HD30
Module Dimensions (LxWxH)	28.3 x 16 x 10.3 in
Module Weight	160 lbs
Rack Dimensions (LxWxH)	42.1 x 30 x 78.7 in
Modules/Rack	4
Rack Weight	1,764 lbs
Modules/Rack	5
Rack Weight	1,919 lbs
Quantity of Racks	2
Total Modules	9
Total Weight	3,683 lbs

Table 14: Tank specifications

Characteristic	
Manufacturer	Luxfer
Model	W320H
Tank Volume	318 L water
Tank Capacity	8 kg
Tank Dimensions (L x D)	10.3 x 1.4 ft
Tank Weight	304 lbs
Quantity of Tanks	12
Total Volume	3,816 L water
Total Capacity	95 kg
Total Weight	3,648 lbs

3.1.6 Regulatory Compliance

While the vessel design is at a concept level, all efforts were made to ensure the vessel is capable of meeting regulatory requirements of the USCG, including the IGF Code. The vessel generally complies with all regulatory rules considered at a concept level. However, due to the vessel's small size, it was impractical to position the fuel cell rooms, tank rooms, and tank vent and the bunkering station in accordance with IGF regulations on hazardous zones. Therefore, it is assumed that a gas dispersion analysis would demonstrate that hydrogen emitting from any of the previously mentioned vents on the upper deck would not reach the non-hazardous passenger embarkation areas on the forward main deck. It is also assumed that the hydrogen would not be drawn down into the non-hazardous ventilation louvers on the sides of the superstructure.

3.2 Weights

3.2.1 Lightship Weight

The baseline lightship weight calculation was based on a combination of a parametric weight estimate and a preliminary steel weight estimate. A 3D model of the hull, internal bulkheads, deck, and superstructure plating was developed in Rhinoceros 3D. The surface areas of each plate were measured in Rhinoceros and a weight calculated based on an estimate of the likely plate thickness. A margin was added to the weight of the plating to account for stiffening. An additional 10% margin was added to the overall total for conservatism. Weights for SWBS groups 200 to 600 were estimated based on the dimensions of the vessel and a weight coefficient taken from a database of previous vessels.

The weight of a representative main engine and an estimate of the main engine systems were then removed from the baseline lightship weight estimate. Further, items which were required for the hydrogen power plant were added to the estimate. The weights of the H2 system equipment were based on manufacturer specifications with the exception of the propulsion system electrical components (DC-DC converters, DC-AC inverters, filters, line Reactors, etc.) which were scaled by installed power from the line item estimate of the SF-BREEZE [2]. For simplicity, all H2 system weights were added to Group 200. Table 15 lists the equipment which was added to and removed from the baseline weight estimate.

Table 15: Line item weights added to and removed from the baseline estimate

Weights Added	Weights Removed
• Electric Propulsion Motors • Propulsion System Electrical Components • Fuel Cell Racks • H2 Tanks	• Main Propulsion Engines • Main Engine Systems

Margins were added to each weight group in accordance with standard naval architecture practice. The center of gravity of Group 100 was measured in the 3D plate model and the center of Group 600 was assumed to be in the same location. The centers of gravity of Groups 200, 300, and 500 were placed in the engine room, while the Group 400 was positioned in the bridge. The overall center of gravity was estimated in order to verify vessel trim and stability.

The estimated lightship weight of the vessel is 71.7 LT. Table 16 shows the total weight broken down by SWBS group.

Table 16: Lightship weight estimate summary

SWBS Group	Description	Weight [LT]
100	Structure	32.6
200	Machinery	12.3
300	Electrical	2.7
400	Electronics	0.6
500	Auxiliary Systems	14.9
600	Outfit	8.6

SWBS Group	Description	Weight [LT]
	Total	**71.7**

3.2.2 Deadweight

The vessel's deadweight was calculated with an itemized estimate of all cargo and variable loads. Passengers were assigned a weight of 185 lbs in accordance with USCG regulations. Crew members were assigned a weight of 225 lbs. A 5% service life margin was included to provide an allowance for weight growth over the life of the vessel. The weights of potable water, sewage, and compressed hydrogen gas were also included in the deadweight. The total deadweight was estimated to be 11.1 LT. Table 17 shows a summary of the deadweight calculation.

Table 17: Summary of deadweight for Vessel #2

Item	Weight [LT]
Crew and Effects	0.3
Passengers	5.0
Stores	0.5
Potable Water	0.8
Sewage	0.8
H2	0.1
Service Life Margin	3.7
Total	**11.1**

3.2.3 Full Load Condition

Summing the lightship weight and the deadweight results in a full load displacement of 82.8 LT. The hullform was designed to displace 83.6 LT at the design load water line of 6 ft. The vertical center of gravity of the full load condition is estimated to be 8.8 ft above baseline.

3.2.4 Weight Reduction

As previously discussed, reducing the vessel's lightship weight is beneficial as it results in a reduction in required propulsion power. One method of reducing the lightship weight is to construct the vessel out of aluminum. To estimate the impact, it is assumed an aluminum structure weighs 70% of an equivalent steel structure. Therefore, the total structural weight reduction with aluminum is approximately 9.8 LT, or 14% of the vessel's lightship weight. Note that the use of aluminum in a vessel's structure impacts other aspects of the design, such as a need for increased fire protection. While this would likely reduce the weight savings by some amount, it is feasible that an aluminum vessel could have a reduced propulsion power compared to the steel-hulled vessel explored in this design.

3.3 Speed and Power

As with Vessel #1, a speed and powering analysis was completed in NavCAD 2016. The vessel parameters required for the analysis were measured from the general arrangement and from a 3D model of the hullform created in Rhinoceros 3D.

The hull resistance was estimated in calm water with a clean hull at even keel. A 10% margin was added to the hull resistance for conservatism. Propeller characteristics were optimized in NavCAD based on a 33" propeller diameter. Figure 13 shows a plot of the required shaft power over the anticipated speed range. It may be noted that the power required for Vessel #2 is higher than Vessel #1. While counterintuitive, this is not unexpected. Vessel #2 has a much shorter hullform which results in the wave-making drag being a much more dominant component of the total vessel resistance. The vessel also has a fuller hullform than Vessel #1 which leads to added resistance. In addition, Vessel #2 has smaller, less efficient propellers. All of these factors lead to Vessel #2 requiring more propulsion power than Vessel #1.

A vessel of this size and capacity is often used as a water taxi. This type of service can occur in rivers where there may be strong currents. Therefore, for conservatism, the vessel's propulsion system was designed around an 8-knot speed, allowing the vessel to maintain its design speed of 6 knots in up to a 2 knot current. At a speed of 8 knots, the vessel requires 183 kW of propulsion power.

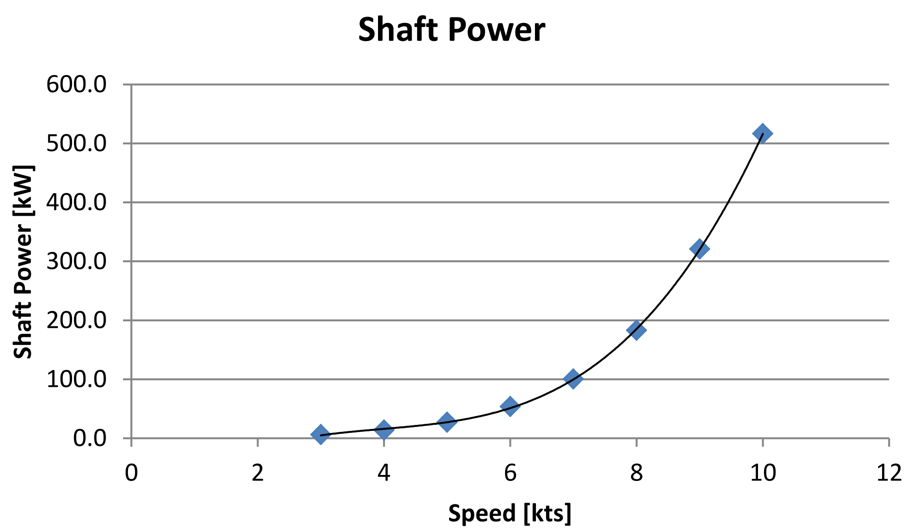

Figure 13: Required shaft power for Vessel #2

The power plant was sized assuming a vessel cruise condition at 85% of the maximum continuous rating (MCR). Propulsion system efficiencies were assumed to be as shown in Table 18. From these, the required brake power was calculated to be 240 kW.

Table 18: Propulsion electrical system efficiencies

Equipment	Efficiency
Electric Motor	96%
AC Inverter	97%
DC Converter	97%

To estimate the hotel loads, the electrical system of a vessel of similar capacity and arrangement was studied. The house loads for Vessel #2 were assumed to be equal to the previous design's generator capacity of 20 kW.

Considering the propulsion system efficiencies and MCR requirements, and including the hotel loads requirements, the required capacity of the hydrogen power plant was calculated to be 258 kW. This load is generated by two fuel cell racks, one containing five Hydrogenics HyPM HD 30 modules each generating 30 kW of power and the other containing four identical modules.

3.3.1 CFD Analysis

A CFD analysis was not completed for Vessel #2 as the economic viability of this vessel was considered low. This determination was made based on the high installed power per passenger compared to other concept designs in this report.

3.4 Stability

A preliminary stability assessment was completed in order to confirm the feasibility of the vessel design. The preliminary assessment considered USCG subdivision and intact stability requirements for passenger vessels. The analysis was completed using General Hydrostatics (GHS) version 15. The GHS model was created from the Rhinoceros model used in the speed and power analysis.

The maximum allowable vertical center of gravity (VCG) was calculated based on the following criteria:

- 46 CFR §170.170 Weather Criteria
- 46 CFR §170.173 Criterion for Vessels of Unusual Proportion and Form
- 46 CFR §171.050 Passenger Heel Requirements

Figure 14 shows a plot of all criteria over the expected trim and displacement range. It was assumed the vessel was operating on partially protected waters. Calculations are provided in Appendix B. The full load VCG is estimated to be 8.8 ft. indicating the concept vessel arrangements comply with intact stability criteria.

To increase the H2 storage capacity of Vessel #2, additional tanks would need to be added to the upper deck. Doing so would raise the vessel's center of gravity. With the current design there is only a 3" margin between the full load VCG and the maximum allowable VCG at the corresponding displacement. Therefore, it is not feasible at this stage of design to increase the H2 capacity further. As a more detailed design is completed and greater certainty in the weight estimate is developed, it may be possible to add additional H2 tanks to the upper deck.

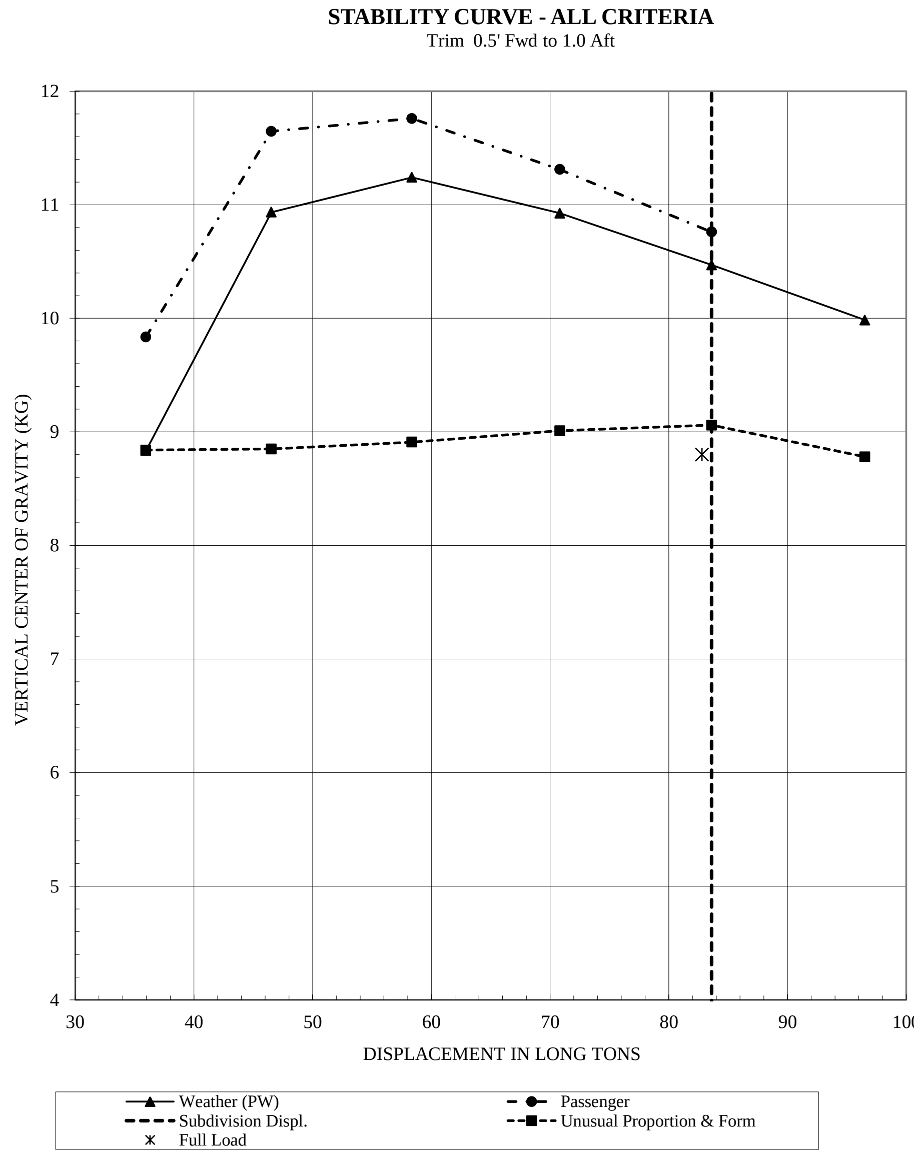

Figure 14: Maximum VCG curves for Vessel #2

The single-compartment subdivision requirements were verified with a floodable length curve at the vessel's full load draft. Figure 15 shows the floodable length curve with 95% and 85% compartment permeabilities. In each case, the bulkhead arrangement passes the floodable length calculation.

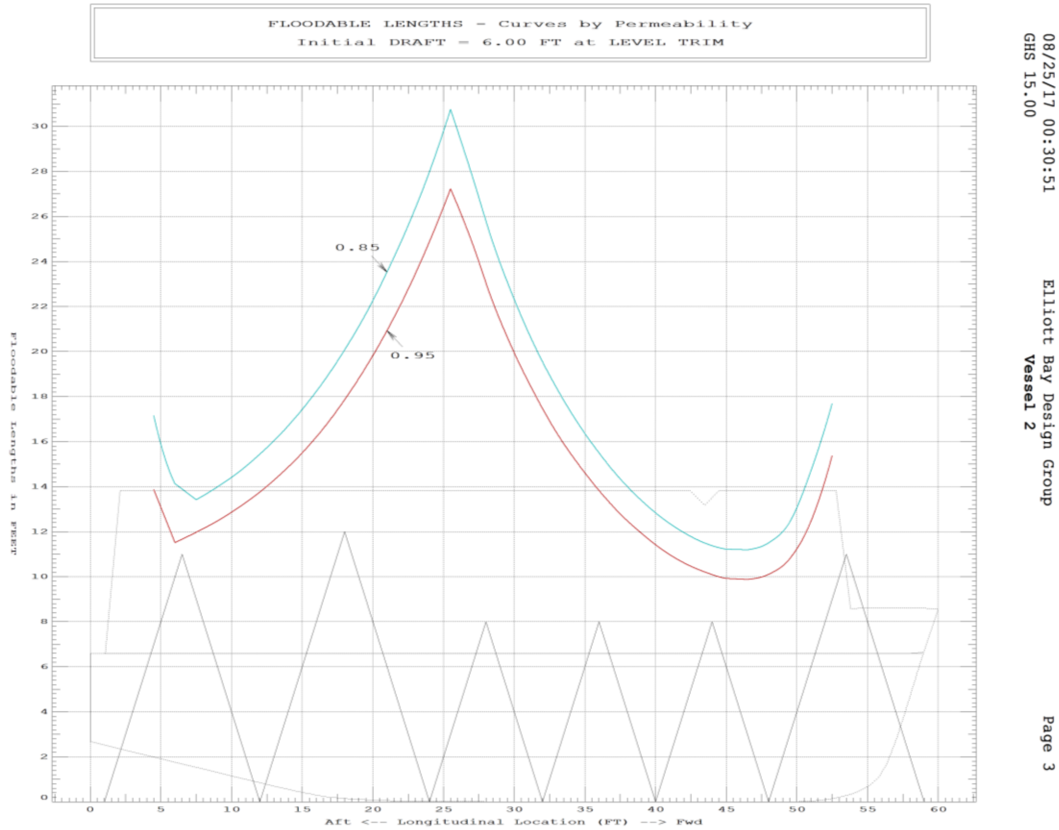

Figure 15: Floodable length curve for Vessel #2

3.5 Tonnage

An estimate of the vessel's GRT was completed to confirm the vessel would comply with the tonnage limitations of Subchapter T. The under-deck tonnage was measured with eight stations over a tonnage length of 56 ft. For conservatism, the slope of the hull bottom was disregarded when calculating the under-deck tonnage. The superstructure tonnage was estimated with block estimates of each space.

With this methodology, the tonnage is estimated to be 73.42 GRT. Detailed calculations are included in Appendix B.

3.6 Route and Endurance

A vessel of this size and capacity is typically used for a water-taxi type application. Table 19 shows a selection of water taxi routes in Chicago and Boston for reference.

Table 19: Example routes for Vessel #2

Route	Distance (nm)
Chicago Water Taxi: Michigan Avenue	0.9
Chicago Water Taxi: Chinatown	1.5
Boston Water Taxi: Boston - Logan Airport	1.1
Boston Water Taxi: Charlestown – Long Warf	1.1

For conservatism, a two nautical mile notional route was developed with a 9-minute passenger load and unload period. A small amount of propulsion power was included during the loading period as it is common for the vessel to push against the embarkation ramp or pilings during loading operations. A short maneuvering period is included at the start and end of the route with the remainder of the route at cruising speed. A breakdown of the route and the estimate fuel consumption is shown below. The fuel consumption assumes a fuel cell efficiency of 45%. Based on this notional route, the vessel is capable of completing 18 one-way trips before needing to refuel which is about one full day of operation during peak season.

Table 20: Notional route for Vessel #2

Speed (kts)	Distance (nm)	Time (min)	Propulsion Power (kW)	Hotel Load (kW)	Total Power (kW)	% Load of Installed Power	Total Energy (kW-hr)	Fuel Consumption (kg)
2	0.05	1.5	72	20	92	34%	2.3	0.2
8	1.90	14.3	203	20	223	83%	53.0	3.5
2	0.05	1.5	72	20	92	34%	2.3	0.2
0	0.00	9.0	24	20	44	16%	6.6	0.4
Total	**2.0**	**26.3**					**64.2**	**4.3**

3.7 Capital Cost Estimate

A parametric estimate of the capital cost of Vessel #2 was made. The estimate was based on the lightship weight of the vessel. Each SWBS group was assigned a material cost per ton and labor hours per ton factor based on previously constructed vessels. The estimate assumed a labor rate of $73 per hour which is an average between the typically assumed rates for Pacific Northwest and Gulf Coast shipyards. A 10% margin was included for conservatism and 10% contingency was included to account for cost growth during the time between estimate completion and vessel delivery. The cost of engineering and constructions services were assumed to be higher than for a traditionally power vessel due to the added complexity of the H2 system.

The material cost of the hydrogen fuel cells and the cryogenic fuel tank were considered separate from the parametric weights based analysis. The cost of the fuel cells was assumed to be $2,200/kW. This cost was given by Hydrogenics as the upper range of expected fuel cell cost today based on a one-time order with ruggedization and marinization options. The lower range was given as $1,800/kW without the additional options. Since the fuel cells will be located in a controlled environment fuel cell room, the ruggedization and marinzation options may be unnecessary, according to Hydrogenics. The cost of the hydrogen tanks was assumed to be

$1000 per kilogram of tank weight based on previous experience with the cost of composite hydrogen tanks. The cost of the additional components in the H2 system was assumed to be included in the estimated cost of Group 200.

The total capital cost to construct Vessel #2, including engineering and construction services, is estimated to be $3,500,000. Additional calculation details are provided in Appendix B.

4 VESSEL #3

Vessel #3 is a high speed catamaran ferry design to carry 350 passengers. The Subchapter K vessel has an aluminum hull and a cruising speed of 24 knots.

Table 21: Vessel #3 particulars

Particulars	
Length Overall	140 ft 2 in
Beam	38 ft 4 in
Depth	13 ft 1 in
Hullform	Catamaran
Passenger Capacity	350 PAX
Vehicle Capacity	-
Cruising Speed	24 kts
Installed Power	4,200 kW
Fuel Cell Modules	140
Tank Volume	20,355 L water
Tank Capacity	1,369 kg

4.1 General Arrangements

4.1.1 Main Deck Arrangements

The main deck features a large primary passenger cabin with fixed seating for 260 passengers. Each side of the vessel has an embarkation door located at midship. There is a small passenger accessible deck at the bow of the vessel. At the rear of the passenger cabin there is a bar and three ADA accessible heads. Aft of the passenger cabin is a control space with the switchboard and electrical conversion and motor drive equipment.

Two fuel cells rooms which contain a total of 35 fuel cell racks are located at the stern of the vessel. The entrance to these spaces is from the aft deck which is accessed by a crew-only stair from the upper deck. The fuel cell rooms are vented directly to the aft deck. While the fuel cell racks could be placed below deck in the demihulls, this would lead to the fuel cells being split up between four compartments, each requiring an individual air lock. To eliminate the need for airlocks and to consolidate the racks into two spaces, the fuel cell racks were put on the aft end of the main deck.

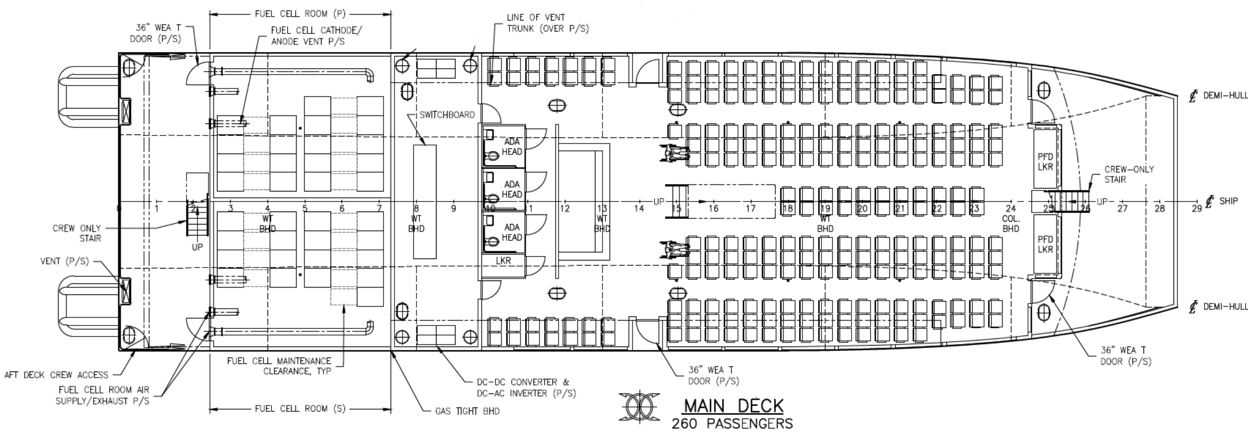

Figure 16: Vessel #3 main deck arrangement

4.1.2 Upper Deck Arrangements

The cryogenic LH2 fuel tank is located on the upper deck. There is a tank connection and vaporizer space immediately aft of the tank with bunkering station on the starboard side. The tank is flanked by a cabin with seating for 90 passengers. The pilothouse is located forward of the passenger cabin. The upper deck is accessed via a stair on centerline, or by a crew-only stair from the forward deck.

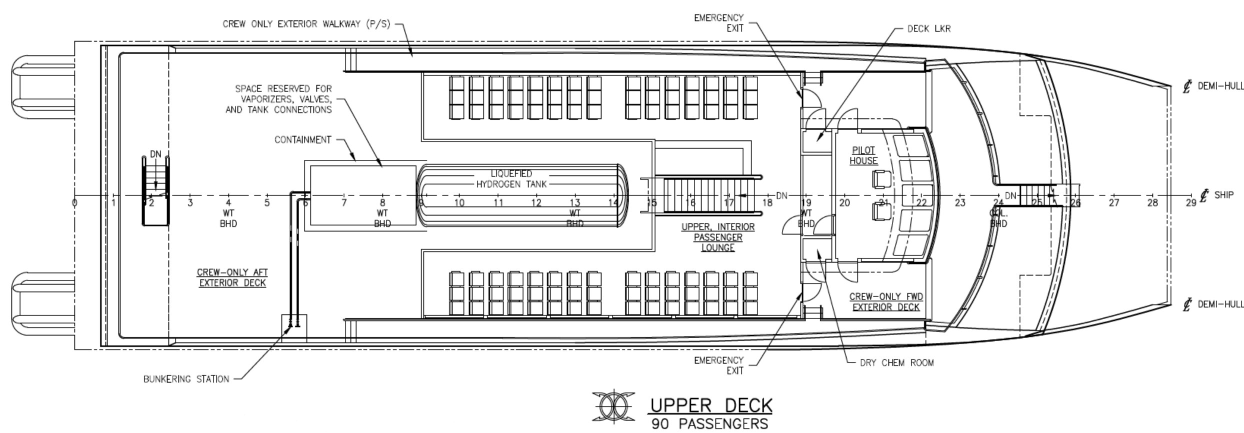

Figure 17: Vessel #3 upper deck arrangement.

4.1.3 Hold Arrangements

Two Rolls-Royce waterjets are located at the stern of the vessel. These are directly driven by two electric motors located in the compartments immediately forward. Two auxiliary machinery rooms are located forward of the motor rooms. The remainder of the demihulls is void spaces. All spaces in the hold are accessed via a hatch and vertical ladder from the main deck.

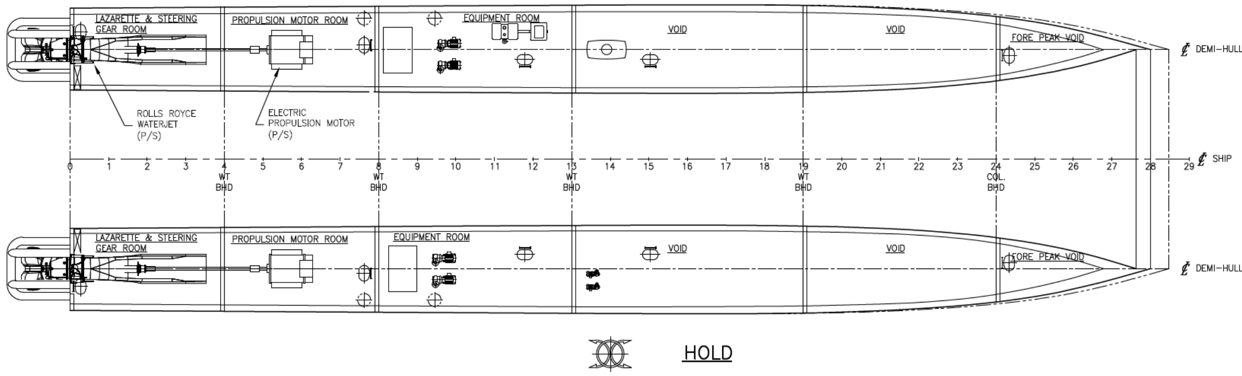

Figure 18: Vessel #3 hold arrangement

4.1.4 Outboard Profile

The outboard profile is shown in Figure 19. The tank vent can be seen extending up from the tank connection and vaporizer space. Motor room and passenger space ventilation is located forward below the pilothouse to ensure it is outside the hazardous zone created by the tank.

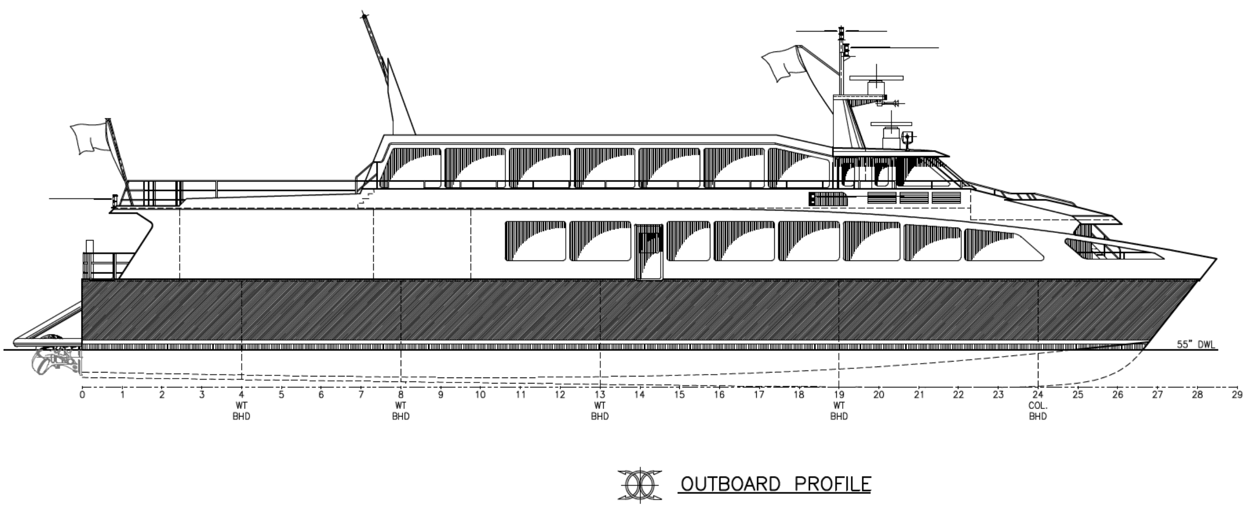

Figure 19: Vessel #3 outboard profile

4.1.5 LH2 Equipment

The fuel cell specifications are provided in Table 22. LH2 tank specifications are provided in Table 23.

Table 22: Fuel cell specifications

Characteristic	
Manufacturer	Hydrogenics
Model	HyPM HD30
Module Dimensions (LxWxH)	28.3 x 16 x 10.3 in
Module Weight	160 lbs
Modules/Rack	4
Rack Dimensions (LxWxH)	42.1 x 30 x 78.7 in
Rack Weight	1,764 lbs
Quantity of Racks	35
Number of Modules	140
Total Weight	61,740 lbs

Table 23: Tank specifications

Characteristic	
Manufacturer	Linde
Model	Size 200 Cryogenic Tank
Tank Volume	20,355 L water
Tank Capacity	1,369 kg
Tank Dimensions (L x D)	27.4 x 7.9 ft
Tank Weight	27,139 lbs

4.1.6 Regulatory Compliance

While the vessel design is at a concept level, all efforts were made to ensure the vessel is capable of meeting regulatory requirements of the USCG, including the IGF Code. The vessel generally complies with all regulatory rules considered. However, the passenger cabin on the upper deck has two dead end corridors where the cabin flanks the LH2 tank on centerline. It would be up to the discretion of the USCG whether to allow these dead end corridors in the passenger cabin as they can cause confusion during emergency situations.

4.2 Weights

4.2.1 Lightship Weight

The lightship weight calculation was based on a combination of an itemized weight estimate and a parametric weight estimate. The total lightship weight was estimated by scaling the weight of an existing high-speed aluminum ferry by the overall dimensions of length, beam, and depth. The weights of the engines and associated systems were then removed from lightship weight based on the installed power. After the total lightship weight was calculated, it was divided into SWBS groups based on the typical percentage of total weight. The assumed percentages are given in Table 24.

Table 24: Assumed breakdown of weight by SWBS group

SWBS Group	Description	Percentage
100	Structure	44%
200	Machinery	10%
300	Electrical	10%
400	Electronics	1%
500	Auxiliary Systems	20%
600	Outfit	15%

Items which were required for the hydrogen power plant were then added to the estimate. The weights of the LH2 system equipment were based on manufacturer specifications with the exception of the propulsion system electrical components (DC-DC converters, DC-AC inverters, filters, line reactors, etc.) which were scaled by installed power from the line item estimate of the SF-BREEZE. For simplicity, all LH2 system weights were added to Group 200. Table 25 lists the equipment which was added to the baseline weight estimate.

Table 25: Line item weights added to the baseline estimate

Weights Added
• Electric Propulsion Motors • Propulsion System Electrical Components • Fuel Cell Racks • Vaporizers • LH2 Tank

Margins were included for each weight group in accordance with standard naval architecture practice. The centers of gravity of the baseline weights were estimated and estimates of equipment locations were made for each line item weight. The overall center of gravity was estimated in order to verify vessel trim and stability.

The estimated lightship weight of the vessel is 170.3 LT. Table 26 shows the total weight broken down by SWBS group.

Table 26: Lightship weight estimate summary

SWBS Group	Description	Weight [LT]
100	Structure	47.8
200	Machinery	72.6
300	Electrical	10.9
400	Electronics	1.1
500	Auxiliary Systems	21.7
600	Outfit	16.3
	Total	**170.3**

4.2.2 Deadweight

The vessel's deadweight was calculated with an itemized estimate of all cargo and variable loads. Passengers were assigned a weight of 185 lbs in accordance with USCG regulation. Crew members were assigned a weight of 225 lbs. A 5% service life margin was included to provide an allowance for weight growth over the life of the vessel. The weight of LH2 was also included in the deadweight. The total deadweight was estimated to be 43.5 LT. Table 27 shows a summary of the deadweight calculation.

Table 27: Summary of deadweight for Vessel #3

Item	Weight [LT]
Crew and Effects	0.5
Passengers	28.9
Stores	0.45
Potable Water	3.8
Sewage	0.2
LH2	1.4
Service Life Margin	8.33
Total	**43.5**

4.2.3 Full Load Condition

Summing the lightship weight and the deadweight results in a full load displacement of 213.8 LT. The hullform was designed to displace 223 LT at the design load water line of 55 in. The vertical center of gravity of the full load condition is estimated to be 12 ft above baseline.

4.3 Speed and Power

A speed and powering analysis was undertaken to estimate the required vessel propulsion power. The analysis used a combination of parametric regression analysis with NavCAD 2016 and CFD.

The need for CFD was driven by the vessel's size and speed. At the desired cruising speed of 24 knots, the vessel is transitioning from a displacement regime to a planing regime. Regression analysis is known to provide inaccurate results for vessels operating in this transition. Therefore, the hull resistance was calculated using CFD in order to provide better confidence in the solution. The superstructure resistance was calculated in NavCAD as this is not affected by the planing transition.

The parameters required for the NavCAD analysis were measured from the general arrangement. The CFD geometry was taken from a 3D model of the hullform created in Rhinoceros 3D. The CFD simulation used a full width domain in order to capture the effects of wake interference between the two demihulls. The simulation was performed on a mesh with 4.6 million elements and the vessel was allowed to heave and trim throughout the run. The transient simulation was run for a length of time sufficient to achieve a converged result. Figure 20 shows an image of the vessel's wake at the cruising speed as predicted by the CFD.

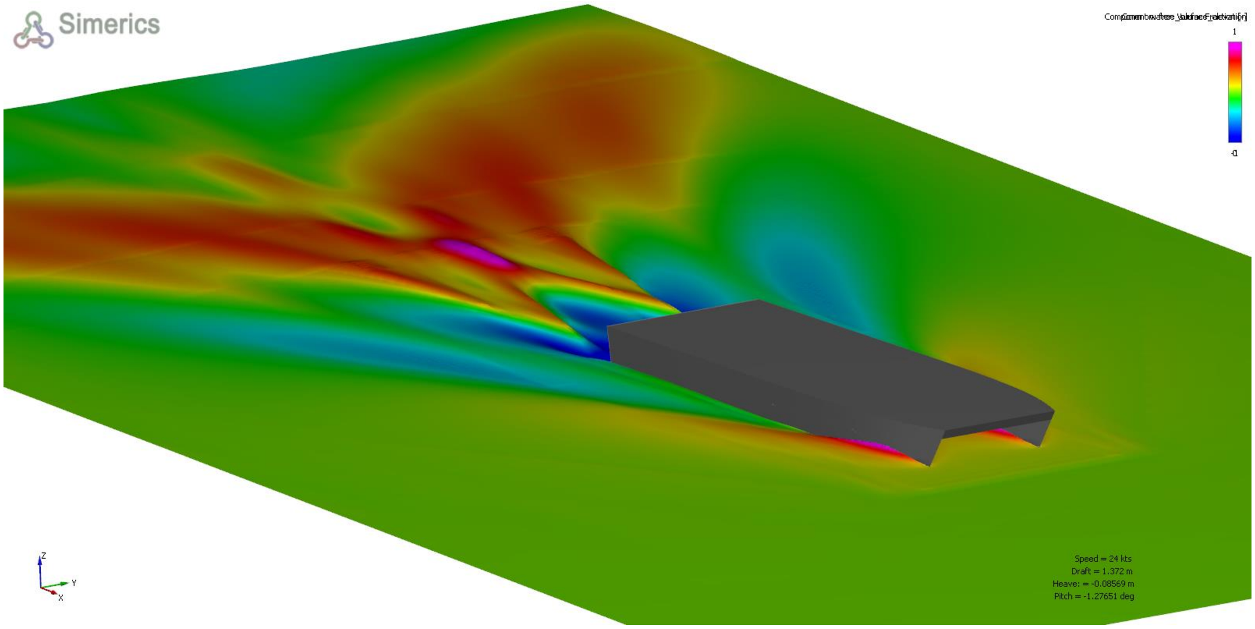

Figure 20: The wake at 24 knots

The hull resistance was estimated in calm water with a clean hull at even keel. A 5% margin was added to the vessel drag to account for any potential appendages and an 8% margin was added for conservatism. At 24 knots, the vessel requires 1,895 kW of effective power.

To determine the required propulsion shaft power, the efficiency of the waterjets had to be calculated. Twin Rolls-Royce KAMEWA S80-4 waterjets were selected for propulsion as they offered the highest efficiency compared to several other models considered. Using thrust curves provided by Rolls-Royce, the required shaft power at 24 knots was determined to be 3,320 kW.

The power plant was sized assuming a vessel cruise condition at 90% of the maximum continuous rating (MCR). Propulsion system efficiencies were assumed to be as shown in Table 28. From these, the required brake power was calculated to be 4,085 kW.

Table 28: Propulsion electrical system efficiencies

Equipment	Efficiency
Electric Motor	96%
AC Inverter	97%
DC Converter	97%

The vessel's hotel loads were estimated from the loads analysis of a recently designed high-speed passenger ferry. While Vessel #3 is larger than the source design, the required electrical load was scaled up based on the ratio of length, beam, and depth between the two designs. With this method, the total required electrical load was calculated to be 102 kW.

Considering the propulsion system efficiencies and MCR requirements, and including the hotel loads, the total capacity of the hydrogen power plant was calculated to be 4,187 kW. This load is generated by 35 fuel cell racks, each containing four Hydrogenics HyPM HD 30 modules generating 30 kW of power.

4.4 Stability

A preliminary stability assessment was completed in order to confirm the feasibility of the vessel design. The preliminary assessment considered USCG subdivision and intact stability requirements for passenger vessels. The analysis was completed using GHS version 15. The GHS model was created from the Rhinoceros model used in the speed and power analysis.

The maximum allowable VCG was calculated based on the following criteria:

- 46 CFR §170.170 Weather Criteria
- 46 CFR §170.173 Criterion for Vessels of Unusual Proportion and Form
- 46 CFR §171.050 Passenger Heel Requirements

Figure 21 shows a plot of all criteria over the expected trim and displacement range. For conservatism, it was assumed the vessel was operating on exposed waters. Calculations are provided in Appendix C. The full load VCG is estimated to be 12 ft. indicating the concept vessel arrangements comply with intact stability criteria.

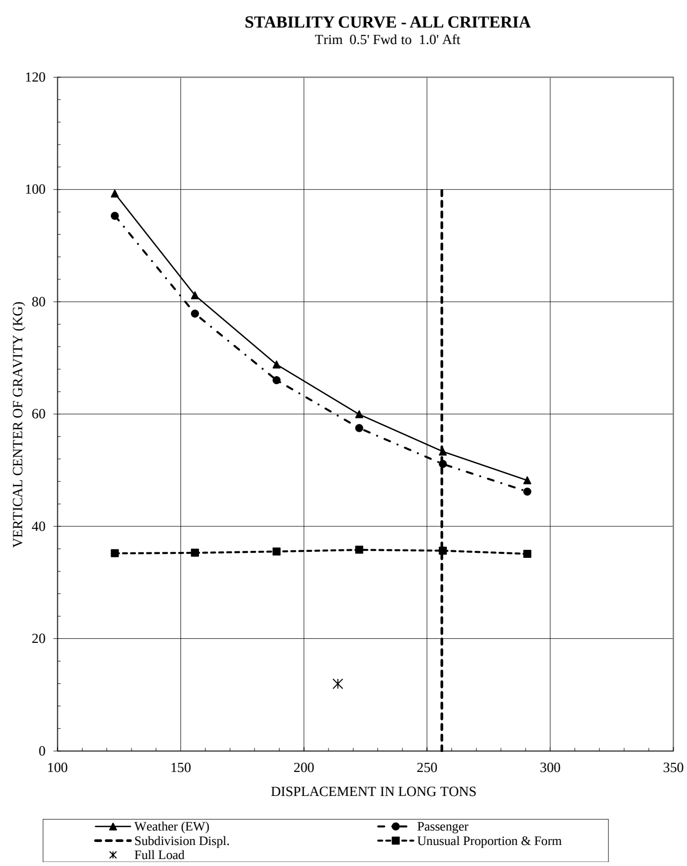

Figure 21: Maximum VCG plot for Vessel #3

The subdivision requirements were verified with a floodable length curve at the vessel's full load draft. Per 46 CFR § 171.070, the floodable length analysis uses a two compartment standard of flooding for all of the vessel forward of the first main transverse watertight bulkhead aft of the collision bulkhead and a single compartment standard of flooding throughout the remainder of the vessel. Figure 22 shows the floodable length curve with 95% and 85% compartment permeabilities. In each case, the bulkhead arrangement passes the floodable length calculation.

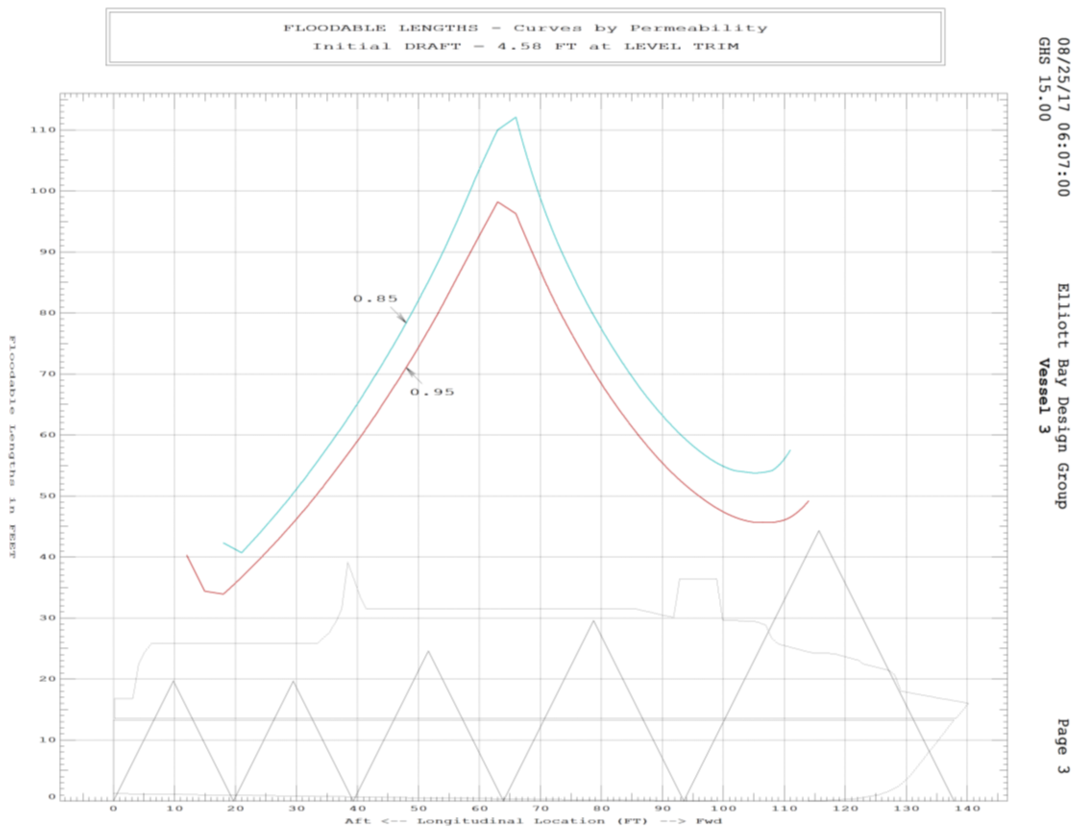

Figure 22: Floodable length curve for Vessel #3

4.5 Tonnage

An estimate of the vessel's GRT was completed to confirm the vessel would comply with the tonnage limitations of Subchapter K. The under-deck tonnage was measured with 10 stations over a tonnage length of 131 ft 4 in. The main deck passenger cabin was assumed to be deducted from tonnage through the use of a qualified tonnage opening on the forward end of the passenger cabin. The switchboard room and fuel cell rooms were deducted from tonnage as they are a machinery space. The upper deck passenger cabin was deducted from tonnage with a qualified tonnage opening in way of one emergency exit door on the forward bulkhead. With this methodology, the tonnage was estimated to be 97.20 GRT. Detailed calculations are included in Appendix C.

4.6 Route and Endurance

Table 29 gives examples of routes which use high-speed ferries of approximately the same capacity. Based on these examples, a notional route was developed for Vessel #3 (see Table 30). The route is 25 nautical miles in length and includes a short maneuvering period and 20 minutes for passenger loading and unloading. A small amount of propulsion power was included during the loading period as it is common for the vessel to push against the embarkation ramp or pilings during loading operations. The fuel consumptions calculation assumes a fuel cell efficiency of 45%. Based on this notional route, the vessel is capable of completing four one-way trips before needing to refuel. This may result in the vessel needing to bunker multiple times a day. It is not feasible to increase the size of the LH2 tank for this arrangement as it would lead to excessive trim by the stern.

Table 29: Example routes for Vessel #3

Route	Distance (nm)	Vessel Capacity (PAX)
Hyannis - Nantucket	26	400
Vallejo - Pier 41	23	320

Table 30: Notional route for Vessel #3

Speed (kts)	Distance (nm)	Time (min)	Propulsion Power (kW)	Hotel Load (kW)	Total Power (kW)	% Load of Installed Power	Total Energy (kW-hr)	Fuel Consumption (kg)
0	0.00	20.0	205	102	307	7%	102.3	6.8
6	0.50	5.0	1022	102	1124	27%	93.7	6.2
24	24.00	60.0	3473	102	3575	85%	3575.0	238.3
6	0.50	5.0	1022	102	1124	27%	93.7	6.2
Total	**25.0**	**90.0**					**3864.7**	**257.6**

4.7 Capital Cost Estimate

A parametric estimate of the capital cost of Vessel #3 was made. The estimate was based on the lightship weight of the vessel. Each SWBS group was assigned a material cost per ton and labor hours per ton factor based on previously constructed vessels. The estimate assumed a labor rate of $73 per hour which is an average between the typically assumed rates for Pacific Northwest and Gulf Coast shipyards. A 10% margin was included for conservatism and 10% contingency was included to account for cost growth during the time between estimate completion and vessel delivery. The cost of engineering and constructions services were assumed to be higher than for a traditionally power vessel due to the added complexity of the LH2 system.

The material cost of the hydrogen fuel cells and the cryogenic fuel tank were considered separate from the parametric weights based analysis. The cost of the fuel cells was assumed to be $2,200/kW. This cost was given by Hydrogenics as the upper range of expected fuel cell cost today based on a one-time order with ruggedization and marinization options. The lower range was given as $1,800/kW without the additional options. Since the fuel cells will be located in a controlled environment fuel cell room, the ruggedization and marinzation options may be unnecessary, according to Hydrogenics. The cost of the hydrogen tank was assumed to be $700 per kilogram of tank weight based on the original SF-BREEZE capital cost estimate. The cost of the additional components in the LH2 system was assumed to be included in the estimated cost of Group 200.

The total capital cost to construct Vessel #3, including engineering and construction services, is estimated to be $35,200,000. Additional calculation details are provided in Appendix C.

5 VESSEL #4

Vessel #4 is a Subchapter K 400 passenger ferry with steel hull. The single-ended vessel is designed to cruise at 12 knots.

Table 31: Vessel #4 particulars

Particulars	
Length Overall	135 ft.
Beam	32 ft.
Depth	11 ft.
Hullform	Single-ended
Passenger Capacity	400 PAX
Vehicle Capacity	-
Cruising Speed	12 kts
Installed Power	870 kW
Fuel Cell Modules	29
Tank Volume	11,535 L water
Tank Capacity	776 kg

5.1 General Arrangements

The performance requirements of Vessel #4 are common of a boat which is operated as an excursion or dinner-cruise vessel. The decks are arranged as such, though the interior spaces could easily be converted to a more traditional passenger ferry arrangement with fixed seating.

5.1.1 Main Deck Arrangement

The main deck features a large open passenger lounge with a bar aft and restroom facilities forward in the bow. The hydrogen tank is positioned in a partially enclosed space on the aft deck with bulkheads separating it entirely from the passenger lounge. The superstructure is set in from the deck edge on both sides near midship, creating passenger embarkation spaces. At the aft ends of these spaces are two doors opening to vertical ladders which provide access to the fuel cell rooms. These fuel cell access doors are position far enough from the passenger doors to be outside the hazardous zone. This arrangement means the fuel cell rooms can easily be accessed without the need for airlocks.

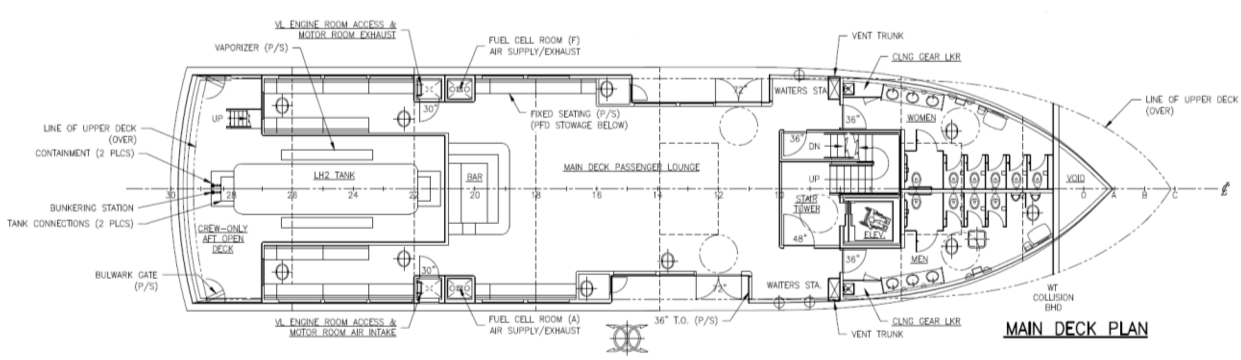

Figure 23: Vessel #4 main deck plan

5.1.2 Upper Deck Arrangement

The upper deck features another large passenger lounge with a bar aft. Crew access to the fuel tank is made from a stair at the aft deck. Passengers are allowed on the remaining portions of open deck with a rail keeping them forward of the hazardous zone boundaries.

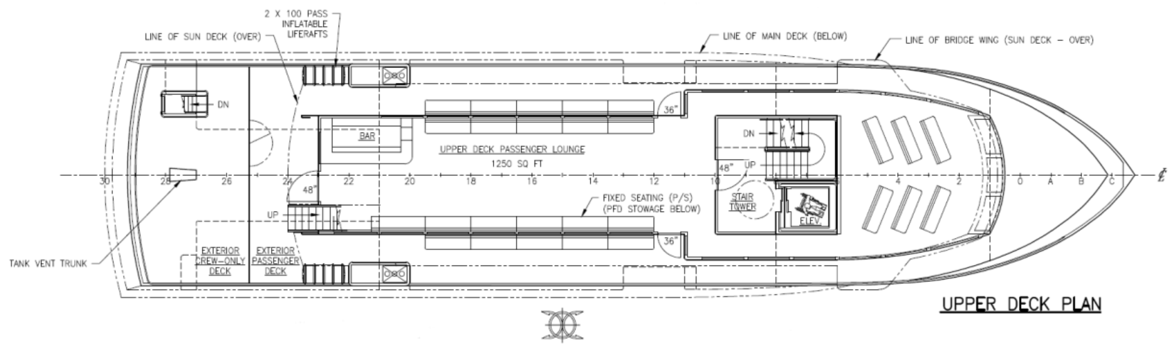

Figure 24: Vessel #4 upper deck plan

5.1.3 Sun Deck Arrangement

The open-air sun deck is available for passenger access. The fuel cell rooms vent from the stacks near the sun deck. It is assumed that a dispersion analysis would show that hydrogen would travel up from the vents and not contact the passenger spaces on the sun deck.

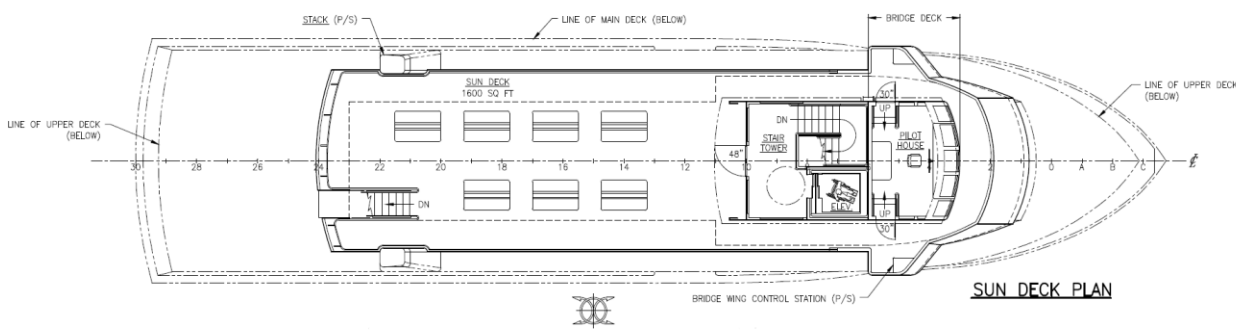

Figure 25: Vessel #4 sun deck plan

5.1.4 Hold Arrangement

The fuel cell rooms are full transverse compartments located near midship. Forward of the fuel cell rooms is a storeroom for crew use only. A potable water tank is forward of the stair and elevator. The motor room is aft of the fuel cell rooms with access from vertical ladders through the stacks above. A sewage tank is located aft of the motor room with a steering gear compartment at the stern of the vessel. The fuel cell rooms are vented with double-walled piping which leads aft from the compartment and runs up the stacks to louvers above the sun deck.

Double wall piping was selected for venting the fuel cell rooms as these vent pipes travel through non-hazardous spaces. As an alternative, single wall piping could be run through ducting. However, it was believed this would lead to more costly construction and maintenance compared to double-walled piping.

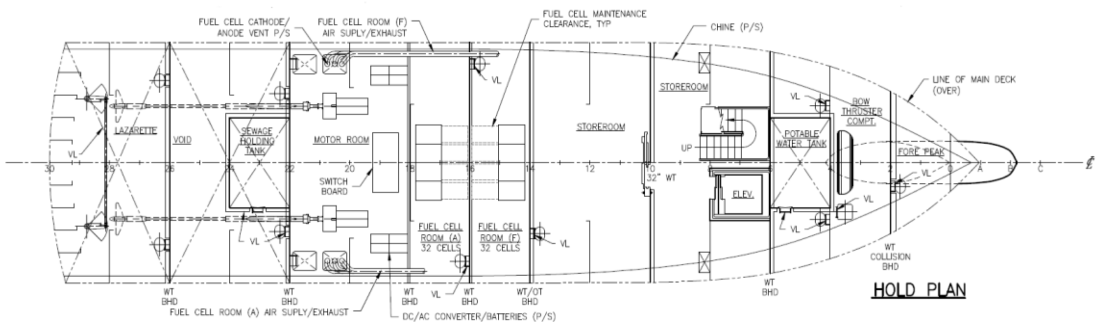

Figure 26: Vessel #4 hold plan

5.1.5 Outboard Profile

The outboard profile is shown in Figure 27. The tank vent is located on the upper deck at the stern of the vessel.

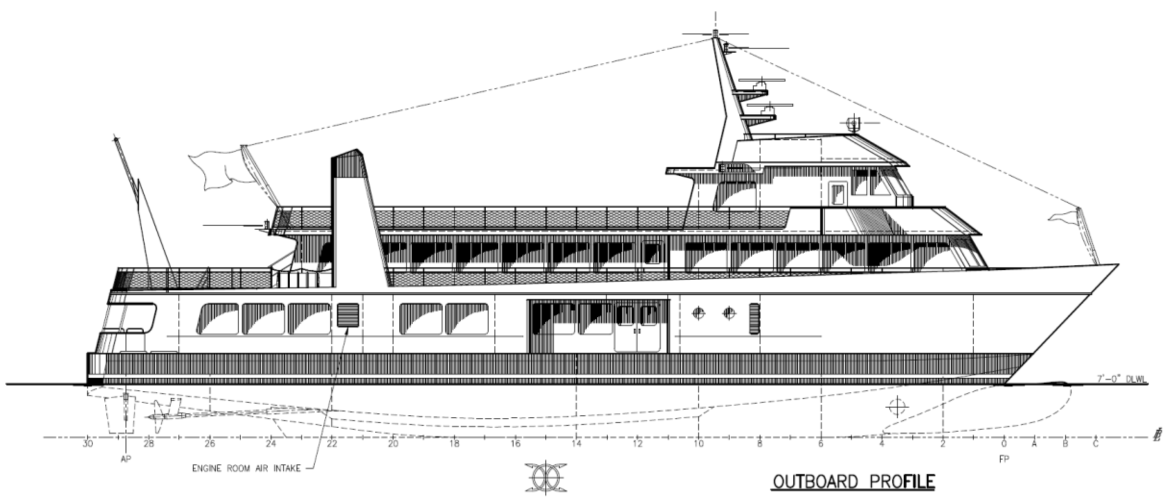

Figure 27: Vessel #4 outboard profile

5.1.6 LH2 Equipment

The fuel cell specifications are provided in Table 32. The vessel has a total of eight racks which hold 29 HyPM HD30 modules. LH2 tank specifications are provided in Table 33.

Table 32: Fuel cell specifications

Characteristic	
Manufacturer	Hydrogenics
Model	HyPM HD30
Module Dimensions (LxWxH)	28.3 x 16 x 10.3 in
Module Weight	160 lbs
Modules/Rack	4
Rack Dimensions (LxWxH)	42.1 x 30 x 78.7 in
Rack Weight	1,764 lbs
Quantity of Racks	8
Total Modules	29
Total Weight	14,122

Table 33: Tank specifications

Characteristic	
Manufacturer	Linde
Model	Size 110 Cryogenic Tank
Tank Volume	11,535 L water
Tank Capacity	776 kg
Tank Dimensions (L x D)	24.1 x 6.6 ft
Tank Weight	15,829 lbs

5.1.7 Regulatory Compliance

While the vessel design is at a concept level, all efforts were made to ensure the vessel is capable of meeting regulatory requirements of the USCG, including the IGF Code. The vessel generally complies with all regulatory rules considered. However, the passenger accessible sun deck is currently within the hazardous zone of the fuel cell room ventilation outlet. It is assumed that a dispersion analysis would demonstrate that any expelled hydrogen would travel up and not down towards the sun deck. The ventilation outlet could also be raised, though the height is limited by the navigation light requirements. In addition, the tank and bunkering station are contained within a partially enclosed space. The IGF Code requires that such spaces have a sloping ceiling. Presently, the vessel is designed without this type of ceiling detail due to the size of the space and the limited height between the decks.

5.2 Weights

5.2.1 Lightship Weight

The baseline lightship weight calculation was based on a combination of a parametric weight estimate and a preliminary steel weight estimate. A 3D model of the hull, internal bulkheads, deck, and superstructure plating was developed in Rhinoceros 3D. The surface areas of each plate were measured in Rhinoceros and a weight calculated based on an estimate of the likely plate thickness. A margin was added to the weight of the plating to account for stiffening. An additional 15% margin was added to the total to account for tanks and structural details and for general conservatism. Weights for SWBS groups 200 to 600 were estimated based on the dimensions of the vessel and a weight coefficient taken from a database of previous vessels.

The weight of a representative main engine and an estimate of the main engine systems were then removed from the baseline lightship weight estimate. Further, items which were required for the hydrogen power plant were added to the estimate. The weights of the LH2 system equipment were based on manufacturer specifications with the exception of the propulsion system electrical components (DC-DC converters, DC-AC inverters, filters, line reactors, etc.) which were scaled by installed power from the line item estimate of the SF-BREEZE [2]. For simplicity, all LH2 system weights were added to Group 200. Table 34 lists the equipment which was added to and removed from the baseline weight estimate.

Table 34: Line item weights added to and removed from the baseline estimate

Weights Added	Weights Removed
• Electric Propulsion Motors • Propulsion System Electrical Components • Fuel Cell Racks • LH2 Tanks • Vaporizers	• Main Propulsion Engines • Main Engine Systems • Electrical Generators

Margins were added to each weight group in accordance with standard naval architecture practice. The center of gravity of Group 100 was measured in the 3D plate model and the center of Group 600 was assumed to be in the same location. The centers of gravity of the remaining groups were based on a weight estimate for a vessel of the same length and depth with a similar arrangement, but with a slightly wider beam. As the boat is assumed symmetric, these centers could be used directly. The overall center of gravity was estimated in order to verify vessel trim and stability.

The estimated lightship weight of the vessel is 244.0 LT. Table 35 shows the total weight broken down by SWBS group.

Table 35: Lightship weight estimate summary

SWBS Group	Description	Weight [LT]
100	Structure	160.3
200	Machinery	25.2
300	Electrical	5.7
400	Electronics	0.4
500	Auxiliary Systems	28.7
600	Outfit	23.7
	Total	**244.0**

5.2.2 Deadweight

The vessel's deadweight was calculated with an itemized estimate of all cargo and variable loads. Passengers were assigned a weight of 185 lbs in accordance with USCG regulation. Crew members were assigned a weight of 225 lbs. A 5% service life margin was included to provide an allowance for weight growth over the life of the vessel. The weight potable water, sewage, and of the compressed hydrogen gas was also included in the deadweight. The total deadweight was estimated to be 80.6 LT. Table 36 shows a summary of the deadweight calculation.

Table 36: Summary of deadweight for Vessel #4

Item	**Weight [LT]**
Crew and Effects	1.0
Passengers	32.0
Stores	4.5
Potable Water	15.7
Sewage	15.7
LH2	0.7
Service Life Margin	12.2
Total	**80.6**

5.2.3 Full Load Condition

Summing the lightship weight and the deadweight results in a full load displacement of 324.6 LT. The hullform was designed to displace 327 LT at the design load water line of 7 ft. The vertical center of gravity of the full load condition is estimated to be 13.4 ft above baseline.

5.2.4 Weight Reduction

As previously discussed, reducing the vessel's lightship weight is beneficial as it results in a reduction in required propulsion power. One method of reducing the lightship weight is to construct the vessel out of aluminum. To estimate the impact, it is assumed an aluminum structure weighs 70% of an equivalent steel structure. Therefore, the total structural weight reduction with aluminum is approximately 48 LT, or 20% of the vessel's lightship weight. Note that the use of aluminum in a vessel's structure impacts other aspects of the design, such as a need for increased fire protection. While this would likely reduce the weight savings by some amount, it is feasible that an aluminum vessel could have a reduced propulsion power compared to the steel-hulled vessel analyzed in this design.

5.3 Speed and Power

As with Vessels #1 and #2, a speed and powering analysis was completed in NavCAD 2016. The parameters required for the analysis were measured from the general arrangement and from a 3D model of the hullform created in Rhinoceros 3D.

The hull resistance was estimated in calm water with a clean hull at even keel. For conservatism, the hullform had an excess displacement of 15% so an additional margin on the resistance was not included. Propeller characteristics were optimized in NavCAD based on a 52" propeller diameter. Figure 28 shows a plot of the required shaft power over the anticipated speed range. At the cruising speed of 12 knots, the vessel requires 535 kW of shaft power.

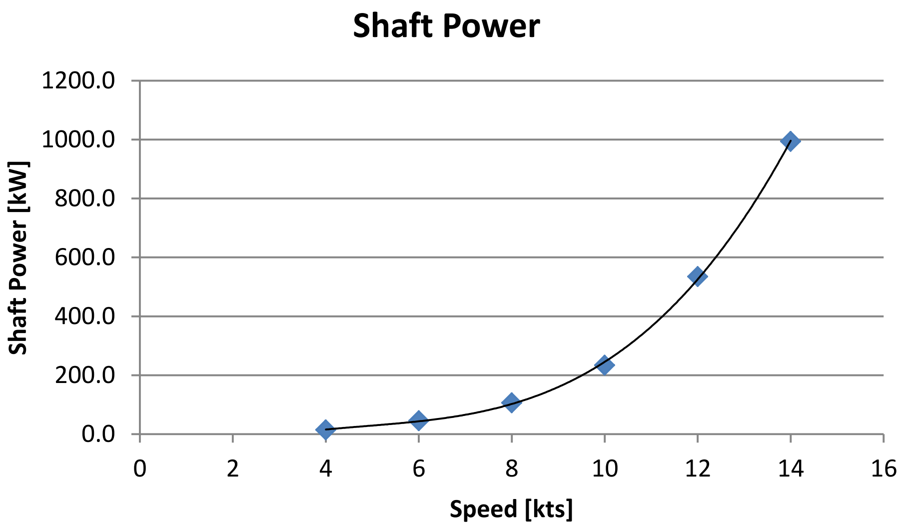

Figure 28: Required shaft power for Vessel #4

The power plant was sized assuming a vessel cruise condition at 85% of the maximum continuous rating (MCR). Propulsion system efficiencies were assumed to be as shown in Table 37. From these, the required brake power was calculated to be 700 kW.

Table 37: Propulsion electrical system efficiencies

Equipment	Efficiency
Electric Motor	96%
AC Inverter	97%
DC Converter	97%

To estimate the hotel loads, the electrical system of a vessel of similar capacity and arrangement was studied. The previous design used two generators with a total of 170 kW of power. While the generators are likely oversized, it was decided that the full generator capacity would be included for conservatism.

Considering the propulsion system efficiencies and MCR requirements, and including the hotel loads requirements, the required capacity of the hydrogen power plant was calculated to be 870 kW. This load is generated by eight fuel cell racks, containing a total of 29 Hydrogenics HyPM HD 30 modules generating 30 kW of power.

5.3.1 CFD Analysis

After completion of the concept design, a CFD analysis was performed in order to determine the vessel's resistance with greater accuracy. The CFD geometry was taken from a 3D model of the hullform created in Rhinoceros 3D and was modeled up to the main deck level. The CFD simulation mesh had 4.4 million elements and utilized a symmetry plane on the vessel's centerline to reduce the cell count. The vessel was allowed to heave and trim throughout the run.

The transient simulation was run for a length of time sufficient to achieve a converged result. Figure 29 shows the wake at the cruising speed of 12 knots.

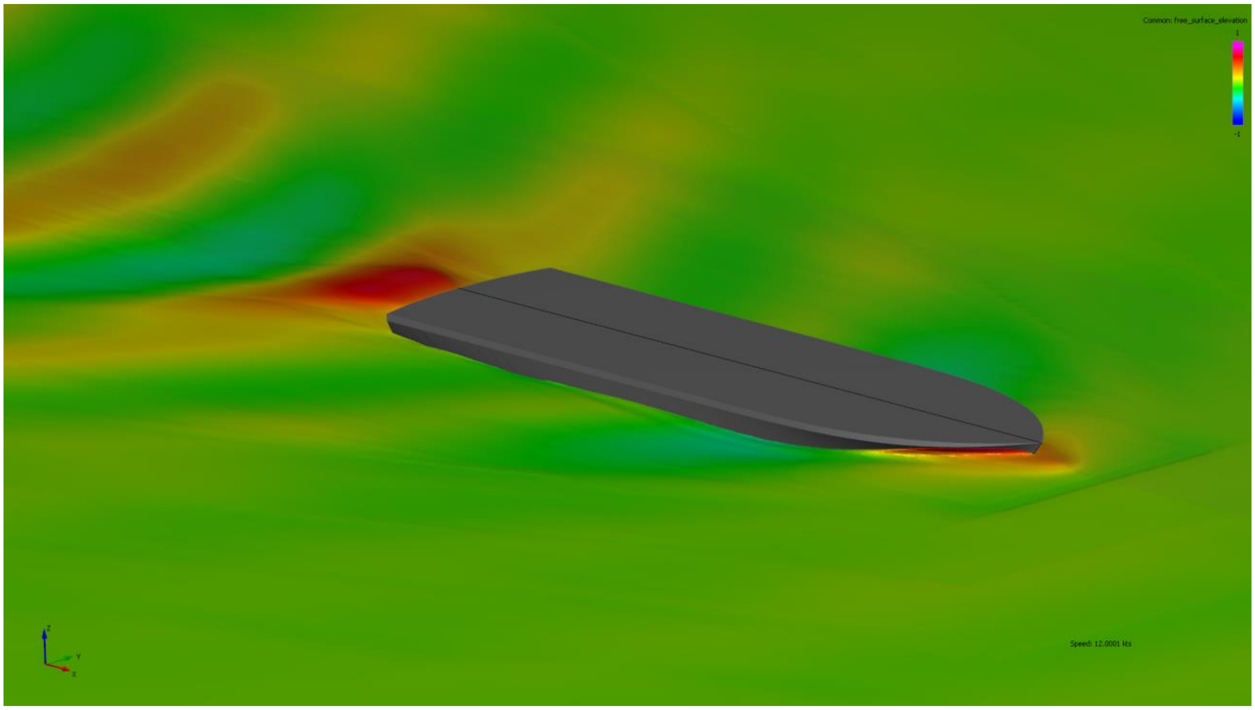

Figure 29: The vessel's wake at 12 knots

The CFD simulation indicated the vessel's resistance would be 15% less than was predicted with the initial parametric analysis. The resulting reduction in propulsion power reduces the fuel cell module count from 29 to 26 and reduces the fuel consumption per trip by 10 kg to 92.6 kg. The overall endurance is not changed. See Section 5.6 for additional details on the endurance.

5.4 Stability

A preliminary stability assessment was completed in order to confirm the feasibility of the vessel design. The preliminary assessment considered USCG subdivision and intact stability requirements for passenger vessels. The analysis was completed using GHS version 15. The GHS model was created from the Rhinoceros model used in the speed and power analysis.

The maximum allowable VCG was calculated based on the following criteria:

- 46 CFR §170.170 Weather Criteria
- 46 CFR §170.173 Criterion for Vessels of Unusual Proportion and Form
- 46 CFR §171.050 Passenger Heel Requirements

Figure 30 shows a plot of all criteria over the expected trim and displacement range. For conservatism, it was assumed the vessel was operating on exposed waters. Calculations are provided in Appendix D. The full load VCG is estimated to be 13.4 ft indicating the concept vessel arrangements comply with intact stability criteria.

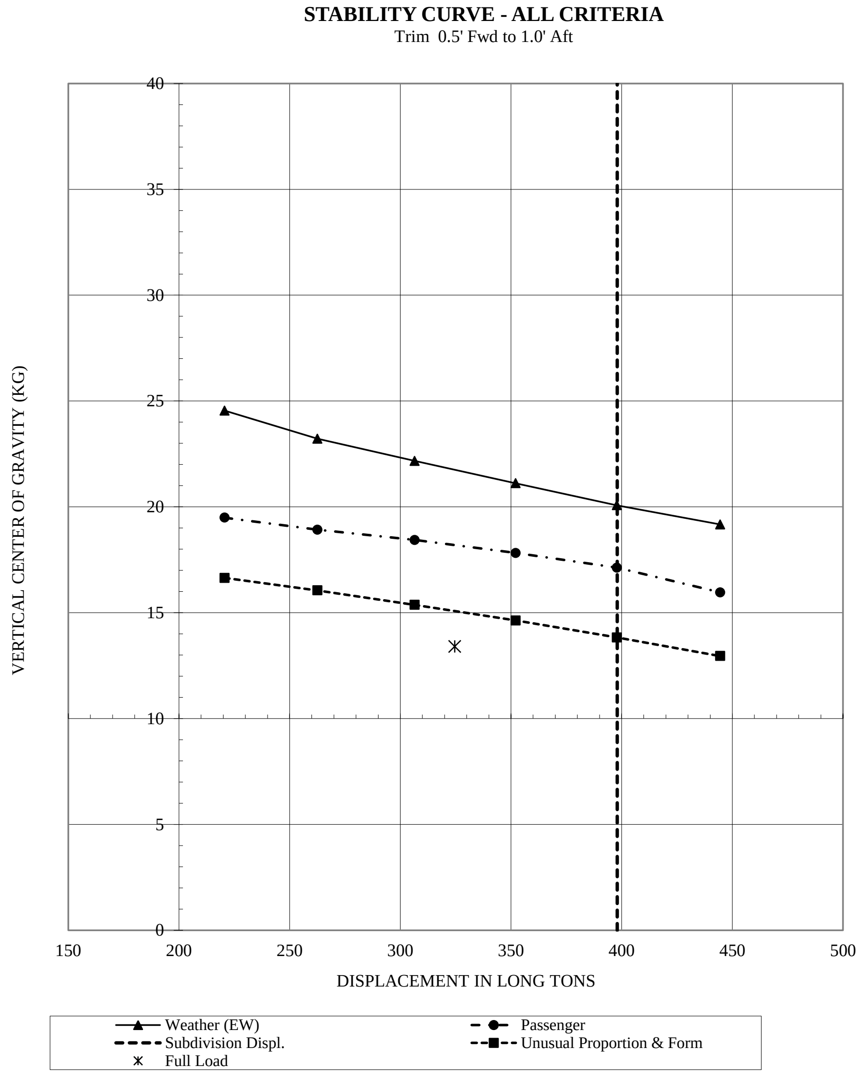

Figure 30: Maximum VCG curve for Vessel #4

The subdivision requirements were verified with a floodable length curve at the vessel's full load draft. Per 46 CFR § 171.070, the floodable length analysis uses a two compartment standard of flooding for all of the vessel forward of the first main transverse watertight bulkhead aft of the collision bulkhead and a single compartment standard of flooding throughout the remainder of the vessel. Figure 31 shows the floodable length curve with 95% and 85% compartment permeabilities.

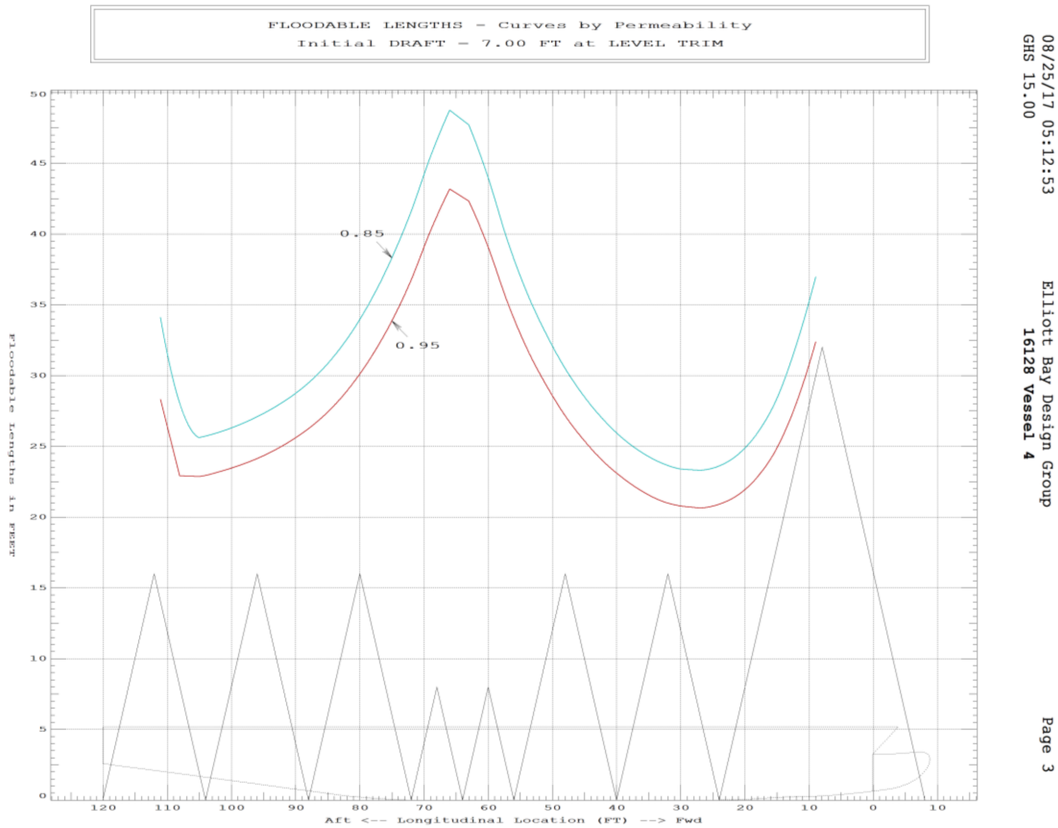

Figure 31: Floodable length curve for Vessel #4

5.5 Tonnage

An estimate of the vessel's GRT was completed to confirm the vessel would comply with the tonnage limitations of Subchapter K. The under-deck tonnage was measured with 10 stations over a tonnage length of 120 ft. The main deck passenger cabin was assumed to be deducted from tonnage through the use of two qualified tonnage openings on the forward ends of the embarkation areas (see Figure 32). The upper decks are assumed to be removed from tonnage through the use of additional qualified tonnage openings.

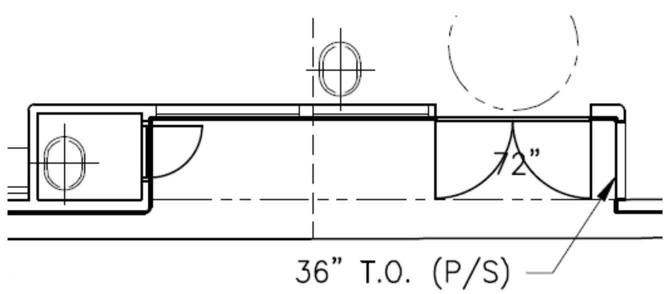

Figure 32: The embarkation starboard area indicating the tonnage opening

With this methodology, the tonnage was estimated to be 97.20 GRT. Detailed calculations are included in Appendix D.

5.6 Route and Endurance

A vessel of this size and capacity is typically operated as an excursion or coastal cruise vessel. Coastal cruise routes are more often based on trip duration than distance. Cruises offered in Seattle, San Francisco, and New York were surveyed and nearly all lasted two hours or less. Therefore, the notional route was developed to result in a two-hour duration, rather than travel a particular distance. Two 15-minute maneuvering periods were included in the route as well as a one-hour period at the dock to account for setup and passenger loading. While conservative for the likely operation of this vessel, a small amount of propulsion power was included during the loading period as it is common for the vessel to push against the embarkation ramp or pilings during loading operations. A breakdown of the route and the estimated fuel consumption is shown below. The fuel consumption assumes a fuel cell efficiency of 45%. Based on this notional route, the vessel is capable of completing six one-way trips before needing to refuel. This may require such a vessel to bunker daily.

Table 38: Notional route for Vessel #4

Speed (kts)	Distance (nm)	Time (min)	Propulsion Power (kW)	Hotel Load (kW)	Total Power (kW)	% Load of Installed Power	Total Energy (kW-hr)	Fuel Consumption (kg)
0	0.00	60.0	35	170	205	24%	205.0	13.7
4	1.00	15.0	210	170	380	44%	95.0	6.3
12	18.00	90.0	595	170	765	88%	1147.5	76.5
4	1.00	15.0	210	170	380	44%	95.0	6.3
Total	**20.00**	**180.0**					**1542.5**	**102.8**

5.7 Capital Cost Estimate

A parametric estimate of the capital cost of Vessel #4 was made. The estimate was based on the lightship weight of the vessel. Each SWBS group was assigned a material cost per ton and labor hours per ton factor based on previously constructed vessels. The estimate assumed a labor rate of $73 per hour which is an average between the typically assumed rates for Pacific Northwest and Gulf Coast shipyards. A 10% margin was included for conservatism and 10% contingency was included to account for cost growth during the time between estimate completion and vessel delivery. The cost of engineering and construction services were assumed to be higher than for a traditionally power vessel due to the added complexity of the LH2 system.

The material cost of the hydrogen fuel cells and the cryogenic fuel tank were considered separate from the parametric weights based analysis. The cost of the fuel cells was assumed to be $2,200/kW. This cost was given by Hydrogenics as the upper range of expected fuel cell cost today based on a one-time order with ruggedization and marinization options. The lower range was given as $1,800/kW without the additional options. Since the fuel cells will be located in a controlled environment fuel cell room, the ruggedization and marinzation options may be unnecessary, according to Hydrogenics. The cost of the hydrogen tank was assumed to be $700 per kilogram of tank weight based on the original SF-BREEZE capital cost estimate. The cost of the additional components in the LH2 system was assumed to be included in the estimated cost of Group 200.

The total capital cost to construct Vessel #4, including engineering and construction services, is estimated to be $15,300,000. Additional calculation details are provided in Appendix D.

6 VESSEL #5

Vessel #5 is double-ended vehicle/passenger ferry constructed with a steel hull and an aluminum superstructure. The Subchapter H vessel carries 64 vehicles and 800 passengers. The vessel has a cruising speed of 12 knots.

Table 39: Vessel #5 particulars

Particulars	
Length Overall	273 ft 8 in
Beam	64 ft
Depth	17 ft 7 in
Hullform	Double-ended
Passenger Capacity	800 PAX
Vehicle Capacity	64 SV
Cruising Speed	12 kts
Installed Power	2,045 kW
Fuel Cell Modules	68
Tank Volume	60,410 L water
Tank Capacity	4,064 kg

6.1 General Arrangements

Vessel #5 has a typical arrangement for a vehicle ferry from the main deck and up. Due to the vessel's size, all of the hydrogen equipment is able to be contained within the hold.

6.1.1 <u>Hold Arrangements</u>

Vessel #5 features two 7,979-gallon (water) cryogenic LH2 fuel tanks at midship. This gives the vessel a large fuel capacity with reasonable endurance. The tank vents run vertically through the stack to the top of the vessel. The tank room can be accessed from the accommodations block immediately aft, or by way of the void space immediately forward of the tank room. In both instances, air locks are used to separate the tank from the adjacent compartments.

The engineers operating station (EOS) is at the port side of the tank room, separate by a solid bulkhead. Access is not allowed directly from the EOS to the tank room in order to eliminate the need for explosion proof equipment in the EOS.

Motor rooms are located from Frames 19 to 28. The vessel is propelled by two electric motors with reduction gears driving controllable pitch propellers. The motor rooms can be accessed through watertight doors or through stairs leading down from the vehicle deck.

The fuel cell rooms are located at each end of the vessel from Frames 28 to 37. The fuel cell spaces are separated from the primary compartments by airlock. The fuel cell rooms vent directly over the side of the vessel. Each fuel cell room contains six racks holding five Hydrogenics HyPM HD 30 modules and one rack holding four Hydrogenics HyPM HD 30 modules.

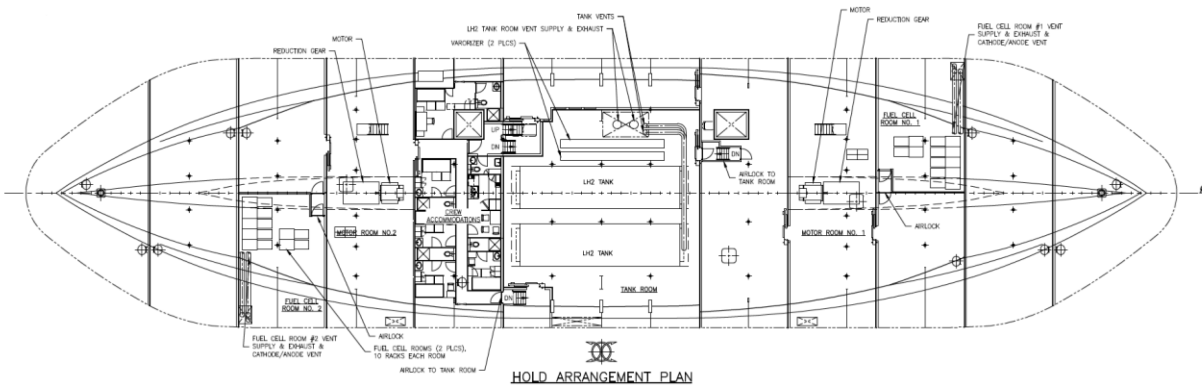

Figure 33: Vessel #5 hold arrangements

6.1.2 Outboard Profile

As discussed previously, the tank room and tanks vent out the top of the stack at midship. This arrangement requires a dispersion analysis to demonstrate that any escaping hydrogen travels immediately upwards and is not drawn towards the pilothouse or down into the ventilation louvers one deck below.

The fuel cell room vent louvers are located near Frame 34 above the vehicle deck. These louvers are positioned high enough so as not to impact stability, but low enough for the hazardous zone around them to stay below the passenger accessible deck above. There is a bunkering station located open to weather on the starboard side of the vessel which is accessed from the mezzanine deck.

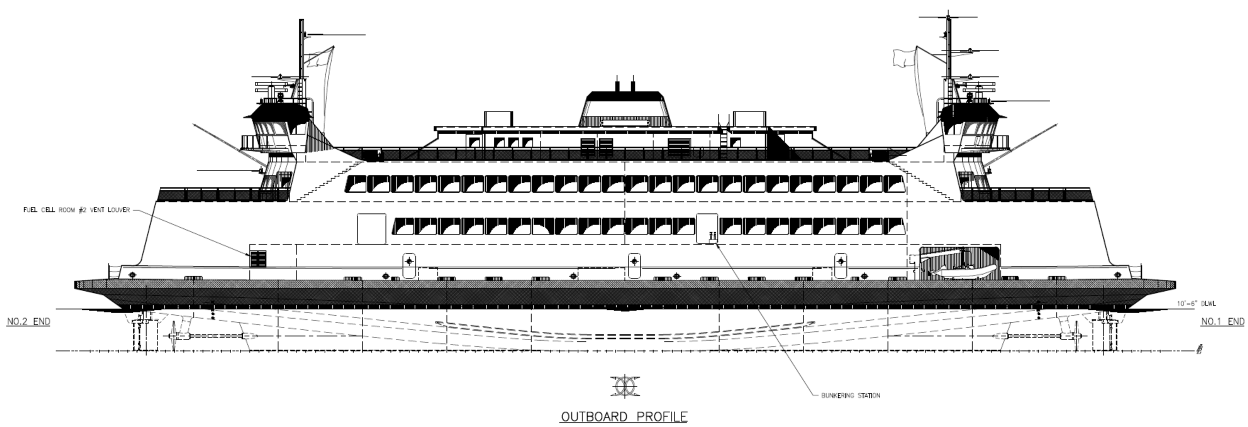

Figure 34: Vessel #5 outboard profile

6.1.3 LH2 Equipment

The fuel cell specifications are provided in Table 40. LH2 tank specifications are provided in Table 41.

Table 40: Fuel cell specifications

Characteristic	
Manufacturer	Hydrogenics
Model	HyPM HD30
Module Dimensions (LxWxH)	28.3 x 16 x 10.3 in
Module Weight	160 lbs
Rack Dimensions (LxWxH)	42.1 x 30 x 78.7 in
Modules/Rack	4
Rack Weight	1,764 lbs
Modules/Rack	5
Rack Weight	1,919 lbs
Quantity of 5 Mod/4 Mod Racks	12/2
Total Modules	68
Total Weight	26,556 lbs

Table 41: Tank specifications

Characteristic	
Manufacturer	Linde
Model	Size 300 Cryogenic Tank
Tank Volume	30,205 L water
Tank Capacity	2,032 kg
Tank Dimensions (L x D)	37.9 x 7.9 ft
Tank Weight	37,677 lbs
Quantity of Tanks	2
Total Volume	60,410 L water
Total Capacity	4,064 kg
Total Weight	75,354 lbs

6.1.4 Regulatory Compliance

While the vessel design is at a concept level, all efforts were made to ensure the vessel is capable of meeting regulatory requirements of the USCG, including the IGF Code. The vessel generally complies with all regulatory rules considered at a concept level. However, the tank room and tank vent are located adjacent to the ventilation louvers on the sun deck. It is assumed that a dispersion analysis would demonstrate that any released hydrogen would travel up into the atmosphere and would not be drawn down into the ventilation louvers. The ventilation outlets could also be raised; however their height is limited by the navigation light requirements.

6.2 Weights

6.2.1 Lightship Weight

The lightship weight calculation was based on a detailed weight estimate of a similarly arranged vessel. Equipment and systems which were not required on a hydrogen-powered ferry were then removed on a line item basis. Further, items which were required for the hydrogen power plant were added to the estimate. The weights of the LH2 system equipment were based on manufacturer specifications with the exception of the propulsion system electrical components (DC-DC converters, DC-AC inverters, filters, line reactors, etc.) which were scaled by installed power from the line item estimate of the SF-BREEZE [2]. For simplicity, all LH2 system weights were added to Group 200. Table 42 lists the equipment which was added to and removed from the baseline weight estimate.

Table 42: Line item weights added to and removed from the baseline estimate

Weights Added	Weights Removed
• Electric Propulsion Motors • Propulsion System Electrical Components • Fuel Cell Racks • Vaporizers • LH2 Tanks	• Main Engines and Systems • Main Engine Exhaust • Fuel Oil System • Main Engine Lube Oil System • Waste Oil System • Entrained Liquids • Ship Service Generators

Margins were increased for each weight group in accordance with standard naval architecture practice. The baseline weights included the centers of gravity from the similar vessel, and estimates of equipment locations were made for each line item weight. The overall center of gravity was estimated in order to verify vessel trim and stability.

The estimated lightship weight of the vessel is 1,486.5 LT. Table 43 shows the total weight broken down by SWBS group. Note that the structure weight assumes the hull is constructed of steel and the superstructure is constructed of aluminum. This structural arrangement was chosen to reduce weight and improve the performance of the vessel.

Table 43: Lightship weight estimate summary

SWBS Group	Description	Weight [LT]
100	Structure	965.9
200	Machinery	116.8
300	Electrical	13.5
400	Electronics	14.5
500	Auxiliary Systems	125.0
600	Outfit	250.8
	Total	**1486.5**

6.2.2 Deadweight

The vessel's deadweight was calculated with an itemized estimate of all cargo and variable loads. Passengers were assigned a weight of 185 lbs in accordance with USCG regulation. Crew members were assigned a weight of 225 lbs. Vehicles were assumed to weigh 4000 lbs. A water ballast weight of 20,000 lbs was included as it is common for vehicle ferries to use ballast to offset the trim effects of partial vehicle loads. A 5% service life margin was also included. Ship stores, galley stores, potable water, and sewage were also included in the deadweight calculation. The total deadweight was estimated to be 300.2 LT. Table 44 shows a summary of the deadweight calculation.

Table 44: Summary of deadweight for Vessel #1

Item	Weight [LT]
Passengers	66.1
Vehicles	114.3
Crew and Effects	1.2
Ship Stores	5.0
Galley Stores	4.0
Potable Water	7.5
Sewage	11.5
LH2	6.5
Water Ballast	8.9
Service Life Margin	75.2
Total	**300.2**

6.2.3 Full Load Condition

Summing the lightship weight and the deadweight results in a full load displacement of 1786.7 LT. The hullform is designed to displace 1823 LT at the design load water line of 10.5 ft. The vertical center of gravity of the full load condition is estimated to be 20.6 ft above baseline.

6.3 Speed and Power

Unlike the previous vessels which required analysis to predict the speed and power, Vessel #5 was based on a hullform which had previously undergone a physical scale model test. Such tests are very accurate and provide a high level of confidence in the results. The estimated full load displacement is approximately 2% less than the hullform displacement at the 10.5 ft design load draft. Therefore, the model test results were used directly. The model tests were conducted at even keel.

Assuming a 97% shafting efficiency, the model test report indicated that the total required shaft power at 12 knots was 916 kW. However, the propulsive load was shared by the forward and aft propeller, with the aft end requiring 664 kW and the forward end requiring 252 kW. Figure 35 shows a plot of the required shaft power over a speed range.

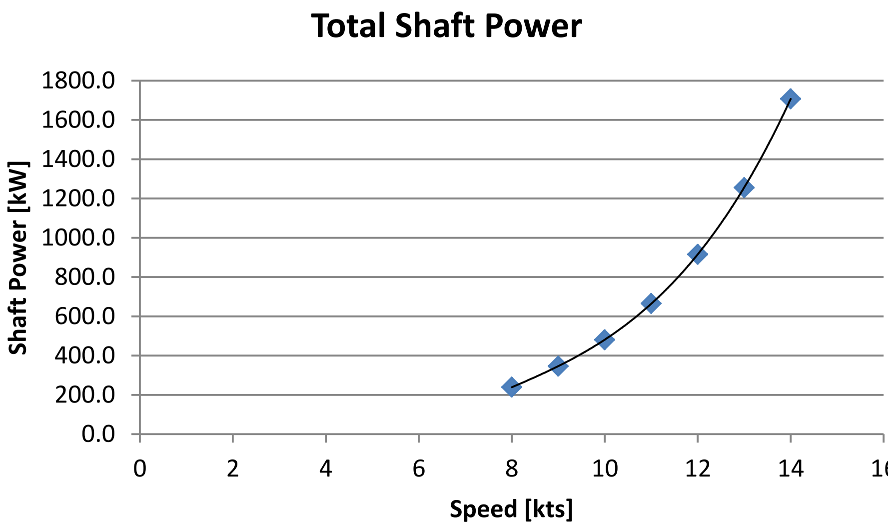

Figure 35: Required total shaft power for Vessel #5

The power plant was sized assuming a vessel cruise condition at 85% MCR. In addition, it was assumed that a vessel of this size would operate in open waters where environmental loads would likely be higher than the other vessels in this report. Therefore, a 20% margin was added to the shaft power to account for wind and waves. The propulsion system efficiencies were assumed to be as shown in Table 45. From these, the required brake power was calculated to be 1448 kW.

Table 45: Propulsion electrical system efficiencies

Equipment	Efficiency
Electric Motor	95%
AC Inverter	97%
DC Converter	97%

The hotel loads were estimated from a previous design of similar size and capacity. That vessel had 600 kW of installed power to account for the house loads. While the detailed loads analysis indicated this was oversized, it was decided that the full generator capacity would be included for conservatism.

Considering the propulsion system efficiencies and MCR requirements, and including the hotel load requirements, the total capacity of the hydrogen power plant was calculated to be 2045 kW. This load is generated by 68 Hydrogenics HyPM HD 30 modules generating 30 kW of power each.

One advantage of the electric propulsion system over a conventional diesel propulsion system is the ability to distribute power from a single source to both ends of the vessel. In a conventional diesel arrangement, both ends of the vessel would require engines large enough to power the boat. In the electrical propulsion arrangement, only the electric motors must be sized to meet the required propulsion power on each end. The power generation equipment can simply provide power to whichever end of the vessel is providing the driving thrust. This reduces the total amount of installed power compared to a conventional diesel arrangement.

6.3.1 CFD Analysis

A CFD analysis was not completed for Vessel #5 as the accuracy of a physical model test is considered as good as or better than a CFD analysis.

6.4 Stability

A preliminary stability assessment was completed in order to confirm the feasibility of the vessel design. The preliminary assessment considered USCG subdivision and intact stability requirements for passenger vessels. The analysis was completed using GHS version 15. The GHS model was created from the Rhinoceros model used in the speed and power analysis.

The maximum allowable VCG was calculated based on the following criteria:

- 46 CFR §170.170 Weather Criteria
- 46 CFR §170.173 Criterion for Vessels of Unusual Proportion and Form
- 46 CFR §171.050 Passenger Heel Requirements

Figure 36 shows a plot of all criteria over the expected trim and displacement range. For conservatism, it was assumed the vessel was operating on exposed waters. Calculations are provided in Appendix E. The full load VCG is estimated to be 20.6 ft. indicating the concept vessel arrangements comply with intact stability criteria.

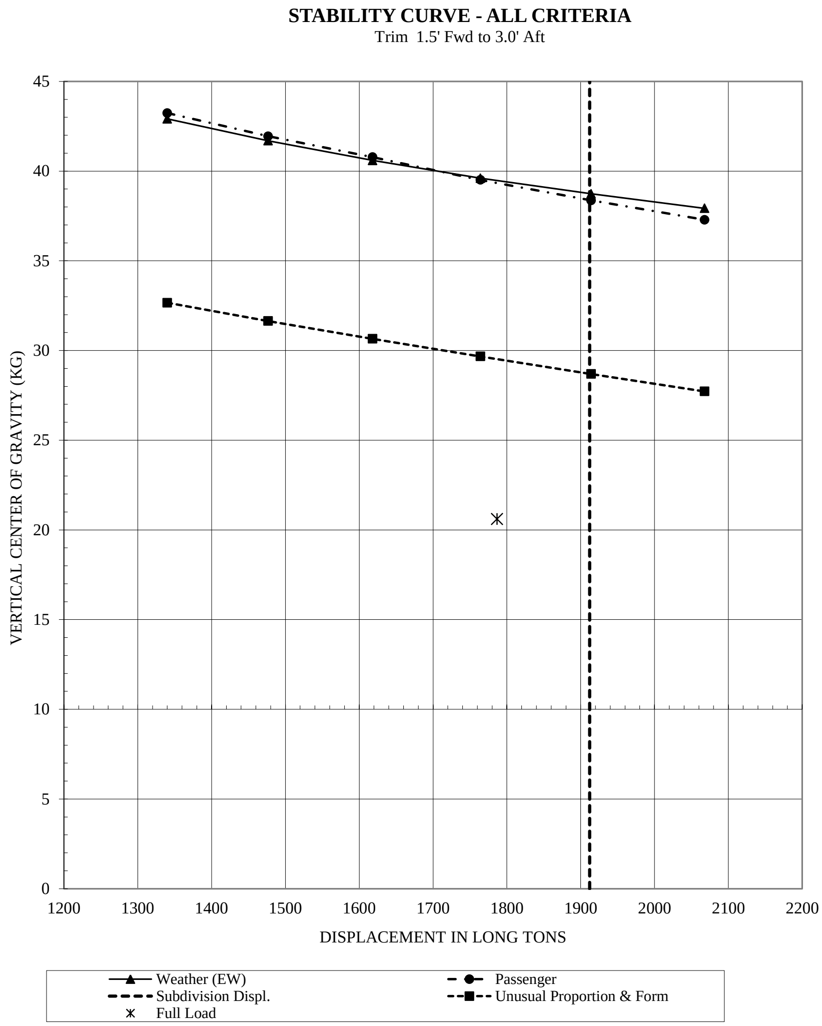

Figure 36: Maximum VCG plot for Vessel #5

The two-compartment subdivision requirements were verified with a floodable length curve at the vessel's full load draft. Figure 37 shows the floodable length curve with 95% and 85% compartment permeabilities. In each case, the bulkhead arrangement passes the floodable length calculation.

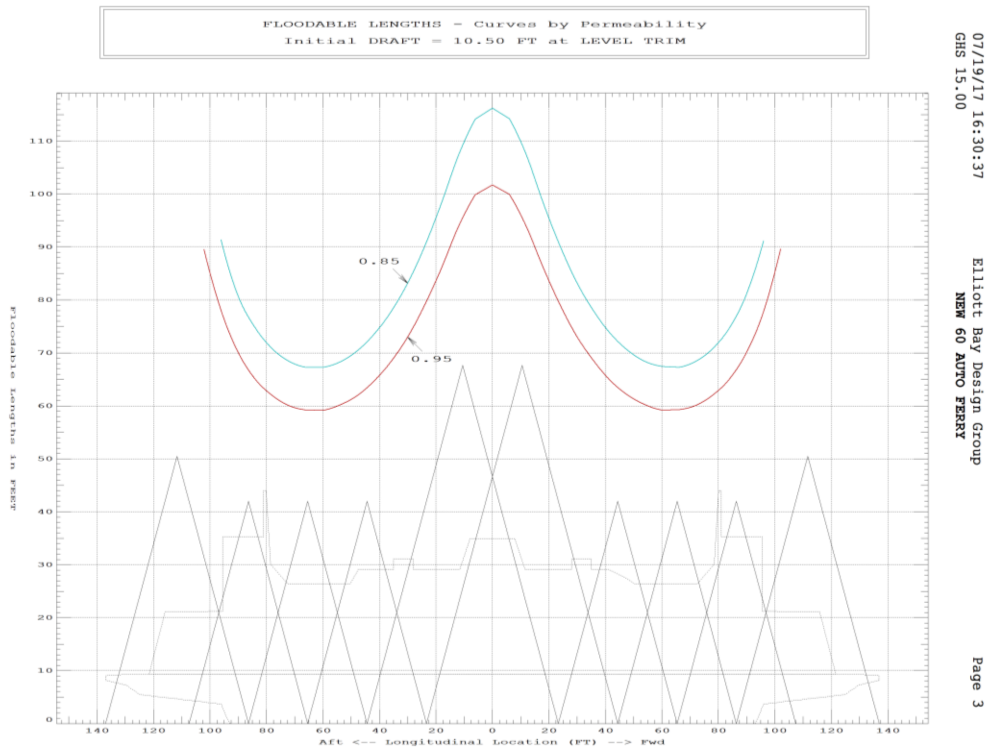

Figure 37: Floodable length curve for Vessel #5

6.5 Tonnage

Gross registered tonnage is less critical in the design of Subchapter H vessels, unlike Subchapter T or Subchapter K vessels where it is often a limiting factor driving below deck arrangements. While there are some instances where benefits arise from limiting the tonnage of a Subchapter H vessel, these occur at a level of detail that is beyond the scope of this concept design. Therefore, tonnage was not calculated for Vessel #5.

6.6 Route and Endurance

Vessels of this size and capacity often operate on moderate length routes, as indicated in the example routes in Table 46. For conservatism, a 10 nautical mile notional route was developed with a 30-minute loading period. A small amount of propulsion power was included during the loading period as it is common for the vessel to push against the embarkation ramp or pilings during loading operations. Two 0.25 nautical mile maneuvering periods were also included in the route. A breakdown of the notional route is given in Table 47. The fuel consumption assumes a fuel cell efficiency of 45%.

Based on this notional route, the vessel is capable of completing 26 one-way trips before needing to refuel. Assuming the vessel completes six to eight one-way trips per day, the vessel would need to bunker every three to four days.

Table 46: Example routes for Vessel #5

Route	Distance (nm)	Vessel Capacity (SV)
Woods Hole - Martha's Vineyard	7	76
Port Townsend - Coupeville	5	64
Point Defiance - Tahlequah	2	64
Vancouver Island - Descano Bay	3	63

Table 47: Notional route for Vessel #5

Speed (kts)	Distance (nm)	Time (min)	Propulsion Power (kW)	Hotel Load (kW)	Total Power (kW)	% Load of Installed Power	Total Energy (kW-hr)	Fuel Consumption (kg)
3	0.25	5	362	600	962	47%	80	5.3
12	9.50	48	1229	600	1829	89%	1448	96.5
3	0.25	5	362	600	962	47%	80	5.3
0	0.00	30	73	600	673	33%	337	22.4
Total	**10.00**	**88**					**1945**	**129.7**

6.7 Capital Cost Estimate

A parametric estimate of the capital cost of Vessel #5 was made. The estimate was based on the lightship weight of the vessel. Each SWBS group was assigned a material cost per ton and labor hours per ton factor based on previously constructed vessels. The estimate assumed a labor rate of $73 per hour which is an average between the typically assumed rates for Pacific Northwest and Gulf Coast shipyards. A 10% margin was included for conservatism and 10% contingency was included to account for cost growth during the time between estimate completion and vessel delivery. The cost of engineering and constructions services were assumed to be higher than for a traditionally power vessel due to the added complexity of the LH2 system.

The material cost of the hydrogen fuel cells and the cryogenic fuel tank were considered separate from the parametric weights based analysis. The cost of the fuel cells was assumed to be $2,200/kW. This cost was given by Hydrogenics as the upper range of expected fuel cell cost today based on a one-time order with ruggedization and marinization options. The lower range was given as $1,800/kW without the additional options. Since the fuel cells will be located in a controlled environment fuel cell room, the ruggedization and marinzation options may be unnecessary, according to Hydrogenics. The cost of the hydrogen tank was assumed to be $700 per kilogram of tank weight based on the original SF-BREEZE capital cost estimate. The cost of the additional components in the LH2 system was assumed to be included in the estimated cost of Group 200.

The total capital cost to construct Vessel #5, including engineering and construction services, is estimated to be $70,800,000. Additional calculation details are provided in Appendix E.

7 REFERENCES

[1] Elliott Bay Design Group, 16128-070-0, SF-BREEZE Optimization Study - Mapping Study Results, 02/17/17.

[2] Elliott Bay Design Group, 15051-001-070-2, SF-BREEZE Ferry Feasibility Study - Design Study Report, 02/12/16.

[3] Congressional Budget Office, "An Analysis of the Navy's Fiscal Year 2017 Shipbuilding Plan," Washington, DC, February 2017.

Appendix A

Vessel #1 Drawings and Calculations

GENERAL ARRANGEMENTS

WEIGHT ESTIMATE

SWBS No.	Description	Qty.	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)	Notes
	VESSEL WEIGHT ESTIMATE						
	SUMMARY						
100	STRUCTURE		420,300	0.00	-0.50	9.15	
200	MACHINERY		27,188	-1.66	-0.07	6.03	
300	ELECTRICAL		8,495	0.00	2.65	10.16	
400	ELECTRONICS & IC		625	0.00	4.97	25.60	
500	AUXILIARY SYSTEMS		18,679	4.70	-0.49	7.15	
600	OUTFIT		40,790	2.24	9.02	15.58	
	VESSEL WEIGHT - SUBTOTAL		516,077 (230.39LT)	0.26	0.33	9.46	
	Add Margin to Structure for Roll & Weld	0%	0	0.00	-0.50	9.15	Included in baseline
100	STRUCTURE	5%	21,015	0.00	-0.50	9.15	
200	MACHINERY	12%	3,263	-1.66	-0.07	6.03	
300	ELECTRICAL	12%	1,019	0.00	2.65	10.16	
400	ELECTRONICS & IC	12%	75	0.00	4.97	25.60	
500	AUXILIARY SYSTEMS	8%	1,494	4.70	-0.49	7.15	
600	OUTFIT	8%	3,263	2.24	9.02	15.58	
	VESSEL WEIGHT WITH MARGINS		**546,207 (243.8 LT)**	**0.26**	**0.35**	**9.46**	

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
100	**Basline Design Weight**	1.00	400286	400,286	0.00	-0.50	9.15
	Weights to Remove						
	-						
	Weights to Add						
	Added 5% for additional gas tight bulkheads	0.05	400286	20,014	0.00	-0.50	9.15

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
200	**Basline Design Weight**	1.00	16206	16,206	0.00	0.00	5.83
	Weights to Remove						
	Main Engines	-2.00	3326	-6,652	0.00	0.00	8.00
	Weights to Add						
	Electric Motors	2.00	2937	5,874	0.00	0.00	5.00
	Propulsion System Electrical Components	1.00	300	300	0.00	-7.00	8.00
	Fuel Cells - 120 KW	1.00	1764	1,764	6.50	3.33	9.00
	Fuel Cells - 120 KW	1.00	1764	1,764	6.50	-1.25	9.00
	LH2 Tank	1.00	5732	5,732	-11.50	-1.00	8.00
	Vaporizers	2.00	1100	2,200	-1.00	1.00	6.00

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
300	**Basline Design Weight**	1.00	8495	8,495	0.00	2.65	10.16
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
400	**Basline Design Weight**	1.00	625	625	0.00	4.97	25.60
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
500	**Basline Design Weight**	1.00	29684	29,684	1.38	1.64	8.77
	Weights to Remove						
	Fuel Oil System	-1.00	218	-218	0.00	0.00	6.00
	Exhaust System	-1.00	5857	-5,857	-1.96	10.46	15.58
	Compressed Air System	-1.00	1130	-1,130	15.74	-3.10	8.49
	Generators	-2.00	1900	-3,800	-14.00	0.00	6.50
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
600	**Basline Design Weight**	1.000	40790	40,790	2.24	9.02	15.58
	Weights to Remove						
	-						
	Weights to Add						
	-						

Deadweight Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
Crew and Effects	3.00	225	675	0.00	18.0	18.00
Passengers	100.0	185	18,500	0.00	18.0	18.00
Vehicles	22.00	4000	88,000	0.00	-4.0	18.00
Ballast Tanks	1.00	10000	10,000	0.00	0.0	7.00
LH2	1.00	467	467	-11.50	-1.00	8.00
Service Life Margin	0.05	546207	27,310	0.26	0.35	9.46

STABILITY CALCULATIONS

WEATHER CRITERION MAXIMUM KG CALCULATION
from 46 CFR 170.170
for service on exposed waters

$$GM_{reqd} = \frac{PAH}{W \operatorname{Tan}(T)}$$

P = 0.0050 + (L/14200)2 = 0.0050667 Long tons / Ft^2
A = lateral area above waterline
H = vertical distance from centroid of A to 1/2 draft point
W = displacement in long tons
T = 14 degrees or angle of heel where 1/2 freeboard is submerged, whichever is less.

Length on max waterline:	116.00	ft
Depth to freeboard deck: (low point, at edge)	12.00	ft
Beam:	46.00	ft
Superstructure Height:	9.00	ft	Full breadth of vessel, full length

Draft, T:	5.00	5.50	6.00	6.50	7.00	7.50
Displacement to T:	163	196	232	270	310	352
Area above waterline:	2002	1953	1903	1851	1763	1734
h of area above waterline:	10.86	10.63	10.40	10.18	9.92	9.84
h of area to baseline:	15.86	16.13	16.40	16.68	16.92	17.34
Vertical distance, H:	13.36	13.38	13.40	13.43	13.42	13.59
Freeboard, f:	7.00	6.50	6.00	5.50	5.00	4.50
Tangent to 1/2 freeboard:	0.152	0.141	0.130	0.120	0.109	0.098
Tangent 14 deg:	0.249	0.249	0.249	0.249	0.249	0.249
GM required:	5.47	4.77	4.26	3.90	3.56	3.47
KMt at draft T:	30.61	28.80	27.29	26.09	25.14	24.42
Max KG incl. free surface:	25.14	24.03	23.03	22.19	21.58	20.95

SUMMARY TABLE

DRAFT	DISP	MAX KG	MIN GMt
5.00	162.79	25.14	5.47
5.50	196.33	24.03	4.77
6.00	232.27	23.03	4.26
6.50	270.10	22.19	3.90
7.00	310.06	21.58	3.56
7.50	351.78	20.95	3.47

PASSENGER CRITERION MAXIMUM KG CALCULATION

from 46 CFR 171.050(a), effective March 14, 2011

$$GM_{reqd} = \boxed{\frac{W}{\Delta} * \frac{2}{3} * \frac{b}{\tan(T)}}$$

W = total weight of persons other than required crew, including effects, in long tons
b = distance off centerline to centroid of passenger deck on one side
(beam/4 used to be conservative)
Δ = displacement in long tons
T = 14 degrees or angle of heel where freeboard is submerged, whichever is less.

Number of passengers:	104	
Depth to freeboard deck: (low point, at edge)	12.00	ft
Beam:	46.00	ft
b:	17.50	ft
W:	9.29	LT

Draft, T:	5.00	5.50	6.00	6.50	7.00	7.50
Displacement to T:	162.79	196.33	232.27	270.10	310.06	351.78
Freeboard:	7.00	6.50	6.00	5.50	5.00	4.50
Tangent to freeboard:	0.304	0.283	0.261	0.239	0.217	0.196
Tangent 14 deg:	0.249	0.249	0.249	0.249	0.249	0.249
GM required:	2.67	2.21	1.87	1.68	1.61	1.57
KMt at draft T:	30.61	28.80	27.29	26.09	25.14	24.42
Max KG incl. free surface:	27.94	26.59	25.42	24.41	23.53	22.85

PASSENGER CRITERION VALIDITY CALCULATION

from 46 CFR 171.050(b), effective March 14, 2011

The calculation of 46 CFR 171.050(a) is valid when the Righting Arm (GZ) at heel angle T is not less than the minimum Metacentric Height (GM) calculated in paragraph (a) multipied by sin(T).

Heel Angle, T, degrees:	14.00	14.00	14.00	13.45	12.26	11.07
sin(T) :	0.24	0.24	0.24	0.23	0.21	0.19
GM required (ft):	2.67	2.21	1.87	1.68	1.61	1.57
GZ required @ angle T (ft):	0.65	0.54	0.45	0.39	0.34	0.30

Compare required GZ to actual GZ from GHS output

SUMMARY TABLE

DRAFT	DISP	MAX KG	MIN GMt
5.00	163	27.94	2.67
5.50	196	26.59	2.21
6.00	232	25.42	1.87
6.50	270	24.41	1.68
7.00	310	23.53	1.61
7.50	352	22.85	1.57

```
08/25/17 01:14:51          Elliott Bay Design Group
GHS 15.00                          Vessel 1


              MAXIMUM VCG vs. DISPLACEMENT with ROLL
           Heeling moment is present from: user specification
    Trim = Fwd 0.50/101.08 at zero heel (trim righting arm held at zero)
             Displacement          ------ Margins ------
              LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4
             -------------------------------------------
                 162.79    24.30    8d   10d   13%   13%
                 196.33    24.14    5d    8d    0%   11%
                 232.14    23.70    4d    6d    0%   10%
                 269.97    23.19    4d    4d    0%    9%
                 309.94    22.49    3d    3d    0%    2%
                 351.66    21.47    4d    1d    0%    0%
             -------------------------------------------
           Heeling moment is present from: user specification
          Trim = zero at zero heel (trim righting arm held at zero)
             Displacement          ------ Margins ------
              LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4
             -------------------------------------------
                 162.79    24.32    8d   10d    5%   11%
                 196.33    24.13    5d    8d    0%   11%
                 232.14    23.71    4d    6d    0%   12%
                 269.97    23.13    4d    4d    0%    9%
                 309.94    22.52    3d    3d    0%    3%
                 351.66    21.60    4d    1d    0%    0%
             -------------------------------------------
           Heeling moment is present from: user specification
    Trim = Aft 0.50/101.08 at zero heel (trim righting arm held at zero)
             Displacement          ------ Margins ------
              LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4
             -------------------------------------------
                 162.79    24.33    8d   10d    5%   11%
                 196.33    24.11    5d    8d    0%   12%
                 232.14    23.69    4d    6d    0%   12%
                 269.97    23.13    4d    4d    0%    9%
                 309.94    22.52    3d    3d    0%    2%
                 351.66    21.59    4d    1d    0%    0%
             -------------------------------------------
           Heeling moment is present from: user specification
    Trim = Aft 1.00/101.08 at zero heel (trim righting arm held at zero)
             Displacement          ------ Margins ------
              LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4
             -------------------------------------------
                 162.79    24.35    8d   10d    4%   10%
                 196.33    24.11    5d    8d    0%   12%
                 232.14    23.69    4d    6d    0%   12%
                 269.97    23.12    4d    4d    0%    9%
                 309.94    22.53    3d    3d    0%    2%
                 351.66    21.59    4d    1d    0%    0%
        Distances in FEET.---Specific Gravity = 1.025.---d = degrees.


    LIM------------46CFR 170.173e-Unusual Form------------Min/Max
    (1) Absolute Angle at RAzero                      >    25.00 deg
    (2) Absolute Angle at Flood                       >    15.00 deg
    (3) Area from abs 0 deg to MaxRA or Flood         >    10.00 Ft-deg
    (4) Area from abs 0 deg to 40 or Flood            >    10.00 Ft-deg
    -----------------------------------------------------------------
```

TONNAGE

Tonnage length:	112.00	Number of decks:	1		
Number of divisions of length:	10.00	Number of Masts:	2		
Common interval:	11.200	Stem	Plumb		
1/3 common interval:	3.733	Stern:	Plumb		
Tonnage depth:	9.50	Material:	Steel		
Number of divisions of depth:	4	Service:	Passenger		

UNDER TONNAGE DECK VOLUME				TONNAGE	
Section Number	Simpson's Multiplier	Section Area Square Feet	Product		
				UNDER TONNAGE DECK:	56.71
1	1	0.00	0.00	Between Decks:	
2	4	0.00	0.00		
3	2	0.00	0.00	Forecastle:	
4	4	189.21	756.83		
5	2	182.75	365.50	Bridge:	
6	4	153.00	612.00		
7	2	182.75	365.50	Deck Houses:	
8	4	204.25	817.00		
9	2	0.00	0.00	Side Houses:	
10	4	0.00	0.00		
11	1	0.00	0.00	Mast Houses:	
12	0	0.00	0.00		
13	0	0.00	0.00	Trunks:	
	Total:		2916.83		
1/3 common interval:			3.733	Excess Hatchways:	
Under Deck Volume:			10889.51		
				Light and Air:	
Deducted Volume:			0.00		
Propelling Machinery Deduction:			5218.69		
				Shelter Deck:	
Under Deck Volume w/ Deductions:			5670.82		
				Superstructures: (estimated)	32.15
UNDER DECK TONNAGE AS MEASURED:			56.71	**GROSS TONNAGE:**	**88.86**

UNDER TONNAGE DECK BREADTHS AND PRODUCTS

	Section No: 1		Section No: 2		Section No: 3		Section No: 4		Section No: 5		Section No: 6	
	Depth:	3.67	Depth:	5.95	Depth:	7.50	Depth:	9.50	Depth:	8.50	Depth:	8.50
	Interval:	0.92	Interval:	1.49	Interval:	1.88	Interval:	2.38	Interval:	2.13	Interval:	2.13
Simpson's Multiplier	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product
1	0.00	0.00	0.00	0.00	0.00	0.00	21.50	21.50	21.50	21.50	18.00	18.00
4	0.00	0.00	0.00	0.00	0.00	0.00	21.50	86.00	21.50	86.00	18.00	72.00
2	0.00	0.00	0.00	0.00	0.00	0.00	21.50	43.00	21.50	43.00	18.00	36.00
4	0.00	0.00	0.00	0.00	0.00	0.00	21.50	86.00	21.50	86.00	18.00	72.00
1	0.00	0.00	0.00	0.00	0.00	0.00	2.50	2.50	21.50	21.50	18.00	18.00
0		0.00		0.00		0.00		0.00		0.00		0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
Total:		0.00		0.00		0.00		239.00		258.00		216.00
1/3 interval:		0.31		0.50		0.63		0.79		0.71		0.71
Area in square feet:		0.00		0.00		0.00		189.21		182.75		153.00

	Section No: 7		Section No: 8		Section No: 9		Section No: 10		Section No: 11		Section No: 12	
	Depth:	8.50	Depth:	9.50	Depth:	7.50	Depth:	5.95	Depth:	3.67	Depth:	0.00
	Interval:	2.13	Interval:	2.38	Interval:	1.88	Interval:	1.49	Interval:	0.92	Interval:	0.00
Simpson's Multiplier	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product
1	21.50	21.50	21.50	21.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	21.50	86.00	21.50	86.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	21.50	43.00	21.50	43.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	21.50	86.00	21.50	86.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	21.50	21.50	21.50	21.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
Total:		258.00		258.00		0.00		0.00		0.00		0.00
1/3 interval:		0.71		0.79		0.63		0.50		0.31		0.00
Area in square feet:		182.75		204.25		0.00		0.00		0.00		0.00

Deckhouse/Superstructures:

	L	W	H	T
Fwd Lounge	11.67	8.58	7.58	759.1
Crew Compt 1	13.08	8.58	7.58	851.2
Crew Compt 2	2.00	6.83	7.58	103.6
Over Stair	11.00	3.83	3.75	158.1
Aft Lounge	21.58	8.58	7.58	1343.1
Total Volume				3215.1
Total Gross Tons				**32.15**

Note:
1. The superstructure admeasurement assumes:
   No tonnage openings
   Uptake trunks, HVAC spaces and wheelhouse exempt.
2. See 00023-4-1042, Deck Arrangements, for superstructure configuration.

CAPITAL COST ESTIMATE

PARAMETRIC CONSTRUCTION COST ESTIMATE

Assumptions

1) This estimate is inteded for new construction of ONE vessel.
2) This vessel is assumed to be built in the USA
3) This estimate is intended for budgeting purposes ONLY.
4) Costs are organized in accordance with the EBDG interpretation of the SWBS System.
5) Weights are taken from 16128-833-0P0 Vessel 1 Weight Estimate
6) Other Assumptions as needed.
7) Non-trade labor rates are as follows:
   PM & Admin = 120% of Labor
   Engineering = 180% of Labor
8) Other vessel costs inflated to 2017 dollars based on Shipbuilding Inflation (Reference [3])

Calculations

SWBS COST GROUPS	Weight in LT	$/LT	HRS/LT	$ MATERIAL + Mark-up	LABOR HRS	LABOR COST
000 - PM & ADMIN					2,192	$ 191,990
100 - HULL	197.0	2,353	87.11	$ 542,296	17,161	$ 1,252,777
200 - PROP MACH'Y	9.0	80,072	99.40	$ 839,774	891	$ 65,042
300 - ELECTRICAL	4.2	60,845	3,816.56	$ 302,363	16,210	$ 1,183,342
400 - NAVIGATION	0.3	386,136	3,907.90	$ 141,181	1,221	$ 89,149
500 - AUXILIARY	9.0	17,753	252.67	$ 187,063	2,275	$ 166,108
600 - OUTFIT	19.7	24,697	308.85	$ 568,284	6,074	$ 443,407
LH2 EQUIPMENT	4.6	NA	200.00	$ 791,716	926	$ 67,598
800 - ENGINEERING					4,476	$ 588,136
900- CONST. SERVICES				$ 101,180	6,266	$ 457,439
Totals	**243.84**			**$ 3,473,857**	**57,693**	**$ 4,504,989**

Inputs

Current Vessel	**Value**	**Unit**		
Length	120.00	*ft*	Vessel Type	Ferry
Beam	46.00	*ft*		
Depth	12.00	*ft*		
Light Ship Δ	243.80	*LT*		
Structure Weight	187.63	*LT*		

Shipyard	**Value**	**Units**		
Labor Rate	$73.00	*/hr*		
Material Mark-Up	17.0%		000 - PM & Admin	5.0%
Mat'l & Labor Margin	10.0%		800 - Engineering	10.0%
Contingency	10.0%		900 - Construction Services	14.0%

Other Vessels	**Cube Number**	**Light Ship Δ**	**Structure Wt**	**Labor Hours**	**Cost**
Units	*ft^3*	*LT*	*LT*	*hrs*	*$*
Fischer Island Ferry	662.40	233.84	173.49	31,352.00	4,068,586
Christine Anderson II	2,423.52	731.84	545.83	48,275.00	16,197,400
Port Aransas	976.18	373.19	300.14	51,662.00	8,794,800
Whatcom 35 Car	1,028.13	396.10	298.97	54,830.00	9,545,551

Output

Labor & Material Sub-Total	$7,978,846
Material & Labor Margin @ 10%	$797,884.56
Cost without Contingency =	**$8,776,730**
Contingency	$877,673
Total Vessel Construction Cost Estimate with 10% CONTINGENCY	**$9,654,403**
Rounded Up Total	**$9,700,000**

Appendix B

Vessel #2 Drawings and Calculations

GENERAL ARRANGEMENTS

WEIGHT ESTIMATE

	VESSEL WEIGHT ESTIMATE						
SWBS No.	Description	Qty.	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)	Notes
	SUMMARY						
100	STRUCTURE		73,000	27.33	0.00	10.85	
200	MACHINERY		25,249	19.73	0.01	5.94	
300	ELECTRICAL		5,387	20.00	0.00	6.00	
400	ELECTRONICS & IC		1,120	48.00	0.00	18.00	
500	AUXILIARY SYSTEMS		29,831	20.00	0.00	6.00	
600	OUTFIT		17,280	27.50	0.00	10.85	
	VESSEL WEIGHT - SUBTOTAL		151,867 (67.80LT)	24.54	0.00	8.96	
	Add Margin to Structure for Roll & Weld	0%	0	27.33	0.00	10.85	In steel weight
100	STRUCTURE	0%	0	27.33	0.00	10.85	In steel weight
200	MACHINERY	9%	2,272	19.73	0.01	5.94	
300	ELECTRICAL	12%	646	20.00	0.00	6.00	
400	ELECTRONICS & IC	12%	134	48.00	0.00	18.00	
500	AUXILIARY SYSTEMS	12%	3,580	20.00	0.00	6.00	
600	OUTFIT	12%	2,074	27.50	0.00	10.85	
	VESSEL WEIGHT WITH MARGINS		**160,573 (71.7 LT)**	**24.41**	**0.00**	**8.87**	

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)
100	**Basline Design Weight**	1.00	73000	73,000	27.33	0.00	10.85
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)
200	**Basline Design Weight**	1.00	18222	18,222	16.00	0.00	4.00
	Weights to Remove						
	Main Engines	-2.00	2328	-4,656	16.60	0.00	5.00
	Main Engine Systems	-2.00	349	-698	20.00	0.00	5.00
	Weights to Add						
	Electric Motors	2.00	2425	4,850	16.40	0.00	3.00
	Propulsion System Electrical Components	1.00	200	200	18.17	0.00	5.00
	Fuel Cells Rack	1.00	1764	1,764	26.67	-1.58	4.75
	Fuel Cells Rack	1.00	1919	1,919	26.67	1.58	4.75
	H2 Tank	12.00	304	3,648	31.92	0.00	19.42

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)
300	**Basline Design Weight**	1.00	5387	5,387	20.00	0.00	6.00
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)
400	**Basline Design Weight**	1.00	1120	1,120	48.00	0.00	18.00
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)
500	**Basline Design Weight**	1.00	30822	30,822	20.00	0.00	6.00
	Weights to Remove						
	Fuel Oil System	-0.26	128	-33	20.00	0.00	6.00
	Exhaust System	-0.26	1212	-310	20.00	0.00	6.00
	Steam System	-0.26	1385	-355	20.00	0.00	6.00
	Generators	-0.26	660	-169	20.00	0.00	6.00
	Lube Oil System	-0.26	146	-37	20.00	0.00	6.00
	Compressed Air System	-0.26	340	-87	20.00	0.00	6.00
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)
600	**Basline Design Weight**	1.000	17280	17,280	27.50	0.00	10.85
	Weights to Remove						
	-						
	Weights to Add						
	-						

Deadweight Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)
Passengers	60.00	185	11,100	24.00	0.00	12.50
Crew	3.00	225	675	43.83	0.00	15.42
Stores	1.00	1000	1,000	5.75	-5.67	12.50
Potable Water	210	9	1,791	5.58	6.17	5.33
Sewage	210	9	1,791	5.58	-6.17	5.33
H2	1.00	214	214	31.92	0.00	19.42
SLM	0.05	167026	8,351	24.41	0.00	8.87

STABILITY CALCULATIONS

WEATHER CRITERION MAXIMUM KG CALCULATION
from 46 CFR 170.170
for service on protected waters

$$GM_{reqd} = \frac{PAH}{W \operatorname{Tan}(T)}$$

P = 0.0025 + (L/14200)2 = 0.0025160 Long tons / Ft^2
A = lateral area above waterline
H = vertical distance from centroid of A to 1/2 draft point
W = displacement in long tons
T = 14 degrees or angle of heel where 1/2 freeboard is submerged, whichever is less.

Length on max waterline:	56.75	ft	
Depth to freeboard deck: (low point, at edge)	10.00	ft	
Beam:	18.00	ft	
Superstructure Height:	9.00	ft	Full breadth of vessel, full length

Draft, T:	4.00	4.50	5.00	5.50	6.00	6.50
Displacement to T:	36	47	58	71	84	97
Area above waterline:	929	901	873	844	816	788
h of area above waterline:	8.26	8.01	7.76	7.51	7.26	7.02
h of area to baseline:	12.26	12.51	12.76	13.01	13.26	13.52
Vertical distance, H:	10.26	10.26	10.26	10.26	10.26	10.27
Freeboard, f:	6.00	5.50	5.00	4.50	4.00	3.50
Tangent to 1/2 freeboard:	0.333	0.306	0.278	0.250	0.222	0.194
Tangent 14 deg:	0.249	0.249	0.249	0.249	0.249	0.249
GM required:	2.68	2.01	1.55	1.23	1.13	1.08
KMt at draft T:	11.51	12.94	12.79	12.16	11.48	10.83
Max KG incl. free surface:	8.83	10.93	11.24	10.93	10.35	9.75

SUMMARY TABLE

DRAFT	DISP	MAX KG	MIN GMt
4.00	35.95	8.83	2.68
4.50	46.52	10.93	2.01
5.00	58.36	11.24	1.55
5.50	70.82	10.93	1.23
6.00	83.61	10.35	1.13
6.50	96.52	9.75	1.08

PASSENGER CRITERION MAXIMUM KG CALCULATION

from 46 CFR 171.050(a), effective March 14, 2011

$$GM_{reqd} = \boxed{\frac{W}{\Delta} * \frac{2}{3} * \frac{b}{\tan(T)}}$$

W = total weight of persons other than required crew, including effects, in long tons
b = distance off centerline to centroid of passenger deck on one side
(beam/4 used to be conservative)
Δ = displacement in long tons
T = 14 degrees or angle of heel where freeboard is submerged,
whichever is less.

Number of passengers:	63	
Depth to freeboard deck:	10.00	ft
(low point, at edge)		
Beam:	18.00	ft
b:	4.00	ft
W:	5.63	LT

Draft, T:	4.00	4.50	5.00	5.50	6.00	6.50
Displacement to T:	35.95	46.52	58.36	70.82	83.61	96.52
Freeboard:	6.00	5.50	5.00	4.50	4.00	3.50
Tangent to freeboard:	0.667	0.611	0.556	0.500	0.444	0.389
Tangent 14 deg:	0.249	0.249	0.249	0.249	0.249	0.249
GM required:	1.67	1.29	1.03	0.85	0.72	0.62
KMt at draft T:	11.51	12.94	12.79	12.16	11.48	10.83
Max KG incl. free surface:	9.84	11.65	11.76	11.31	10.76	10.21

PASSENGER CRITERION VALIDITY CALCULATION

from 46 CFR 171.050(b), effective March 14, 2011

The calculation of 46 CFR 171.050(a) is valid when the Righting Arm (GZ) at heel angle T is not less than the minimum Metacentric Height (GM) calculated in paragraph (a) multipied by sin(T).

Heel Angle, T, degrees:	14.00	14.00	14.00	14.00	14.00	14.00
sin(T) :	0.24	0.24	0.24	0.24	0.24	0.24
GM required (ft):	1.67	1.29	1.03	0.85	0.72	0.62
GZ required @ angle T (ft):	0.40	0.31	0.25	0.21	0.17	0.15

Compare required GZ to actual GZ from GHS output

SUMMARY TABLE

DRAFT	DISP	MAX KG	MIN GMt
4.00	36	9.84	1.67
4.50	47	11.65	1.29
5.00	58	11.76	1.03
5.50	71	11.31	0.85
6.00	84	10.76	0.72
6.50	97	10.21	0.62

```
08/25/17 01:14:20          Elliott Bay Design Group
GHS 15.00                          Vessel 2

              MAXIMUM VCG vs. DISPLACEMENT with ROLL
          Heeling moment is present from: user specification
     Trim = Fwd 0.50/54.08 at zero heel (trim righting arm held at zero)
          Displacement          ------ Margins ------
            LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4
           --------------------------------------------
               35.88     8.84    36d   78d    2%   86%
               46.46     8.85    33d   61d    0%  105%
               58.31     8.91    28d   45d    0%  104%
               70.79     9.01    23d   35d    0%   87%
               83.60     9.06    19d   27d    0%   64%
               96.51     8.78  LARGE   20d    0%   56%
           --------------------------------------------
          Heeling moment is present from: user specification
        Trim = zero at zero heel (trim righting arm held at zero)
          Displacement          ------ Margins ------
            LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4
           --------------------------------------------
               35.88     8.92    37d   71d    0%   95%
               46.46     8.92    33d   54d    0%  112%
               58.31     8.97    28d   41d    0%  110%
               70.79     9.05    23d   31d    0%   92%
               83.60     9.14  LARGE   23d    1%   57%
               96.51     8.78  LARGE   17d    2%   44%
           --------------------------------------------
          Heeling moment is present from: user specification
     Trim = Aft 0.50/54.08 at zero heel (trim righting arm held at zero)
          Displacement          ------ Margins ------
            LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4
           --------------------------------------------
               35.88     9.01    37d   64d    0%  104%
               46.46     9.01    32d   48d    0%  117%
               58.31     9.04    27d   36d    0%  115%
               70.79     9.10  LARGE   27d    0%   95%
               83.60     9.19  LARGE   20d    3%   46%
               96.51     8.78  LARGE   14d    0%   30%
           --------------------------------------------
          Heeling moment is present from: user specification
     Trim = Aft 1.00/54.08 at zero heel (trim righting arm held at zero)
          Displacement          ------ Margins ------
            LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4
           --------------------------------------------
               35.88     9.14    36d   57d    1%  106%
               46.46     9.10    32d   42d   -4%  122%
               58.31     9.14  LARGE   32d    2%  116%
               70.79     9.15  LARGE   24d    0%   94%
               83.60     9.17  LARGE   17d    0%   39%
               96.51     8.78  LARGE   11d    0%   15%
       Distances in FEET.---Specific Gravity = 1.025.---d = degrees.

   LIM------------46CFR 170.173(e) CRITERION-------------Min/Max
   (1) Absolute Angle at RAzero                     >    25.00 deg
   (2) Absolute Angle at Flood                      >    15.00 deg
   (3) Area from abs 0 deg to MaxRA or Flood        >    10.00 Ft-deg
   (4) Area from abs 0 deg to 40 or Flood           >    10.00 Ft-deg
   -----------------------------------------------------------------
```

TONNAGE

	Tonnage length:	55.92	Number of decks:	1	
	Number of divisions of length:	8.00	Number of Masts:	2	
	Common interval:	6.990	Stem	Plumb	
	1/3 common interval:	2.330	Stern:	Plumb	
	Tonnage depth:	8.50	Material:	Steel	
	Number of divisions of depth:	4	Service:	Passenger	

UNDER TONNAGE DECK VOLUME				TONNAGE	
Section Number	Simpson's Multiplier	Section Area Square Feet	Product		
				UNDER TONNAGE DECK:	30.98
1	1	94.95	94.95	Between Decks:	
2	4	117.45	469.80		
3	2	127.50	255.00	Forecastle:	
4	4	127.50	510.00		
5	2	0.00	0.00	Bridge:	
6	4	0.00	0.00		
7	2	0.00	0.00	Deck Houses:	
8	4	0.00	0.00		
9	1	0.00	0.00	Side Houses:	
10	0	0.00	0.00		
11	0	0.00	0.00	Mast Houses:	
12	0	0.00	0.00		
13	0	0.00	0.00	Trunks:	
	Total:		1329.75		
1/3 common interval:			2.330	Excess Hatchways:	
Under Deck Volume:			3098.32		
				Light and Air:	
Deducted Volume:			0.00		
Propelling Machinery Deduction:			0.00		
				Shelter Deck:	
Under Deck Volume w/ Deductions:			3098.32		
				Superstructures: (estimated)	42.43
UNDER DECK TONNAGE AS MEASURED:			30.98	**GROSS TONNAGE:**	**73.42**

UNDER TONNAGE DECK BREADTHS AND PRODUCTS

	Section No: 1		Section No: 2		Section No: 3		Section No: 4		Section No: 5		Section No: 6	
	Depth:	6.33	Depth:	7.83	Depth:	8.50	Depth:	8.50	Depth:	8.50	Depth:	8.50
	Interval:	1.58	Interval:	1.96	Interval:	2.13	Interval:	2.13	Interval:	2.13	Interval:	2.13
Simpson's Multiplier	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product
1	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	0.00	0.00	0.00	0.00
4	15.00	60.00	15.00	60.00	15.00	60.00	15.00	60.00	0.00	0.00	0.00	0.00
2	15.00	30.00	15.00	30.00	15.00	30.00	15.00	30.00	0.00	0.00	0.00	0.00
4	15.00	60.00	15.00	60.00	15.00	60.00	15.00	60.00	0.00	0.00	0.00	0.00
1	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	0.00	0.00	0.00	0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
Total:		180.00		180.00		180.00		180.00		0.00		0.00
1/3 interval:		0.53		0.65		0.71		0.71		0.71		0.71
Area in square feet:		94.95		117.45		127.50		127.50		0.00		0.00

	Section No: 7		Section No: 8		Section No: 9		Section No: 10		Section No: 11		Section No: 12	
	Depth:	8.50	Depth:	8.50	Depth:	8.50	Depth:	0.00	Depth:	0.00	Depth:	0.00
	Interval:	2.13	Interval:	2.13	Interval:	2.13	Interval:	0.00	Interval:	0.00	Interval:	0.00
Simpson's Multiplier	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
Total:		0.00		0.00		0.00		0.00		0.00		0.00
1/3 interval:		0.71		0.71		0.71		0.00		0.00		0.00
Area in square feet:		0.00		0.00		0.00		0.00		0.00		0.00

Deckhouse/Superstructures:

	L	W	H	T
Passenger Lounge	38.42	14.83	7.00	3988.9
Passenger Lounge Fwd	5.50	8.04	7.00	309.6
Ventilation Ducts	-2.92	1.50	3.00	-13.1
Ventilation Ducts	-4.00	1.50	7.00	-42.0
				0.0
Total Volume				4243.4
Total Gross Tons				**42.43**

Note:

1. The superstructure admeasurement assumes:
   No tonnage openings
   Uptake trunks, HVAC spaces and wheelhouse exempt.
2. See 00023-4-1042, Deck Arrangements, for superstructure configuration.

CAPITAL COST ESTIMATE

PARAMETRIC CONSTRUCTION COST ESTIMATE

Assumptions

1) This estimate is inteded for new construction of ONE vessel.
2) This vessel is assumed to be built in the USA
3) This estimate is intended for budgeting purposes ONLY.
4) Costs are organized in accordance with the EBDG interpretation of the SWBS System.
5) Weights are taken from 16128-833-0P0 Vessel 2 Weight Estimate
6) Other Assumptions as needed.
7) Non-trade labor rates are as follows:
   PM & Admin = 120% of Labor
   Engineering = 180% of Labor
8) Other vessel costs inflated to 2017 dollars based on Shipbuilding Inflation (Reference [3])

Calculations

SWBS COST GROUPS	Weight in LT	$/LT	HRS/LT	$ MATERIAL + Mark-up	LABOR HRS	LABOR COST
000 - PM & ADMIN					489	$ 42,873
100 - HULL	34.8	2,240	89.60	$ 91,260	3,120	$ 227,760
200 - PROP MACH'Y	8.7	22,400	179.20	$ 228,501	1,562	$ 114,055
300 - ELECTRICAL	1.3	67,200	336.00	$ 105,897	453	$ 33,036
400 - NAVIGATION	0.6	67,200	739.20	$ 44,015	414	$ 30,209
500 - AUXILIARY	14.9	8,960	89.60	$ 156,363	1,336	$ 97,560
600 - OUTFIT	8.6	13,440	336.00	$ 135,865	2,903	$ 211,926
H2 EQPT	4.2	NA	200.00	$ 932,958	843	$ 61,553
800 - ENGINEERING					1,063	$ 139,698
900- CONST. SERVICES				$ 50,846	1,488	$ 108,654
Totals	**73.22**			**$ 1,745,705**	**13,672**	**$ 1,067,324**

Inputs

Current Vessel	**Value**	**Unit**		
Length	60.00	ft	Vessel Type	Ferry
Beam	18.00	ft		
Depth	10.00	ft		
Light Ship Δ	74.60	LT		
Structure Weight	34.82	LT		
Shipyard	**Value**	**Units**		
Labor Rate	$73.00	/hr		
Material Mark-Up	17.0%		000 - PM & Admin	5.0%
Mat'l & Labor Margin	10.0%		800 - Engineering	10.0%
Contingency	10.0%		900 - Construction Services	14.0%
Other Vessels				**Cost**
				$
Shipyard Quote for Similar Sized Vessel				1,750,000

Output

Labor & Material Sub-Total	$2,813,030
Material & Labor Margin @ 10%	$281,302.99
Cost without Contingency =	**$3,094,333**
Contingency	$309,433
Total Vessel Construction Cost Estimate with 10% CONTINGENCY	**$3,403,766**
Rounded Up Total	**$3,500,000**

Appendix C

Vessel #3 Drawings and Calculations

GENERAL ARRANGEMENTS

WEIGHT ESTIMATE

	VESSEL WEIGHT ESTIMATE						
SWBS No.	Description	Qty.	Total Wt. (lbs)	LCG **(+ fwd)**	TCG **(+ stbd)**	VCG **(+ abl)**	Notes
	SUMMARY						
100	STRUCTURE		97,259	68.50	0.00	12.78	
200	MACHINERY		147,887	33.68	-0.08	14.13	
300	ELECTRICAL		22,104	51.50	0.00	5.00	
400	ELECTRONICS & IC		2,210	102.58	0.00	24.88	
500	AUXILIARY SYSTEMS		44,209	51.50	0.00	5.00	
600	OUTFIT		33,156	68.50	0.00	12.78	
	VESSEL WEIGHT - SUBTOTAL		346,826 (154.83LT)	50.62	-0.04	11.95	
	Add Margin to Structure for Roll & Weld	0%	0	68.50	0.00	12.78	In steel weight
100	STRUCTURE	10%	9,726	68.50	0.00	12.78	
200	MACHINERY	10%	14,789	33.68	-0.08	14.13	
300	ELECTRICAL	10%	2,210	51.50	0.00	5.00	
400	ELECTRONICS & IC	10%	221	102.58	0.00	24.88	
500	AUXILIARY SYSTEMS	10%	4,421	51.50	0.00	5.00	
600	OUTFIT	10%	3,316	68.50	0.00	12.78	
	VESSEL WEIGHT WITH MARGINS		**381,509 (170.3 LT)**	**50.62**	**-0.04**	**11.95**	

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)
100	**Basline Design Weight**	0.44	221043	97,259	68.50	0.00	12.78
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)
200	**Basline Design Weight**	0.10	221043	22,104	39.33	0.00	5.00
	Weights to Remove						
	-						
	Weights to Add						
	Electric Motors	2.00	13224	26,448	30.00	0.00	3.67
	Propulsion System Electrical Components	1.00	4374	4,374	41.75	0.00	6.50
	Fuel Cells Rack	19.00	1764	33,516	24.50	-7.00	16.42
	Fuel Cells Rack	18.00	1764	31,752	24.50	7.00	16.42
	LH2 Tank	1.00	21693	21,693	57.21	0.00	27.13
	Vaporizers	2.00	4000.00	8,000	36.89	0.00	24.25

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)
200	**Basline Design Weight**	0.10	221043	22,104	39.33	0.00	5.00
	Weights to Remove						
	-						
	Weights to Add						
	Electric Motors	2.00	13224	26,448	30.00	0.00	3.67
	Propulsion System Electrical Components	1.00	4374	4,374	41.75	0.00	6.50
	Fuel Cells Rack	19.00	1764	33,516	24.50	-7.00	16.42
	Fuel Cells Rack	18.00	1764	31,752	24.50	7.00	16.42
	LH2 Tank	1.00	21693	21,693	57.21	0.00	27.13
	Vaporizers	2.00	4000.00	8,000	36.89	0.00	24.25

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)
400	**Basline Design Weight**	0.01	221043	2,210	102.58	0.00	24.88
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)
500	**Basline Design Weight**	0.20	221043	44,209	51.50	0.00	5.00
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ fwd)	TCG (+ stbd)	VCG (+ abl)
600	**Basline Design Weight**	0.150	221043	33,156	68.50	0.00	12.78
	Weights to Remove						
	-						
	Weights to Add						
	-						

STABILITY CALCULATIONS

WEATHER CRITERION MAXIMUM KG CALCULATION
from 46 CFR 170.170
for service on exposed waters

$$GM_{reqd} = \frac{PAH}{W \tan(T)}$$

P = 0.0050 + (L/14200)2 = 0.0050851 Long tons / Ft^2
A = lateral area above waterline
H = vertical distance from centroid of A to 1/2 draft point
W = displacement in long tons
T = 14 degrees or angle of heel where 1/2 freeboard is submerged, whichever is less.

Length on max waterline:	131.00	ft	
Depth to freeboard deck: (low point, at edge)	13.08	ft	
Beam:	39.30	ft	
Superstructure Height:	9.00	ft	Full breadth of vessel, full length

Draft, T:	3.00	3.50	4.00	4.50	5.00	5.50
Displacement to T:	123	156	189	222	256	291
Area above waterline:	3302	3238	3173	3107	3042	2976
h of area above waterline:	12.88	12.64	12.39	12.15	11.90	11.66
h of area to baseline:	15.88	16.14	16.39	16.65	16.90	17.16
Vertical distance, H:	14.38	14.39	14.39	14.40	14.40	14.41
Freeboard, f:	10.08	9.58	9.08	8.58	8.08	7.58
Tangent to 1/2 freeboard:	0.257	0.244	0.231	0.218	0.206	0.193
Tangent 14 deg:	0.249	0.249	0.249	0.249	0.249	0.249
GM required:	7.85	6.24	5.32	4.68	4.22	3.89
KMt at draft T:	107.12	87.23	73.75	64.05	56.79	51.19
Max KG incl. free surface:	99.27	80.99	68.43	59.37	52.57	47.30

SUMMARY TABLE

DRAFT	DISP	MAX KG	MIN GMt
3.00	123.29	99.27	7.85
3.50	155.81	80.99	6.24
4.00	188.92	68.43	5.32
4.50	222.49	59.37	4.68
5.00	256.45	52.57	4.22
5.50	290.75	47.30	3.89

PASSENGER CRITERION MAXIMUM KG CALCULATION

from 46 CFR 171.050(a), effective March 14, 2011

$$GM_{reqd} = \boxed{\frac{W}{\Delta} * \frac{2}{3} * \frac{b}{\tan(T)}}$$

W = total weight of persons other than required crew, including effects, in long tons
b = distance off centerline to centroid of passenger deck on one side
(beam/4 used to be conservative)
Δ = displacement in long tons
T = 14 degrees or angle of heel where freeboard is submerged,
whichever is less.

Number of passengers:	354	
Depth to freeboard deck:	13.08	ft
(low point, at edge)		
Beam:	39.30	ft
b:	17.25	ft
W:	31.61	LT

Draft, T:	3.00	3.50	4.00	4.50	5.00	5.50
Displacement to T:	123.29	155.81	188.92	222.49	256.45	290.75
Freeboard:	10.08	9.58	9.08	8.58	8.08	7.58
Tangent to freeboard:	0.513	0.488	0.462	0.437	0.411	0.386
Tangent 14 deg:	0.249	0.249	0.249	0.249	0.249	0.249
GM required:	11.82	9.36	7.72	6.55	5.68	5.01
KMt at draft T:	107.12	87.23	73.75	64.05	56.79	51.19
Max KG incl. free surface:	95.30	77.87	66.03	57.50	51.11	46.18

PASSENGER CRITERION VALIDITY CALCULATION

from 46 CFR 171.050(b), effective March 14, 2011

The calculation of 46 CFR 171.050(a) is valid when the Righting Arm (GZ) at heel angle T is not less than the minimum Metacentric Height (GM) calculated in paragraph (a) multipied by sin(T).

Heel Angle, T, degrees:	14.00	14.00	14.00	14.00	14.00	14.00
sin(T) :	0.24	0.24	0.24	0.24	0.24	0.24
GM required (ft):	11.82	9.36	7.72	6.55	5.68	5.01
GZ required @ angle T (ft):	2.86	2.26	1.87	1.59	1.38	1.21

Compare required GZ to actual GZ from GHS output

SUMMARY TABLE

DRAFT	DISP	MAX KG	MIN GMt
3.00	123	95.30	11.82
3.50	156	77.87	9.36
4.00	189	66.03	7.72
4.50	222	57.50	6.55
5.00	256	51.11	5.68
5.50	291	46.18	5.01

```
08/25/17 08:25:22          Elliott Bay Design Group
GHS 15.00                          Vessel 3

                 MAXIMUM VCG vs. DISPLACEMENT with ROLL
             Heeling moment is present from: user specification
   Trim = Fwd 0.50/131.00 at zero heel (trim righting arm held at zero)
          Displacement          ------ Margins ------
            LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4
           -------------------------------------------
               123.23    35.21     0d   54d  342%  462%
               155.77    35.30     0d   48d  374%  332%
               188.89    35.52     0d   44d  358%  204%
               222.44    35.83     0d   39d  349%   74%
               256.41    35.75     0d   35d  305%    0%
               290.71    35.11     1d   30d  279%    0%
           -------------------------------------------
             Heeling moment is present from: user specification
         Trim = zero at zero heel (trim righting arm held at zero)
          Displacement          ------ Margins ------
            LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4
           -------------------------------------------
               123.23    35.20     0d   51d  342%  463%
               155.77    35.29     0d   46d  382%  332%
               188.89    35.52     0d   41d  358%  203%
               222.44    35.83     0d   37d  347%   71%
               256.41    35.72     0d   32d  321%    0%
               290.71    35.10     1d   27d  279%    0%
           -------------------------------------------
             Heeling moment is present from: user specification
   Trim = Aft 0.50/131.00 at zero heel (trim righting arm held at zero)
          Displacement          ------ Margins ------
            LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4
           -------------------------------------------
               123.23    35.20     0d   49d  340%  461%
               155.77    35.30     0d   44d  389%  328%
               188.89    35.53     0d   39d  358%  199%
               222.44    35.84     0d   35d  344%   68%
               256.41    35.70     0d   30d  317%    0%
               290.71    36.08     0d   23d  245%    0%
           -------------------------------------------
             Heeling moment is present from: user specification
   Trim = Aft 1.00/131.00 at zero heel (trim righting arm held at zero)
          Displacement          ------ Margins ------
            LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4
           -------------------------------------------
               123.23    35.21     0d   46d  332%  452%
               155.77    35.32     0d   41d  380%  320%
               188.89    35.55     0d   37d  356%  192%
               222.44    35.86     0d   32d  339%   61%
               256.41    35.67     0d   27d  298%    0%
               290.71    36.60     0d   19d  224%  175%
       Distances in FEET.---Specific Gravity = 1.025.---d = degrees.


   LIM------------46CFR 170.173(e) CRITERION-------------Min/Max
   (1) Absolute Angle at RAzero                      >    25.00 deg
   (2) Absolute Angle at Flood                       >    15.00 deg
   (3) Area from abs 0 deg to MaxRA or Flood         >    10.00 Ft-deg
   (4) Area from abs 0 deg to 40 or Flood            >    10.00 Ft-deg
   -----------------------------------------------------------------
```

TONNAGE

		Tonnage length:	120.00	Number of decks:	1	
		Number of divisions of length:	10.00	Number of Masts:	2	
		Common interval:	12.000	Stem	Raked	
		1/3 common interval:	4.000	Stern:	Square	
		Tonnage depth:	7.00	Material:	Steel	
		Number of divisions of depth:	4	Service:	Passenger	
		UNDER TONNAGE DECK VOLUME			TONNAGE	
Section Number	Simpson's Multiplier	Section Area Square Feet	Product	UNDER TONNAGE DECK:		97.20
1	1	0.00	0.00	Between Decks:		
2	4	0.00	0.00			
3	2	84.00	168.00	Forecastle:		
4	4	108.50	434.00			
5	2	108.50	217.00	Bridge:		
6	4	108.50	434.00			
7	2	108.50	217.00	Deck Houses:		
8	4	140.00	560.00			
9	2	120.00	240.00	Side Houses:		
10	4	40.00	160.00			
11	1	0.00	0.00	Mast Houses:		
12	0	0.00	0.00			
13	0	0.00	0.00	Trunks:		
	Total:		2430.00			
1/3 common interval:			4.000	Excess Hatchways:		
Under Deck Volume:			9720.00			
				Light and Air:		
Ballast Tank Volume:			0.000			
				Shelter Deck:		
Under Deck Volume w/ Ballast Exemption:			9720.00			
				Superstructures:		
UNDER DECK TONNAGE AS MEASURED:			97.20	**GROSS TONNAGE:**		**97.20**

UNDER TONNAGE DECK BREADTHS AND PRODUCTS

	Section No: 1		Section No: 2		Section No: 3		Section No: 4		Section No: 5		Section No: 6	
	Depth:	0.00	Depth:	0.00	Depth:	7.00	Depth:	7.00	Depth:	7.00	Depth:	7.00
	Interval:	0.00	Interval:	0.00	Interval:	1.75	Interval:	1.75	Interval:	1.75	Interval:	1.75
Simpson's Multiplier	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product
1	0.00	0.00		0.00	12.00	12.00	15.50	15.50	15.50	15.50	15.50	15.50
4	0.00	0.00		0.00	12.00	48.00	15.50	62.00	15.50	62.00	15.50	62.00
2	0.00	0.00		0.00	12.00	24.00	15.50	31.00	15.50	31.00	15.50	31.00
4	0.00	0.00		0.00	12.00	48.00	15.50	62.00	15.50	62.00	15.50	62.00
1	0.00	0.00		0.00	12.00	12.00	15.50	15.50	15.50	15.50	15.50	15.50
0		0.00		0.00		0.00		0.00		0.00		0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
	Total:	0.00		0.00		144.00		186.00		186.00		186.00
1/3 interval:		0.00		0.00		0.58		0.58		0.58		0.58
Area in square feet:		0.00		0.00		84.00		108.50		108.50		108.50

	Section No: 7		Section No: 8		Section No: 9		Section No: 10		Section No: 11		Section No: 12	
	Depth:	7.00	Depth:	7.00	Depth:	6.00	Depth:	5.00	Depth:	0.00	Depth:	0.00
	Interval:	1.75	Interval:	1.75	Interval:	1.50	Interval:	1.25	Interval:	0.00	Interval:	0.00
Simpson's Multiplier	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product
1	15.50	15.50	20.00	20.00	20.00	20.00	8.00	8.00	0.00	0.00	0.00	0.00
4	15.50	62.00	20.00	80.00	20.00	80.00	8.00	32.00	0.00	0.00	0.00	0.00
2	15.50	31.00	20.00	40.00	20.00	40.00	8.00	16.00	0.00	0.00	0.00	0.00
4	15.50	62.00	20.00	80.00	20.00	80.00	8.00	32.00	0.00	0.00	0.00	0.00
1	15.50	15.50	20.00	20.00	20.00	20.00	8.00	8.00	0.00	0.00	0.00	0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
	Total:	186.00		240.00		240.00		96.00		0.00		0.00
1/3 interval:		0.58		0.58		0.50		0.42		0.00		0.00
Area in square feet:		108.50		140.00		120.00		40.00		0.00		0.00

	Section No: 13		Section No: 14		Section No: 15		Section No: 16		Section No: 17	
	Depth:	0.00	Depth:	0.00	Depth:	0.00	Depth:	0.00	Depth:	0.00
	Interval:	0.00	Interval:	0.00	Interval:	0.00	Interval:	0.00	Interval:	0.00
Simpson's Multiplier	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product
1	0.00	0.00		0.00		0.00		0.00		0.00
4	0.00	0.00		0.00		0.00		0.00		0.00
2	0.00	0.00		0.00		0.00		0.00		0.00
4	0.00	0.00		0.00		0.00		0.00		0.00
1	0.00	0.00		0.00		0.00		0.00		0.00
0		0.00		0.00		0.00		0.00		0.00
0		0.00		0.00		0.00		0.00		0.00
	Total:	0.00		0.00		0.00		0.00		0.00
1/3 interval:		0.00		0.00		0.00		0.00		0.00
Area in square feet:		0.00		0.00		0.00		0.00		0.00

CAPITAL COST ESTIMATE

PARAMETRIC CONSTRUCTION COST ESTIMATE

Assumptions

1) This estimate is inteded for new construction of ONE vessel.
2) This vessel is assumed to be built in the USA
3) This estimate is intended for budgeting purposes ONLY.
4) Costs are organized in accordance with the EBDG interpretation of the SWBS System.
5) Weights are taken from 16128-833-0P0 Vessel 3 Weight Estimate
6) Other Assumptions as needed.
7) Non-trade labor rates are as follows:
   PM & Admin = 120% of Labor
   Engineering = 180% of Labor
8) Other vessel costs inflated to 2017 dollars based on Shipbuilding Inflation (Reference [3])

Calculations

SWBS COST GROUPS	Weight in LT	$/LT	HRS/LT	$ MATERIAL + Mark-up	LABOR HRS	LABOR COST
000 - PM & ADMIN					1,627	$ 142,527
100 - HULL	47.8	5,936	448.00	$ 331,707	21,397	$ 1,561,981
200 - PROP MACH'Y	29.9	268,800	110.00	$ 9,409,468	3,291	$ 240,251
300 - ELECTRICAL	10.9	112,000	78.40	$ 1,422,428	851	$ 62,125
400 - NAVIGATION	1.1	145,600	450.00	$ 184,878	488	$ 35,651
500 - AUXILIARY	21.7	33,600	150.00	$ 853,439	3,256	$ 237,718
600 - OUTFIT	16.3	33,600	200.00	$ 640,084	3,256	$ 237,719
LH2 EQPT	42.7	NA	200.00	$ 11,932,011	8,541	$ 623,479
800 - ENGINEERING					3,254	$ 427,580
900- CONST. SERVICES				$ 385,260	4,556	$ 332,562
Totals	**170.32**			**$ 25,159,273**	**50,518**	**$ 3,901,593**

Inputs

Current Vessel	Value	Unit		
Length	140.17	*ft*	Vessel Type	Ferry
Beam	39.33	*ft*		
Depth	13.08	*ft*		
Light Ship Δ	170.30	*LT*		
Structure Weight	47.80	*LT*		

Shipyard	Value	Units		
Labor Rate	$73.00	*/hr*		
Material Mark-Up	17.0%		000 - PM & Admin	5.0%
Mat'l & Labor Margin	10.0%		800 - Engineering	10.0%
Contingency	10.0%		900 - Construction Services	14.0%

Other Vessels	Cost
	$
Scaled from similar vessel constructed in 2003	18,800,000

Output

Labor & Material Sub-Total	$29,060,867
Material & Labor Margin @ 10%	$2,906,086.66
Cost without Contingency =	**$31,966,953**
Contingency	$3,196,695
Total Vessel Construction Cost Estimate with 10% CONTINGENCY	**$35,163,649**
Rounded Up Total	**$35,200,000**

Appendix D

Vessel #4 Drawings and Calculations

GENERAL ARRANGEMENTS

WEIGHT ESTIMATE

	VESSEL WEIGHT ESTIMATE						
SWBS No.	Description	Qty.	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)	Notes
	SUMMARY						
100	STRUCTURE		359,127	60.00	0.00	13.50	
200	MACHINERY		51,773	76.37	0.00	11.99	
300	ELECTRICAL		11,491	60.00	0.00	13.50	
400	ELECTRONICS & IC		718	60.00	0.00	13.50	
500	AUXILIARY SYSTEMS		57,461	57.44	0.00	14.14	
600	OUTFIT		47,305	60.00	0.00	13.50	
	VESSEL WEIGHT - SUBTOTAL		527,875 (235.66LT)	61.33	0.00	13.42	
	Add Margin to Structure for Roll & Weld	0%	0	60.00	0.00	13.50	Included in baseline
100	STRUCTURE	0%	0	60.00	0.00	13.50	Included in baseline
200	MACHINERY	9%	4,660	76.37	0.00	11.99	
300	ELECTRICAL	12%	1,379	60.00	0.00	13.50	
400	ELECTRONICS & IC	12%	86	60.00	0.00	13.50	
500	AUXILIARY SYSTEMS	12%	6,895	57.44	0.00	14.14	
600	OUTFIT	12%	5,677	60.00	0.00	13.50	
	VESSEL WEIGHT WITH MARGINS		**546,571 (244.01 LT)**	**61.39**	**0.00**	**13.42**	

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
100	**Basline Design Weight**	1.00	359127	359,127	60.00	0.00	13.50
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
200	**Basline Design Weight**	0.26	70762	18,115	60.00	0.00	13.50
	Weights to Remove						
	Main Engines	-0.26	28826	-7,379	75.75	0.00	7.00
	Main Engine Systems	-0.26	3906	-1,000	75.75	0.00	7.00
	Weights to Add						
	Electric Motors	2.00	4140	8,280	80.00	0.00	7.00
	Propulsion System Electrical Components	1.00	815	815	74.75	0.00	7.00
	Fuel Cells - 120 KW rack	4.00	1764	7,056	69.50	0.00	7.00
	Fuel Cells - 120 KW rack	4.00	1764	7,056	58.50	0.00	7.00
	LH2 Tank	1.00	15830	15,830	99.58	0.00	14.83
	Vaporizers	2.00	1500	3,000	99.58	0.00	12.50

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
300	**Basline Design Weight**	0.26	44888	11,491	60.00	0.00	13.50
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
400	**Basline Design Weight**	0.26	2805	718	60.00	0.00	13.50
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
500	**Basline Design Weight**	0.26	256689	65,712	60.00	0.00	13.50
	Weights to Remove						
	Fuel Oil System	-0.26	1062	-272	72.00	0.00	7.00
	Exhaust System	-0.26	10092	-2,584	84.00	0.00	13.50
	Steam System	-0.26	11533	-2,952	72.00	0.00	7.00
	Generators	-0.26	5500	-1,408	84.00	0.00	7.00
	Lube Oil System	-0.26	1215	-311	72.00	0.00	7.00
	Compressed Air System	-0.26	2830	-724	72.00	0.00	7.00
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
600	**Basline Design Weight**	0.256	184784	47,305	60.00	0.00	13.50
	Weights to Remove						
	-						
	Weights to Add						
	-						

Deadweight Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
Passengers and Crew, Main Deck	70.00	205	14,350	72.00	0.00	14.00
Passengers and Crew, Upper Deck	####	205	47,150	64.00	0.00	22.00
Passenger and Crew, Sun Deck	50.00	205	10,250	62.00	0.00	30.00
Stores	1.00	10000	10,000	60.55	0.00	6.00
Crew	10.00	225	2,250	48.00	0.00	19.00
Potable Water	1.00	33757	33,757	20.00	0.00	6.00
Sewage	1.00	33757	33,757	92.00	0.00	6.00
LH2	1.00	1620	1,620	99.58	0.00	14.83
SLM	0.05	546571	27,329	61.39	0.00	13.42

STABILITY CALCULATIONS

WEATHER CRITERION MAXIMUM KG CALCULATION
from 46 CFR 170.170
for service on exposed waters

$$GM_{reqd} = \frac{PAH}{W \, Tan\,(T)}$$

P = 0.0050 + (L/14200)2 = 0.0050714 Long tons / Ft^2
A = lateral area above waterline
H = vertical distance from centroid of A to 1/2 draft point
W = displacement in long tons
T = 14 degrees or angle of heel where 1/2 freeboard is submerged, whichever is less.

Length on max waterline:	120.00	ft
Depth to freeboard deck: (low point, at edge)	11.00	ft
Beam:	32.00	ft
Superstructure Height:	9.00	ft

Full breadth of vessel, full length

Draft, T:	5.00	5.50	6.00	6.50	7.00	7.50
Displacement to T:	221	263	307	352	398	445
Area above waterline:	2253	2190	2126	2061	1997	1937
h of area above waterline:	10.19	9.98	9.77	9.57	9.37	9.16
h of area to baseline:	15.19	15.48	15.77	16.07	16.37	16.66
Vertical distance, H:	12.69	12.73	12.77	12.82	12.87	12.91
Freeboard, f:	6.00	5.50	5.00	4.50	4.00	3.50
Tangent to 1/2 freeboard:	0.188	0.172	0.156	0.141	0.125	0.109
Tangent 14 deg:	0.249	0.249	0.249	0.249	0.249	0.249
GM required:	3.51	3.13	2.87	2.71	2.62	2.61
KMt at draft T:	27.18	25.38	23.97	22.64	21.39	20.31
Max KG incl. free surface:	23.67	22.25	21.10	19.93	18.77	17.70

SUMMARY TABLE

DRAFT	DISP	MAX KG	MIN GMt
5.00	220.62	23.67	3.51
5.50	262.54	22.25	3.13
6.00	306.52	21.10	2.87
6.50	352.16	19.93	2.71
7.00	397.85	18.77	2.62
7.50	444.50	17.70	2.61

PASSENGER CRITERION MAXIMUM KG CALCULATION

from 46 CFR 171.050(a), effective March 14, 2011

$$GM_{reqd} = \boxed{\frac{W}{\Delta} * \frac{2}{3} * \frac{b}{\tan(T)}}$$

W = total weight of persons other than required crew, including effects, in long tons
b = distance off centerline to centroid of passenger deck on one side
(beam/4 used to be conservative)
Δ = displacement in long tons
T = 14 degrees or angle of heel where freeboard is submerged,
whichever is less.

Number of passengers:	412	
Depth to freeboard deck: (low point, at edge)	11.00	ft
Beam:	32.00	ft
b:	17.25	ft
W:	36.79	LT

Draft, T:	5.00	5.50	6.00	6.50	7.00	7.50
Displacement to T:	220.62	262.54	306.52	352.16	397.85	444.50
Freeboard:	6.00	5.50	5.00	4.50	4.00	3.50
Tangent to freeboard:	0.375	0.344	0.313	0.281	0.250	0.219
Tangent 14 deg:	0.249	0.249	0.249	0.249	0.249	0.249
GM required:	7.69	6.46	5.54	4.82	4.26	4.35
KMt at draft T:	27.18	25.38	23.97	22.64	21.39	20.31
Max KG incl. free surface:	19.49	18.92	18.43	17.82	17.13	15.96

PASSENGER CRITERION VALIDITY CALCULATION

from 46 CFR 171.050(b), effective March 14, 2011

The calculation of 46 CFR 171.050(a) is valid when the Righting Arm (GZ) at heel angle T is not less than the minimum Metacentric Height (GM) calculated in paragraph (a) multipied by sin(T).

Heel Angle, T, degrees:	14.00	14.00	14.00	14.00	14.00	12.34
sin(T) :	0.24	0.24	0.24	0.24	0.24	0.21
GM required (ft):	7.69	6.46	5.54	4.82	4.26	4.35
GZ required @ angle T (ft):	1.86	1.56	1.34	1.17	1.03	0.93

Compare required GZ to actual GZ from GHS output

SUMMARY TABLE

DRAFT	DISP	MAX KG	MIN GMt
5.00	221	19.49	7.69
5.50	263	18.92	6.46
6.00	307	18.43	5.54
6.50	352	17.82	4.82
7.00	398	17.13	4.26
7.50	445	15.96	4.35

```
08/25/17 04:53:40         Elliott Bay Design Group
GHS 15.00                      16128 Vessel 4

                  MAXIMUM VCG vs. DISPLACEMENT with ROLL
              Heeling moment is present from: user specification
    Trim = Fwd 0.50/115.00 at zero heel (trim righting arm held at zero)
        Displacement          ------------ Margins ------------
          LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4  LIM5  LIM6
         --------------------------------------------------------
              220.42    16.64  1953%    2d  187%    0%   70%   70%
              262.34    16.05  1720%    4d  184%    0%   97%   97%
              306.52    15.37  1584%    5d  183%    0%  104%  104%
              352.16    14.63  1521%    4d  180%    0%   88%   88%
              397.85    13.83  1428%    4d  175%    0%   75%   75%
              444.50    12.98  1409%    3d  168%    0%   63%   63%
         --------------------------------------------------------
              Heeling moment is present from: user specification
          Trim = zero at zero heel (trim righting arm held at zero)
        Displacement          ------------ Margins ------------
          LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4  LIM5  LIM6
         --------------------------------------------------------
              220.42    16.79  2021%    2d  189%    0%   69%   69%
              262.34    16.17  1781%    4d  187%    0%   97%   97%
              306.52    15.46  1636%    5d  185%    0%  106%  106%
              352.16    14.68  1523%    4d  181%    0%   88%   88%
              397.85    13.86  1412%    4d  176%    0%   75%   75%
              444.50    12.98  1395%    3d  168%    0%   63%   63%
         --------------------------------------------------------
              Heeling moment is present from: user specification
    Trim = Aft 0.50/115.00 at zero heel (trim righting arm held at zero)
        Displacement          ------------ Margins ------------
          LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4  LIM5  LIM6
         --------------------------------------------------------
              220.42    16.94  2068%    2d  192%    0%   68%   68%
              262.34    16.28  1838%    4d  190%    0%   98%   98%
              306.52    15.54  1693%    5d  187%    0%  108%  108%
              352.16    14.72  1512%    4d  183%    0%   88%   88%
              397.85    13.87  1425%    4d  176%    0%   75%   75%
              444.50    12.97  1386%    3d  167%    0%   62%   62%
         --------------------------------------------------------
              Heeling moment is present from: user specification
    Trim = Aft 1.00/115.00 at zero heel (trim righting arm held at zero)
        Displacement          ------------ Margins ------------
          LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4  LIM5  LIM6
         --------------------------------------------------------
              220.42    17.08  2115%    2d  196%    0%   69%   69%
              262.34    16.38  1887%    4d  192%    0%   99%   99%
              306.52    15.60  1703%    5d  189%    0%  110%  110%
              352.16    14.75  1499%    4d  183%    0%   88%   88%
              397.85    13.87  1416%    4d  176%    0%   75%   75%
              444.50    12.95  1380%    3d  167%    0%   62%   62%
        Distances in FEET.---Specific Gravity = 1.025.---d = degrees.

    LIM--------170.173C RIGHTING ENERGY CRITERION---------Min/Max
    (1)  GM Upright                                   >     0.49 Ft
    (2) Angle from 0 deg to MaxRA                     >    15.00 deg
    (3) Area from 0 deg to 40 or Flood                >    16.90 Ft-deg
    (4) Area from 30 deg to 40 or Flood               >     5.60 Ft-deg
    (5) Area from 0 deg to MaxRA at 15                >    13.11 Ft-deg
    (6) Area from 0 deg to MaxRA at 30                >    10.30 Ft-deg
    -----------------------------------------------------------------
```

TONNAGE

Tonnage length:	131.33	Number of decks:	1	
Number of divisions of length:	10.00	Number of Masts:	2	
Common interval:	13.133	Stem	Raked	
1/3 common interval:	4.378	Stern:	Square	
Tonnage depth:	10.83	Material:	Steel	
Number of divisions of depth:	4	Service:	Passenger	

UNDER TONNAGE DECK VOLUME

Section Number	Simpson's Multiplier	Section Area Square Feet	Product
1	1	0.00	0.00
2	4	159.03	636.12
3	2	159.03	318.06
4	4	159.03	636.12
5	2	159.03	318.06
6	4	0.00	0.00
7	2	0.00	0.00
8	4	0.00	0.00
9	2	0.00	0.00
10	4	0.00	0.00
11	1	0.00	0.00
12	0	0.00	0.00
13	0	0.00	0.00
	Total:		1908.36
1/3 common interval:			4.378
Under Deck Volume:			8354.38
Ballast Tank Volume:			0.000
Under Deck Volume w/ Ballast Exemption:			8354.38
UNDER DECK TONNAGE AS MEASURED:			83.54

TONNAGE

UNDER TONNAGE DECK:	83.54
Between Decks:	
Forecastle:	
Bridge:	
Deck Houses:	
Side Houses:	
Mast Houses:	
Trunks:	
Excess Hatchways:	
Light and Air:	
Shelter Deck:	
Superstructures:	
GROSS TONNAGE:	**83.54**

UNDER TONNAGE DECK BREADTHS AND PRODUCTS

	Section No: 1		Section No: 2		Section No: 3		Section No: 4		Section No: 5		Section No: 6	
	Depth:	9.00	Depth:	9.00	Depth:	9.00	Depth:	9.00	Depth:	9.00	Depth:	9.00
	Interval:	2.25	Interval:	2.25	Interval:	2.25	Interval:	2.25	Interval:	2.25	Interval:	2.25
Simpson's Multiplier	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product
1	0.00	0.00	17.67	17.67	17.67	17.67	17.67	17.67	17.67	17.67	0.00	0.00
4	0.00	0.00	17.67	70.68	17.67	70.68	17.67	70.68	17.67	70.68	0.00	0.00
2	0.00	0.00	17.67	35.34	17.67	35.34	17.67	35.34	17.67	35.34	0.00	0.00
4	0.00	0.00	17.67	70.68	17.67	70.68	17.67	70.68	17.67	70.68	0.00	0.00
1	0.00	0.00	17.67	17.67	17.67	17.67	17.67	17.67	17.67	17.67	0.00	0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
	Total:	0.00		212.04		212.04		212.04		212.04		0.00
1/3 interval:		0.75		0.75		0.75		0.75		0.75		0.75
Area in square feet:		0.00		159.03		159.03		159.03		159.03		0.00

	Section No: 7		Section No: 8		Section No: 9		Section No: 10		Section No: 11		Section No: 12	
	Depth:	9.00	Depth:	9.00	Depth:	9.00	Depth:	9.00	Depth:	9.00	Depth:	0.00
	Interval:	2.25	Interval:	2.25	Interval:	2.25	Interval:	2.25	Interval:	2.25	Interval:	0.00
Simpson's Multiplier	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
0		0.00		0.00		0.00		0.00		0.00		0.00
	Total:	0.00		0.00		0.00		0.00		0.00		0.00
1/3 interval:		0.75		0.75		0.75		0.75		0.75		0.00
Area in square feet:		0.00		0.00		0.00		0.00		0.00		0.00

	Section No: 13		Section No: 14		Section No: 15		Section No: 16		Section No: 17	
	Depth:	0.00	Depth:	0.00	Depth:	0.00	Depth:	0.00	Depth:	0.00
	Interval:	0.00	Interval:	0.00	Interval:	0.00	Interval:	0.00	Interval:	0.00
Simpson's Multiplier	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product	Breadth	Product
1	0.00	0.00		0.00		0.00		0.00		0.00
4	0.00	0.00		0.00		0.00		0.00		0.00
2	0.00	0.00		0.00		0.00		0.00		0.00
4	0.00	0.00		0.00		0.00		0.00		0.00
1	0.00	0.00		0.00		0.00		0.00		0.00
0		0.00		0.00		0.00		0.00		0.00
0		0.00		0.00		0.00		0.00		0.00
	Total:	0.00		0.00		0.00		0.00		0.00
1/3 interval:		0.00		0.00		0.00		0.00		0.00
Area in square feet:		0.00		0.00		0.00		0.00		0.00

CAPITAL COST ESTIMATE

PARAMETRIC CONSTRUCTION COST ESTIMATE

Assumptions

1) This estimate is inteded for new construction of ONE vessel.
2) This vessel is assumed to be built in the USA
3) This estimate is intended for budgeting purposes ONLY.
4) Costs are organized in accordance with the EBDG interpretation of the SWBS System.
5) Weights are taken from 16128-833-0P0 Vessel 4 Weight Estimate
6) Other Assumptions as needed.
7) Non-trade labor rates are as follows:
   PM & Admin = 120% of Labor
   Engineering = 180% of Labor

Calculations

SWBS COST GROUPS	Weight in LT	$/LT	HRS/LT	$ MATERIAL + Mark-up	LABOR HRS	LABOR COST
000 - PM & ADMIN					2,848	$ 249,498
100 - HULL	160.3	4,928	134.40	$ 924,393	21,548	$ 1,572,976
200 - PROP MACH'Y	10.6	35,840	448.00	$ 445,442	4,759	$ 347,407
300 - ELECTRICAL	5.7	134,400	1,008.00	$ 903,474	5,792	$ 422,780
400 - NAVIGATION	0.4	224,000	1,792.00	$ 94,068	643	$ 46,954
500 - AUXILIARY	28.7	13,440	179.20	$ 451,779	5,148	$ 375,839
600 - OUTFIT	23.7	17,920	806.40	$ 495,902	19,073	$ 1,392,341
LH2 EQPT	14.6	NA	350.00	$ 2,874,924	5,099	$ 372,263
800 - ENGINEERING					6,206	$ 815,501
900- CONST. SERVICES				$ 185,699	8,689	$ 634,278
Totals	**244.00**			**$ 6,375,682**	**79,806**	**$ 6,229,836**

Inputs

Current Vessel	Value	Unit		
Length	135.00	*ft*	Vessel Type	Ferry
Beam	32.00	*ft*		
Depth	11.00	*ft*		
Light Ship Δ	244.01	*LT*		
Structure Weight	160.32	*LT*		

Shipyard	Value	Units		
Labor Rate	$73.00	*/hr*		
Material Mark-Up	17.0%		000 - PM & Admin	5.0%
Mat'l & Labor Margin	10.0%		800 - Engineering	10.0%
Contingency	10.0%		900 - Construction Services	14.0%

Other Vessels	Cube Number	Light Ship Δ	Structure Wt	Labor Hours	Cost
Units	*ft^3*	*LT*	*LT*	*hrs*	*$*

Output

Labor & Material Sub-Total	$12,605,518
Material & Labor Margin @ 10%	$1,260,551.82
Cost without Contingency =	**$13,866,070**
Contingency	$1,386,607
Total Vessel Construction Cost Estimate with 10% CONTINGENCY	**$15,252,677**
Rounded Up Total	**$15,300,000**

Appendix E

Vessel #5 Drawings and Calculations

GENERAL ARRANGEMENTS

WEIGHT ESTIMATE

SWBS No.	Description	Qty.	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)	Notes
	VESSEL WEIGHT ESTIMATE						
	SUMMARY						
100	STRUCTURE		2,060,551	0.26	-0.24	20.42	
200	MACHINERY		227,567	-0.05	1.39	8.85	
300	ELECTRICAL		26,928	-0.28	-0.54	29.80	
400	ELECTRONICS & IC		29,015	-0.30	0.57	34.57	
500	AUXILIARY SYSTEMS		259,248	4.77	0.07	19.83	
600	OUTFIT		510,740	1.65	-0.68	26.01	
	VESSEL WEIGHT - SUBTOTAL		3,114,049 (1,390.20LT)	0.83	-0.16	20.66	
	Add Margin to Structure for Roll & Weld	0%	0	0.26	-0.24	20.42	Included in baseline
100	STRUCTURE	5%	103,028	0.26	-0.24	20.42	
200	MACHINERY	15%	34,135	-0.05	1.39	8.85	
300	ELECTRICAL	12%	3,231	-0.28	-0.54	29.80	
400	ELECTRONICS & IC	12%	3,482	-0.30	0.57	34.57	
500	AUXILIARY SYSTEMS	8%	20,740	4.77	0.07	19.83	
600	OUTFIT	10%	51,074	1.65	-0.68	26.01	
	VESSEL WEIGHT WITH MARGINS		**3,329,739 (1,486.5 LT)**	**0.84**	**-0.15**	**20.63**	

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
100	**Basline Design Weight**						
	Hull	1.00	1270021	1,270,021	0.51	0.42	10.94
	Superstructure	1.00	790530	790,530	-0.14	-1.29	35.66
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
200	**Basline Design Weight**	1.00	204077	204,077	-0.03	-1.22	8.76
	Weights to Remove						
	Main Engines and Systems	-1.00	79770	-79,770	0.00	0.00	7.50
	Combustion Air	-1.00	840	-840	0.00	0.00	13.50
	Propulsion Control System	-1.00	1500	-1,500	3.25	-11.50	8.50
	Main Engine Exhaust	-1.00	13965	-13,965	0.00	-13.10	30.90
	Fuel Oil System	-1.00	5015	-5,015	-3.70	9.70	11.20
	Lube Oil System	-1.00	3991	-3,991	0.60	-8.60	8.10
	Waste Oil System	-1.00	600	-600	2.30	8.80	8.00
	Liquids	-1.00	1359	-1,359	0.00	-9.00	7.00
	Weights to Add						
	Electric Motors	2.00	10810	21,620	0.00	0.00	5.67
	Propulsion System Electrical Components	1.00	3000	3,000	0.00	0.00	12.08
	Fuel Cells - 150 KW	12.00	1919	23,028	0.00	0.00	12.08
	Fuel Cells - 120 KW	2.00	1764	3,528	0.00	0.00	12.08
	LH2 Tank	2.00	37677	75,354	-0.33	5.50	11.50
	Vaporizers	2.00	2000	4,000	2.50	-10.25	9.08

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
300	**Basline Design Weight**	1.00	64326	64,326	0.75	3.77	22.69
	Weights to Remove						
	Generators	-1.00	26099	-26,099	2.40	10.20	13.40
	Generator Systems	-1.00	11299	-11,299	-0.60	-0.80	27.20
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
400	**Basline Design Weight**	1.00	29015	29,015	-0.30	0.57	34.57
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
500	**Basline Design Weight**	1.00	259248	259,248	4.77	0.07	19.83
	Weights to Remove						
	-						
	Weights to Add						
	-						

SWBS No.	Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
600	**Basline Design Weight**	1.000	510740	510,740	1.65	-0.68	26.01
	Weights to Remove						
	-						
	Weights to Add						
	-						

Deadweight Description	Qty.	Unit Wt. (lbs)	Total Wt. (lbs)	LCG (+ aft)	TCG (+ stbd)	VCG (+ abl)
Passengers	800.0	185	148,000	0.00	0.0	37.00
Vehicles	64.00	4000	256,000	0.00	4.5	22.25
Crew and Effects	12.00	225	2,700	0.00	0.0	26.50
Ship Stores	1.00	11200	11,200	0.00	0.0	26.50
Galley Stores	1.00	8960	8,960	-17.00	0.0	42.17
Potable Water	1.00	16800	16,800	93.33	0.0	13.33
Sewage	1.00	25760	25,760	-93.33	0.0	13.33
Service Life Margin	0.05	3329739	166,487	0.84	-0.15	20.63
LH2	1.00	14537	14,537	-0.33	5.50	11.50
Water Ballast	1.00	20000	20,000	0.00	0.0	10.83

STABILITY CALCULATIONS

WEATHER CRITERION MAXIMUM KG CALCULATION
from 46 CFR 170.170
for service on exposed waters

$$GM_{reqd} = \frac{PAH}{W \tan(T)}$$

P = 0.0050 + (L/14200)2 = 0.0053124 Long tons / Ft^2
A = lateral area above waterline
H = vertical distance from centroid of A to 1/2 draft point
W = displacement in long tons
T = 14 degrees or angle of heel where 1/2 freeboard is submerged, whichever is less.

Length on max waterline:	251.00	ft	
Depth to freeboard deck: (low point, at edge)	17.50	ft	
Beam:	64.00	ft	
Superstructure Height:	9.00	ft	Full breadth of vessel, full length

Draft, T:	8.50	9.00	9.50	10.00	10.50	11.00
Displacement to T:	1340	1477	1618	1764	1914	2068
Area above waterline:	11117	11007	10893	10774	10652	10526
h of area above waterline:	23.64	23.37	23.12	22.87	22.63	22.39
h of area to baseline:	32.14	32.37	32.62	32.87	33.13	33.39
Vertical distance, H:	27.89	27.87	27.87	27.87	27.88	27.89
Freeboard, f:	9.00	8.50	8.00	7.50	7.00	6.50
Tangent to 1/2 freeboard:	0.141	0.133	0.125	0.117	0.109	0.102
Tangent 14 deg:	0.249	0.249	0.249	0.249	0.249	0.249
GM required:	8.74	8.31	7.97	7.72	7.54	7.43
KMt at draft T:	47.84	46.12	44.59	43.23	42.04	40.95
Max KG incl. free surface:	39.10	37.81	36.62	35.51	34.50	33.52

SUMMARY TABLE

DRAFT	DISP	MAX KG	MIN GMt
8.50	1340.00	39.10	8.74
9.00	1476.72	37.81	8.31
9.50	1618.24	36.62	7.97
10.00	1764.19	35.51	7.72
10.50	1914.20	34.50	7.54
11.00	2067.81	33.52	7.43

PASSENGER CRITERION MAXIMUM KG CALCULATION

from 46 CFR 171.050(a), effective March 14, 2011

$$GM_{reqd} = \boxed{\frac{W}{\Delta} * \frac{2}{3} * \frac{b}{\tan(T)}}$$

W = total weight of persons other than required crew, including effects, in long tons
b = distance off centerline to centroid of passenger deck on one side
(beam/4 used to be conservative)
Δ = displacement in long tons
T = 14 degrees or angle of heel where freeboard is submerged,
whichever is less.

Number of passengers:	808	
Depth to freeboard deck: (low point, at edge)	17.50	ft
Beam:	64.00	ft
b:	32.00	ft
W:	72.14	LT

Draft, T:	8.50	9.00	9.50	10.00	10.50	11.00
Displacement to T:	1340.00	1476.72	1618.24	1764.19	1914.20	2067.81
Freeboard:	9.00	8.50	8.00	7.50	7.00	6.50
Tangent to freeboard:	0.281	0.266	0.250	0.234	0.219	0.203
Tangent 14 deg:	0.249	0.249	0.249	0.249	0.249	0.249
GM required:	4.61	4.18	3.81	3.72	3.68	3.66
KMt at draft T:	47.84	46.12	44.59	43.23	42.04	40.95
Max KG incl. free surface:	43.23	41.94	40.78	39.51	38.36	37.29

PASSENGER CRITERION VALIDITY CALCULATION

from 46 CFR 171.050(b), effective March 14, 2011

The calculation of 46 CFR 171.050(a) is valid when the Righting Arm (GZ) at heel angle T is not less than the minimum Metacentric Height (GM) calculated in paragraph (a) multipied by sin(T).

Heel Angle, T, degrees:	14.00	14.00	14.00	13.19	12.34	11.48
sin(T) :	0.24	0.24	0.24	0.23	0.21	0.20
GM required (ft):	4.61	4.18	3.81	3.72	3.68	3.66
GZ required @ angle T (ft):	1.11	1.01	0.92	0.85	0.79	0.73

Compare required GZ to actual GZ from GHS output

SUMMARY TABLE

DRAFT	DISP	MAX KG	MIN GMt
8.50	1340	43.23	4.61
9.00	1477	41.94	4.18
9.50	1618	40.78	3.81
10.00	1764	39.51	3.72
10.50	1914	38.36	3.68
11.00	2068	37.29	3.66

```
08/25/17 03:13:35          Elliott Bay Design Group
GHS 15.00                          Vessel 5

                 MAXIMUM VCG vs. DISPLACEMENT with ROLL
              Heeling moment is present from: user specification
    Trim = Fwd 1.50/238.00 at zero heel (trim righting arm held at zero)
        Displacement          ------------ Margins ------------
          LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4  LIM5  LIM6
         -------------------------------------------------------
           1,337.12    32.71  2985%    5d  405%    0%  284%  284%
           1,473.91    31.69  2843%    4d  414%    0%  263%  263%
           1,615.57    30.70  2731%    4d  420%    0%  246%  246%
           1,761.75    29.74  2651%    3d  422%    0%  241%  241%
           1,912.01    28.77  2606%    3d  421%    0%  230%  230%
           2,065.88    27.80  2584%    3d  418%    0%  220%  220%
         -------------------------------------------------------
              Heeling moment is present from: user specification
          Trim = zero at zero heel (trim righting arm held at zero)
        Displacement          ------------ Margins ------------
          LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4  LIM5  LIM6
         -------------------------------------------------------
           1,337.12    32.72  2993%    5d  405%    0%  283%  283%
           1,473.91    31.70  2850%    4d  414%    0%  264%  264%
           1,615.57    30.72  2736%    4d  420%    0%  246%  246%
           1,761.75    29.76  2653%    3d  422%    0%  240%  240%
           1,912.01    28.80  2605%    3d  421%    0%  230%  230%
           2,065.88    27.83  2579%    3d  418%    0%  219%  219%
         -------------------------------------------------------
              Heeling moment is present from: user specification
    Trim = Aft 1.50/238.00 at zero heel (trim righting arm held at zero)
        Displacement          ------------ Margins ------------
          LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4  LIM5  LIM6
         -------------------------------------------------------
           1,337.12    32.71  2985%    5d  405%    0%  284%  284%
           1,473.91    31.69  2843%    4d  414%    0%  264%  264%
           1,615.57    30.70  2731%    4d  420%    0%  246%  246%
           1,761.75    29.74  2651%    3d  422%    0%  241%  241%
           1,912.01    28.77  2606%    3d  421%    0%  231%  231%
           2,065.88    27.80  2585%    3d  418%    0%  221%  221%
         -------------------------------------------------------
              Heeling moment is present from: user specification
    Trim = Aft 3.00/238.00 at zero heel (trim righting arm held at zero)
        Displacement          ------------ Margins ------------
          LONG TONS  Max VCG  LIM1  LIM2  LIM3  LIM4  LIM5  LIM6
         -------------------------------------------------------
           1,337.12    32.66  2965%    5d  405%    0%  274%  274%
           1,473.91    31.64  2824%    4d  414%    0%  262%  262%
           1,615.57    30.65  2718%    4d  419%    0%  248%  248%
           1,761.75    29.67  2647%    3d  422%    0%  242%  242%
           1,912.01    28.69  2610%    3d  421%    0%  232%  232%
           2,065.88    27.72  2599%    3d  418%    0%  223%  223%
        Distances in FEET.---Specific Gravity = 1.025.---d = degrees.

    LIM--------170.173C RIGHTING ENERGY CRITERION---------Min/Max
    (1)  GM Upright                                  >     0.49 Ft
    (2) Angle from 0 deg to MaxRA                    >    15.00 deg
    (3) Area from 0 deg to 40 or Flood               >    16.90 Ft-deg
    (4) Area from 30 deg to 40 or Flood              >     5.60 Ft-deg
    (5) Area from 0 deg to MaxRA at 15               >    13.11 Ft-deg
    (6) Area from 0 deg to MaxRA at 30               >    10.30 Ft-deg
    -----------------------------------------------------------------
```

CAPITAL COST ESTIMATE

PARAMETRIC CONSTRUCTION COST ESTIMATE

Assumptions

1) This estimate is inteded for new construction of ONE vessel.
2) This vessel is assumed to be built in the USA
3) This estimate is intended for budgeting purposes ONLY.
4) Costs are organized in accordance with the EBDG interpretation of the SWBS System.
5) Weights are taken from 16128-833-0P0 Vessel 5 Weight Estimate
6) Other Assumptions as needed.
7) Non-trade labor rates are as follows:
   PM & Admin = 120% of Labor
   Engineering = 180% of Labor
8) Other vessel costs inflated to 2017 dollars based on Shipbuilding Inflation (Reference [3])

Calculations

SWBS COST GROUPS	Weight in LT	$/LT	HRS/LT	$ MATERIAL + Mark-up	LABOR HRS	LABOR COST
000 - PM & ADMIN					10,797	$ 945,833
100 - HULL	965.9	3,629	69.44	$ 4,100,848	67,071	$ 4,896,179
200 - PROP MACH'Y	64.5	16,016	189.50	$ 1,208,865	12,225	$ 892,440
300 - ELECTRICAL	13.5	306,656	1,039.14	$ 4,830,658	13,991	$ 1,021,325
400 - NAVIGATION	14.5	109,133	412.83	$ 1,852,407	5,989	$ 437,211
500 - AUXILIARY	125.0	29,792	238.34	$ 4,356,893	29,791	$ 2,174,723
600 - OUTFIT	246.2	25,536	352.80	$ 7,357,227	86,877	$ 6,342,010
LH2 EQPT	68.3	NA	200.00	$ 10,664,316	13,660	$ 997,146
800 - ENGINEERING					22,960	$ 3,016,986
900- CONST. SERVICES				$ 1,031,136	32,144	$ 2,346,545
Totals	**1,497.91**			**$ 35,402,350**	**295,505**	**$ 23,070,399**

Inputs

Current Vessel	Value	Unit		
Length	273.67	ft	Vessel Type	Ferry
Beam	64.00	ft		
Depth	17.50	ft		
Light Ship Δ	1,497.90	LT		
Structure Weight	965.88	LT		

Shipyard	Value	Units		
Labor Rate	$73.00	/hr		
Material Mark-Up	17.0%		000 - PM & Admin	5.0%
Mat'l & Labor Margin	10.0%		800 - Engineering	10.0%
Contingency	10.0%		900 - Construction Services	14.0%

Other Vessels	Cube Number	Light Ship Δ	Structure Wt	Labor Hours	Cost
Units	*ft^3*	*LT*	*LT*	*hrs*	*$*
WSF 64 Car	3,065.00	1,478.70	922.69	293,377.00	53,155,543
ACF Day Boat	3,752.00	2,054.79	1,478.90	281,201.00	53,300,000
Island Home	2,852.30	1,459.10			52,854,728

Output

Labor & Material Sub-Total	$58,472,749
Material & Labor Margin @ 10%	$5,847,274.94
Cost without Contingency =	**$64,320,024**
Contingency	$6,432,002
Total Vessel Construction Cost Estimate with 10% CONTINGENCY	**$70,752,027**
Rounded Up Total	**$70,800,000**

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