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Project Nautilus: Introducing Hydrogen Fuel Cell Technology as a Retrofit on a Hybrid Electric Vessel

Leonard E. Klebanoff, Narendra Pal, Nicholas G. Monroe

Prepared by
Sandia National Laboratories,
Livermore, CA, 94550

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Project Nautilus: Introducing Hydrogen Fuel Cell Technology as a Retrofit on a Hybrid Electric Vessel

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I. List of Acronyms

ABS:	American Bureau of Shipping
AIP:	Approval in Principle
AIS:	Alcatraz Island Services
ALARP:	As Low as Reasonably Practicable
CFD:	Computational Fluid Dynamics
DME:	Dimethyl Ether
FMEA:	Failure Mode and Effects Analysis
GHG:	Greenhouse Gas
HyPM:	Hydrogen Power Module
ICE:	Internal Combustion Engine
IEC:	International Electrotechnical Commision
IGF:	International Gas-fueled
IMO:	International Maritime Organization
LEED:	Leadership in Energy and Environmental Design
LH_2:	Liquid Hydrogen
LHV:	Lower Heating Value
MARAD:	Maritime Administration
MEA:	Metal Electrode Assembly
MSC:	Marine Safety Center (of the United States Coast Guard).
MW:	Megawatt
PCV:	Pressure Control Valve
PEM:	Proton Exchange Membrane
P&ID:	Piping and Instrumentation Diagram
PI:	Principal Investigator
PM:	Particulate Matter
POC:	Point of Contact
POSF:	Port of San Francisco
PRD:	Pressure Relief Device
SF-BREEZE:	San Francisco Bay Renewable Energy Electric Vessel with Zero Emissions
SFFD:	San Francisco Fire Department
SIO:	Scripps Institution of Oceanography
SSM:	System Support Module
STBD:	Starboard
TPRD:	Thermally-activated Pressure Relief Device
USCG:	United States Coast Guard
VDC:	Volts Direct Current

II. Executive Summary

In support of the IMO's GHG emission goals, and to promote the introduction of hydrogen fuel cell technology onto vessels in North America, the Hornblower Group company Alcatraz Island Services, LLC (AIS), organized a project named "Nautilus" to retrofit an existing diesel-battery hybrid passenger ferry with a hydrogen fuel-cell system in order to test and evaluate hydrogen technology as a new approach to reduce reliance on diesel fuel for motive and auxiliary power. With funding from U.S. Department of Transportation's Maritime Administration (MARAD) for Phase 1 of the project, AIS aimed to design a "buildable" hydrogen fuel cell hybrid drivetrain to supply auxiliary power to the vessel, and submit the plans for United States Coast Guard (USCG) approval in order to retrofit the existing hybrid electric passenger ferry, newly christened the Discover Zero. The improved propulsion system integrates power supplied by hydrogen fuel cells with the existing lithium-ion batteries already onboard the vessel, providing a battery/fuel-cell hybrid capability supplementing the diesel engines already on the vessel. In future phases, Phase 2 (installation) and Phase 3 (deployment), the Discover Zero will reduce emissions on the San Francisco Bay, and further promote maritime hydrogen use. Phase 1 has been completed, such that buildable plans and drawings for the vessel's reconfiguration have been created and have received a Design Basis Letter of approval by the USCG Marine Safety Center (MSC). MARAD has provided a "Go" decision to proceed to Phase 2 of the project. This report describes the activities and results of Phase 1.

The Core Project Team for the Nautilus Project consisted of the following companies and institutions:

Alcatraz Island Services (AIS): provided overall project management (oversight, coordination, budget), and brought a critical vessel-owner/operator's perspective to the project.

Sandia National Laboratories (Livermore, CA): provided independent technical analysis and assessment of the Discover Zero hydrogen power arrangements, as well application of relevant safety codes and standards.

Cummins (formerly Hydrogenics): The initial fuel-cell power system design was based on the Hydrogenics (now Cummins) HD 30 33 kW fuel cell module.

PowerCell: provided advanced fuel-cell system design based on PS-185, a 185 kW fuel cell module.

DeJong & Lebet, Inc.: provided naval architecture services for the Nautilus Project.

Hexagon Purus: provided critical information on their Type IV hydrogen storage tanks.

While not part of the Nautilus Project Core Team, other institutions made important contributions to the Project, including DNV-GL, The American Bureau of Shipping (ABS), the Port of San Francisco and the USCG.

The Hornblower Discover Zero, formerly the New York Hornblower Hybrid, is shown in Fig. A as it sails underneath the Golden Gate Bridge into San Francisco Bay. The Discover Zero is the baseline vessel to which hydrogen fuel cell technology is to be added.

Figure A: The New York Hornblower Hybrid sailing underneath the Golden Gate to its new home on the San Francisco Bay. Indicated are the storage spaces allotted to H_2 tanks and the Fuel Cell Room designed to house PEM fuel cells.

A preliminary design for the combination of hydrogen tanks, fuel cell, hydrogen distribution system and integration into the Discover Zero was generated in order to received technical feedback from DNV-GL via a HazID meeting. Figure B shows that preliminary design.

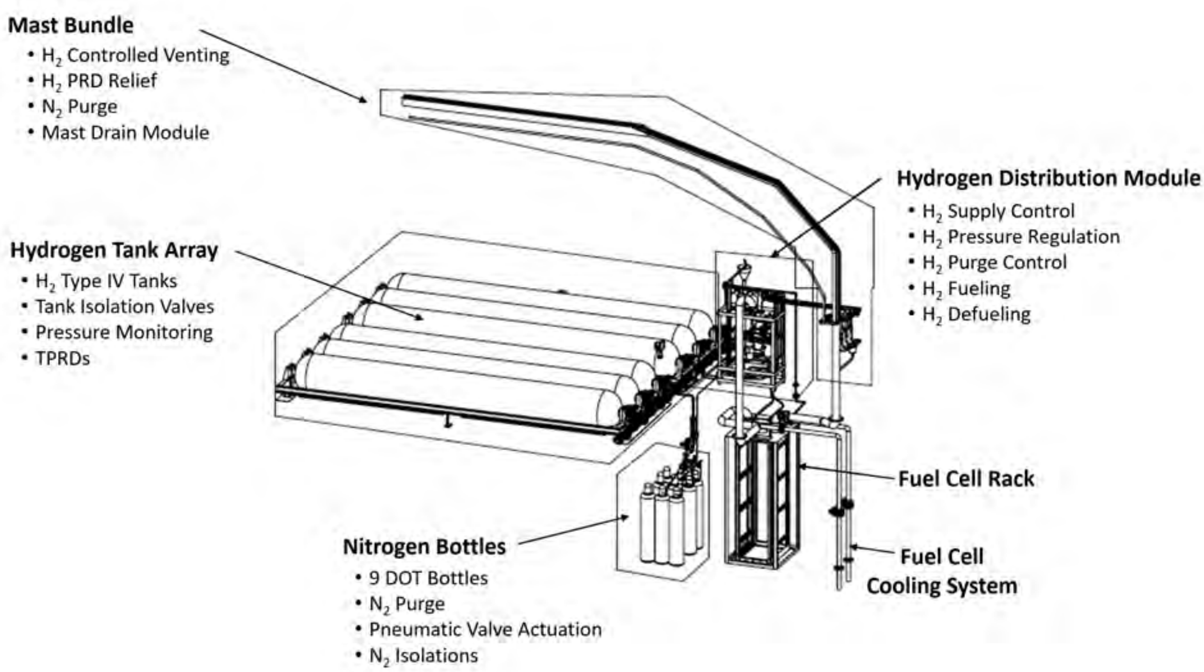

Figure B: Preliminary design of the hydrogen gas systems onboard the Discover Zero.

Using the existing space allotted for the hydrogen tanks on the Discover Zero, 6 Type IV Hexagon Purus/Magnum tanks could be accommodated. Each tank stores 28 kg of hydrogen, bringing the total amount of stored hydrogen on the vessel to 168 kg of hydrogen, stored at 250 bar pressure. The preliminary design also incorporated a 100 kW Hydrogenics HyPM-R 120S Fuel Cell Rack.

With the hydrogen technology elements integrated into the existing vessel design, suggested by Figure B, the next step was a risk assessment exercise to get initial technical guidance on the design effort. Toward that end, a Risk Assessment was conducted by a team of experts led by DNV-GL, including representatives from Hornblower, USCG, Sandia, DeJong & Lebet and DOT/MARAD. The risk assessment took the form of a traditional "HazID" workshop, held on March 12 and 13 of 2019, onboard the New York Hornblower Hybrid while it was still operating in New York City. No "show-stopping" problems were discovered with the design. There were 30 "failure scenarios" that were identified that required risk mitigation actions, and 49 "action items" which were implemented in the advanced design that resulted from the workshop recommendations. Overall, the fuel cell system design and vessel integration were evaluated by DNV-GL and was granted an "Approval in Principle" (AIP), which is an approval of the basic concept and the preliminary design to that point.

It was the task of DeJong & Lebet to take the existing Discover Zero ship spaces allowed for hydrogen, and the feedback from the HazID Risk Assessment provided by DNV-GL and create an advanced design for safely and effectively introducing the hydrogen technology elements onto the Discover Zero. At the same time, this advanced design needed to adhere to the proscriptions imposed by the IGF Code and the DNV-GL Class rules regarding hazardous zones and ventilation, and also enable straightforward bunkering of the vessel. The advanced design was examined in detail by the USCG, who made further recommendations for safe design and operation. The final Discover Zero design incorporates these USCG recommendations, while maintaining the recommended actions provided by the initial HazID study conducted by DNV-GL.

We followed an overall safety philosophy to eliminate, as much as possible, confined spaces where hydrogen can collect. This involved making some modifications to the baseline vessel in the hydrogen storage area, allowing the H_2 tanks to be "out in the weather." Figure C shows the design of putting the six hydrogen tanks on the 3rd Deck of the Discover Zero. In this arrangement, any leak in the hydrogen storage system would rapidly rise and disperse, without risk of collection. We did provide a notional canopy covering the tank array space, which would allow rapid dispersion of any leaked hydrogen, while also providing protection from animal life.

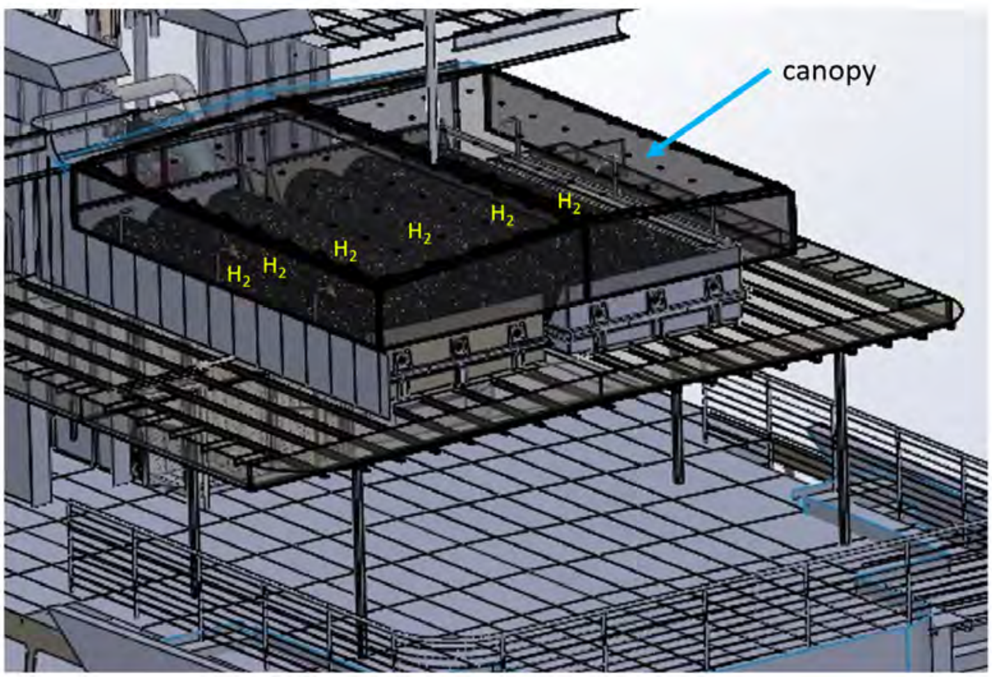

Figure C: 3D model image of the H_2 Tank Array with notional canopy.

A challenge for DeJong & Lebet was to incorporate a fuel cell and all associated equipment in the space allowed in the Fuel Cell Room and adjacent to it. The original advanced design which was reviewed by the USCG and resulted in a Design Basis Letter, considered the use of a 100 kW Hydrogenics HyPM-R 120 S Fuel Cell Rack. However, after completion of the existing design, it was decided for the future to consider migrating to a 185 kW PowerCell PS-185 fuel cell, taking advantage of the improved technology with higher power density within the same footprint as the 100 kW Hydrogenics HyPM-R 120 S fuel cell. A second Design Basis Letter for the higher fuel cell power design is in progress. The figures presented here apply equally well to either Fuel Cell

Rack since the approach to rack ventilation and the balance-of-plant facilities (air, cooling water) are analogous.

Figure D shows the installation of the PEM Fuel Cell Rack in the Discover Zero's Fuel Cell Room. Provisions are shown for the hydrogen supply, as well as the independent ventilation system for the Fuel Cell Rack and the Fuel Cell Room.

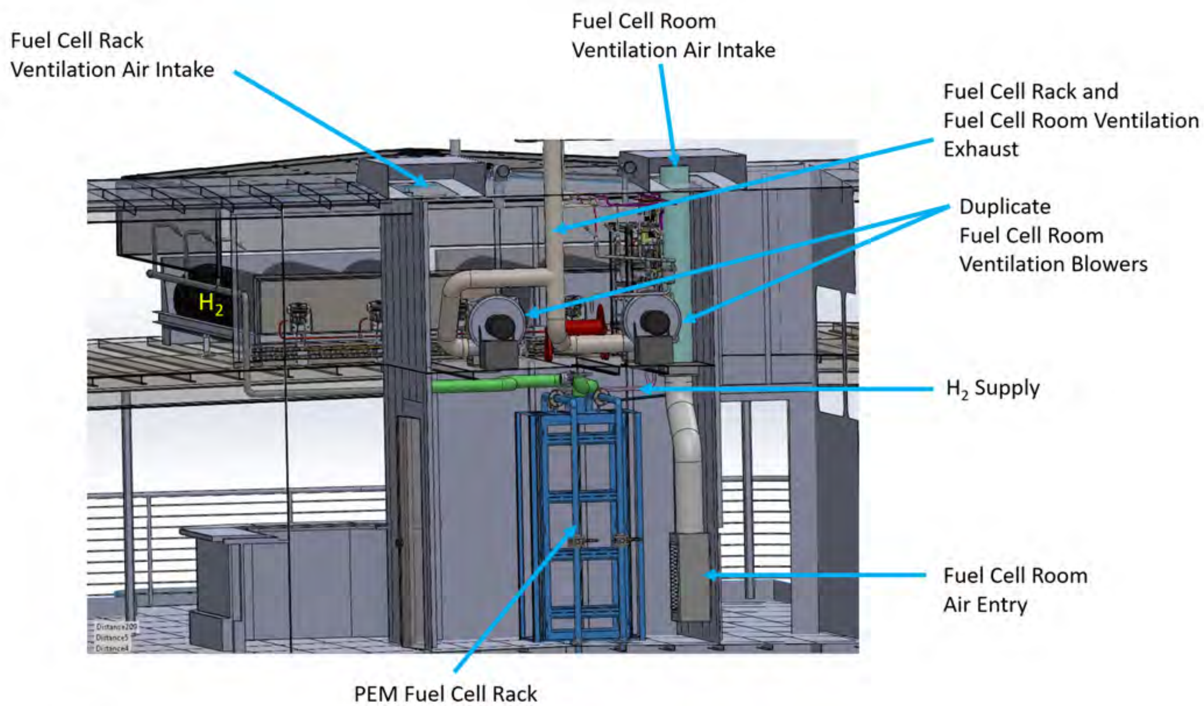

Figure D: 3D model of the placement of the PEM Fuel Cell Rack in the Discover Zero's Fuel Cell Room, with important gas handling components identified. This is a view from forward looking in the aft direction.

Two separate and independent ventilation paths are provided for the Fuel Cell Rack, and the Fuel Cell Room. These form complementary and somewhat redundant mitigation for any small Fuel Cell Rack hydrogen leaks that might occur and discharge them to Vent Masts on the vessel.

The organization of the Vent Masts takes advantage of the existing "Swept Back" Vent Mast already on the Discover Zero vessel but adds an additional Vertical Vent Mast to handle other venting needs. The Vent Masts on the Discover Zero are shown in Figure E.

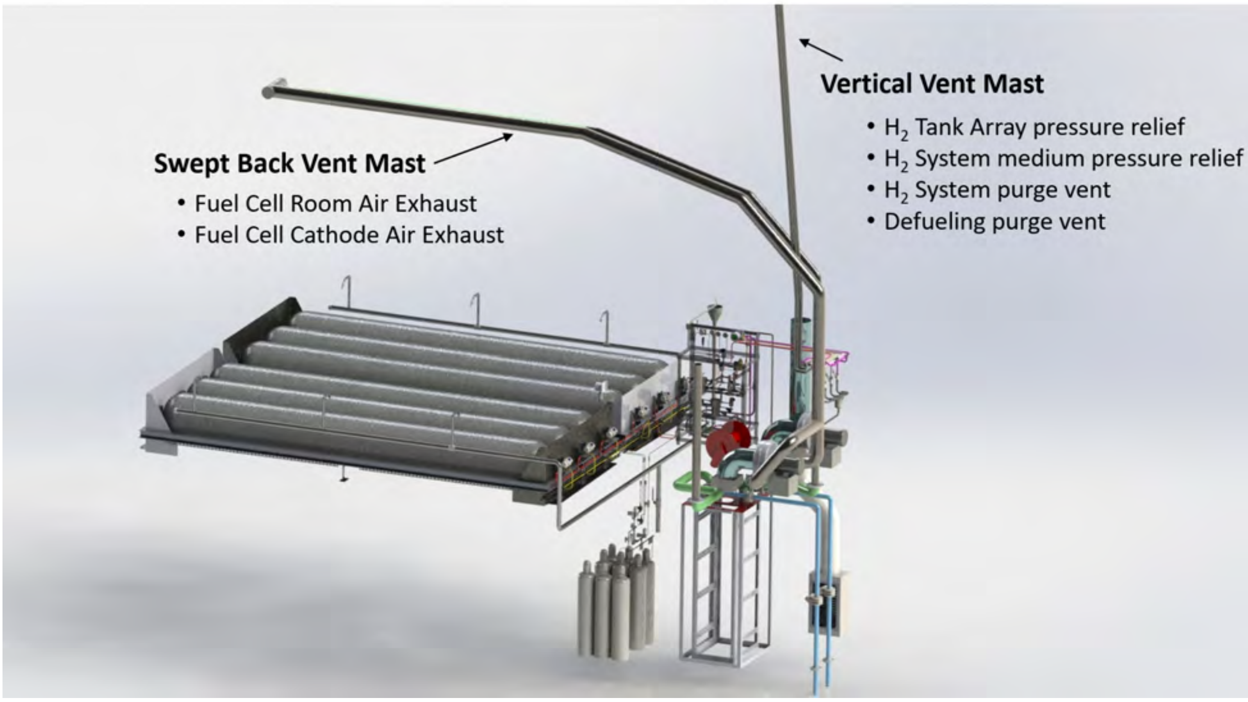

Figure E: Organization of the Vent Masts on the Discover Zero and the hydrogen-containing flows that are directed to each. Two vent masts are shown, the existing Swept Back Vent Mast Bundle and the Vertical Vent Mast.

An important aspect of the design of a safe vessel is the specification of the "hazardous zones" on the vessel. These zones, dictated by regulations such as the IGF Code, identify areas where possible ignition sources cannot be placed. The Nautilus Project team developed technically sound hazardous zones on the Discover Zero associated with the Vent Masts, the hydrogen tanks, the hydrogen fuel distribution system and the Fuel Cell Room. These hazardous zones were a particular focus of the USCG review that resulted in the issuing of a Design Basis Letter.

An application for approval of the advanced design of the Discover Zero in the form of a Design Basis Letter was submitted to US Coast Guard on April 18, 2020. The design package was reviewed by the USCG MSC. Based on a review of these materials, as well as regular meetings between the Project Nautilus team with the MSC to discuss and address various hydrogen safety issues, the USCG determined that the advanced Discover Zero design basis package submitted provided an equivalent level of safety to that of a title 46 CFR Subchapter K diesel-fueled vessel. The Design Basis Letter was issued on March 11, 2022. Subsequently, Hornblower submitted on June 29, 2022 an application to increase fuel-cell capacity to 185 kW (in place of 100 kW) using the PowerCell fuel cell module. The application to update the Design Basis Letter is in the final stage of evaluation at USCG.

Since Phase 1 produced a design with sufficient detail to be constructed (a "buildable design), very specific lessons were learned as the design was evaluated by DNV-GL as well as by the USCG. Some of these issues and the lessons they taught are summarized.

Protective Steel Plates:
In conversations with the USCG, it was pointed out that a significant risk to the Type IV composite tanks can come from a jet fire caused by a hydrogen release from the high-pressure (250 bar) manifold, followed by "spontaneous ignition." To protect the tanks against this threat, a protective steel plate was included in between the tank necks and the tank isolation valves. These plates were placed both fore and aft of the tank array. We believe these protective plates are a good precaution for any application involving an array of hydrogen tanks.

Temperature-activated Pressure Relief Device (TPRD):
The TPRD is a device that prevents over-pressurization of a hydrogen tank in the event of fire. In the course of discussions with the USCG there was a concern that the water deluge system that would be used to cool the tanks in the event of a fire might also cool the TPRDs. This is a problem because the water cooling might not allow the TPRD to sense the heat of the fire and perform their function of pressure relief. This problem was resolved by installing a splash shield over the TPRD, which the USCG found to be a resolution to the problem.

Composite Hydrogen Tanks:
In the course of our work with USCG, it became apparent that the Hexagon Purus Type IV composite hydrogen tanks we wanted to use, while approved by ABS for maritime storage and transport of hydrogen, were not approved for actual use of the hydrogen contained in the tanks. This was a restriction that had no technical basis, and so needed to be corrected. As a result of a series of communications with the Nautilus Project Team, ABS was able to approve using the hydrogen in the tanks already approved for storage. This broader Class approval will benefit other projects and vessels wanted to use lightweight Type IV composite tanks for hydrogen storage in a maritime environment.

Fuel Cell Technology:
Over the 3 years of the project, fuel cell technology advanced to the point where a 185-kW fuel cell rack could replace the original 100-kW fuel cell rack with no increase in footprint. This has required a second review by the USCG of the Discover Zero design with a higher power fuel cell. A lesson learned here is that it might be advantageous to anticipate that product development into the design of the vessel. By this we mean creating a vessel design that accommodates a fuel cell system that is actually 20 to 50% more than commercially available when the design was being created. That way, since it takes time for the USCG to fully review a specific design, a higher-power fuel cell design will have already been approved.

HazID Workshop:

A productive approach in this project was to develop a preliminary vessel design that did not contain all of the necessary features, but enough to be assessed for hazards in a HazID workshop. Then, the feedback from the Class Society running the HazID meeting could be folded into an advanced Discover Zero design to be submitted to the USCG. This approach worked well in this project, and could be a model for other projects engaged in a similar design activity for hydrogen fuel cell technology.

USCG:

A lesson learned in this Nautilus Project was to have a very early engagement with the USCG, and then have continuing discussion with them as the design progressed. This occurred even before the official submission of the design package for consideration for a Design Basis Letter. Discussions took the form of bi-weekly Zoom meetings with the USCG, even if the only point of the meeting was maintaining contact. This developed a collaborative relationship between the Nautilus Project Team and the USCG which we found be very helpful, aided the USCG review of the project, and help expedite the Design Basis approval process. Also, as issues arose with the USCG (e.g., the initially limited ABS hydrogen tank approval), these issues could be promptly addressed.

With the Design Basis Letter issued by the USCG, the next step is to secure funding for Phase 2 of the project, involving building, installing and testing the hydrogen fuel cell technology components for use on the Discover Zero.

1. Introduction

The International Maritime Organization (IMO) has specified a targeted reduction of the total annual greenhouse gas (GHG) emissions from international shipping by 70% (compared to 2008 levels) 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 both GHG emissions as well as criteria pollutant emissions (NO_x, hydrocarbons (HC) and particulate matter (PM)) that immediately 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 also assessed different methods of storing hydrogen or generating it on-board. Bicer and Dincer performed a comparative analysis of using hydrogen or ammonia in internal combustion engines (ICEs) as a replacement for burning heavy fuel oils on transoceanic vessels [15]. The 2018 IMO proscriptions [1] increased the interest in using hydrogen fuel cell technology on ships. Since then, a number of 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]. Supplemental to these studies, 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].

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 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 safety (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 versed in the safety-related properties of hydrogen and how to manage them in the design of vessels, and shore side refueling facilities.

These prior studies [23, 24] 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 also 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 used dual fuel (H_2/diesel) internal combustion engines supplied with 36 kg of useable hydrogen stored in 200 bar 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 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), with the hydrogen stored as compressed hydrogen. The Hydrocat 48 contains 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 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, originally named “Water-Go-Round” but renamed “Sea Change,” has been designed, built, has passed USCG Sea Trials and is now in San Francisco Bay [29]. The Sea Change will be used for public transport in the summer of 2023. 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 hold 80 passengers, and can reach a top speed of 13 knots. The vessels uses PEM hydrogen fuel cells for propulsion power, and stores ~ 250 kg of hydrogen in 250 bar hydrogen tanks. The Sea Change has the distinction of being the only maritime hydrogen vessel in the world that is USCG approved.

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 MARAD-funded 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, and is currently in the detailed design phase [30].

In 2018, Hornblower Group organized a project to address this question for the ferry vessel application. 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 Hornblower Hybrid, was transferred to San Francisco for potential retrofitting of the hydrogen systems once a Design Basis letter from the USCG was received, and funding was acquired for retrofit construction. The design project was funded by the U.S. Department of Transportation's Maritime Administration (MARAD). This report describes the design process for the hydrogen variant of the vessel, renamed the Discover Zero, provides detailed buildable design elements, and also discusses the regulatory engagement the project had with the USCG.

2. Project Description/Goals and Project Participants

In support of the IMO's GHG emission goals, and to promote the introduction of hydrogen fuel cell technology onto vessels in North America, the Hornblower Group company Alcatraz Island Services, LLC (AIS), organized a project code-named "Nautilus" to retrofit an existing diesel-battery hybrid passenger ferry with a hydrogen fuel cell system to augment electricity with a view to reduce or completely remove reliance on diesel fuel for motive and auxiliary power. With funding from MARAD for Phase 1 of the project, AIS aimed to design a "buildable" hydrogen fuel cell hybrid drivetrain, and submit the plans for USCG approval to retrofit the existing hybrid electric passenger ferry, newly christened the Discover Zero. The improved propulsion system integrates power supplied by hydrogen fuel cells to the already existing lithium-ion batteries that supplement the diesel engines on the vessel. Thus, the final vessel would have two sources of non-diesel electricity: hydrogen fuel cells and lithium-ion batteries. Ultimately in Phase 2 (installation) and Phase 3 (deployment) of the project, the Discover Zero will reduce emissions on the San Francisco Bay, and further promote maritime hydrogen use. Phase 1 has been completed, such that buildable plans and drawings for the vessel's reconfiguration have been created and have received a Design Basis Letter of approval by the USCG Marine Safety Center (MSC). With the Design Basis Letter in hand for the Phase 1 design, MARAD can now consider moving to Phase 2 of the project. This report describes the activities and results of Phase 1.

2.1. Core Project Team

The Core Project Team for the MARAD-funded Nautilus Project consisted of the following companies, institutions and personnel:

Alcatraz Island Services (AIS)

Narendra Pal (Principal Investigator, PI)
Nick Monroe (Business Lead)
Gordon Loebl (former PI)
Matt Unger (former Hornblower technical lead)

AIS provided overall project management (oversight, coordination, budget), and brought a critical vessel-owner/operator's perspective to the project. AIS also evaluated the commercial value proposition for the introducing hydrogen fuel cell technology onto an existing vessel. From a technical and business perspective. AIS was supported by the parent company Hornblower Group, Inc. for this project.

Sandia National Laboratories (Livermore)
Lennie Klebanoff (Hydrogen Expertise)
Joe Pratt (initial Sandia POC, formerly Sandia)

Sandia provided an independent technical analysis and assessment of the Discover Zero hydrogen fueling arrangements, as well application of relevant safety codes and standards. This input is based on Sandia hydrogen storage expertise derived from prior studies using hydrogen fuel cells in different applications, including in aviation [31], construction equipment [32], as range extenders in vehicles [33], shore-side power applications [34] and hydrogen vessels [11, 24, 25]. Also, Sandia provided input on safe design of the fuel cell powertrain system, and interpretation of the IGF code [35] as it relates to hydrogen use on vessels. Sandia participated in the HazID study of the system on March 19, 2019 in New York City.

Cummins (formerly Hydrogenics)
Ryan Sookhoo (Business and Technical Lead)
Nader Zaag (Fuel cell Technology Lead)

The initial fuel cell power system design was based on the Hydrogenics (now Cummins) HD 30 33 kW fuel cell module. These modules were assembled into a HyPM-R 120S fuel cell rack, with the total fuel cell output power being initially 100 kW. Cummins provided technical guidance on the required hydrogen input, the ventilation requirements for the Fuel Cell Room, as well as details on the fuel cell output power required for proper integration into the overall vessel power system. Cummins also participated in the HazID review onboard the vessel while it was still operating in New York City. Cummins provided information on fuel cell safety and operation procedures, and performed detailed engineering of the fuel cell power, control, storage and safety systems.

DeJong & Lebet, Inc.
Brian Boudreau (Naval Architect)
Ed Vaugh (Naval Architect, Business Development)

Dejong & Lebet provided naval architecture services for the Nautilus Project. This included producing all required plans and drawings (including for hazardous zones) for submission to USCG for approval. Plans include developing schematics and evaluating vendor hydrogen storage and fuel cell system technical details to integrate and interface into the existing on-board ship systems within the envelop of the ship's limited hydrostatics and stability. DeJong & Lebet performed considerable work creating installation designs for the hydrogen systems (hydrogen tanks, manifolding, fuel cells and ventilation requirements) that satisfied the IGF code [35] for gas fueled ships. Hence, the naval architect was the driver for integrating various inputs from the battery manufacturer, fuel cell manufacturer, propulsion system integrator, and Classification Society.

Hexagon Purus
Kevin Harris (former Director of Business Development)

Hexagon provided critical information on the dimension and capacities of their Type IV hydrogen storage tanks, as well as providing guidance on hydrogen refueling such that the tank temperatures did not exceed 85 ºC during a refueling to 250-bar pressure. Hexagon also helped AIS coordinate with the Class Society ABS on the type approval required for using Hexagon tanks in this maritime application, and the required regulations surrounding the use of Temperature-activated Pressure Relief Devices (TPRDs) for the tank array planned for the Discover Zero vessel. Hexagon also helped the Project Team develop a method to prevent a hydrogen manifolding jet fire from impacting the composite hydrogen tanks, an added safety feature.

2.2. Other Project Contributors

While not part of the Nautilus Project Core Team, these other institutions and personnel made important contributions to the Project.

PowerCell Group
Johan Beyer (Business Lead)

Later in the design Phase 1, it was realized that with improvements in the footprint of hydrogen PEM fuel cells, that a higher power fuel cell could be accommodated in the Fuel Cell Room of the Discover Zero with very little change in the overall hydrogen power system design. A second design, based on the PowerCell 185 kW fuel cell system was generated, and submitted to the USCG for approval. A Design Basis approval for this modification is in its final review with USCG.

DNV-GL
Benjamin Scholz (Ship Type Expert)
Lars Langfeldt (Marine)
Anthony Teo (Business Development)

A Class Society based in Hovik, Norway, DNV-GL provided technical consultation on the application of the IGF Code to the Discover Zero hydrogen hybrid drivetrain. DNV-GL organized and ran the HazID meeting in New York City, and generally assisted with the interpretation of applicable codes to the technical layout of the hydrogen storage, fuel cell room, and their interfaces. DNV-GL has published class society "rules" for using hydrogen onboard vessels [36].

The American Bureau of Shipping (ABS)
Harish Patel (Pressure Vessel Expert)

ABS is a Class Society based in Houston Texas. They have been active in the hydrogen regulatory space, and was a participant in the SF-BREEZE study [24]. ABS has published guidelines for using hydrogen fuel cells on vessels [37]. Hexagon composite hydrogen tanks specified for this project are type approved by ABS. Further to clarify the ambiguity about whether these tanks can be used for carrying hydrogen for electricity production via fuel cell onboard marine vessel, Hornblower commissioned a study by ABS.

United States Coast Guard (USCG)
Tim Meyers
Frank Strom
Virginia Buys

As the Discover Zero hydrogen design advanced, the project engaged the USCG MSC in Washington DC. The MSC reviewed technical plans and drawings, provided feedback and ultimately a Design Basis Letter of regulatory approval was granted in March 2023. The local USCG office, Sector San Francisco was also involved in the design review for Phase 1 but will be even more heavily involved when the Discover Zero will be retrofitted with hydrogen fuel cells, and is ready to be place in service in Phase 3. At that time, Sector San Francisco will serve as the local field command, overseeing Discover Zero operations, including hydrogen refueling and fuel cell operation, with respect to safety, security, and environmental protection.

Port of San Francisco (POSF)
Rich Berman (Environmental Lead)

The Port of San Francisco is the San Francisco agency and landowner with oversight responsibilities of port facilities and waterfront, where the Discover Zero is expected to refuel and take on passengers. Even during the design Phase 1, the project team engaged with the POSF to receive guidance and policies for hydrogen delivery and fueling, as well as the barometer for acceptance of hydrogen fueled vessels at berth. The POSF has its own Fire Department, part of the overall San Francisco Fire Department (SFFD) organization. The Project will continue to engage the POSF fire/safety staff to ensure the Discover Zero design is fully compatible with established industry procedures for the safe storage and use of hydrogen, that the vessel has the proper fire prevention and emergency response procedures in place, and the public's safety is protected.

3. Technical Approach and Design Philosophy

3.1. The Baseline Vessel

The Hornblower Discover Zero, formerly the New York Hornblower Hybrid, is shown in Figure 1, as it sails underneath the Golden Gate Bridge into San Francisco Bay. The Discover Zero is the baseline vessel to which hydrogen fuel cell technology is to be added.

Figure 1: (A) The New York Hornblower Hybrid sailing underneath the Golden Gate to its new home on the San Francisco Bay. Indicated are the storage spaces allotted to H_2 tanks and the Fuel Cell Room designed to house PEM fuel cells; (B) Photo of the existing H_2 tank storage space; (C) Photo of the existing Fuel Cell Room. Photos in (B) and (C) are courtesy of L.E. Klebanoff.

This vessel was completed on October 26, 2011, and was originally designed to incorporate a hydrogen fuel cell system. Hornblower's underlying motivation was to gain experience with hydrogen fuel cell technology, but within the limited scope of providing hydrogen-based auxiliary power to the vessel. Thus, space was left in the design to accommodate high pressure hydrogen tanks and a PEM fuel cell. However, prior to the Nautilus project, no fuel cell capability was installed. There were at least two historic reasons for this. First, a decade ago the USCG was unfamiliar with hydrogen, which rendered USCG regulatory approval of hydrogen use on a passenger vessel problematic. This situation changed considerably in the 2016 – 2019 timeframe with the Sandia SF-BREEZE hydrogen vessel study [24] which included regular meetings with the USCG to provide "technical transfer" of hydrogen "know-how" to the USCG. Thus, it would have been premature, if not infeasible, in 2011 to bring a hydrogen vessel all the way through the USCG approval process to receive permission to use compressed hydrogen and carry passengers.

The second reason was that hydrogen had little availability on the East Coast of the United States in 2011, and there were restrictions on transporting hydrogen onto Manhattan Island through the various traffic tunnels servicing New York City. The codes and safety understanding of how to safely transport hydrogen through tunnels has advanced considerably since that time [38]. Thus, in 2011, the New York Hornblower Hybrid was a little too far ahead of its time to immediately incorporate hydrogen technology. When the Nautilus Project commenced in 2019, the regulatory and infrastructure environment for hydrogen fuel cell technology was much more supportive.

The original embodiment of the Hornblower New York Hybrid incorporated solar power, wind power, and low-emission diesel technology. It can carry 600 passengers. It is an diesel-electric propelled ship, powered by conventional Scania motors augmented by batteries, solar power and wind power. It originally featured two Helix wind 5-kilowatt wind turbines, a 20-kilowatt solar array, as well as LEED certified carpets, LED lighting, and an interior made partly of recycled and sustainable materials to promote state-of-the-art environmental practice at the time. In the 2018 timeframe, the wind and solar capabilities completed their demonstration periods, and were removed leaving the potential to add hydrogen fuel cell technology. Arriving in San Francisco in 2019, the vessel was rechristened the Discover Zero.

The features of the Discover Zero baseline are as follows (battery and associated improvements were delayed due to Covid and are pending as of the date of this report).

Length: 168 feet

Beam (width): 40 feet

Draft: 6 feet

Electric Drive Motors: Two 700 HP each HP AC Induction Motors, for a total of 1400 HP

Diesel Generators: Two Scania 03-65A DI16 082M Tier III Diesel Engines, 588 kW each.

Batteries: Two 700 VDC AGM Batteries, with total energy capacity of 1.6MWh.

Total Diesel Fuel Capacity = 8,000 gallons (30383 L).

Top Speed: ~ 10 knots.

Assuming a density of diesel fuel of 0.832 kg/L [17] and a diesel lower heating value (LHV) of 43.4 MJ/kg [17], the total diesel fuel energy stored on-board the Discover Zero 1.09×10^6 MJ. The Scania engines are 41% efficient, so the usable diesel fuel energy is $0.41 \times 1.09 \times 10^6$ MJ = 4.47×10^5 MJ. The total installed battery energy is 5760 MJ. The total usable battery installed energy capacity is 95% of 5760 MJ = 5472 MJ which is only 1.2% of the diesel fuel energy installed on Discover Zero. Nonetheless, for very short runs, such as the Park Cruise tour the Discover Zero is currently serving, the vessel can complete one tour before it requires recharging .

To gain experience with hydrogen fuel cells Hornblower approached MARAD with a three-phase project (each Phase one year in duration) to design, build and deploy hydrogen fuel cells on the Discover Zero. The original concept was to put 100 kW of fuel cell power (from Cummins) onboard the vessel in the Fuel Cell Room. However, with advances in reducing the fuel cell footprint, this power spec was later increased to 185 kW, which led the project to PowerCell as a fuel cell provider. The function of the hydrogen fuel cell is to provide electricity to the vessel's electrical grid, where that energy can be used for propulsion or auxiliary power (lights, ventilation, etc.).

3.2. Hydrogen Storage

Using the existing space allotted for the hydrogen tanks (Figure 1), the hydrogen storage was specified as follows:

Capacity:	168 kg compressed gaseous hydrogen
Pressure:	250 bar
Type of storage:	Type IV Composite Tanks
Number of tanks:	6
Capacity per Tank:	28 kg hydrogen
Make / Model:	Hexagon Purus / Magnum
Type Approval:	ABS Type Approval
Pressure Relief:	Thermally activated Pressure Relief Device (TPRD)

These tanks have dimensions as follows: Outside diameter = 660.4 mm (26 in), Overall length = 5690 mm (224 inches), water volume = 1520 L, yielding a hydrogen capacity of 28 kg each [39], giving a total stored hydrogen mass of 6 x 28 = 168 kg.

Using a LHV of hydrogen of 119.96 MJ/kg [17], the total amount of stored hydrogen fuel energy is 2.01×10^4 MJ. Assuming a fuel cell efficiency of 50%, we have $0.50 \times 2.01 \times 10^4$ MJ = 1.00×10^4 MJ of useable hydrogen energy, or 2.2% of the installed usable diesel fuel energy. Thus, the hydrogen in this instance is providing a purely auxiliary energy function, and not attempting to displace a significant amount of diesel-derived propulsion energy on the vessel. The amount of useable hydrogen energy is ~ 1.8x that of the total useable battery energy currently on the vessel.

Figure 2 shows a picture of the Hexagon Purus Tank considered for the Discover Zero.

Figure 2: Example of the Type IV Composite Tank from Hexagon Purus planned for the Discover Zero. Photo Credit: Bikram Roy-Chaudhury, Air Liquide.

The hydrogen tanks selected are "Type IV" tanks. A Type IV tank involves a plastic inner liner surrounded by a black fiberglass and carbon composite overwrap. The advantage of the Hexagon tank selected is that it has already been approved by the Class Society ABS for hydrogen transport in maritime settings. A second advantage is the Nominal Working Pressure of 250 bar presents the lowest tank cost per kilogram of hydrogen stored. One characteristic of these tanks is that one needs to maintain the temperature of the tank below 85 ºC, or else one threatens the epoxy adhesive that is used to bind the overwrap to the inner liner. This is an important consideration when fueling the tank to a high pressure of hydrogen, where compression heating of the hydrogen can warm the tank [40].

Although the 250-bar Hexagon Purus Type IV composite tanks are type approved by ABS for carrying compressed hydrogen at 250 bar onboard a marine vessel, we discovered during the course of the Nautilus Project that there was no approval issued for using the hydrogen contained therein for the purpose of generating electricity via fuel cell onboard the vessel. This was brought to our attention by the USCG. Since this restriction on hydrogen use made little technical sense, to clear this ambiguity, AIS awarded a study to ABS to assess if it was safe to use hydrogen stored in Hexagon Purus tanks for feeding a PEM fuel cell for generating electricity onboard a marine vessel. The ABS study concluded that these ABS-type approved Hexagon composite tanks with the current design setup of hydrogen system on Discover Zero can be safely used to not only carry hydrogen onboard Discover Zero but it is also safe to utilize hydrogen in these tanks for fuel cell electricity generation onboard. This was a significant regulatory accomplishment of the project, in that the USCG, seeing the ABS report, saw no barrier to using 250-bar hydrogen in the manner desired for the Discover Zero, or for other applications of using compressed hydrogen, stored in composite tanks, onboard vessels.

3.3. Hydrogen Fuel Cell

Our original concept was to base the Discover Zero hydrogen system on the Hydrogenics (now Cummins) HYPM 30 33 kW fuel cell module, shown in Figure 3. All of the detailed design work reported here considers a 100 kW PEM fuel cell system assembled from 4 HYPM HD 30 modules place in a HyPM-R 120 S rack, shown in Figure 3. Subsequently, a PowerCell 185 kW was found to provide higher power with the same footprint, so provisions are currently being made to pursue that fuel cell for the Phase 2 build.

Figure 3: Hydrogenics HyPM-R 120S fuel rack (right) assembled from four HyPM HD 30 33 kW PEM fuel cell modules (left). Photo courtesy of Ryan Sookhoo, Cummins.

3.4. Bunkering System

The bunkering of the Discover Zero from a shoreside H_2 delivery trailer is depicted notionally in Figure 4. The system mainly consists of high-pressure hose, tubing, valves, and fittings to facilitate the safe transfer of hydrogen from a pierside tube trailer to high pressure Type IV composite tanks onboard the Discover Zero.

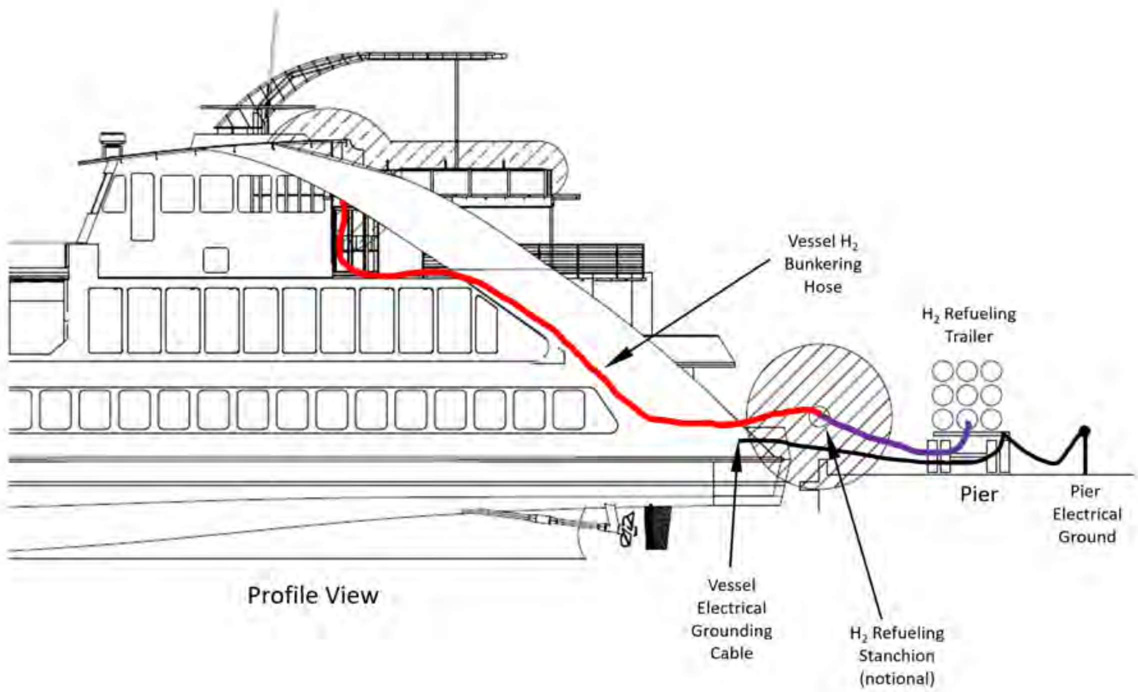

Figure 4: Profile view of the Discover Zero showing the bunkering of the vessel from a shoreside hydrogen delivery trailer. The high-pressure refueling hose is shown in red from the Discover Zero to a notional shoreside H_2 refueling stanchion. The high-pressure hose from the pierside stanchion to the H_2 delivery trailer is shown in purple. Electrical grounding of the vessel and delivery trailer is indicated by the black line.

The high-pressure hose stays on the vessel and is un-coiled and brought down to the hydrogen fueling trailer for bunkering. The bunkering system is located on the top deck which is open to air for better ventilation. The bunkering system will be fully assembled, and pressure tested in the shop before being brought to the vessel for installation and connection to the rest of the system. The bunkering system will also facilitate the transfer of hydrogen to the fuel cell after reducing its pressure around 100 psig as needed by the fuel cell system.

4. HazID Risk Assessment Based on Preliminary Design

A preliminary design for the hydrogen technology system for the Discover Zero was created for the purpose of capturing risk assessment feedback from DNV-GL and the USCG via a HazID workshop. The preliminary conceptual design is shown in Figure 5.

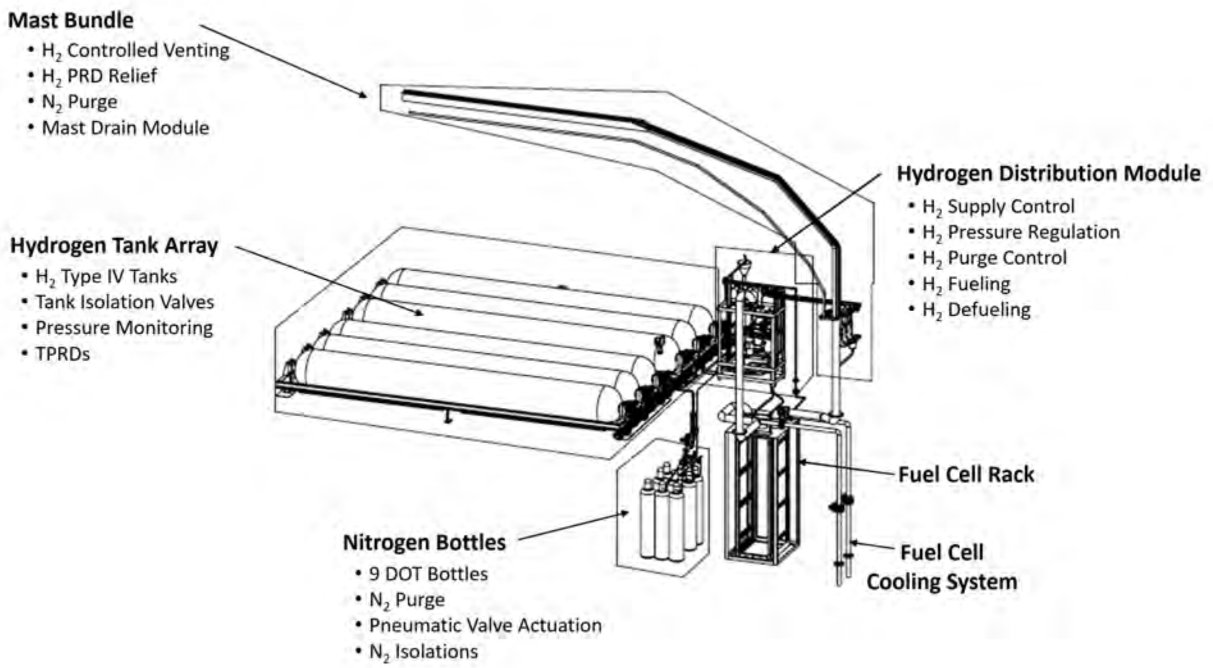

Figure 5: Preliminary design of the hydrogen technology systems onboard the Discover Zero.

A Risk Assessment was then conducted by a team of experts led by DNV-GL. Figure 6 shows the participants, with representation from Hornblower, DNV-GL, USCG, Sandia, DeJong & Lebet and DOT/MARAD. The risk assessment took the form of a traditional "HazID" workshop, held on March 12 and 13 of 2019, onboard the New York Hornblower Hybrid while it was still operating in New York City.

Figure 6: Participants in the HazID study. (L-R, front row) Sujit Ghosh (MARAD), Alex Haugh (USCG), Ed Vaughn(DeJong & Lebet), Saul Rosser (Hornblower), Nader Zaag (Hydrogenics), Anthony Teo (DNV-GL); (L-R, back row) Chris Bierker (Hornblower), Lars Langfeldt (DVN-GL), Allan Krogsgaard (DNV-GL, Nick check), Ben Scholz (DNV-GL), Shawn Ware (Hornblower), Gordon Loebl (Hornblower), Matt Unger (Hornblower), Lennie Klebanoff (Sandia).

The objectives of the HazID workshop were to review the design of the hydrogen fuel and PEM fuel cell system, as specified in the preliminary design of Figure 5, in order to:

1. Evaluate the hydrogen system's ability to operate safely and reliable during different pre-defined operational scenarios and potential unintended events,

2. Review the effectiveness of existing safety measures and, where required, to expand the safety measures as a means of establishing an equivalent level of safety to that achieved with new and comparable conventional oil-fueled and diesel-fueled vessels, and

3. Satisfy the requirement for risk assessment as stated in DNV GL Rules Part 6, Chapter 2, Section 3 and the draft (at the time) IMO Interim Guidelines for Fuel Cells.

To achieve these objectives, the overall process of the workshop is summarized in the flowchart of Figure 7, which involves a review of the entire design and operational plans for the hydrogen systems. Doing this ensures that any risks arising from the use of the hydrogen fuel and fuel cell system are addressed.

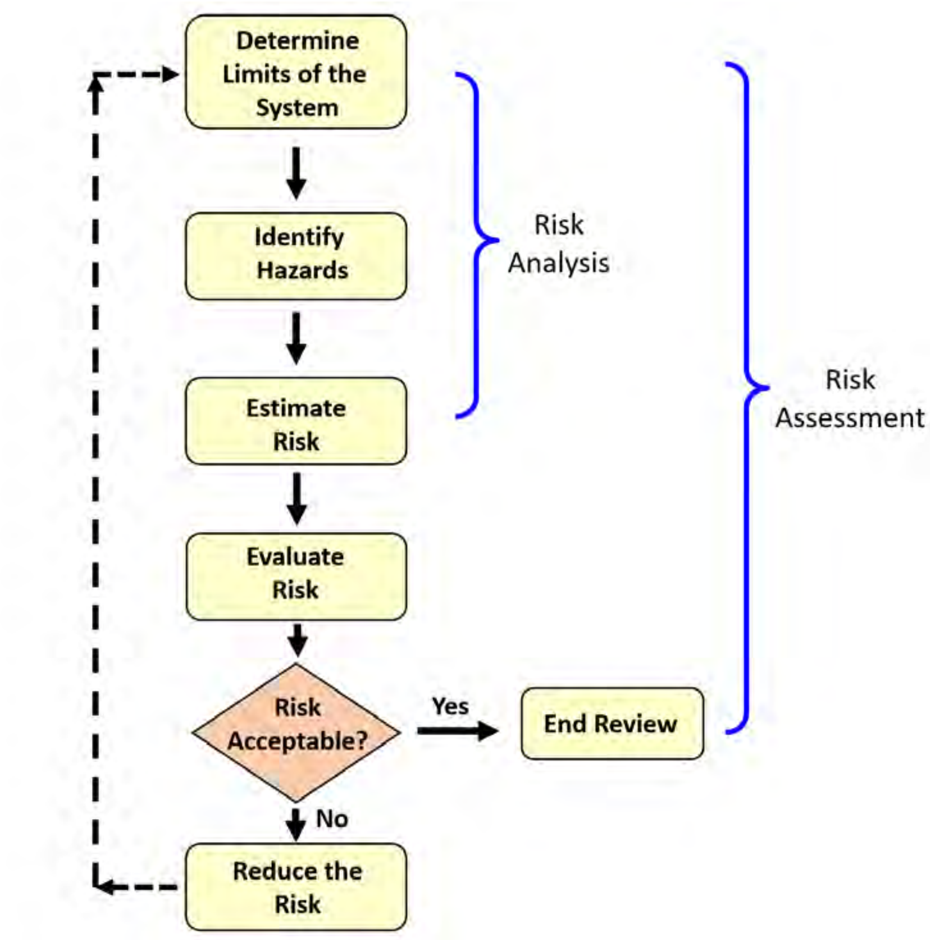

Figure 7: Flowchart for the risk assessment activity.

These risk assessment steps are described as follows:

1. **Determine the Limits of the System:** define the scope of the investigation, specify the overall system in terms of identifiable subsystems.

2. **Identify Hazards:** Evaluate the system to identify "what could go wrong." It is important that the list of items be complete, based on awareness and knowledge of past accidents and other work, and to be flexible in the sense of encouraging input and thinking from diverse experiences.

3. **Estimate Risks:** Discuss and capture the consequences of the hazards and the probability with which they will occur.

4. **Evaluate Risks:** Rank the relative importance of the hazards. Investigate to see if there are any "show-stopping" risks which make the whole activity unacceptable. If there are no "show-stopping" problems, the low, medium and higher risk scenarios are evaluated

further and ranked. If a risk is already acceptable, no further work is needed on that issue. If the risk being evaluated is not yet acceptable, the risk must be reduced.

5. **Reduce the Risk:** Formulate design or operational measures that reduce risk and improve overall safety.

The risks were ranked using a conceptual "risk matrix," shown in Figure 8, that captures and weights risks according to their severity and likeliness to occur (the so-called "frequency"), all in the context of the applicable regulatory guidelines (IGF Code, DNV-GL Draft rules, IMO).
As indicated in red, some risks may be intolerable, and essentially show-stopping if not mitigated in some way. Green represents risks that are negligible and no measures for risk mitigation are required. Between the green and red areas lies the region where most risks fall, namely in the yellow area. For these risks, designs and operations must mitigate the risk to as low as reasonably practicable (ALARP) given the economic and technical limitations. Measures for risk mitigation should be technically feasible and proportional to their benefits.

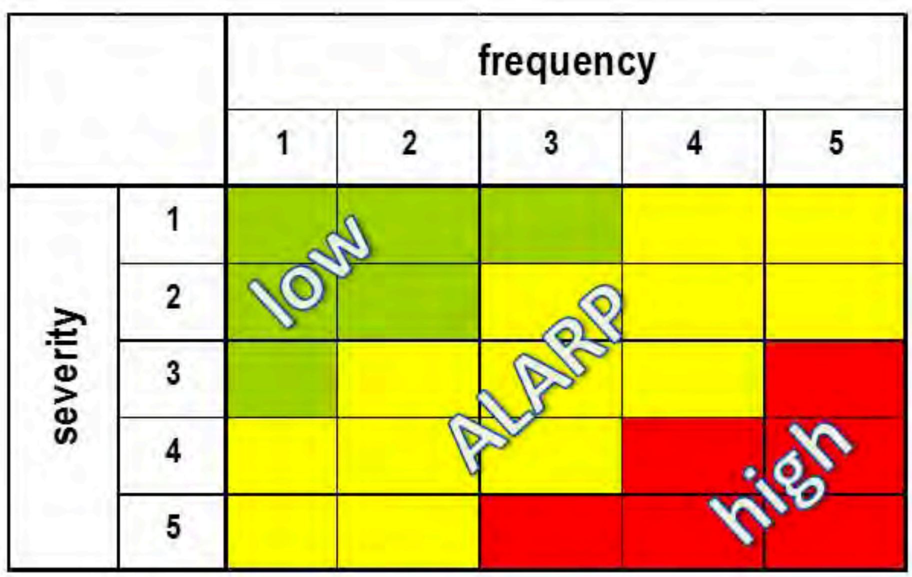

Figure 8: Example of a Risk Matrix. ALARP stands for "as low as reasonably practicable."

The basis for the discussion was the "first order" design of Figure 5, which proposed an arrangement of the hydrogen storage tanks, fuel cell system, approach to bunkering and safety features (ventilation, fire protection), which was subsequently modified in response to the HazID workshop output.

DNV-GL led the HazID workshop, with the understanding that the design in Figure 5 was nominally attempting to comply with the IGF Code and DNV-GL's draft (at the time) document "Rules for Classification: Ships, Part 6, Chapter 2, Propulsion, power generation and auxiliary systems."

Using the approach described in Figures 7 and 8, the risk assessment was conducted in the form of a Failure Mode and Effects Analysis (FMEA) in accordance with IEC 60812. During the workshop, potential failure scenarios were identified, described, and rated against a predefined rating scale. Examples of failures that were examined are: leakage of hydrogen out of the hydrogen manifold entering the Fuel Cell Room; loss of ventilation in the Fuel Cell Room, and a leak in the bunkering connection during fueling, just to name a few.

Pictures from the HazID workshop are shown in Figure 9.

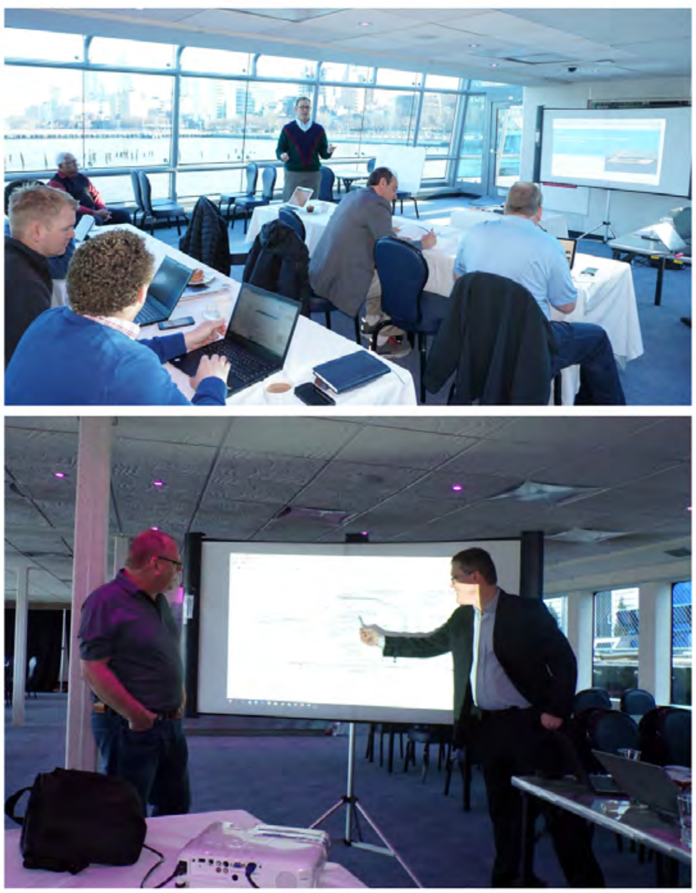

Figure 9: (Top) Gordon Loebl of Hornblower welcomes the workshop participants to the meeting; (Bottom) Ed Vaughn (L) and Lars Engveld (R) discuss a design feature.

Altogether, 50 failure scenarios were identified during the HazID workshop, related to anticipated operational modes and potential external events. Forty-two of the failure scenarios were ranked based on the preliminary vessel design of Fig. 5. From the 42 ranked failure scenarios, no scenario was assessed to have "show-stopping" risk (red in Fig. 8). One scenario was found to have negligible risk (green in Fig. 8), and the other 41 scenarios exhibit tolerable risk (yellow in Fig. 8) that needed to be managed.

For 30 failure scenarios, 49 further "recommended actions" were discussed and captured in order to reduce the risk in the next vessel design. Examples of recommended actions are:

1. Inspect the existing A60 insulation surrounding the Fuel Cell Room and underneath the H_2 Tank Array for structural integrity.

2. Means should be established to ventilate the Fuel cell Room if one of the ventilation fans fails.

3. Install a proper water spray system above the H_2 tanks to ensure cooling of the composite tanks in the event of a fire.

Provided all recommended actions are suitably implemented, the analysis team concluded that risks can be mitigated as far as reasonably practicable (yellow in Figure 8), and the hydrogen power systems can be operated safely. A full account of the results from the HazID workshop is provided in the report from DNV-GL, with cover page shown in Figure 10.

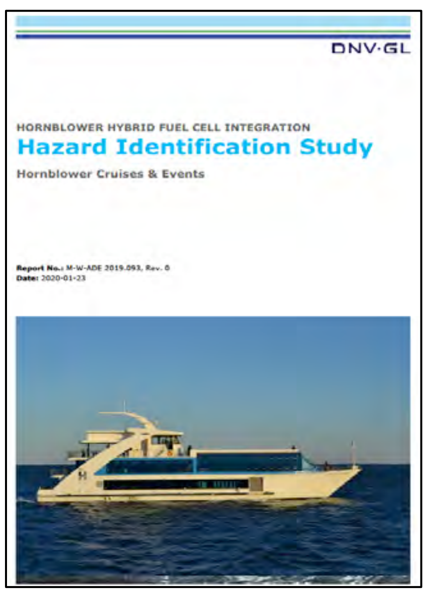

Figure 10: Front Cover of the HazID report from DNV-GL to Hornblower.

The fuel cell system design and vessel integration was evaluated by DNV-GL and was granted an "Approval in Principle" (AIP), which, as the name implies, is not an approval of a final design, but more an approval of the basic concept and the preliminary design to that point.

5. Discover Zero Advanced Hydrogen Technology Design

It was the task of DeJong & Lebet to take the existing Discover Zero ship spaces allowed for hydrogen, and the feedback from the HazID Risk Assessment provided by DNV-GL (based on the preliminary design of Fig. 5) and create an advanced design for introducing the hydrogen technology elements onto the Discover Zero. This advanced design also needs to accommodate the proscriptions imposed by the IGF Code and the DNV-GL Class rules regarding hazardous zones and ventilation and allowing straightforward bunkering of the vessel. The advanced design was examined in detail by the USCG, who made further recommendations for safe design and operation. The design to be described responds to these USCG recommendations, while also holding true to the recommended actions provided by the initial HazID study conducted by DNV-GL.

We followed an overall design philosophy to eliminate, as much as possible, confined spaces where hydrogen can collect. Figure 11 captures the essential pieces of the hydrogen technology and supporting equipment, and the need to mate them to the existing available spaces on the Discover Zero.

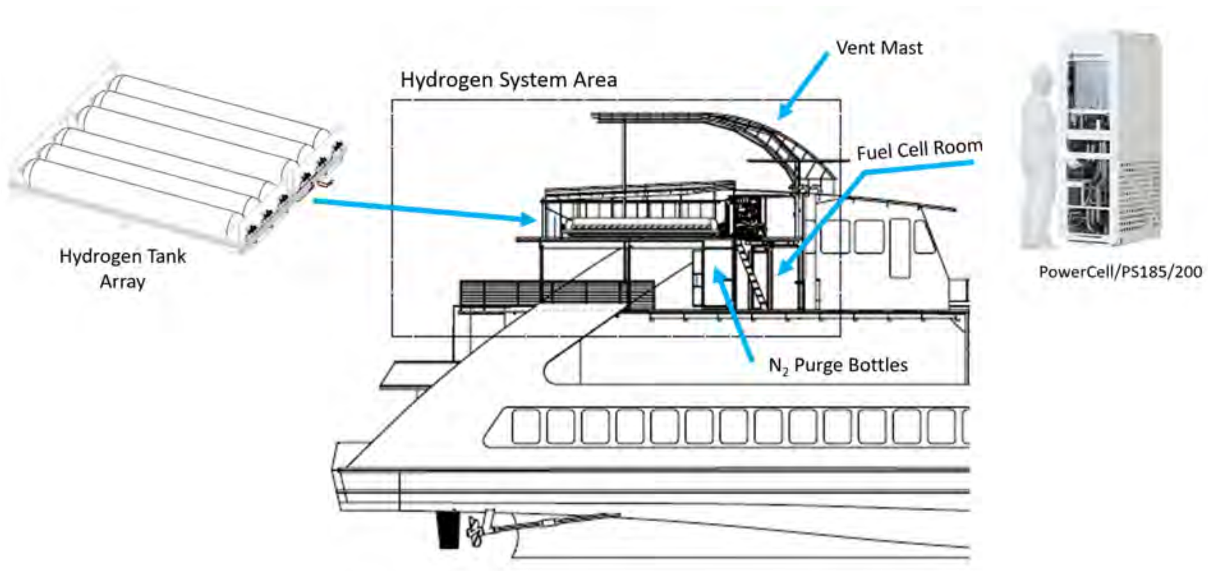

Figure 11: The challenge to integrate hydrogen technology components and supporting equipment onboard the Hydrogen System Area reserved on the Discover Zero.

5.1. Hydrogen Storage

Figure 12 shows the final design of the hydrogen storage system. It consists of an array of 6 Hexagon Purus Type IV tanks as shown in Figure 12.

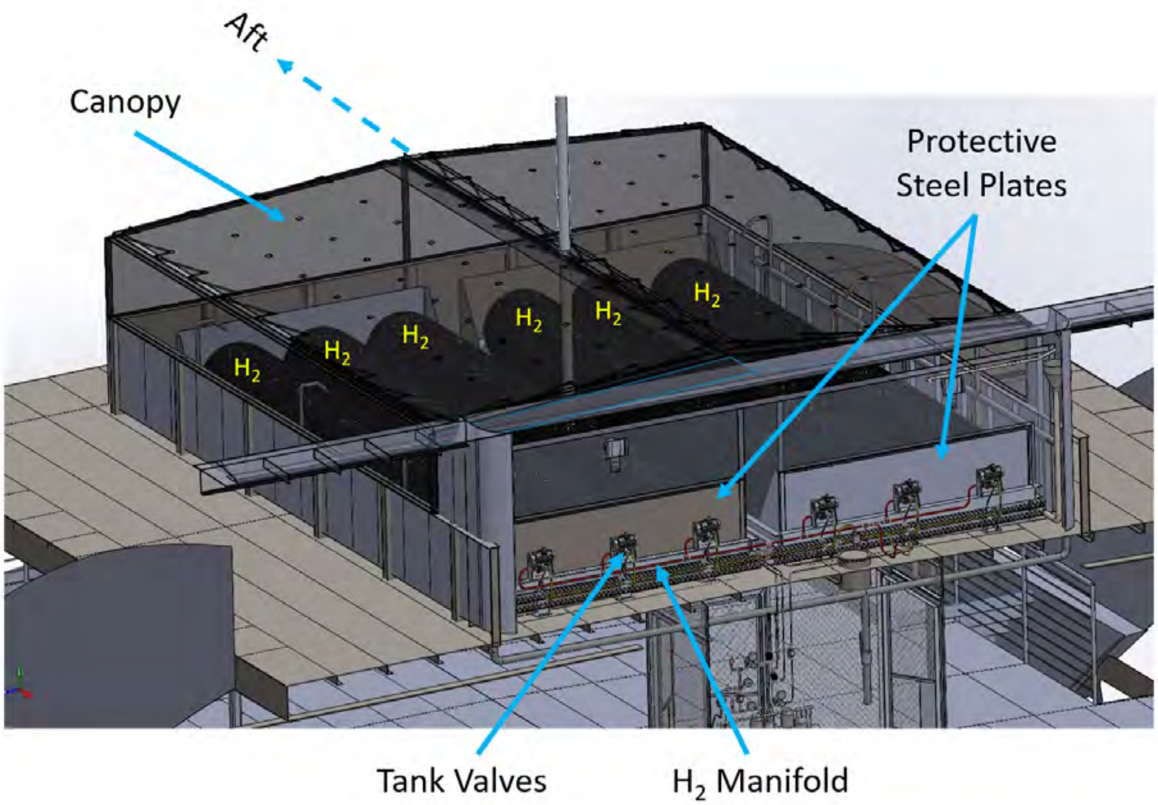

Figure 12: 3D model image of the hydrogen storage area, consisting of 6 250-bar Type IV hydrogen tanks with capacity 28 kg each. Also shown are protective steel plates, the hydrogen manifold and a canopy that covers the area.

Currently, the Discover Zero has a fully enclosed space for the H_2 tanks, as shown in Figure 1(B). Initially, the preliminary design evaluated by DNV-GL maintained this enclosure, but provided forced ventilation within the enclosure to ensure any hydrogen coming from a leak would not collect in the enclosed space. Following our design philosophy of minimizing enclosed spaces, and responding to feedback from DNV-GL, we decided in our advanced design to eliminate the walls and top of the enclosure and put the H_2 tanks out in the weather. This way, any leak in the hydrogen storage system would rapidly rise and disperse, without risk of collection. Figure 12 shows that we did provide a notional canopy covering the tank array space. Our thinking here is that such a canopy could be readily permeable (either via its material or through canopy holes (shown in Figure 12) so that any leaked hydrogen would rapidly dissipate. At the same time, the canopy could reduce nuisance animals (primarily birds) from disturbing the hydrogen array.

A hydrogen storage safety concern that came out of the discussions with USCG was it is possible that a leak from the high-pressure manifold could spontaneously ignite, as described by Klebanoff et al. [23], putting the Type IV tanks at risk. To mitigate this risk, protective steel plates were added as indicated in Figure 12. Figure 13 shows these protective plates with a close-up view, and shows that the plates are planned on both fore and aft sides of the H_2 tank array.

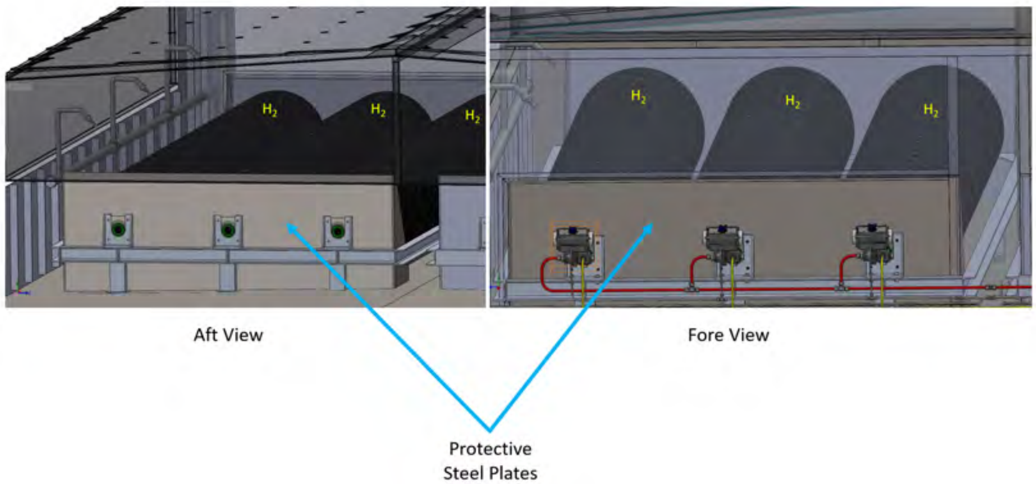

Figure 13: (L) Aft and (R) fore close-up 3D model images of the hydrogen storage area showing placement of the protective steel plates.

Each tank has a pneumatically actuated valve that has three associated gas lines, as depicted in Figure 13 (R). Figure 14 shows a close-up view of one of these tank valves. The red manifold is for high-pressure (250-bar) hydrogen, the yellow manifold is the exhaust route should the TPRD activate, and the grey manifold is for pressurized nitrogen that activates these and other valves in the hydrogen fueling system.

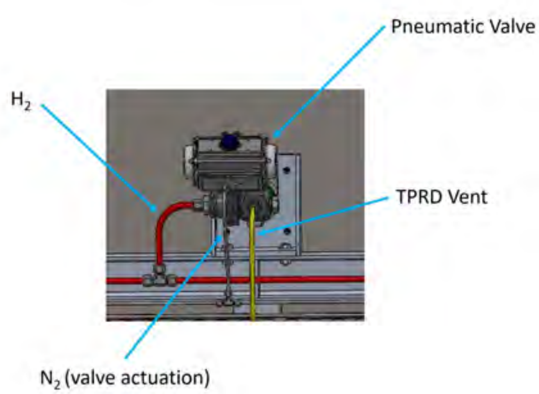

Figure 14: Close-up 3D model image of the pneumatic valve mounted on each hydrogen storage tank, with connections for nitrogen valve actuation, and piping for the high-pressure hydrogen and TPRD venting.

The IGF Code requires that the hydrogen tank array has a water spray "deluge" system (based on sea/river water) in the event of fire. Water deluge spray nozzles are mounted on the Port and Starboard sides of the tank array, as shown in Figure 15. Such nozzles are standard on vessels using flammable gas (natural gas, hydrogen, propane) as a fuel for power. The function of the water spray system is not to extinguish a hydrogen fire in the tank array, but rather to cool the tanks so they cannot burn, while at the same time allowing the hydrogen fire to safely burn itself out.

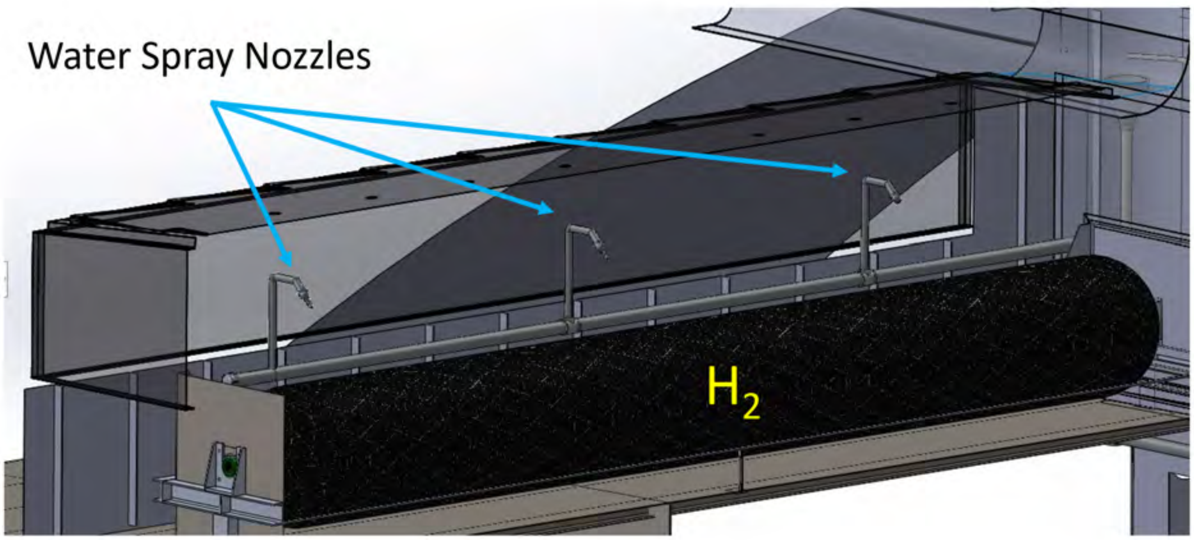

Figure 15: 3D model image of three water spray nozzles mounted on the Port side of the hydrogen tank array. Only one tank is shown for clarity.

The water spray system introduced a significant compatibility concern for the use of TPRDs. TPRDs open (typically at 150 F) in the event of a fire, thereby preventing over-pressurization of the H_2 tanks. The concern was that if the TPRDs are being sprayed with water, they will be sufficiently cooled so as not to lift even though the temperature is sufficiently high elsewhere in the array to pressurize the hydrogen in the tanks to the point of rupture. A design feature was introduced that mitigates this risk and is shown in Figures 16 and 17.

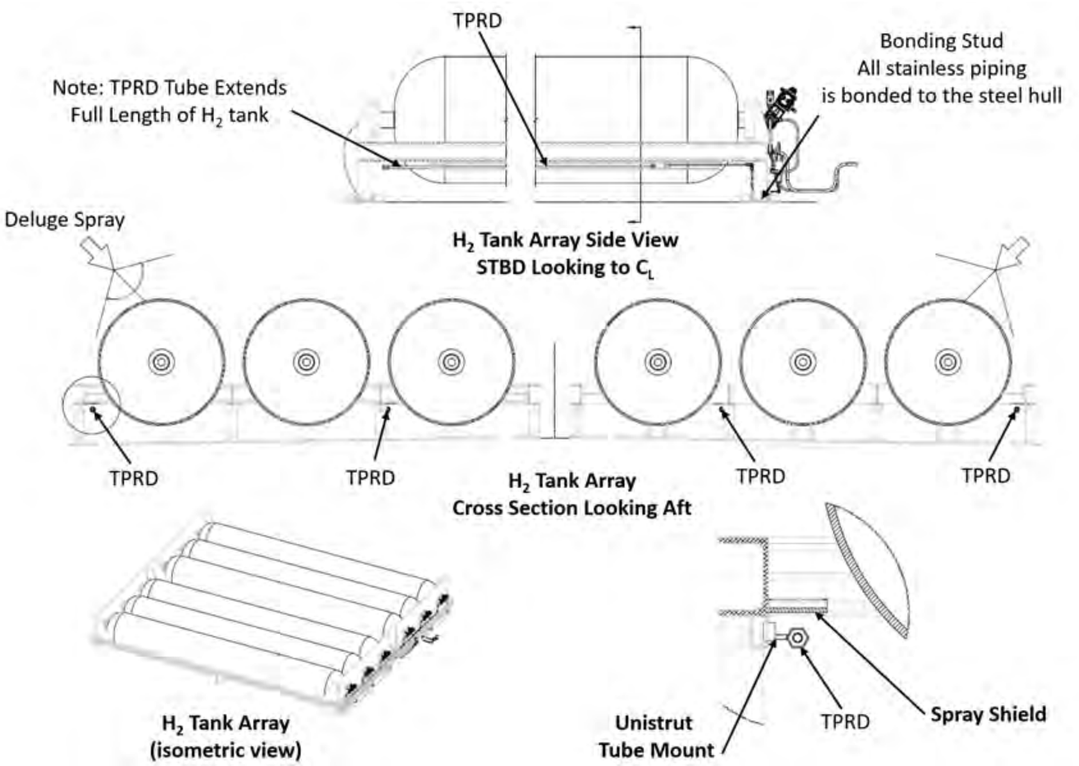

Figure 16: Schematic diagrams of the placement of TPRDs lengthwise along each hydrogen tank, with protection of the TPRD by an overhanging spray shield. Also shown in the bonding stud that electrically grounds the entire hydrogen systems piping and structure to the steel hull of the ship.

Figures 16 and 17 show that because the H_2 tanks are so long (224 inches, 18.7 feet), the TPRD also needs to be long to adequately respond to the risk of fire over the entire length of the tank. Each tank is protected by a TPRD, as shown in Figure 16. To prevent cooling of the TPRD by the water spray in the event of fire, each TPRD is mounted underneath a spray splash shield (Figs. 16, 17) so that the TPRD can still sense the heat of a fire, but not be significantly cooled by the water spray.

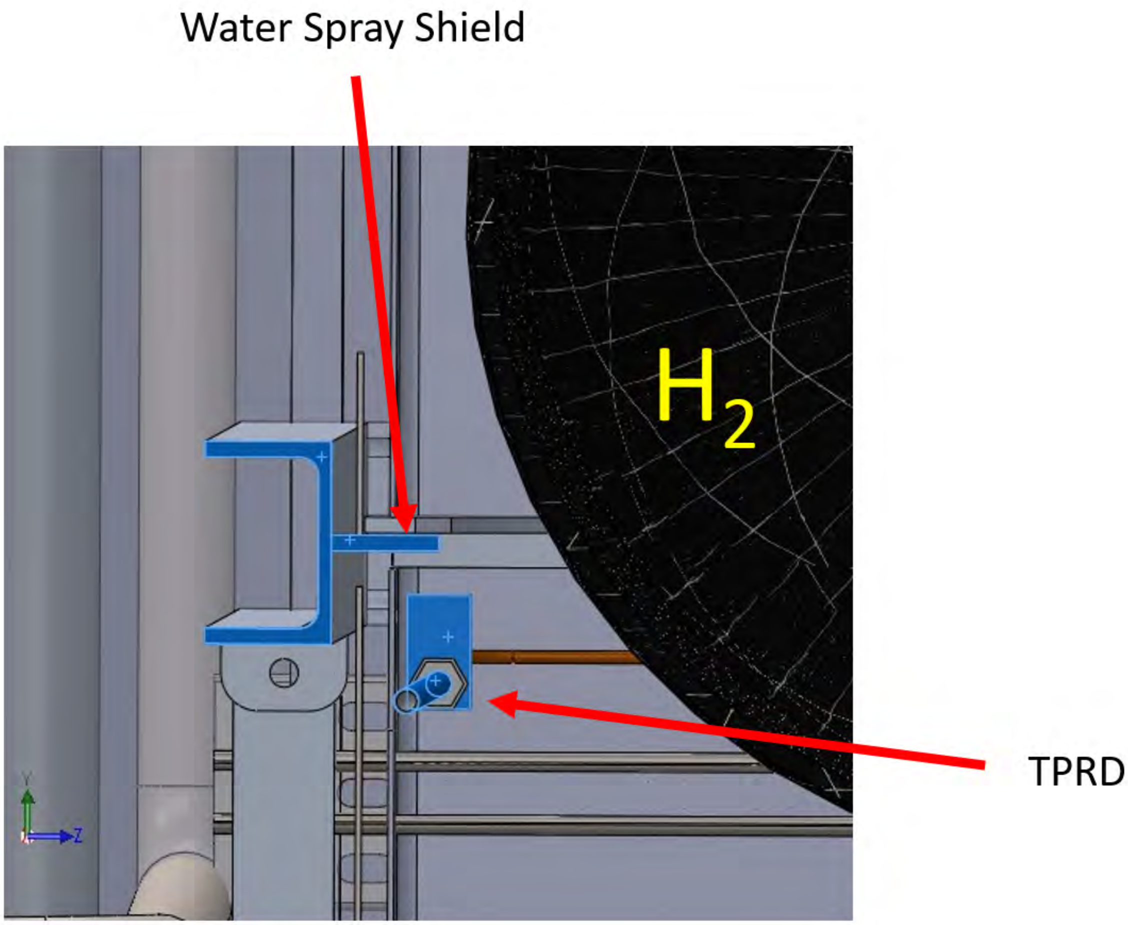

Figure 17: Close-up 3D model image of the location of a TPRD relative to a hydrogen tank, and the protection of the TPRD from water spray by a water spray shield.

Figure 18 shows a canopy over the hydrogen storage system. Unlike the enclosure currently on the Discover Zero, a canopy would allow any leaked hydrogen to readily disperse, either through the material itself (for example a mesh), or via holes fashioned onto the canopy, as shown in Figure 18. At the same time, a canopy would provide partial shade for the tanks, and full protection from wildlife (birds).

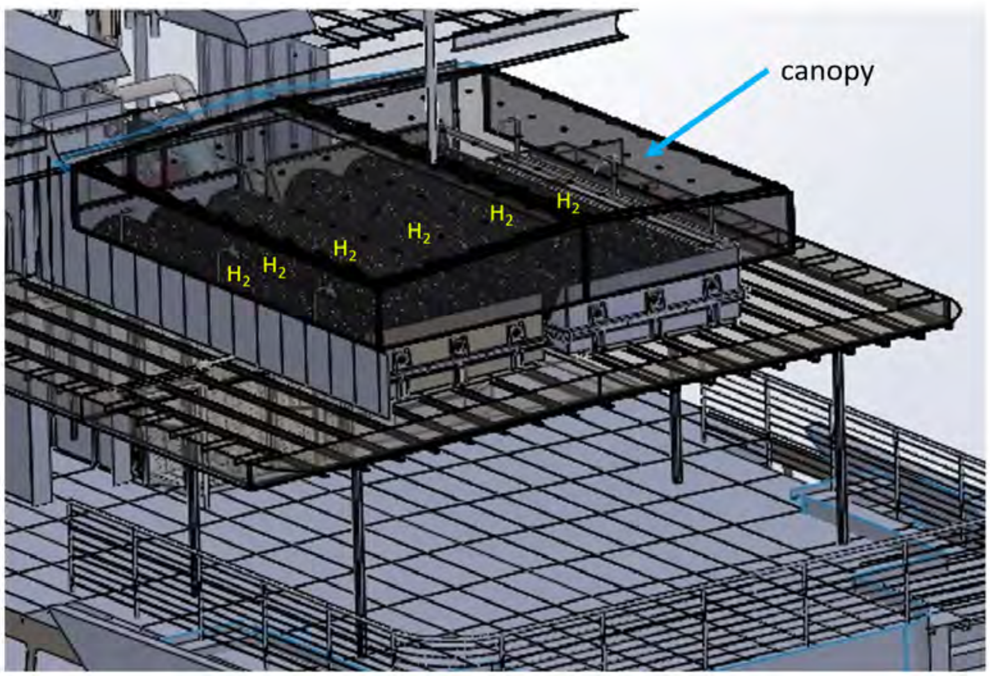

Figure 18: 3D model image of the canopy covering the hydrogen storage area. The canopy is notional only.

Most of the valves in the Hydrogen System, such as that shown in Figures 12 - 14, are pneumatically actuated. Figure 19 shows the location of nine 1A nitrogen bottles that provide pneumatic actuation of these valves.

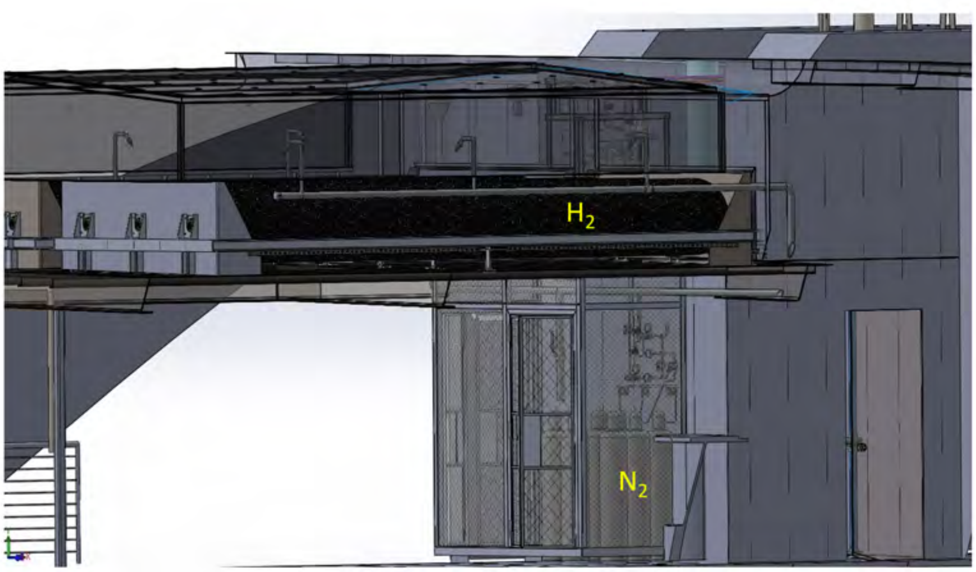

Figure 19: 3D model image of the nitrogen tanks providing gas pressure for operating pneumatic valves withing the hydrogen technology system.

5.2. Fuel Cell Installation

The challenge for the naval architect DeJong & Lebet is to incorporate the fuel cell and all associated equipment in the space allowed in the Fuel Cell Room and adjacent to it. The design, which was reviewed by the USCG and resulted in a Design Basis Letter, considered the use of Hydrogenics HyPM-R 120 S Fuel Cell Rack that incorporates four HyPM HD 30 30 kW fuel cell modules. All diagrams and 3D models in this report were generated using the HyPM-R 120 S fuel cell system. However, after completion of the existing design, it was decided for the future to consider migrating to a 185 kW PowerCell PS-185 fuel cell, taking advantage of advanced technology with higher power density within the same footprint as the 100 kW Hydrogenics HyPM-R 120 S fuel cell. A second Design Basis Letter with advanced and higher fuel cell power (185 kW) from PowerCell (PS-185) is in progress. The figures presented here apply equally well to the PowerCell PS-185 Fuel Cell Rack since the approach to rack ventilation and the balance-of-plant facilities (air, cooling water) are analogous to the original HyPM-R 120 S fuel cell.

An excellent presentation of the science and engineering of fuel cells can be found in the book "Fuel Cell Systems Explained" by Larminie and Dicks [41]. A review of hydrogen fuel cells can also be found by Klebanoff et al. in Reference [17], upon which a lot of the following discussion is based.

A hydrogen fuel cell is an electrochemical device that executes the hydrogen/oxygen reaction (1) without direct combustion [42]:

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

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. The PEM fuel cell is perhaps the simplest of the fuel cells [42].

Figure 20 shows the two spatially separated "half reactions" in a H_2 PEM fuel cell [17], which added together, equates to the overall reaction (1) and can provide power to an external circuit. 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).

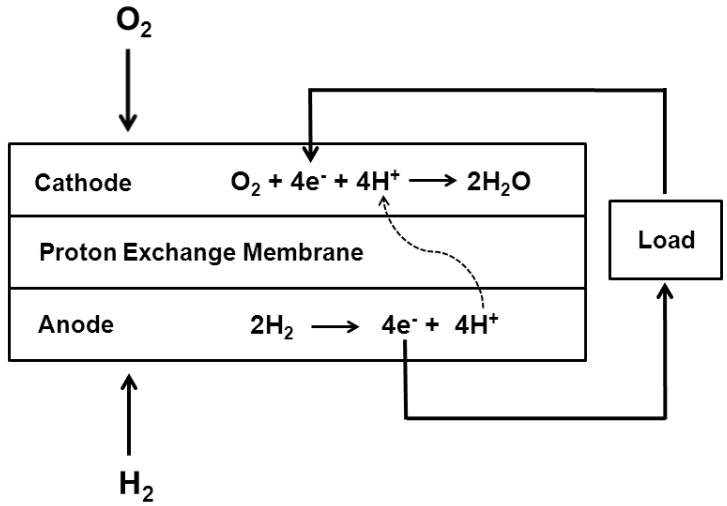

Figure 20: Schematic diagram of a PEM fuel cell, with the hydrogen oxidation (anode) and oxygen reduction (cathode) half reactions written. Reproduced with permission from Ref. 17.

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 20. The PEM fuel cell generates electricity with a thermal efficiency (electrical work out/fuel energy in) of ~ 41 – 53%, depending on the load. Concomitantly, ~ 59% to 47% 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 hydrocarbons (HC) and zero particulate emission.

Figure 21 shows the overall block diagram for an individual hydrogen power module (HyPM) for the Discover Zero.

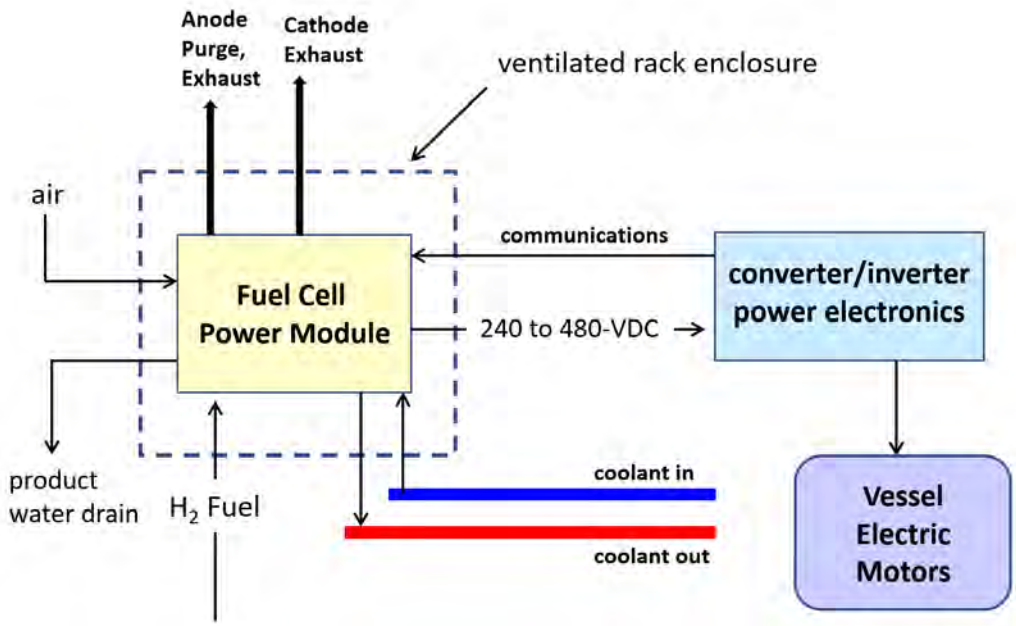

Figure 21: Fuel Cell Power Module System Block Diagram.

Hydrogen and air are directed to the Hydrogen Fuel Cell Power Module (HyPM) anode and cathode, respectively. Therein, the electrochemical half-reactions at the anode and cathode take place. The product water from the reaction is removed by a 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 also an exhaust line for the cathode which consists of oxygen depleted air and water vapor. The power out of the HyPM is typically conditioned with a DC-DC converter, and then transformed to AC power by a DC-AC inverter. The fuel cell rack integrates together the H_2 and air supply lines, the liquid coolant lines to remove waste heat, water discharge lines for the wastewater, the exhaust gases from the anode and cathode spaces within the fuel cells, as well as hydrogen detectors and ventilations systems for safety.

The PowerCell PS-185 fuel cell power rack is assembled from a single HyPM of nominal power 185 kW. General information is provided in Figure 22.

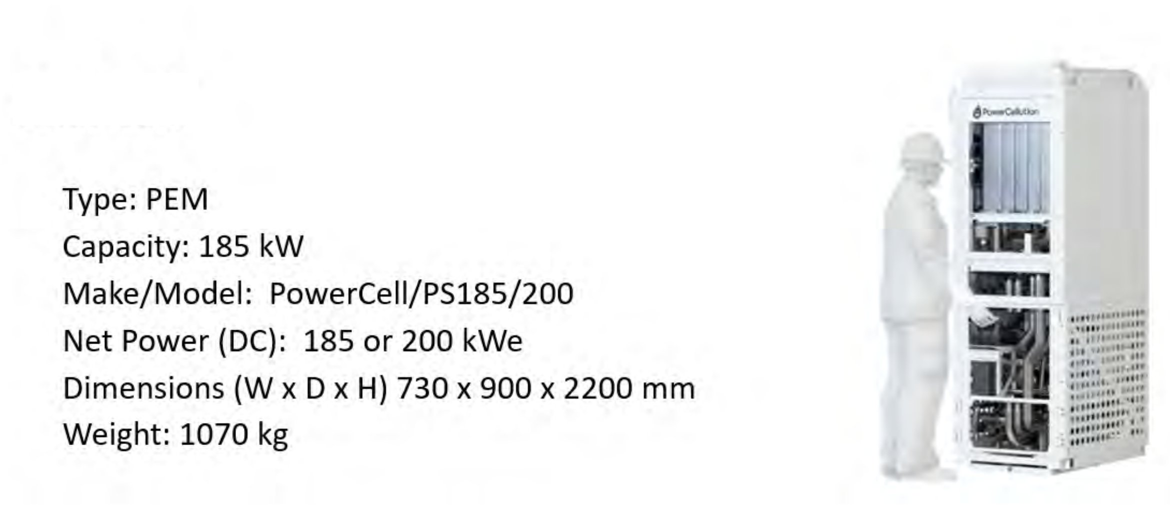

Figure 22: General information and picture of the PowerCell PS-185 fuel cell power rack

The rack also provides for strong ventilation of the entire rack space, with flow from bottom to top. This rack ventilation flow is completely independent of the Fuel Cell Room ventilation flow. A hydrogen sensor is located inside each rack towards the top, and its activation can be used to shut down both electricity within the fuel cell power module as well as shut off the hydrogen gas supply, thereby eliminating electrical ignition risks of the flammable hydrogen gas.

In a manner consistent with Figures 20 and 21, the PowerCell PS-185 fuel cell stack uses PEM technology and is designed to be fueled by pure gaseous hydrogen and uses ambient air as the source of oxygen. The electrochemical reaction between hydrogen and oxygen create an electric potential between the anode and cathode, from which direct current can be drawn from the stack. In addition to electricity, a significant amount of heat is also generated and is removed from the stack through a liquid coolant which is fed through the stack and comes into direct contact with each and every individual cell within the stack. The stack delivers a compact, dynamic and robust fuel cell technology that has a market competitive volumetric energy density and is designed to meet the IEC 62282-2 safety standard.

Figure 23 shows the installation of the PEM fuel cell rack in the Discover Zero's Fuel Cell Room. The Fuel Cell Room is forward and below the array of hydrogen tanks, as indicated in Figure 1(A) and Figure 23. Provisions are shown for the hydrogen supply, as well as the independent ventilation system for the Fuel Cell Rack and the Fuel Cell Room.

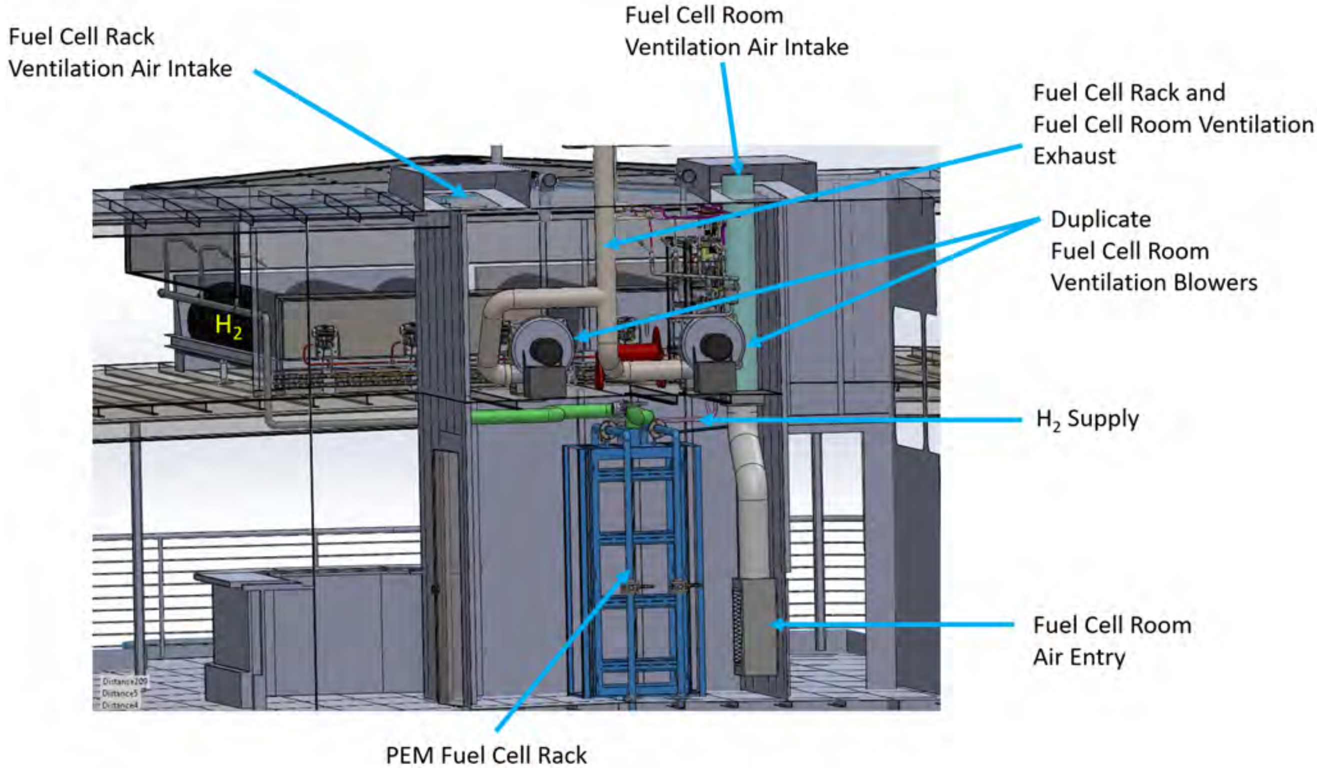

Figure 23: Placement of the PEM Fuel Cell Rack in the Discover Zero's Fuel Cell Room, with important gas handling components identified. This is a view from forward looking in the aft direction.

Two separate and independent ventilation paths are provided for the Fuel Cell Rack, and the Fuel Cell Room. These form complementary and somewhat redundant mitigation for small fuel cell Rack hydrogen leaks. Separately, the Fuel Cell Room is provided with air, and exhausted by redundant air blowers, directing the exhaust flow out to the swept-back vent mast. Figure 24 depicts the Fuel Cell Rack airflow, coming in from the top, flowing down the periphery of the Fuel Cell Rack, then directed up the center of the rack and out to the swept-back mast. There is internal vent fan incorporated into the Fuel Cell Rack, located at the top, that drives this airflow (see Figure 22).

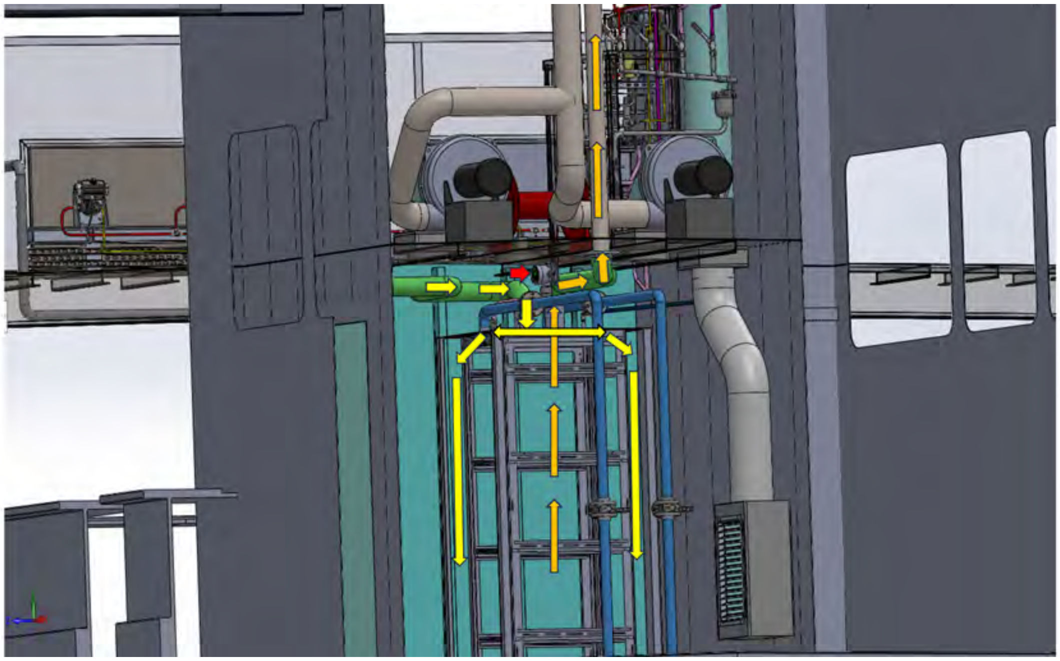

Figure 24: Diagram of the Fuel Cell Rack ventilation airflow. Airstreams are indicated by yellow arrows. The red arrow identifies a hydrogen detector located outside the Fuel Cell Rack but within the Fuel Cell Room.

Figure 25 shows a diagram of the Fuel Cell Room ventilation airflow.

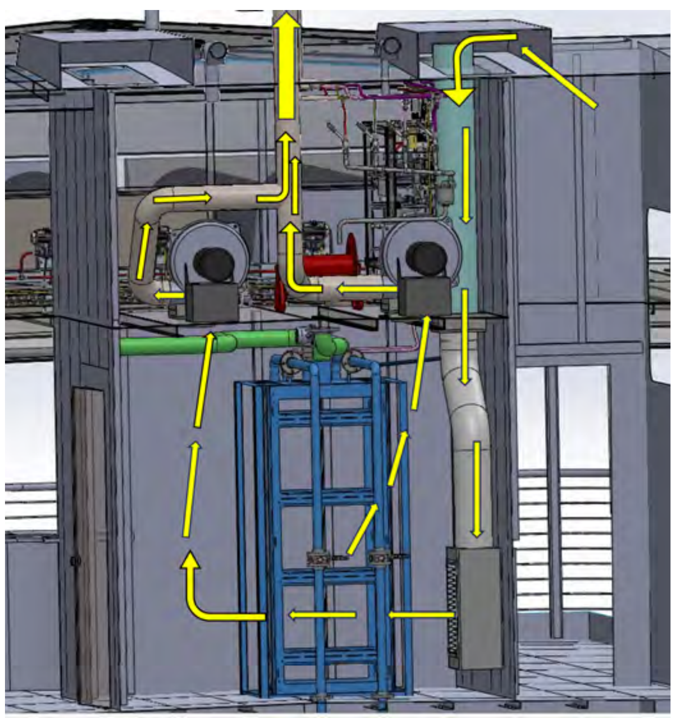

Figure 25: Pattern of Fuel Cell Room ventilation air flow, indicated by the yellow arrows.

Thus, redundant ventilation provides for safe and secure operation of a fuel cell in the Fuel Cell Room. Prior work by Gitushi [43] has investigated the effect of room ventilation on mitigating a leak from the top of Fuel Cell Rack, in the event the Fuel Cell Rack ventilation fails and the hydrogen detector internal to the rack also fails, so the hydrogen fuel shutoff is not executed. This computational fluid dynamics (CFD) modeling work showed the manner in which Fuel Cell Room ventilation can limit the expected leak, and also predicted how quickly the Fuel Cell Room can be evacuated once the leak is terminated by a shutoff valve. Such a shutoff would be activated by the hydrogen detector located in the Fuel Cell Room, as shown by the red arrow in Figure 24.

This strategy of mitigating leaks associated with the Fuel Cell Rack, or leaks within the Fuel Cell Room, has been deemed acceptable by the USCG, as evidenced by the Design Basis Letter which was issued for introducing hydrogen to the Discover Zero.

5.3. Vent Masts

The organization of the Vent Masts takes advantage of the existing "Swept Back" Vent Mast already on the Discover Zero vessel but adds an additional Vertical Vent Mast to handle other venting needs. In principle, the Vertical Vent Mast could handle all venting needs of the system. The Vent Masts on the Discover Zero are shown in Figure 26.

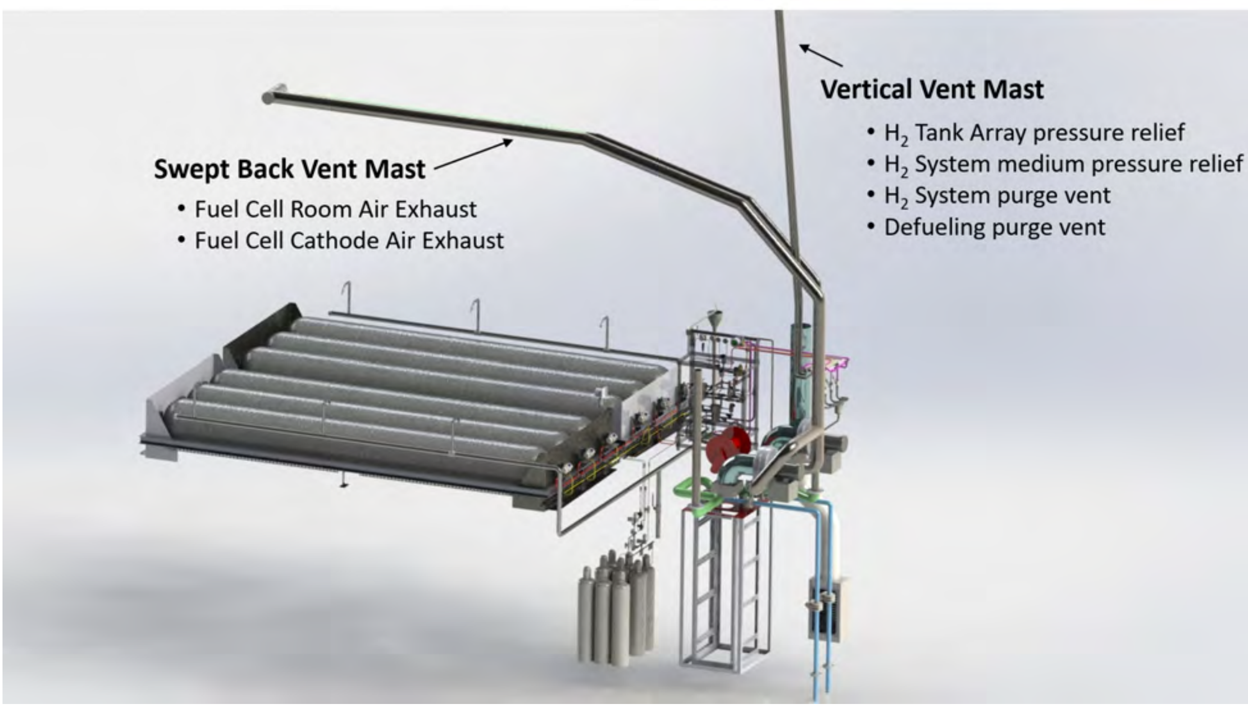

Figure 26: Organization of the Vent Masts on the Discover Zero and the hydrogen-containing flows that are directed to each. Two vent masts are shown, the existing Swept Back Vent Mast Bundle and the Vertical Vent Mast.

In the process of managing the hazardous areas on the vessel, it was decided to only direct airflows that had very low probability of containing any hydrogen out to the Swept Back Vent Mast. This was due to the proximity of the exit of this mast to the hydrogen storage area below, which will be discussed in more detail later in this report. The flows entering the Swept Back Vent Mast are the Fuel Cell Room ventilation air exhaust, and the fuel cell cathode exhaust. Neither of these sources of gas, in normal operation of the vessel, would have any hydrogen in them and would only have hydrogen/air mixtures in the event of an abnormal event (e.g., accident).

The Vertical Vent Mast is for flows that might have larger amount of hydrogen in them, for example TPRD release in the event of a fire, or dumping hydrogen from the tanks if that should be needed for a maintenance activity. This tank dumping is called "defueling."

5.4. Bunkering

As described earlier, the bunkering system mainly consists of high-pressure hose, tubing, valves, and fittings to facilitate the safe transfer of hydrogen from a tube trailer located on the adjacent Pier to onboard hydrogen storage system. The hose path down to the Pier level is depicted in Figure 27.

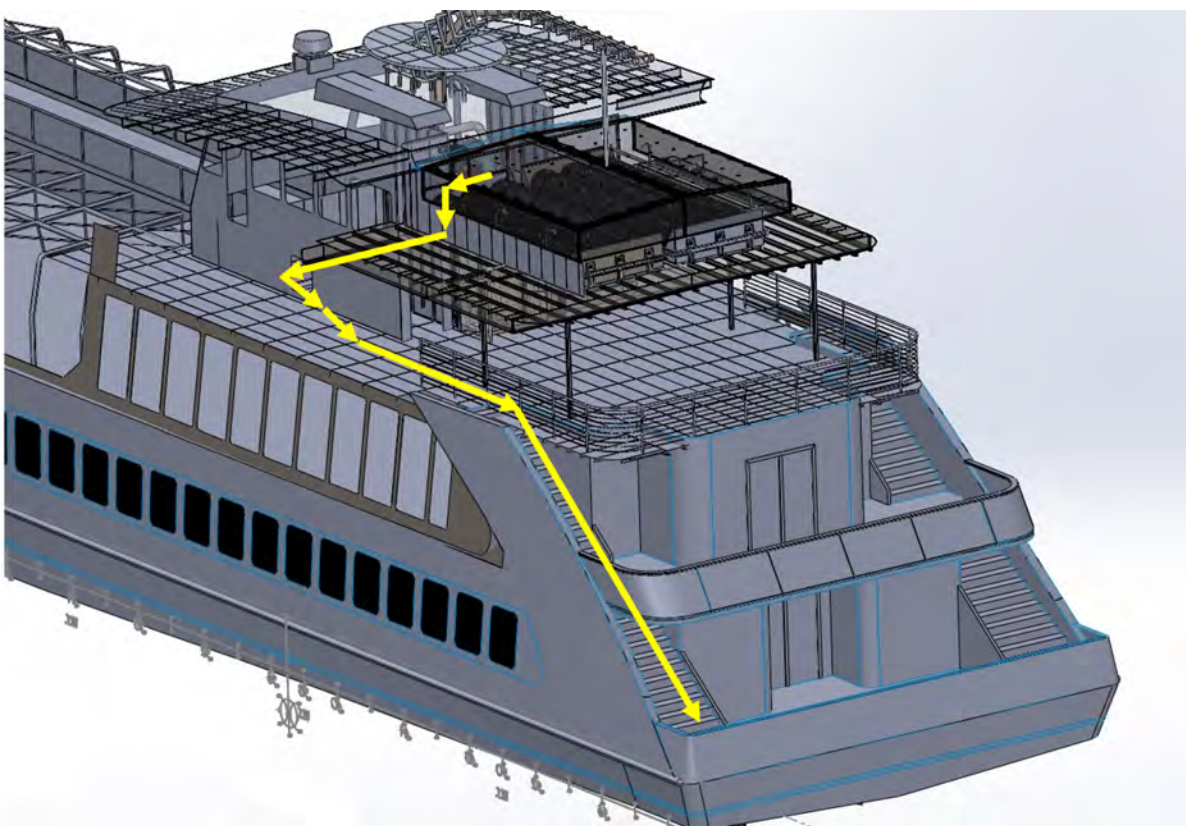

Figure 27: Path of hydrogen refueling hose, from its coiled storage location down the Port side of the Discover Zero to the Pier level.

Figure 28 shows in a 3D model the location of the bunkering hose spool around which the vessel bunkering hose (not shown) will be stored. The high-pressure hose stays on the vessel and is uncoiled and brought down (Figure 27) to the hydrogen fueling trailer for bunkering.

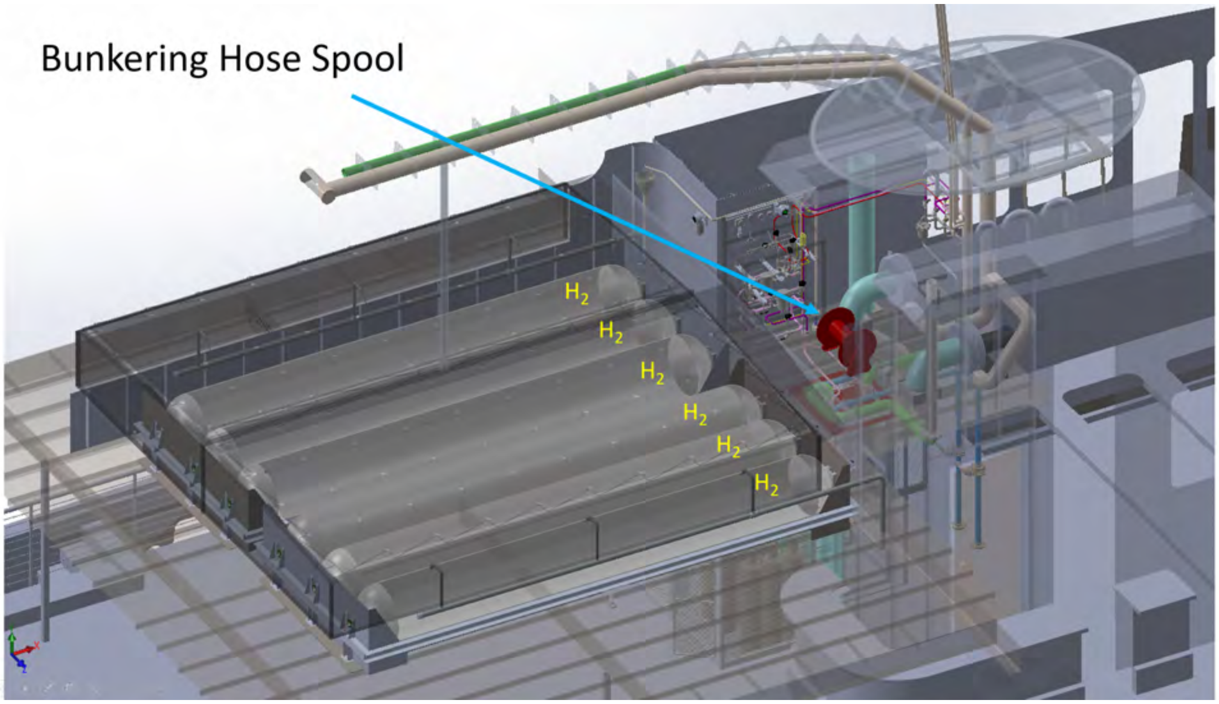

Figure 28: 3D model showing the location of the Bunkering Hose Spool (highlighted in red). The hose itself is not shown.

There are multiple options for how the hose connects to the Discover Zero hydrogen fueling port, as shown in Figure 29.

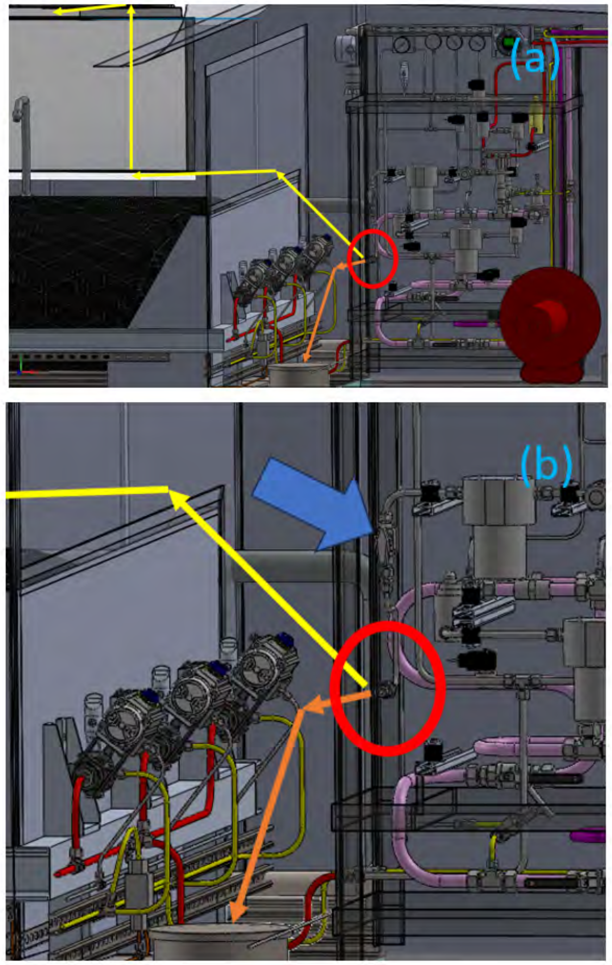

Figure 29: (a) 3D model images showing connection of the refueling hose to the fueling port and two different options for passing the hose down to the Pier to make connection to the hydrogen fueling trailer. The hydrogen fueling port is shown by the red circle. (b) an expanded view of panel (a). The blue arrow points to a valve that connects the Discover Zero hydrogen refueling port to the rest of the hydrogen manifold and ultimately to the hydrogen tank array.

The orange arrow shows that the hose can be transferred down to the lower deck through a usually gas-tight passthrough Scuttle (which would be opened only for bunkering conditions). The yellow arrow, depicted in Figure 27, shows that the refueling hose can be transferred over the side of the hydrogen tank array and down to the refueling trailer. The hydrogen refueling port is shown in the red circle.

This overall Discover Zero refueling hose strategy is the same as that used by the Sea Change, the recently arrived hydrogen-powered ferry on the San Francisco Bay. The bunkering system is located on the top deck, open to air for better ventilation. The Discover Zero bunkering system will be fully assembled, and pressure tested in the shop before being brought to the vessel for installation connection to the rest of the system.

A plausible set-up procedure for refueling the H_2 tank array can be envisaged as follows:

A. With the hose on reel, roll hose out from the reel, feed the hose down to the lower level (either through the pass (orange) or over the side (yellow)).

B. Operator below will pull the hose down to the truck connection at the transom.

C. Once the hose is connected to the truck's supply line, prior to pressurizing; connect other end to the hydrogen refueling port (red circle).

D. Using the gas supplied by the truck, purge and test the lines for tightness. Once leak free operation is confirmed, open the isolation (blue arrow in Fig. 30 (c)). Hydrogen flow control and pump velocity can be maintained at the refueling trailer.

E. Once bunkering is completed, the Operator can stop the fill at the truck; the isolation valve is closed at the distribution manifold (blue arrow). Then the hose evacuation and purge is conducted at the truck.

F. After purge, the Discover Zero refueling hose can be disconnected and stored back on the reel.

More discussion with a hydrogen gas supplier would be needed to provide more design detail.

6. Hazardous Area Classification

The first step in designing the hydrogen modifications to the Discover Zero, or any gas-fueled ship, it to understand the regulatory environment of the proposed vessel.

The *Discover-Zero* was originally built to be in compliance with regulations 46 CFR Subchapter K. However, Subchapter K does not include hydrogen as a fuel for motive and auxiliary power onboard a vessel. Consequently, we used the IGF Code [35] along with latest DNV-GL "Rules" [36] were used to generate a safe design for the hydrogen powered Discover Zero and to determine "hazardous zones" around expected and potential points of hydrogen gas release.

The IGF Code was written considering compressed and liquefied natural gas. Though, many properties and behaviors of natural gas and hydrogen are similar [23], for example both are lighter than air, some differences in properties and behaviors of these gases are density and explosive limits in air. While natural gas is 1.8-times lighter than air (ρ = 1.204 kg/m^3), hydrogen is 14.4-times lighter than air, which means hydrogen dissipates and disperses into air much faster than natural gas. Having similar lower flammability limits, hydrogen being highly dispersive can reach a non-flammable condition in a shorter time and distance than natural gas in the event of their release into air. However, given the absence of a definitive hydrogen vessel regulatory code, we adopt the IGF Code, where applicable as the starting point for the design the Discover Zero, as well as feasibility vessels investigated in prior studies [11, 24, 25].

The IGF Code addresses many design aspects, including prescriptive requirements on the establishment and characteristics of "hazardous zones" around expected and potential points of hazardous gas release. These zones are defined as:

Zone 0: Explosive or flammable gas with flash point below 60 ºC is present continuously or for long periods (e.g., inside a gas pipe or tank). The practical significance of this designation is that one needs to understand this zone designation to develop safe maintenance protocols for Zone 0 systems before maintenance is performed, and assess if nitrogen inerting is required if the pipe or tank needs to be opened up for maintenance. We will not show the Zone 0 locations in the Hazardous Area figures because it is understood where they are from the other figures.

Zone 1: Explosive or flammable gas with a flash point below 60 ºC is likely to occur in normal operation (e.g., at the discharge the vent mast). This zone is a recognition that hydrogen could be present in a location (perhaps at well below flammability levels) because no seal is perfect, and there will be (perhaps infinitesimal) hydrogen leakage at seals, valves and pressure release devices. Also, Zone 1 is appropriate for larger releases, for example at the discharge exit of a Vent Mast. The designation of a Zone 1 region takes these hydrogen releases into account.

Zone 2: Explosive or flammable gas with a flash point below 60 ºC is not likely to occur in normal operation and if it does occur, it would be infrequent or exist for a short period. This zone is appropriate for operational productions of released hydrogen, for example operation of the anode purge. This is a brief, planned release. Zone 2 is often used for a small hydrogen release in an area where the hydrogen can accumulate. Thus, Zone 2 is appropriate for enclosed spaces, such as the Fuel Cell Room.

To prevent ignition of flammable gasses, electrical equipment installations in hazardous zones are restricted. Electrical wiring and equipment are generally prohibited from installation in hazardous areas unless they are essential to operation of equipment within the hazardous area. Where electrical equipment is installed in hazardous areas, they must be certified safe for use in the applicable hazardous zone. For example, such wiring must be intrinsically safe, explosion-proof, flame proof or fabricated using some other accepted method of protection in accordance with applicable USCG and DNV GL requirements for the intended zone of use. As a practical matter, this means that there must be no splices in the electrical cabling and no exposed wiring or connectors, no electrical junction boxes, a wire with an end or screw, no solenoids, motors, drills or non-explosion rated fans.

We assume that the natural-gas-motivated hazardous area classifications (zones) of the IGF code are applicable to hydrogen gas as well. In arranging the hazardous zones, care needs to be taken in the locations of sources of hazardous areas to avoid air intakes or passenger entrances into the interior of the vessel.

Additional assessment concerning possible H_2 leaks was conducted using IEC 60079-10-1:2015, "Classification of Areas: Explosive Atmospheres [44]. This regulation was seen as complementary to the IGF Code and additionally allowed assessment using the particular properties of hydrogen gas. Our general approach to developing hazardous zones was thus to use the IGF Code, with further understanding of the nature of some of the releases gleaned from calculations using IEC 60079-10-1:2015.

The Fuel Cell Room is treated separately. Under normal operating conditions, the atmosphere of the Fuel Cell Room would contain no hydrogen and is gas safe. However, the construction of the fuel cells is such that due to potential failures in the rack manifolding itself and a failure in the Fuel Cell Rack Ventilation, there could be a release of hydrogen into the Fuel Cell Room causing the space to become gas hazardous. This requires the Fuel Cell Room to be arranged as emergency shutdown (ESD) protected machinery space. In the event of a hydrogen leak in this room, as detected by a hydrogen alarm either in the fuel cell rack or the Fuel Cell Room, emergency shutdown of non-safe equipment (ignition sources) and machinery are automatically executed. Any equipment in the room that must remain in use or operating during these conditions must be of a certified safe type. The ESD of equipment is achieved by complete and immediate disconnection of electrical power to all non-gas safe equipment in the Fuel Cell Room. In general, all electrical equipment that is not essential for the safe operation of the vessel would be part of the ESD circuits. ESD of a Fuel Cell Room would be initiated upon detection of a gas leak or fire within the space or from a failure of the ventilation serving the space. In addition to electrical disconnection, ESD of a Fuel Cell Room would initiate immediate shutdown of the hydrogen supply to the space.

Essential results from these Hazardous Zone analyses for the advanced design of the Discover Zero are now presented. The proposed hazardous zones were approved by the USCG via the Design Basis Letter.

At a high level, the overall sources of hydrogen gas that require assessment of hazardous zones are shown in Figure 30.

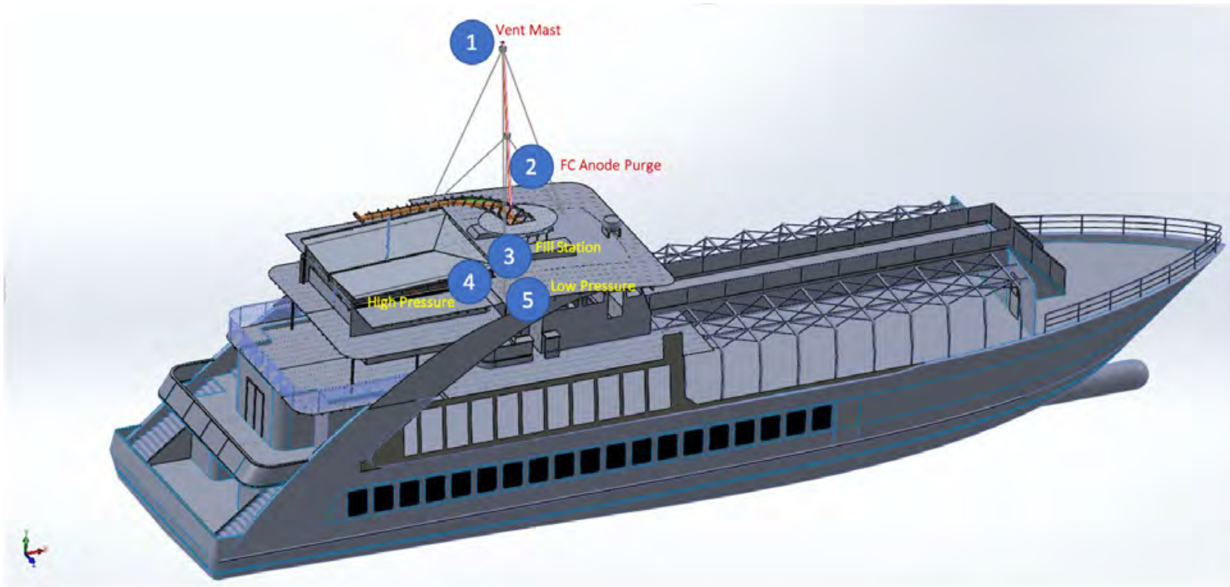

Figure 30: Approximate locations of potential hydrogen release points (sources) on the Discover-Zero, derived from pressure relief devices on the vessel.

There are five potential outdoor hydrogen release points on the advanced vessel design where hydrogen could or will be released and should be analyzed to determine the type and extent of a hazardous zone (if any). Approximate locations of these potential outdoor release points are shown in Figure 30:

1. Vertical Vent Mast outlet, for pressure relief associated with:
    - A. Pressure Relief valves
        - a) H_2 Storage Tanks
        - b) Bunkering
        - c) Medium Pressure lines
        - d) Low Pressure lines
    - B. Line purges
    - C. Defueling
2. Anode (hydrogen) purge, which is an outlet located about halfway up the Vertical Vent Mast
3. Bunkering (Fill Station)
4. High pressure hydrogen piping, manifolds, and tank connections
5. Low pressure hydrogen piping

The Hazardous Zones arising from the hydrogen "sources" are now presented in turn. In depicting the zones graphically, the convention shown in Figure 31 is used.

Symbol	Item
N/A	Zone 0
	Zone 1
	Zone 2
	ESD Protected
	Relief Valve Safety Area
	Leak Source

Figure 31: Symbol convention for the Discover Zero Hazardous Zones

6.1. Vertical Vent Mast

The Vertical Vent Mast is the final outlet point of any primary releases of hydrogen from vessel hydrogen systems other than purging of unconverted hydrogen from the fuel cell anodes, which has an outlet located approximately halfway up the Vertical Vent Mast. The Vertical Vent Mast includes all relief valves, defueling ports, and purge vents of the bunkering system, high pressure system, and low-pressure system.

A determination of the extent of IGF hazardous zones around the Vertical Vent Mast outlet was made which accounted for flow of hydrogen out of the vent mast due to both pressure relief valves (Secondary Grade releases) and line purging/defueling (Primary Grade releases). The resulting Zone 1 hazardous zone at the top of the Vertical Vent Mast has a 3 m (10’) radius, as shown in Figure 32.

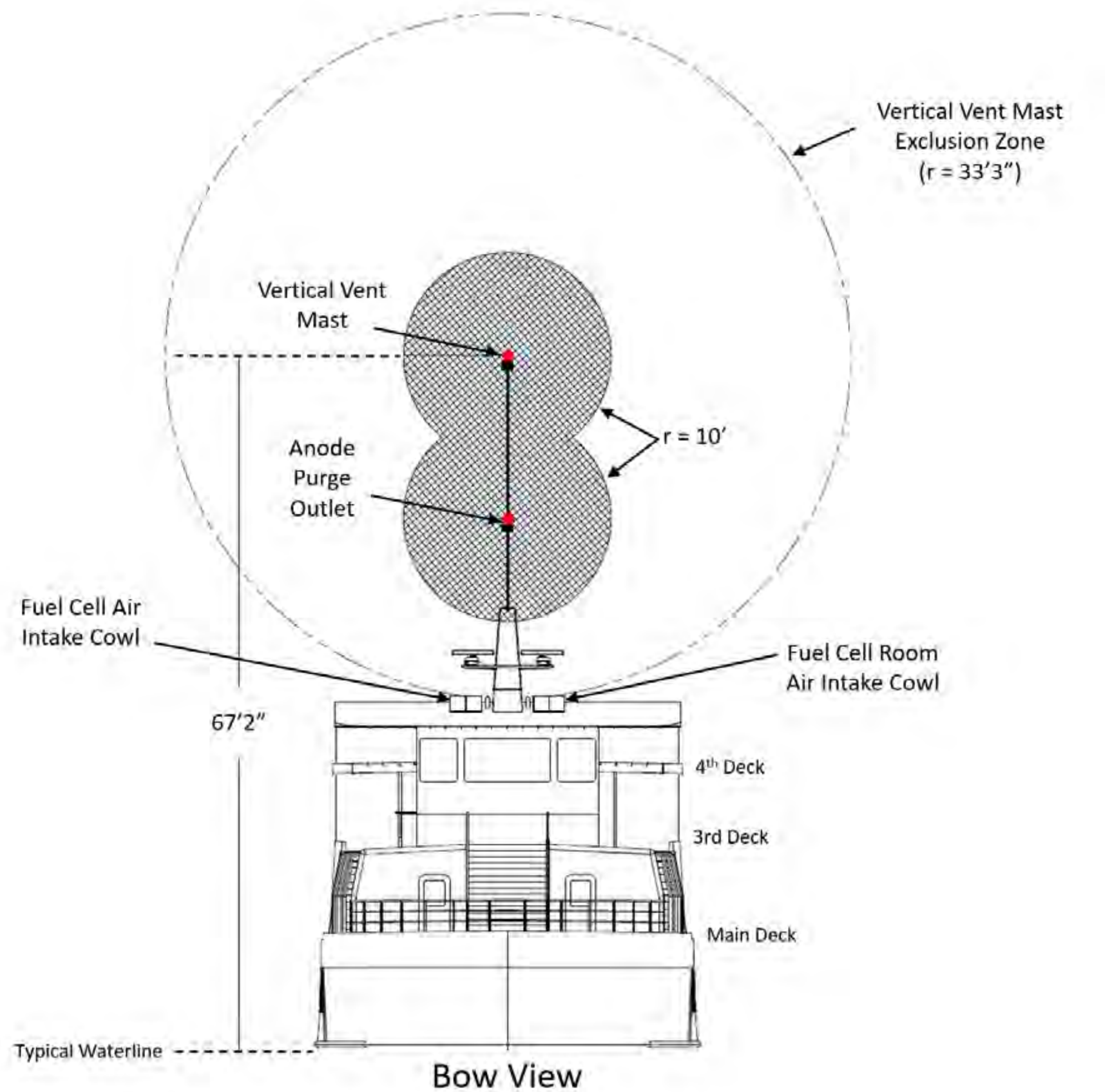

Figure 32: Vertical Vent Mast Zone 1 hazardous areas and associated exclusion zone.

Recall that one purpose of the IGF Hazardous Zones is to define a volume of space where ignition sources (splices in electrical wiring, exposed wiring or connectors, electrical junction boxes, motors, etc.) cannot be located. Another use for the hazardous zones is to protect areas of the vessel where passengers are located, or other critical features such as air intakes. This introduces the "exclusion zone" concept, which conveys the distances from sources of flammable gas release to these critical features of the vessel. The IFG Code specifically requires the venting of PRDs to be located 10 m away from air intakes, as indicated by the Vertical Vent Mast Exclusion Zone in Figure 32.

According to the IGF Code, the following prescriptive requirements apply to the Vertical Vent Mast Outlet:

1. Shall be unimpeded and normally directed upward,
2. Shall be arranged so as to minimize possibility of rain or snow entering the vent mast,
3. Shall normally be at least 10 m (33’10”) from the boundary of any vessel space *classified as non-hazardous* and from the boundary of any *machinery exhaust outlets,*
4. Shall be at least Z m in vertical height above the weather deck, where Z is the greater of 6 m or B/3, where B is the beam length (width) of the vessel (for the *Discover-Zero*, Z = 6m as B(12m)/3=4m<6m),
5. Shall be at least 6 m above working areas or walkways.

Note how the Vertical Vent Mast design places the exclusion zone (radius = 10 m (33’3”)) free and clear of the Fuel Cell Room Air intake cowls and other non-hazardous areas of the vessel.

We note here that prior feasibility studies of H_2 vessels [11, 24, 25] have argued for a hemispherical Zone 1 exclusion area at the outlet of Vent Masts, due to the high buoyancy of hydrogen at room temperature. Recently, CFD studies of Vent Mast releases of hydrogen in cross-winds have been published by Blaylock and Klebanoff [44]. 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 question represents an interesting case where the properties of hydrogen, differing from natural gas upon which the IGF Code is based, could dramatically affect the vessel requirements. Since this question has not been definitively resolved, we maintain the spherical shape of the Zone 1 hazardous zones and associated exclusion area in Fig. 32.

6.2. Anode Purge

Figure 32 also shows the hazardous area associate with the Anode Purge. This outlet is located along the side of the Vertical Vent Mast, about halfway up. Recall that product water tends to collect in the anode region of the fuel cell, which blocks H_2 gas. This water is removed by a brief pulse of hydrogen called the “anode purge.” As a result, a mixture of hydrogen and water vapor is periodically released from fuel cell stack and directed out the Anode Purge outlet. It too is assigned a Zone 1 spherical hazardous area of 3 m (10’) radius.

IEC calculations were used to evaluate the amount of hydrogen expected to be released from the Anode Purge. The results indicated the amount was far less than that expected from the top of the Vertical Vent Mast. As a result, it was more technically sound to center the 10 m (33’, 3”) exclusion zone at the top of the Vertical Vent Mast, as shown in Figure 32.

6.3. H_2 Tank Array (High Pressure)

Figure 33 shows the hazardous zones for the H_2 Tank Array/Manifold (High Pressure), the Fill Station (Bunkering) and “Low Pressure” features (shown in Figure 30), in relation to the Vent

Mast and Anode Purge hazardous zones already discussed. Figure 34 shows an expanded view emphasizing the H_2 Tank Array location.

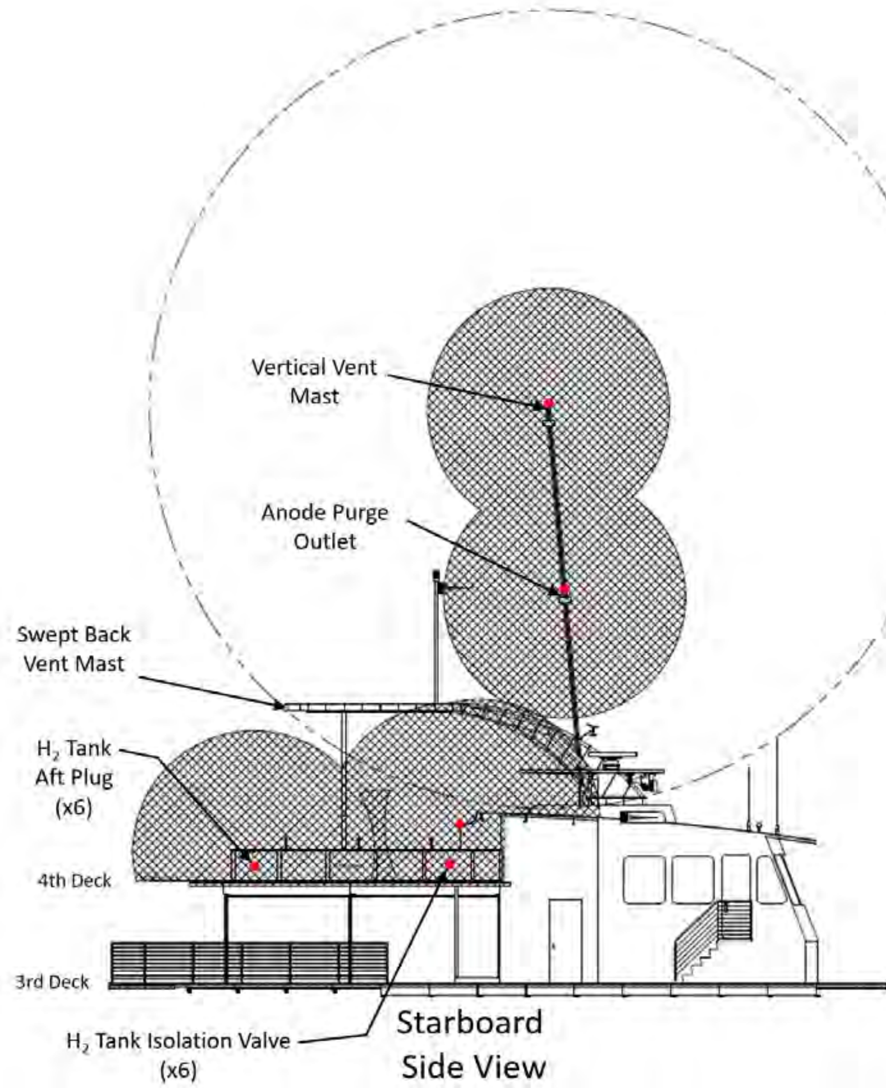

Figure 33. Zone 1 hazardous areas associated with the H_2 Tank Array and the hydrogen bunkering station, in relation to the Vertical Vent Mast and Anode Purge hazardous zones.

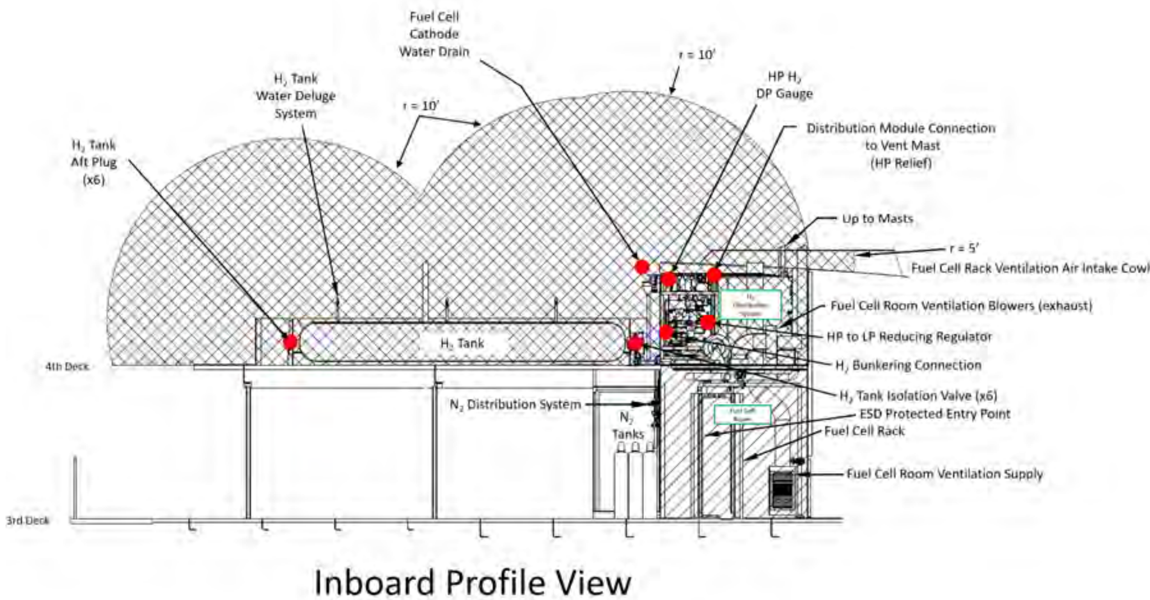

Figure 34. Expanded view of the Zone 1 hazardous areas associated with the H_2 Tank Array and the H_2 Bunkering connection. Also shown are other potential sources of hydrogen leak associated with the high pressure and low-pressure hydrogen systems as indicated, along with the Fuel Cell Room Zone 2 hazardous area.

Per the IGF Code, a 10' (3m) radius spherical Zone 1 exclusion zone issues from each of the 6 H_2 Tank Aft Plugs, and all 6 of the H_2 Tank Isolation Valves. Figure 35 shows a combined overhead and cross-sectional view of these IGF Zone 1 hazardous areas generated by the H_2 Tank Array.

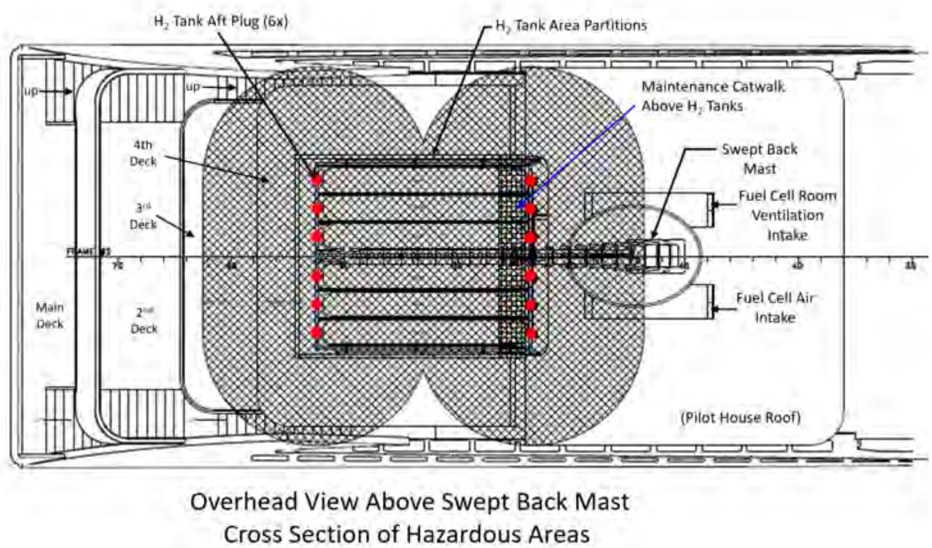

Figure 35. Overhead view above the Swept Back Mast of the Zone 1 hazardous areas associated with the H_2 Tank Array. The Zone 1 areas are shown in cross section.

6.4. Fill Station (Bunkering)

Figure 36 shows an expanded view of the Fill (Bunkering) Station.

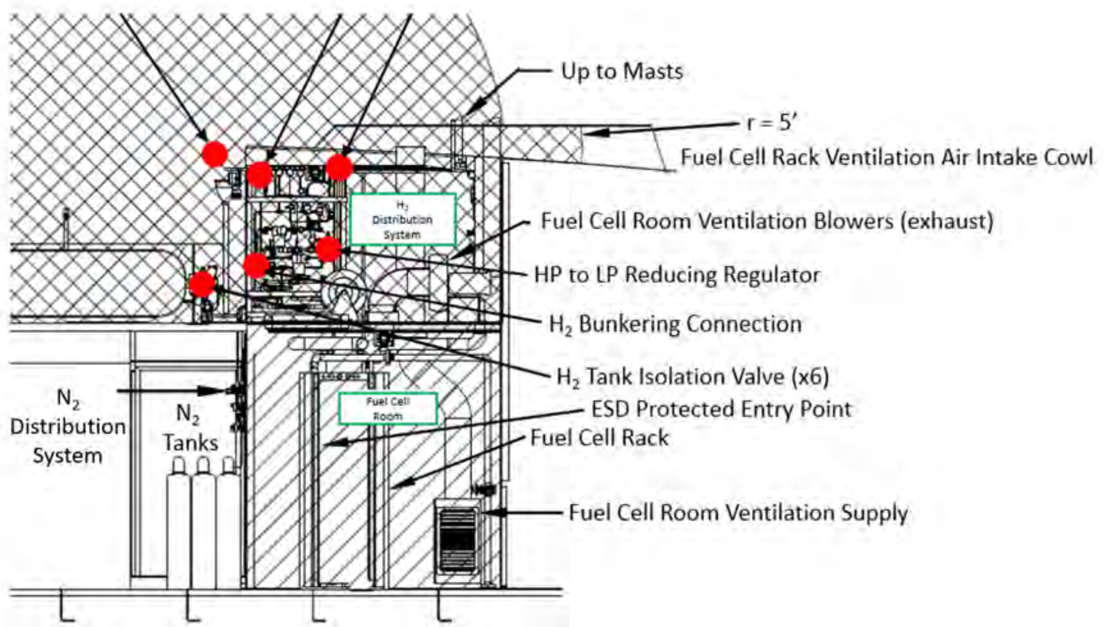

Figure 36: Expanded view showing the Zone 1 hazardous areas associated with the H_2 Bunkering connection and nearby potential leak sources associated with Hydrogen Distribution System. The Fuel Cell Room Zone 2 hazardous area is also shown.

The bunkering station consists of a high-pressure hose (see Figs. 4, 27 and 29) to connect to the fueling truck, and regulators, valves (hand-operated, solenoid-operated and pressure-relief types) and fittings to purge and vent the fuel lines and to transfer fuel to the hydrogen storage system consisting of high-pressure piping, manifold, and tanks. The truck pressure may be as high as 350 bar, so components on the bunkering station will be exposed to this pressure as well. Some of the components on the bunkering panel are downregulated by a pressure control valve (PCV) to 276 bar, however, they are in sufficiently close proximity to the higher-pressure components on the panel that the hazardous zone extent for the entire panel will be dictated by the high pressure (350 bar).

Per the IGF Code, a 10' (3m) radius spherical Zone 1 hazardous area is centered on the H_2 Bunkering connection. Other sources contributing to the Zone 1 hazardous area are also shown in Figure 36 (e.g., HP to LP reducing regulator).

6.5. Low-Pressure Piping

The low-pressure piping consists of piping, valves and instrumentation downstream of a pressure regulator valve (PRV) set at 6.62 bar (96 psi) are all directed to connection to the Fuel Cell Power Rack. We used the IEC formalism to understand the possible levels of hydrogen leakage coming from these low-pressure connection points. The analysis indicated a negligible extent of hazardous area, so no such hazardous zone is indicated.

6.6. Fuel Cell Room

Under normal operating conditions, the atmosphere of the Fuel Cell Room would consist of normal air, the same as in the outside environment. However, fuel cells do use hydrogen and because the fuel cell unit is not permanently sealed, so there is potential for leakage in abnormal situations. The Fuel Cell Rack is designed to prevent hydrogen leakage into the Fuel Cell Room. For example, the manifolds within the fuel cell are built to approved standards and leak checked. Also, there is a continuous Fuel Cell Rack ventilation flow that is designed to take any leaking hydrogen and remove it from the rack. A hydrogen detector in the top of the rack is designed to detect any hydrogen that might be produced by a leak.

Even with system mitigations in place and operating, there is a risk, however slight, where hydrogen could escape into the Fuel Cell Room. This possibility also has preventative measures in place, because the Fuel Cell Room has its own independent ventilation, and its own hydrogen detector in the on the ceiling. Nonetheless, in any closed space, small concentrations of hydrogen could possibly accumulate in pockets within the overhead structure or in areas where ventilation eddies have developed (creating dead spots), or in areas not sampled by the Fuel Cell Room hydrogen detector. Over long periods of time, hydrogen gas concentrations may rise to levels that cause the space to become gas hazardous.

To accommodate the low probable risk, the Fuel Cell Room is considered a Zone 2 area while the unit is operating. As such, the Fuel Cell Room is designated as an Emergency Shutdown (ESD) protected machinery space. Designation of the Zone 2 restricts the installation of equipment in the room to those satisfying the Zone 2 requirements. In the event of a detectable hydrogen leak (hydrogen detector alarms trigger at 0.1 the lower flammability limit), within the fuel cell rack or in the Fuel Cell Room; an emergency shutdown of non-essential equipment (ignition sources) and machinery are automatically executed. In addition to electrical disconnection, ESD of a Fuel Cell Room would initiate immediate shutdown of the hydrogen supply to the space. From these considerations, the IGF Code assignment of the Fuel Cell Room is a Zone 2 hazardous area, as shown in Figure 36.

Since our hazardous zone analysis was performed before IMO's "*Interim Guidelines For The Safety of Ships Using Fuel Cell Power Installations"* (MSC. 1/Cir. 1647, June 15, 2022) was released, the "fuel consumer room" (Fuel Cell Room as per older nomenclature) is now considered a non-hazardous area and only the Fuel Cell Rack (cabinet having fuel cell module along with accessories) is considered as a Zone 1 of negligible extent. This practically means the Fuel Cell Room is now considered a non-hazardous area.

We also assessed the IGF hazardous zone that would issue from a pierside bunkering stanchion. Figure 37 shows the Zone 2 hazardous zone around the notional H_2 refueling stanchion. The radial extent of the zone is 10' (3 m). It is an estimate only, as the real refueling stanchion has not yet been designed in detail. Note that this hazardous zone would only be in effect during bunkering.

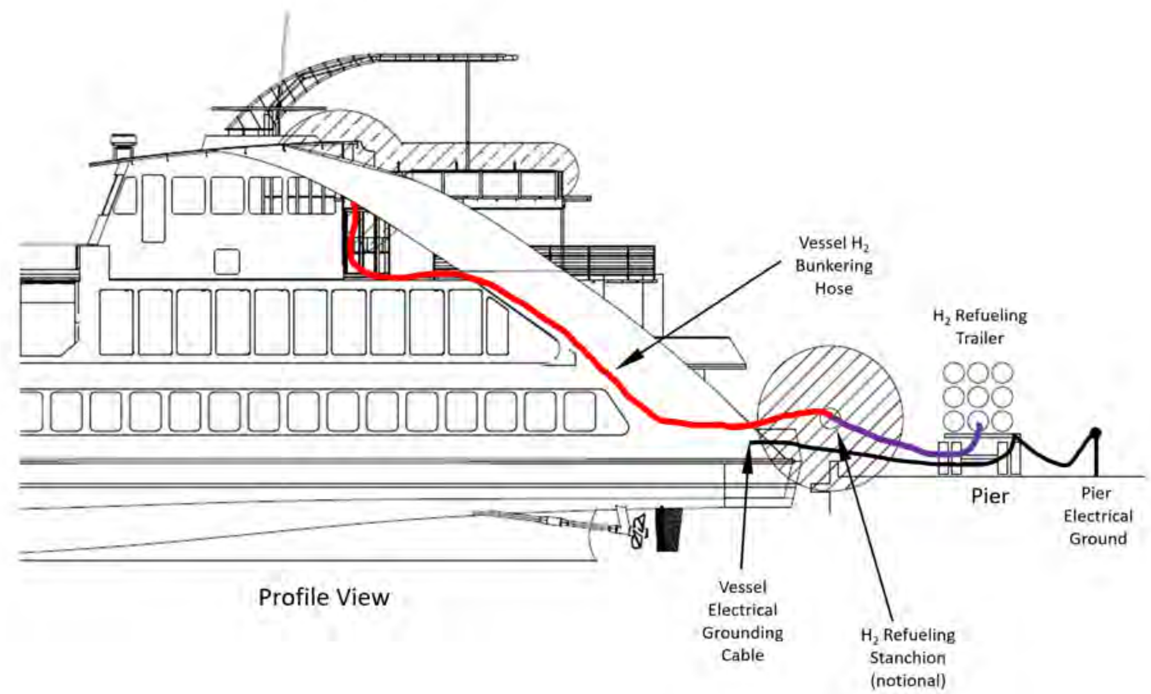

Figure 37. Profile view of the Discover Zero refueling with a pierside H_2 Refueling Trailer. A Zone 2 hazardous area, in effect only during bunkering, is indicated centered on the notional H_2 Refueling Stanchion.

A summary of these Discover Zero hazardous areas is given in Table I.

Table I: Summary of Discover Zero Hazardous Areas*

H_2 Source	Applied Regulatory Code	Zone Assignment	Physical Extent Radius
Vertical Vent Mast	IGF Code	1	3m (~ 10’)
Vertical Vent Mast	IGF Code	Exclusion Zone	10m (33’,10”)
Anode Purge	IGF Code	1	3m (10’)
H_2 Tank Array	IGF Code	1	3m (10’)
Fill/Bunkering Station	IGF Code	1	3m (10’)
Low Pressure	IEC60079-10-1	N/A	negligible
Fuel Cell Room	IGF Code	2	Entire Room
Bunkering Stanchion	IGF Code	2	3m (~ 10’)

*Note: Subsequent to our analysis of Table I, the Fuel Cell Room is now considered non-hazardous per IMO’s most recent “*Interim Guidelines For The Safety of Ships Using Fuel Cell Power Installations.” See text above.*

7. Design Basis Letter from the US Coast Guard

An application for approval of the advanced design of the Discover Zero in the form of a Design Basis Letter was submitted to US Coast Guard on April 18, 2020. The electronic submission package included:

- The General Arrangements
- Hazardous Area Zone Plans
- Emergency Egress Plan
- Structural Fire Protection Plan
- Hexagon Lincoln drawings of the hydrogen tanks
- Hydrogen piping and Instrumentation Diagram (P&ID)
- Documentation from Hydrogenics on the ventilation requirements for the fuel cell
- Hydrogenics HyPM-R 120 S fuel cell manual
- The DNV-GL HazID report
- The Hornblower Hazardous Analysis document using IEC.
- ABS document on requirements for construction of carbon composite H_2 tanks

The design package was reviewed by the USCG MSC. Based on a review of these materials, as well as regular meetings between the Project Nautilus team with the MSC to discuss and address various hydrogen safety issues, the USCG determined that the advanced Discover Zero design basis package submitted provided an equivalent level of safety to that of a title 46 CFR Subchapter K. The scope of the review was limited to the design, arrangement and engineer aspects of the hydrogen fuel cell power system and associated safety systems. The review did not address requirements for bunkering operations, manning, crew training or other such operational issues associate with the use of hydrogen as a fuel. The Design Basis Letter was issued on March 11, 2022.

Subsequently, Hornblower submitted on June 29, 2022 an application to increase fuel cell capacity to 185 kW (in place of 100 kW) using the PowerCell fuel cell module. The application to update the Design Basis Letter is in the final stage of evaluation at USCG.

8. Lessons Learned

In the course of the Nautilus Project, there were a number of issues encountered because this was a buildable design, not a feasibility study. Some of these issues and the lessons they taught us are now described.

8.1. Protective Steel Plates

In conversations with the USCG, it was pointed out that a significant risk to the Type IV composite tanks can come from a jet fire caused by a hydrogen release from the high-pressure (250 bar) manifold, followed by "spontaneous ignition" [23]. Spontaneous ignition is a poorly understood phenomenon for which a hydrogen release above 40 bar can self-ignite [23]. To protect the tanks against this threat, Figures 12 and 13 show the installation of protective steel plates in between the tank body and the next piping element. These plates are placed both fore and aft of the tank array, as shown in Figure 13. We believe these protective plates are a good precaution for any application involving an array of hydrogen tanks.

8.2. TPRDs

The TPRD is a device that prevents over-pressurization of a hydrogen tank in the event of fire. In the course of discussions with the USCG there was a concern that the water deluge system (shown in Fig. 15) that would be used to cool the tanks would also cool the TPRD. This is a problem because the water cooling might not allow the TPRD to sense the heat of the fire and perform their function of pressure relief. This problem was resolved by installing a splash shield over the TPRD, as indicated in Figures 16 and 17. We want to thank Joe Pratt, developer of the Sea Change hydrogen vessel, for sharing with us their approach to solving this problem.

8.3. Composite Hydrogen Tanks

In the course of our work with USCG, it became apparent that the Hexagon Purus Type IV composite hydrogen tanks we wanted to use, while approved by ABS for maritime storage and transport of hydrogen, were not approved for maritime use of the hydrogen contained in the tanks. This was a restriction that had no technical basis, and so needed to be corrected. As a result of a series with the Nautilus Project Team, ABS was able to approve using the hydrogen in the tanks to be stored, thereby extending the Class Approval for composite hydrogen tanks for the full scope of their use on the Discover Zero. This broader Class approval will benefit other projects and vessels wanted to use lightweight Type IV composite tanks for hydrogen storage in a maritime environment.

8.4. Fuel Cell Technology

Over the 3 years of the project, fuel cell technology advanced to the point where a 185-kW fuel cell rack could replace the original 100-kW fuel cell rack with no increase in footprint. This has required a second review by the USCG of the Discover Zero design with a higher power fuel cell. A lesson learned here is that it might be advantageous to anticipate that product development into the design of the vessel. By this we mean creating a vessel design that accommodates a fuel cell system that is actually 20 to 50% more than commercially available when the design was being created. That way, since it takes time for the USCG to fully review a design, a higher-power fuel cell design will have already been approved. This would eliminate the need to seek a second Design Basis Letter to allow for a fuel cell vessel of increased power.

8.5. Class Society

A productive approach in this project was to develop a preliminary vessel design (Fig. 5) that did not contain all of the necessary features, but enough to be assessed for hazards in a HazID workshop. Then, the feedback from the Class Society running the HazID meeting (DNV-GL) could be folded into an advanced Discover Zero design to be submitted to the USCG. This approach worked well in this project and could be a model for other projects engaged in a similar design activity for hydrogen fuel cell technology.

8.6. USCG

A lesson learned in this Nautilus Project was to have a very early engagement with the USCG, and then have continuing discussion with them as the design progressed. This occurred even before the official submission of the design package for consideration for a Design Basis Letter. Discussions took the form of bi-weekly Zoom meetings with the USCG, even if the only point of the meeting was maintaining contact. This developed a teaming relationship between the Nautilus Project Team and the USCG which we found be very helpful, aided the USCG review of the project, and help expedite the Design Basis approval process. Also, as issues arose with the USCG (e.g., the initially limited ABS hydrogen tank approval), these issues could be promptly addressed.

9. Summary

This report had described the activities and results of Phase 1 of the Nautilus Project. In Phase 1 AIS aimed to design a "buildable" hydrogen fuel cell hybrid drivetrain to supply auxiliary power to the existing Discover Zero vessel as a retrofit. The improved propulsion system integrates power supplied by hydrogen fuel cells with the existing lithium-ion batteries already onboard the vessel, providing a battery/fuel-cell hybrid capability supplementing the diesel engines already on the vessel. A preliminary design for the combination of hydrogen tanks, fuel cell, hydrogen distribution system and integration to the Discover Zero was generated in order to received technical feedback from technical experts. Toward that end, a risk assessment HazID meeting was conducted by a team led by DNV-GL, including representation from Hornblower, USCG, Sandia, DeJong & Lebet and DOT/MARAD. Overall, the hydrogen power technology design and vessel integration was evaluated by DNV-GL and was granted an "Approval in Principle" (AIP), which, represents an approval of the basic concept and the preliminary design to that point.

Subsequently, naval architect DeJong & Lebet created an advanced design for safely and effectively introducing the hydrogen technology elements onto the Discover Zero. At the same time, this advanced design adhered to the proscriptions imposed by the IGF Code and the DNV-GL Class rules regarding hazardous zones and ventilation and allowing straightforward bunkering of the vessel. The advanced design was examined in detail by the USCG, who made further recommendations for safe design and operation. The final Discover Zero design incorporates these USCG recommendations, and includes buildable designs for the H_2 Tank Array, the hydrogen fuel distribution systems, placement of the Fuel Cell, along with detailed hardware for safety features such as water spray fire control and Fuel Cell and Fuel Cell Room ventilation. In addition, a hazardous zone analysis was conducted and guided placement of the hydrogen technology pieces so as to satisfy maritime regulations such as the IGF Code and the DNV-GL rules for fuel cells.

An application for approval of the advanced design of the Discover Zero in the form of a Design Basis Letter was submitted to US Coast Guard on April 18, 2020. The USCG determined that the advanced Discover Zero design basis package submitted provided an equivalent level of safety to that of a title 46 CFR Subchapter K diesel vessel. The Design Basis Letter was issued on March 11, 2022. Subsequently, Hornblower submitted on June 29, 2022 an application to increase fuel cell capacity to 185 kW (in place of 100 kW) using the PowerCell fuel cell module. The application to update the Design Basis Letter is in final stage of evaluation at USCG.

Since Phase 1 produced a design with sufficient detail to be constructed (a "buildable design"), very specific lessons were learned as the design was evaluated by DNV-GL as well as by the USCG. These lessons included specific design aspects such as the use of protective steel plates to protect the hydrogen tanks from a jet fire issuing from the high-pressure manifold, and the proper placement of TPRDs and protecting them from water spray should the fire-fighting system be engaged. Other lessons were more regulatory (ABS approval for use of hydrogen from storage tanks), or procedural (the best way to engage the regulatory entities DNV-GL and USCG).

With the Design Basis Letter issued by the USCG and MARAD approval for Phase 2, the next step is to secure funding for building, installing and testing the hydrogen fuel cell technology components for use on the Discover Zero. The Nautilus Project team is currently exploring federal and state sources for such support.

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