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Exploring Liquid Hydrogen Tank Technology for Zero-Emission Fuel Cell Vessels

Leonard E. Klebanoff, Thomas K. Drube, Jacob M. Gerlach and Timothy S. Leach

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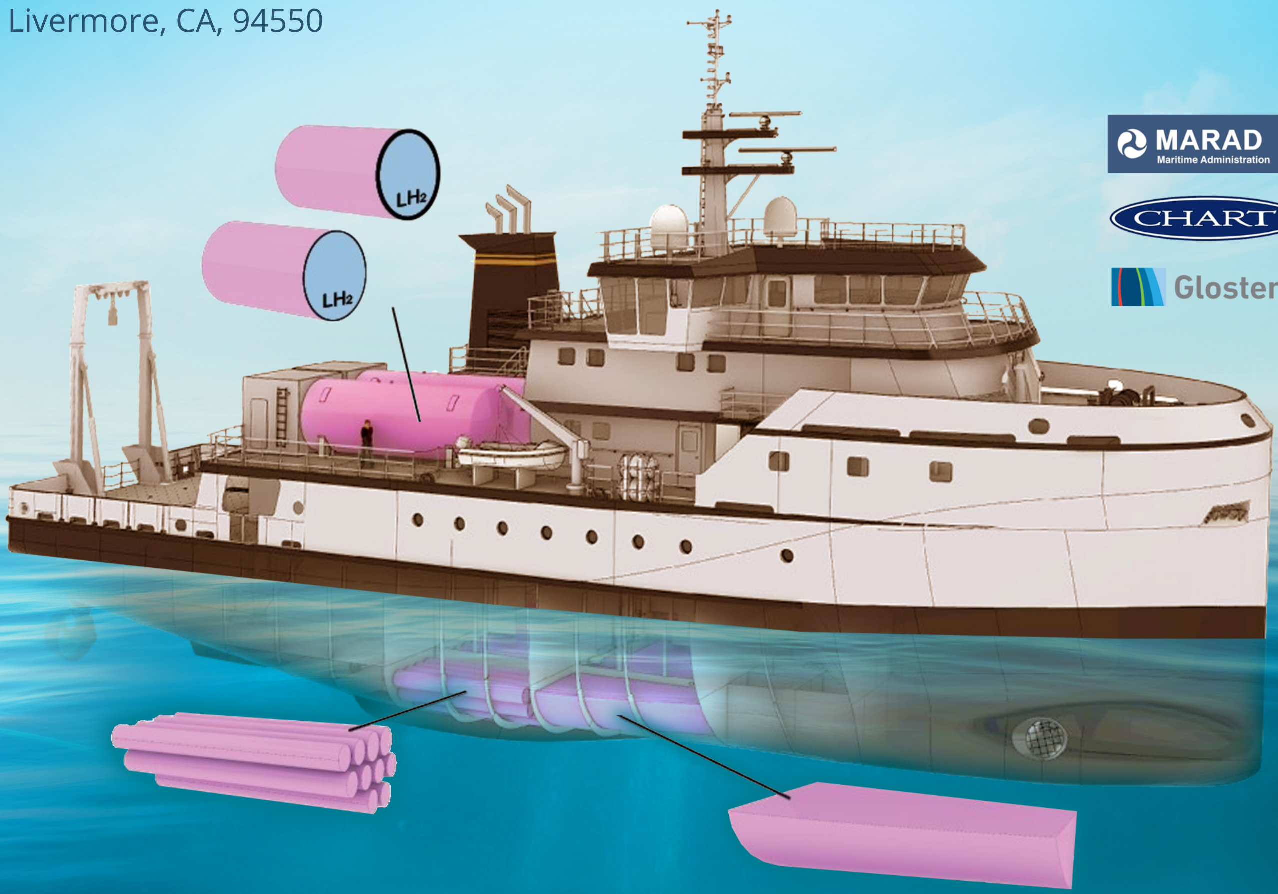

MARAD Maritime Administration

CHART

Glosten

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Exploring Liquid Hydrogen Tank Technology for Zero-Emission Fuel cell Vessels

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ABSTRACT

As the transportation industry moves to adopt more environmentally conscious sources of fuel, interest in hydrogen technology for maritime applications has increased. This study explored how improvements in liquid hydrogen (LH_2) tank weight, shape, and multiplicity might increase hydrogen storage aboard watercraft using hydrogen fuel cells for propulsion. We also sought to identify the most promising R&D routes to improving LH_2 tank performance in the areas investigated. We found that improvements in tank shape can yield a significant increase in quantify of stored LH_2. On the contrary, our results found that decreases in tank mass were of marginal benefit and increases in tank multiplicity (having multiple smaller tanks with high length-to-width ratios) was detrimental to the goal of increasing the amount of LH_2 that could be stored on ships. Limitations of tank manufacturing and emerging maritime regulations also need to be considered for future research into LH_2 tank improvements.

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Sandia National Laboratories is a multi-mission laboratory managed by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. We now close with the DOE vote of confidence: This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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EXECUTIVE SUMMARY

This study is an exploration of liquid hydrogen (LH_2) tank technology in the areas of tank weight, multiplicity (high-performing small tanks), and tank shape. The purpose is two-fold. First, we aim to investigate if improving LH_2 tank weight, multiplicity, and shape enables more hydrogen to be stored on hydrogen vessels. The improvements investigated are well beyond the current LH_2 technology state-of-the-art. Second, by assessing the important technical factors governing tank weight, multiplicity, and shape, we seek to identify the most promising R&D routes to improving LH_2 tank performance in these ways, should a benefit be found.

The platform for this study is a monohull research vessel powered 100% by hydrogen. An H_2 Baseline Vessel was designed using current commercial LH_2 technology to evaluate the design impacts of improving tank mass, multiplicity, and shape. The H_2 Baseline Vessel has a design speed of 12 knots, requiring approximately 1500 kW of fuel cell electrical power, including both propulsion and service (hotel) loads. The H_2 Baseline Vessel has two large LH_2 tanks out in the weather, with a LH_2 storage capacity (100% filled) of 3220 kg each, giving a total stored LH_2 capacity of 6440 kg.

Two tank weight reductions were considered, while maintaining the same quantity of stored LH_2 as the H_2 Baseline Vessel. First, a 50% reduction in mass of the inner pressure vessel was assessed, a case we call the “Inner Vessel Reduction Study,” achieved by a presumed reduction of the Inner Vessel wall thickness. Such a reduction led to a 3.1% reduction in the total research vessel weight. For the second weight study, we investigated the asymptotic limit of having zero LH_2 tank weight. This “Zero Tank Mass Study” led to a 7.1% reduction in the overall research vessel weight. Since a ship designer would typically be carrying a 10–15% design margin in the vessel weight estimate at this preliminary design level, the possible weight savings that could possibly come from LH_2 tank improvements are within these pre-existing margins. We conclude that the maritime application, while benefitting from a reduction in LH_2 tank weight, is not a strong driver for LH_2 tank weight improvements.

For the multiplicity study, we assumed that the two large LH_2 tanks of the H_2 Baseline Vessel were replaced with a multitude of smaller LH_2 tanks that still maintained excellent LH_2 storage performance, allowing them to be placed in greater number anywhere on the vessel. Stored LH_2 quantities per tank were in the range ~45–600 kg for Multiplicity Variant 1. Extending the study even further, we also considered a Multiplicity Variant 2 with even smaller LH_2 tanks, of capacity ~30–55 kg each. For Multiplicity Design Variant 1, the total amount of stored LH_2 was 5% less than that of the H_2 Baseline Vessel. For the Multiplicity Variant 2, the stored LH_2 capacity was 8.8% less than the H_2 Baseline Vessel. Given the reduced fuel storage as well as practical difficulties associated with managing many LH_2 tanks, deploying LH_2 tanks for a marine vessel with multiplicity does not look like a promising technical direction, and would not

motivate conducting the needed R&D that would drive the technology to smaller high-performing LH_2 tanks with high length-to-width aspect ratios.

In contrast, we did find a significant benefit to improving the shape of LH_2 tanks, in particular prismatic tanks that would afford a better match of the LH_2 tank shape to the vessel hullform. We considered a shape variant that incorporated beyond state-of-the-art prismatic LH_2 tanks with capacities in the range ~600–3,000 kg each. Our initial investigation, which ignored some vessel hardware requirements, indicated a very promising 41% improvement in stored LH_2 compared to the H_2 Baseline Vessel. Considering required space-consuming features such as tank connection spaces, manifolding and ventilation, we still found a 26% improvement in stored LH_2 compared to the H_2 Baseline Vessel. The large improvement in storage capacity warrants warrant further LH_2 tank R&D that can enable high performing prismatic LH_2 tanks, such as pressure vessel steel developments allowing for higher strength/ductility at 20 K, improved insulation systems, methods for efficiently building prismatic tanks with insulation systems fit for 20 K and flare-less techniques for managing heat leak (venting).

These studies assumed significant relaxations of current regulations for the use of cryogenic fuels on ships, regulations which were established to ensure the safety of ship and personnel. In considering any R&D investment to improving LH_2 tank technology (e.g., shape as described above) as well as a proposed implementation of that technology, it's vitally important to also assess if effective strategies can also be identified to address the risks and safety concerns which motivated the regulations in the first place. The results presented here are reviewed considering the current regulatory restrictions as well as prevailing limitations in LH_2 tank manufacturing.

ACRONYMS AND TERMS

Acronym/Term	Definition
AC	Alternating current
ATK	Alliant Techsystems
C	Celsius/Centigrade
CCRV	Coastal Class Research Vessel
CCTD	Composite cryotank technology demonstration
CFRP	Carbon fiber reinforced polymer
CH_4	Methane
CHATT	Cryogenic Hypersonic Advanced Tank Technologies
DC	Direct current
DME	Dimethyl ether
DNV	Det Norske Veritas
DOT	Department of Transportation
DP	Dynamic positioning
F	Fahrenheit
GHG	Greenhouse Gas
GL	Germanischer Lloyd
H_2	Hydrogen (gaseous)
HALE	High-altitude long endurance
HC	Hydrocarbon
HyPM	Hydrogen fuel-cell power module
ICE	Internal combustion engine
IGF	International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organization
J	Joules
K	Kelvin
kg	Kilogram
KSC	Kennedy Space Center
kts	Knots
kW	Kilowatts
LFL	Lower flammability limit
LH_2	Liquid hydrogen
LHV	Lower heating value
LNG	Liquified Natural Gas

Acronym/Term	Definition
LO_2	Liquid oxygen
LPV	Lattice pressure vessels
MARAD	Maritime Administration
MAWP	Maximum allowable working pressure
META	Maritime Environmental and Technical Assistance
MLI	Multi Layer Insulation
MT	Metric Tonnes
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane Project
NBP	Normal boiling point
NER	Nominal evaporation rate
NGLT	Next Generation Launch Technology
NM	Nautical miles
NO_x	Nitrogen oxides
NTP	Normal temperature and pressure
O.D.	Outside diameter
P	Pressure
PBU	Pressure build unit
PEM	Proton-exchange membrane
PFSA	Polyfluorinated sulfonic acid
PM	Particulate matter
PMC	Polymer matrix composite
PRD	Pressure relief device
Q	Heat leak
R	Rankine
R&D	Research and development
SIO	Scripps Institution of Oceanography
T	Temperature
TCS	Tank connection space
UAV	Unmanned aerial vehicle
USCG	United States Coast Guard
VCG	Vertical center of gravity

1. INTRODUCTION

The International Maritime Organization (IMO) established in 2023 a greenhouse gas (GHG) reduction strategy with a goal to reach net-zero GHG emissions by 2050 [1]. Such a reduction will require a change in vessel fuel, away from traditional fossil-derived fuels to alternative fuels that over their lifecycle reduce or eliminate GHG emissions. Such fuels may also reduce criteria pollutant emissions (nitrogen oxides [NO_x], hydrocarbons [HC], and particulate matter [PM]) that directly impact human health [2]. Prior work has summarized possible alternative fuels [3 - 5] with individual studies examining specific candidate fuels such as dimethyl ether (DME) [6], methanol [7], ammonia [8], liquid natural gas [9], and biodiesel [10].

Hydrogen has great potential for replacing fossil hydrocarbon fuels in maritime. Studies have been ongoing since the beginning of the 21st century, well before the IMO strategy was formulated. As summarized by Klebanoff et al. [11], Foster [12], and Kickulies [13] examined the applicability of hydrogen, both in fuel cells and internal combustion engines (ICEs), for shore power, as well as for propulsion and auxiliary power. In 2016, van Biert et al. [14] reviewed different types of fuel cells for their applicability to vessels and assessed different methods of storing hydrogen or generating it onboard. Bicer and Dincer performed a comparative analysis of using hydrogen or ammonia in ICEs as a replacement for burning heavy fuel oil on transoceanic vessels [15]. The IMO strategy, from 2014 to the present [1], increased the interest in using hydrogen fuel-cell technology on ships. Several studies have been published with a focus on lifecycle emissions [16, 17], maritime fuel-cell thermodynamics [18], safety [19], and comparative reports of the varying types of fuel cells and hydrogen storage approaches available to future low-emission shipping [20 - 22]. A review of the safety-related physical and combustion properties of hydrogen in the maritime context has been published by Klebanoff and co-workers [23].

1.1. Prior work on Hydrogen Fuel-cell Vessels

Since 2016, there have been several studies looking at the feasibility of introducing hydrogen fuel-cell power to ships, with a particular focus on ship attributes and performance. Pratt and Klebanoff examined the feasibility of a high-speed hydrogen ferry called the *SF-BREEZE* [24]. As a follow-on to this project, the feasibility and attributes of a zero-emission hydrogen fuel-cell coastal research vessel named the *Zero-V* was investigated [25]. Detailed vessel designs incorporating hydrogen technology demonstrated that the combination of hydrogen (stored as liquid hydrogen [LH_2]) and proton-exchange membrane (PEM) fuel cells can in principle provide the basis for very capable vessels. These studies examined feasibility of such vessels from the points of view of vessel performance (speed, range, passenger complement), as well as managing safety issues (hazardous zones), fueling practicality (speed of refueling and available quantities) and local acceptance (Ports). These studies also provided an opportunity the United States Coast Guard (USCG), naval architects, Ports of call (for both ferries and research vessels), and Class Societies to become familiar with the safety-related properties of hydrogen and how to manage them in the design of vessels and shore side refueling facilities.

These prior studies [24, 25] examined the use of hydrogen PEM fuel cells to provide all the required propulsion power for the vessel. Due to the commercial implementation for hydrogen fuel cells in automobiles, and in part to the feasibility of hydrogen fuel-cell vessels shown in these prior studies, hydrogen fuel-cell vessels are starting to be realized. The first commercial hydrogen-powered ferry was the *Hydroville* [26] built by CMB Tech. The *Hydroville* employed dual fuel (H_2/diesel) internal combustion engines supplied with 36 kg of useable hydrogen stored in 200 barg hydrogen tanks. The top speed of the vessel was 27 knots (cruising speed 22 knots) and could carry 16 passengers. The vessel operated on the River Scheldt in the Port of Antwerp, Belgium, as a commuter ferry. Today, the vessel is used as a testing and exhibition vessel and is also available for business meetings and excursions.

As a follow-on to the *Hydroville*, CMB Tech built a hydrogen-powered work boat [27]. The *Hydrocat 48* is powered by dual-fuel (H_2/diesel) engines, with the hydrogen stored as compressed hydrogen. The *Hydrocat 48* holds 210 kg of compressed hydrogen and has a cruising speed of 30 knots. Very recently, the MF *Hydra*, built by Norled, has entered service along the Hgelmeland-Nesvik route in Norway [28]. The *Hydra* uses PEM fuel cells, fueled with hydrogen gas provided by a 4,000 kg LH_2 tank. The *Hydra* can carry 299 passengers, 80 cars, 10 cargo trailers and has a top speed of 9 knots.

The first hydrogen-powered ferry in the western hemisphere is now in San Francisco Bay. The ferry, originally named "*Water-Go-Round*" and later renamed "*Sea Change*," was designed and built by Golden Gate Zero Emission Marine (now Zero Emission Industries) [29]. Based on an aluminum catamaran hull, the *Sea Change* can carry 78 passengers with 2 crew and has 360 kW of installed PEM fuel-cell power. The vessel can reach a top speed of 13 knots. The vessel uses PEM hydrogen fuel cells for propulsion power and stores ~ 250 kg of hydrogen in 250 barg hydrogen tanks. The *Sea Change* has the distinction of being the only maritime hydrogen vessel in the world that is USCG approved. The *Sea Change* will be used for public transport early in 2024.

It may be that the more widespread initial introduction of hydrogen onto ships may take a more limited form, where the hydrogen fuel-cell power acts as a hybrid power component supplementing a primarily diesel-based powertrain. It is reasonable to ask: how useful is hydrogen fuel-cell technology as a hybrid power system component? For the research vessel application, this question was answered with the feasibility study of the H_2 Hybrid Research Vessel [11]. This concept vessel, a smaller coastal/local research vessel intended as a replacement for the Scripps Institution of Oceanography (SIO) R/V *Robert Gordon Sproul*, has recently received $35M in funding from the State of California. The vessel, named the *Coastal Class Research Vessel* (CCRV), is currently in the functional design phase [30].

For the ferry application, in 2018, Hornblower Yachts addressed the H_2 hybrid question via Project Nautilus [31]. In Project Nautilus, a design activity was initiated to incorporate a hydrogen PEM fuel-cell auxiliary power system onto an existing vessel for eventual operation on

San Francisco Bay. The existing vessel, originally called the *New York Hybrid* but recently rechristened the *Discover Zero*, was transferred to San Francisco for retrofitting of the hydrogen systems once a Design Basis Agreement letter from the USCG was received and retrofit funding acquired. The design project was funded by the U.S. Department of Transportation's Maritime Administration (MARAD) and recently received a Design Basis Agreement Letter from the USCG.

All prior feasibility studies, as well as the first hydrogen vessels themselves, advanced the application of hydrogen and fuel cells to vessels using commercially available hydrogen storage technology. The reason for this is straightforward. For the feasibility studies, it is not possible to assess feasibility if one of the pieces of the hydrogen technology (such as the storage tanks) is unknown. Thus, the approach of these studies was to investigate vessel feasibility and benefits assuming commercially available technology. Although both compressed gas (350 barg, 700 barg) hydrogen tanks have been examined in applications where the amount of required hydrogen is relatively low (250 kg for *Sea Change*, 170 kg for *Discover* Zero), considerably more hydrogen is needed in most applications of hydrogen on vessels: *SF-BREEZE* (1200 kg) [29], *Zero-V* (11,000 kg) [25], H_2 Hybrid (~ 800 kg) [11], CCRV (1400 kg) [30], and *Hydra* (4000 kg) [28]. These relatively large quantities of hydrogen dictate the use of liquid storage since liquid hydrogen (LH_2) is currently the most commercially available dense form to store it in. Solid-state storage [32] offers potentially even higher storage density but remains a research area.

Given that LH_2 is the future for large-scale storage of hydrogen on vessels, it raises the question: can LH_2 tank technology be advanced beyond that commercially available today? Particularly for the maritime application, would it be advantageous to use many smaller (but still high performing) LH_2 tanks rather than large tanks (i.e., LH_2 tank "multiplicity")? Would there be a benefit to having LH_2 tanks with shapes chosen to fit in the hull of a vessel rather than using shapes typical of commercial LH_2 tanks (cylinders, spheres)? Would there be a benefit to having lighter LH_2 tanks? Is there a benefit to the ease of design of H_2 vessels if we can have LH_2 tanks that are lighter, can be deployed with multiplicity, or have any shape desired? Is there a vessel operational advantage if LH_2 tank design were unconstrained regarding multiplicity, shape, and weight? While the answer to such questions might be obviously "yes," ultimately the question is how large a benefit is accrued in the face of the barriers to achieving those benefits. Such barriers could be technical or regulatory in nature. This study assesses how large such tank improvement benefits could be to the hydrogen vessel, primarily how much hydrogen can be stored on the vessel.

1.2. Relevant Prior work on LH_2 Tank Technology

Liquid hydrogen tank technology is as old as the discovery of liquid hydrogen itself. Excellent textbook references [33, 34] can be consulted for general information on cryogenic engineering. Barron has given an interesting historical account of the key role that liquid hydrogen storage tanks played in the actual discovery of liquid hydrogen. Indeed, it was not until Sir James Dewar invented the vacuum-jacketed storage vessel for cryogenic liquids in 1892 that the first clear example of producing LH_2 was achieved in 1898. Barron summarizes the progress made in liquid hydrogen technology from these earliest works through the middle of the 20th Century where LH_2 tanks aboard the Apollo 11 launch vehicle enabled man's landing on the moon in 1969. Since then, LH_2 has been the signature fuel of NASA including use in the Space Shuttle that operated from 1981 to 2011.

The essential components of a generic liquid hydrogen tank are described in the Figure 1, with a caution that there are many hardware connections in an actual LH_2 tank that are not shown in the figure.

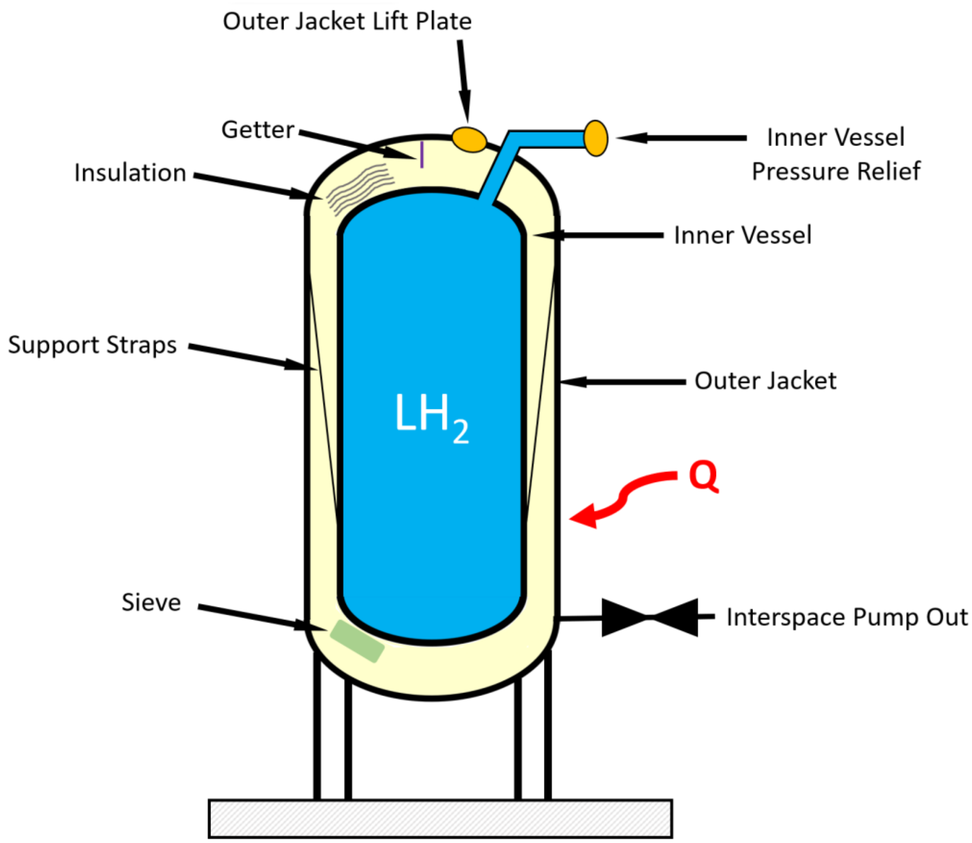

Figure 1. Essential components of an LH_2 Tank. An Inner Vessel is suspended by support straps within an Outer Jacket, with the interspace region insulated with a combination of material insulation and vacuum to minimize the heat leak Q from the ambient environment into the stored LH_2. A sieve material provides for vacuum maintenance of residual air and water vapor. A getter is used to address potential outgassing of hydrogen from vacuum space surfaces. This hydrogen outgassing should not be confused with potential container leaks. All vacuum systems are subject to adsorbed hydrogen releases from surfaces. Pressure relief devices are provided for the Inner Vessel and a vacuum lift plate for the Outer Jacket.

While there are many possible designs for a LH_2 tank, they are all directed to minimizing the heat leak Q from the environment into the LH_2 charge. The essential components are an Inner Vessel, made of a strong, ductile material such as 304 stainless steel (~ 0.325" thick) that can sustain pressurization and is also resistant to hydrogen embrittlement [34]. The Inner Vessel is surrounded by insulation placed in a vacuum pumped annular region between the Inner Vessel and the Outer Jacket. Both vacuum and thermal insulation minimize the entry of the heat leak Q into the LH_2 charge via either thermal conduction or radiant heat transfer. The Outer Jacket, which is exposed to the outside world, is typically carbon steel (~ 0.25" thick), which is durable and properly isolated from cryogenic temperatures.

From a safety perspective, a primary design feature of LH_2 tanks is to avoid excessive hydrogen gas pressure build up in the Inner Vessel from fast LH_2 evaporation caused by rapid introduction of heat (as in the case of a complete loss of annular space vacuum). Thus, the Inner Vessel has a relief device(s) installed that activates to provide Inner Vessel pressure relief when the hydrogen gas pressure within the Inner Vessel exceeds the design maximum allowable working pressure (MAWP). If the interspace region should pressurize, the Outer Jacket also has a lift plate to provide pressure relief. These devices are sized to handle expected hydrogen flow rates in various failure scenarios. In a maritime application [25], Inner Vessel relief device outlets are connected to vent piping that directs the hydrogen away, typically up a vent mast.

Minimizing the heat leak Q usually involves minimizing the surface-to-volume ratio of both the Inner Vessel and Outer Jacket. As a result, LH_2 tanks have historically been spherical (lowest surface/volume ratio) or cylindrical (next lowest). The cylindrical shape is the easier to manufacture and transport. Consequently, most LH_2 commercial tanks are cylindrical. Cylindrical or spherical tanks are typical of stationary LH_2 tanks for which there is ample outside room to accommodate the tanks and they are installed on a concrete foundation on the ground.

When the hydrogen application has moved away from stationary applications to ones involving mobility, prior studies have examined approaches to decreasing LH_2 tank weight, reducing their size (and increasing multiplicity), and changing their shape to better fit the intended application. Those prior studies most relevant to the maritime investigation reported here are now summarized.

1.2.1. Weight

The influence of LH_2 tank weight, and the concomitant effort to reduce tank weight, has been most prominently investigated in the aerospace and aviation fields [36 - 39]. An excellent historical review has been written by Mital [36], which traces the arc of LH_2 tank technology development from the earliest hydrogen aircraft, the Saturn V, The Space Shuttle, the National Aerospace Plane Project (NASP), the X-33 hypersonic flight technology demonstrator project, to NASA's Next Generation Launch Technology (NGLT) program. The sensitivity of the space application to weight is evident by the estimates that it costs $10K/pound [38] to deliver an object to orbit, and ~ 70% of a launch vehicle's dry mass consists of tankage for the fuel (LH_2) and oxidizer (liquid oxygen [LO_2]) [37]. The first approaches to LH_2 tank weight reduction occurred in the Saturn V program, where instead of a stainless-steel tank, the LH_2 tank consisted of the lighter aluminum surrounded by foam insulation. The next approach to reducing LH_2 tank weight came with the Space Shuttle Program. There, an aluminum-lithium (Al-Li) alloy (2195) was used for the Inner Vessel to improve the strength of aluminum, offering an overall weight savings.

Interest in creating reusable launch vehicles, and the general area of hypersonic flight, required more drastic LH_2 tank weight reductions, moving beyond metal-based tanks to tanks composed of polymer matrix composites (PMCs), or more simply "composite materials." As summarized by Mital [36] and McCarville [37], there existed several difficulties using these composite materials for LH_2 storage. First is the problem of hydrogen diffusion. The diffusion of hydrogen through metals is nonzero, but vanishingly low [23]. However, hydrogen diffusion/permeation through composite materials is much higher and can lead to hydrogen loss and ultimately tank failure if not properly mitigated. A second problem is that being heterogenous materials, composite materials suffer from the differential thermal expansion of the material components (graphite, epoxies, laminates, liners) which can lead to microcracking with the repeated tank thermal cycling that accompanies refueling. A third problem is the production cost associated with compositive manufacturing.

The NASP project [36, 37] pushed weight concerns to a level beyond the Space Shuttle. Carbon-fiber-reinforced epoxy materials were investigated in support of weight reduction for a single-stage-to-orbit vehicle that could take off and land horizontally. The objective was later modified to produce an intercontinental hypersonic aircraft. A natural follow-on project to the NASP, the X-33 program designed, built, and tested a composite LH_2 tank for hypersonic flight composed of graphite/epoxy materials. An excellent review of the materials used in compositive tanks has been written by Grimsley et al. [38]. Although the X-33 tank failed in testing due to the development of microcracks, the project showed the promise of composite materials in lowering the weight of LH_2 tanks for aerospace and hypersonic aircraft. The NGLT Program followed the X-33 effort and advanced the design of LH_2 composite tanks, particularly with regard to their stiffness and strength, and reducing hydrogen diffusion and permeability [36].

More recently, NASA and four industry partners (Boeing, Alliant Techsystems [ATK], Lockheed Martin and Northrup Grumman) have been advancing composite materials and processes to reduce the overall weight and cost of LH_2 tanks via the Composite Cryotank Technology Demonstration (CCTD) Project. The goal was to reduce the weight of LH_2 tanks by 30% relative to a comparable tank using the 2195 Al-Li alloy. Results found that a 40 – 43% reduction in weight was possible using advanced composite designs. An excellent overall review of LH_2 composite tanks materials, design, and manufacturing approaches is provided by McCarville [37]. Composite LH_2 tank technology continues to be an active area of research and development (R&D) for NASA and its partners.

1.2.2. Shape

Spherical or cylindrical shapes are used to store LH_2 in stationary (land-based) applications, or for very large quantities of LH_2 (e.g., Saturn V, stationary storage at the Kennedy Space Center [KSC]). However, when the space available for the storage has become significantly limited, nonstandard shapes for LH_2 tanks have been investigated.

An early foray into the shape question was made by Robinson and Dutton [40] who examined the stress and buckling properties of a “bi-lobe” or “double bubble” shape for a metal-based LH_2 tank for the Space Shuttle Orbiter. Ultimately, this bi-lobe design was not adopted for implementation in the Shuttle Program. Achary and co-workers [41] have discussed nontraditional tank shapes for launch vehicles employing composite materials, including dual-lobe tanks as well as “semi-conformal tanks” which have flat or arbitrarily curved surfaces.

Hypersonic flight dramatically pushed investigation of the shape dependence of LH_2 tanks due to the limited space available and the high fuel energy demand of hypersonic flight. Within the Cryogenic Hypersonic Advanced Tank Technologies (CHATT) Project, Sippel et al. [42] discussed design issues with carbon fiber reinforced plastic (CFRP) LH_2 tanks and explored interesting multi-lobe shapes for tankage to fit into the various available spaces on a concept hypersonic cruise vehicle. Rodriguez-Segade et al. [43, 44] reported studies of the design of multi-lobe (multi-bubble) LH_2 tank technology for hypersonic flight, focusing on how the tank structurally integrated into the rest of the aerospace vehicle. These authors examined the trade-off between tank shape (multi-lobe) and structural integrity to assess the optimal tank configuration that maximizes the fuel capacity while maintaining the overall structural stability and strength of the hypersonic vehicle. Structural integration includes another issue associated with hypersonic flight, namely exposure of the LH_2 tank to the proximate high vehicle fuselage temperature of 1250 ºC that can develop during flight. Such nearby temperatures are not conducive to storing a cryogenic liquid such as hydrogen with a very low enthalpy of vaporization [23].

Single-lobe LH_2 tanks of an ellipsoidal shape have also been studied for future aerospace and aviation applications [45, 46]. Interestingly, a prismatic LH_2 tank has been investigated for heavy duty fuel-cell trucks. Choi et al. [47] have investigated such a metal-based tank from the point of view of compatibility with the existing codes and standards for this heavy-duty truck application.

The influence of shape on cryogenic tank performance is not limited to LH_2. Liquified natural gas (LNG) is a cryogenic liquid very similar to LH_2 [23] and is an important energy vector for stationary and mobile applications. Bergan et al. [48] have studied the design and manufacture of a prismatic double-barrier tank for LNG storage and transportation. Xue et al. [49] have performed numerical simulations of the dependence of LNG sloshing on spherical, cylindrical, and rectangular cryogenic tank shapes. Also, Kim et al. [50] have studied prismatic trapezoidal lattice pressure vessels (LPVs) for LNG storage on a tugboat. The emphasis of this study was structural and heat transfer analyses, with predictions for the rate of boil-off gas generation.

1.2.3. Size

Our study examines if there is a benefit to increased multiplicity in LH_2 tank deployment on marine vessels. That is, is there a benefit to the vessel capabilities if LH_2 can be stored in many smaller LH_2 tanks, taking advantage of all possible storage spaces on the vessel, instead of in one or more large LH_2 tanks. The hypersonic studies have taken a similar approach by working to fit LH_2 tanks in the available space on the hypersonic vehicle. However, we are unaware of any prior study that has taken the comparative approach we take, comparing a large single LH_2 tank to its equivalent in a multiple array of smaller tanks. However, deploying LH_2 tanks with multiplicity necessarily involves tanks of different aspects ratios as well as smaller size, both of which have been examined previously in prior studies for other applications. For example, Kumar and co-workers [51] have examined how the aspect ratio (tank length to tank diameter) influences surface evaporation and stratification (the distribution of heat and its effect on pressure rise) in cylindrical LH_2 tanks.

Prior study of smaller LH_2 tanks has been driven by two specific applications: fuel-cell cars, and high-altitude long endurance (HALE) aircraft. Wolf [52] has reviewed, in a general way, LH_2 tank technology for automotive (light duty vehicle) applications. Peschka et al. [53 - 55] were the first to investigate LH_2 tank technology for automobiles, using a BMW 518 car as an example. For this application, small tanks, which contain 8 to 10 kg of LH_2 are required, with limited space for tank installation on the vehicle. A particular requirement of these small tanks is to be able to refill them (at a LH_2 dispensing station) in the roughly 5 minutes that the public has become accustomed to at gasoline stations. Due to the small size with high surface to volume ratios, a boil off rate of 3 to 7% per day was observed depending on the tank size and material [53].

Subsequently, Krainz and coworkers [56 - 58] developed and tested a 10 kg double-walled cylindrical LH_2 tank for a BMW hydrogen concept car. Krainz provides an excellent description of the essential components and automotive requirements [56]. Boil-off rates of 1 to 5% per day were reported. Amaseder and Krainz [58] also discussed the integration of the tank into the BMW Series 7 model, including safety aspects and overall hydrogen system functionality. Bünger et al. [59] discussed improved vacuum/powder insulation driven by the need to improve the hydrogen boil-off rates in small LH_2 tanks.

The HALE application has also driven interest in “small” LH_2 tanks, because the long endurance requirements put a premium on stored hydrogen energy density and requires liquid hydrogen storage as opposed to other storage approaches. Recall that the specific lower heating value (LHV) of hydrogen is 119.96 MJ/kg [23], 2.8 times greater than gasoline or jet fuel. The Naval Research Lab [60] investigated a LH_2 fuel system for a small unmanned aerial vehicle (UAV). The LH_2 tank stored 1.5 kg of liquid hydrogen and was constructed of nested aluminum vessels with vacuum insulation in between. The system was flight tested on the Ion Tiger UAV.

Mills et al. [61] reported on the LH_2 tank for the Boeing Phantom Eye HALE demonstration aircraft. A spherical aluminum tank insulated with spray-on foam was chosen as the approach.

The tank was constructed and tested for boil off performance. The mass of stored LH_2 has not been reported, but an estimate from published photographs [61] puts it in the neighborhood of ~ 400 kg.

Xu et al. [62] have reported on the design and analysis of a LH_2 tank for HALE aircraft. In their spherical tank design (totaling 25.4 kg of stored liquid hydrogen), they used 304 stainless steel for the Inner Vessel because aluminum had too high thermal conductivity for their application and titanium, another candidate lightweight tank material, is too difficult to weld.

This preceding review of prior work in the LH_2 tank technology field is by no means comprehensive, but it does point the interested reader to earlier LH_2 tank studies impacting weight, shape, and size in the aerospace, aviation, and automotive applications. Ustolin and co-workers [63] have recently written an excellent review of LH_2 use in these different applications, as well as in rail/locomotives, and of interest to our study, maritime vessels. A good summary is given of the prior hydrogen vessel work discussed previously that employs LH_2, which to date have all used commercially available LH_2 tanks built for land-based uses.

We are aware of only one paper examining advanced (non-commercial) LH_2 tank technology for ships. Abe and coworkers [64] developed a first order design of liquid hydrogen tankage for an LH_2 transport trailer, building off existing LNG tank technology. The conceptual designs included both spherical LH_2 tanks as well as a novel prismatic LH_2 tank.

In a closely related application, advanced cryogenic LNG tank design for ships continues to be of interest. Ahn et al. [65] have reported the development of a prismatic LNG tank based on an internal X beam structure that can increase the volumetric storage efficiency considerably over cylindrical tanks. Similarly, Choi et al. [66] have investigated prismatic LNG pressure vessel design for fuel storage.

We note here that the "membrane" LNG tanks used for large commercial transport of LNG as cargo do not have sufficient thermal insulation to be considered for LH_2 service. Membrane tanks use the hull of a ship as the Outer Jacket and load bearing structure. The ship's hull is then lined with an insulating structure (typically not vacuum based) that is then covered by a metallic skin that is so engineered to manage thermal shrinkage when it is wetted by the cryogenic fluid. [67]. While sufficient for very large volumes of LNG, with relatively low surface to volume ratio, such tanks have, so far, not been found suitable for smaller volume (non-cargo) LNG applications, and in any event are not suitable for LH_2 applications because of the exceptionally low enthalpy of vaporization of LH_2 compared to LNG [23].

Amongst the prior studies of LH_2 tank technology, there have been several studies focusing on the cryogenic properties of tank materials. These studies have considered the Inner Vessel and Outer Jacket materials [68], the performance of fiber reinforced materials at cryogenic temperature [69,70], and the thermal conductivity of LH_2 tank insulation materials [71].

During this review, the authors came across some miscellaneous LH_2 papers that a reader might find useful, although they are not directly related to issues of LH_2 tank mass, size, and shape.

Sherif et al. [72] summarized the potential of liquid hydrogen in energy applications, giving a nice summary of properties, and likely problems, circa 1997. Hastings et al. reported on NASA efforts to eliminate boiloff from LH_2 tanks using a cryocooler [73], Liu and Li [74] have discussed the influence of slosh baffles on the thermodynamic performance of LH_2 tanks. Recently, Yao et al. [75] have discussed the thermodynamic principles associate with hydrogen boil off in LH_2 tanks and the progress towards "lossless" storage of cryogenic hydrogen. Wang and coworkers have recently presented a thermodynamic analysis of the thermal performance of self-pressurized LH_2 tanks [76]. Finally, Zuo et al. [77] have reviewed the thermodynamics of quasi-steady liquid vapor phase changes in cryogenic liquids including LH_2.

Over the past several years, MARAD's Maritime Environmental and Technical Assistance (META) program has been partnering with government agencies, industry, and academia in efforts to study the use of alternative fuel and energy sources, in particular the use of hydrogen. In all the hydrogen vessel designs studied to date, the proposed LH_2 tank technology was based on what is commercially available today. Furthermore, all the LH_2 tanks utilized were originally designed for on-land industrial applications, with pressure ratings, shapes, insulation and boil-off specifications appropriate for the land-based industrial application. The objective of this design study project, also funded by MARAD, is to understand how LH_2 tanks could be improved not for stationary land applications, but for watercraft (ships), and how that tank improvement could benefit the design and capabilities of hydrogen fuel-cell ships. We assume fuel-cell propulsion because, although hydrogen internal combustion engines exist, fuel cells are zero-emission at the point of use and are more widely being considered for implementation on hydrogen vessels.

We explore improvements in the areas of tank weight, multiplicity (high-performing small tanks), and tank shape. Our purpose is two-fold. First, we aim to investigate how varying LH_2 tank weight, multiplicity and shape might enable more hydrogen to be stored on hydrogen vessels. Second, by analyzing the important technical factors governing tank weight, multiplicity, and shape, we seek to identify what would be the most promising R&D routes to improving LH_2 tank performance in these ways. Toward those goals, Sandia National Laboratories, Chart Industries, and Glosten have conducted an LH_2 tank design and naval architecture study, investigating the design criteria related to tank weight, multiplicity, and shape to improve hydrogen storage aboard vessels using hydrogen fuel cells for propulsion power.

2. APPROACH TO RESEARCH

2.1. Philosophy

Our purpose in this study is to understand how conceivable variations in LH_2 tank weight, multiplicity or shape might positively affect the quantity of LH_2 stored onboard a LH_2 fueled vessel. In doing so, we reduce to the absolute minimum currently applied regulatory constraints on vessel design that would otherwise restrict our exploration of the theoretical limits of implementation of LH_2 tank technology on a hydrogen fuel-cell vessel. Thus, our investigation relaxes (in many cases completely) requirements currently placed on vessel design by international (IMO) and domestic (USCG) vessel regulations. Beyond vessel design regulations, there are also regulations associated with the use of cryogenic tanks, for example required hold-time (boil off rate and pressure rating) and maximum amount of fill to accommodate possible fluid expansion (ullage). After our asymptotic results are presented, we subsequently revisit for context the maritime regulatory relaxations that were assumed.

We not only push our thinking past current vessel design practices (constrained by regulation) but also push our thinking past current LH_2 tank manufacturing capability and practice. LH_2 tanks have developed into highly engineered devices that must manage a variety of physical phenomena that are often in tension. At the highest and most practical level, LH_2 tanks must at least be manufacturable. In addition, they must be able to store LH_2 for some customer-determined amount of time (hold time or dormancy period) which can vary dramatically (minutes for the Space Shuttle, weeks for the automotive application). They must be of a size, shape and weight that satisfies customer needs. Underlying all of these attributes is managing the complicated kinetic and thermodynamic state of a cryogenic liquid in contact with a cold gas phase, with changes in hydrogen mass and volume within each phase over time, fluid (both gas and liquid) in contact with tank walls subjected to heat ingress, with operational constraints on the pressure of the gaseous phase, and also with the cryogenic liquid subjected to possible shock and vibration, and orientation effects (vertical, elevator effect). Here we explore LH_2 tank designs that are also asymptotic in nature, considering LH_2 tanks with performance and assumed physical attributes well beyond the current manufacturing state-of-the-art. After presenting results for the asymptotic explorations, the current LH_2 tank manufacturing limitations that were relaxed will also be revisited to provide context and to identify fruitful areas of further R&D.

2.2. H_2 Baseline Vessel

To study the impact of novel (beyond commercial) LH_2 tank design on improved storage of hydrogen on a vessel, a basis of comparison is needed, namely a “Baseline Vessel.” The H_2 Baseline Vessel needs to be based on current commercial hydrogen technology and be in some sense “generic,” to maximize the usefulness of our results to the naval architecture field and to LH_2 tank technology stakeholders. Using existing LH_2 technology for the H_2 Baseline Vessel also allows us to leverage results from the prior feasibility studies.

For this project, we consider as our H_2 Baseline Vessel a 100% hydrogen powered coastal research vessel similar in size to the previously studied *Zero-V* [25]. This choice allows us to leverage the prior *Zero-V* work from 2017, as well as recent design work on a diesel-powered research vessel similarly sized to the *Zero-V*. Whereas the *Zero-V* was a trimaran design, the H_2 Baseline Vessel for this work will be a monohull (a more common hull form), allowing the results of the study to be more directly applicable to other types of ships, both smaller (inland waterways) and larger (ocean going). The H_2 Baseline Vessel should demand the large amounts of hydrogen (thousands of kilograms) which require LH_2 storage, avoiding smaller amounts (~ 500 – 800 kg) where there could be ambiguity if the hydrogen vessel should use high-pressure storage (700 barg) of hydrogen gas. The H_2 Baseline Vessel design will assume the hydrogen is stored in two identical LH_2 tanks. Redundant fuel tanks are a current functional and regulatory requirement for a vessel powered entirely by hydrogen. The H_2 Baseline Vessel will adopt the cylindrical geometry and weight/volume characteristics of current LH_2 tank technology.

One could question basing such a study on the format of a research vessel. There are many more commercial vessels (ferries, etc.) than there are research vessels. Although research vessels are designed to maximize the power of scientific oceanographic inquiry and not the number of passengers, our H_2 Baseline Vessel does provide an appropriate platform for answering the primary questions of this project. Our H_2 Baseline Vessel will be a monohull, the most common hullform. Also, the H_2 Baseline Vessel will be a "medium size" vessel, relevant to many types of vessels of commercial interest. In addition, the ~ 1.7 MW propulsion power demands of the H_2 Baseline Vessel will be broadly relevant to many types of vessels.

The primary questions explored in our study are:

- How would a decrease in LH_2 tank weight affect the amount of stored hydrogen and the research vessel capabilities?
- Would an increase in LH_2 tank multiplicity increase the amount of hydrogen that can be stored on the ship?
- Can LH_2 tank shape positively influence hydrogen storage on a hydrogen ship?

These questions are captured in three different potential implementation concepts in Figure 2.

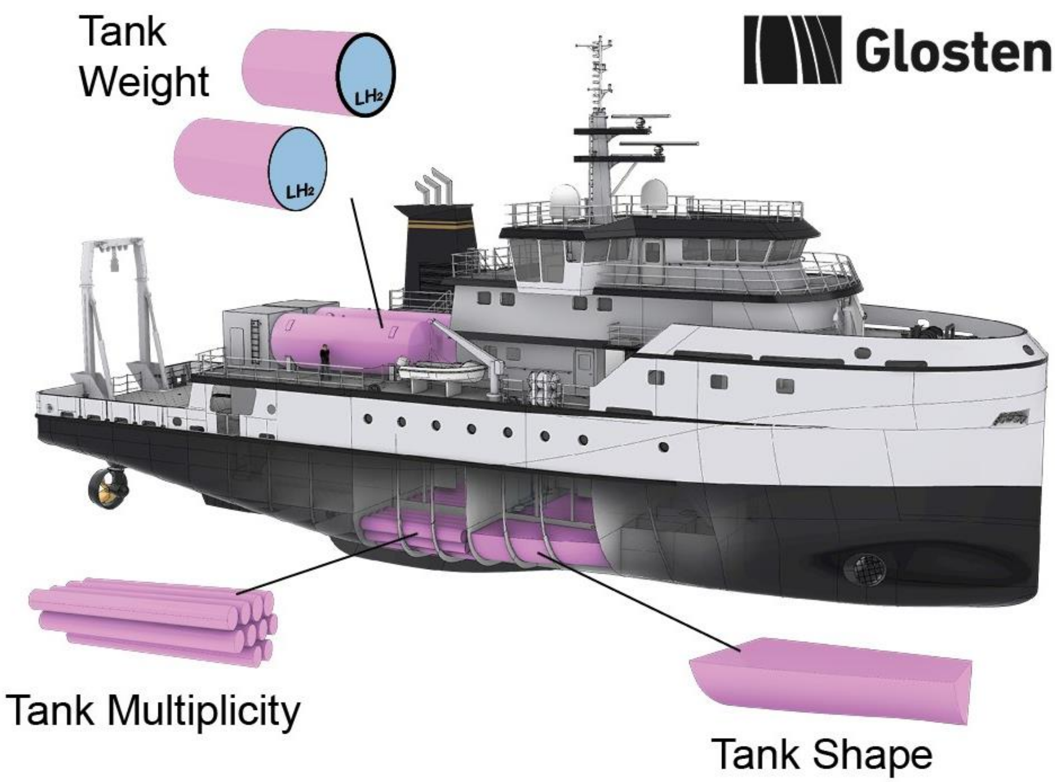

Figure 2. The questions addressed in this study: Using the H_2 Baseline Vessel as a comparative norm, how does varying tank weight (for example by using thinner Inner Vessel walls) affect vessel performance? (Note the thinner and thicker walls of the LH_2 tanks indicated for "Tank Weight."). Can more LH_2 can be stored on the vessel if improved LH_2 tank technology allowed the placement of many smaller LH_2 tanks with Tank Multiplicity? Can more LH_2 can be stored on the vessel if LH_2 tanks could be deployed with improved Tank Shape?

The influence of tank mass will be examined by parametric study, imposing a reduction in LH_2 tank mass for the H_2 Baseline Vessel, and assessing its impact on vessel range. As suggested by Figure 2, such a weight reduction could be achieved by making the Inner Vessel walls thinner. Recommendations will then be made for which routes to improvement (i.e., the research areas) are needed in LH_2 tank technology to enable meaningful reductions in LH_2 tank mass.

Similarly, we will then explore multiplicity variants which assume the LH_2 mass can be stored in a multitudinous array of smaller separate tanks (Figure 2), examining if greater quantities of LH_2 can be accessed by this approach compared to the H_2 Baseline Vessel. Similarly, we highlight the enabling R&D areas for the development of high performing but smaller LH_2 tanks for the maritime space.

Finally, we will explore the shape variant that assumes the LH_2 mass can be stored in LH_2 tanks with a hull conforming tank shape, as indicated in Figure 2, and compare the performance of the Shape Variant to that of the H_2 Baseline Vessel. If an improvement is found, we highlight those R&D areas in LH_2 tank technology to enable the desired non-traditional LH_2 tank shape.

We note here that the vessel variants in this study all maintain the same hull form and propulsion system. As such, there are no significant differences amongst the variants in major performance characteristics such as speed. The main differences between the designs are total fuel storage (which determines range), utilization of topside deck area, and total displacement. In other words, our focus is on the space available on a research vessel and the ways (weight, multiplicity, shape) that LH_2 technology could be improved to maximize stored fuel volume in those spaces.

The remainder of this report is organized as follows: Basic aspects of LH_2 tank technology are described to provide sufficient information for the reader to understand the choices that were made in tank specifications for the various inquires on weight, multiplicity and shape. The results of the studies and the possible R&D directions that arise are then discussed. Also, since all vessel variants are based on hydrogen fuel-cell power, a description of PEM fuel-cell technology is provided. Our results for the LH_2 tank studies regarding weight, multiplicity and shape are presented in order. Finally, Appendix A gives an abridged report emphasizing the essential results of the study for those who may be mostly interested in the naval architecture aspects of the work.

3. LH_2 TANK TECHNOLOGY BASICS

A basic understanding of cryogenic storage of hydrogen is needed to understand the trade-offs of the concepts examined. The following sections explain the key drivers in LH_2 storage tank design.

3.1. LH_2 Tanks and the Liquid-Vapor Equilibrium

Storing hydrogen as a liquid increases both the gravimetric and volumetric storage efficiencies beyond that available from compressed gaseous hydrogen. The volumetric density of liquid hydrogen at atmospheric pressure (0 barg and 20 K) is 71 grams per liter, which is nearly twice that of 700 barg compressed gas at room temperature [78]. Still, LH_2 is itself a low-density liquid. For context, the density of water is 1000 g/L, and the volumetric density of hydrogen in water is 111 g hydrogen per liter. Some of the basic properties of LH_2 have been described previously, and this discussion leans in part on that prior work [79].

Here we consider the storage of LH_2 in a low-pressure dewar, as indicated in Figure 1. By "low pressure," we mean vessels with a maximum allowable working pressure (MAWP) of ~ 10 barg. This distinguishes these tanks from "cryo-compressed" cryogenic storage tanks with a rated pressure of 350 barg, which are still the subject of research [79]. Low pressure LH_2 dewars are mechanically strong specialized vessels that attempt to minimize internal thermal conduction, thermal convection, and thermal radiation.

Unfortunately, heat leaks from the outside environment to the cryogenic hydrogen cannot be eliminated entirely. If storage is intended for extended periods of time, the cryogenic storage vessels must also safely manage the release of the evaporated gas (i.e., boil-off) [80 – 82].

As depicted in Figure 1, most commercial LH_2 storage vessels are metallic double-walled containers that are evacuated and contain multiple layers of alternating metallic and thermally insulating films to reduce heat leaks to the liquid hydrogen charge. Designs and materials used to construct the containers and all of the components are chosen to minimize thermal conduction. The maximum vessel pressure of conventional LH_2 tanks is ~10 barg. The combination of non-zero heat leak rate, low ΔH_{vap} for hydrogen, and low vessel pressure (10 barg) conspire to produce non-zero boil off from the LH_2 tank. Boil-off occurs when the pressure in the vapor portion of the tank exceeds 10 barg and a PRD lifts, venting the hydrogen away. Since hydrogen is nontoxic, not a direct greenhouse gas, and can be safely vented, the loss of hydrogen is primarily an economic loss. It becomes an operational problem when the amount of boil-off is a significant portion of the amount of hydrogen stored as a liquid in the LH_2 tank, or if storage for long periods of time without venting gas is required.

The evaporation of liquid hydrogen by the heat leak Q is the single most important physical process in our consideration of LH_2 tank design for hydrogen vessels. Here, we provide sufficient detail to enable an understanding of the results of our study. Consider the fate of a quantity of LH_2, stored in the Inner Vessel, and subjected to a heat leak Q as shown in Figure 3, where the double-walled design of the LH_2 tank (i.e., with Outer Jacket) shown in Figure 1 is suppressed for clarity. The vessel is fitted with a pressure relief device (PRD) such that the pressure in the vessel is always 1 atmosphere (0 barg), less than the 10.0 barg of real tanks but chosen for discussion purposes. We imagine the Inner Vessel of the tank is precooled to 20.3 K. LH_2 is placed in the vessel. Since the vessel is pre-cooled, the LH_2 does not immediately vaporize and can exist as a liquid in the vessel for some amount of time. Initially, the temperature of the LH_2 may be below that of its normal boiling point of 20.3 K.

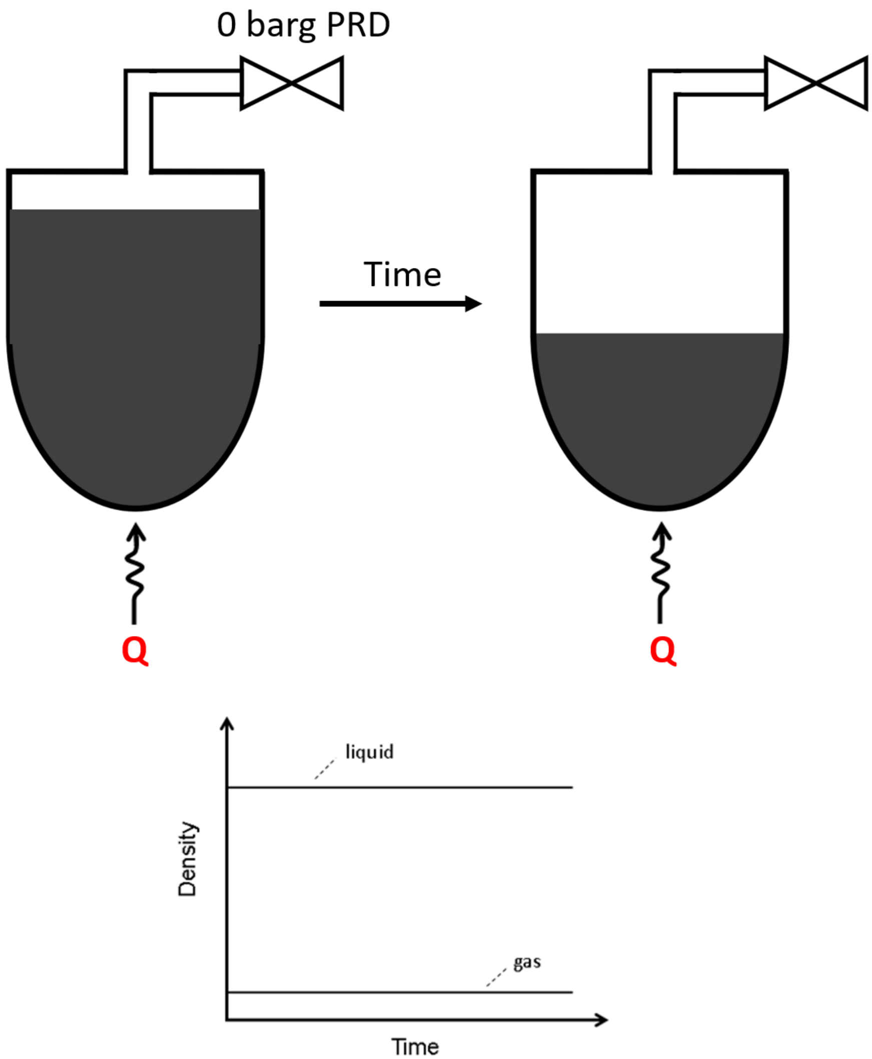

Figure 3. (Top) Evolution of LH_2 in a vessel configured to freely vent to atmosphere at time = 0, subjected to a heat leak Q. (Bottom) Variation in the densities of the H_2 gas and liquid phases as the liquid hydrogen evaporates at constant pressure (1 atm).

As the LH_2 is subject to heat leak Q with time, the temperature in the liquid will rise, with a concomitant increase in the equilibrium hydrogen vapor pressure above the liquid. Assuming equilibrium is always maintained, the liquid temperature maintains the normal boiling point of LH_2 (20.3 K), the vapor pressure will maintain 1 atmosphere (0 barg), and “boil-off” begins (time = 0) in Figure 3. If the PRD is set to vent at pressures above 1 atmosphere (0 barg), then as the heat leak continues, more and more liquid will boil, with the temperature of the liquid holding constant at 20.3 K, and the pressure in the vapor will be maintained at the equilibrium vapor pressure at 20.3 K of 0 barg. As a result, under the conditions of Figure 3, the temperature of both phases will remain constant at boiling, and thus the density of each phase remains unchanged as time progresses, as indicated in Figure 3 (bottom). However, as hydrogen is leaking through the PRD, the heat transfer Q from the environment vaporizes the liquid hydrogen (dark shading at the bottom of the vessel), reducing the amount of LH_2 over time. As a result, the volume of cold hydrogen gas (at 1 atm pressure, 0 barg) is increasing with time. The boil-off will proceed until there is no liquid hydrogen remaining. At that time, only hydrogen vapor exists, slowly warming from 20.3 K to room temperature. The gaseous hydrogen can still be used by fuel cell, but as a practical matter, one does not want all the liquid to evaporate because one needs to keep ~ 5% of the LH_2 charge in the tank to leave a cold heat sink to absorb heat and mitigate vessel wall warming to facilitate the next tank refill.

The situation changes dramatically if one now uses a stronger LH_2 tank, with a PRD set to vent at 17 barg. This situation is shown in Figure 4.

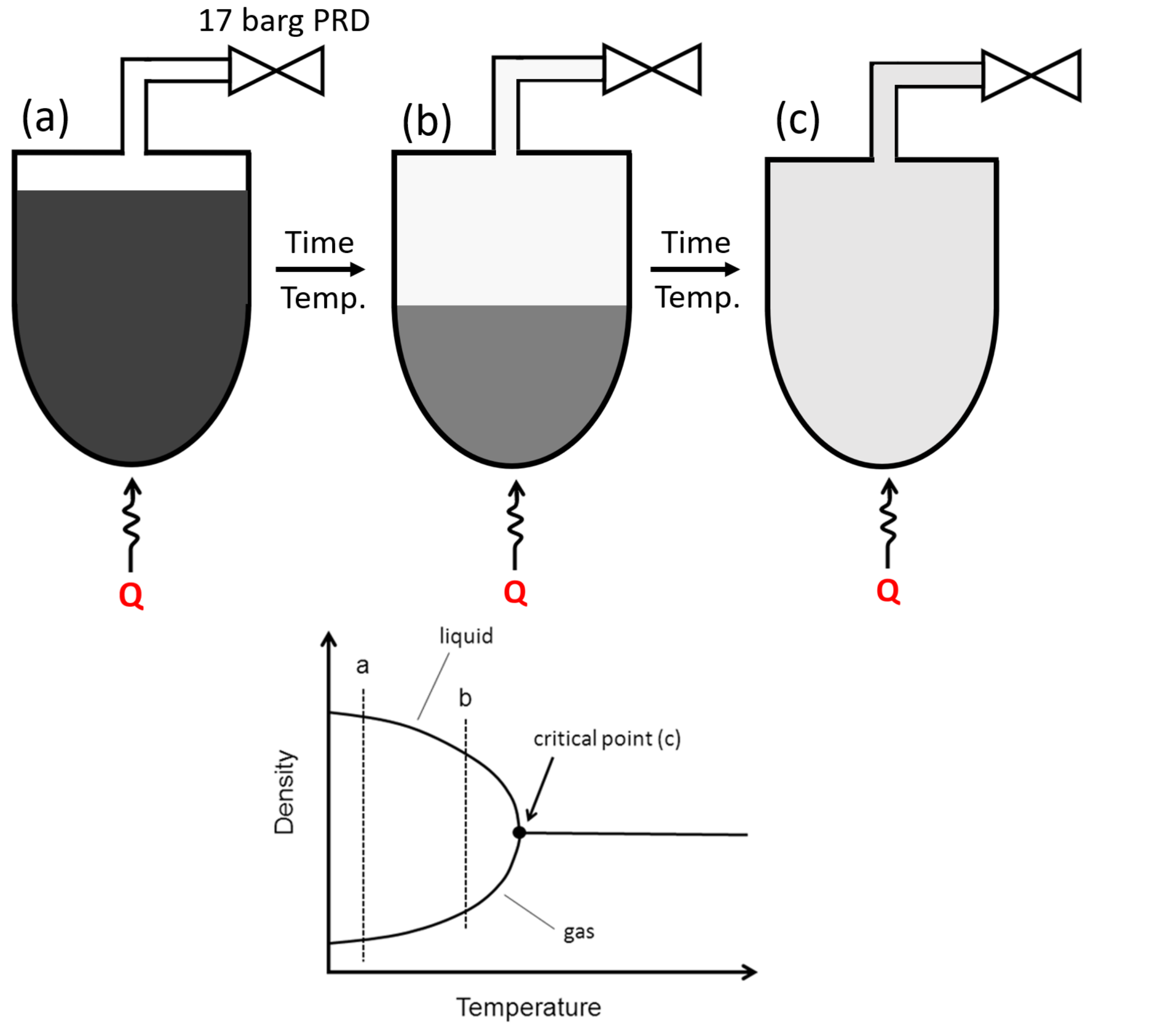

Figure 4. (Top) Evolution of LH_2 in a sealed vessel rated to 17 barg, subjected to a heat leak *Q*. As time progresses, the densities of the LH_2 and vapor components change (indicated by the shadings). Darker shading indicates higher density. (Bottom) Schematic of liquid and gaseous densities as a function of temperature (and time) at the critical density (30.6 g/L). The dotted lines "a" and "b" correspond to the densities depicted in the top pictures a and b, with the top figure c corresponding to the critical point (32.9 K, 11.8 barg) labeled c in the bottom figure. Note that since the density of the gas phase is increasing with temperature, the gas phase pressure is increasing as well. Figure reproduced with modification from Reference 79.

When using a stronger tank, LH_2 is loaded into the precooled system at an initial temperature of 20.3 K, Figure 4 (top (a)). Since the vessel is rated for a higher pressure of 17 barg and the PRD is set to release at 17 bar, as heat is added to the LH_2, the temperature will increase and the gas pressure will rise above the near atmospheric pressure of boil-off, increasing the vapor phase density and decreasing the liquid phase density. Thus, the higher-pressure rating of the tank and the PRD allows the system to access higher temperatures, both gas and liquid. The density of the vapor phase will increase because the pressure is rising with more molecular hydrogen being transferred to the gas phase, and with the temperature rising as well. The shadings in Figure 4 (top, (a) – (c)) indicate the density variations in the liquid and vapor phases for this “17 barg” scenario, with the vapor phase becoming progressively darker, and the liquid phase becoming progressively lighter as evaporation takes place, both phases being in equilibrium with each other. Eventually, as the heat leak continues and the temperature rises, the gas-phase and liquid-phase densities merge to a common value, and the physical distinction between gas and liquid disappears. This point is called the critical point, indicated in Figure 4 (c).

The densities of the liquid and gaseous phases for the “17 barg vessel” with a heat leak are plotted in a schematic way in Figure 4 (bottom). The LH_2 density drops, and the vapor density rises, until merging at the critical temperature. Beyond the critical point, only a single “supercritical” phase exists, and with no changes in hydrogen mass in the fixed volume of the vessel, the density remains constant as time progresses and the heat leak Q continues. As the heating continues, the temperature rises, as does the gas pressure. However, the single-phase supercritical gas density remains unchanged, as indicated by the graph in Figure 4.

The critical temperature and pressure are unique values (32.9 K and 11.8 barg for para hydrogen) and correspond to a unique critical density (30.6 g/L). Thus, in the entire phase space possible for pressure, temperature, and mass of H_2 in the vessel (i.e., density), there is only one special combination of the three such that when the liquid just starts to evaporate, it creates a vapor of identical density. For all other combinations of temperature, pressure, and mass of hydrogen, the very first quantities of gas produced by evaporation will have a density lower than the liquid from which it came, producing a discontinuous change in density in going from liquid to vapor (and vice versa). As a practical matter, because the pressure rating of actual LH_2 tanks is typically 10 barg, below the 11.8 barg pressure of the critical point, most commercial LH_2 tanks for vessels will be operating below the critical point, and we can confine our attention to the behavior of a 2-phase liquid/gas fluid inside the LH_2 tank.

An important operational aspect of LH_2 tank technology is the concept of “ullage space.” Ullage is the space left unfilled in a tank to allow for liquid expansion with increased temperature. Ullage space tank design is intended to ensure that the safety relief valves open prior to a tank becoming 100% filled with expanded liquid, the so-called “liquid skin full” condition of the tank. With a vapor space, thermally expanding liquid can safely compress the vapor space up to the pressure relief setting. Should the tank geometry be (poorly) designed so that below the pressure relief setting, there is no vapor space left, the compression must happen in the liquid itself. Since the compressibility of the liquid is very low compared to the vapor, the pressure rise in the tank will be dramatically higher, possibly leading to tank overpressure before the PRD lifts, or liquid (instead of vapor) is discharged from the Inner Vessel PRD, which is undesirable from a safety perspective.

Ullage space design on stationary equipment has a different basis than that on mobile equipment. Mobile equipment will tend to slosh the liquid while in motion and in doing so distribute the energy evenly into the liquid and vapor. This keeps the cryogenic liquid and vapor in thermodynamic equilibrium. This equilibrium will make the pressure rise from heat input track the thermodynamic saturation pressure curve. For mobile equipment the required ullage volume can be calculated from the net expansion of the liquid from a delivered energy state to the energy state when the vapor of the system activates the Inner Vessel PRD. These considerations are the basis for the maximum fill amounts (or "ullage targets") as seen in the Code of Federal Regulations for cargo tanks.

For our maritime LH_2 tanks, current (but still developing) regulations being applied by the USCG to emerging LH_2 vessels specify that for a 10 barg relief pressure setting, the maximum amount of LH_2 that can be loaded into the tank is 64%. For refueling, it is desirable to have ~ 5% of the tank still filled with LH_2 so the tank system is cold, and one does not have to waste precious LH_2 in cooling the tank down. So, from an operational point of view, the LH_2 tank fill limits are 64% – 5%. This represents the "usable" or "consumable" capacity of a LH_2 tank. Because these limits are a function of relief valve pressure and to possible future changes in regulations, we will focus on the 100% fill capacity of the LH_2 tanks for comparison purposes, but we also list the consumable hydrogen quantities for completeness.

Our exploration of improvements in tank weight, multiplicity, and shape starts by investigating if there is a maritime hydrogen storage benefit in these areas. Then, if a benefit is found, we seek to identify the technical path realizing such LH_2 tanks. Understanding the technical R&D path requires understanding the tanks design influences on the liquid/gas equilibrium presented in Figure 3 and Figure 4.

Figure 3 and Figure 4 are meant to give the reader a qualitative understanding of the liquid-vapor equilibrium taking place in LH_2 tanks, with different pressure settings for the PRD. We now move to a semiquantitative discussion of LH_2 tank technology, which requires a deeper description of some of the key properties of both hydrogen and the tank itself. We start with some basic information about gaseous hydrogen first, then liquid hydrogen, both being necessary background for talking about LH_2 tanks. This background information leans heavily on the publication of Klebanoff et al. [23].

Hydrogen is the lightest gas, with a density of 0.084 kg/m^3 at normal temperature and pressure (NTP), 293K, 1 atmosphere pressure. Hydrogen at NTP is much more buoyant than air, which has a NTP density of 1.20 kg/m^3. Being a homolytic diatomic molecule, hydrogen has no dipole moment, and vibrations of the molecule cannot produce charge separation along the bond axis. Consequently, hydrogen does not interact with infrared radiation, and is not a greenhouse gas [23]. However, current R&D is investigating how H_2 photochemistry in the atmosphere could, in a secondary way, impact the heat retaining properties of the atmosphere [83].

A defining characteristic of molecular hydrogen is the very weak attractive van der Waals interactions between nonpolar H_2 molecules. The intermolecular attractions between H_2 molecules are much weaker than those between CH_4 molecules, which explains the lower boiling temperature for LH_2 compared to LCH_4 (LNG). For discussion purposes, we will assume LNG can be described by the properties of LCH_4, which typically makes up ~ 93% of the LNG composition [23]. The normal boiling point for hydrogen is 20.3 K; the normal boiling point for

LCH_4 is 111.5 K. An important consequence for the difference in boiling points is that liquid methane (at its boiling point) cannot liquefy air, whereas LH_2 can liquefy air, whose components N_2 and O_2 condense at 77.3 K and 90.2 K, respectively [23]. These atmospheric gases can also solidify when exposed to LH_2, as the melting points for solid N_2 and solid O_2 are 63.3 K and 54.8 K, respectively [23]. The potential for liquefying or solidifying air introduces safety concerns. The impact of cryogenic air condensate dripping onto other structures must also be considered. Additionally, should the internal surface of piping be left open to atmosphere, such condensation could freeze to an oxygen rich solid and create a future risk of reacting with hydrogen. As a practical matter, these air condensation issues are routinely handled in LH_2 fueling operations by purging the LH_2 plumbing lines with hydrogen or helium (more typically hydrogen due to its availability at the site and lower cost).

The weak intermolecular attraction between H_2 molecules, combined with hydrogen's low mass, makes LH_2 a low-density fluid. The density of LH_2 is 71 g/L at its normal boiling point (NBP) of 20.3 K at 1 atmosphere pressure. The density of LCH_4 at its NBP of 111.5 K at 1 atmosphere pressure is 422 g/L. Interestingly, the NBP molecular number density for LCH_4 (1.59×10^{25} molecules/L) is lower than that for LH_2 (2.14×10^{25} molecules/L) because H_2 is a smaller molecule than CH_4. However, what matters is the potential combustion energy density. Since more energy is obtained by "burning" a molecule of CH_4 than H_2, the useable energy density for LCH_4 is higher. The lower heating value (LHV) for methane is 50.02 MJ/kg; the LHV for hydrogen is 119.96 MJ/kg [23]. For the same amount of stored fuel energy, LH_2 has 0.42 times the mass of LCH_4, but has 2.5 times the volume. LCH_4 itself has 1.7 times the volume of diesel fuel on an equivalent LHV basis. Thus, LH_2 requires 4.2 times the volume as diesel fuel to store, just considering the fluids themselves (no tankage) on a LHV basis.

The weak intermolecular attractions between hydrogen molecules leads to the enthalpy of vaporization ΔH_{vap} of LH_2 being only 0.92 kJ/mole, 9.2 times less than that of LCH_4, whose ΔH_{vap} value is 8.5 kJ/mole [23]. For comparison, the ΔH_{vap} of liquid water is 40.66 kJ/mole, due to the strong hydrogen bonding found between water molecules. The extraordinarily low ΔH_{vap} value for hydrogen drives LH_2 tank design and is the primary reason making and storing LH_2 is considerably more difficult than making and storing LCH_4 (LNG).

3.2. Thermodynamics

Fundamental to understanding the design choices for LH_2 tanks is to understand the thermodynamics of cold liquid/gas phases. Here we will assume that these two phases (liquid H_2 and the cold H_2 gas above it) are in equilibrium with each other. However, it is important to point out that there are many instances in real LH_2 tank operations where the phases are not in equilibrium, for example during fueling, or sloshing of the LH_2 in the tank. We ignore those complications for this study.

Thermodynamics is the study of how energy changes the physical properties of substances. Thermodynamics is ultimately determined by the molecular properties (discussed above for H_2), but the concepts refer to macroscopic properties of the system. Liquefied gases that exist at temperatures below minus -150 ºF (172 K, -101 ºC) are considered “cryogenic liquids.” Changes in the macroscopic fluid physical properties in turn effect the performance of equipment designed to store and flow the cryogenic liquid.

There are four macroscopic properties which are typically used to describe any fluid: pressure, density, heat, and temperature.

3.2.1. Pressure

Both liquid and gaseous phases can create pressure, but for LH_2 tanks, it’s the gas phase portion of the liquid/gas system that is of most concern, since any contributions of the liquid state to pressure are negligible in comparison. Pressure is particularly important for hydrogen. The volume expansion factor for hydrogen is 847.6 when a given mass of liquid hydrogen is warmed from the NBP to a gas at NTP. The pressures possible with LH_2 evaporation must be accommodated by the LH_2 tank design. Also, the gas pressure is the driving force for moving gaseous hydrogen from the LH_2 storage tank through manifolding to the fuel cell. Pressure is measured as force/area (psi, atmospheres, barg).

3.2.2. Density

Density refers to stored hydrogen mass per volume, and has units of kg/L. For the gas phase component, density depends on the pressure and temperature. The density of the liquid phase depends mostly on temperature. As mentioned previously, for LH_2 at its NBP, the liquid density is 71 g/L. For hydrogen at 350 bar, the gas phase’s density is 23.1 g/L and at 700 bar it is 39.0 g/L using the Abel Nobel real gas equation of state for hydrogen [84]. These density values show why LH_2 is preferred for storing large quantities of hydrogen.

3.2.3. Heat

Measured in BTU or Joules, heat energy refers to the internal and potential energy of the fluid, which in a system with well-defined pressure, is referred to as enthalpy H. The enthalpy is typically referenced relative to that at absolute zero of temperature, 0 K. The enthalpy change associated with taking a given mass of liquid hydrogen at a given temperature and converting it to gas at the same temperature is known as the enthalpy of vaporization, ΔH_{vap}. Note that the enthalpy of liquid or gaseous hydrogen should not be confused with the change in energy associated with combusting hydrogen by reaction with oxygen to make water via the reaction: $2H_2 + O_2 = 2H_2O$. This is commonly called the “enthalpy of combustion,” which, if the water is produced in the gaseous state (as opposed to the liquid state), is called the lower heating value (LHV) of hydrogen, which has the value 119.96 MJ/kg [23]. Thermodynamic heat is very closely related to the temperature of the fluid. In most cases the measurement of the temperature can be considered a direct measurement of the heat content of the fluid.

3.2.4. Temperature

Measured in degrees Fahrenheit (ºF), degrees Rankine (ºR), degrees Celsius or Centigrade (ºC), or degrees Kelvin (K), temperature is a measure of the internal energy (or heat content) of a fluid, whether it be in the gas phase or the liquid phase. This internal energy is partitioned between the energy of molecular motion (kinetic energy), the energy of vibrations of the H_2 molecule and the energy associated with the rotation of these molecules. For our consideration of LH_2 in equilibrium with its associated gas phase, the temperature of the liquid and gas are the same at equilibrium. The very low temperatures of a cryogenic liquid also act as an important driving force for heat transfer within the LH_2 tank structure since heat transfer scales as the temperature difference between a fluid phase and its surroundings. Heat transfer into a fluid phase increases its internal energy.

The molecular structure of any fluid determines these macroscopic properties in a specific and predictable relationship. Figure 4 showed a qualitative picture of the relation between the density (d) and temperature (t) of liquid hydrogen in equilibrium contact with the gas phase, a so-called d-t diagram. A more complete diagram is a quantitative p-d-t diagram, which allows the mapping of any two properties (say d and t) to a third, pressure (p). The result is a well-defined 3D p-d-t landscape, as shown in Figure 5. Note that points a, b, and c in Figure 5 correspond to the same points in Figure 4.

The green line in Figure 5 marks the hydrogen vapor phase in equilibrium with liquid hydrogen at the same temperature. The blue line marks the liquid phase in equilibrium with gaseous hydrogen at the same temperature. Moving from blue point “a” to blue point “b” corresponds to an increase in liquid temperature (T↑), driving a decrease in liquid density (ρ↓) and an increase in gas-phase pressure (P↑). Such a move could be created by heat leak Q entering the cryogenic liquid hydrogen. Green point “a” gives the p-d-t values for hydrogen gas in equilibrium with hydrogen liquid at blue point “a.” The “dome” that is defined by values of equilibrium pressure and density at elevated temperatures is called the “saturation dome.” The saturation dome is the surface of behavior of the fluid as it changes from a liquid to a gas, and thus is the most critical area for LH_2 tank technology discussion.

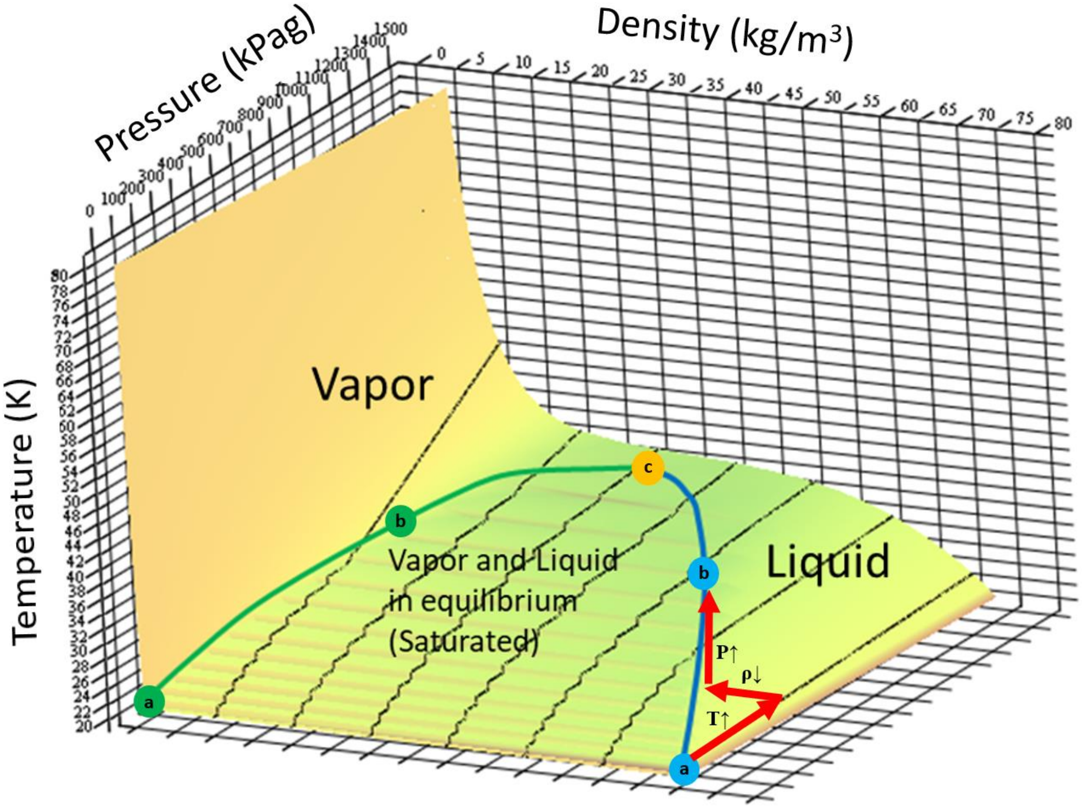

Figure 5. Pressure-density-temperature (p-d-t) 3D plot for liquid hydrogen in equilibrium with a hydrogen vapor phase. Points a, b and c correspond to the same points in Figure 4.

Where within Figure 5 an LH_2 tank ideally operates depends on the application. For example, if the LH_2 tank's function is purely for storage, with no active use of the hydrogen on an on-going basis, the ideal state within the p-d-t diagram of Figure 5 would be at blue point "a." In this instance, one wants to minimize any loss of hydrogen by boil-off. To accomplish this, the liquid should be as cold as possible, minimizing the equilibrium vapor pressure corresponding to green point "a." On the other hand, if the LH_2 tank is meant to provide hydrogen on an ongoing basis, boil-off may not be a top concern. In this case, one may want a significant equilibrium gas pressure to draw off for use. In this scenario, it would be best to design the LH_2 tank to operate at blue and green point "b." In a mobile application such as a marine vessel with tank sloshing, the instantaneous position of the liquid/gas system can vary within saturation dome.

The saturation dome of liquid/gaseous hydrogen exists within the confines of the LH_2 tank. How the LH_2 system (gas + liquid) moves within the p-d-t space depends entirely on the LH_2 tank design. The heat leak Q that can enter the Inner Vessel originates from the "threatening" prevailing environmental conditions (atmospheric temperature), mitigated by tank design measures (i.e., material of the Inner Vessel, insulation in the gap between the Inner Vessel and Outer Jacket, material of the Outer Jacket). The gas pressure that the LH_2 tank can manage while maintaining gas-liquid equilibrium (saturation) is determined by the mechanical strength and thermal cycling stability of the Inner Vessel material. The density of the hydrogen fluid system, either gas density or liquid density, depends on the range of temperatures that the tank can operate over, combined with available volume within the Inner Vessel. If one wants to contemplate an advancement of LH_2 tank design to accommodate a maritime mission need (the topic of this Report), it is essential to understand how LH_2 tank design impacts the p-d-t space within Figure 5. In addition, by investigating what LH_2 tank designs would improve stored quantities of hydrogen for maritime use, the connection between tank design attributes and the saturation dome allows us to identify what LH_2 tank components (Figure 1) need R&D improvement to provide the desired behavior in p-d-t space.

Understanding the thermodynamics of cryogenic liquid hydrogen is foundational in informing a storage tank design. Maritime applications demand a unique tank performance to be fit for the application as compared to stationary industrial usage or one-time aerospace usage. Ultimately, we seek to understand what desirable extensions of current LH_2 technology practice can enable better maritime performance. In this study, we examine the highest-level aspects of this enabling. For example, when considering using LH_2 as a fuel onboard a ship, some high-level ship performance attributes of interest include:

- Ship Range (driven by mission requirements)
- Ship Stability (driven by safety regulations)
- LH_2 Tank hold time without venting (to comply with prevailing regulations).
- Available fuel storage space (driven by the ship design that devotes space to other uses in accomplishing its mission).

Several LH_2 tank design aspects link to these high-level ship performance aspects. For example, LH_2 tank volume (and therefore stored hydrogen mass) links to ship range. The weight and installation location of the LH_2 tankage directly determines the ship stability. The LH_2 tank surface/area ratio, performance of the insulation and pressure rating of the LH_2 tankage contribute to the hold time. As a result, our internal analysis kept track of these relationships as our overall assessment of LH_2 tank weight, multiplicity and shape progressed.

4. FUEL CELL BASICS

A hydrogen fuel cell is an electrochemical device that executes the hydrogen/oxygen reaction (1) without direct combustion [85]:

$$2H_2\ (g) + O_2\ (g) \rightarrow 2H_2O\ (g) + Q \qquad (1)$$

where hydrogen (H_2) is stored in some fashion, oxygen (O_2) typically comes from the air, and Q is the energy released by the reaction, apportioned between electrical work and thermal energy (waste heat). The PEM fuel cell is perhaps the simplest of the fuel cells [85].

Figure 6 shows the relevant spatially separated "half-reactions" in a H_2 PEM fuel cell [85]. At the anode, hydrogen gas ionizes, releasing protons to the membrane and electrons to the external circuit. At the cathode, oxygen molecules are reduced in an acidic environment by electrons from the circuit, forming water molecules. Protons pass through the proton exchange membrane, from anode to cathode, completing the circuit while electrons are driven through the load by the electromotive force of reaction (1).

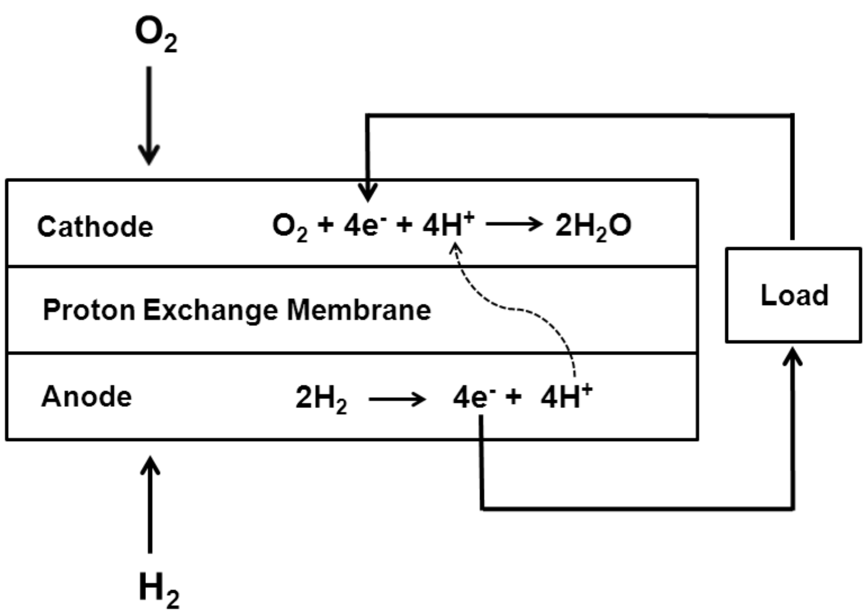

Figure 6. Schematic diagram of a PEM fuel cell. Reproduced from Reference 85.

Traditional PEM fuel cells use a solid proton conducting polymer membrane called Nafion, a type of polyfluorinated sulfonic acid (PFSA) material, which allows proton transfer between the anode and cathode. Nafion-based fuel cells operate at low temperatures, around 80°C. The low-temperature operation provides for rapid start-up, which is essential for most low-power or mobile applications. However, for temperatures at or below ~80 °C, the reaction product is liquid water, making management of liquid water an important issue.

Commercial fuel-cell units consist of "stacks" of the fundamental PEM fuel-cell unit shown in Figure 6. The PEM fuel cell generates electricity with a thermal efficiency (electrical work out/fuel energy in) of ~ 50%, depending on the load. Concomitantly, ~ 50% of the hydrogen fuel energy is converted to waste heat, that must be managed with a cooling system. The PEM fuel cell uses pure hydrogen (typically > 99.95% pure) at the anode and can operate at relatively low temperatures (50 – 100 ºC), using a catalyst (typically platinum) to increase the reaction kinetics. Since there is no combustion occurring in the fuel cell and the fuel is pure hydrogen, there is zero NO_x emission, zero SO_x, zero HC, and zero PM emissions.

Figure 7 shows the overall block diagram for a generic PEM hydrogen fuel-cell power module (HyPM).

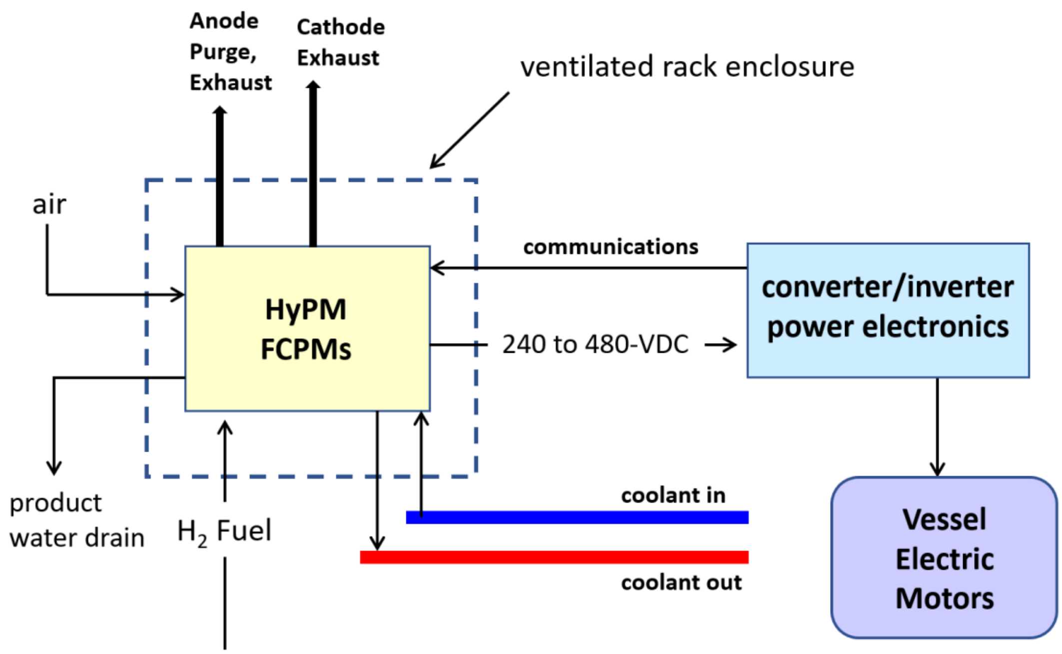

Figure 7. Generic PEM hydrogen fuel-cell system block diagram.

Hydrogen and air are directed to the fuel-cell anode and cathode, respectively. Therein, the electrochemical reactions at the anode and cathode take place. The product water from the reaction is removed by the water drain. Sometimes water tends to collect in the anode region, which blocks H_2 gas. This water is removed by a brief pulse of hydrogen called the "anode purge." The fuel cell contains an exhaust line for the anode purge and an exhaust line for the cathode which consists of oxygen depleted air and water vapor. These exhaust lines are typically routed to the vessel's Vent Mast [11, 24, 15]. The power out of the rack is typically conditioned with a DC-DC converter, and then transformed to AC power by a DC-AC inverter.

In the Ballard FCwaveTM fuel-cell modules [86] adopted for our hydrogen systems design, fuel-cell stacks are integrated together with power electronics and balance of plant components into a modular cabinet rated for ~200 kW. A picture of the Ballard FCwaveTM fuel-cell module is shown in Figure 8 [86].

Figure 8. Picture of a Ballard FCwaveTM fuel-cell Module. Reproduced from Reference 86.

5. RESULTS AND DISCUSSION

5.1. The H_2 Baseline Vessel and It's Diesel Electric Parent

As stated previously, the H_2 Baseline Vessel needs to be rooted in current commercial hydrogen technology and be in some sense "generic," to maximize the usefulness of our results to the naval architecture field. Also, we wish to leverage results from the prior feasibility studies [11, 24, 25]. For this project, we consider as our H_2 Baseline Vessel to be a 100% hydrogen powered coastal research vessel similar in size to the previously studied *Zero-V* [25]. This choice allows us to leverage the prior *Zero-V* work from 2017. In addition, this choice permits us to leverage recent design work on a diesel-powered research vessel similarly sized to the *Zero-V*. This "Parent Vessel" is shown along with the H_2 Baseline Vessel in Figure 9.

Figure 9. 3D renderings of H_2 Baseline Vessel and diesel-electric Parent Vessel from which the H_2 Baseline Vessel is derived.

The H_2 Baseline Vessel has design and capabilities summarized in Table 1.

Table 1. Design and Capabilities of the H_2 Baseline Vessel

H_2 Baseline Vessel Characteristic	Value
Length (m)	49.99
Beam (m)	12.8
Design Draft[1] (m)	3.65
Depth[2] (m)	5.65
Displacement (MT)	1331
Crew	12
Scientists	18
Speed (kts)	12
Range (@ 10 kts) (NM)[3]	710
Endurance (days)	3
[1]Design Draft is reported for the full load (departure) condition. [2]Depth is the vertical dimension of the watertight hull volume, draft plus freeboard. [3]Range is calculated with 64% fill limit and 5% tank heel, per "current" regulations (see text). NM = nautical miles.	

The H_2 Baseline Vessel has the same hull shape and hull dimensions as the Diesel Parent Vessel. However, there are differences in the use of deck space, as required by the placement of two large LH_2 tanks on deck. The largest difference of course is the removal of diesel generators and diesel fuel from the Parent Vessel and replacing them with PEM fuel cells and LH_2 for the H_2 Baseline Vessel.

An interesting difference involves the ballast tanks. The diesel-electric Parent Vessel uses seawater ballast to compensate for the lost displacement and upward shift in vertical center of gravity (VCG) as diesel fuel is burned from the fuel tanks at the bottom of the hull. The seawater ballast tanks are located below the First Platform on the Parent Vessel. The Parent Vessel has 152 m^3 of ballast volume and 127 m^3 of diesel fuel volume. In the H_2 Baseline Vessel, the consumption of hydrogen fuel does not constitute a meaningful change in the displacement or VCG of the vessel. This has a design advantage, discovered in our Weight Study, to be discussed. Accordingly, variable seawater ballast is not required in the H_2 Baseline Vessel. However, permanent ballast was required to achieve a VCG that satisfies stability regulations. Although this eliminated the need to separate the double bottom into functionally separate tanks, transverse bulkheads for watertight stability and longitudinal bulkheads for strength are still needed, so there was no significant change to the overall double bottom structure in going from Parent Vessel to H_2 Baseline Vessel. We do not compare the performance attributes of the H_2 Baseline Vessel with the Diesel Parent Vessel. Rather, the Diesel Parent Vessel is only used to establish the general architecture of the H_2 Baseline Vessel.

The H_2 Baseline Vessel has been configured to evaluate the design impacts of varying tank mass, multiplicity, and shape as objectively as possible and to also provide a platform for examining novel placement of LH_2 tanks on a vessel. The H_2 Baseline Vessel is designed in accordance with design principles arising from the prior H_2 vessel feasibility studies [11, 24, 25], in particular the choice to put the LH_2 tanks “out in the weather.” Although specific regulations for the hydrogen vessels are not fully developed, the designs reported in those studies were generally compliant with the prevailing regulatory environment for LNG vessels. Although there are differences, draft regulations from the IMO and project-specific regulatory approvals have been largely similar to date. Thus, the H_2 Baseline Vessel is generally compliant with the IGF Code (written for natural gas vessels) [87], which requires redundancy in fuel tanks.

Figure 10 shows a cross-sectional view of the H_2 Baseline Vessel with key vessel components identified.

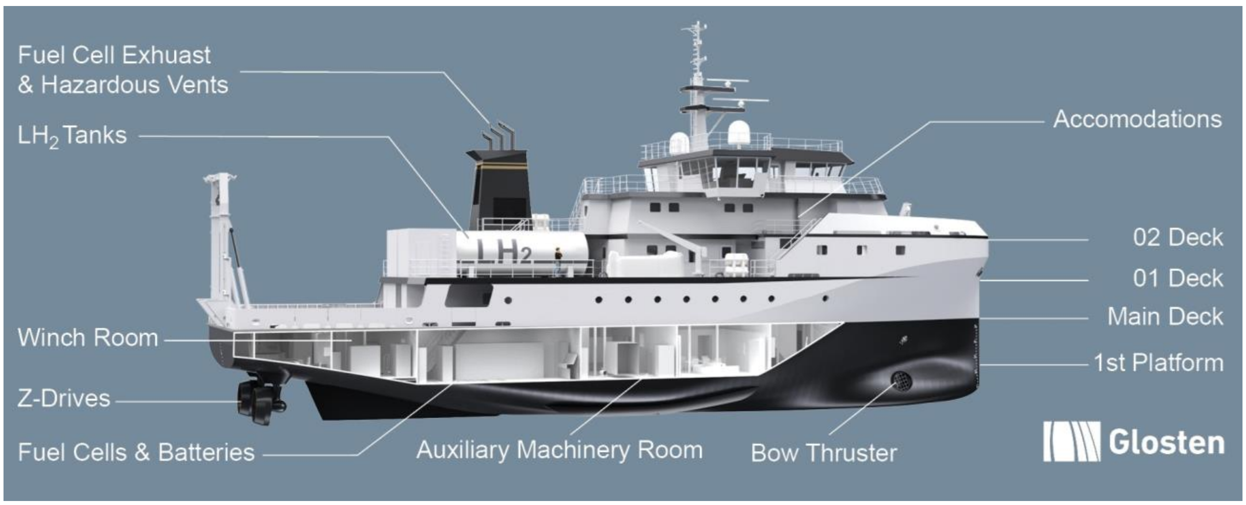

Figure 10. Cross-sectional view of H_2 Baseline Vessel outboard and machinery arrangements.

The First Platform contains mainly machinery spaces, with one science space. The Main Deck is comprised of exterior working spaces, science labs, galley and mess, and ship storage. The 01 Deck holds the LH_2 tanks and some scientist and crew accommodations. The 02 Deck contains the remainder of the scientist and crew accommodations. The 03 Deck is the Pilothouse.

5.1.1. H_2 Baseline Vessel LH_2 Tanks

A prominent feature of the H_2 Baseline Vessel is the placement of two large LH_2 tanks out in the weather. These tanks are shown mounted on the 01 Deck in Figure 10. These LH_2 tanks provide a baseline representation of current commercial LH_2 tank design and manufacturing practice to which advanced LH_2 tank designs that deviate in weight, multiplicity or shape can be compared. For the H_2 Baseline Vessel tanks, we assume a commercial standard cylindrical LH_2 tank currently offered by Chart, shown schematically in Figure 11 (top) and by photograph in Figure 11 (bottom).

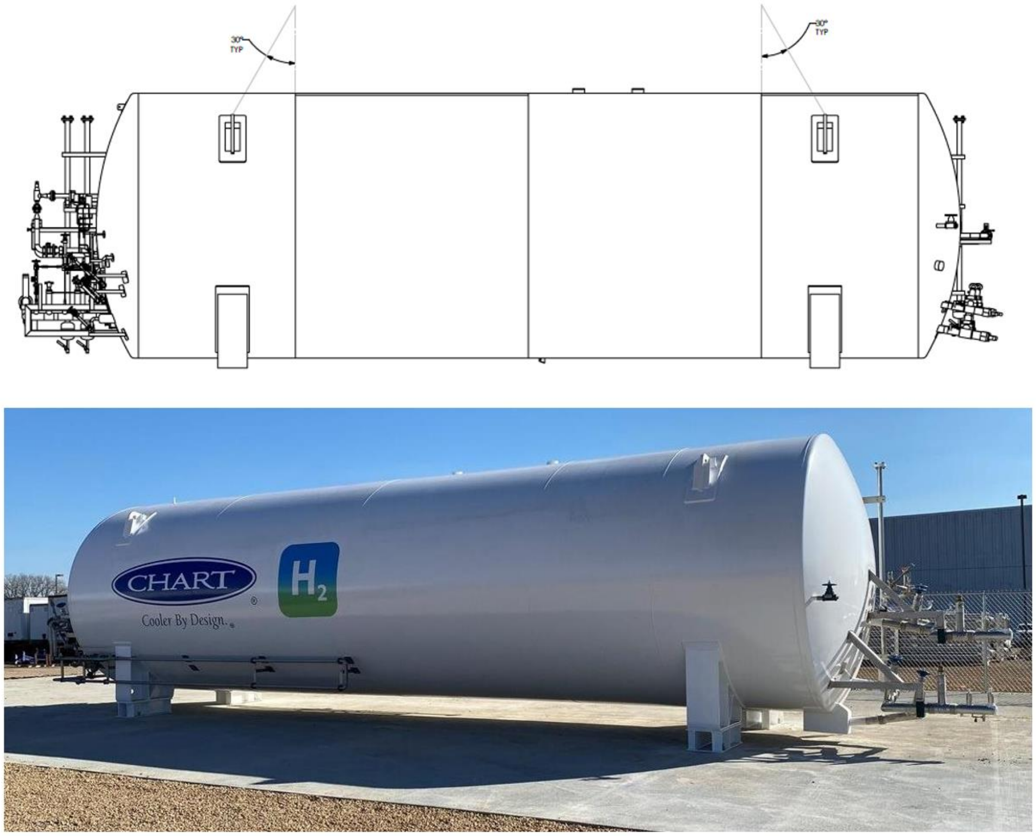

Figure 11. (Top) Schematic design of one of the two identical LH_2 tanks assumed for the H_2 Baseline Vessel. (Bottom) Photograph of the actual commercial tank manufactured by Chart. Photo Credit: Tom Drube.

The LH_2 tanks in Figure 10 are identical, and each tank has the attributes summarized in Table 2. These tanks are very typical of the current LH_2 tank technology used in ground-based applications as depicted in Figure 11. The LH_2 tanks on the H_2 Baseline Vessel were sized in a practical way to hold the maximal total amount (summed over two tanks) of LH_2 that can be stored given that deck location.

Table 2. Attributes of an H_2 Baseline Vessel LH_2 tank.

Baseline LH_2 Tank Attribute	Value
Inner Vessel Material	SA 240 T304 stainless steel
Inner Vessel Thickness[1] (mm)	11
Inner Vessel Diameter (m)	2.7
Inner Vessel Length (m)	8.6
Outer Jacket Material	SA 36 carbon steel
Outer Jacket Thickness (mm)	12.7
Outer Jacket Diameter (m)	2.9
Outer Jacket Length (m)	9.2
Gap Between Inner Vessel and Outer Jacket (mm)	100
Inner Vessel Water Volume (m^3)	45.5
Empty Tank Weight (kg)	17230
Tank Weight When 100% Full of LH_2 (kg)	20450
Stored LH_2 (100% full) (kg)	3220
Consumable LH_2 Per Regulations (64 – 5%) (kg)	2061-161 = 1900
Maximum Allowable Working Pressure (bar)	10
Insulation[2]	50 mm of MLI and full vacuum
Nominal evaporation rate (NER) (%/day)	0.30
Estimated Hold Time to 5 barg (days)	32
[1]Based on ASME Sec. VIII div. 1. [2]Alternating layers of low emissivity aluminum foil and glass fiber paper. MLI stands for Multi Layer Insulation.	

Each LH_2 tank provides 45.5 m^3 of Inner Vessel "water volume" (100% fill volume) for storing LH_2, giving a total of 91 m^3 for the two LH_2 tanks in total. With the water volume filled, each tank stores 3220 kg of LH_2, for a total of 6440 kg. As discussed previously, we base all volume comparisons for our study of weight, multiplicity, and shape on tank water volume (100% filled). We do report vessel range based on the consumable volume, to be conservative and to recognize the current regulatory limitations on the loading limits and minimum reserve fuel levels.

Hold time is the elapsed time from a starting pressure to relief valve lift. The heat input to the vessel increases its pressure. With higher heat input, the pressure rises faster. With lower heat input, the pressure rises slower. A slow pressure rise and a high pressure relief setting will give longer hold times than higher heat input and lower pressure relief settings.

Note that the large quantities of hydrogen needed for propulsion can only be stored via LH_2 and are far outside that which could be contemplated for 700 barg gas storage. Two LH_2 tanks are required by current USCG regulations for function and safety purposes when maintenance or emergencies require fully isolating one of the LH_2 tanks. Thus, the total fuel load needed to provide power and range to the ship is equally shared between two identical LH_2 tanks mounted side by side, as shown in Figure 12.

Figure 12. 3D rendering of H_2 Baseline Vessel LH_2 fuel tanks and tank connection spaces (TCSs).

The tank connection spaces (TCSs) are ventilated or inerted enclosures that surround the hydrogen manifolding and valves associated with the liquid hydrogen tank. A TCS is not strictly required by regulations, at least for tanks installed in the weather. Rather, it is common design practice, as it makes it easier to manage regulatory requirements, such as hazardous areas and mitigating the impact of cryogenic leaks (e.g., risk of embrittlement/cracking of ship's structures). The use of a TCS also has a benefit of protecting the various equipment therein from the marine environment.

Figure 13 shows an example of LH_2 tank hardware that would typically reside in the TCS, here for a LH_2 tank located at the AC Transit Hydrogen Fueling Station located in Emeryville, CA. In addition to basic tank functions such as fill, vent, and pressure relief, the TCS might also contain a water-based heat exchanger to vaporize LH_2 to gas and heat the cold gas up to ambient temperatures as required by fuel-cell operation. The TCS could also enclose pressure regulators that reduce and limit the hydrogen pressure to that needed for fuel-cell function. The actual hardware contained within a TCS depends on the design of the hydrogen systems on the ship.

Figure 13. LH_2 tank at the AC Transition Hydrogen Fueling Station in Emeryville, CA. Photo Credit: L.E. Klebanoff.

5.1.2. Power and Propulsion System

The H_2 Baseline Vessel is powered exclusively by hydrogen, using a fuel-cell/battery-electric system connected by DC main busses. The fuel-cell system we adopted was the Ballard FCwaveTM 200 kW Fuel Cell [86], shown previously in Figure 8.

The design speed of 12 knots requires approximately 1500 kW of electrical power, including both propulsion and service (hotel) loads. To meet this requirement, ten Ballard FCwaveTM 200 kW Fuel-cell Modules are provided. Figure 14 shows the H_2 Baseline Vessel electrical system block diagram, with the fuel cells divided into two groups.

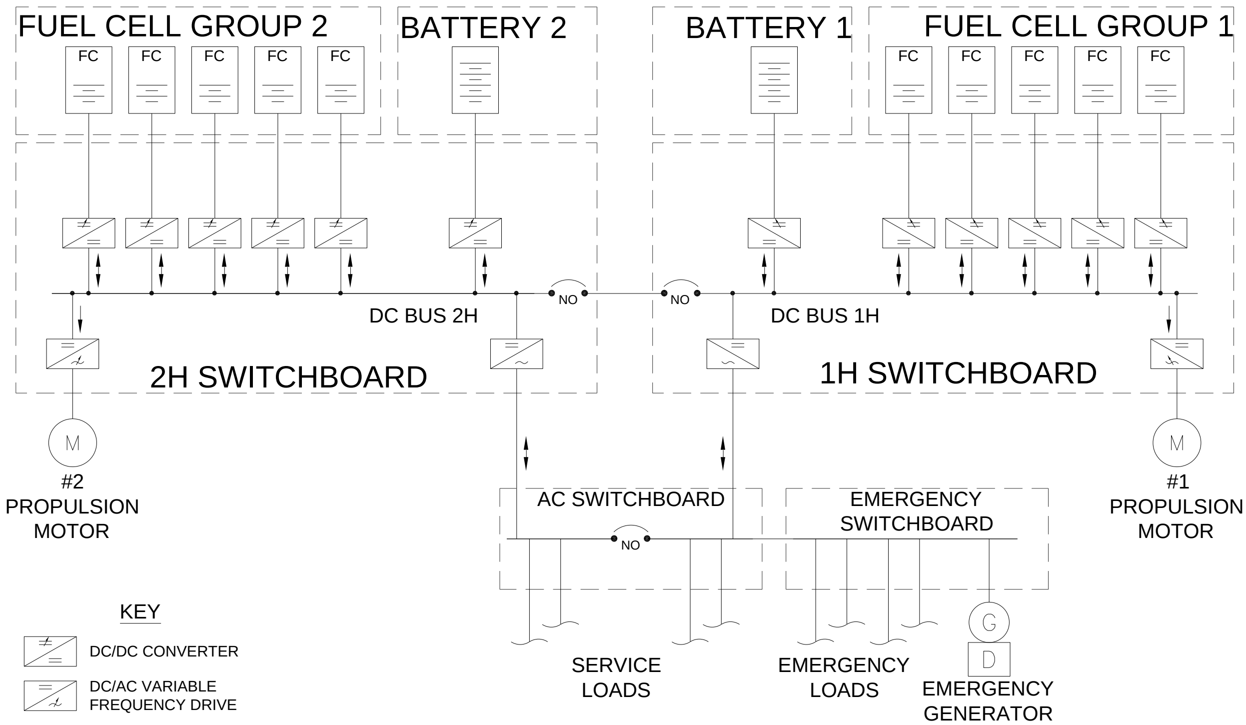

Figure 14. Electrical system architecture block diagram for H_2 Baseline Vessel.

Power input during fuel-cell startup and conversion of the fuel cell's variable output voltage are provided by a DC/DC converter, which interfaces to the main DC buses. The converters also enforce various limits related to fuel-cell safety, performance, and longevity.

Fuel cells can assume load fairly quickly. The fuel cells take on the order of seconds to switch from offline to standby and take somewhat longer to switch from standby to rated power output. However, operations such as dynamic positioning (DP) and docking can produce very fast, transient spikes in vessel propulsion electrical demand that challenge the fuel cell response time. Additionally, propulsion demand varies continuously as waves and other environmental forces act on the ship. To account for these transient loads, the electrical plant also has two lithium-ion battery banks, depicted in Figure 14 as Battery 1 and Battery 2.

Batteries can provide large amounts of power nearly instantaneously in response to load demands. With the fuel cells providing the base load power, the batteries will charge or discharge as required to manage transient loads. Additionally, the batteries can be used as a power sink for dynamic braking of large motors such as propulsion motors or winches. This eliminates the need to provide separate braking resistors, saving space and weight. In Figure 14, a battery bank is provided for each group of five fuel cells to accommodate maneuvering and environmental transients. A nominal battery capacity of 225 kWh is assumed, divided into two 113 kWh strings at 1000 VDC each. For short term (~10 seconds) transients, batteries can tolerate charge/discharge rates approximately six times their energy rating (6C), so the 225-kWh system provides over 1300 kW of short-term transient power capability, sufficient for the vessel. Over longer periods, batteries are limited to 3C, or 675 kW. Detailed station keeping requirements associated with specific DP missions could motivate alternative battery sizing, but exploration of this is beyond the scope of the present study.

DC power from the fuel cells and batteries is converted to AC for propulsion and service loads. Although some specific details of equipment configuration would be customized for integration with the fuel cells, this basic DC grid arrangement is typical for many marine propulsion systems and is not developed further here. The electrical block diagram integrating fuel cells into the ship's electrical system (Figure 14) is like that reported previously in the hydrogen vessel feasibility studies [11, 24, 25].

The H_2 Baseline Vessel has an A-Frame on the transom served by two winches below the Main Deck. A hangar and side working deck space could be served by a hydroboom for over-the-side operations, but these have not been detailed in this study. Dedicating the aft 01 Deck to LH_2 hydrogen storage prevents using that area for science activities. In a conventional diesel-powered research vessel like the Parent Vessel, this area would typically be outfitted with additional cranes and winches to enhance the vessel's scientific capabilities (see Figure 9). Further design work could develop a solution to restore some lifting capability, such as placing cranes outboard of the LH_2 tanks on the 01 deck or on dedicated pedestals. Such compromises would be inefficient from a space, weight, and cost perspective but could be implemented if deemed necessary.

5.1.3. Machinery Space Arrangements

The 1st platform of the H_2 Baseline Vessel contains some vessel features that remain unchanged from the Diesel Parent Vessel. These spaces include propulsion drives and motors, winches, control room and bow thruster which are located in separate compartments on this level and are assumed to be unaffected by the use of hydrogen fuel-cell technology for propulsion.

What has changed from the Parent Vessel is the Main Machinery Room as shown in Figure 15. This was split into four spaces: two Fuel Cell Rooms, a Battery Room, and additional space for auxiliary and support equipment such as fire suppression equipment, cooling pumps, heat exchangers, and miscellaneous control panels. The control room contains switchboards and machinery controls and monitoring equipment (details not shown).

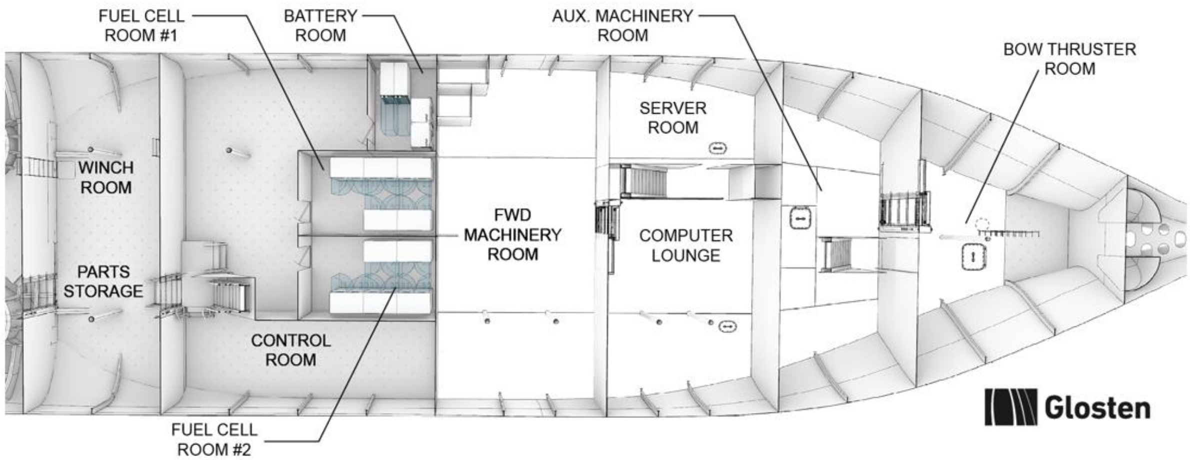

Figure 15. Cross-sectional diagram of H_2 Baseline Vessel machinery spaces.

The H_2 Baseline Vessel fuel cells are distributed amongst two separate Fuel Cell Rooms for redundancy and reliability. The fuel cell room dimensions (L × W × H) are: ~ 5 m × 3 m × 3 m. A fuel cell failure removing one of these rooms from service would significantly reduce the ship's power generation and propulsion capacity. However, power for emergency systems and low speed propulsion would be maintained. The Fuel Cell Rooms have fire detection, fire suppression, and ventilation systems (these details not shown) to meet the current and anticipated regulatory requirements. These aspects have been described in the prior hydrogen vessel feasibility studies [11, 24, 25].

Marine regulations for Fuel Cell Rooms have been developing over the past 7 years. The earliest feasibility approaches [11, 24, 25] placed Fuel Cell Racks (containing fuel cell modules), with dedicated ventilation and hydrogen detectors, into a Fuel Cell Room with its own dedicated ventilation and hydrogen detector. This approach was reviewed and approved in principle by the USCG in conjunction with those studies. More recently, some fuel cell manufacturers have been working to make their fuel cells "self-contained" such that a hydrogen leak would not have a leak path into the Fuel Cell Room. The main benefit of this second approach is that it eliminates the "hazardous" designation for the Fuel Cell Room, relieving requirements on the level of Fuel Cell Room ventilation, the type of equipment that can be installed, and access by personnel. For example, it is acceptable to access the Fuel Cell Rooms in the H_2 Baseline Vessel directly from the Main Machinery Room (Figure 15), without a need for an intermediate air lock to separate a hazardous-rated atmosphere in the Fuel Cell rooms from a safe atmosphere outside.

The Battery Room is also separated from the Main Machinery Room. However, since the battery is not critical to vessel operation, only a single (i.e., not redundant) space is provided. The

Battery Room has fire and gas detection, fire suppression, and ventilation systems in compliance with regulatory requirements. These details are not shown.

5.1.4. Mechanical Systems and Integration

The fuel cells require several auxiliary systems for their operation, as indicated in Figure 7. These include dedicated ventilation, anode and cathode exhaust vents from the FCwave cabinets to the vessel Vent Mast, and a coolant loop. Space and weight are reserved in the H_2 Baseline Vessel design for these systems, but they are held constant for the variants used in the weight, multiplicity, and shape studies, and are not developed further.

As depicted in Figure 12, each LH_2 tank for the H_2 Baseline Vessel includes an integral tank connection space (TCS) which is fully enclosed and ventilated. All the penetrations into the tank itself are in the TCS, including supply lines, vents, and relief valves, an example of which was shown in Figure 13 for a land-based LH_2 tank. Supporting equipment that handles liquid hydrogen could also be arranged in the TCS, including the heat exchanger in the pressure-build unit (PBU), which takes LH_2 and coverts it to gas to pressurize the vapor space in the LH_2 tank to drive pressurized dispensing. Also, the TCS could, depending on the design, house the heat exchanger for LH_2 vaporization and heating the gas to room temperature as required by the fuel cells. In this case, a master gas valve in the TCS allows gaseous hydrogen from the vaporizer to flow down into the vessel to a sealed gas supply enclosure near the Fuel Cell Room. Inside are block and bleed valves as well as a nitrogen supply for maintenance. From there hydrogen is supplied to the fuel cells. The TCSs shown in Figure 12 are sized to contain these functionalities, although these functionalities were not developed in detail for this study.

All hydrogen piping within the vessel will either be double walled or routed inside a dedicated ventilation duct, as was specified in the prior feasibility studies [11, 24, 25]. The final feature is the fuel bunkering station, that allows a LH_2 refueling trailer to transfer LH_2 to nearly empty vessel LH_2 tanks. The fuel bunkering station (not detailed in this study) would be a dedicated area that includes hose connections, valving, and pressure reliefs. Regulations around LH_2 bunkering are still under development and may differ from LNG bunkering, so the bunker station is assumed to be on the open deck rather than in an enclosed space.

In the prior feasibility studies [11, 24, 25], much attention was paid to managing the “hazardous zones” onboard the vessel. The use of flammable hydrogen fuel results in several hazardous areas on the vessel that must be carefully considered in the design, usually issuing from Vent Masts, hydrogen tank connections, bunkering stations, and other vessel locations. The purpose of these hazardous areas is to ensure that exposed wiring and other ignition risks are kept out of these areas, and also, that critical air intakes do not draw air from these zones. Since our focus is on understanding the influence of conceivable LH_2 tank designs (weight, multiplicity, shape) on maximizing the amount of LH_2 stored, and not on designing a vessel compliant with prevailing regulations, we have not fully defined the placement of hazardous zones in our designs. For simplicity, we consider hazardous zones are notionally co-located at the top of the Vent Mast for the H_2 Baseline Vessel. Additional refinement of the various safe and hazardous zones would be required in a more detailed design effort to ensure regulatory acceptance.

5.1.5. LH_2 Tank Weight Study

Weight is a critical design aspect for ships and a major variable in the "design spiral" [25] involving size, propulsion power, and range. At the highest level, a vessel must be able to float. But assuming vessel buoyancy, vessel weight increases the draft of the vessel. An increased draft increases the water resistance to vessel motion and therefore the fuel energy it takes to move the vessel at a given speed, thereby affecting range.

Closely related to weight is the overall VCG of the vessel, which plays a major role in ship stability. Large weights, located high on the vessel, are scrutinized in vessel design. The heavy LH_2 tanks located relatively high in the H_2 Baseline Vessel required the addition of permanent ballast so that the VCG of the H_2 Baseline Vessel was acceptable. The low weight of the LH_2 fuel itself helps mitigate the amount of permanent ballast required. Since the inclusion of permanent ballast is inefficient from the perspective of both capital and operating costs, we investigated how much benefit could arise from a reduction in LH_2 tank weights due to improved (but currently unavailable) tank technology.

Our approach in the Weight Study was to make no changes in the H_2 Baseline Vessel physical structure at all, except for the weight of the LH_2 tanks. Thus, no redesign of the ship's systems was needed, and the weight study took the form of a parametric model study using a realistic research vessel design.

Two tank weight reductions were considered. First, a 50% reduction in Inner Vessel weight was assessed, a case we call the "Inner Vessel Reduction Study." This tank weight reduction approach is captured notionally in Figure 2. So, instead of an empty LH_2 tank weight of 17230 kg used in the H_2 Baseline Vessel (Table 2), we adopted a LH_2 tank mass of 13618 kg by reducing the Inner Vessel mass by half. This reduction is not currently available using today's manufacturing methods but could conceivably be produced using "pressure strengthening" in tank manufacturing, which is a common practice for LNG vessels, but has not yet been applied to LH_2 tanks due to concerns with respect to the remaining ductility of the vessel after the pressure strengthening process.

Cryogenic pressure vessels are manufactured from high ductility material which deforms greatly without fracture. This material is needed to accommodate the normal shift in material properties at low temperature into increasingly brittle behavior. Liquid hydrogen is much colder than other common cryogens and demands a commensurately higher level of ductility. The pressure strengthening processes developed for pressure vessel design standards including the ASME code recognize the high level of available ductility and allow for vessels to be pressure tested to a level that permanently plastically deforms the vessel wall. This reduces the generous ductility but preserves enough for the application while it strengthens the material. This has a net effect of nearly doubling the allowable stress of the material and in turn the required thickness is reduced by half. Studies on the remaining ductility have not been focused on assessing fit for purpose with liquid hydrogen temperatures. Additional work must be done to affirm that the material is sufficiently ductile after the process to tolerate 20 K service.

For this first Inner Vessel Reduction scenario, the applicable LH_2 tank attributes are listed in Table 3, which gives the attributes for one of the two identical LH_2 tanks used in the Inner Vessel Reduction Study.

Table 3. Attributes of an LH_2 tank for the Inner Vessel Reduction Study.

Inner Vessel Reduction Study Attribute	Value
Inner Vessel Material	SA 240 T304 stainless steel
Inner Vessel Thickness[1] (mm)	5.5
Inner Vessel Diameter (m)	2.7
Inner Vessel Length (m)	8.6
Outer Jacket Material	SA 36 carbon steel
Outer Jacket Thickness (mm)	12.7
Outer Jacket Diameter (m)	2.9
Outer Jacket Length (m)	9.2
Gap Between Inner Vessel and Outer Jacket (mm)	105.5
Inner Vessel Water Volume (m^3)	45.5
Empty Tank Weight[2] (kg)	13618
Tank Weight When 100% Full of LH_2 (kg)	16838
Stored LH_2 (100% full) (kg)	3220
Consumable LH_2 Per Current Regulations (64 – 5%) (kg)	2061 – 161 = 1900
Maximum Allowable Working Pressure (barg)	10
Insulation[3]	50 mm of MLI and full vacuum
Nominal evaporation rate (NER) (%/day)	0.37
Estimated Hold Time to 5 barg (days)	28

[1]Based on ASME Sec. VIII div. 1, assuming an approved pressure strengthening process.
[2]Inner vessel weight reduction of 3612 kg.
[3]Alternating layers of low emissivity aluminum foil and glass fiber paper.

Note the reduction in the Inner Vessel thickness (5.5 mm) compared to that of the H_2 Baseline Vessel tank (11 mm) shown in Table 2, and the concomitant increase in the gap between the Inner Vessel and the Outer Jacket.

The second weight reduction was to assume zero LH_2 tank weight. This asymptotic calculational scenario bounds the question of what vessel performance benefits could possibly arise due to LH_2 tank weight minimization (in this second case to zero). In this case, with zero tank weight, the only weights to be considered are that of the LH_2 fuel itself, along with the piping and appurtenances which would necessarily be connected to any tank.

For both weight reduction scenarios, weight and stability calculations where performed, both for the vessel fully fueled and for selected points on a voyage where the LH_2 fuel is being steadily used. We also calculated the required propulsion power for each weight reduction scenario and compared to the H_2 Baseline Vessel.

The first task of our Weight Study was to assess the contribution of the LH_2 tank weight to the overall ship weight for the H_2 Baseline Vessel, as this would be an early indicator for the sensitivity of the ship to proposed reductions in LH_2 tank weight. For the H_2 Baseline Vessel (see Table 2), the total LH_2 empty tankage weight is 2 x 17230 kg = 34460 kg, which can be compared with the total weight of the H_2 Baseline Vessel (including LH_2 tanks and fuel) of 1331 MT (1.33 x 10^6 kg). Thus, the percentage of the overall vessel weight due to LH_2 tankage is 2.6%. Thus, we see that the weight of the LH_2 tanks constitutes a small, but not negligible, contributor to overall vessel weight.

Before we can assess the influence on vessel characteristics of LH_2 tank weight reduction, we need to account for cascading effects of changing LH_2 tank weight on the overall ship weight. Like any complex engineered system, a marine vessel is highly integrated, with changes in one ship characteristic affecting others. For example, as discussed previously, the H_2 Baseline Vessel carries permanent ballast to achieve adequate stability. Reducing the LH_2 tank weight up on the 01 Deck lowers the vessel's VCG, which allows a cascading weight savings because less permanent ballast is required to meet stability requirements. Thus, for a marine vessel with tankage above the overall vessel VCG, the positive effects of reducing LH_2 tank weight can be amplified. Our parametric weight study, and the results we present below, takes this cascading effect of LH_2 tank weight changes into account.

At full load conditions including variable loads like fuel, water, and people, our parametric model predicts that for the Inner Vessel Reduction case, the total vessel weight is reduced from 1331 MT of the H_2 Baseline Vessel to 1290 MT for this weight study. This corresponds to a 3.1% reduction in the total ship weight. For the second weight study (zero tank weight), the total ship weight is reduced further to 1236 MT. This represents a total weight savings of 7.1% as an asymptotic value for the possible benefits from LH_2 tank weight reduction in this research vessel example. These vessel weight reductions, while modest, would result in noticeable reductions of required propulsion power from the 1500 kW of the H_2 Baseline Vessel, down 1.4% for the Inner Vessel Reduction Study, and 4.3% for the asymptotic limit for LH_2 tank weight reduction. For a 10-knot cruising speed in calm water, this translates to a range improvement of 12 NM and 36 NM, respectively, for the Inner Vessel reduction and zero tank mass cases.

These weight reduction results need some context from the naval architecture perspective. The question arises: would a ~ 3 – 7% reduction in vessel weight (displacement) be significant enough that it would have major spiraling/cascading design impacts resulting in a different vessel length, hullform, lower-power thrusters, or a reduced number of fuel cells? The answer is "no," but that does not mean "don't pursue weight reductions." For some context, at this conceptual phase of design, a ship designer would typically be carrying a 10 – 15% design margin in the vessel weight estimate. So, the possible weight savings that could possibly come from LH_2 tank improvements are within these pre-existing margins, but are not, in and of themselves, negligible. Rather we conclude that the maritime application, while benefitting from a reduced LH_2 tank weight, is not a strong motivator the LH_2 tank weight improvements, in contrast to aerospace applications of LH_2.

Having concluded that, should one wish to pursue LH_2 tank weight reduction R&D, research possibilities include new cryogenic materials that are fit for 20 K service or methods for pressure strengthening available materials. The indirect impact of step changes in thermal insulation performance can drive pressure requirements lower which in turn reduces pressure vessel thickness. Additionally, the vacuum jacket weight could be reduced by insulation systems that do not require vacuum or by deploying lighter weight materials for jacket design.

5.2. LH_2 Tank Multiplicity Study

There are as of today no fully agreed-to regulatory schemes for using hydrogen on a vessel. Regulations are still in development, so the baseline regulatory approach has been to use the IGF code, which was written for LNG. The IGF code does not forbid placing cryogenic tanks below deck. As a result, some questions naturally arise: assuming we are not constrained by the current commercial LH_2 tank technology for which much smaller LH_2 tanks suffer poor thermal performance, would there be a naval architecture benefit, relative to the H_2 Baseline Vessel, for putting more numerous smaller (but still cylindrical) tanks in the hull compared to out in the weather? Could more LH_2 be stored by taking advantage of available space on the vessel? If one could place LH_2 tanks with multiplicity in the hull, what would be the impact on vessel stability, fuel storage, deck space or other performance criteria?

To answer these questions, we want to study multiplicity in isolation from any other influence. Thus, we assume the same shape LH_2 tank as used in the H_2 Baseline Vessel (i.e., cylindrical), but assume conceivable (but still credible) performance improvements for the multiplicity tanks that would allow them to be placed in greater number anywhere on the vessel, replacing the two large LH_2 tanks of the H_2 Baseline Vessel example. As discussed in the introduction, prior study of smaller LH_2 tanks has been driven by the fuel-cell car [52 – 59] and HALE applications [60 – 62], involving 8 – 10 kg and ~ 25 – 400 kg of stored hydrogen, respectively. The hypersonic studies [36 - 44] have taken a similar approach to the one taken here, by working to fit LH_2 tanks in the available space on the hypersonic vehicle. However, we are unaware of any prior study that has taken the comparative approach we take, comparing hydrogen storage in large LH_2 tanks to its equivalent in a multiple array of smaller tanks.

The design of the LH_2 tank for the multiplicity study needs to support the aims of the study, namely, to examine what quantifiable benefits to future hydrogen vessels might accrue if one could store LH_2 with multiplicity, and what R&D progress in LH_2 tank technology would be required to achieve it. Potential vessel benefits include, but are not limited to, improved deck space and arrangements, working areas, more flexibility with vessel arrangements, increased fuel volume and range, as well as improved vessel stability.

We follow the study philosophy described previously. We seek to understand in an asymptotic way how deployments of LH_2 tanks with multiplicity might positively affect the quantity of LH_2

stored on a hybrid vessel, as suggested in Figure 2. In doing so, we reduce to the absolute minimum current vessel regulatory constraints that would otherwise restrict our asymptotic exploration of the implementation of LH_2 tank technology on a hydrogen fuel-cell vessel. Thus, our investigation relaxes (in many cases completely) requirements that would be expected to be placed on vessel design by international (IMO) or domestic (USCG) vessel regulations. We subsequently examine the current regulatory and tank manufacturing limitations to better understand how aggressive the asymptotic study assumptions are and how challenging the recommended R&D directions will be.

The Multiplicity Study required two broad choices regarding:

1. The LH_2 tank performance that enables deployment with multiplicity, and
2. What ship spaces are suitable for multiple tank installations.

The LH_2 tank performance that was specified involved engineered insulation system beyond that achievable using today's manufacturing capabilities. For this study we assumed LH_2 tank sizes commensurate to commercially available Department of Transportation (DOT) 4L code (49CFR178.57) cylinders for liquified gases, which are manufactured in the thousands per year. However, we assume for this study a level of performance not yet achievable in such small tanks. Figure 16 shows a picture of a "small" LH_2 tank manufactured by Chart.

Figure 16. Small commercial LH_2 tank manufactured by Chart with hydrogen storage capacity of 35 kg. Photo Credit: Tom Drube.

Our choices for the Multiplicity LH_2 tanks were inspired by this commercially available LH_2 tank. There are many possible choices for the assumed attributes of the small high-performing LH_2 tanks for the Multiplicity Study. For simplicity, we decided to use the basic advanced tank design employing typical construction but allowing for the length to be increased as needed while slightly increasing the space between the Inner Vessel and the Outer Jacket. Tank arrangements within the ship were developed using the dimensions of the Outer Jacket. A reasonable combination of Inner Vessel and Outer Jacket diameters commensurate to commercially available designs were chosen for the study.

Our Multiplicity Study does not initially consider associated hardware such as TCSs, piping, tank supporting structure, ventilation requirements that would all go into a full naval architecture assessment of the deployment of LH_2 tanks with multiplicity. These considerations would degrade the LH_2 fuel storage capacity in any multiplicity design. Rather, we initially excluded such items to identify if any benefit at all would accrue to tank multiplicity in the most optimistic of cases.

As for which ship spaces are suitable for the deployment of LH_2 tanks, we again relax regulatory constraints on where such tanks could be placed. For this study, we placed the multitude of LH_2 tanks in the compartments in the bottom of the ship that were formerly devoted to storage of diesel fuel. This is the largest volume inside the H_2 Baseline Vessel that is available, and thus is the primary candidate for locating a multiple-tank array. While existing LNG regulations and draft LH_2 regulations require tanks be arranged with significant setbacks from all sides and the bottom of the vessel to minimize the risk of damage to the tanks in accidents such as collisions or groundings, alternative approaches can be allowed based on a risk assessment. Here we relax this significant requirement but will revisit it later for context. Thus, the multiplicity design represents an extreme limit/asymptote of the benefits that could be attained by arraying many small tanks belowdecks.

To store the maximal amount of LH_2 fuel in the double-bottom area of the vessel, tradeoffs were made to clear interferences. Modifications from the H_2 Baseline Vessel for the Multiplicity Study include elimination of variable ballast tanks, relocation of potable water and wastewater tanks, and the loss of the transducer void. The latter would have a negative impact on the scientific mission capabilities of the vessel, but an alternative transducer arrangement with decreased performance could be designed if necessary. Alternative options were considered, such as integrating small tanks into small unused spaces between and around equipment in other compartments. These options were determined to be impractical during preliminary inspection and would in any event not significantly increase the fuel storage in a LH_2 tank deployment with multiplicity.

5.2.1. Tank Multiplicity Design Variant 1

Two multiple-tank array design concepts were investigated. The first attempted to fill the designated double-bottom fuel storage compartments as much as practicable while still maintaining reasonable limits on the minimum tank size and the number of separate tanks. Figure 17 shows the result of that multitudinous placement of LH_2 tanks, which we call Multiplicity Design Variant 1.

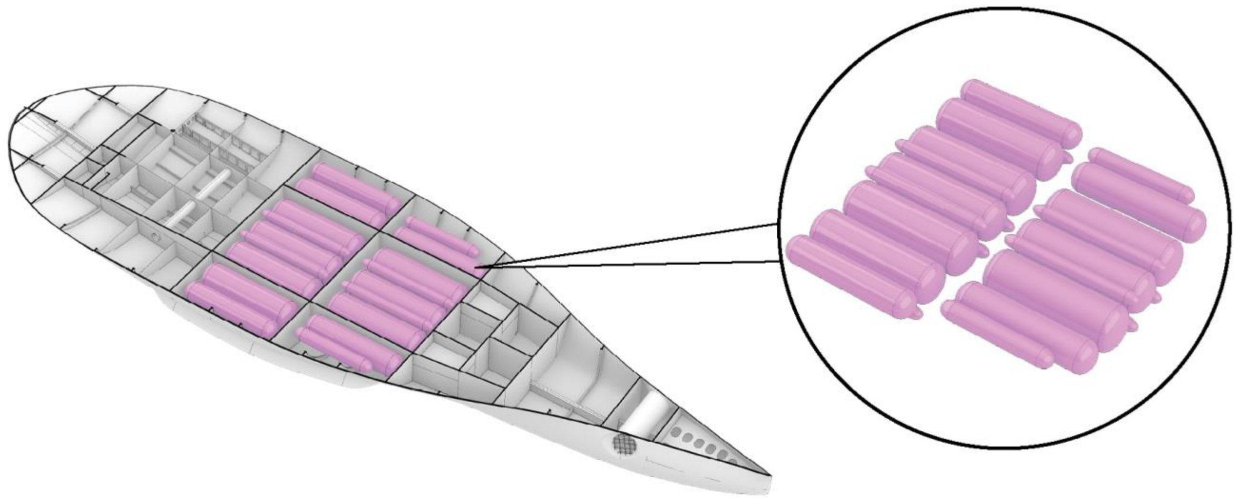

Figure 17. Cross-sectional rendering of the LH_2 Tank Multiplicity Design Variant 1.

Six sizes of LH_2 tanks were chosen to maximally fill the space at the bottom of the vessel. Larger tanks were chosen to fit comfortably in the spaces allotted; the smaller tanks were chosen to fill residual space between the large tanks and the ship's hull or other structural members. Requirements pertaining to tank connection spaces, ventilation, inerting, and similar integration requirements were not considered at this preliminary/conceptual stage.

These tanks have the following characteristics, shown in Table 4. The Multiplicity Study Design Variant 1 adopted ten Tank 1's, two Tank 2's, two Tank 3's, two Tank 4's, two Tank 5's, and six Tank 6's.

The tanks shown in Figure 17, with attributes listed in Table 4, are a significant challenge with current technology, but represent a credible stretch in future LH_2 tank technology towards smaller sizes. For example, we consider and use the tanks indicated in Table 4 despite their hold time, calculated assuming existing insulation properties, being well below the currently required 15-day hold time. Nonetheless, our use of them assumes that in the future, improvements in insulation and the thermal properties of all aspects of the tank construction would allow the tanks to be used in the manner contemplated in Figure 17.

Table 4. Characteristics of LH_2 Tanks Used in the Multiplicity Design Variant 1.

Multiplicity Design Variant 1 Attribute	Tank 1	Tank 2	Tank 3	Tank 4	Tank 5	Tank 6
Number of Tanks Used	10	2	2	2	2	6
Inner Vessel Material	SA 240 T304 stainless steel					
Inner Vessel Thickness (mm)	1.7	2.3	3.7	4.2	5.4	6.0
Inner Vessel Diameter (m)	0.403	0.560	0.890	1.02	1.30	1.47
Inner Vessel Length (m)	5.3	4.2	5.3	5.3	5.3	5.3
Outer Jacket Material	A 240 T304 stainless steel					
Outer Jacket Thickness (mm)	5					
Outer Jacket Diameter (m)	0.5	0.7	1.1	1.25	1.6	1.8
Outer Jacket Length (m)	5.5	4.5	5.5	5.5	5.5	5.5
Gap Between Inner Vessel and Outer Jacket (mm)	44	62	98	111	140	157
Inner Vessel Water Volume (m^3)	0.65	1.02	3.12	4.04	6.61	8.37
Empty Tank Weight (kg)	920	1017	1959	2229	3352	3911
Tank Weight When 100% Full of LH_2 (kg)	966	1089	2181	2515	3820	4505
Stored LH_2 (100% full) (kg)	46	72	222	286	468	593
Consumable LH_2 Per Current Regulations (64 – 5%) (kg)	27	42	131	169	276	350
Maximum Allowable Working Pressure (barg)	10					
Insulation	25 mm of MLI and full vacuum					
Nominal evaporation rate (NER) (%/day)	4.49	2.66	1.25	1.06	0.79	0.70
Estimated Hold Time to 10 barg (days)	1.80	3.60	7.65	9.00	12.20	13.95
Aggregate 100%-fill LH_2 Mass (kg)	6114					
Aggregate 100% Full Tankage Mass (kg)	55900					
Hold Time (based on shortest hold time) (days)	1.80					

Note that as the LH_2 tank design diameter increases, so does the required thickness of the vessel or jacket material. High surface-to-volume ratios present in long and skinny tanks drive higher heat inputs. This in turn drives lower hold times.

The LH_2 tank Multiplicity Design Variant 1 (Figure 17) was evaluated for benefits compared to the H_2 Baseline Vessel. The total amount of stored LH_2 in Variant 1 (100% filled) was found to be 6113 kg. Compared to the H_2 Baseline Vessel hydrogen storage (6440 kg, 100% filled), this corresponds to a 5% reduction in stored LH_2. This is an asymptotic assessment of multiplicity since no space is allocated for associated hardware such as TCSs. If increases in the quantity of stored hydrogen had been found, the Multiplicity Study would have been refined for more accuracy. For Multiplicity Variant 1, no further analysis was conducted.

5.2.2. Tank Multiplicity Design Variant 2

Review of the Multiplicity Design Variant 1 raised the question of whether the principle behind this investigation needed to be extended further. Multiplicity Variant 1 still had some concession towards conventional practice – maintain the biggest sizes possible – and that left un-filled interstitial space around the tank array. What if future insulation technology was so effective that the tanks could be reduced in size even further to the minimum size that could be practically manufactured while still providing some insulation allowance? This would allow the multiplicity tanks to be placed even closer together. This idea was investigated by arranging a matrix of 24" outside diameter (O.D.) LH_2 tanks in the same compartments used in Multiplicity Variant 1. Supporting structural arrangements were not examined, but it is assumed that these tanks could be supported at the ends with limited need for support in the middle of the tanks. The tanks used in the Multiplicity Design Variant 2 study are described in Table 5. Design Variant 2 used 4 Tank 1's and 74 Tank 2's.

Table 5. Characteristics of Tanks Used in the Multiplicity Study, Design Variant 2.

Multiplicity Design Variant 2 Attribute	Tank 1	Tank 2
Number of Tanks Used	4	74
Inner Vessel Material	SA 240 T304 stainless steel	
Inner Vessel Thickness (mm)	2.2	2.2
Inner Vessel Diameter (m)	0.533	0.533
Inner Vessel Length (m)	2.93	5.08
Outer Jacket Material	A 240 T304 stainless steel	
Outer Jacket Thickness (mm)	3.5	5.0
Outer Jacket Diameter (m)	0.61	0.61
Outer Jacket Length (m)	3.15	5.42
Gap Between Inner Vessel and Outer Jacket (mm)	38	38
Inner Vessel Water Volume (m^3)	0.62	1.09
Empty Tank Weight (kg)	740	1142
Tank Weight When 100% Full of LH_2 (kg)	784	1219
Stored LH_2 (100% full) (kg)	44	77
Consumable LH_2 Per Current Regulations (64 – 5%) (kg)	26	45
Maximum Allowable Working Pressure (barg)	10	
Insulation	25 mm of MLI and full vacuum	
Nominal evaporation rate (NER) (%/day)	3.7	2.8
Estimated Hold Time to 10 barg (days)	2.25	3.2
Aggregate 100%-fill LH_2 Mass (kg)	5874	
Aggregate 100% Full Tankage Mass (kg)	93342	
Hold Time (based on shortest holdtime) (days)	2.25	

Figure 18 shows the result of that even more multitudinous placement of LH_2 tanks.

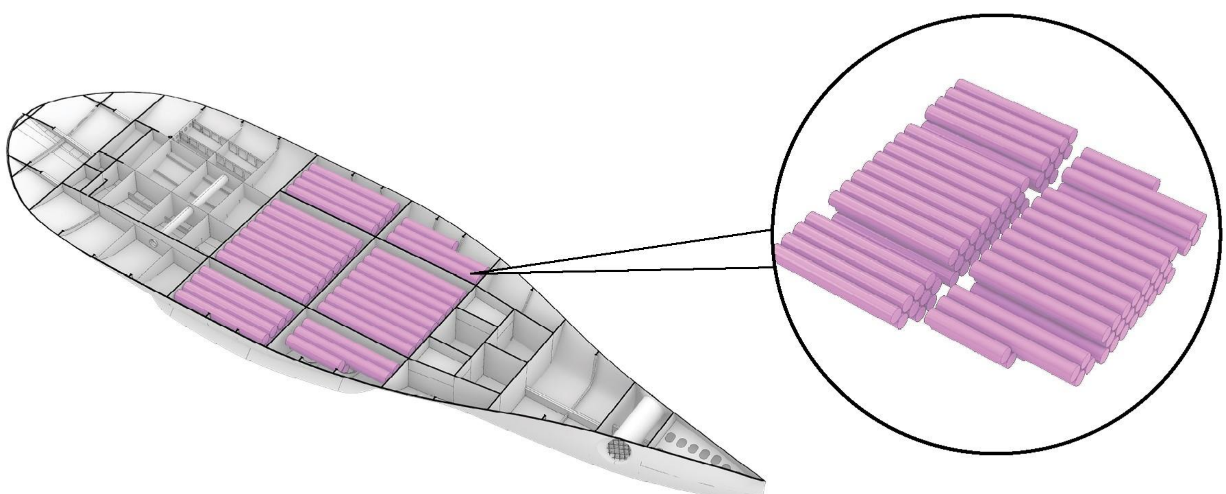

Figure 18. Cross-sectional rendering of the LH_2 Tank Multiplicity Design Variant 2.

The Multiplicity Variant 2 was evaluated similarly to Multiplicity Variant 1. The total estimated hydrogen fuel storage (100% tank fill) for Variant 2 is 5874 kg, which is 4% less than that of Multiplicity Variant 1 (6113 kg), and 8.8% less than the H_2 Baseline Vessel (6440 kg). The Multiplicity Variant 2 tanks are generally smaller than those used in Multiplicity Variant 1, which would favorably act to reduce void space between the tanks and improve the stored LH_2 volume. However, there were only two types of tanks considered for Multiplicity Variant 2, and as a result, Multiplicity Variant 2 was found to be geometrically less efficient at filling the irregular hull space.

Compared to the H_2 Baseline Vessel, the fuel storage volume of the tank multiplicity variants was reduced by ~ 5 - 9%. This is a significant drop in volume from the H_2 Baseline Vessel and would likely be deemed problematic despite other benefits coming from the tank multiplicity design, such as recovering unrestricted use of the 01 deck for mission equipment. Also, such a deployment of LH_2 in the double bottom relaxes currently applied regulatory restrictions ensuring safety of the ship and personnel. While such regulations are still in development, the safety concerns remain and would need to be addressed and mitigated.

This was also an optimistic assessment of the Multiplicity deployment of LH_2 tanks, since TCSs and other needed hardware were not included. These additional features would lower the LH_2 capacity of the multiplicity tank arrays shown in Figure 17 and Figure 18 even further. There are also practical difficulties associated with the multiplicity arrangement of LH_2 tanks. When multiple cryogenic tanks are networked through piping systems, that chances for hydrogen leaks go up. Additionally, the inherently different thermal performances will tend to drive hydrogen from low pressure tanks to high pressure tanks. During this forced pressure balance even more heat is absorbed by the hydrogen in the less efficient piping systems. Methods to isolate each tank and selectively withdraw from them based on pressure are achievable but introduce increased complexity and more connections. Additionally, access to any one tank may be very difficult and servicing the tanks a challenge. It is clear from the Multiplicity Study that given the choice of storing LH_2 as two large tanks out in the weather (Baseline Vessel), or with multiplicity in the bottom of the hull (Multiplicity Design Variants 1 and 2), the clear, but perhaps counterintuitive, choice is for the H_2 Baseline Vessel implementation.

We conclude that given the reduced fuel storage, practical difficulties associated with managing many LH_2 tanks, and the likely regulatory challenge with this storage location, deploying LH_2 tanks with multiplicity does not look like a promising technical direction, and would not motivate conducting the needed R&D that would drive the technology into smaller LH_2 tanks with high length-to-width aspect ratios, at least for the maritime research vessel application.

5.2.3. Tank Multiplicity R&D Recommendations

Although our study suggests that the H_2 Baseline Vessel, with two large LH_2 tanks out in the weather, affords a greater amount of stored LH_2 than the Multiplicity Variants, it could be that for some other reason, storing LH_2 in the hull could be desirable. In addition, a non-maritime application could conceivably benefit from having a multitude of smaller LH_2 tanks, with attributes beyond current LH_2 tank technology. The main R&D challenge will be to improve the performance of multiple small tanks to achieve useful hold times. A breakthrough in thermal insulation performance is needed for this. Such a breakthrough would need to be followed by improving the networking of so many tanks for filling, withdrawing and isolation efficiency. However, using such a complex system to feed cryogenic pumps may be nearly impossible to achieve. A breakthrough in insulation performance of the order of 1/10 the current conductivity and a practical means to pump from such tanks without undermining thermal performance would be needed.

5.3. LH_2 Tank Shape Study

The final step in our study, away from the H_2 Baseline Vessel of Figure 10, is to examine if there is a benefit to non-traditional shapes in maritime LH_2 tank deployment. That is, in the application of marine vessels, is there is a benefit to the vessel operation if LH_2 can be stored in tanks with non-cylindrical or non-spherical shapes that better match the LH_2 tank shape to the vessel?

Spherical or cylindrical shapes have traditionally been used to store LH_2 in stationary (land-based) applications, or for very large quantities of LH_2. As discussed previously for Figure 1, such tanks are double walled with an Inner Vessel holding the cryogenic liquid surrounded by an engineered insulation system and an Outer Jacket. Minimizing the heat leak Q usually involves minimizing the surface-to-volume ratio of both the Inner Vessel and Outer Jacket. As a result, LH_2 tanks have historically been spherical (lowest surface/volume ratio) or cylindrical (next lowest). The cylindrical shape is the easier to manufacture and transport, so as a result, most LH_2 commercial tanks are cylindrical. Though not quite as insulating as spheres, cylindrical tanks also more readily fit into the physical arrangement of a modestly sized maritime vessel. Cylindrical tanks also perform well as pressure vessels, which is required as the hydrogen gas pressure starts to build as the LH_2 charge starts to evaporate. Thus, the Inner Vessel has to be able to sustain pressure buildup to the relief valve set point, typically set at ~ 10 bar in most commercial LH_2 tanks.

However, when the space available for the storage has become significantly limited (e.g., aerospace, hypersonic flight), nonstandard shapes for LH_2 tanks have been investigated, such as the “bilobe” or “double bubble” shape [40], as well as semi-conformal tanks with flat or arbitrarily curved surfaces [41]. Here we consider improvement of maritime LH_2 tanks for shape, where we examine, taking a “clean sheet” approach, what tank shape would be most advantageous for use on a hydrogen vessel. As with the Multiplicity Study, our purpose is two-fold. First, we seek to understand if an improved hydrogen storage capacity is enabled by an modified shape for the LH_2 tankage. Second, by analyzing the important technical factors governing tank shape, we seek to identify what would be the most promising R&D routes to maritime LH_2 tanks with improved shaped.

Some specific questions we aim to answer are: Assuming we are not constrained by the current commercial technology on LH_2 tanks, would there be a naval architecture benefit, relative to the H_2 Baseline Vessel, for having an improved shaped LH_2 tank? Could more LH_2 be stored if the LH_2 tanks conformed to shapes (e.g., the hull) found on the vessel? What would be the effect of improved tank shape on the vessel stability, range, deck space or vessel considerations? Because we want to study tank shape as a step beyond the traditional LH_2 storage as embodied in the H_2 Baseline Vessel, we will consider relatively few LH_2 tanks shaped to take the greatest advantage of the prevailing shapes on the vessel. The result will be a pair-wise comparison with the H_2 Baseline Vessel.

5.3.1. LH_2 Tank Design for the Shape Study

We follow the study philosophy described previously. We seek to understand in a (highly optimistic) asymptotic way how deployment of better-shaped LH_2 tanks might positively affect maritime hydrogen storage and vessel attributes. We will subsequently examine the current regulatory and manufacturing limitations for context.

The shape study required two broad choices regarding:

1. What ship spaces are suitable for the shape study?
2. What LH_2 tank shape (prismatic, bilobe, or other) enables increased storage of liquid hydrogen on this particular vessel?

Because we are interested in the effect of shape only, and not multiplicity, we consider a relatively few tanks, which means these tanks would hold much more hydrogen per tank than those assumed for the Multiplicity Study. Thus, only large spaces on the hydrogen vessel can be considered. This led us to choose, as was the case with the Multiplicity Study, the space in the lower parts of the ship that were devoted to diesel fuel in the Diesel Parent Vessel as the location for assessing LH_2 tank shape improvement. Our hope is that larger shape-improved tanks lead to a more efficient use of the below-deck space, and thus more stored hydrogen fuel.

The hull space for the shape study is shown in Figure 19.

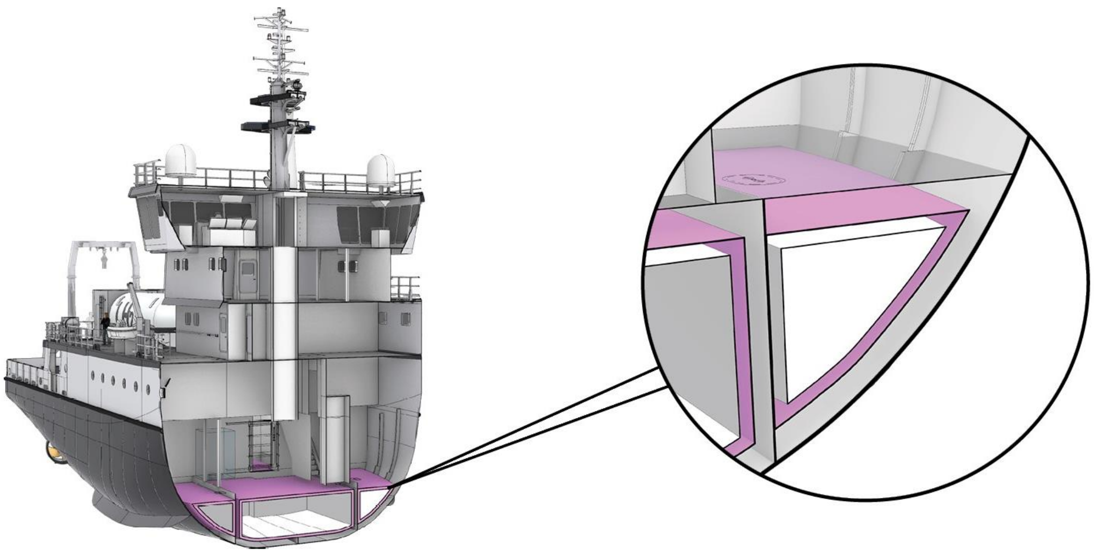

Figure 19. Hull space adopted for the shape study, emphasizing the need to accommodate hull shape**.**

Figure 20 shows LH_2 tank shapes chosen to fill the hull space of Figure 19.

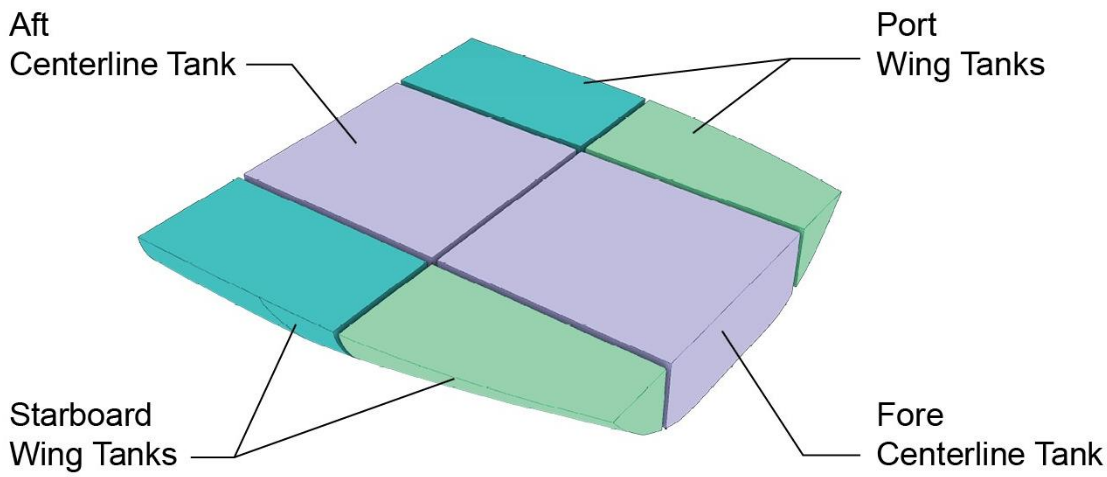

Figure 20. Prismatic tanks considered for the shape study.

Such tanks are generally termed "prismatic tanks." Prismatic tanks have more flat sides. The corners of a prismatic tank may or may not have a curved feature used to minimize local stresses. If insulated with a vacuum dependent system, the jacket may have external stress issues. Such systems demand an internal structural load bearing element to achieve its shape. The main attributes of the prismatic tanks in Figure 20 are that the side of the wing tanks follows the shape of the hull in the lower regions of the vessel, and the flat profile conforms to the available hull space, as depicted in Figure 19. Also, it's flat profile allows optimal use of the space previously used for diesel fuel. The benefit of prismatic tanks is to provide maximum volumetric efficiency while storing LH_2 fuel inside the structure of a ship in a manner similar to diesel fuel. This allows for containment of most LH_2 storage equipment outside of normal work areas while maximizing fuel load.

The LH_2 tank performance required for the shape study assumed engineered insulation and pressure accommodation well beyond that achievable using the standard practices of today. The LH_2 tank arrangements of Figure 20 were developed in 3D modeling software scaling from the previously existing space and hull shape. An estimated offset was then added to allow for an insulation system and support structure.

To level the playing field for the various tank types in this study, they were compared to each other at 100% loading, which will then be revisited given regulatory limitations on fuel loading during refueling. This revisiting is important because the benefit of improved insulation allowing low pressures like 1 barg pressure would also apply to standard tanks. Comparing the tanks at different loading limits might show inaccurate benefits to one tank style.

5.3.2. Shape Design Variant

Using the prismatic concept of Figure 20, we attempted to fill the designated double-bottom fuel storage compartments (Figure 19) as much as practicable. A total of six compartments were used to maintain necessary vessel structure and subdivision. The Outer Jacket of the tank was offset from the ship hull to allow for standard ship structural components. The Inner Vessel holding the LH_2 was then offset from the tank Outer Jacket to allow for insulation.

The prismatic tank arrangement allows for three forward tanks and three aft tanks as shown in Figure 20. These prismatic tanks have the attributes summarized in Table 6. These tanks are a significant departure from the LH_2 tanks assumed for the H_2 Baseline Vessel (Table 2), for the Weight Study (Table 3) or the Multiplicity Study (Table 4 and Table 5). Rather than principally cylindrical shapes, prismatic tank use flat walls and generally squarish volumes. This has the geometric advantage of leveraging the corners of typical areas that would be used to accommodate the storage tanks.

Table 6. Characteristics of the LH_2 Tanks used in the Shape Design Variant Study

Shape Design Variant Attribute	Centerline Tank	Wing Tank Aft	Wing Tank Fore
Number of Tanks Used	2	2	2
Inner Vessel Material[1]	A 240 T304 stainless steel		
Inner Vessel Thickness[2] (mm)	9.53	9.53	9.53
Representative Inner Vessel Length[3] (m)	4.8	4.8	4.0
Representative Inner Vessel Width[3] (m)	4.8	1.95	4.8
Representative Inner Vessel Height[3] (m)	1.8	1.5	1.2
Outer Jacket Material[4]	A36 Carbon Steel		
Outer Jacket Thickness[5] (mm)	11	11	11
Representative Outer Length[6] (m)	5.05	5.05	5.05
Representative Outer Jacket Width[6] (m)	5.05	2.20	1.75
Representative Outer Jacket Height[6] (m)	2.05	1.75	1.45
Gap Between Inner Vessel and Outer Jacket[7] (mm)	127		
Inner Vessel Water Volume (m^3)	41.4	14.0	8.6
Empty Tank Weight (kg)	15056	7839	6199
Tank Weight When 100% Full of LH_2 (kg)	17994	8833	6811
Stored LH_2 (100% full) (kg)	2938	994	612
Consumable LH_2 per Current Regulations (64 – 5%) (kg)	1733	586	361
Max. Allowable Working Pressure[8] (barg)	1		
Insulation	Would need R&D development. 25mm of MLI assumed for the analysis.		
Nominal evaporation rate (NER) (%/day)	2.7	3.9	4.9
Estimated Hold Time to 1 barg from 0.14 barg (days)	2.8	1.95	1.5
Aggregate 100%-fill LH_2 Mass (kg)	9088		
Aggregate 100% Full Tankage Mass (kg)	67276		
Hold Time (based on shortest holdtime) (days)	1.5		

[1]A ductile material with pleat or a material that will contract is required to maintain tank structure.
[2]9.5 mm is chosen for the analysis. This dimension could be thinner based on design constraints.
[3]These dimensions are reduced to accommodate the insulation space.
[4]A mild carbon steel is adequate for the Outer Jacket material in contact with the ship structure.
[5]11 mm is chosen for the design analysis. This could be thinner based on the design constraints.
[6]These representative dimensions for a monolith are used for the design analysis, but the actual shape of the tank will conform to the space available within the ship.
[7]In addition to vacuum loading and insulation space, prismatic tanks will require stays between the Outer Jacket and Inner Vessel.
[8]One barg is chosen, a refined number would be design driven based on the structural design of both the Outer Jacket and the Inner Vessel.

A particular area of concern for these prismatic tanks was the pressure rating. Such prismatic tanks, due to their large flat surfaces, would be severely challenged regarding rated pressure compared to cylindrical tanks which accommodate gas pressure stress more easily. Typically, the PRD settings for commercial cylindrical tanks is about 10 barg. Our assessment was that 10 barg would be inappropriate even for prismatic tanks that were aggressively challenging current LH_2 tank manufacturing standards. We decided for the prismatic shape study tanks to constrain the maximum operating pressure to be 1 barg. This has two major impacts on the tank design. First, insulation will need to be capable of maintaining this pressure in the tank for 15 days. This will need to be an area of major development before such a prismatic tank can be practical. Second, the low pressure of tank means the volumetric expansion of the fuel during its time in the tank is minimized. This in turn means the regulatory allowed loading level for this type of tank could be much higher than a standard tank. For our initial comparisons, we ignore the effects of loading allowance, and compare according to 100% LH_2 fill numbers. We will then revisit the effect of the current regulatory loading levels for all the H_2 Baseline, Multiplicity and Shape scenarios.

We initially evaluated the tank concept of Figure 20, where the LH_2 tanks were sized to fit in the hull, but no account was made of required hardware such as TCSs and piping. For the 100%-fill stored volumes of the LH_2 tanks, the total stored mass of H_2 in the Shape Variant is 9088 kg, compared to the total stored mass of hydrogen on the H_2 Baseline Vessel of 6440 kg. Thus, the fuel storage of the Shape Variant led to a 41% increase in the hydrogen fuel storage compared to the H_2 Baseline Vessel. This provides a significant benefit to the vessel range while also moving the fuel storage system to an area of the vessel which would otherwise be unused.

As the preliminary calculations for the prismatic tank arrangement show a significant benefit in comparison to the H_2 Baseline Vessel, further investigation and design work was pursued, as discussed below.

5.3.3. Consideration of Mechanical Systems for the Shape Variant

The preliminary prismatic tank design of Figure 20 utilized the entire inner-bottom tank area for LH_2 storage. However, the effects of adding TCSs (estimated at 11 m^3) and tunnels for tank piping are needed for a refined estimate of the stored LH_2 quantity. Estimates for the size of these components was based on the LH_2 tank for the H_2 Baseline Vessel. Both the TCSs and piping tunnels cut into the potential fuel storage area.

The ventilation required for in-hull tank connection spaces and air locks was also roughly sized to meet regulations and verify that routing the ducting is realistic. The required air flow for these spaces is 30 air changes per hour. Based on the current volume reservations for these spaces a 6-inch round duct is sufficient for supply to each tank connection space and a 4-inch round duct is required for each air lock. These are reasonable duct sizes that can be routed throughout a normal vessel, so no further ventilation work has been completed. The effects of including these hardware considerations are shown in Shape Variant arrangement of Figure 21.

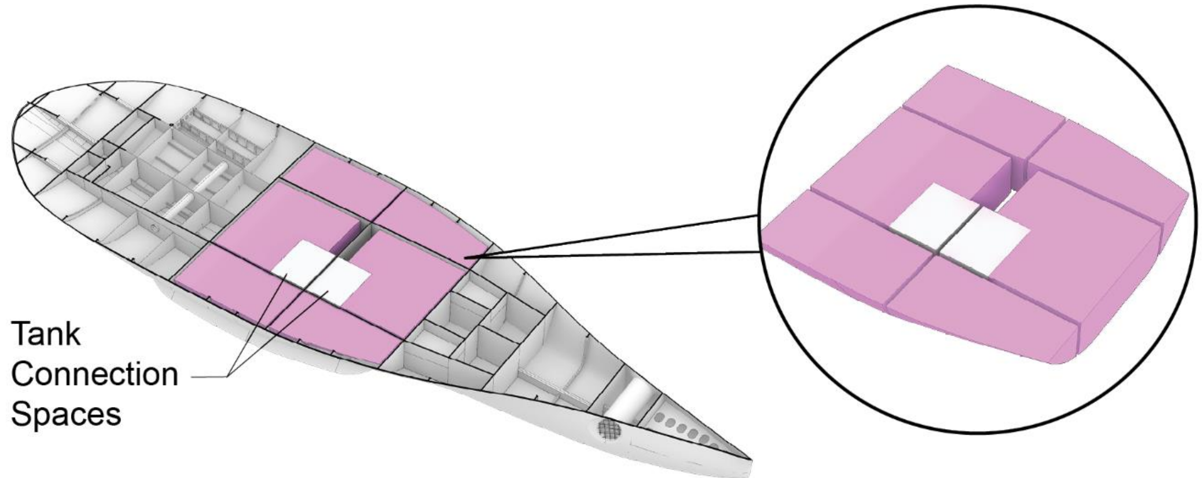

Figure 21. 3D model arrangement of the prismatic LH_2 tanks used in the shape study. White squares indicate notional tank connection spaces (TCSs). The rectangular cut outs in the fore and aft centerline tanks are to accommodate a piping tunnel that allows the Port wing tanks to connect to the TCSs.

Taken together, the effects of accommodating volumes for the TCSs, piping tunnels, and ventilation components is to reduce the Shape Variant capacity improvement over the H_2 Baseline Vessel. The reduced LH_2 fuel complement decreases to 8087 kg, which still represents a 26% increase over the H_2 Baseline Vessel (6440 kg) fuel load.

5.3.4. Tank Shape R&D Recommendations

The LH_2 tanks assumed for the shape study are not currently available using today's technology. What R&D advances would need to be made for them to function operationally as intended for a hydrogen fuel-cell vessel? The following are productive areas for future R&D:

1. Flat sided containers present a challenge when pressurized. A prismatic container would need to either be of very low-pressure bearing capacity or be so designed with curved corners and stayed walls to create a useful pressure bearing capacity.
2. Should the prismatic design be of low-pressure capacity, a pumping system would likely be needed to provide fuel pressure. Networking multiple prismatic tanks into a pumping manifold would need to be developed.
3. Anticipating a vacuum requirement, insulation systems for the flat-walled prismatic container would have similar load bearing issues as the hydrogen container. Development of load bearing insulation systems may provide a solution for the insulation jacket.
4. Presuming a prismatic system is below deck, servicing the insulation system would present challenges to overcome. Access to vacuum space and piping would need to be engineered.

5.4. Current Regulatory and Tank Manufacturing Restrictions:

These explorations of LH_2 Tank technology for Zero-emission Fuel Cell Vessels has been conducted with significant (and in some cases total) relaxation of current regulatory restrictions. In addition, our specification of LH_2 tankage is well beyond current LH_2 technology. For context, we describe some of the existing regulatory considerations and tank manufacturing limitations, both of which are subject to change in the future.

5.4.1. Current Regulatory Restrictions

The results shown for the Multiplicity and Shape Studies involved a significant relaxation of the current regulatory guidelines for using hydrogen fuel-cell technology onboard vessels. While these regulations are still being developed and could potentially be relaxed because of future science-based assessments of risk, the Multiplicity (both 1 and 2) Variants and Shape Variants need to be examined in light of current regulatory practice to better understand how aggressive our asymptotic analysis really was.

Currently, cryogenic tanks (both LNG [87] and LH_2) used for fuel on ships are required to have the capability to maintain pressure within design limits, without venting, for 15 days. The a "current" (but still developing) LH_2 regulations now being applied to emerging LH_2 vessels have the same requirement, and we anticipate this requirement will persist when the LH_2 regulations are fully developed and approved in the future. There are options available to prevent the venting of hydrogen gas from an LH_2 tank. These methods include consuming the vented hydrogen (for example by a catalytic reactor, turning the hydrogen into water and waste heat), creating electricity through the fuel cell, or reliquefying the gaseous hydrogen. However, these approaches are negated by another applicable regulation [88]. As a result, it is currently required by the USCG that marine cryogenic LH_2 tanks must accommodate the pressure rise associated with 15 days of ambient heat transfer with no fuel leaving the tank. The LH_2 tanks assumed for the Multiplicity and Shape Studies would not meet this requirement using today's tank technology.

The 15-day hold time of the "current" regulations being applied today may be overly conservative. Prior studies have shown that the normal boil off from LH_2 tanks is below the lower flammability limit (LFL) of hydrogen (4%) upon exiting the Vent Mast [89], making its venting not a safety concern, although it is undesirable for economic reasons. Other studies have shown that due to the high buoyancy of hydrogen at room temperature, vented hydrogen rises up even in a crosswind, making the release of hydrogen through a tall vent mast a safe procedure. Recently, CFD studies of Vent Mast releases of hydrogen in crosswinds have been published by Blaylock and Klebanoff [90]. The tentative conclusion drawn was that a hemispherical hazardous zone would be sufficient as was assumed in the previous feasibility studies, but further CFD modeling of this question would be useful.

The initial comparisons of the LH_2 storage capacity of the H_2 Baseline Vessel, the Multiplicity Variants, and the Shape Variant all assumed 100% filling of these tanks with LH_2. However, the current regulations dictate that residual tank levels, and LH_2 tank filling and storage must be carefully calculated and controlled, as described in the *Zero-V* study [25]. These considerations impose a "usable" or "consumable" LH_2 capacity, which is less than the 100% filled LH_2

capacity. Current regulations indicated a 64 – 5% consumable hydrogen quantity as discussed previously.

There are engineering approaches that the regulations allow that may increase the initial loading of the tanks up to 95% full. Both the DNV-GL rules and the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF code) allow a higher loading limit to be used when the tanks are located where there is a very small probability of an external fire and engineering means are introduced to control the tank pressure. Such controls could be using a catalytic burner to convert boil-off hydrogen to water and waste heat. Another approach is to introduce a reliquification system, that reliquefies boil-off hydrogen and returns it to the tank. A third approach is to introduce active means of cooling the LH_2 load to prevent heating to the reference temperature. However, there is also a requirement for a 15-day hold time on the LH_2 charge with the tank fully isolated, which would make these engineered approaches unavailable [88]. Given the possibility of these engineering approaches, the possibility of future changes in the regulations, and for simplicity, we have made the comparison of the stored LH_2 amounts for the H_2 Baseline Vessel, the Multiplicity Variants, and the Shape Variant to be based on the 100% filled tank amounts. However, in recognition of the regulations described above on heel and fuel loading limits, we also list in Table 2, Table 3, Table 4, Table 5, and Table 6 the "consumable" LH_2 tank capacities.

Apart from LH_2 tank venting and operational characteristics of fill, the IGF code [87] and currently applied (but still developing) USCG LH_2 guidelines require cryogenic tanks be arranged with significant setbacks from all sides and the bottom of the vessel to minimize the risk of damage to the tanks in the event of collisions with other ships, allisions with structures, or grounding. These current setback requirements were completely relaxed in both the Multiplicity and Shape Studies. For example, the regulations require the tanks be at least B/5 (B references vessel beam, or width) from the side of the ship. The tank also needs to be offset from the vessel bottom. The specifics vary but are at minimum B/10 or 0.8 meters, whichever is greater. Although arranging tanks in the double bottom, as in the Multiplicity and Shape Studies could still be possible, these regulatory setbacks would dramatically reduce the volume available for tanks, and accordingly the possible fuel storage.

The fuel storage hold space, which is defined as the space that the tank is installed within, also currently has requirements which would apply to the LH_2 tanks in our study. The fuel storage hold space shall be separated from the sea by a double bottom and requires a 0.9-meter cofferdam toward category A machinery spaces and between separate fuel storage hold spaces. Any space with fuel preparation equipment is a category A machinery space. These requirements cause significant arrangement issues which were not included in the calculations for this study.

There are currently maritime regulations that specify the materials used in fuel spaces shall be capable of withstanding a spill of cryogenic fuel. This likely entails a special material selection for the TCS to separate it from the hull of the vessel. This material consideration was not evaluated in the present work but would need to be in a design placing LH_2 tanks with either multiplicity or improved shape in the hull of a vessel.

Finally, the variants put forth in the Multiplicity and Shape studies do not consider the placement of hazardous areas, which keep areas which could be contaminated with flammable hydrogen gas away from ignition sources, air intakes, etc. The regulations prescribe that these TCSs and air locks will be classified as hazardous areas requiring independent ventilation at 30 air changes per hour. Ventilation supplies to these spaces need to be from non-hazardous areas, but they will create their own hazardous areas. Ventilation discharges also create hazardous areas. Other vessel intakes shall be at least 1.5 meters from any of these hazardous areas. Arrangement of these areas poses fewer challenges than the regulatory relaxations discussed above, but neither hazardous areas nor ventilation intakes and discharges were considered in detail in this study.

5.4.2. Current Tank Manufacturing Limitations

From a tank manufacturing point of view, the LH_2 tanks used in the Multiplicity and Shape Studies are beyond the current technology. R&D areas that could have a positive impact on liquid hydrogen use in maritime applications include:

- Pressure vessel steel developments for higher strength/ductility at 20 K. Liquid hydrogen temperatures are as low as 20 K. Current materials have relatively low strength but preserve the necessary ductility to accommodate this temperature. A stronger material that still preserves ductility at 20 K would allow for thinner vessels and/or higher pressures.
- Pressure strengthening rules fit for 20 K service. Recent code rules allow for the stretching of vessels under hydrostatic loads to improve strength improvements while preserving sufficient ductility for cryogenic service down to 77 K. Demonstration of ductility fit for 20 K service would allow for improved strength and thinner vessels or higher-pressure ratings.
- Improved insulation systems. Reduced thermal conductivity can drive lower heat transfer and longer hold times.
- Methods for efficiently building prismatic tanks with insulation systems fit for 20 K service. Insulation systems that demand a vacuum for function are challenged with flat walls that tend to bend under external pressure loads. Improved thermal performance which does not demand vacuum, or structural design that do not bend under vacuum loads may be necessary for functional hold times.
- Flare-less techniques for managing heat leak (venting). When venting is unavoidable, oxidation of the hydrogen to harmless water vapor without an external flare or cloud may satisfy an equivalent safety for systems that otherwise do not vent. Such methods may be catalytic oxidation or the selective use of fuel cells to consume the otherwise vented hydrogen.

6. CONCLUSIONS

This study explores possible improvements of liquid hydrogen (LH_2) tank technology in the areas of tank weight, multiplicity (high-performing small tanks), and tank shape. The purpose was two-fold. First, we aimed to investigate if improving LH_2 tank weight, multiplicity, and shape in a manner well beyond the current state-of-the-art would enable more hydrogen to be stored on hydrogen vessels. Second, by assessing the important technical factors governing tank weight, multiplicity, and shape, we sought to identify the most promising R&D routes to improving LH_2 tank performance in these ways, should a benefit be found.

In the area of LH_2 tank weight reduction, the results indicated that at most a 7.1% reduction in overall research vessel weight (compared to a H_2 Baseline Vessel) could be achieved with an asymptotic (and unobtainable) zero-mass LH_2 storage technology. Even in this most optimistic of cases, the hydrogen fuel-cell vessel application, at least for the type of vessel considered here, is not a strong driver for LH_2 tank weight improvements. It's possible that for much larger quantities of hydrogen, for example LH_2 tankers, a greater motivation for decreasing the mass of LH_2 tanks might be found. Such a study was beyond the scope of the current project.

For the Multiplicity Study, where small LH_2 tanks were placed in the hull, the total amount of stored LH_2 was ~ 5 - 9% less than that of the H_2 Baseline Vessel. This was the case even for the most optimistic of assumptions concerning other hardware competing for fuel storage space. Given the reduced fuel storage, deploying tanks for a ship with multiplicity does not look like a promising technical direction, and would not motivate conducting the needed R&D that would drive the technology into smaller LH_2 tanks with high length-to-width aspect ratios.

In contrast, we did find a significant benefit to improving the shape of LH_2 tanks, enabling prismatic tanks that would afford a better match of the LH_2 tank shape to the vessel hullform. We considered a Shape Variant that incorporated beyond state-of-the-art prismatic LH_2 tanks with hydrogen capacities in the range 600 – 3,000 kg each. We found a 26% improvement in the quantity of stored LH_2 even when required hardware such as tank connection spaces and ventilation equipment was considered. Such an improvement could warrant further LH_2 tank R&D. Desirable R&D paths are those that can enable high performing prismatic LH_2 tanks, such as pressure vessel steel developments allowing for higher strength/ductility at 20 K, improved insulation systems, methods for efficiently building prismatic tanks with insulation systems fit for 20 K and flare-less techniques for managing heat leak (venting).

These studies assumed aggressive relaxation of current regulations for the use of cryogenic fuels on ships, regulations which were established to ensure the safety of ship and personnel. In considering any R&D investment to improving LH_2 tank technology as well as a proposed implementation of that technology on a ship, it's vitally important to also assess if effective strategies can also be identified to address the very real risks and safety concerns which motivated the regulations in the first place. In other words, although the maritime regulations for hydrogen are still developing, such LH_2 tank improvements need to be viewed against projected future regulations and possible future limitations on LH_2 tank manufacturing.

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APPENDIX A. ABRIDGED REPORT GIVING ESSENTIAL RESULTS

The International Maritime Organization (IMO) established in 2023 a greenhouse gas (GHG) reduction strategy for international shipping with a goal to reach net-zero GHG emissions by 2050 [1]. Such a reduction will require a change in vessel fuel, away from traditional fossil-derived fuels to alternative fuels that over their lifecycle reduce or eliminate GHG emissions. Many such fuels also reduce criteria pollutant emissions (NO_x, hydrocarbons [HC], and particulate matter [PM]) that directly impact human health [2]. Prior work has summarized possible alternative fuels [3 - 5] with individual studies examining specific candidate fuels such as dimethyl ether (DME) [6], methanol [7], ammonia [8], liquid natural gas [9], and biodiesel [10].

Hydrogen has great potential for replacing fossil hydrocarbon fuels in maritime applications. Studies have been ongoing since the beginning of the 21st century, well before the IMO strategy was formulated. As summarized by Klebanoff and co-workers [11], Foster [12] and Kickulies [13] examined the applicability of hydrogen, both in fuel cells and internal combustion engines (ICEs), for shore power, as well as for propulsion and auxiliary power. In 2016, van Biert et al. [14] reviewed different types of fuel cells for their applicability to vessels and assessed different methods of storing hydrogen or generating it on-board. Bicer and Dincer performed a comparative analysis of using hydrogen or ammonia in ICEs as a replacement for burning heavy fuel oils on transoceanic vessels [15]. The IMO strategy, from 2014 to the present [1], increased the interest in using hydrogen fuel-cell technology on ships. Several studies have been published with a focus on lifecycle emissions [16, 17], maritime fuel-cell thermodynamics [18], safety [19], and comparative reports of the varying types of fuel cells and hydrogen storage approaches available to future low-emission shipping [20 - 22]. A review of the safety-related physical and combustion properties of hydrogen in the maritime context has been published by Klebanoff and co-workers [23].

6.1. Prior Work on Hydrogen Fuel-cell Vessels:

Since 2016, there have been several studies of the feasibility of introducing hydrogen fuel-cell power to ships, with a particular focus on ship attributes and performance. Pratt and Klebanoff examined the feasibility of a high-speed hydrogen ferry called the *SF-BREEZE* [24]. Subsequently, the feasibility and attributes of a zero-emission hydrogen fuel-cell coastal research vessel named the *Zero-V* was investigated [25]. Detailed vessel designs incorporating hydrogen technology demonstrated that the combination of hydrogen (stored as liquid hydrogen [LH_2]) and proton-exchange membrane (PEM) fuel cells can in principle provide the basis for very capable vessels. These studies examined feasibility of such vessels from the points of view of vessel performance (speed, range, passenger complement), as well as managing safety issues (hazardous zones), fueling practicality (speed of refueling and available quantities) and local acceptance (Ports). These projects also provided an opportunity for the United States Coast Guard (USCG), naval architects, Ports of call (for both ferries and research vessels), and Class

Societies (e.g., ABS, DNV-GL) to become familiar with the safety-related properties of hydrogen and how to manage them in the design of vessels and shore side refueling facilities.

All prior feasibility studies, as well as the first hydrogen vessels themselves, advanced the application of hydrogen and fuel cells to vessels using commercially available hydrogen storage technology. Compressed gas (350 barg, 700 barg) hydrogen tanks have been proposed or adopted in applications where the amount of required hydrogen is relatively low, for example 250 kg for the *Sea Change* [26] and 170 kg for the *Discover Zero* [27]. In other applications of hydrogen on vessels, considerably more hydrogen is needed, for example 1200 kg for the SF BREEZE [24], 11,000 kg for the *Zero-V* [25], 800 kg for the H_2 Hybrid [11], 1400 kg for the *CCRV* [28] and 4,000 kg for the MF *Hydra* [29]. These relatively large quantities of hydrogen dictate the use of liquid storage, since LH_2 is currently the densest form to store it in. Solid-state storage [30] offers potentially even higher storage density but remains a research area.

Given that LH_2 is the future for large scale storage of hydrogen on vessels, it raises the question: can LH_2 tank technology be advanced beyond that commercially available today? Particularly for the maritime application, would it be advantageous to use many smaller (but still high performing) LH_2 tanks rather than large tanks (a concept we term LH_2 tank "multiplicity")? Would there be a benefit to having LH_2 tanks with shapes chosen to fit in the hull of a vessel rather than using shapes typical of commercial LH_2 tanks (cylinders, spheres). Would there be a benefit to having lighter LH_2 tanks? Our work here assesses how large such tank improvement benefits could be to the hydrogen vessel capabilities, primarily how much hydrogen can be stored on the vessel.

We consider improvements in the areas of tank weight, multiplicity (high-performing small tanks) and tank shape. Our purpose is two-fold. First, we aim to investigate how varying LH_2 tank weight, multiplicity and shape might enable more hydrogen to be stored on hydrogen vessels. Second, by assessing the important technical factors governing tank weight, multiplicity, and shape, we seek to identify what would be the most promising R&D routes to improving LH_2 tank performance in these ways. This exploration is asymptotic in nature, meaning that we are assuming almost complete relaxation of "current" regulations which might otherwise limit the actual implementation of the weight, multiplicity and shape options being studied. We call such requirements "current" because such requirements are currently being used by the USCG to evaluate LH_2 vessels, while also recognizing there is still regulatory development occurring for the use of hydrogen on vessels. These current limitations will be reviewed for their impact on the study.

6.2. H_2 Baseline Vessel:

To study the impact of novel (beyond commercial) LH_2 tank design on the increased storage of hydrogen on a vessel, a basis of comparison is needed, namely a "Baseline Vessel." The H_2 Baseline Vessel is based on current commercial technology and is also in some sense "generic," to maximize the usefulness of our results to the naval architecture field. Also, we seek to leverage results from the prior feasibility studies.

For this project, we consider as our H_2 Baseline Vessel a 100% hydrogen powered coastal research vessel similar in size to the previously studied *Zero-V* [25]. This choice allows us to leverage the prior *Zero-V* work from 2017, as well as recent design work on a diesel-powered research vessel similarly sized to the *Zero-V*. Whereas the *Zero-V* was a trimaran design, the H_2 Baseline Vessel for this work is a monohull (a more common hull form), allowing the results of the study to be more directly applicable to other types of ships, both smaller (inland waterways) and larger (ocean going). The H_2 Baseline Vessel demands large amounts of hydrogen (thousands of kilograms), requiring LH_2 storage and avoiding smaller amounts (~ 500 – 800 kg) where there could be ambiguity if the hydrogen vessel should use high-pressure storage (700 barg) of hydrogen gas or LH_2.

The H_2 Baseline Vessel design will assume the hydrogen is stored in two LH_2 tanks. Redundant fuel tanks are a current regulatory requirement for a vessel powered entirely by hydrogen. The H_2 Baseline Vessel assumes the cylindrical geometry and weight/volume characteristics of current LH_2 tank technology.

Using the H_2 Baseline Vessel as a basis for comparison, the essential questions addressed in our study are:

- How would a decrease in LH_2 tank weight affect the amount of stored hydrogen on the vessel and the vessel performance?
- Would an increase in LH_2 tank multiplicity increase the amount of hydrogen that can be stored on the vessel?
- Can LH_2 tank shape positively influence hydrogen storage on a hydrogen vessel?

These questions are captured conceptually in Figure A, where the specific fuel locations considered in the study are indicated. All comparisons for the quantity of LH_2 stored will be based on the 100% fill amount of a tank, assuming the "water volume" of the tank is completely filled with LH_2.

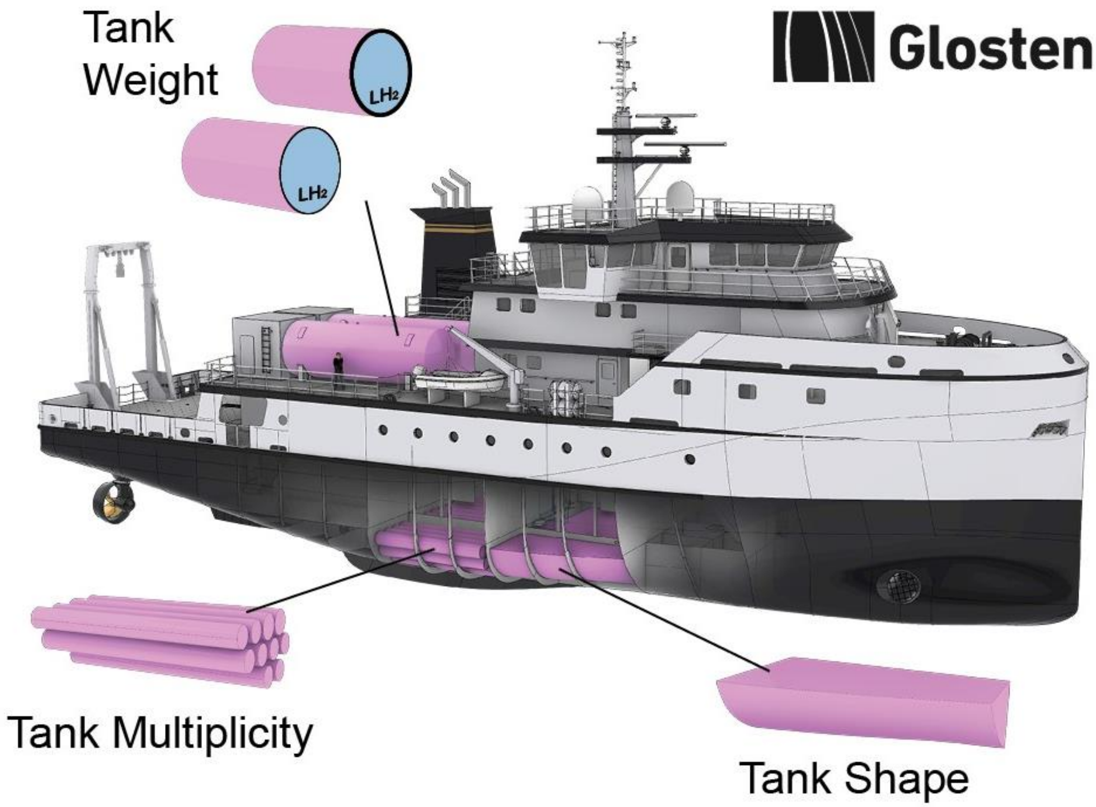

Figure A. The questions addressed in this study: Using the H_2 Baseline Vessel as a comparative norm, how does varying tank weight (for example by using thinner Inner Vessel walls) affect vessel performance? (Note the thinner and thicker walls of the LH_2 tanks indicated for "Tank Weight."). Can more LH_2 can be stored on the vessel if improved LH_2 tank technology allowed the placement of many smaller LH_2 tanks with Tank Multiplicity? Can more LH_2 can be stored on the vessel if LH_2 tanks could be deployed with improved Tank Shape?

The influence of tank mass was examined by parametric study, imposing a reduction in LH_2 tank mass for the H_2 Baseline Vessel, and assessing its impact on vessel range. As suggested by Figure A, one option for weight reduction was achieved by making the Inner Vessel walls thinner. Subsequently, we identify the routes to improvement (i.e., the research areas) that are needed in LH_2 tank technology to enable such reductions in LH_2 tank mass, while still, presumably, maintaining required cryogenic storage performance.

Similarly, we then explored Multiplicity Variants which assume the LH_2 mass can be stored with Tank Multiplicity in an array of smaller separate tanks (Figure A), examining if greater quantities of LH_2 can be accessed by this approach compared to the H_2 Baseline Vessel without undermining other important performance attributes. Similarly, we highlight the enabling R&D areas for the development of high performing but smaller LH_2 tanks for the maritime space.

Finally, we explore the Shape Variant that assumes the LH_2 mass can be stored in LH_2 tanks with a hull conforming Tank Shape, also indicated in Figure A, and compare the amounts of stored

LH_2 of the Shape Variant to that of the H_2 Baseline Vessel. If an improvement is found, we highlight those R&D areas in LH_2 tank technology to enable the desired non-traditional LH_2 tank shape.

The vessel variants in this study all maintain the same hull form and propulsion system. As such, there are no significant differences amongst the variants in major performance characteristics such as speed. The main differences between the designs are total fuel storage (which determines range), utilization of topside deck area, and total displacement. In other words, our focus is on the space available on a research vessel and the ways (weight, multiplicity, shape) that LH_2 technology could be improved to maximize stored fuel volume in those spaces.

Figure B shows 3D renderings of the H_2 Baseline Vessel and the Diesel Parent Vessel from which it is conceptually derived.

Figure 22. The 3D rendering of the H_2 Baseline Vessel used for comparison purposes in this study, along with a rendering of diesel-electric Parent Vessel from which the H_2 Baseline Vessel is derived.

The H_2 Baseline Vessel has the same hull shape and hull dimensions as the Diesel Parent Vessel. However, there are differences in the use of deck space, as required by the placement of two large LH_2 tanks on deck. The largest differences of course are the removal of diesel generators and diesel fuel from the Parent Vessel and replacing them with PEM fuel cells and LH_2 for the H_2 Baseline Vessel. We do not compare the performance attributes of the H_2 Baseline Vessel with the Diesel Parent Vessel. Rather, the Diesel Parent Vessel is only used to establish the general architecture of the H_2 Baseline Vessel.

Figure C shows a cross-sectional view of the H_2 Baseline Vessel with key vessel components identified.

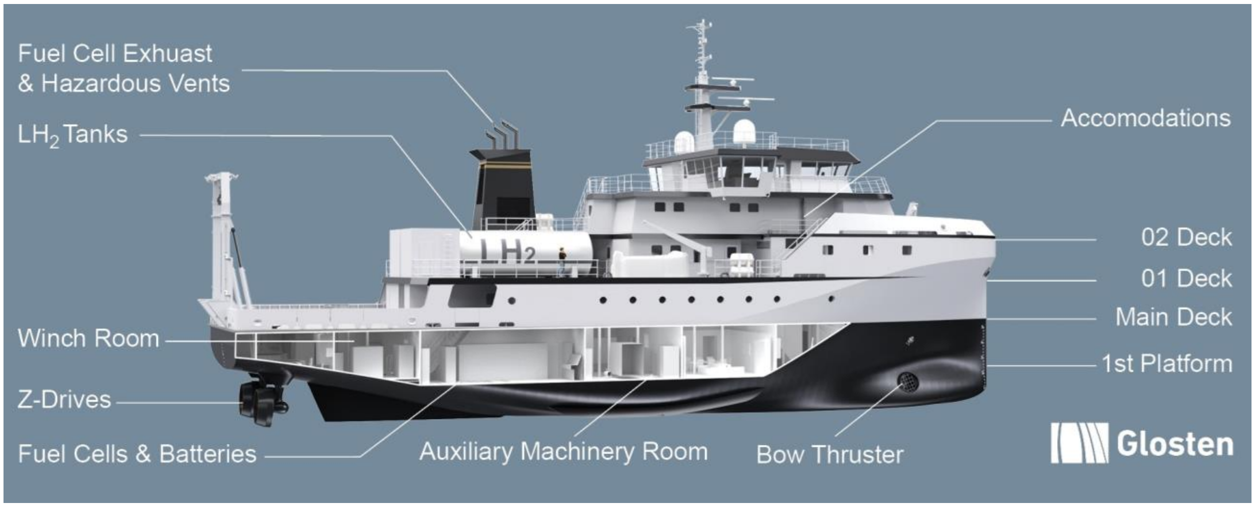

Figure 23. Top: Cross-sectional view of the H_2 Baseline Vessel outboard and machinery arrangements.

The First Platform contains mainly machinery spaces, with one science space. The Main Deck is comprised of exterior working spaces, science labs, galley and mess, and ship storage. The 01 Deck holds the LH_2 tanks and some scientist and crew accommodations. The 02 Deck contains the remainder of the scientist and crew accommodations. The 03 Deck is the Pilothouse.

Figure D shows a closer view of the LH_2 tank area of the H_2 Baseline Vessel.

Figure D. 3D rendering of H_2 Baseline Vessel. LH_2 fuel tanks and tank connection spaces (TCSs) are indicated.

The H_2 Baseline Vessel is powered exclusively by hydrogen, using a fuel-cell/battery-electric system connected by DC main busses. The fuel-cell system we adopted was the Ballard FCwaveTM 200 kW Fuel Cell. The design speed of 12 knots requires approximately 1500 kW of electrical power, including both propulsion and service (hotel) loads. To meet this requirement, ten Ballard FCwaveTM 200 kW fuel-cell modules are provided. The LH_2 tanks on the H_2

Baseline Vessel hold 3220 kg each of LH_2 (100%-filled), with the total, 6440 kg, being the maximal amount of hydrogen that can be stored given that deck location.

6.3. LH_2 Tank Weight Study:

Two weight reductions were considered. First, a 50% reduction in Inner Vessel weight was assessed, a case we call the “Inner Vessel Reduction Study.” This tank weight reduction approach is captured notionally in Figure A. So, instead of an empty LH_2 tank weight of 17230 kg (per tank) used in the H_2 Baseline Vessel, we adopted a LH_2 tank mass of 13681 kg for the Inner Vessel Reduction Study by reducing the Inner Vessel mass by one half, while still holding the same total amount of LH_2 (3220 kg per tank, total of 6440 kg in two tanks). This tank mass reduction is not currently available using today’s manufacturing methods but could conceivably be produced using “pressure strengthening” in tank manufacturing, which is a common practice for LNG tanks, but has not yet been applied to LH_2 tanks due to concerns with respect to the remaining ductility of the vessel after the pressure strengthening process.

The second weight reduction was to assume zero LH_2 tank weight for the same amount of total stored LH_2 (6440 kg) as for the H_2 Baseline Vessel. This asymptotic calculational scenario bounds the question of what vessel performance benefits could possibly arise due to LH_2 tank weight minimization (in this second case to zero). In this case, with zero tank weight, the only weights to be considered are that of the LH_2 fuel itself, along with the piping and appurtenances which would necessarily be connected to any tank.

For both weight reduction scenarios, weight and stability calculations where performed, both for the vessel fully fueled and for selected points on a voyage where the LH_2 fuel is being steadily used. These results are compared to the corresponding values for the H_2 Baseline Vessel. We also calculated the required propulsion power for each weight reduction scenario and compared that to the H_2 Baseline Vessel.

At full load conditions including variable loads like fuel, water, and people, our parametric model predicts that for the Inner Vessel Reduction Study, the total ship weight is reduced from 1331 MT of the H_2 Baseline Vessel to 1290 MT. This corresponds to a 3.1% reduction in the total ship weight. For the second weight study (zero tank weight), the total ship weight is reduced further to 1236 MT. This represents a total weight savings of 7.1% as an asymptotic value for the possible benefits from LH_2 tank weight reduction in this research vessel example. These ship weight reductions, while modest, would result in noticeable reductions of required propulsion power from the 1500 kW of the H_2 Baseline Vessel, down 1.4% for the Inner Vessel Reduction case, and 4.3% for the asymptotic zero LH_2 tank weight reduction. For a 10-knot cruising speed in calm water, this translates to a range improvement of 12 and 36 nautical miles (NM), respectively.

These weight reduction results need some context from the naval architecture perspective. The question arises: would a ~ 3 - 7% reduction in vessel weight (displacement) be significant enough that it would have major spiraling/cascading design impacts resulting in a different vessel length, hullform, lower-power thrusters, or a reduced number of fuel cells? The answer is "no," but that does not mean "don't pursue weight reductions." For some context, at this conceptual phase of design, a ship designer would typically be carrying a 10 - 15% design margin in the vessel weight estimate. So, the possible weight savings that could possibly come from LH_2 tank improvements are within these pre-existing margins, but are not, in and of themselves, negligible. Rather we conclude that the maritime application, while benefitting from a reduced LH_2 tank weight, is not a strong motivator the LH_2 tank weight improvements, in contrast to aerospace applications of LH_2.

Despite that conclusion, should one wish to pursue LH_2 tank weight reduction R&D, research possibilities include new cryogenic materials that are fit for 20 K service or methods for pressure strengthening available materials. The indirect impact of step changes in thermal insulation performance can drive pressure requirements lower which in turn reduces pressure vessel thickness. Additionally, the vacuum jacket weight could be reduced by insulation systems that do not require vacuum or by deploying lighter weight materials for jacket design.

6.4. LH_2 Tank Multiplicity Study:

We seek to understand how conceivable deployments of LH_2 tanks with multiplicity might positively affect the quantity of LH_2 stored on the vessel, as indicated in Figure A. We take an "asymptotic" approach, almost fully relaxing regulatory requirements that could impact such a consideration. Thus, our Multiplicity Study does not initially involve considerations of associated hardware such as TCSs, piping, tank supporting structure and ventilation requirements that would all go into a full naval architecture assessment of the deployment of LH_2 tanks with multiplicity. These considerations would degrade the LH_2 fuel storage capacity in any multiplicity design. Rather, we initially excluded such items in order to identify if any benefit would accrue to tank multiplicity in the most optimistic of cases.

Two Multiplicity design concepts were investigated, both of which replace the two large LH_2 tanks of the H_2 Baseline Vessel. The first concept attempted to fill the available double bottom compartments of the H_2 Baseline Vessel as much as practicable while still maintaining reasonable limits on the minimum tank size and the number of separate tanks. We call this variant Multiplicity Design Variant 1. Figure E shows the result of that multitudinous placement of LH_2 tanks. Compared to the H_2 Baseline Vessel hydrogen storage (6440 kg total in two tanks, 100% filled), Multiplicity Design Variant 1 holds 6114 kg. This corresponds to a 5% reduction in stored LH_2 compared to the H_2 Baseline Vessel.

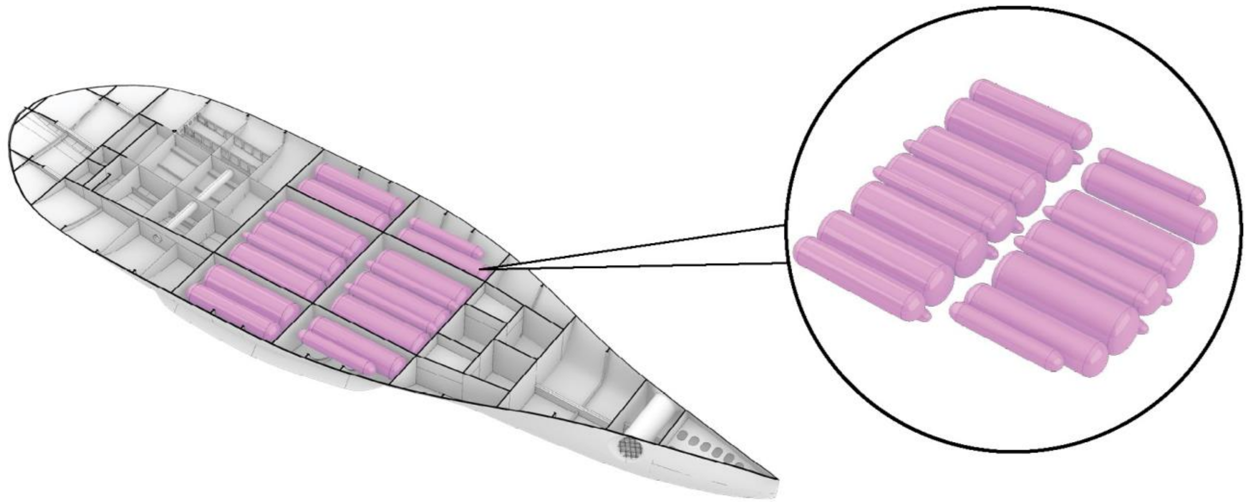

Figure E. Cross-sectional rendering of the LH_2 Tank Multiplicity Design Variant 1.

Variant 1 still had some concession towards conventional practice – maintaining the biggest sizes possible – and that left a fair bit of un-filled interstitial space around the tank array. This concession assumes that larger tanks are needed to achieve adequate thermal performance. What if future insulation technology was so effective that the tanks could be reduced in size even further to the minimum size that could be practically manufactured while still providing some insulation allowance? This would allow the multiplicity tanks to be placed even closer together. This idea was investigated by arranging a matrix of 0.61 m (24”) outside diameter (O.D.) LH_2 tanks in the same compartments used in the first Multiplicity Variant. Supporting structural arrangements were not examined, but it is assumed that these tanks could be supported at the ends with limited need for support in the middle of the tanks.

Figure F shows the result of that even more multitudinous placement of LH_2 tanks. The Multiplicity Variant 2 was evaluated similarly to Multiplicity Variant 1. The total estimated hydrogen fuel storage (100% tank fill) for Variant 2 is 5874 kg, which is 4% less than that of Multiplicity Variant 1 (6114 kg) and 8.8% less than the H_2 Baseline Vessel. This is a significant drop in volume from the H_2 Baseline Vessel and would likely be deemed problematic despite other benefits coming from the tank multiplicity design, such as recovering unrestricted use of the 01 deck for mission equipment. Also, such a deployment of LH_2 in the double bottom relaxes currently applied regulatory restrictions ensuring safety of the ship and personnel. While such regulations are still in development, the safety concerns remain and would need to be addressed and mitigated.

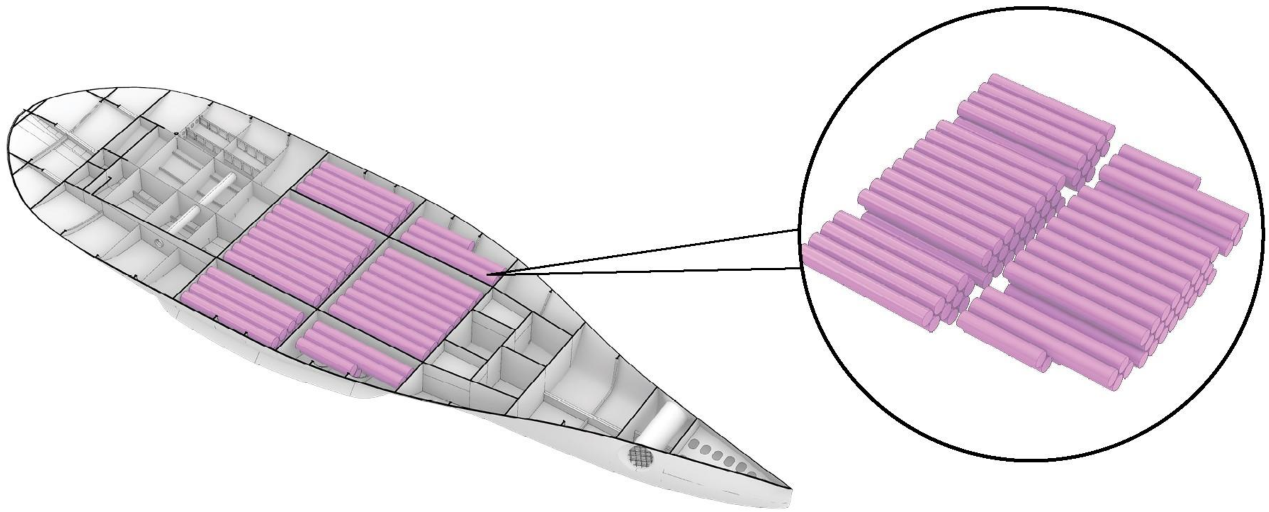

Figure F. Cross sectional rendering of the LH_2 Tank Multiplicity Design Variant 2.

Note that this was an optimistic assessment of the Multiplicity deployment of LH_2 tanks, since TCSs and other needed hardware were not included. We conclude that given the reduced fuel storage, practical difficulties associated with managing many LH_2 tanks, and the likely regulatory challenge with this storage location, deploying LH_2 tanks with multiplicity does not look like a promising technical direction, and would not motivate conducting the needed R&D that would drive the technology into smaller LH_2 tanks with high length-to-width aspect ratios, at least for the maritime research vessel application.

Although our study suggests that the H_2 Baseline Vessel, with two large LH_2 tanks out in the weather, affords a greater amount of stored LH_2 than the Multiplicity Variants, it could be that for some other reason, storing LH_2 in the hull could be desirable. In addition, a non-maritime application could conceivably benefit from having a multitude of smaller LH_2 tanks, with attributes beyond current LH_2 tank technology. The main R&D challenge will be to improve the performance of multiple small tanks to achieve useful hold times. A breakthrough in thermal insulation performance is needed for this. Such a breakthrough would need to be followed by improving the networking of so many tanks for filling, withdrawing and isolation efficiency. However, using such a complex system to feed cryogenic pumps may be nearly impossible to achieve. A breakthrough in insulation performance of the order of 1/10 the current thermal conductivity, and a practical means to pump from such tanks without undermining thermal performance, would be needed.

6.5. LH_2 Tank Shape Study

The final step in our study, away from the H_2 Baseline Vessel is to examine if there is a benefit to non-traditional shapes in maritime LH_2 tank deployment. That is, in the application of marine vessels, is there is a benefit to the amount of stored hydrogen if LH_2 can be stored in tanks with non-cylindrical or non-spherical shapes, shapes that allow a better match of the LH_2 tank shape to the vessel hullform? As in the weight and multiplicity studies, we reduce to the absolute minimum current vessel regulatory constraints that would otherwise restrict our "clean sheet" exploration of LH_2 tank technology on a hydrogen fuel-cell vessel, with subsequent assessment of how current regulations provide context for the results.

Because we are interested in the effect of Shape only, and not multiplicity, we consider relatively few tanks, which means these tanks would hold much more hydrogen per tank than those assumed for the Multiplicity Study. Thus, only large spaces on the hydrogen ship can be considered. This led us to choose, as was the case with the Multiplicity Study, the space in the lower parts of the ship that were devoted to diesel fuel in the Diesel Parent Vessel as the location for exploring LH_2 tank shape.

The hull space for the shape study is shown in Figure G. Tank shapes were chosen to fill the hull space, and are shown in Figure H. Such tanks are generally termed "prismatic tanks." Their main attributes are that the sides of the wing tanks follow the shape of the hull in the lower regions of the vessel, and the flat profile conforms to the available hull space. Also, their flat profile allows improved use of the space previously used for diesel fuel. The benefit of prismatic tanks is to provide maximum volumetric efficiency while storing LH_2 fuel inside the structure of a vessel in a manner similar to diesel fuel. This allows for containment of most LH_2 storage equipment outside of normal work areas while maximizing fuel load. The manufacturing challenge is satisfying pressure requirements, which are difficult to maintain in wide flat structures.

Using the prismatic concept of Figure H, we attempted to fill the designated double-bottom fuel storage compartments, as much as practicable. A total of six compartments were used to maintain necessary ship structure and stability. The Outer Jackets of the prismatic tanks were offset from the ship's hull to allow for standard ship structural components. The Inner Vessel fuel storage compartments of the LH_2 tanks were then offset from the tank's Outer Jacket to allow for tank insulation.

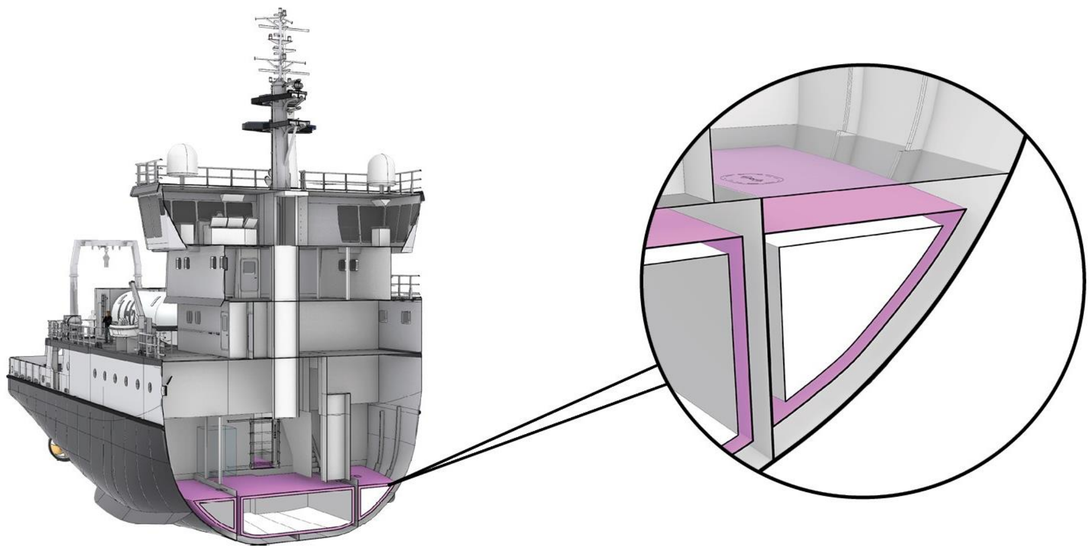

Figure G. The hull space adopted for the shape study, emphasizing the need to accommodate hull shape.

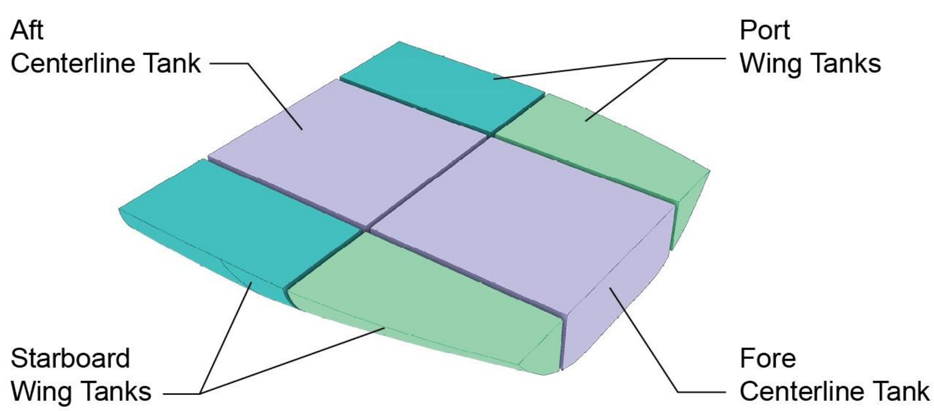

Figure H. Prismatic tanks considered for the shape study.

We initially evaluated the tank concept of Figure H, where no account was made of required hardware such as TCSs and piping. For the 100%-fill stored volumes of the LH_2 tanks, the total stored mass of H_2 in the Shape Variant is 9088 kg, compared to the total stored mass of hydrogen on the H_2 Baseline Vessel of 6440 kg. Thus, the fuel storage of the Shape Variant led to a 41% increase in the hydrogen fuel storage compared to the H_2 Baseline Vessel. This provides a significant benefit to the vessel range while also moving the fuel storage system to an area of the vessel which would otherwise be unused.

As the preliminary calculations for the prismatic tank arrangement showed a significant benefit in comparison to the H_2 Baseline Vessel, further investigation and design work was pursued. The effects of accommodating volumes for the TCSs, piping tunnels, and ventilation components reduces the space available for the LH_2 fuel storage on the Shape Variant. Figure I shows the shape study tanks where notional TCSs are indicated, and a piping channel is cut out in the centerline tanks to allow the Port LH_2 wing tanks to connect to the TCSs. Taking this hardware into account, the Shape Variant LH_2 storage (100% filled) becomes 8087 kg. This is still a significant 26% increase compared to the H_2 Baseline Vessel.

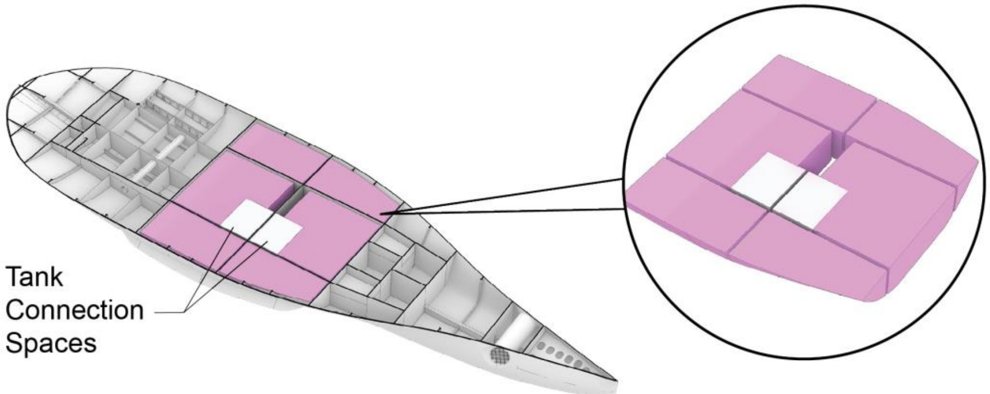

Figure I. 3D model arrangement of the prismatic LH_2 tanks used in the shape study. White squares indicated notional TCSs. The rectangular cut outs in the fore and aft centerline tanks are to accommodate a piping tunnel that allows the Port wing tanks to connect to the TCSs.

The LH_2 tanks assumed for the shape study are not currently available using today's technology. They are, however, the best opportunity considered in this study for future advancement of LH_2 fuel usage on ships beyond the current baseline. A working prismatic tank solution requires advancement in the following areas of tank and vessel design:

- Tank insulation shall allow for the current regulatory requirement of 15-day hold time with no hydrogen release with a 1 bar relief valve pressure. Such performance may be difficult without vacuum being used in the insulation space which in turn creates difficulty in maintaining jacket shape.
- Tank shape adaptability to numerous potential vessels and hull shapes. Networking multiple tanks to act as one storage tank is challenging. Doing so while balancing differing thermal performance and low pressures creates flow and heat transfer challenges between the separated tanks.

6.6. Current Regulatory and Tank Manufacturing Restrictions:

The results shown for the Multiplicity and Shape Studies involved a significant relaxation of the current regulatory guidelines for using hydrogen fuel-cell technology onboard vessels. While these regulations are still being developed and could potentially be relaxed as a result of future science-based assessments of risk, the Multiplicity Variants (both 1 and 2) and Shape Variant need to be examined in light of current regulatory practice to better understand how asymptotic the studies really were.

Currently, cryogenic tanks (both LNG and LH_2) on ships are required to have the capability to maintain pressure within design limits, without venting, for 15-day [31]. Thus, it is currently required that marine cryogenic LH_2 tanks must accommodate the pressure rise associated with 15-days of ambient heat transfer with no fuel leaving the tank. The LH_2 tanks assumed for the Multiplicity and Shape Studies could not meet this requirement using today's tank technology.

Similarly, the IGF code [31] and current (but developing) LH_2 regulations being applied to emerging LH_2 vessel designs require cryogenic tanks be arranged with significant setbacks from all sides and the bottom of the vessel to minimize the risk of damage to the tanks in the event of collisions with other ships, collisions with structures, or running aground. These current setback requirements were completely relaxed in both the Multiplicity and Shape Studies. For example, the IGF regulations require the tanks be at least B/5 (B references vessel beam, or width) from the side of the ship [31]. The tank also needs to be offset from the vessel bottom; the specifics vary but are at minimum B/10 or 0.8 meters, whichever is greater. Although arranging tanks in the double bottom, as in the Multiplicity and Shape Studies could still be possible if safety concerns could be addressed, these regulatory setbacks would dramatically reduce the volume available for the LH_2 tanks, and accordingly the possible LH_2 fuel storage.

There are currently maritime regulations that specify the materials used in fuel spaces shall be capable of withstanding a spill of cryogenic fuel. This likely entails a special material selection for the TCS to separate it from the hull of the vessel. This material consideration was not evaluated in the present work but would need to be in a design placing LH_2 tanks with either multiplicity or improved shape in the hull of a vessel.

Finally, the variants put forth in the Multiplicity and Shape studies do not consider the placement of hazardous areas, which keep areas which could be contaminated with flammable hydrogen gas away from ignition sources, air intakes, etc. The current regulations prescribe that these TCSs and air locks will be classified as hazardous areas requiring independent ventilation at 30 air changes per hour. Ventilation supplies to these spaces need to be from non-hazardous areas, but they will create their own hazardous areas. Ventilation discharges also create hazardous areas. Other vessel intakes need to be at least 1.5 meters from any of these hazardous areas. Arrangement of these areas poses fewer challenges than the regulatory relaxations discussed above, but neither hazardous areas nor ventilation intakes and discharges were considered in detail in this study.

These regulatory considerations do not change the basic conclusions of the study, namely that the research vessel is not a strong motivator for LH_2 tank weight reductions, that there is no motivation to develop LH_2 tanks that would allow deployment with multiplicity, but improving LH_2 technology to allow hullform-fitting prismatic tanks could be a productive R&D direction. It would be important to pursue such R&D while at the same time being cognizant of the need to preserve the safety of ship and personnel, as promoted by the prevailing regulations. This would require mitigation of risks (to both ship and personnel) associated with storing LH_2 in the ship's double bottom, as proposed here.

From a tank manufacturing point of view, the LH_2 tanks used in the Weight Multiplicity and Shape Studies are beyond the current technology.

- Weight reductions would demand new materials that have the required strength and ductility at 20 K.
- Substantial insulation performance improvements would be needed to make a network of multiple small tanks that possessed a useful hold time.
- Flat walled prismatic tanks that can support reasonable pressures would need to be developed to enable both vacuum insulation and hydrogen pressures that in combination could create a useful hold time.

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