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Feasibility Study of Replacing the *R/V Robert Gordon Sproul* with a Hybrid Vessel Employing Zero-emission Propulsion Technology

--A Comparison of Hydrogen Fuel Cell and Battery Hybrid Technologies for a Coastal/Local Research Vessel Application--

Prepared by:

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Feasibility Study of Replacing the *R/V Robert Gordon Sproul* with A Hybrid Vessel Employing Zero-emission Propulsion Technology

--A Comparison of Hydrogen Fuel Cell and Battery Hybrid Technologies for a Coastal/Local Research Vessel Application--

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Sandia National Laboratories

Glosten

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The authors wish to thank Bryan Vogel at MARAD for his technical contributions, encouragement of the work and providing project management from the MARAD side. Thanks are also extended to Michael Carter at MARAD for ongoing support of hydrogen vessel technology studies.

We wish to acknowledge the Scripps Marine Operations Committee (MOC), particularly an ad-hoc group who helped develop the science mission requirements for the *R/V Sproul* replacement. These included MOC Chair Mark Zumberge along with members Simone Baumann-Pickering, Ralf Goericke, John Hildebrand, Gabi Laske, Drew Lucas, Kathleen Ritzman, and Uwe Send. Zoltan Kelety (SIO Marine Superintendent) provided valuable input regarding practical aspects of scientific vessel operations. Lee Ellet advised on appropriate oceanographic instrumentation.

We also thank Daljit Bawa of Ballard Power Systems who reviewed a section of the report and provided information about the Ballard fuel cell power system upon which this study is based. In addition, Aleem Quraishi of MAN Energy Solutions provided critical information about the liquid hydrogen (LH_2) tank assumed in this study.

Thanks are extended to Jon Zimmerman, the Sandia Hydrogen Program Manager, for his helpful suggestions and constructive review of this report.

Project Summary:

This project is a natural "follow-on" to the 2017 MARAD-funded project [1,2] establishing the technical, regulatory, and economic feasibilities of a zero-emission hydrogen fuel-cell coastal research vessel named the Zero-V. In this follow-on project, we examine the applicability of hydrogen fuel-cell propulsion technology for a different kind of vessel, namely a smaller coastal/local research vessel targeted as a replacement for the Scripps Institution of Oceanography (SIO) *R/V Robert Gordon Sproul* (Figure 1), which is approaching the end of its service life.

Figure 1: The *R/V Robert Gordon Sproul*. Photo Credit: The Scripps Institution of Oceanography.

Sandia National Laboratories provided project leadership (Project PI: Lennie Klebanoff) and hydrogen fuel-cell technology expertise, particularly with regard to the physical and safety properties of hydrogen [3], hydrogen storage [4] and greenhouse gas (GHG) and criteria pollutant emissions from hydrogen vessels [5]. Glosten (PIs: Sean Caughlan and Robin Madsen) provided the vessel design work and with Sandia engaged commercial suppliers of LH_2 tanks (MAN Energy) and hydrogen proton exchange membrane (PEM) fuel cells (Ballard Power Systems). The Scripps Institution of Oceanography (PI: Bruce Appelgate) developed the Sproul Replacement Vessel (SRV) mission requirements and solicited broader feedback from the Scripps oceanographic science community on the results of the study. All three partners evaluated the various SRV designs as they were being developed and contributed to “mid-course corrections” during this first trip around the vessel design spiral [6].

This feasibility study had several boundary conditions for the SRV design, with the objective to replace the *R/V Sproul*. The first boundary condition was vessel performance. The SRV had to meet the oceanographic research mission profiles specified by SIO. Establishing these science mission profiles involved engagement between the project team and the Scripps Marine Operations Committee (MOC). The vessel requirements for the Sproul SRV were developed by merging the existing *R/V Sproul* performance specifications with additional requirements SIO desired for the replacement vessel. The result was a list of 34 individual science missions constituting 14 unique mission profiles that the SRV had to meet.

The science missions represent a fascinating mix of SIO research and instructional activities at sea. One profile envisioned (Profile: Class Cruise: Marine Geology and invertabrates) is based on recent projects that have explored for Monoplacophora, the least-known of the seven classes of Mollusca, which are found living on phosphoritic nodules on the seabed in water deeper than 300 meters in the Channel Islands. Previously thought to have gone extinct 380 million years ago, live specimens were first recovered in 1952 and recent sequencing of their genome has revealed implications for evolutionary biology. Obtaining new specimens for study is challenging due to their restricted habitat in very deep water. Students and scientists would use the SRV sonars to map and characterize the seabed to find a likely site. Then, they would position the ship over that spot using the ship's dynamic positioning system to remain locked into place while they lower a seabed sampling device (a Van Veen Grab Sampler) down to the seafloor on a wire spooled from the ship's deep-sea winch. Once a seabed sample is acquired, it is brought back up to the ship, carefully removed from the sampler into the ship's wet laboratory, and assessed for nodules that host the Monoplacophora. New specimens must be preserved in shipboard deep freezers (-80 °C) to preserve their genetic material for analysis ashore.

Other common research activities include, a combined deep-ocean mooring and towed sonar program (Profile: Deep Moorings (4000 m) + Towed Sonar I) envisioned for acousticians who are trying to understand how sound propagates in the deep sea (with implications for the way animals use sound underwater, or how underwater sound can be used for communications). Other mission examples are a systematic Autonomous Underwater Vehicle (AUV) video survey (Profile: AUV OPS I) of the ocean's "twilight zone," home of a multitude of organisms that are too fragile to be recovered using any kind of sampling system, and a nearshore data acquisition mission (Profile: Coastal Physical Oceanography) that uses the ship's Acoustic Doppler Current Profiling system in conjunction with shallow-water moorings deployed through the ship's A-frame in order to study the ocean's hidden internal waves. Each of these missions requires different kinds of instruments, sampling systems and shipboard support -- but all require an exceptionally-capable general-purpose research vessel. Such activities are shown in Figure 2.

Figure 2: Research and instructional activities onboard the *R/V Robert Gordon Sproul*. Clockwise from top left: A marine biology class sorts through the contents of a successful Isaacs-Kidd Midwater Trawl; a fresh seabed sample from a multicore is carried by a student across the deck to the laboratory; scientists and technicians deploying a Remotely-Operated Vehicle (ROV) to investigate deep-sea ecosystems associated with a natural seabed methane vent offshore La Jolla; students in the ship's Electronics Laboratory download data from a sensor (that they built in class) that had been lowered to the seabed; a group of students prepares to deploy a Conductivity-Temperature-Depth (CTD) profiling rosette. Photo Credits: The Scripps Institution of Oceanography.

The second boundary condition was budget. The normal SIO funding channels limited the capital cost for the SRV to be at or near $30 M. A third boundary condition was that the SRV had to reduce greenhouse gas (e.g., CO_2) and criterial pollutant emissions (including NO_x, hydrocarbons (HC) and particulate matter (PM)), compared to the *R/V Sproul*. In addition, the SRV design should allow some of the shorter mission profiles to be performed completely under zero-emissions propulsion power.

From a regulatory perspective, a fourth boundary condition was that the SRV design and operation should be compliant with regulations for a load-lined, 46 CFR Subchapter C uninspected vessel. The SRV designs developed in the study allow for the same regulatory compliance regime. For example, uninspected vessels must have a domestic tonnage of under 300 Gross Registered Tonnage (GRT).

To fully understand the attributes of introducing hydrogen fuel-cell technology to a coastal/local research vessel, four independent vessel variants were developed, all considered SRVs.

Baseline Vessel:
The first SRV variant is a "Baseline Vessel" with conventional diesel-electric propulsion. This Baseline Vessel allows a comparison of SRVs incorporating zero-emission technology to the incumbent vessel technology based on diesel-electric propulsion, both in terms of vessel performance but also air emissions.

Battery Hybrid Vessel:
The second SRV vessel was a "Battery Hybrid Vessel" in which most of the propulsion power is provided by a diesel-electric powerplant, supplemented with the introduction of a lithium-ion battery bank acting as a hybrid power system. This SRV variant allows exploration of battery-hybrid performance as an SRV and also permits hydrogen fuel-cell technology, another zero-emission alternative that has found application in vessels, to be compared to battery technology.

Hydrogen Hybrid Vessel:
The third SRV variant is a "Hydrogen Hybrid Vessel" in which most of the propulsion power is provided by a diesel-electric powerplant, supplemented with a hydrogen/fuel cell hybrid power system. By comparing this SRV variant to the diesel-electric "Baseline Vessel" and the "Battery Hybrid Vessel" we can assess the benefits of a partial introduction of hydrogen technology to the SRV.

All Hydrogen Vessel:
The fourth and final SRV variant was an "All Hydrogen Vessel," in which the entire diesel-electric propulsion system is removed and replaced with a hydrogen fuel-cell propulsion system. For this vessel, all power on the vessel (both propulsion and auxiliary) derives from the hydrogen/fuel cell power plant.

All four SRV vessel variants were based on the same hull design as the Baseline Vessel. Vessel performance (speed, range), capital cost and pollutant emissions (both GHG and criteria) were developed for the variants. Detailed SRV results can be found in the Glosten Design Study Report that follows this Project Summary. Some high-level results are summarized here.

The Baseline, Battery Hybrid and Hydrogen Hybrid SRVs were all able to meet the performance requirements (propulsion and service power) and mission profiles specified by SIO. The All

Hydrogen SRV was not able to carry enough LH_2 within the volume of the baseline hull to meet the required SIO performance targets. This difficulty can be traced to the relatively poor volumetric storage density of LH_2 compared to diesel fuel (~ 4x worse). As a result, the All Hydrogen SRV design was not developed in detail or investigated further.

The Battery Hybrid SRV endurance is approximately three hours of zero-emission (battery only) operation at the average power consumption level of all the SRV mission profiles. The Battery Hybrid could not complete any of the identified SRV missions using battery-only power. The Battery Hybrid vessel's zero-emission (i.e. battery only) endurance is 2.5 hours at a nominal 10 knot cruise speed, representing a zero-emission range of 25 nautical miles. When compared to the diesel-electric Baseline Vessel, the Battery Hybrid Vessel increases overall SRV energy efficiency and would reduce annual diesel fuel consumption by approximately 9%.

In contrast, the Hydrogen Hybrid SRV can satisfy 74% of the annual missions (25 of 34) with zero-emission operation (running entirely on hydrogen fuel). The vessel's zero-emissions endurance is 23.4 hours at a nominal 10 knot cruising speed, yielding a total hydrogen-powered zero-emission range of 234 nautical miles. The 25 missions that can be completed running on hydrogen power alone are one-day missions. Longer missions must be completed using a combination of hydrogen fuel and diesel fuel, a combination which still reduces emissions and diesel fuel consumption compared to the Baseline Vessel running solely on diesel fuel. The superior vessel performance of the Hydrogen Hybrid SRV compared to the Battery Hybrid SRV is attributable to the higher volumetric energy storage density of the LH_2/fuel cell combination compared to lithium-ion battery storage for the amounts of energy stored for hybrid vessel operations. The Hydrogen Hybrid can store 22.4% of the SRV fuel energy as hydrogen compared to the Baseline Diesel vessel. In contrast, the Battery Hybrid variant provides ~ 2% of the stored energy as stored electricity compared to the diesel-electric Baseline Vessel.

The capital costs of these vessels are estimated to be: $21.4 M for the diesel-electric Baseline Vessel, $26.0 M for the Battery Hybrid SRV vessel and $34.4 M for the Hydrogen Hybrid SRV. Thus, of the zero-emission options, only the Hydrogen Hybrid SRV meets all the technical requirements, but falls somewhat higher than the budget target of $30 M.

The "well-to-waves" (WTW) GHG and criteria pollutant emissions were estimated for the diesel-electric Baseline Vessel operating on conventional diesel fuel or biodiesel fuel, for the Hydrogen Hybrid Vessel (using various sources of LH_2 with companion diesel and biodiesel fuel for the diesel engines) and for the Battery Hybrid Vessel (using various sources of shore power with companion diesel and biodiesel fuel) vessels, all in performing the same suite of SIO science missions in a given year. The best performing hybrid vessel is the Hydrogen Hybrid variant using 100% renewable hydrogen, because of the superior stored energy available with hydrogen fuel cell technology. The annual WTW GHG emissions from the Hydrogen Hybrid using renewable LH_2 in combination with fossil diesel in the hybrid arrangement yields a 26.7% GHG emissions reduction from the diesel-electric Baseline Vessel. When using biodiesel as the companion fuel to renewable hydrogen, the GHG emissions are reduced 53.0% from the Baseline Vessel. The Battery Hybrid vessel with 100% renewable electricity combined with diesel fuel provides a 6.9% reduction in GHG emissions. Similar results are seen for the criteria pollutant emissions.

Summarizing, feasibility is demonstrated for a SRV that employs hydrogen fuel-cell technology as a hybrid propulsion system. The Hydrogen Hybrid SRV offers significant performance advantages compared with a Battery Hybrid SRV in terms of zero-emission range, overall vessel energy efficiency and reduced pollutant emissions (both GHG and criteria). These advantages are due to the increased volumetric energy storage associated with the Hydrogen Hybrid utilizing liquid storage of hydrogen.

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Glosten

R/V SPROUL REPLACEMENT

DESIGN STUDY REPORT

PREPARED FOR

SANDIA NATIONAL LABORATORIES
LIVERMORE, CA

26 JUNE 2020
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REV. -

PREPARED	CHECKED	APPROVED
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Revision History

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List of Acronyms

ABL – Above Baseline

ABS – American Bureau of Shipping

AC – Alternating Current

ADCP – Acoustic Doppler Current Profiler

AFFF – Aqueous Film Forming Foam

ASTM – American Society for Testing and Materials

AUV – Autonomous Underwater Vehicle

BMS – Battery Management System

CFD – Computational Fluid Dynamics

CFR – Code of Federal Regulations

CL – Centerline

COTP – Captain of the Port

CTD – Conductivity, Temperature, and Depth

DC – Direct Current

DNV GL (DNV) – Det Norske Veritas / Germanischer Lloyd

DOD – Depth of Discharge

DOT – Department of Transportation

DP – Dynamic Positioning

ELA – Electrical Load Analysis

EOS – Engineers Operating Station

EPA – Environmental Protection Agency

ESD – Emergency Shutdown

FMEA – Failure modes and effects analysis

FR – Frame

GHG – Greenhouse Gas

GPS – Global Positioning System

GRT – Gross Registered Tonnage

GSU – Gas Supply Unit

HAZID – Hazard Identification

HC – Hydrocarbons

HVAC – Heating Ventilation and Air Conditioning

IGF Code (IGF) – International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels

IMO – International Maritime Organization

IR – Infrared

KW – Kilowatts

KWh – Kilowatt Hours

LCG – Longitudinal Center of Gravity

LH_2 – Liquid Hydrogen

LHV – Lower Heating Value

LNG – Liquified Natural Gas

LOA – Length Overall

LT – Long Tons

LWL – Length at Waterline

MM – Million

MARVS – Maximum Allowable Relief Valve Setting

MCR – Maximum Continuous Rating

MDO – Marine Diesel Oil

NM – Nautical Miles

NO_x – Oxides of Nitrogen

Ops – Operations

PBU – Pressure Build Up

PEM – Proton Exchange Membrane

PM – Particulate Matter

RCRV – Regional Class Research Vessel

SAWE – Society of Allied Weight Engineers

SCR – Selective Catalytic Reduction

SIO – Scripps Institution of Oceanography

SLA – Service Life Allowance

SMR – Science Mission Requirements

SRV – Sproul Replacement Vessel

SW – Seawater

SWBD – Switchboard

SWBS – Ship Work Breakdown Structure

SWL – Safe Working Load

TCG – Transverse Center of Gravity

UNOLS – University National Oceanographic Laboratory System

URN – Underwater Radiated Noise

USBL – Ultra-short baseline

USCG – United States Coast Guard

UV – Ultraviolet

VAC – Volts Alternating Current

VCG – Vertical Center of Gravity

VDC – Volts Direct Current

WTW – Well to Waves

XBT – Expendable Bathythermograph

Executive Summary

This study was funded by the U.S. Department of Transportation Maritime Administration (MARAD) in collaboration with Sandia National Laboratories, Glosten, Inc., and University of California San Diego's Scripps Institution of Oceanography (SIO). It builds on previous work which established the feasibility of a hydrogen fueled coastal research vessel, the *Zero-V* (Reference 14).

SIO's current coastal research vessel is the R/V *Robert Gordon Sproul.* Built in 1981, the R/V *Sproul* is nearing the end of its service life and will require replacement soon. This study compares three different propulsion variants for an R/V *Sproul* replacement vessel (SRV) with a conventional diesel-electric baseline vessel. The completed study includes a comparison of vessel designs, capital cost, and performance of the propulsion systems considered.

SIO would like the SRV to have a significant zero-emissions capability within an estimated $30 million budget constraint. The goal of the study was to compare the various propulsion systems in order to better understand how the vessel performance and cost would be impacted by the different systems. Science Mission Requirements (SMR) similar to those of the R/V *Sproul* were developed by SIO. For each variant, the intention of the concept design was to meet the SMR with a minimum of changes from the baseline Diesel-Electric SRV. All variants were based on the same hull. The propulsion variants include:

1. Battery Hybrid SRV (diesel-electric with battery)
2. Hydrogen Hybrid SRV (diesel-electric with fuel cell)
3. All-Hydrogen SRV (fuel cell)

All variants except the All-Hydrogen SRV were found to meet the SMR. The All-Hydrogen SRV was not able to carry enough hydrogen within the volume of the baseline hull to meet required range and endurance and the design was not developed further.

The Battery Hybrid SRV would able to provide approximately three hours of zero emissions (battery only) operation at average power consumption levels but could not complete any of the identified missions without the diesel generators. The vessel's zero emissions endurance is 2.5 hours at a nominal 10 knot cruise speed, representing a battery only range of 25 nautical miles. Some specific operations within a few one-day missions could be achieved with batteries alone, for example on-station science operations (ops), or loitering. When compared to the Diesel-Electric SRV, the Battery-Hybrid increases overall efficiency and would reduce annual diesel fuel consumption by approximately 9%.

The Hydrogen Hybrid SRV would be able to satisfy 74% of the annual missions (25 of 34) with zero-emissions operations (hydrogen only). The vessel's zero-emissions endurance is 23.4 hours at a nominal 10 knot cruising speed, yielding a total hydrogen powered range of 234 nautical miles. All of the 25 missions that can be completed with only the liquid hydrogen storage onboard are under one day. Longer missions could be completed by using a combination of hydrogen and diesel fuel which reduces emissions and diesel fuel consumption compared to operations solely on diesel fuel. Many specific operations within longer missions could also be completed fully with zero emissions operations. For example, the operator could make long distance transits using the diesel generators but conduct on station science work or operations in sensitive environments using zero emission operation. The Hydrogen Hybrid SRV would reduce annual diesel fuel consumption by 30% compared to the baseline Diesel-Electric vessel.

The Diesel-Electric baseline SRV is estimated to cost between $20.7MM and $22.2MM. The Battery Hybrid SRV would cost between $25.1MM and $27.0MM. The Hydrogen Hybrid SRV would cost between $33.1MM and $35.6MM. The Hydrogen Hybrid SRV could meet all technical requirements though it falls slightly over (between 10% and 17%) the budget goal of $30MM.

Section 1 Introduction

Sandia National Laboratories (Sandia), in collaboration with the U.S. Department of Transportation Maritime Administration (MARAD), University of California San Diego's Scripps Institution of Oceanography (SIO), and other partners, recently completed a project focused on the feasibility of using hydrogen fuel cell technology to perform the research missions required of a California coastal research vessel (see Reference 14). *Zero-V*, the concept vessel developed in the feasibility study, was found to be technically feasible, but the estimated vessel construction cost of $79 million exceeded what was believed to be available to the operator through conventional government funding channels.

Sandia and MARAD remains interested in a hydrogen fuel cell powered research vessel. Contemporaneously, the University of California San Diego's Scripps Institution of Oceanography (SIO) has an ongoing need for a new coastal research vessel, and the University of California's Carbon Neutrality Initiative provides an impetus for seeking less carbon-intensive powering and fueling options.

SIO is one of the world's premier oceanographic research institutions, operating a fleet of research vessels ranging from coastal to global class ships. SIO's current coastal research vessel is the R/V *Robert Gordon Sproul.* Built in 1981, the R/V *Sproul* is nearing the end of its service life and will require replacement soon. SIO and Sandia are both interested in exploring the feasibility of several powering options for a new coastal research vessel to replace the R/V *Sproul* and support the University of California's goals to reduce emissions of air pollutants and greenhouse gases.

The purpose of this study is to compare three different propulsion variants for an R/V *Sproul* replacement vessel (SRV) within a budget limit of approximately $30 million. The propulsion variants include:

1. Hybrid Diesel-Electric with Battery,
2. Hybrid Diesel-Electric with Hydrogen, and
3. an All-Hydrogen.

All three variants were compared with a conventional Diesel-Electric baseline vessel. The baseline vessel is designed to meet, but not exceed, the performance of the R/V *Sproul*. The completed study includes a comparison of vessel designs, capital cost, emissions, and performance of the propulsion systems considered.

Section 2 Vessel Requirements

The vessel requirements for the Sproul Replacement Vessel (SRV) were developed by merging the existing R/V *Sproul* specifications with requirements SIO provided for the intended operating locations of a new California coastal research vessel (see Table 1).

The general vessel requirements are the following:

- US flagged.
- United States Coast Guard uninspected vessel, 46 CFR Subchapter C Uninspected Vessels.
- Reduced air emissions, with some zero-emissions operation.

Table 1 SRV Science Mission Requirements (SMR)

Vessel Requirements	Details	Meets Requirement
Cruise Speed	10 knots	✓
Maximum Speed	11 knots, calm water	✓
Range	2,400 nm (nautical miles) at cruise	✓
Endurance	10 days	✓
Sewage Holding	Minimum 2,000 gallons	✓
Laboratory Area	Minimum 340 ft^2	✓
Students	Minimum 30 (40 desired)	✓
Crew Berths	Minimum 5 (single berths preferred)	✓
Science Berths	Minimum 12 (more preferred)	✓
Portable Vans	Minimum 2	✓
Station Keeping	Dynamic positioning (desired)	✓
Deck Tie Down	UNOLS Compliant on aft deck (desired in labs)	✓
Science and Support Equipment		
Main Crane	2,400 lbs SWL	✓
Stern A-Frame	SWL 10,000 to 21,000 lbs	✓
Winches	Trawl, CTD/Hydro	✓
Side Frame	J-Frame	✓
ADCP	Two: 1 medium & 1 high frequency (desired)	✓
Echosounder	Knudsen 3260 3.5 & 12 kHz (desired)	✓
XBT	Turo Devil (desired)	✓
GPS	Redundant survey quality (desired)	✓
Broadband	HiSeasNet (desired)	✓
Azimuth	Ashtec ADU (desired)	✓
Motion Reference	Seapath (desired)	✓
Multibeam	EM 712 (desired)	✓
Fisheries sonar	Kongsberg EK80 (desired)	✓
USBL	HiPAP (desired)	✓

SIO additionally provided yearly mission profile data to define necessary vessel performance characteristics. As shown in Table 2, this data included 34 individual missions constituting 14 unique mission profiles.

It should be noted that 25 of the 34 missions are one day or less in duration. However, because the vessel would serve approximately 92 days at sea, the 25 one-day missions make up only 27% of the vessel's annual operating time. Nevertheless, early in the project it was agreed that if all the one-day missions could be entirely or partially met with zero emissions technology, that would still be a significant capability and of great interest to SIO (this is discussed further in Section 6.8).

Table 2 SRV Science Missions

Mission	Length (Days)	Participants Science	Participants Techs	Number of Missions/Year
Physical Oceanography	1	12	1	1
Class Cruise: Biology of Fishes	1	28	2	2
Class Cruise: AUV Ops	1	28	1	2
Class Cruise: Marine Geology & Invertebrates	1	28	2	4
Coastal Mooring	1	12	2	5
Class Cruise: Biology (Typ)	1	28	2	11
Geology Sampling (Multicore)	5	12	2	1
Deep Moorings (4000m) & Towed Sonar I	5	7	1	1
Deep Moorings (4000m) & Towed Sonar II	7	7	1	1
AUV Ops I	7	8	1	1
AUV Ops II	7	6	1	1
Cyanobacteria: CTDs and Incubations	8	12	1	2
Geology: Vibracore & Box Core	10	12	1	1
Coastal Physical Oceanography	10	11	1	1
Total				34

Section 3 Basic Vessel Design

3.1 Regulatory Requirements

SIO operates the R/V *Sproul* as a load lined, uninspected vessel. The R/V *Robert Gordon Sproul* carries a USCG letter of designation as an Oceanographic Research Vessel. While uninspected, Scripps voluntarily maintains a number of areas at inspected vessel status including stability, damage control and many safety systems. While not required, Scripps has a Safety Management System in place on R/V *Robert Gordon Sproul*.

The SRV is designed to allow for the same regulatory compliance regime. Research was conducted to ensure that this mode of operation is consistent with the vessel's mission requirements. Uninspected vessels must have a domestic tonnage of under 300 GRT and must meet various requirements related to paying passengers. The designation given to oceanography students during class cruises would drive the requirements. Per 46 CFR Subchapter U, scientific personnel are defined as anyone onboard a research vessel to engage in scientific research, or to instruct or receive instruction in oceanography. As the students will be onboard to receive instruction in oceanography, they can be classified as scientific personnel. Because scientific personnel do not count as passengers per 46 CFR, the vessel will qualify as an uninspected vessel so long as the tonnage is kept below 300 GRT.

This study therefore assumes that the vessel is uninspected per 46 CFR Subchapter C, will comply with load line requirements. It also assumes the design will comply with 46 CFR Subchapter U even though it will not be inspected. At this stage, this decision mainly affects stability requirements and gross tonnage limitations. During a future contract design of the vessel, the full extent of the impacts will need to be considered and implemented in the design.

3.2 Hull Type

Monohulls are the most common type of ocean-going vessel and the vast majority of oceanographic research vessels are monohulls. Monohulls offer the largest amount of volume within the hull below the main deck and have a relatively simple and efficient hull structure, making them typically less expensive to build than a multihull of the same displacement. This is the primary reason that monohulls are the most common and conventional hull for ocean-going research vessels. Additionally, monohulls of conventional proportions (ratios of length, beam, draft, and displacement) can have excellent seakeeping performance and maneuverability. A trimaran hull was used for the Zero-V, as the previous Zero-V project determined that a monohull vessel would not provide sufficient stability for an all hydrogen powered vessel of that size. However, a monohull was the only design pursued for the SRV, as this vessel is cost limited and a monohull of conventional proportions will be the most cost-effective design.

In order to leverage previous work and provide a starting point for this comparison study, Glosten started with an existing research vessel concept design which was the correct size and power for the starting point (Figure 1). The arrangements were modified to meet SIO's requirements for the SRV as a baseline. All three variants utilize the same baseline hull form with minimal modifications to deck arrangements. The intention of this comparison study is to understand the differences between the different technologies, so changes to the baseline hull were minimized.

Figure 1 SRV baseline hull - 125-foot research vessel concept

3.3 Principal Characteristics

Table 3 Baseline Vessel Characteristics common to all variants

Principal Dimensions	
LOA [ft]	125
LWL [ft]	120
Depth [ft]	14
Beam [ft]	34
Draft [ft]	10
Air draft [ft]	52
Freeboard [ft]	4
Propulsion	
Propellers	Two (2) Veth VL400si semi-integrated L-drive, 375 kW
Generators	Three (3) Bollard 395 kW, EPA Tier 3
Bow Thruster	One (1) Fixed pitch ducted propeller, 150 kW
Additional Details	
Speed (cruise) [kts]	10
Speed (max) [kts]	11
Endurance [days]	10
Range [NM]	2,400
Tonnage [GRT]	<300
Class	None
Load line	yes

3.4 Speed/Power

Estimating the SRV's speed and power requirements is very important for determining its fuel consumption while underway. This is especially important for the hydrogen powered variant, because the low volumetric energy density of LH_2 makes the fuel storage requirements to meet range a major design driver. At this level of design, the best industry practice for determining powering is to rely upon parametric hull series data for similar hull designs. Using regression analysis, an estimate of the hull resistance can be developed using the vessel's principal hull dimensions. The regression analysis accounts for the shape and characteristics of the hull to estimate the design's overall resistance.

The calm water resistance and powering calculations were performed with HydroComp's NavCad® 2017 software using the Holtrop prediction method for resistance. The calm water powering, given as the required power delivered by each propeller in kilowatts (kW), is plotted in Figure 2 below. Sea state 4 (SS4) and SS5 speed power curves were calculated from the calm water powering using factors developed through Glosten's previous work with computational fluid dynamics (CFD) analysis and model testing of research vessels with similar hull forms. This accounts for added resistance in wind and waves. Based on the vessel's operating area of coastal southern California, the typical sea state is between SS2 and SS4 depending on season. SS4 was chosen as the design condition to account for the majority of potential operating conditions without designing for an atypical scenario. In SS4, at the design speed of 10 knots the power delivered per propeller is estimated to be 215 kW.

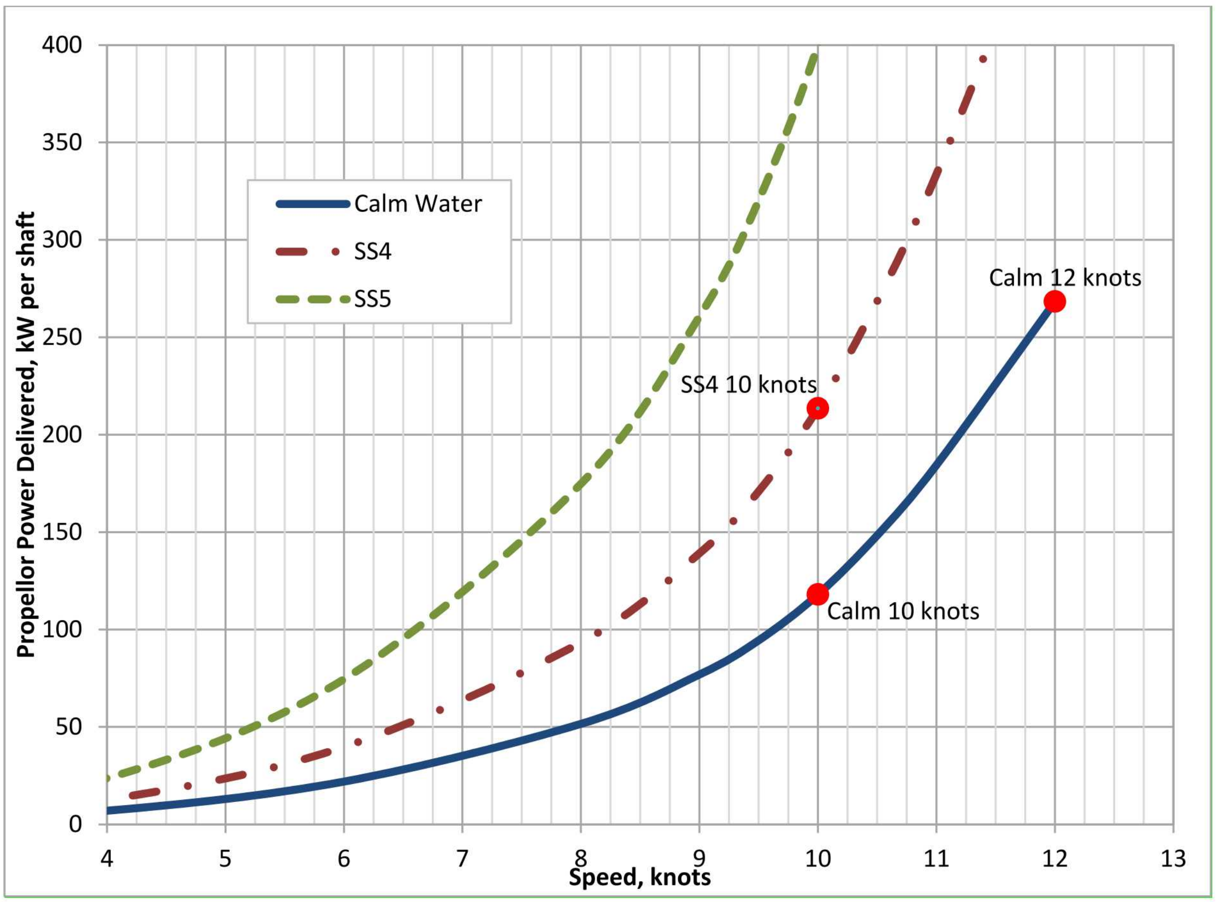


Figure 2 Speed and power

This resistance and powering assessment is a high-level estimate. If the design goes forward, a detailed analysis using computational fluid dynamics (CFD) and/or model testing will be required to optimize the hullform and more accurately determine the propulsion requirements for this vessel.

The design speed power curve was provided to Veth Propulsion (an equipment vendor) for sizing of Veth Integrated L-Drives. They recommended two 375 kW drives and provided electrical power requirements for the specific drives that were proposed. The total electrical power draw per drive is plotted against speed in Figure 3.

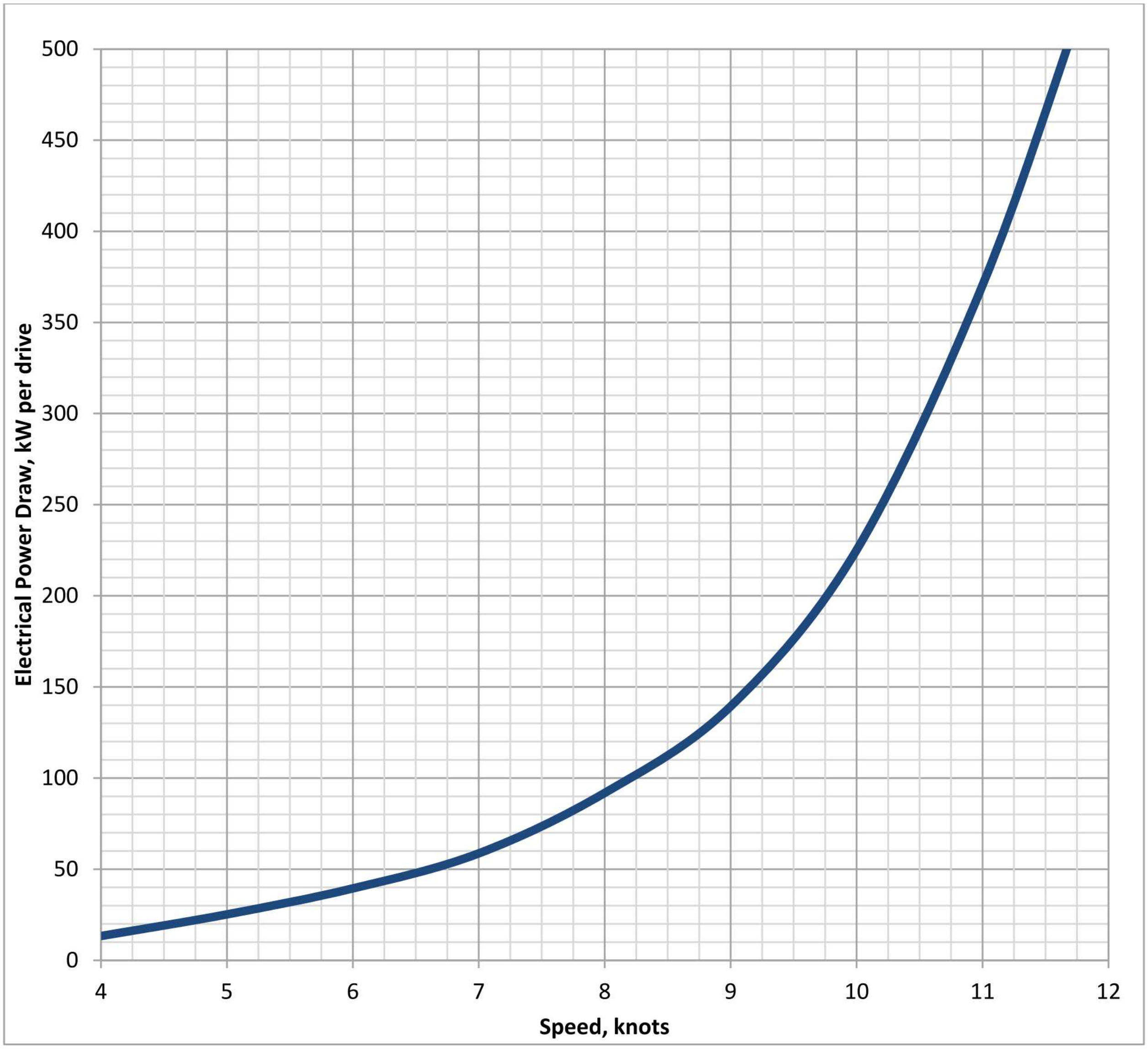


Figure 3 Electrical power draw of Veth integrated L-drive

3.5 Range/Endurance

To accomplish the SRV's mission profiles, a maximum mission time of 10 days at sea was defined by SIO. Based on 10 days at sea with a cruise speed of 10 knots, the range was established at 2,400 nautical miles. Additionally, SIO provided 14 unique mission profiles the vessel needed to accomplish. The fuel consumption for each of the mission profiles as well as for the 2,400 nm endurance cruise at 10 knots was calculated. It was found that the governing condition for fuel consumption was the endurance cruise.

The purpose of this study was to compare four different electric vessel variants: a baseline diesel-electric vessel, a fully hydrogen fuel cell powered vessel, a hydrogen hybrid vessel using both diesel generators and hydrogen fuel cells, and a battery hybrid vessel using both diesel generators and batteries. Based on vessel operating scenarios, the total "fuel" consumption of each mission profile in terms of diesel fuel, hydrogen, and battery energy is given in Table 4. The detailed calculations can be seen in Appendix B. These values are calculated based on energy requirements for each mission. The fuel consumption numbers in Table 4 were calculated by assuming the efficiency for diesel electric (Diesel), hydrogen (fuel cells), and batteries.

Fuel storage tank and battery sizing was completed for each propulsion variant based on these fuel consumption calculations. The total quantity of fuel and/or energy stored onboard is limited by the footprint, stability considerations, and functionality of the vessel. Energy storage design and requirements are discussed in detail in each of the individual variant sections.

Table 4 Fuel/energy consumption per fuel type

Mission	Hydrogen Consumed, kg	Diesel Consumed, kg	Battery Energy Consumed, kWh
Class Cruise: Biology of Fishes	196	835	3,683
Class Cruise: Biology (Typ)	264	1,113	4,938
Class Cruise: Marine Geology & Invertebrates	277	1,164	5,142
Class Cruise: AUV Ops	394	1,640	7,278
Physical Oceanography	417	1,780	7,897
Coastal Mooring	641	2,674	11,847
Geology Sampling (Multicore)	2,717	11,452	50,657
Deep Moorings (4000m) & Towed Sonar II	3,143	13,096	58,016
AUV Ops II	3,413	14,459	63,721
Deep Moorings (4000m) & Towed Sonar I	4,023	16,856	74,698
Coastal Physical Oceanography	4,223	17,981	79,040
AUV Ops I	4,384	18,357	81,361
Cyanobacteria: CTDs and Incubations	4,452	18,649	82,512
Geology: Vibracore & Box Core	5,720	24,045	106,412
Range Endurance (not a mission)	7,526	30,872	136,981

3.5.1 Electrical Load Analysis

An electrical load analysis (ELA) for the SRV was developed using estimates for the ship service, emergency, propulsion, and science system electrical loads. Electrical load and demand factor estimates from other research vessels, including the Regional Class Research Vessel (RCRV) developed for Oregon State University, were scaled and used as a reference. The ELA is preliminary and requires further refinement as the vessel design is developed and specific equipment is selected. The current ELA can be seen in Appendix B.

The generators provide 1,185 kW of electrical power for the vessel. Under SS4 cruise conditions, approximately 451 kW are used for the vessel propulsion, while 70 kW supplies the ship's service loads. Under sprint conditions at maximum propulsion power, the total electrical load is 1,169 kW. To ensure that as the ship service loads fluctuate the total power demanded does not exceed the plant capacity, an automated power management system would control and limit the power to the propulsion motors. Reference 4 and Figure 11 show the details of the electrical system architecture.

The ELA considers six operating profiles. The *Transit* scenario is applicable when the vessel is transiting between stations and not performing science operations. The *Survey* scenario represents when the vessel is moving at relatively high speed (8 knots) and completing survey operations. The *Towing* scenario represents when the vessel is moving at slow speed (2 knots) and towing science packages. The *Loitering* and *On Station* profiles represent light and heavy dynamic positioning (holding vessel position relative to a fixed position on the seabed), respectively. In *Loitering* and *On Station* scenarios, the bow and stern thrusters are being utilized along with heavy science equipment demands. *Sprint* was also included in the ELA but is not a normal operating profile.

The *Transit* and *On Station (DP)* operations are the most demanding in terms of power (excluding *Sprint*). These scenarios will require a minimum of 2 generators to be operating to supply sufficient power.

The small emergency load is assumed to be 50 kW and could be accommodated by an emergency generator located in the superstructure.

The shore power load for the vessel is assumed to be 60 kW. The shore power connection will be sized to accommodate this load.

3.5.2 Propulsion Motors

The proposed SRV design uses twin Veth VL-400si semi-integrated L-drives to provide propulsion power, see Figure 4. Based on the resistance and powering calculations, Veth determined that 375 kW drives will provide sufficient power for the various mission requirements, with enough reserve power for safe operation in heavy seas and for dynamic positioning.

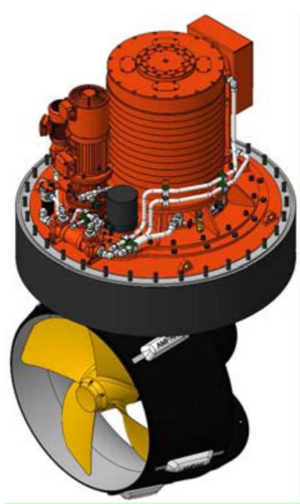


Figure 4 Veth VL400si L-drive

This Veth L-drive uses an alternating current (AC) permanent magnet type motor that is partially integrated into the frame of the L-drive. This substantially reduces the overall size of the drive and offers one of the most compact drives available for the power provided. This drive was chosen specifically due to its small size, as the SRV is a small research vessel with limited below deck machinery area availability.

The Veth L-drive is outfitted with a fixed pitch propeller in a VG40 nozzle. Each propeller is approximately 44.5 inches (1130 mm) in diameter. The propellers should be of wake-adapted design to minimize underwater noise as well as maximize efficiency. The proposed L-drives and propellers have been sized to provide plenty of margin, allowing them to operate well below their maximum allowed loading. Reducing the propeller loading helps minimize propeller cavitation for quiet operation. The propellers are assumed to be non-cavitating at speeds up to 10 knots.

3.5.3 Bow Thruster

A 150 kW tunnel bow thruster is located in the forward section of the hull. This thruster provides sufficient maneuvering and dynamic positioning capability for the vessel under the required operating conditions. The thruster operates in a tunnel within the hull. In this position, the thruster only provides sideways thrust. The bow thruster is powered by a permanent magnet AC motor for maximum efficiency and minimum size. A Veth tunnel bow thruster is shown in Figure 5.

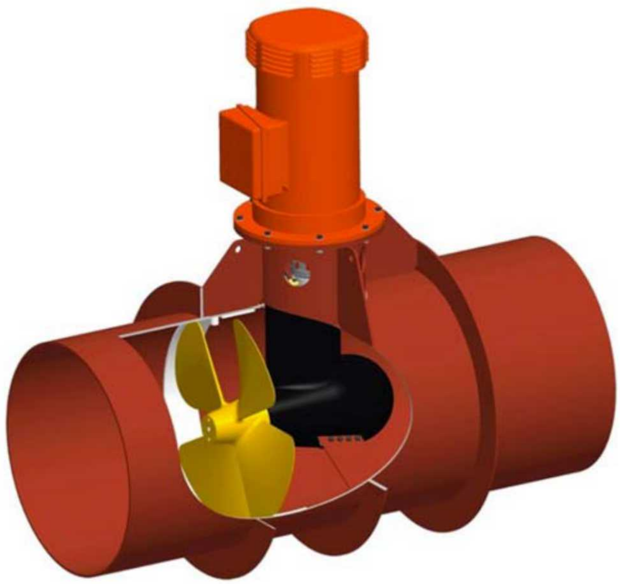


Figure 5 Veth tunnel thruster

3.6 Weight Estimates for All Design Variants

Preliminary structural weight models were developed for the three SRV variants. The structural models were based upon the existing hull design used as the basis for this project and are designed with an aluminum deckhouse built upon a steel hull. This combination of steel and aluminum is commonly used on research vessels to help reduce the structure's weight and the vessel's vertical center of gravity.

For the SRV variants, the mechanical system and outfitting weights were parametrically scaled based upon structural weight from a recent Glosten-designed monohull research vessel of slightly larger proportions than the SRV. Given the similarities in size, mission, and crew complement, the weight estimate for the existing design was exploited as a basis to build out a weight estimate for this vessel. Where the designs diverged, such as with the variants' propulsion systems and generally simpler auxiliary systems and overboard handling gear, the weight estimates were adjusted as necessary to represent the components in the SRV variants. The centers of gravity of the various ship work breakdown structure (SWBS) groups were estimated based upon the expected locations of the systems in the SRV variants.

Normally weight and vertical center of gravity (VCG) margins are selected per the Society of Allied Weight Engineers' (SAWE) suggested margins (Reference 10). The monohull research vessel that these weight estimates are based upon is under construction, and the weights have been refined to a detail design level. Due to the high level of confidence in the system and outfitting weights from this existing design it was decided that using concept level margins would be overly conservative for the SRV variants. Instead, a weight margin of 5% of the final weight and a 5-inch VCG margin was decided to be sufficient for this feasibility study.

A breakdown of the lightship weights for each SRV variant, including post-delivery modifications, can be found in the respective sections (4.5, 5.6, and 6.9). The weight estimates, organized by SWBS numbering, detail the breakdown of the weights and their longitudinal center of gravity (LCG), transverse center of gravity (TCG) and vertical center of gravity (VCG).

3.7 Stability

While the SRV will not be inspected, it will still be designed to meet the requirements of a USCG subchapter U vessel. This means that it must meet the intact stability criteria of CFR46 170.170 (Weather), and 170.173 (Unusual proportions and Form). The intact stability criteria were evaluated to determine the maximum VCG that the vessel may have and still pass the criteria. A simplified analysis was also completed to check if the vessel meets Damage Stability per CFR46 171.080. The analysis did not highlight any issues with damage stability but the additional work will need to be completed in the next phase of the design to fully vet all damage stability cases.

Based upon the operating weight estimates, the Hydrogen Hybrid SRV has the highest VCG. Consequently, stability was checked only for that design, since if the Hydrogen Hybrid SRV is proven to be stable then the other two variants should also meet the stability requirements. The Hydrogen Hybrid SRV was evaluated in GHS™ (General Hydrostatics) to determine the maximum operational VCG over its range of operational displacements. A plot was developed from the results of this analysis and is shown in Figure 6. The trim range reflected in the plot covers 0.25 degrees aft and 0.5 degrees forwards. The figure also includes three load cases (Departure, Mid Voyage, and Arrival) to show that the vessel meets the stability criteria across the operational range of loads.

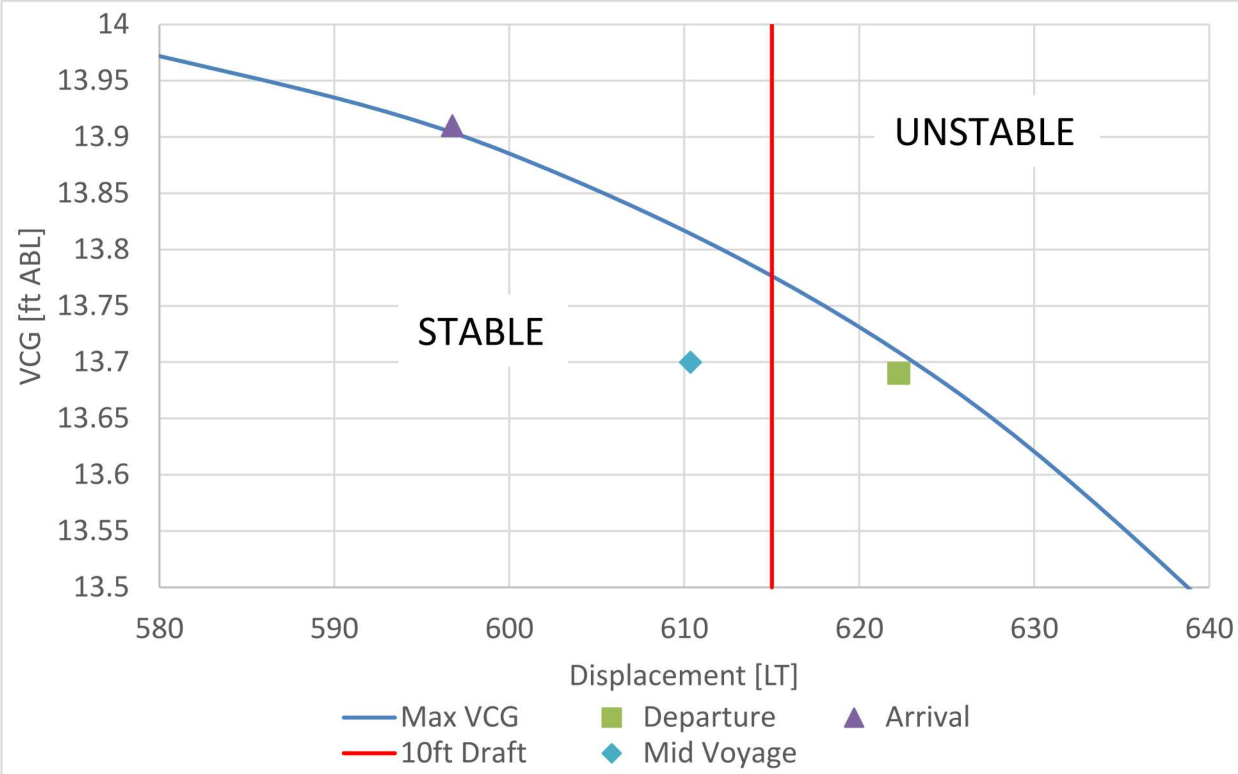


Figure 6 Stability plot for Hydrogen Hybrid SRV

To achieve a stable VCG, 22LT of fixed ballast will need to be installed in the double bottom centered 42.5 ft aft of Frame 0. Additionally, a centerline double bottom ballast tank will need to be pressed full in the arrival condition. As only the Hydrogen Hybrid SRV was evaluated for this feasibility study, it is possible that the other two variants will not need as much fixed/SW ballast to pass the stability requirements. None of the proposed stability conditions (fixed ballast, pressed double bottom tank) are onerous but the next phase of design could optimize the hull form to eliminate the need for fixed ballast.

Also, to accommodate the variable science equipment and stores weights that will be loaded on board for each mission, the forepeak ballast tank can be utilized to manage vessel trim. The fuel tanks can be used to manage heel.

Currently the Hydrogen Hybrid SRV exceeds the design draft of 10 feet, but this can be corrected in the future by refining the hull form to increase displacement. Hull form refinement may also be utilized to improve stability, which could help to minimize the need for fixed/SW ballast.

3.8 Position Keeping

A preliminary dynamic positioning (DP) capability study was performed by Kongsberg assuming the 150 kW tunnel bow thruster is selected. SIO has indicated that when the SRV is dynamic positioning, the orientation of the vessel is generally not critical to the science mission, so the vessel can be positioned at best heading (i.e. current at the bow). With 2 knots current at the bow, the vessel can maintain position with more than 30 knots wind and waves from any heading. In addition, the vessel is still able to maintain position with 1 knot beam current and more than 25 knots wind and waves from any heading. Figure 7 and Figure 8 show the DP capability plots for these conditions.

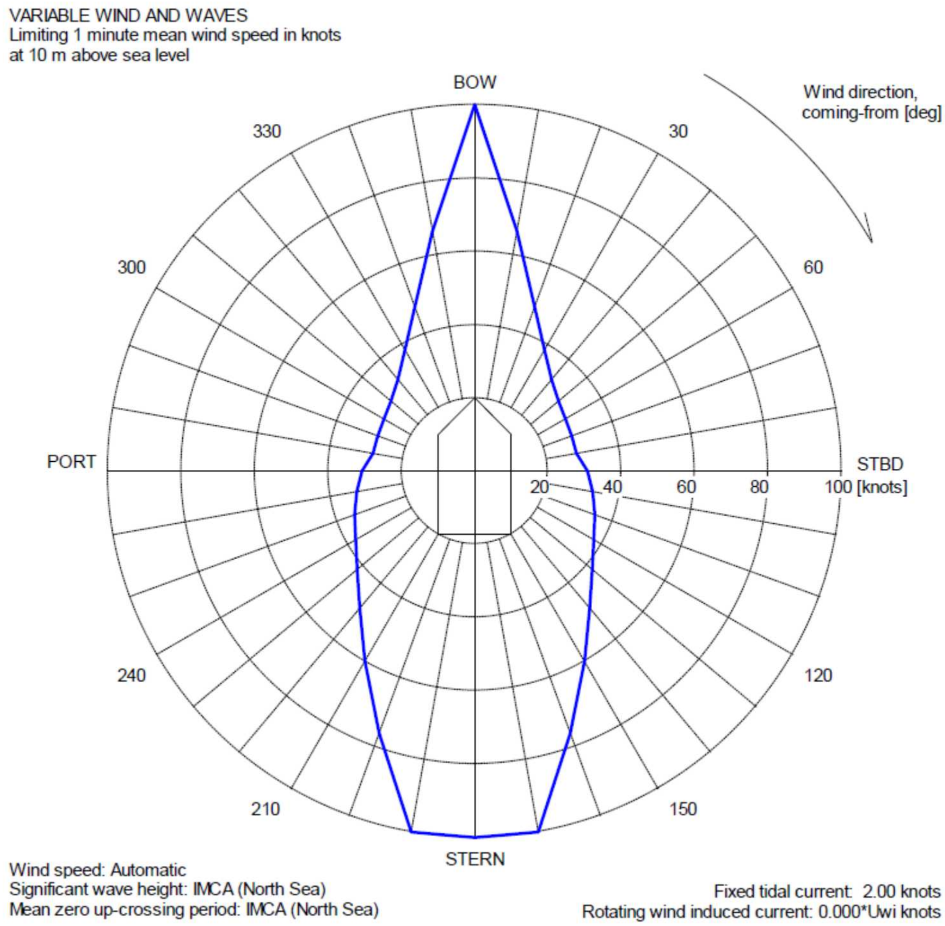


Figure 7 DP capability plot in two knots bow current

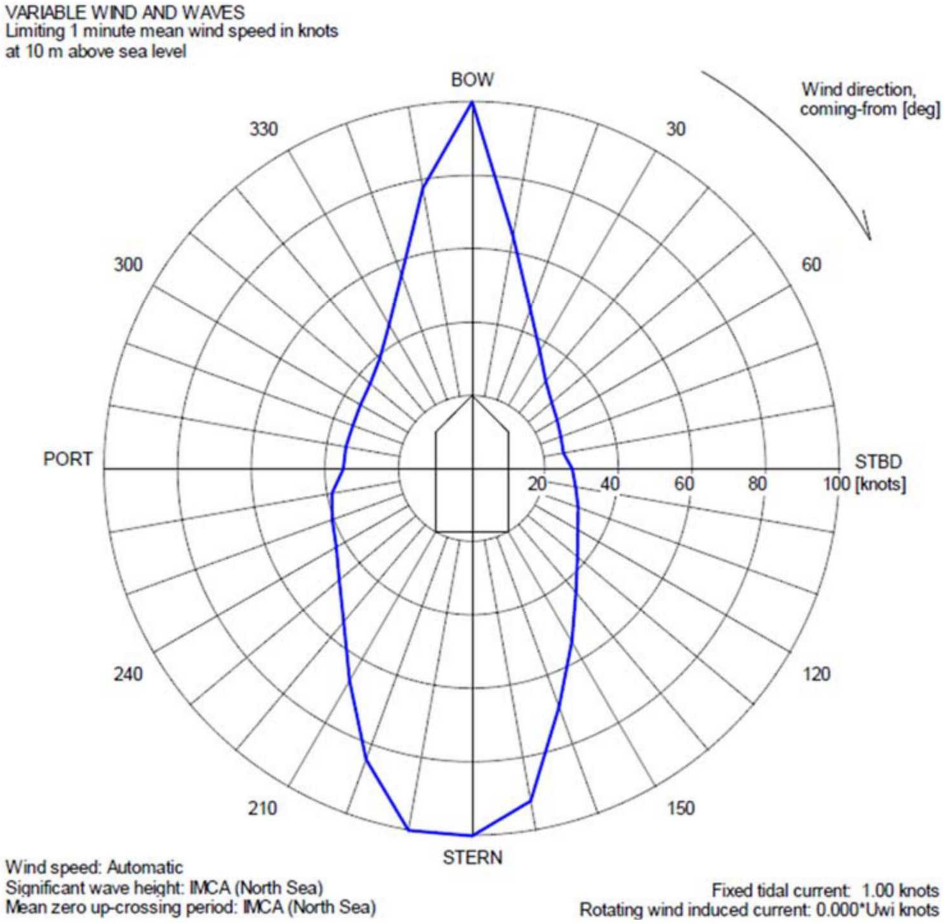


Figure 8 DP capability plot in one knot beam current

These DP capabilities are expected to be sufficient to perform the typical on-station work this vessel would engage in.

3.9 Underwater Radiated Noise

SIO did not provide specific underwater radiated noise (URN) performance requirements for the SRV. Generally, low URN is beneficial for research vessels to avoid interference with scientific instruments such as sonars and to minimize detection by or disruption of marine wildlife. This study does not quantitatively compare the URN performance between the SRV variants, but if URN requirements were developed they could be included in further design steps. Generally it is understood that the addition of batteries or fuel cells would provide some level of noise reduction in specific situations or operating modes where low noise was desired.

Section 4 Diesel-Electric SRV Design

This section defines the baseline conventional diesel-electric powered vessel to which the other three variants are compared. The sections below pertaining to the baseline vessel also apply to the other variants unless specifically discussed under those variants.

4.1 Additional Regulatory Requirements

None.

4.2 Energy Requirements

Energy storage for the baseline vessel will be entirely via diesel fuel. The governing condition for the amount of diesel fuel storage required is the 10-day endurance at a cruise speed of 10 knots (Table 5). This endurance case requires 30,872 kg of diesel fuel, which correlates to roughly 9,160 gallons of fuel consumed, assuming a specific gravity of 0.89 for marine diesel oil (MDO).

The diesel-electric SRV arrangement includes fuel storage for a total of 9,578 gallons, which provides approximately 5% margin on range (2,510 NM range). Table 5 summarizes the fuel consumption per mission and also per year. The annual fuel consumption of 190,541 kg (~56,557 gallons) is based on the projected 34 missions and the per mission load profile that was provided by Scripps.

Table 6 breaks down fuel usage by type of operation for each of the missions shown in Table 5. For example, of the estimated 835 kg of diesel consumed during Class Cruise: Biology of Fishes, roughly 46% (386 kg) is used in transit. By contrast, AUV Ops 1 uses 18,357 kg, of which 81% (14,859 kg) is used on station. This understanding is important in evaluating the design variants to determine which operations may benefit the most from various technologies.

Table 5 Baseline Diesel-electric SRV fuel consumption

Mission	Missions Per Year	Baseline Diesel kg/mission	Baseline Diesel kg/year
Class Cruise: Biology of Fishes	2	835	1,671
Class Cruise: Biology (Typ)	11	1,113	12,242
Class Cruise: Marine Geology & Invertibrates	4	1,164	4,656
Class Cruise: AUV Ops	2	1,640	3,280
Physical Oceanography	1	1,780	1,780
Coastal Mooring	5	2,674	13,368
Geology Sampling (Multicore)	1	11,452	11,452
Deep Moorings (4000m) & Towed Sonar II	1	13,096	13,096
AUV Ops II	1	14,459	14,459
Deep Moorings (4000m) & Towed Sonar I	1	16,856	16,856
Coastal Physical Oceanography	1	17,981	17,981
AUV Ops I	1	18,357	18,357
Cyanobacteria: CTDs and Incubations	2	18,649	37,297
Geology: Vibracore & Box Core	1	24,045	24,045
Range Endurance (Not a Mission)	0	30,872	0
Total	**34**		**190,541**

Table 6 Baseline Diesel-electric SRV fuel use per mission and per operation (DG = Diesel Fuel)

Missions	Sprint	Transit	Survey	Towing	Loiter	On Station Science Ops	Totals	
Class Cruise: Biology of Fishes	0	3	0	6	3	0	12	Hours
	0	386	0	347	103	0	835	kg (DG)
Class Cruise: Biology (Typ)	0	3	3	3	0	3	12	Hours
	0	386	216	173	0	338	1113	kg (DG)
Class Cruise: Marine Geology & Invertebrates	0	3	0	0	3	6	12	Hours
	0	386	0	0	103	675	1164	kg (DG)
Class Cruise: AUV Ops	0	4	0	0	0	10	14	Hours
	0	515	0	0	0	1126	1640	kg (DG)
Physical Oceanography	0	4	0	18	0	2	24	Hours
	0	515	0	1040	0	225	1780	kg (DG)
Coastal Mooring	0	8	0	0	2	14	24	Hours
	0	1029	0	0	69	1576	2674	kg (DG)
Geology Sampling (Multicore)	0	20	20	0	20	60	120	Hours
	0	2573	1440	0	685	6754	11452	kg (DG)
Deep Moorings (4000m) & Towed Sonar II	0	48	6	0	12	54	120	Hours
	0	6174	432	0	411	6079	13096	kg (DG)
AUV Ops II	0	16	8	0	56	88	168	Hours
	0	2058	576	0	1919	9906	14459	kg (DG)
Deep Moorings (4000m) & Towed Sonar I	0	48	6	30	12	72	168	Hours
	0	6174	432	1733	411	8105	16856	kg (DG)
AUV Ops I	0	24	0	0	12	132	168	Hours
	0	3087	0	0	411	14859	18357	kg (DG)
Cyanobacteria I: CTDs and Incubations	0	64	0	30	30	68	192	Hours
	0	8232	0	1733	1028	7655	18649	kg (DG)
Cyanobacteria II: CTDs and Incubations	0	64	0	30	30	68	192	Hours
	0	8232	0	1733	1028	7655	18649	kg (DG)
Coastal Physical Oceanography	0	48	24	24	96	48	240	Hours
	0	1505	397	317	715	1288	4223	kg (H2)
Geology: Vibracore & Box Core	0	36	18	0	36	150	240	Hours
	0	4631	1296	0	1234	16885	24045	kg (DG)
Range Endurance	0	240	0	0	0	0	240	Hours
	0	30872	0	0	0	0	30872	kg (DG)

The fuel usage calculations in Table 5 and Table 6 account for differing generator efficiencies as a function of generator load.

4.3 Arrangements

Vessel arrangements were developed to meet all the space and volume requirements and provide for fitment of the machinery, service, and control spaces necessary for operation. Additionally, the arrangements consider aspects that affect the efficiency of science operations, for example access between science spaces, the working deck, and science handling systems as well as visibility and sight lines from control stations to the working areas and equipment.

The SRV design follows traditional arrangements for a research vessel. The power plant, machinery, stores, science berthing, and scientific acoustic equipment are located below the main deck in the hull (Figure 9). The main deck contains the working deck, laboratories, main service spaces, and main winches (Figure 10). The upper decks contain the crew berthing and navigation spaces. Fuel storage and all other required tanks are located in the inner bottom of the hull.

The baseline vessel arrangement was adjusted to account for structural changes required to meet stability in the hydrogen hybrid variant, as installing a heavy liquid hydrogen tank high up in the vessel structure created stability challenges.

Detailed vessel arrangements can be seen in the General Arrangement Drawing in Appendix A.

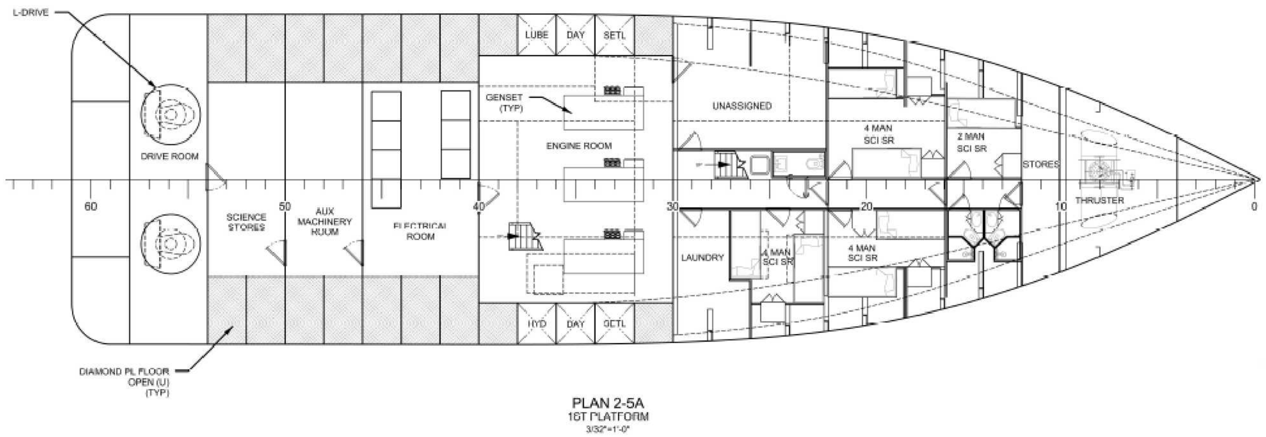


Figure 9 Baseline SRV design, below deck arrangements

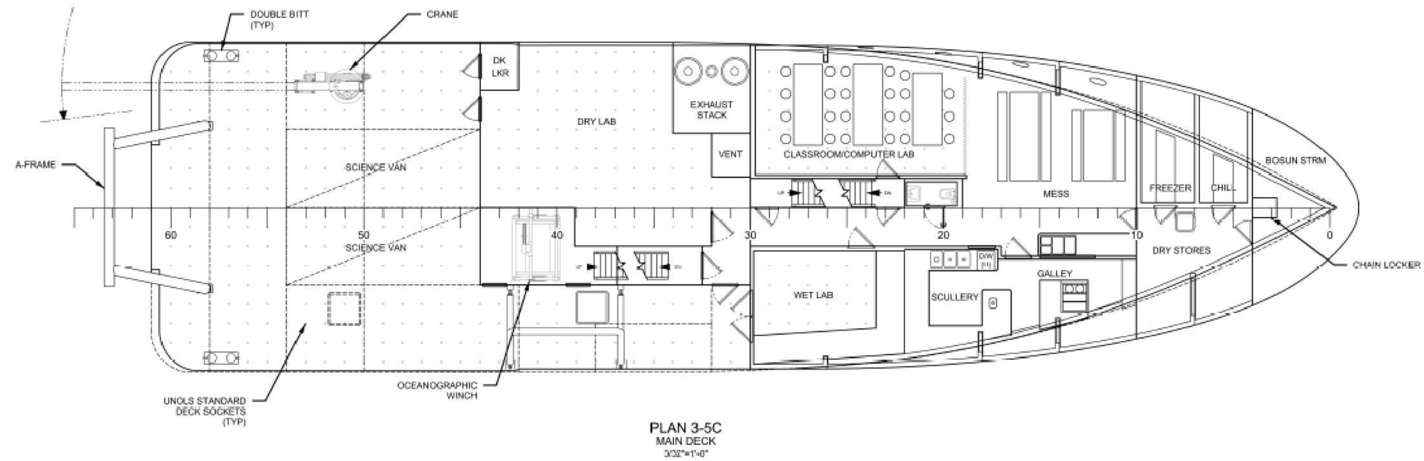


Figure 10 Baseline SRV Main Deck arrangement

4.4 Propulsion System

4.4.1 Objectives and Requirements

The primary objective of the propulsion system selection is to allow the vessel to achieve the mission and design requirements given in Section 2. A twin electric, L-drive, azimuthing propeller arrangement was selected. In this arrangement, each propeller is directly driven by an integrated permanent magnet motor. Permanent magnet motors are selected due to their simple, compact arrangement in addition to their efficient and quiet performance. The integrated design minimizes space and weight for the propulsion system, eliminates the need to align shafting, and simplifies construction. The azimuthing propeller allows high maneuverability and enhances dynamic positioning capability. An integrated diesel-electric power plant provides both propulsion and ship service electrical power. Three generators of equal size provide redundancy and improve efficiency by allowing flexible operation on one or more engines to best suit the required load.

To provide the required position keeping ability for on-station science work, the vessel is fitted with a bow thruster in addition to the propulsion L-drives. These thrusters provide thrust at the bow and stern of the vessel to help control the ship's heading and position during maneuvering, docking, and station keeping. Table 7 summarizes the propulsion equipment specifications.

Table 7 Diesel-electric SRV Propulsion system equipment

Equipment	Type	Description
Electrical Power	Three (3) diesel generators	Bollard 395ekW marine generators, EPA tier 3
Propulsion Motors/ Propellers	Two (2) propulsion L-drives	Veth VL400si semi-integrated L-drive electric drives, 375 kW permanent magnet motor, VG40 nozzle, 44.5″ (1130mm) propeller
Bow Thruster	One (1) tunnel thruster	Fixed pitch ducted propeller, 150 kW

4.4.2 Integrated Electrical Plant

Propulsion power for SRV is supplied by an integrated electric generating plant consisting of three 395 kW Bollard marine generator sets. These generators were chosen to maximize power delivered and fuel efficiency while minimizing size. With three total generators, the vessel has 1,185 kW of installed power. The generators are all located within a single engine room (Figure 9). The generators have been sized such that under most operating conditions the entire vessel load can be carried on two operating generators. At very high loads, such as sprint condition or in high seas, the third generator would be started to carry the full load without a reduction in speed. Due to the short mission duration and range and the relatively low number of days in operation per year, this arrangement was deemed acceptable by SIO even though it does not provide full redundancy.

The propulsion system block diagram showing the main propulsion switchboard (SWBD) and the ship service switchboard is depicted in Figure 11. The propulsion switchboard provides power to all the major propulsion loads and to the ship service switchboard. The ship service switchboard provides power to the vessel's auxiliary equipment, hotel loads, and lighting systems. The propulsion system is configured to provide redundancy and flexibility for different operating conditions. This creates a capable propulsion system that can operate efficiently for the varied operational and mission demands of a general-purpose research vessel.

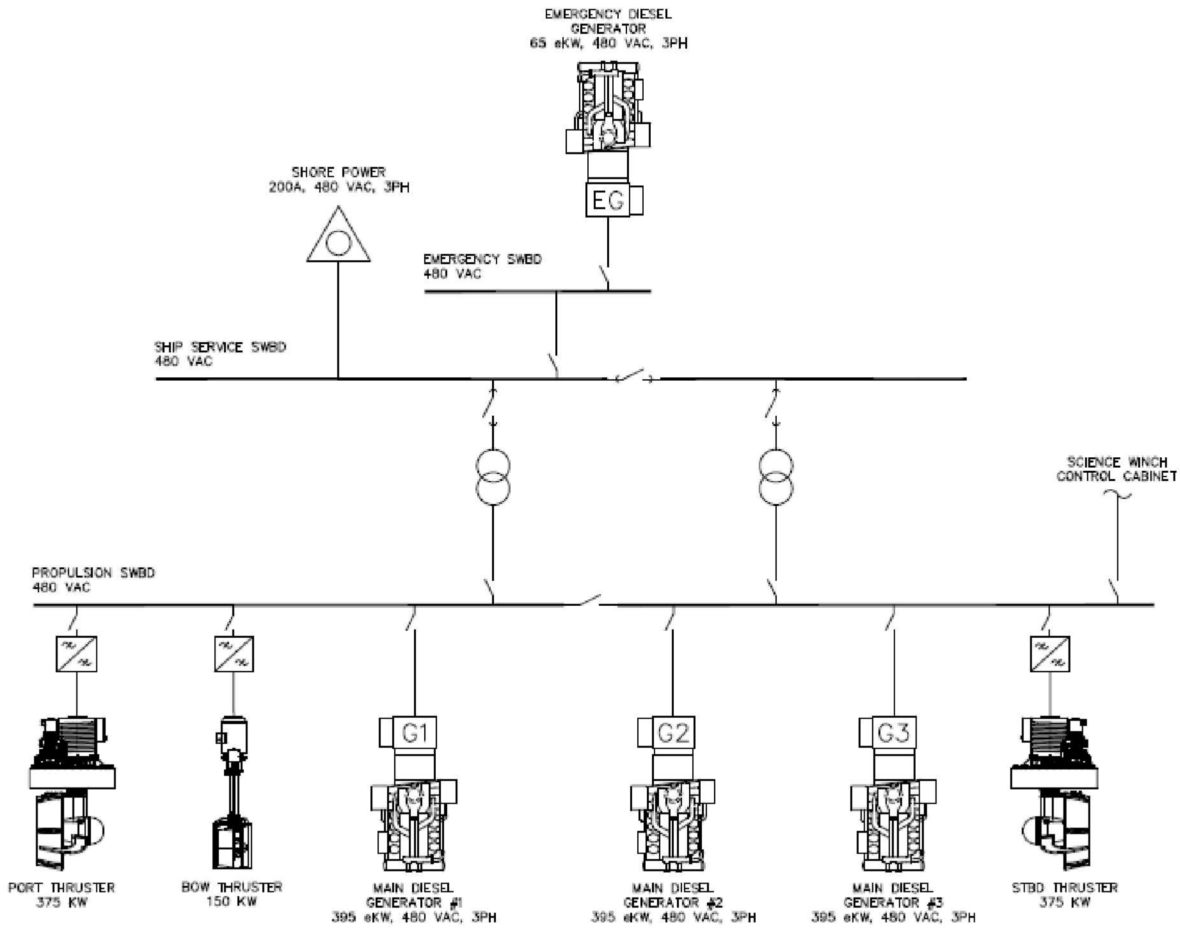


Figure 11 Baseline SRV propulsion system block diagram

4.4.3 Diesel Engine Emissions Requirements

US EPA emissions requirements for engines of this size differ from the IMO regulations. However, IMO regulations only come into effect if the vessel engages in international voyages. For the purposes of this study, it is assumed that the vessel only undertakes domestic voyages and therefore only must comply with US EPA regulations. The EPA requires that engines of less than 600 kW comply with EPA Tier 3 requirements. The chosen engines comply with EPA Tier 3 requirements without any type of exhaust aftertreatment. If the vessel were required to have the capability to sail internationally, all engines larger than 130 kW would be required to comply with IMO Tier III requirements. Compliance with IMO Tier III would require exhaust treatment to meet nitrogen oxides (NO_X) emissions limits, likely via a selective catalytic reduction (SCR) exhaust gas aftertreatment system. If compliance with IMO Tier III is deemed necessary, a compliant generator package would need to be sourced and integrated.

4.5 Weight Estimate

Table 8 provides the baseline vessel's estimated lightship weight and centers of gravity, broken down by SWBS number. The light ship weight, Table 8, is the actual weight of a vessel when construction is complete and ready for service but empty of tank fluids such as fuel or ballast, stores, and payload.

Table 8 Diesel electric lightship weight

SWBS	Entry Description		Weight [LT]	LCG [ft-FR 0]	TCG [ft-CL +S]	VCG [ft-ABL]
100	**Hull Structure**		226.94	61.60	0.00	13.35
	Welding Allowance	1.5%	3.09			
	Mill Tolerance Allowance	2%	4.13			
	Brackets, Inserts, and Doublers Allowance	2%	4.13			
	Total Hull Structure		238.28	61.60	0.00	13.35
200	**Propulsion System**		17.16	114.37	0.00	0.69
300	**Electrical System**		38.80	76.66	0.00	8.31
400	**Command and Surveillance**		3.50	42.50	0.00	37.17
500	**Auxiliary Systems**		45.25	60.30	0.00	15.21
600	**Outfitting and Furnishings**		59.79	37.09	0.00	21.83
700	**Mission Equipment**		26.26	92.08	0.00	18.33
	Total w/o margins		429.04	63.23	0.00	14.26
	Margins	5%	21.45			0.42
	Total Lightship		450.49	63.23	0.00	14.68

In addition to the lightship weights in Table 8, the operational weights for the vessel were estimated and presented in Table 9. The diesel-electric and battery hybrid variants use the same operational weights. The operational weights are not related to vessel construction, but rather science and crew outfitting as well as necessary operating fluids such as fuel and ballast (and fixed ballast).

Table 9 Diesel Electric and Battery Hybrid SRV operating weights

Item	Weight [LT]	LCG [ft-FR 0]	TCG [ft-CL +S]	VCG [ft-ABL]
Science Payload	30.00	93.90	0.00	18.26
Crew & Scientist Effects	3.47	35.23	0.00	17.16
Consumables	9.76	37.00	0.00	17.19
Diesel Fuel	31.06	53.98	0.00	6.51
Fixed Ballast	22.00	42.50	0.00	2.00
Total Operating Weights	96.29	61.40	0.00	10.61

New research vessels typically have a long planned service life. Therefore, a service life allowance (SLA) is normally added to the weight estimate to account for future modifications to the vessel throughout its life. It was determined that the previously designed hull used for this feasibility study did not have enough displacement to carry the additional weight for a SLA. Along with refining the design for more accurate weights, future design work will need to incorporate a SLA.

The departure weight, Table 10, is the total vessel weight at the time of departure. It is the summation of the lightship weight and the operational weights (Table 8 and Table 9 respectively).

Table 10 Diesel-electric departure weight summary

Item	Weight [LT]	LCG [ft-FR 0]	TCG [ft-CL +S]	VCG [ft-ABL]
Operational Lightship w/margins	450.49	63.23	0.00	14.68
Operating Weights	96.29	61.40	0.00	10.61
New Departure Weight	546.78	62.91	0.00	13.96

4.6 Diesel-Electric SRV Cost Estimate

A parametric construction cost estimate was developed for the baseline vessel. This cost estimate leveraged as a basis the cost estimate data from the Regional Class Research Vessel (RCRV) that Glosten designed for Oregon State University. The cost estimate has been broken down using the ship work breakdown structure to provide more discrete division and organization of the cost items. Cost were organized into nine SWBS groups (000 through 800).

A detailed steel and aluminum weight estimate was made for the baseline SRV based on a structural model of the vessel. Typical cost to weight ratios were used to derive a cost for Group 100 (Structure). Since the RCRV cost distributions between groups were found to be similar to other research vessels, the ratio of RCRV structure cost to total cost was used to derive the total baseline cost for the SRV which were grouped into the eight SWBS groups. Following that, groups 200, 300, and 400 have been adjusted based on quotes with allowances for labor costs and extra items not in the quotes. The costs not related to known equipment costs were then inflated from 2017 to 2020 dollars using the Producers Price Index for commercial shipbuilding.

The RCRV cost estimate from which the SRV estimate was developed, was based on a $60 per labor-hour rates to represent costs for Gulf Coast yards. The SRV cost for $60 per hour was $20,666,734 (Table 11).

Included in the cost estimate was also a 10% shipyard markup on materials and subcontractors, and a contingency allowance of 15% on contract value. Higher contingencies were used for the hybrid variants based on the uncertainty level of those designs.

To account for the higher $75 per hour labor rate for West Coast Shipyards, the total cost in Table 11 can be adjusted to $22,228,000. Therefore the construction cost range in 2020 dollars is between ~$20.67MM and ~$22.23MM.

Table 11 Diesel electric SRV cost breakdown for Gulf Coast labor rates

SWBS	Item			2020 Cost
000	**Vessel Engineering**	Production design engineering, planning & management, documentation, inspections/tests/trials, models and mockups	**$**	**1,617,000**
100	**Structure (Steel/Alum)**	Hull, foundations, masts and other structures	**$**	**1,827,000**
200	**Main Propulsion**	Propulsion motors, shafting/bearing, propellers	**$**	**668,750**
300	**Electrical Systems**	Switchgear, power distribution and conversion equipment, emergency generator, electric cables, lighting	**$**	**3,637,323**
400	**Command and Control**	Navigation systems, machinery control, alarm and monitoring systems, communication systems, entertainment systems	**$**	**1,000,000**
500	**Auxiliary Machinery**	Piping systems, HVAC, fuel storage, fuel systems, steering, bow/stern thrusters, anchors, mooring systems, pollution control systems, lifesaving equipment, small boats	**$**	**3,107,000**
600	**Vessel Outfit and Furnishings**	Paint and markings, joiner work, furnishings, ship fittings, doors/hatches/ladders, insulation	**$**	**2,174,000**
700	**Science Equipment**	Lab outfit, cranes, winches, over-the-side handling systems, science acoustic suite	**$**	**2,000,000**
800	**Shipyard Support**	Functional design, inspections, and drawing review	**$**	**1,940,000**
			$	**17,971,073**
	Contingency 15%		**$**	**2,695,661**
	Total		**$**	**20,666,734**

Section 5 Battery Hybrid SRV Design

5.1 Regulatory Requirements

In 2019, USCG released a design guidance letter for lithium-ion battery installations onboard commercial vessels (Reference 16). The regulatory and technical basis for this letter is found in the equivalency provisions of 46 CFR Subchapter J, but primarily it incorporates the technical guidance of ASTM F3353-19 (Reference 16). As a Subchapter C uninspected vessel, the SRV would not receive a certificate of inspection and there is not a requirement to meet these USCG provisions. However, as noted in Section 3.1, SIO maintains the R/V *Sproul* as a Subchapter U vessel in terms of safety systems, so meeting these battery safety requirements is assumed and recommended in this study. Table 12 provides an overview of the content of this regulatory document and briefly outlines the design considerations in meeting its requirements.

Table 12 Summary of USCG passenger vessel lithium-ion battery installation design requirements

USCG Requirement	Design Considerations
Testing Requirements – Battery design tests such as short circuit, impact, and overcharging.	Batteries should be type approved (DNV GL or similar) and have met all class testing requirements.
Operating Environment – Control and monitoring of the shipboard battery operating environment.	Battery rooms should be ventilated and air conditioned. HVAC systems must be monitored remotely by crew
Fire Safety – Measures to detect, contain and mitigate emergency situations through battery temperature monitoring, structural fire protection, fire detection, and fire safety systems	Battery room should be insulated and equipped with fire detection and suppression. Insulation could be a combination of thermal and structural fire protection.
Battery system design – Battery Management System (BMS) requirements	Batteries should have a BMS and be type approved (DNV or similar)
Testing and maintenance – Testing procedures for automation systems installed in vessel propulsion, ship service electrical or emergency power applications	Batteries should be Type approved (DNV or similar) and have met all class testing requirements.
System verification and maintenance – maintenance manual including actions to be taken in emergency situations	Batteries should be Type approved (DNV or similar) and have met all class testing requirements.

USCG does not specifically require type approval of batteries, but most battery manufacturers currently designing and building batteries for commercial marine seek type approval. The type approval process, which is carried out by classification societies such as ABS or DNV GL, is currently the best process for ensuring that suppliers meet the minimum safety standards and are verified by a reputable third party. Included in the minimum safety standards is that lithium ion batteries have a battery management system (BMS). A BMS is the electronic system that manages the battery (cell or battery pack), with functions such as by protecting the battery from operating outside its safe operating area, monitoring its state of charge, calculating secondary data, reporting that data, controlling its environment, authenticating it and/or balancing it. All commercial lithium ion batteries have a BMS.

It should be noted that this study has not considered the detailed design impacts of these battery regulations unless they significantly impact to cost, weight, or arrangements. Generally, some additional auxiliary systems will be required in way of ventilation, cooling, venting, and fire suppression for the battery room. The specifics of the installation will vary depending on the battery manufacturer, battery chemistry, cooling method, etc.

5.2 Battery Hybrid Vessel Design and Operation

There are numerous types of battery hybrid vessel designs. In the SRV variant, the battery system augments a traditional diesel electric system by providing additional energy storage. The SRV can charge the battery using shore power and use that energy for any purpose, including propulsion or hotel power. The stored energy from shore is essentially extra fuel, although the battery energy density is very low compared to diesel fuel or even liquid hydrogen.

Storing energy in batteries provides many advantages to an electric vessel. Not only can the vessel use the stored energy taken from shore to provide zero emission power, but the battery can also be used to optimize the performance of the diesel generators. Typically, diesel generators operate with best efficiency somewhere between 75 – 100% of MCR (maximum continuous rating). At low loads in particular, diesel generator efficiency drops off significantly and specific emissions (emissions per kWh) are much higher. In certain types of operations, the vessel may be operating a low load on one more generators.

One common example of this would occur during dynamic positioning. In dynamic positioning operations, propulsion loads can vary significantly and quickly over time as weather conditions or vessel orientation change the forces needed to keep the vessel on station. Operators typically keep several engines online to be available for these load changes and to reduce risk in case an engine were to shut down unexpectedly. This is sometimes called maintaining 'spinning reserve'. Spinning reserve is an operational necessity in numerous situations but results in loss of efficiency and increased emissions.

Battery energy storage can improve operations and safety in situations requiring spinning reserve. For example, if sufficient in size or power, a battery can substitute for one or more diesel engines. This can enable the diesel engine online to operate at a higher load (and efficiency), with the battery available to handle instantaneous load changes. This is a very typical use of batteries on hybrid vessels. In short, batteries can optimize diesel engine efficiency by handling most of the load variations while the operating diesel engine(s) provide a 'base load.'

Batteries have the ability to respond to load demand almost instantaneously, as they can make power available faster than the inertial limits of the rotating propellers and motors. They can also charge and discharge at very high efficiencies. Therefore, equipping the SRV with a sizeable battery could enable the diesel engines to operate at their optimal load almost always. The exception to this would be operations that require continuous high load, such as transit. However, for most of the operations that the SRV would undertake, the battery could improve diesel plant fuel efficiency.

The SRV may carry out some operations that would benefit from quiet or zero emissions operation over a short time period. If the battery capacity is large enough, it could provide several hours of dynamic positioning, low speed survey work, or even loitering on station.

5.2.1 System Architecture

The system architecture for the battery hybrid variant of the SRV is the same as the baseline design, but with a battery bank added to the propulsion bus (Figure 12). In the block diagram shown in Figure 12, the battery bank is installed on one side of a split bus, similar to a fourth engine. This is a reasonable approach, as the vessel would typically operate with a closed bus. Because the battery bank is not required for propulsion, there is not a need to provide battery storage on both sides of the bus. In other words, if there were damage to the battery bank, a fire in the battery room, or a fault on that side of the bus, the other side could be isolated and still provide power for getting to safety.

Many vessels do choose to provide two batteries, one per side. To provide true isolation, however, each battery bank would need to be installed in a separate compartment with structural fire protection and fire suppression. This would require added weight and expense without any obvious safety or reliability advantages.

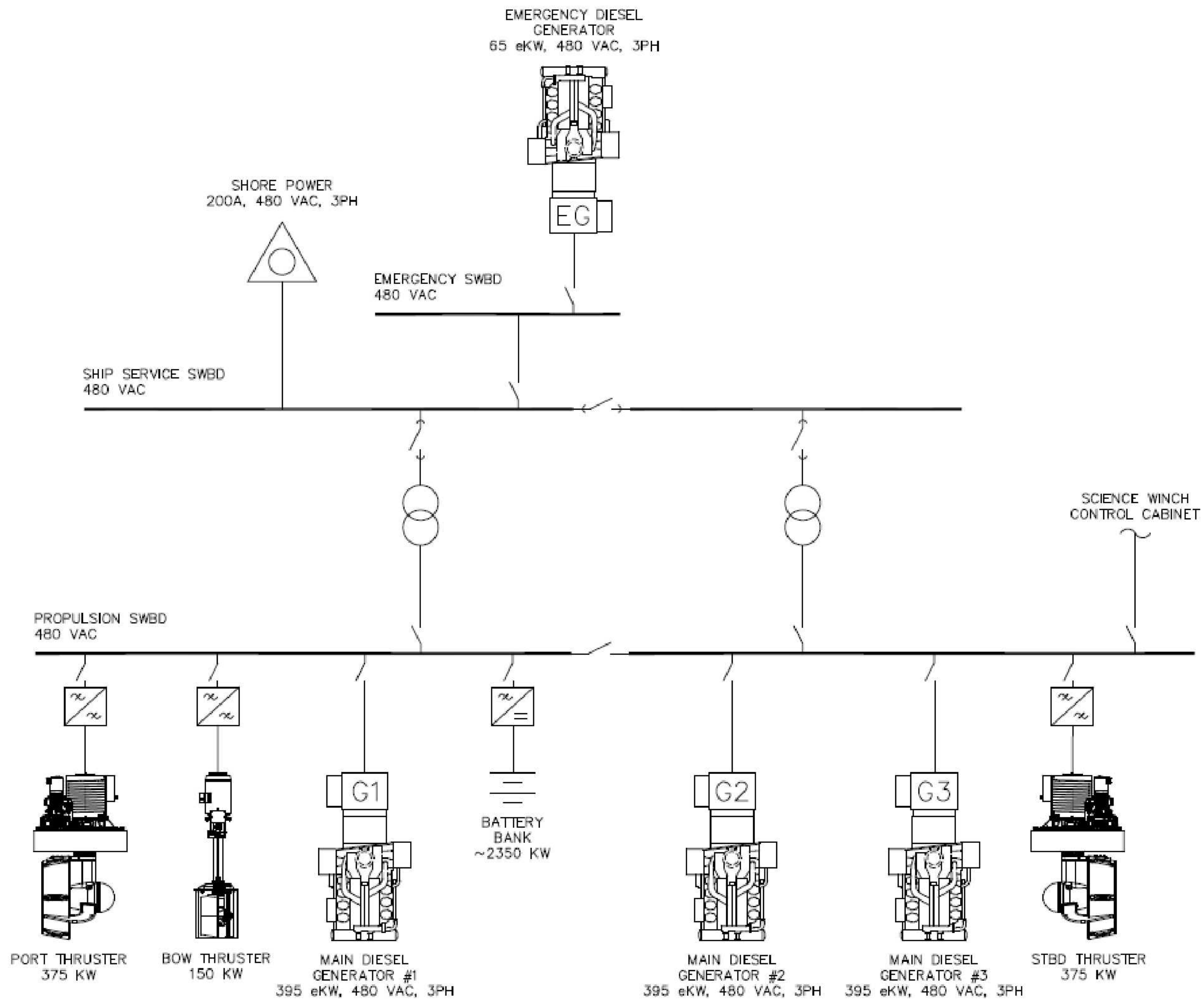


Figure 12 Battery Hybrid SRV propulsion system block diagram

5.3 Energy Requirements

Battery energy and fuel usage are summarized in Table 13, with total battery capacity determined by the constraints discussed in Section 5.4. The per mission charging requirements shown in the table are calculated at 60% of the battery's overall capacity, meaning for a battery bank with a fully charged capacity of 2350 kWh, the SRV would typically use no more than 1410 kWh. The percentage of a battery's fully charged capacity depleted prior to recharging is often called the ‘depth of discharge’ or DOD. This is an important number for calculating the life of the battery bank, as expected battery life decreases as DOD increases. For frequent usage, 60% is a very aggressive DOD, but for the SRV, which only has 34 missions per year, it could provide an acceptable life for the battery. A properly sized battery bank should be able to last 5-10 years. A more detailed battery sizing study should be done in the next stage of the design.

A lifecycle cost analysis, while beyond the scope of this project, should be completed before making a final decision regarding the economics of installing a battery. Since replacing a battery is expensive and could be a major recurring cost, consideration must be given to such factors as fuel savings, maintenance savings, and operational enhancements. One must also account for the number of shallow charge-discharge cases that the battery will see while being used to manage transient loads for example, or when leveling out normal load changes to enhance the efficiency of the diesel engines.

The fuel use shown in Table 13 is calculated with the assumption that the vessel leaves with a full battery and uses the 1,410 kWh of stored energy taken from shore. Additionally, it assumes that the onboard energy storage provides an average efficiency boost of 5% over the baseline diesel-electric SRV by operating in ‘hybrid mode’. The efficiency gains are based on the battery's ability to handle transient loads most of the time given its large capacity, which allows the diesel engines to operate at their best efficiency point by only providing ‘base load’ or recharging the battery. The efficiency gains will be greatest for missions in which the vessel primarily operates at medium to low loads, and with heavy variability.

As mentioned previously, dynamic positioning is an example of an operational mode that would benefit from batteries. Instead of operating two generators, the vessel can operate one generator at optimal load and let the battery handle the load changes. Depending on the type of operation, the battery could even handle the full load, with the generators only turning on to recharge the battery. Overall, the battery would reduce wear on the generators and give the best possible fuel economy. The annual diesel fuel consumption for the battery-hybrid SRV is estimated to be 177,410 kg (52,659 gallons), which represents a 9% reduction in overall fuel consumption from the baseline.

Table 13 Battery Hybrid SRV fuel and battery energy use for each mission

Mission	Missions Per Year	Battery Hybrid*			
		Diesel		Shore Power	
		kg/mission	kg/year	kWh/mission	kWh/year
Class Cruise: Biology of Fishes	2	688	1,375	1,410	2,820
Class Cruise: Biology (Typ)	11	951	10,464	1,410	15,510
Class Cruise: Marine Geology & Invertibrates	4	1,000	4,000	1,410	5,640
Class Cruise: AUV Ops	2	1,452	2,904	1,410	2,820
Physical Oceanography	1	1,585	1,585	1,410	1,410
Coastal Mooring	5	2,434	12,169	1,410	7,050
Geology Sampling (Multicore)	1	10,773	10,773	1,410	1,410
Deep Moorings (4000m) & Towed Sonar II	1	12,335	12,335	1,410	1,410
AUV Ops II	1	13,630	13,630	1,410	1,410
Deep Moorings (4000m) & Towed Sonar I	1	15,907	15,907	1,410	1,410
Coastal Physical Oceanography	1	16,976	16,976	1,410	1,410
AUV Ops I	1	17,334	17,334	1,410	1,410
Cyanobacteria: CTDs and Incubations	2	17,610	35,220	1,410	2,820
Geology: Vibracore & Box Core	1	22,737	22,737	1,410	1,410
Range Endurance (Not a Mission)	0	29,222	0	1,410	0
Total	**34**		**177,410**		**47,940**

* Battery hybrid fuel consumption is calculated assuming that 60% of the total battery is consumed from shore power on every mission along with a 5% diesel fuel consumption reduction on the remaining fuel usage for hybrid operation.

To further evaluate the usefulness of a battery bank with a useable energy content of 1,410 kWh, Table 14 provides a breakdown of energy use for each operational mode within a particular mission. It is clear that very few operational modes for any mission use less than 1,410 kWh. As a result, the battery cannot provide complete coverage for most operational modes, but it can still be very useful. The capacity is equivalent to approximately three hours of on station science operations (dynamic positioning). For shorter missions this could be significant, but for longer missions where the vessel is on station for multiple days, the engines will need to run periodically.

Table 14 SRV battery hybrid energy use (kWh) per mission and per operation

Missions	Sprint	Transit	Survey	Towing	Loiter	On Station Science Ops	Totals	
Class Cruise: Biology of Fishes	0	3	0	6	3	0	12	Hours
	0	1712	0	1538	433	0	3683	kWh (Bat)
Class Cruise: Biology (Typ)	0	3	3	3	0	3	12	Hours
	0	1712	958	769	0	1498	4938	kWh (Bat)
Class Cruise: Marine Geology & Invertebrates	0	3	0	0	3	6	12	Hours
	0	1712	0	0	433	2997	5142	kWh (Bat)
Class Cruise: AUV Ops	0	4	0	0	0	10	14	Hours
	0	2283	0	0	0	4995	7278	kWh (Bat)
Physical Oceanography	0	4	0	18	0	2	24	Hours
	0	2283	0	4615	0	999	7897	kWh (Bat)
Coastal Mooring	0	8	0	0	2	14	24	Hours
	0	4566	0	0	289	6993	11847	kWh (Bat)
Geology Sampling (Multicore)	0	20	20	0	20	60	120	Hours
	0	11415	6388	0	2886	29969	50657	kWh (Bat)
Deep Moorings (4000m) & Towed Sonar II	0	48	6	0	12	54	120	Hours
	0	27396	1916	0	1731	26972	58016	kWh (Bat)
AUV Ops II	0	16	8	0	56	88	168	Hours
	0	9132	2555	0	8079	43954	63721	kWh (Bat)
Deep Moorings (4000m) & Towed Sonar I	0	48	6	30	12	72	168	Hours
	0	27396	1916	7691	1731	35963	74698	kWh (Bat)
AUV Ops I	0	24	0	0	12	132	168	Hours
	0	13698	0	0	1731	65931	81361	kWh (Bat)
Cyanobacteria I: CTDs and Incubations	0	64	0	30	30	68	192	Hours
	0	36528	0	7691	4328	33965	82512	kWh (Bat)
Cyanobacteria II: CTDs and Incubations	0	64	0	30	30	68	192	Hours
	0	36528	0	7691	4328	33965	82512	kWh (Bat)
Coastal Physical Oceanography	0	48	24	24	96	48	240	Hours
	0	27396	7666	6153	13850	23975	79040	kWh (Bat)
Geology: Vibracore & Box Core	0	36	18	0	36	150	240	Hours
	0	20547	5749	0	5194	74922	106412	kWh (Bat)
Range Endurance	0	240	0	0	0	0	240	Hours
	0	136981	0	0	0	0	136981	kWh (Bat)

5.4 Arrangements

The battery bank is housed aft of the engine room (Figure 13). The overall capacity of 2,350 kWh was determined based on the available volume, accounting for realistic arrangements needed for battery removal, ventilation, cooling, and other necessary systems. The battery arrangement assumes use of Spear Power Systems SMAR-11N batteries, which have a volumetric energy density of 98 Wh/L (watt-hours per liter) and a gravimetric energy density of 111 Wh/kg (watt-hours per kilogram).

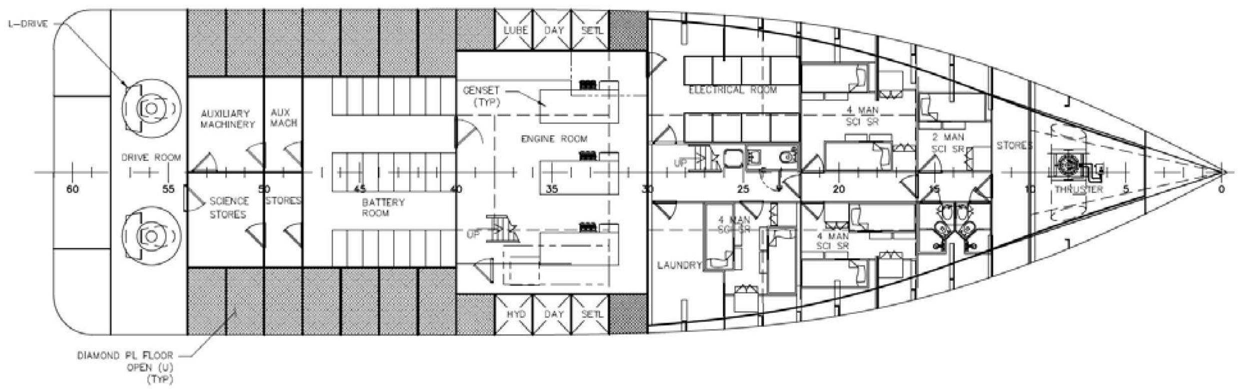


Figure 13 SRV battery hybrid below main deck arrangement

The batteries are in the space that houses the electrical equipment (switchgear, drives, transformers, etc.) in the baseline arrangement. Therefore, in the battery hybrid vessel option, the electrical equipment will be located in the space just forward of the engine room on the port side. This reduces the volume available for science stores and auxiliary equipment compared to the baseline SRV design. However, there is still volume available outboard on the raised grating level for additional auxiliary equipment.

5.5 Auxiliary Systems

Batteries will require additional auxiliary systems such as cooling, air conditioning, ventilation, and fire suppression, and potentially gas detection.

5.5.1 Battery Cooling

Marine batteries are available in both air-cooled and water-cooled configurations. Both cooling methods are acceptable, with some manufacturers only offering one or the other, and some offering both. There are advantages and disadvantages to consider for each. The Spear batteries assumed for the SRV arrangements will be the same volume whether they are air or water cooled, but there is a weight difference between the two options. For weight estimating purposes, the heavier water-cooled batteries are assumed. Air cooling the batteries typically requires using an air conditioning system to remove the heat. Water cooling batteries will at the very least require pumps and use of a seawater source, though the loop that cools the batteries will be fresh water. Regardless of the cooling method, the battery operation will require parasitic loads that must run continuously to keep the battery room cool and free of condensation. Even if water cooling is used, most manufactures require that the space be humidity controlled, so an air conditioning system will be required regardless. A means of monitoring the temperature in the space is required by Reference 16.

5.5.2 Ventilation

Reference 16 requires the battery space to be exhausted with at least 6 air changes per hour using a non-sparking fan. This is to exhaust noxious gases that could be ejected into the space from a battery 'thermal runaway,' an abnormal event that can occur for reasons such as overcharging or excess heat.

Many if not most of the battery regulatory requirements from class societies are intended to reduce the risk of a thermal runaway and to minimize the consequences if one does occur. The vent from the battery space must vent to atmosphere at least three meters from personnel spaces, egress routes, muster stations, air intakes, or ignition sources. Reference 16 also requires continuously monitored gas detection in the battery space. This may be in addition to required smoke detectors. Some battery manufacturers, including Spear, have designed their battery modules with a rupture disk in the back that vents the hot gasses into a plenum and out a vent pipe to atmosphere in the event of a thermal runaway. This design eliminates the possibility of noxious gasses entering the battery room where they could pose a hazard to personnel.

5.5.3 Fire Safety

USCG rules (Reference 16) and class society rules require that battery spaces have structural fire protection, fire detection, and fire suppression. Reference 16 requires the battery room to be a dedicated space. A-60 insulation is required in the overhead or in way of machinery spaces, crew spaces, or fuel tanks, with all other boundaries being at least A-0 fire boundaries (i.e. steel bulkheads). The space needs to be provided with fixed fire and smoke detection as well as a fixed fire-fighting system. Recent testing by DNV GL has shown both water mist systems and clean agent Novec 1230™ to be effective. There may be advantages to each, and there may be good reasons to have two systems. If a watermist system is installed for the engine room, it can also be used for the battery room, minimizing cost and space. A dedicated source of fresh water will be required and can be shared with the vessels potable water supply if installed properly.

5.6 Weight Estimate

The Battery Hybrid SRV weight estimates are very similar to the Diesel Electric SRV. The lightship weight of the Battery Hybrid SRV, Table 15, which is the completed construction weight minus the transient fluids, is greater due to the added weight of the batteries and associated systems. The operational weight of the Battery Hybrid SRV, is the same as the Diesel Electric SRV because they carry the same amount of fuel, science equipment, and supplies (see Table 9). The departure weight of the Battery Electric SRV, Table 16, is the sum of the lightship weight and the operational weight and represents the maximum operating weight when the vessel tanks are full and it is departing for a voyage.

Table 15 Battery hybrid lightship weight estimate

SWBS	Entry Description		Weight [LT]	LCG [ft-FR 0]	TCG [ft-CL +S]	VCG [ft-ABL]
100	**Hull Structure**		225.57	61.35	0.00	13.38
	Welding Allowance	1.5%	3.08			
	Mill Tolerance Allowance	2%	4.10			
	Brackets, Inserts, and Doublers Allowance	2%	4.10			
	Total Hull Structure		236.84	61.35	0.00	13.38
200	**Propulsion System**		17.16	114.37	0.00	0.69
300	**Electrical System**		38.80	76.66	0.00	8.31
400	**Command and Surveillance**		3.50	42.50	0.00	37.17
500	**Auxiliary Systems**		45.25	60.30	0.00	15.21
600	**Outfitting and Furnishings**		59.79	37.09	0.00	21.83
700	**Mission Equipment**		26.26	92.08	0.00	18.33
	Variant Specific Items					
	Batteries		20.98	88.00	0.00	8.83
	Total w/o margins		448.58	64.26	0.00	14.03
	Margins	5%	22.43			0.42
	Total Lightship		471.01	64.26	0.00	14.45

Table 16 Battery hybrid departure weight summary

Item	Weight [LT]	LCG [ft-FR 0]	TCG [ft-CL +S]	VCG [ft-ABL]
Operational Lightship w/margins	471.01	64.26	0.00	14.45
Operating Weights	96.29	61.40	0.00	10.61
New Departure Weight	567.30	63.78	0.00	13.80

5.7 Cost Estimate

To estimate the cost for the Battery Electric SRV, the parametric cost estimate for the Diesel Electric SRV was adjusted up by adding the following:

- 2,350kWh battery bank (assumed material cost of $600/kWh)
- Gas detection system
- Battery cooling system
- Battery Room fire suppression
- Battery Room ventilation
- Battery Room A60 insulation
- Additional 15% to section 000 (Vessel Engineering) to account for added complexity
- Additional 15% to section 800 (Shipyard support) to account for added complextiy
- Additional power electronics
- Additional 5% contingency over baseline

The Battery Hybrid SRV cost breakdown for Gulf Coast labor rates ($60/hr) are presented in Table 17.

To account for the higher $75 per hour labor rate for West Coast Shipyards, the total cost in Table 17 can be adjusted to $26,998,000. Therefore, the construction cost range in 2020 dollars is between ~$25.10MM and ~$27.00MM.

Table 17 Battery hybrid SRV cost breakdown with Gulf Coast labor rates

SWBS	Item		2020 Cost
000	**Vessel Engineering**	Production design engineering, planning & management, documentation, inspections/tests/trials, models and mockups	**$ 1,859,550**
100	**Structure (Steel/Alum)**	Hull, foundations, masts and other structures	**$ 1,827,000**
200	**Main Propulsion**	Propulsion motors, shafting/bearing, propellers	**$ 668,750**
300	**Electrical Systems**	Batteries, switchgear, power distribution and conversion equipment, emergency generator, electric cables, lighting	**$ 5,774,788**
400	**Command and Control**	Navigation systems, machinery control, alarm and monitoring systems, communication systems, entertainment systems, gas detection	**$ 1,075,468**
500	**Auxiliary Machinery**	Piping systems, HVAC, fuel storage, fuel systems, steering, bow/stern thrusters, anchors, mooring systems, pollution control systems, lifesaving equipment, small boats	**$ 3,257,379**
600	**Vessel Outfit and Furnishings**	Paint and markings, joiner work, furnishings, ship fittings, doors/hatches/ladders, insulation	**$ 2,224,000**
700	**Science Equipment**	Lab outfit, cranes, winches, over-the-side handling systems, science acoustic suite	**$ 2,000,000**
800	**Shipyard Support**	Functional design, inspections, and drawing review	**$ 2,231,000**
			$ 20,917,935
	Contingency 20%		**$ 4,183,587**
	Total		**$ 25,101,522**

Section 6 Hydrogen Hybrid SRV Design

6.1 Regulatory Requirements

As previously noted, the SRV is designated as a USCG uninspected vessel. As such it will not have certificate of inspection (COI) and would not be subject to USCG design requirements outside of 46CFR Subchapter C. However, the intention is to design to safety standards of subchapter U, and where specific systems are concerned, such as carriage of cryogenic fuel and use of hydrogen, it is assumed that these systems will be designed to the latest safety standards.

In addition to the general classification and build requirements, a hydrogen fueled vessel must meet a separate set of requirements specific to hydrogen fuel cells and cryogenic fuel storage. USCG, ABS, and DNV GL requirements related to hydrogen powered vessels and fuel storage are still in development, as the first hydrogen fuel cell powered vessels are currently being designed and built. As more of these vessels are built and brought into service, the requirements related to this type of design are expected to be continually updated and refined.

USCG does not have any rules or guidelines specific to hydrogen fuel cell vessels. ABS recently released hydrogen fuel cell rules. DNV GL has integrated specific requirements related to hydrogen fueled vessels into DNV Rules for Classification of Ships Part 6 Chapter 2 (Reference 1). While this vessel does not adhere specifically to DNV GL or ABS rules, they are useful for guidance during design.

This design has primarily deferred to the IMO Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF Code), Reference 2 as the basis for the gas fuel related requirements. The IGF Code was originally created for liquid natural gas (LNG) powered vessels but is also generally applicable to liquid hydrogen (LH_2) powered vessels. The IGF code was used to provide high level guidance during this study, but it is recommended if the design moves forward that it is developed around a specific rule set for the gas fuel systems.

6.2 Energy Requirements

This study examines two types of hydrogen powered vessel. This section discusses the first type, a hybrid vessel with a combined hydrogen and diesel-electric power plant, while Section 7 discusses the second, a fully hydrogen powered vessel.

The operating profile provided by SIO includes two general mission types the vessel is expected to complete. The first type is a one-day class cruise mission and the second is a multi-day (up to ten days) mission. Table 4 shows the calculated amount of hydrogen required to complete each mission. Analysis of the required hydrogen yields a natural break between these two types of missions. A hydrogen tank sized to handle any of the multi-day missions is a minimum of four times larger than a tank sized to handle the one-day missions. Due to the vessel's size constraints, this break was used as the design point for a hydrogen hybrid vessel, yielding a vessel fully capable of completing all the one-day missions on hydrogen power. The rest of the missions are handled using both the hydrogen power and the same diesel-electric power plant used in the baseline. The hydrogen system is integrated on top of the existing diesel electric power plant, so the vessel is fully capable of meeting all mission requirements with diesel power even if the hydrogen system is offline.

From Table 18, the minimum usable amount of LH_2 required to complete a one day mission is 603 kilograms (Coastal Mooring mission). However, LH_2 tank filling and storage must be carefully calculated and controlled due to some unique properties of cryogenic liquefied gases. Because the fuel is delivered and stored at cryogenic temperatures, the tanks must undergo a special cool down procedure before they can be filled with LH_2 for the first time. Once the tanks are filled with LH_2, they must always be kept cold. To accomplish this, some amount of liquid fuel must remain in the tanks at the end of every voyage. This liquid amount is known as a "heel". With LNG applications, a heel of approximately 5% is fairly common and it has been assumed that a 5% heel is sufficient for the SRV LH_2 tank.

Table 18 Hydrogen Hybrid SRV fuel use per mission and per operation

Missions	Sprint	Transit	Survey	Towing	Loiter	On Station Science Ops	Totals	
Class Cruise: Biology of Fishes	0	3	0	6	3	0	12	Hours
	0	94	0	79	22	0	196	kg (H2)
Class Cruise: Biology (Typ)	0	3	3	3	0	3	12	Hours
	0	94	50	40	0	80	264	kg (H2)
Class Cruise: Marine Geology & Invertebrates	0	3	0	0	3	6	12	Hours
	0	94	0	0	22	161	277	kg (H2)
Class Cruise: AUV Ops	0	4	0	0	0	10	14	Hours
	0	125	0	0	0	268	394	kg (H2)
Physical Oceanography	0	4	0	18	0	2	24	Hours
	0	125	0	238	0	54	417	kg (H2)
Coastal Mooring	0	8	0	0	2	14	24	Hours
	0	251	0	0	15	376	641	kg (H2)
Geology Sampling (Multicore)	0	20	20	0	20	60	120	Hours
	0	627	331	0	149	1610	2717	kg (H2)
Deep Moorings (4000m) & Towed Sonar II	0	48	6	0	12	54	120	Hours
	0	1505	99	0	89	1449	3143	kg (H2)
AUV Ops II	0	16	8	0	56	88	168	Hours
	0	502	132	0	417	2361	3413	kg (H2)
Deep Moorings (4000m) & Towed Sonar I	0	48	6	30	12	72	168	Hours
	0	1505	99	397	89	1932	4023	kg (H2)
AUV Ops I	0	24	0	0	12	132	168	Hours
	0	753	0	0	89	3542	4384	kg (H2)
Cyanobacteria I: CTDs and Incubations	0	64	0	30	30	68	192	Hours
	0	2007	0	397	224	1825	4452	kg (H2)
Cyanobacteria II: CTDs and Incubations	0	64	0	30	30	68	192	Hours
	0	2007	0	397	224	1825	4452	kg (H2)
Coastal Physical Oceanography	0	48	24	24	96	48	240	Hours
	0	1505	397	317	715	1288	4223	kg (H2)
Geology: Vibracore & Box Core	0	36	18	0	36	150	240	Hours
	0	1129	298	0	268	4025	5720	kg (H2)
Range Endurance	0	240	0	0	0	0	240	Hours
	0	7526	0	0	0	0	7526	kg (H2)

Because the density of LH_2 changes substantially with temperature, it is necessary to account for the expansion of the liquid in the storage tank. The LH_2 that is loaded into the tank is typically cooled to a temperature at or below –423°F (–217°C), the saturation temperature (liquid phase boiling point) at atmospheric pressure. However, heat ingress into the tank causes the fuel to continually boil, and the buildup of the boiloff gas increases the pressure in the tank.

If the boiloff gas were continually vented from the tank, the fuel would remain at a steady temperature until all the fuel is boiled off, since some heat ingress into the tank is unavoidable. Conversely, because saturation temperature increases as pressure increases, the pressure increase in the tank allows the liquid fuel to warm and expand, also increasing pressure in the tank (assuming hydrogen is not consumed).

As the pressure builds in the tank, the fuel can continue to warm and expand up to the point at which it reaches the Maximum Allowable Relief Valve Setting (MARVS) and the tank starts venting boiloff gas. Liquid is relatively incompressible, so to prevent the volume of liquid within the tank from exceeding the tank's volume as the fuel expands, the tank must have sufficient volume to allow the fuel to expand from its loading condition density to its density at the saturation temperature associated with the MARVS, knows as the 'reference temperature'. The regulations require that the maximum fill level of the tanks be such that at the reference temperature, the tank will not be more than 98% liquid full.

The fuel is delivered at -253°C from the LH_2 refueling trucks, so the tanks can only be loaded to 74% full to prevent the tank from being liquid full when the gas warms up to the reference temperature of -243°C at the 130 psia MARVS.

The combined effect of the heel and the loading limit is that the consumable volume of the storage tanks is only 69% of the molded volume. Scaling the fuel consumption by this usable volume factor gives a required molded tank volume of 3,318 gallons at minimum. This hydrogen tank volume and rough arrangements were provided to MAN Energy Solutions (MAN-ES), who were able to propose a cryogenic LH_2 system. The tank was sized at 15 cubic meters (3,962 gallons) to allow for future growth during the vessel design phase, which equates to a total consumable fuel amount of 733 kg of hydrogen assuming a 74% loading limit (MAN ES was also able to confirm that 69% usable tank volume and a 5% heel volume were acceptable for their proposed tank). For this study, 733 kg is assumed to the be maximum useable volume of LH_2 based on a 74% standard loading limit.

The standard tank loading limit of 74% was used as the basis for the tank sizing because it is conservative. However, there are allowances in the rules that may permit increased loading of the tanks up to 95% full at loading conditions. Both the DNV GL rules and the IGF code allow a higher loading limit to be used when the tanks are located where there is a very small probability of an external fire and there is a means of controlling the tank pressure other than by fuel consumption. The tank location on the weather deck of the 01 level is a low fire risk location. Although there are no active pressure control devices like a reliquifaction system or a thermal oxidizer to manage pressure in the tanks from boiloff gas, venting of the boiloff through the vent mast has been considered. Venting of boiloff gas to weather is currently standard practice for industrial LH_2 storage and could reasonably be extended to marine installations with careful application and consideration to risk. Venting of hydrogen is discussed more in Section 6.5.3.

Using increased loading limits would significantly increase the useable fuel and the vessel's range on hydrogen fuel. The vessel's range can also be increased by slowing down to an economical cruise speed of 9 knots. Table 19 presents the ranges available at both standard and increased loading for speeds of 9 and 10 knots.

Table 19 Comparison of hydrogen only range with various cruising speeds and increased loading limits

Loading	Speed, kts	Consumable LH_2, kg	Range, nm
Standard Loading Limit (74%)	10	733	234
Increased Loading Limit (85%)	10	850	271
Max Increased Loading Limit (95%)	10	956	305
Standard Loading Limit (74%)	9	733	330
Increased Loading Limit (85%)	9	850	383
Max Increased Loading Limit (95%)	9	956	430

Using the maximum increased loading limit and a cruise speed of 9 knots increases the hydrogen only range by more than 35%. It is recommended that the use of an increased loading limit for the SRV be further explored with regulatory bodies during a future design phase. Currently, the vessel design is capable of performing all required one day missions with hydrogen fuel under the standard loading limit, and an increased loading limit would simply expand the vessel's capabilities while using hydrogen fuel. This would mainly allow maximization of hydrogen powered operation during the vessel's longer missions, thereby allowing for low-noise science operations and reduced overall emissions.

This section applies only to operation on hydrogen power. The fuel usage, range, and capabilities while operating on diesel are the essentially the same as the baseline, only reduced slightly by the increased vessel weight from the hydrogen system.

6.3 Arrangements

The basic general arrangement of the hydrogen hybrid SRV is the same as the baseline design. In order to keep the comparison as consistent as possible, the fewest possible changes were made to support integration of the hydrogen power system. Additionally, some changes that were required to support the hydrogen arrangement were incorporated into the baseline design and are reflected in all options. However, there are still special arrangement considerations related to the use of liquefied gas fuel and fuel cells that are only applicable to this variant. The most significant of these special requirements are hazardous zones (discussed in Section 6.4.2), the restriction that the hydrogen storage tanks be located no closer to the sides of the vessel than 20% of the overall width (beam), and the additional ventilation requirements.

Because LH_2 is a cryogenic liquid stored at pressure, it is stored in vacuum-insulated Type C cylindrical pressure vessels. The fitment of cylindrical type C storage tanks into the prismatic hull of a research vessel is both challenging and space-inefficient. It is desirable to have a smaller number of large LH_2 storage tanks rather than a larger number of small LH_2 tanks, because large diameter tanks are more volume, weight, and cost efficient. In addition, the heat leakage from large diameter LH_2 tanks is, as a percentage of the amount of LH_2 stored, lower than from smaller cryogenic vessels. Thus, undesirable boiloff of the LH_2 is lower for larger LH_2 tanks. Furthermore, the volumetric energy density (energy in the fuel per unit of volume) of LH_2 is 4.2 times lower than that of diesel fuel, so LH_2 requires more than four times the volume of tankage for an equivalent amount of fuel energy.

Due to these tank size factors, it was found that the size of the fuel storage tanks required to meet range was too large to fit inside the hull of a vessel that met the dimensional limitations. For this reason, the fuel tanks are located above the deck in the weather. On research vessels, the Main Deck is the most valuable real estate for working and laboratory spaces. Because large storage tanks located on the Main Deck would be too disruptive to the working spaces and science operations, the tanks are located on the 01 Level aft weather deck (Figure 15).

As this design is a hybrid vessel with a diesel-electric generation plant, there is no need to have any redundancy in the hydrogen system. This means that only a single LH_2 tank and tank connection space need be accommodated on the 01 Level. As mentioned, the tank needs to be located no closer than 81.6 inches (20% of the 34 ft vessel beam) to the side of the vessel.

The fuel cell array is located in the space aft of the engine room, which was designated as an auxiliary machinery space on the baseline design. Because the fuel cells are sealed from the atmosphere and the hydrogen is piping is double-wall into the fuel cell enclosure, there is normally no possibility of hydrogen being present in the fuel cell room. The manufacturer used for this design, Ballard Power Systems, is in the process of getting type approval for the sealed fuel cell enclosure. Depending on the results of that process, there is a possibility that airlocks will not be required. However, to be conservative, it is assumed that this space will be designated as a hazardous area and will require air locks to access the space (Figure 14). The space requires smooth walls and a smooth sloped ceiling leading to an overhead ventilation trunk which collects and removes any hydrogen gas accidentally discharged into the space. Furthermore, the space and the fuel cells within it also require several streams of ventilation air with redundant fans.

The location of the fuel space, below the aft end of the superstructure, allows for a direct ventilation trunk to the weather up the aft side of the superstructure. This trunk is routed up alongside the tank connection space on the port side of the vessel similar to the diesel exhaust trunk, which allows for the discharge of any potentially hazardous gases above the working deck. The trunk also includes a hydrogen gas vent pipe routed to a vent mast located above the vent trunk.

Finally, the hydrogen powered options require a fuel bunkering station, which is only accessible from the aft deck through an air lock. This space is integrated into the port sideshell outboard of the Wet Lab and is accessible from the working deck (Figure 15).

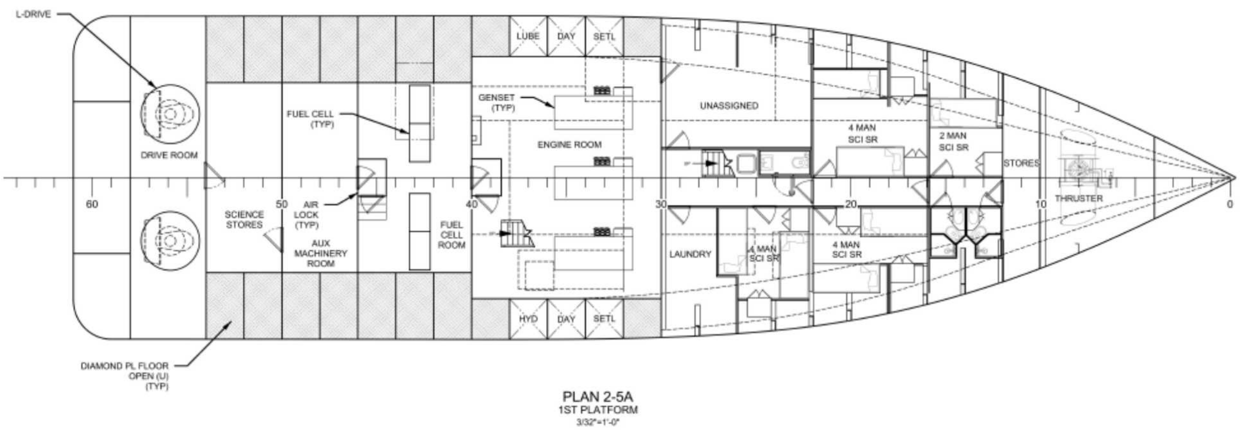


Figure 14 Hydrogen hybrid SRV below deck arrangement

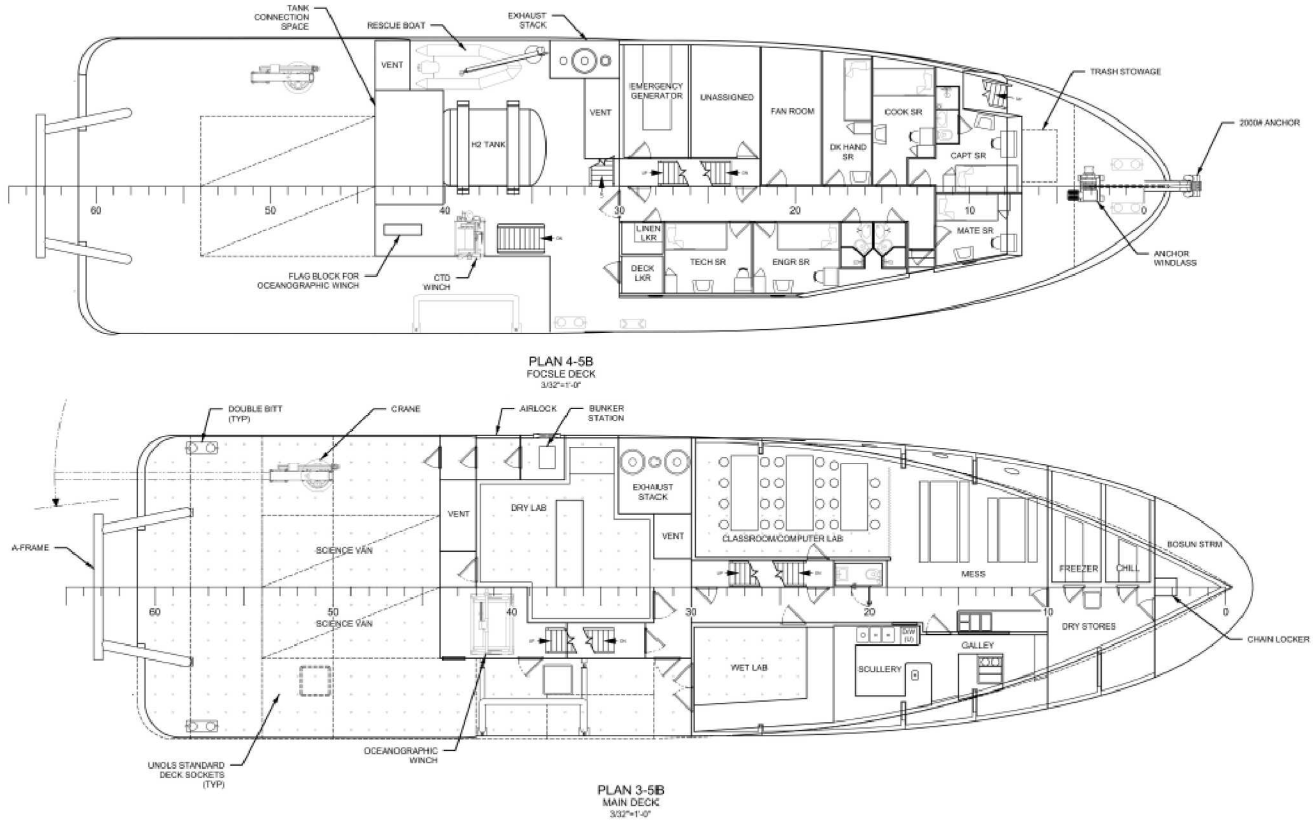


Figure 15 Hydrogen hybrid SRV Main and Focsle Decks

Details of the vessel's arrangements can be seen in the General Arrangement drawing in Appendix A.

6.4 Integrated Electric Plant

Propulsion power for the hydrogen hybrid SRV is supplied by an integrated electric plant consisting of hydrogen proton exchange membrane (PEM) fuel cells and lithium ion batteries. The fuel cells are 200 kW Ballard Power Systems marine fuel cell modules. Each module has a total power output of 200 kW. With four racks total, the vessel has 800 kW of installed hydrogen fuel cell power. This hydrogen fuel cell system is in addition to the diesel generator plant discussed for the baseline vessel.

The fuel cell racks are all arranged within a single fuel cell space. As this vessel has both hydrogen fuel cell and diesel generator power available at any given time, no fuel cell redundancy is necessary. The diesel generators will allow continued operation if the fuel cell space must be taken out of service for maintenance or in response to a hydrogen leak or a failure in the space.

Item	FCwave™		
Performance			Units
Rated power - BOL		200	kW
Minimum power		30	kW
Peak fuel Efficiency		56%	
Operating voltage		350 - 720	V DC
Rated current[1]	2x 300	1 x 550	A
System cooling output		Max 65	°C
Stack technology			
Heat management	Liquid cooled		
Targeted B50 lifetime2		34,000	hrs.
H2 Pressure		3,5 - 5	Barg
Physical			
Dimensions (l x w x h)[3]		1228 x 672 x 2120	mm
Weight (estimate)[4]		875	kg
Reactants & cooling			
Type	Gaseous hydrogen		
Composition	As per SAE spec. J2719*		
Oxidant	Air		
Composition	Particulate, Chemical and Salt filtered*		
Coolant[5]	Water or 50/50 glycol		
Flow Rates			
Hydrogen flow rate @200 kW BOL		3.5	g/s
Design criteria		4.9	g/s
Safety Compliance			
Certifications	DNV-GL compliant		
Enclosure	Hydrogen safe enclosure		
Monitoring			
Control interface	Ethernet, Can		
Emissions			
Exhaust	Zero emission		

Figure 16 Rendering and specifications for a 200 kW fuel cell power module (Ballard Power Systems)

The fuel cell power modules have an operating voltage between 350 and 720 VDC (Volts Direct Current). Each power rack supplies power to the propulsion switchboard through a DC-AC converter that converts the variable DC fuel cell output to a nominal AC propulsion bus voltage. The various large loads such as propulsion, thruster, and winch motors are supplied from the propulsion switchboard through AC-AC drives. Additionally, the ship service electrical power is supplied to the 480 VAC (Volts Alternating Current) ship service switchboard by cross-connects. Smaller loads such as lighting, fans, or pumps are supplied from the ship service switchboard. The high-level the electrical one-line diagram can be seen in Figure 17 and Appendix A.

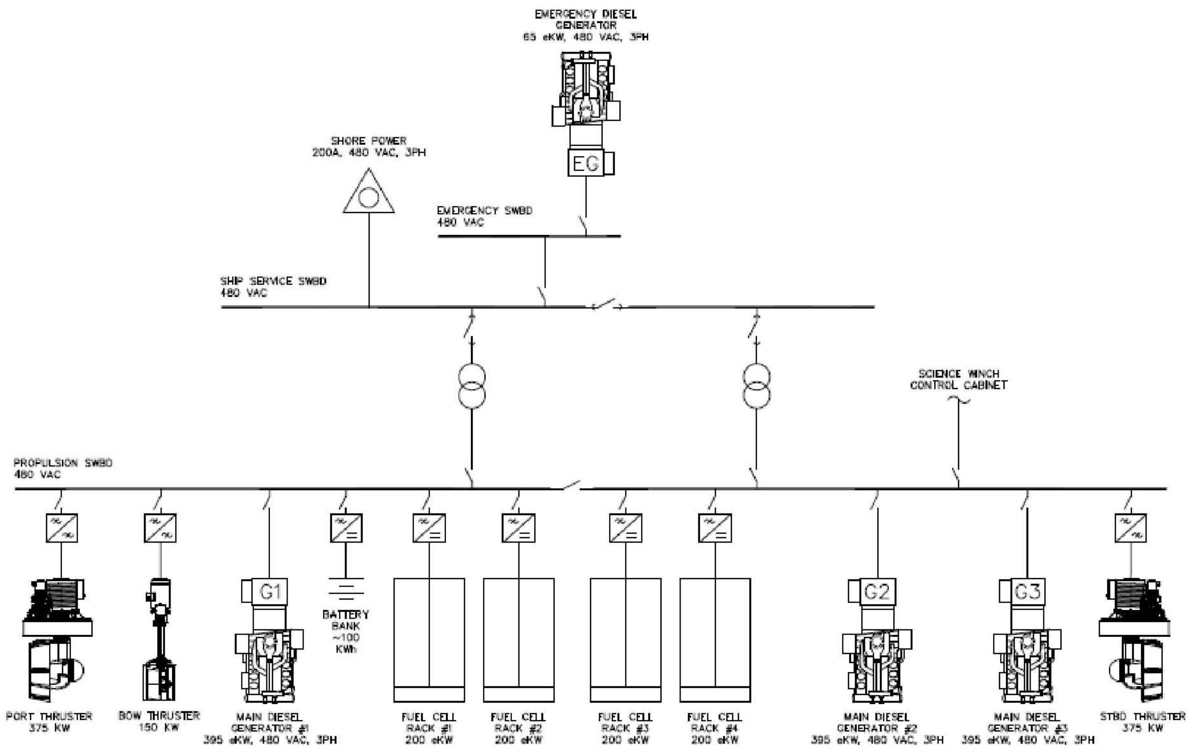


Figure 17 Propulsion system block diagram

The goal would be to operate the fuel cells close to peak efficiency whenever possible to minimize fuel use. The efficiency of the PEM fuel cells varies with power output. It is anticipated the fuel cell power modules will have a peak efficiency of approximately 56%, and up to 10% lower efficiency when operating at rated power output, which would not be a typical operation. The fuel cell efficiency will be slightly higher at the beginning of service but will degrade over time.

Fuel cell service life is driven by the lifetime of the proton exchange membrane inside the fuel cell module. The service life of the membranes is only consumed when the fuel cell is producing power; when the fuel cells are in standby, they are not consuming the operating life. It is anticipated the fuel cells will achieve between 20,000 to 25,000 hours of operation before requiring reconditioning to replace the membranes, but longer lifetimes are also possible depending on usage profile. The fuel cell's voltage degrades throughout their service life; they will continue to produce power, but at increased current and lower efficiency. At the end of service life, the membranes must be replaced.

Fuel cells can assume load fairly quickly. However, operations such as dynamic positioning can create very fast, transient spikes in vessel propulsion electrical load that could challenge the fuels cells' ability to respond quickly enough, and efficiency could also suffer. To account for these transient loads, the electrical plant is fitted with a small lithium-ion battery (100 kWh) able to provide power nearly instantaneously in response to load demands. With the fuel cells providing the base load power, the batteries will charge or discharge as required to manage transient loads. Additionally, the batteries can be used as a power sink for dynamic braking of large motors such as propulsion motors or winches. This allows energy to be recovered during operations such as paying out a winch, thereby increasing overall vessel efficiency.

6.4.1 Load Analysis

The electrical load analysis (ELA) is essentially the same as that developed for the baseline vessel, except that it will also include several additional loads such as ventilation fans and cooling pumps. The ELA is provided in Appendix B.

The main propulsion and ship service loads are supplied with power from four fuel cells. Because the fuel cells operate with a unity power factor (the ratio of real and apparent power), much like a battery, and the propulsion and ship service loads typically have a power factor between 0.8 and 0.9, the limits on apparent power (kVA) govern utilization of the fuel cells. The fuel cells provide 800 kVA for the vessel. Under SS4 cruise conditions, approximately 500 kVA is used for the vessel propulsion, while 90 kVA supplies the ship's service loads. Adding in a 10% design margin and a 10% growth margin for future modification, this requires nearly the full 800 kVA capacity of the electrical plant. To ensure that the total power demanded does not exceed the plant capacity as the ship service loads fluctuate, an automated power management system would control and limit the power to the propulsion motors under high load conditions.

The fuel cell racks supply DC power to the main propulsion switchboard at 350VDC - 720VDC through a power converter. The propulsion switchboard supplies power at 480VAC to the propulsion motors, thrusters, and ship service switchboard through drives and/or transformers. Reference 5 and Figure 17 show the details of the electrical system architecture.

The operating profiles considered in the ELA are the same as those discussed for the baseline.

The most demanding normal operating profiles are *Transit* and *On Station (DP).* These scenarios will require all four fuel cells to be operating to supply sufficient power. However, at low load, fewer fuel cells could be operated to maximize fuel cell life and balance it with efficiency.

6.4.2 Electrical Safety and Hazardous Areas

Besides the standard marine vessel electrical safety considerations, there are several additional considerations specific to the use of gas fuels such as hydrogen. The primary considerations are designation of hazardous areas and the safety of electrical appliances or equipment installed in those areas. Hazardous areas are designated as such if they have hydrogen gas atmospheres under normal conditions (i.e. the inside of fuel piping) or if they potentially could have hydrogen gas atmospheres under normal or abnormal conditions due to a fault or failure.

The IGF code (Reference 2) provides definitions of the zonal classification and size of various hazardous areas associated with the use of natural gas fuel. This hazardous area classification is considered to be applicable to hydrogen gas as well, but a gas dispersion analysis of hydrogen releases is required to validate this assumption. In this classification scheme, hazardous areas are areas where an explosive gas atmosphere with a flashpoint below 60C is or may be expected to be present in quantities that require precautions for construction or use of electrical equipment. They are divided into Zone 0, 1, and 2 as defined below:

Zone 0: Explosive or flammable gas with flash point below 60C is present continuously or for long periods (e.g. inside a gas pipe or tank)

Zone 1: Explosive or flammable gas with a flash point below 60C is likely to occur in normal operation (e.g. at the discharge the vent mast).

Zone 2: Explosive or flammable gas with a flash point below 60C is not likely to occur in normal operation and if it does occur, it would be infrequent or exist for a short period (e.g. gas released due to a leaking joint).

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, it must be certified safe for use in the applicable hazardous zone.

Figure 18 shows a 3D representation of hazardous areas on board the Hydrogen Hybrid SRV. Care was taken in locating the sources of hazardous areas to avoid hazardous areas impinging on science working areas or entrances into the interior of the vessel. It is anticipated that the hazardous zone around the Bunker station would only be hazardous during bunkering and not during normal operation. The intention is that the bunker line would be purged of hydrogen and filled with inert gas up to the tank so that no flammability hazard would normally be present from hydrogen in the line.

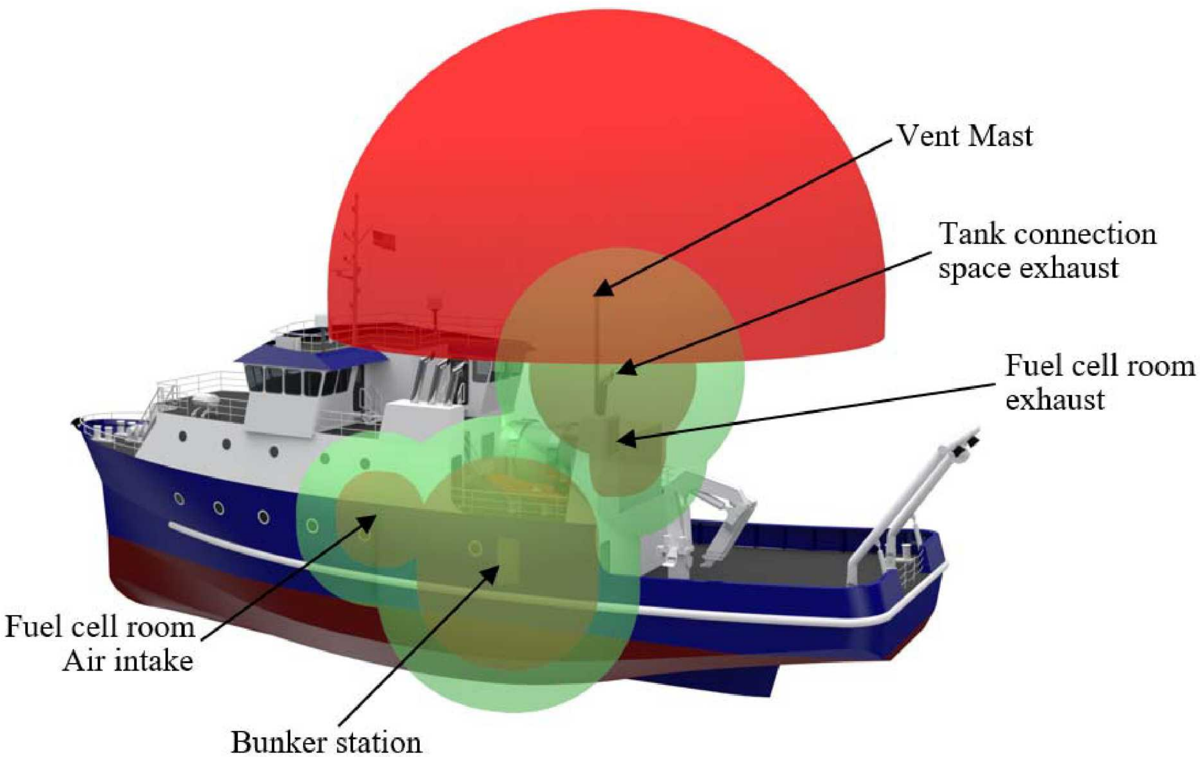


Figure 18 Hydrogen Hybrid SRV Hazardous areas

The Fuel Cell Room of the Hydrogen Hybrid SRV requires additional consideration. Under normal operating conditions, the atmospheres of the Fuel Cell Rooms would contain no hydrogen and would be considered gas safe. The Ballard Power Systems fuel cell modules are designed with double layers of protection. The fuel cells are enclosed in a gas tight and ventilated box, and the piping going into the enclosure is double walled. As such, a double failure would be required for the space to become gas hazardous due the release of hydrogen into the Fuel Cell Room. However, as the design is not yet type approved, this report assumes that the Fuel Cell Room will be arranged as an emergency shutdown (ESD) protected machinery space. This means that in the event of abnormal conditions involving gas hazards, emergency shutdown of non-safe equipment (ignition sources) and machinery must be automatically executed. In addition to electrical disconnection, ESD of a Fuel Cell Room would initiate immediate shutdown of the hydrogen supply to the space. Any equipment that must remain in use or operating during these conditions must be of a certified safe type. The emergency shutdown 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.

6.5 Fuel Gas Systems

The fuel cells are fueled by hydrogen gas. As discussed in Section 6.2, the hydrogen is bunkered and stored as cryogenic liquefied hydrogen gas (LH_2) at –423°F (-253°C) in one storage tank located in the weather on the 01 Level aft deck as shown in Figure 15. To be used for fuel, the liquid hydrogen is piped to a vaporizer in the tank connection space where it is vaporized to gas, warmed above 32°F and delivered to the fuel cells. As such, the fuel gas system consists of a bunkering system, storage tank, gas vaporization equipment, and a gas distribution system. No redundancy is required for this vessel, so the gas storage and distribution systems are arranged as a single system.

A concept of the fundamental fuel gas system architecture was developed, leveraging to a large extent the arrangements of the previously completed Zero-V study, existing marine liquefied natural gas (LNG) fuel systems, and existing industrial liquefied hydrogen systems. A concept sketch of the fuel gas system architecture is included in Appendix A. While this sketch is useful to communicate the fundamental philosophy of the fuel gas system architecture, significant additional system development will be required to flesh out the details and support a comprehensive operational and risk assessment. A cryogenic gas systems supplier experienced with both industrial LH_2 systems and marine LNG systems would be a critical partner in this effort. The final details of the 200kW Ballard Power Systems fuel cell modules were not available during this study as the system is undergoing final design and class type approvals.

6.5.1 Gas Storage

The LH_2 is stored in a single cylindrical pressure vessel storage tank with a molded volume (water volume) of 3,962 gallons (1,009 kg of hydrogen). This gives a capacity of 786 kg of LH_2 at a standard loading limit of 74%. The tank is a Type C independent tank of austenitic stainless steel double wall construction, with vacuum insulation between the primary containment and the outer shell. The tank will have a relief pressure of 130 pounds per square inch gage (psig), and a typical operating pressure around 100 psig. A tank connection space, sometimes called a cold box, is located at the back of the tank. The tank connection space is a ventilated compartment that contains all the pipe penetrations into the tank below the full liquid level. In this way, any liquid leaks resulting from a failure of a pipe penetration into the tank would be contained by the tank connection space. The vent from the tank connection space is a hazardous zone due to the possibility of gasses being present under abnormal conditions.

6.5.2 Gas Distribution System

Each tank connection space will contain all the gas piping and equipment that processes liquefied gas. This includes a pressure-building unit (PBU), a gas vaporizer, and gas delivery piping and valves.

In normal operation, pressurized LH_2 fuel is conveyed from the bottom of the tank to the vaporizer where it is evaporated to "warm" hydrogen vapor at a temperature of approximately 32°F (0°C). The "warm" gas vapor is then delivered to the fuel cells by way of the gas supply piping and a gas supply unit (GSU). The vaporizer is a shell and tube heat exchanger that is specifically designed for cryogenic services and uses glycol water as the heating medium. The SRV uses a combined pressure-building unit and vaporizer supplied by MAN ES.

The LH_2 is pushed through the vaporizer by increasing the pressure in the storage tank to the operating pressure using a pressure-building unit (PBU). The PBU is a small evaporator that takes a small amount of LH_2 from the tank, vaporizes it, and sends the vapor back into the gas cushion at the top of the tank to increase the pressure in the tank. This type of delivery system is commonly used on LNG fueled vessels and cryogenic delivery trucks. Cryogenic pumps are expensive and are typically only used where necessary, such as high-pressure applications.

The gas system is fitted with a remotely operated tank isolation valve immediately at the liquid piping penetration into the tank. This valve can be used to shut off supply of LH_2 in an emergency. Additionally, each gas system is also fitted with a master gas valve where the gas vapor piping exits the tank connection space. This valve can be used for emergency shutdown of vaporized gas. Typically, the master gas valve would be used for emergency shutdown of the gas supply system unless a leak detection alarm has occurred inside the tank connection space.

The gas supply piping is led from each of the tank connection spaces to the master gas valves and then down to the GSU, which is located adjacent to the Fuel Cell Room. From the GSU, the piping is led into the fuel cell spaces and to the fuel cell modules. Everywhere gas piping is led inside the vessel, it is inside of gas-tight ventilated ducts or in double-walled ventilated pipe. The GSU will be mounted inside a dedicated gas-tight enclosure.

All of the gas supply piping will be low pressure piping, with the gas pressure not exceeding 150 psig and typically operating around 100 psig. Pressure relief valves inside the GSU will ensure that the gas pressure does not exceed the maximum allowable pressure.

The gas supply unit (GSU) will consist of a double block-and-bleed valve, pressure control valve, and a nitrogen purging connection. On either side of the double block-and-bleed valve will be a vent valve that allows the gas supply piping upstream and downstream of the double block-and-bleed valve to be vented to the gas vent mast. The nitrogen injection valve will be located upstream of the double block-and-bleed valve to facilitate inerting the gas supply line between the double block-and-bleed valve and the storage tank, as well as from the GSU to the fuel cells. The piping would only be nitrogen inerted if required for maintenance, and only for "warm" gas piping. In normal operation, the gas supply piping would always contain hydrogen. The double block-and-bleed valve is used to secure the hydrogen supply to each fuel cell space for normal shutdown of the equipment in the space or for emergency shutdown.

The GSU will be installed inside a gas tight enclosure in the Generator Room adjacent to the Fuel Cell Room. The ventilation ducting around the gas supply piping will be connected to the GSU enclosure, thereby ventilating the enclosure. The GSU enclosure will be considered a Zone 1 hazardous area and will not have access doors. Hazardous areas are further discussed in Section 6.4.2. Maintenance and service access to the enclosure will be through a bolted hatch that will only be opened when the gas supplying line has been inerted with nitrogen. After the gas supply lines are inerted, the GSU enclosure is not a hazardous space.

The gas supply piping from the GSU enters the fuel cell space where it branches to the fuel cells. Each fuel cell supply branch contains a block-and-bleed valve near the fuel cell rack connection. This valve is remotely operated and is used to isolate the fuel supply to each fuel cell for normal fuel cell shutdown. This allows the branch piping to each fuel cell to be depressurized whenever the module is not operating. This significantly reduces both the risk and consequence of a leak within the fuel cell. An additional manual isolation valve is located upstream of the block-and-bleed valve for maintenance isolation of each fuel cell.

6.5.3 Gas Vents

There are several gas vents in the gas system. The vents are either from pressure relief valves or from bleed lines for purging gas supply and bunkering lines. All the gas vents lead to a gas vent mast.

Gas Vent Mast

Because of the hazardous nature of vented gas, all gas vents are connected to a gas vent mast. In accordance with regulations, the gas vent mast must be located such that the gas outlet is sufficiently far from any potential ignition source (4.5m), working deck (6m), or a ventilation intake (10m). The gas vent mast will be located above the hydrogen ventilation stack at the back of house and will be the highest point of the vessel. It has been assumed that due to the buoyant nature and rapid dispersion characteristics of hydrogen gas, the hazardous area associated with the vent mast is a hemisphere of radius 4.5m above the vent outlet with a cylindrical skirt that extends 3m below the outlet. This assumption requires additional support though gas dispersion modeling to validate the approach for regulatory approval.

Bleed Vents

Bleed vents are used to bleed hydrogen from fuel gas piping and are designed for safe venting and/or purging of gas lines for fuel cell shutdown, bunkering, and in response to a gas system alarm.

The gas supply line will be vented by bleed valves in the GSU enclosure and at the fuel cell modules. When gas supply to a fuel cell or the Fuel Cell Room is stopped with the double block-and-bleed valve, the bleed valve will open to vent the pipe between the stop valves. The bleed valve will be connected via the vent pipe to the gas vent mast. All gas vent piping within the interior of the vessel will run through the ventilated gas pipe ducts.

In addition to the bleed line from the double block-and-bleed valve, there will also be bleed valves on either side of the double block-and-bleed valve that vent the gas supply piping in case of an automatic closure of the master gas valve. These bleed valves will be connected to the vent pipe.

A vent valve in the bunkering line will be located near the tanks. The bunkering vent will be used for purging the bunkering pipe to the vent mast with hydrogen before and after the bunkering process.

The storage tanks will be connected to the vent mast by bleed valves located in the tank connection spaces. These valves will be normally closed but can be opened to allow purging of the tanks for maintenance.

Pressure Relief Valves

There are several pressure relief valves in the system to prevent the hydrogen pressure from exceeding the maximum allowable pressure of the fuel system (150 psig). There will be two sets of pressure relief valves and rupture discs on the tanks, with one set active at all times. The relief valves and rupture discs are set at progressively higher pressure to provide multiple levels of protection of the tank. Additionally, there are pressure relief valves in all sections of liquid piping in which LH_2 could become trapped and a pressure relief valve from each GSU. If any pressure relief valve lifts, the gas is vented to the gas mast through the vent piping.

Gas Release

With marine LNG fuel applications, routine venting of gas to the vent mast is not permitted. The vent mast is solely to be used for emergency or pressure relief valve releases. This LNG gas venting philosophy is not aligned with current widely accepted industrial practices for LH_2 handling. In industrial LH_2 storage and transfer, hydrogen gas is routinely and safely vented to atmosphere during normal operating procedures. One key difference in the release of hydrogen verses natural gas vapors is that the methane vented from LNG is a significant air pollutant and greenhouse gas, while hydrogen is neither. Additionally, unlike natural gas, hydrogen is buoyant in air even for temperatures only a few degrees above the boiling point of -253°C. This prevents hydrogen from ever settling or pooling in low points.

Because there is no established regulatory standard for venting of hydrogen fuel gas in marine applications, it is proposed that the accepted industrial procedures be adapted to marine applications. This proposal is supported by other accepted marine practices involving release of hydrogen gas. One such example is the venting of hydrogen gas that is formed as a byproduct of large scale electrochlorination-type ballast water treatment systems. Electrochlorination systems generate hypochlorite disinfectant products by electrolyzing seawater. In this process, hydrogen gas is evolved as a byproduct and is entrained in the disinfectant process stream. To avoid accumulation of hydrogen gas in the vessel's ballast tanks, the hydrogen gas is separated and vented to weather. The considerations for arrangement and safety of the hydrogen venting in ballast treatment applications is codified in the various shipbuilding rules of the major marine classification societies. With the appropriate diligence and risk assessment, it is reasonable to assume that the practices established for venting of hydrogen in ballast water treatment systems could be extended to venting of hydrogen gas fuel. In fact, for some very large ballast water treatment systems, the amount of hydrogen vented may be comparable to or greater than the amount of boiloff gas from the SRV LH_2 tank if no hydrogen is being consumed.

One of the principle methodologies for handling of hydrogen venting in electrochlorination systems is the use of hydrogen dilution systems. The dilution systems consist of redundant blowers that force sufficient quantity of air into the hydrogen vent system to dilute the hydrogen to a level that is safely below the lower flammability limit. A similar dilution system could be employed for routine venting of hydrogen fuel gas.

Alternatively, there are provisions in the various classification society rules including the DNV GL rules (Reference 1) for venting flammable concentrations of hydrogen from ballast water treatment systems. It is not unreasonable to assume that this could also be extended to venting of hydrogen fuel gas given careful analysis and risk assessment. Hydrogen gas disperses quite rapidly when released to the atmosphere. Sandia National Laboratories is currently examining the dispersion of vented hydrogen using computational fluid dynamics. Through such analysis and prudent placement of the vent mast outlet, it is plausible to demonstrate that the quantities of hydrogen released through routine operations such as from boiloff gas or purging of bunker lines can be released safely.

6.5.4 Bunker Process and Piping

Previous discussions with the gas suppliers for the Zero-V project revealed that the preferred and most flexible way to refuel the SRV is via LH_2 trailer trucks. Tanker truck refueling also eliminates the burden to ports of call of having to establish hydrogen fueling infrastructure at their sites. Truck trailers are currently used to fill industrial and hydrogen fueling station LH_2 storage tanks across United States, and several suppliers are currently operating in the California market. According to one of the LH_2 fuel suppliers serving California, an LH_2 trailer can deliver approximately 4,000 kg of LH_2. With a loadable tank volume of 746 kg of fuel (assuming 74% loading limit), only one trailer would be required to fully fuel the SRV. Delivery of a full trailer load of fuel takes approximately 3.5 to 4 hours. It is estimated that for SRV hydrogen bunkering would take about one to two hours accounting for both time for setup, connection and disconnection of bunkering equipment.

Hydrogen is bunkered into the storage tank as liquid hydrogen. A bunkering station containing the bunkering hose connection flange is located on the port side of the Main Deck. The bunkering station is open to the weather to provide for good natural ventilation and will be constructed with a sloped, smooth overhead such that any released hydrogen vapor will be naturally directed to weather and cannot become trapped. The bunker station consists of a hose connection with dry-break emergency release couplings, pressure gauges, manual stop valve, and remotely operated emergency stop valve.

The bunker piping is led from the bunker station to the tank. To accommodate the cryogenic temperature in the liquid state, all bunker piping is constructed of austenitic stainless steel and is double walled and vacuum insulated in keeping with standard industry practice. The double wall vacuum insulated pipe serves to provide secondary containment and to minimize heat ingress into the LH_2 during bunkering.

Previous discussions with Linde and Air Products regarding the bunkering process provided understanding of current industrial and fueling station LH_2 storage tank filling operations and shed light on potential operations for marine vessel bunkering. It is anticipated that marine bunkering will be similar to filling the storage tanks at hydrogen vehicle refueling stations, with a few notable differences.

One notable difference is that the LH_2 suppliers expressed some uncertainty about connecting a hose directly from the trailer to the vessel bunkering station for several reasons. First, the current experience of the LH_2 trailer operators is to connect to a stationary fueling connection. There was some concern about deviating from standard operations and training to connect to a vessel that could potentially undergo wind or wave induced motions at the dock. Additionally, typical LH_2 transfer hoses are very short in order to manage the heat influx through the hose, and they would likely have inadequate reach to connect from a truck at pierside to the bunker flange on the vessel. As such, it was recommended to make some intermediate LH_2 transfer infrastructure, such as a fueling stanchion, available at the port facilities where the vessel will bunker.

It is anticipated that the intermediate transfer equipment would be similar to loading arms that are already widely used in the marine industry. These have already been developed for cryogenic liquefied gasses such as LNG and could reasonably be extended to LH_2. Potentially, the loading arm would be mobile trailer-based infrastructure that could be moved to various ports where bunkering occurs. Figure 19 shows an example of a mobile marine loading arm. This particular loading arm is a Wiese Europe model Atlanta arm customized for a mobile application. According to Wiese Europe literature, the Atlanta arm is rated for -196°C. Ideally, something similar could be developed with vacuum-insulated transfer piping to handle the -253°C temperature required for LH_2.

Figure 19 Mobile marine loading arm (Wiese Europe)

With a shore-based loading arm, the LH_2 trailers would connect to the stationary arm and the arm would be connected to the vessel via flexible hoses. Because the arm can be positioned close to the bunker flanges, only short hoses would be required.

Bunkering operations would be similar to LNG bunkering currently done by vessels in the United States and around the world. Several authorities including USCG (References 12 and 13) and ABS (Reference 15) have developed guidelines for bunkering of LNG. In general, this guidance can be extended to LH_2 bunkering as well, but some differences will exist due to the differing properties and risks of LH_2. Because marine bunkering of LH_2 is not yet an established practice, detailed bunkering operations and facilities plans, including a risk assessment, would need to be developed in coordination with the cognizant authorities in all locations where bunkering is to occur.

The following conceptual bunkering procedure is adapted with modification from the current practices for LNG bunkering:

Bunkering Procedure

1. Vessel is moored with the port side to the pier and made ready for bunkering. The cognizant authorities such as the local Captain of the Port (COTP) shall be notified that LH_2 bunkering will be performed.
2. Safety checks of all equipment involved in the bunkering process are performed to ensure good operating condition and properly alignment for bunkering operations. This also includes testing of sensing and alarm systems, emergency shutdown systems, and communications systems.
3. Loading arm is brought into position and connected to the vessel bunker flanges.
4. LH_2 truck is brought into position and connected to the loading arm.
5. The truck builds pressure in the LH_2 trailers to the transfer pressure.

6. Bunkering piping valves are aligned to the vessel's vent mast and the truck pushes cold hydrogen vapor through the bunkering hoses and piping and to the vent mast. This is necessary to purge the bunkering piping of any contaminant gases and to cool them down before liquid transfer commences. The use of the vessel vent mast during bunkering is a notable divergence from LNG bunkering procedures. This is further discussed in Section 6.5.3.
7. Once the pipes are purged and cooled, the bunker piping valves are aligned to the LH_2 storage tank and liquid transfer begins.
8. Pressure is controlled in LH_2 tank by alternating between bottom filling and top filling though spray bars inside the tank to collapse the vapor in the head space.
9. Once the tank is filled to the desired level, liquid transfer is stopped. Cold hydrogen gas is used to push remaining liquid to the tank to the greatest extent possible. Any liquid remaining in the transfer piping must be vented to the vessel's vent mast.
10. Bunkering and transfer piping, now containing only cold gas, is isolated from the LH_2 storage tank and the LH_2 trailer. The pipe is then vented to the vent mast to depressurize all bunkering and LH_2 transfer piping and hoses.
11. Valves at the bunkering flange are secured, hose connections to the loading arm are broken, and hoses removed.
12. Bunkering and transfer piping is inerted with liquid nitrogen and any remaining hydrogen gas is pushed through the vent mast, rendering the bunkering station a safe area and relieving hazardous zones associated with bunkering.
13. The truck is moved to a designated safe area at the port facility to depressurize the trailer tank before the trailer drives on public roads (as required by DOT regulations). This may require a fixed vent mast at the port facility.

6.6 Auxiliary Systems

This section will address design aspects of auxiliary systems peculiar to a hydrogen fueled vessel. On the hydrogen hybrid SRV variant, these include unique seawater cooling, cathode air, and ventilation propulsion support systems. This section will not address design aspects of standard vessel auxiliary systems.

6.6.1 Seawater Cooling

The seawater cooling system provides cooling for the fuel cells. The Fuel Cell Room will have a dedicated seawater cooling system with a seawater to freshwater heat exchanger and redundant pumps. Specific cooling requirements will be developed in later design stages.

6.6.2 Cathode Air

Air must be supplied to the fuel cells to provide oxygen to the cathodes. The cathode air is ambient outdoor air that is filtered but otherwise requires no special preparation. This is a similar quantity to the combustion air that would be required by an equivalent diesel generator set. The cathode air would be supplied by two supply fans to a common supply plenum leading to the Fuel Cell Room, with branch supply ducts to each fuel cell module. The supply fans would have variable frequency drives to permit modulation of the flow rate depending on the air demand of the fuel cells.

The air from the cathode is then exhausted by an exhaust fan in each fuel cell module. This is accomplished by exhaust ducts from each rack that are led to a common exhaust plenum in each Fuel Cell Room and then lead to weather. Because the fuel cell cathode air exhaust fans have very low static pressure, two exhaust fans in each cathode air exhaust system would ensure that the plenum is always under slight negative pressure. The exhaust fans would be configured to modulate flow in order to maintain a set point pressure in the exhaust plenum.

6.6.3 Ventilation

Ventilation is very important in a gas fueled vessel as it is used to mitigate the effects of any gas leaks within the vessel. There are two primary ventilation systems serving this purpose. One is for ventilation of the Fuel Cell Room. The other is for ventilation of the secondary containment duct around the fuel gas supply and vent piping.

The Fuel Cell Room has an independent ventilation system consisting of powered supply and powered exhaust. The supply to the space provides outdoor air from a safe location in the weather located on the port side of the Main Deck. Redundant supply fans are required to ensure that ventilation of the space is not interrupted due to equipment failures (Reference 7). Redundant fans are also used to exhaust air from the Fuel Cell Room to a location in the weather on the aft end of the deckhouse on the 01 Level. Because hydrogen is highly buoyant, the exhaust air is taken from the high point in the space. In accordance with DNV GL requirements (Reference 1) for fuel cell spaces where hydrogen is present, the overhead of the space will be smooth with no obstructing structures and arranged to be upward sloping towards the ventilation outlet (Reference 7). Under normal conditions, both the supply and exhaust ducting and weather terminals are not considered hazardous areas. However, in the event of gas detection in the fuel cell space, they would become classified as gas hazardous. Any electrical equipment that impacts the hazardous area would either need to be rated for use in a hydrogen atmosphere or electrically disconnected as part of the emergency shutdown (ESD) sequence. Hazardous areas and emergency shutdown are further discussed in Section 6.4.2.

In accordance with DNV GL regulations (Reference 1) for spaces containing hydrogen pipes, the ventilation rate must be sufficient to avoid gas concentration in the flammable range in all leakage scenarios, including pipe rupture. It is anticipated that the rate of 30 air changes per hour required for spaces containing other flammable gas pipes, such as for natural gas, is sufficient to achieve this requirement. However, a detailed analysis of potential hydrogen releases and the ventilation rate is required in future development.

All hydrogen gas piping routed through enclosed spaces in the vessel will be contained within a gas tight duct that provides a secondary containment of any gas that is leaked from the pipe. Similar to the fuel cell spaces, the gas pipe ducting will be ventilated throughout its entire length at a rate sufficient to avoid gas concentration in the flammable range in all leakage scenarios, including pipe rupture. It is again anticipated that the rate of 30 air changes per hour is sufficient to achieve this requirement, but a detailed analysis is required for confirmation. The gas pipe ducts are ventilated by fully redundant exhaust fans that maintain the ducting under a slight negative pressure and exhaust the air to a location in the weather (Reference 7).

6.7 Fire Safety Specification

This section has been developed using the IGF Code (Reference 2) and the DNV GL regulations for Gas Fueled Ship Installations (Reference 1) and Fuel Cell Installations. Regulatory bodies have developed have several safety requirements for gas fueled vessels beyond those of diesel fueled ships to address the risks of gas fueled propulsion.

IGF code is the primary international construction and safety code for gas-fueled ships. The majority of the rules in the IGF code are contained in Part A-1, which covers specific requirements for ships using natural gas fuel. There is no part of the code specific to hydrogen fuel. However, much of part A-1 can reasonably be extended to hydrogen fuel as a baseline level of requirements. On this basis, the IGF code Part A-1 has been applied to this vessel as guidance for hydrogen fuel cell installations. However, there may be some additional or differing requirements that come about as hydrogen fueled vessel regulation progresses.

The requirements beyond conventional ship fire safety systems pertaining to the hydrogen hybrid SRV variant involve additional structural fire protection surrounding the storage tanks and the Fuel Cell Room, a substantial water-spray system, specific firemain configuration, additional dry chemical fire extinguishing capabilities, and additional fire detection and alarm capabilities. The following sub-sections provide more information on the detailed requirements and how the vessel's design and arrangement will meet them.

6.7.1 Structural Fire Protection

The additional structural fire protection regulations for gas fueled vessels include the following:

- All boundaries facing the fuel tanks on the open deck will be shielded by A-60 class divisions. These spaces include, but are not limited to:
  - Bulkhead forward of the tanks on 01 Deck.
  - Bulkhead forward of the tanks on 02 Deck.
  - 01-Deck below tanks.
- Pilothouse windows will be rated A-0.
- The boundaries of the Fuel Cell Room will be insulated to A-60 rating.
- Fuel Cell Room will have gas-tight steel bulkheads.
- The ventilation trunks into the Fuel Cell Rooms will be insulated A-60.

6.7.2 Water-Spray System

The vessel is required by the regulations to have a water spray system for cooling and fire prevention that covers all exposed parts of the fuel storage tanks located on the open deck. Additionally, the water spray system provides coverage for boundaries of the superstructures, control spaces, bunkering station, and occupied deckhouses facing the storage tanks and within 10m of the tanks.

The water spray and firemain will be a combined system, with a pump capacity capable of serving both systems simultaneously. The combined system will have isolation valves installed to isolate damaged sections near the fuel storage tanks.

The water spray system will be sized at 10 $L/min/m^2$ for horizontal projected surfaces and 4 $L/min/m^2$ for vertical surfaces in accordance with regulatory requirements for LNG fueled vessels (References 1 and 2). There will be isolation valves at least every 40 m to isolate damaged sections as necessary.

The water-spray system will have remote start of the pumps from the Pilothouse. Any normally closed valves in the system will also be controlled from the Pilothouse.

The nozzles of this system will be an approved full bore type and arranged to provide effective distribution of water throughout the spaces.

In other hydrogen fueled projects (Reference 14), the use of aqueous film forming foam (AFFF) fire suppression has been discussed. The current IGF code only specifies the use of a water system. However, the use of an AFFF system around the tank location certainly warrants consideration during a fire risk assessment to determine if it would appreciably reduce the risk or consequence of a fire in the storage tank location.

6.7.3 Firemain

The vessel will be fitted with a firemain system serving all parts of the vessel. The firemain will be configured such that it can be isolated should any part of the system be damaged near the tanks. The isolation of this section will not impede the ability of the firemain to service the rest of the vessel.

6.7.4 Fixed Fire Suppression

The Fuel Cell Room will be fitted with clean agent fixed fire suppression systems. 3M NOVEC 1230 is the recommended agent because it safe for personnel, does not damage electronics or leave residue, and has zero ozone depleting potential and global warming potential. The fixed fire suppression system would be manually deployed. Upon deployment, ventilation to the Fuel Cell Room would be automatically shut down to prevent removal of the clean agent from the space. Consideration should be given during risk assessments in future phases as to whether some passive vents at the top of the space should remain open to allow for natural escape of hydrogen gas. This could be accomplished by shutdown of fans without closure of the dampers in the ventilation exhaust ducts. Deployment of the fixed fire suppression system would also result in emergency shutdown of the fuel gas supply to the affected space.

6.7.5 Dry Chemical Fire-Extinguishing

A portable dry powder extinguisher of at least 5 kg will be located near the bunkering station. As the bunkering station onboard SRV is open to the atmosphere, an enclosed system to flood the space is not practical.

6.7.6 Fire Detection and Alarm

In addition to the standard vessel fire detection system, additional fire detection will be installed in the Fuel Cell Room. The fire detection will be installed such that it is evident from the Pilothouse which detectors have alarmed.

Upon active fire detection in the Fuel Cell Room, automatic shutdown of the fuel gas supply to the Fuel Cell Room will occur. Following typical shutdown procedures in the activation of a fire detector, the ventilation to this space will stop automatically, and the fire dampers will close.

Detecting hydrogen fires presents some challenges. Hydrogen fires do not emit smoke, are nearly invisible to the naked eye, and have little infrared heat radiation. For these reasons, specialized fire detectors specifically for hydrogen fire detection applications will be required in the Fuel Cell Room and other locations where there is risk of a hydrogen fire. There are several technologies available for hydrogen flame detection, including multispectrum IR, UV, and combination IR/UV detectors. Because the consequence of false alarms is emergency shutdown of the Fuel Cell Room, special care will be required to select a flame detection system and to minimize all potential sources of false alarm detections.

6.7.7 Gas Detection and Alarm

A hydrogen gas detection and alarm system is required to monitor areas where a potential hydrogen gas atmosphere could occur. This includes detection in each fuel cell, the Fuel Cell Room, GSU enclosure, gas pipe ducts, and tank connection space. In many cases, multiple detectors will be required depending on the size and arrangement of the protected space. A gas dispersion analysis will be required to determine the quantity and locations for gas detection. Because the Fuel Cell Room is an ESD protected space, a gas detection event in a Fuel Cell Room would trigger immediate shutdown of the gas supply to the space as well as disconnection of all electrical equipment in the space that is not certified safe for use in a hydrogen gas atmosphere.

6.8 Vessel Fuel Usage & Capabilities

The hydrogen hybrid SRV variant fulfills all the same basic mission capabilities as the baseline variant, but also offers additional advantages of zero emissions operation and extended range.

The goal of the hydrogen hybrid SRV design was to develop a vessel design that is both feasible to build and meaningfully capable while using hydrogen as a fuel. Early analysis of the mission profiles provided by SIO yielded a natural break between the one-day class cruise type missions and the longer multi-day missions. As discussed in Section 2, 25 out of 34 (~74%) of the yearly missions are one day or less. Conversely, of the 92 days per year the SRV would spend on the water, only 27% would be one day missions. It was immediately evident that a hydrogen vessel capable of handling *all* the missions was not feasible within the budget and size constraints provided (see Section 7 for discussion on hydrogen-only SRV variant). Instead, a target was set to accomplish all one-day missions using only hydrogen fuel, while longer missions could be completed with a combination of diesel and hydrogen power or strictly on diesel operation.

This design allows for a fully capable vessel while also leveraging the benefits of hydrogen operation, such as zero emissions and low noise. The vessel will operate an estimated 33 total missions per year, where 24 of them are one-day missions which can be completed using only hydrogen fuel. The most demanding one-day mission requires a total of 603 kg of hydrogen fuel, while the proposed LH_2 tank from MAN-ES holds approximately 733 kg of consumable fuel at a standard loading limit of 74% with 5% heel.

The 733 kg of hydrogen allows for approximately 23.4 hours of endurance at a nominal 10 knot cruising speed, yielding a total hydrogen powered range of 234 nautical miles. This is in addition to the baseline endurance and range with diesel fuel discussed in Section 3.5.

Table 20 Hydrogen hybrid SRV fuel consumption

Mission	Missions Per Year	Hydrogen Hybrid*			
		Diesel		LH2	
		kg/mission	kg/year	kg/mission	kg/year
Class Cruise: Biology of Fishes	2	0	0	196	392
Class Cruise: Biology (Typ)	11	0	0	264	2,903
Class Cruise: Marine Geology & Invertibrates	4	0	0	277	1,110
Class Cruise: AUV Ops	2	0	0	394	788
Physical Oceanography	1	0	0	417	417
Coastal Mooring	5	0	0	641	3,207
Geology Sampling (Multicore)	1	9,400	9,400	733	733
Deep Moorings (4000m) & Towed Sonar II	1	11,044	11,044	733	733
AUV Ops II	1	12,407	12,407	733	733
Deep Moorings (4000m) & Towed Sonar I	1	14,804	14,804	733	733
Coastal Physical Oceanography	1	15,929	15,929	733	733
AUV Ops I	1	16,305	16,305	733	733
Cyanobacteria: CTDs and Incubations	2	16,596	33,193	733	1,466
Geology: Vibracore & Box Core	1	21,993	21,993	733	733
Range Endurance (Not a Mission)	0	28,820	0	733	0
Total	**34**		**135,075**		**15,413**

* Hydrogen hybrid fuel consumption is calculated assuming that one day missions are completed using only hydrogen fuel and longer missions are complete utilizing the entire usable capacity of hydrogen supplementing diesel fuel. Diesel fuel reductions were calculated via energy comparison with hydrogen fuel.

Table 20 shows the total fuel consumption by mission and per year for the hydrogen hybrid SRV, including both diesel and hydrogen. If it is assumed that the vessel will operate using the maximum amount of hydrogen possible on every mission (i.e. the greenest operation possible) the total consumption of hydrogen per year is estimated at 15,413 kg, and the total consumption of diesel fuel is estimated at 135,075 kg (40,093 gallons/year diesel). As the diesel electric SRV variant consumes an estimated 190,541 kg of diesel annually (56,557 gallons per year), this equates to a total savings of 55,466 kg or 16,463 gallons savings of diesel fuel per year over the baseline diesel-electric vessel design. This represents approximately 30% annual reduction in diesel fuel consumption.

6.9 Weight Estimate

The lightship weight of the Hydrogen Hybrid SRV is presented in Table 21. The lightship weight is the actual weight of a vessel when construction is complete and ready for service but empty of necessary tank fluids such as fuel or ballast. The operating weight (weight of the science equipment, crew supplies, fuel, and ballast) of the Hydrogen Hybrid SRV Table 22, is slightly heavier than the Battery Hybrid and Diesel Electric variants due to the additional weight of the hydrogen fuel (~750 kg) in the departure condition.

The departure weight, Table 23, which is the sum of the lightship and operating weights is slightly heavier than the Battery Hybrid SRV. As discussed in Section 3.7, the more significant difference between the weights of the variants is that the Hydrogen Hybrid has a higher VCG (vertical center of gravity) due to the added weight of the hydrogen and tank on the 01 level. Ballast is added to compensate for the higher VCG to allow the stability criteria to be met.

Table 21 Hydrogen Hybrid SRV lightship weight estimate

SWBS	Entry Description		Weight [LT]	LCG [ft-FR 0]	TCG [ft-CL +S]	VCG [ft-ABL]
100	**Hull Structure**		231.85	62.17	0.00	13.30
	Welding Allowance	1.5%	3.16			
	Mill Tolerance Allowance	2%	4.22			
	Brackets, Inserts, and Doublers Allowance	2%	4.22			
	Total Hull Structure		243.44	62.17	0.00	13.30
200	**Propulsion System**		17.16	114.37	0.00	0.69
300	**Electrical System**		38.80	76.66	0.00	8.31
400	**Command and Surveillance**		3.50	42.50	0.00	37.17
500	**Auxiliary Systems**		45.25	60.30	0.00	15.21
600	**Outfitting and Furnishings**		59.79	37.09	0.00	21.83
700	**Mission Equipment**		26.26	92.08	0.00	18.33
	Variant Specific Items					
	LH2 Tank		14.76	78.00	0.00	27.25
	Fuel Cells		3.44	86.75	0.00	8.75
	Total w/o margins		452.39	64.18	0.00	14.61
	Margins	5%	22.62			0.42
	Total Lightship		475.01	64.18	0.00	15.03

Table 22 Hydrogen Hybrid SRV operating weights

	Weight [LT]	LCG [ft-FR 0]	TCG [ft-CL +S]	VCG [ft-ABL]
Science Payload	30.00	93.90	0.00	18.26
Crew & Sci Effects	3.47	35.23	0.00	17.16
Consumables	9.76	37.00	0.00	17.19
Diesel Fuel	31.06	53.98	0.00	6.51
LH2 Fuel	0.70	78.00	0.00	27.68
Fixed Ballast	22.00	42.50	0.00	2.00
Total Operating Weights	96.99	61.52	0.00	10.73

Table 23 Hydrogen Hybrid SRV departure weight summary

Item	Weight [LT]	LCG [ft-FR 0]	TCG [ft-CL +S]	VCG [ft-ABL]
Operational Lightship w/margins	475.01	64.18	0.00	15.03
Operating Weights	96.99	61.52	0.00	10.73
New Departure Weight	572.00	63.73	0.00	14.30

6.10 Cost Estimate

To estimate the cost for the Hydrogen Hybrid SRV, the parametric cost estimate for the Diesel Electric SRV was adjusted up by adding the following:

- (4) fuel cells and controls (estimated at $2,500/kW including margin)
- 100 kWh battery (estimated at $600/kWh)
- hydrogen tank, gas piping, bunker piping, vent piping, controls, power electronics (estimated at ~$3.92MM including margin)
- gas detection system
- fuel cell cooling system
- fuel cell air system
- hydrogen tank sprinkler system
- Fuel Cell Room fire suppression
- Fuel Cell Room ventilation
- Additional A60 insulation
- Additional 30% to section 000 (Vessel Engineering) to account for added complexity
- Additional 30% to section 800 (Shipyard support) to account for added complexity
- Additional 10% contingency over baseline

The Hydrogen Hybrid SRV cost breakdown for Gulf Coast labor rates ($60/hr) are presented in Table 24.

To account for the higher $75 per hour labor rate for West Coast Shipyards, the total cost in Table 24 can be adjusted to $35,629,000. Therefore, the construction cost range in 2020 dollars is between ~$33.13MM and ~$35.63MM.

Table 24 Hydrogen Hybrid Cost Breakdown for Gulf Coast labor rates

SWBS	Item	Description	2020 Cost
000	**Vessel Engineering**	Production design engineering, planning & management, documentation, inspections/tests/trials, models and mockups	**$ 2,102,100**
100	**Structure (Steel/Alum)**	Hull, foundations, masts and other structures	**$ 1,827,000**
200	**Main Propulsion**	Propulsion motors, shafting/bearing, propellers	**$ 668,750**
300	**Electrical Systems**	Fuel cells, batteries, switchgear, power distribution and conversion equipment, emergency generator, electric cables, lighting	**$ 6,374,788**
400	**Command and Control**	Navigation systems, machinery control, alarm and monitoring systems, communication systems, entertainment systems, gas detection	**$ 1,300,000**
500	**Auxiliary Machinery**	Piping systems, HVAC, fuel storage, fuel systems, steering, bow/stern thrusters, anchors, mooring systems, pollution control systems, lifesaving equipment, small boats, H2 tank, gas detection	**$ 7,482,484**
600	**Vessel Outfit and Furnishings**	Paint and markings, joiner work, furnishings, ship fittings, doors/hatches/ladders, insulation	**$ 2,224,000**
700	**Science Equipment**	Lab outfit, cranes, winches, over-the-side handling systems, science acoustic suite	**$ 2,000,000**
800	**Shipyard Support**	Functional design, inspections, and drawing review	**$ 2,522,000**
			$ 26,501,121
	Contingency 25%		**$ 6,625,280**
	Total		**$ 33,126,402**

Section 7 Full Hydrogen Vessel Design

7.1 Regulatory Requirements

The regulatory and classification requirements for a fully hydrogen powered vessel are the same as those discussed in Section 6.1 for the hydrogen hybrid variant. Functionally, the operation of a fully hydrogen powered vessel differs little from that of the hydrogen hybrid variant.

However, because the full hydrogen vessel will not have a diesel generator power plant to provide backup to the hydrogen plant, additional redundancy needs to be provided in order to guarantee that power is not completely lost due to single point of failure (i.e. the LH_2 tank or Fuel Cell Room being taken out of service). Similar precautions were developed for the Zero-V project (Reference 14). The regulations for gas fueled vessels are defined in Reference 2. For single fueled LNG vessels, Reference 2 requires that redundancy be provided in gas systems (tanks, vaporizers, fuel cells, etc.). It is assumed that this philosophy is the same for vessels using hydrogen gas as a fuel. For this variant, total capacity is divided between two fully redundant hydrogen systems in order to provide sufficient "get home" capacity in the case of a failure.

7.2 Energy Requirements

In the operating profile provided by SIO, there are two general mission types the vessel is expected to complete. The first is a one-day class cruise type of mission and the second is a multi-day mission (Figure 2). The amount of total hydrogen required to complete each mission is presented in Table 4.

The minimum usable amount of LH_2 required to complete the most demanding mission is 5,546 kilograms. As discussed in Section 6.2 this does not represent the required tank volume. Assuming a usable tank volume of 69% as recommended by vendor MAN-ES, the total molded tank volume required would carry at least 8,055 kilograms of hydrogen. In order to provide redundancy this would need to be split between two LH_2 tanks with a capacity of at least 4,027 kilograms and a volume of about 15,000 gallons (~57m^3)

Initial impressions indicated that this was likely an unreasonable amount of tankage to be supported by a vessel of this size. Therefore, before proceeding any further with the design, a preliminary feasibility arrangement was created to determine whether two tanks 15,000 gallon tanks could physically fit on the vessel while maintaining vessel mission capability.

7.3 Arrangements

To determine the feasibility of carrying at least 5,546 kg of usable LH_2 fuel, two 15,000 gallon tanks were sized to fit within the tank location requirements discussed in Section 6.2. The arrangement left 18 inches of space between the tanks, and the outer edges of the tanks was set at exactly the distance from the shell required by the regulations. Including insulation, this yields two tanks that are each 9.5 feet in diameter and 37 feet long. In addition, each of these tanks would require a tank connection space estimated at 13 feet long.

Figure 20 shows an overlay of these tanks on the baseline vessel. They are shown in the interior of the vessel, but the size shown applies no matter where they are installed. The tanks are also sized to just meet the most demanding mission, whereas in actuality they would be sized even longer to provide some degree of margin.

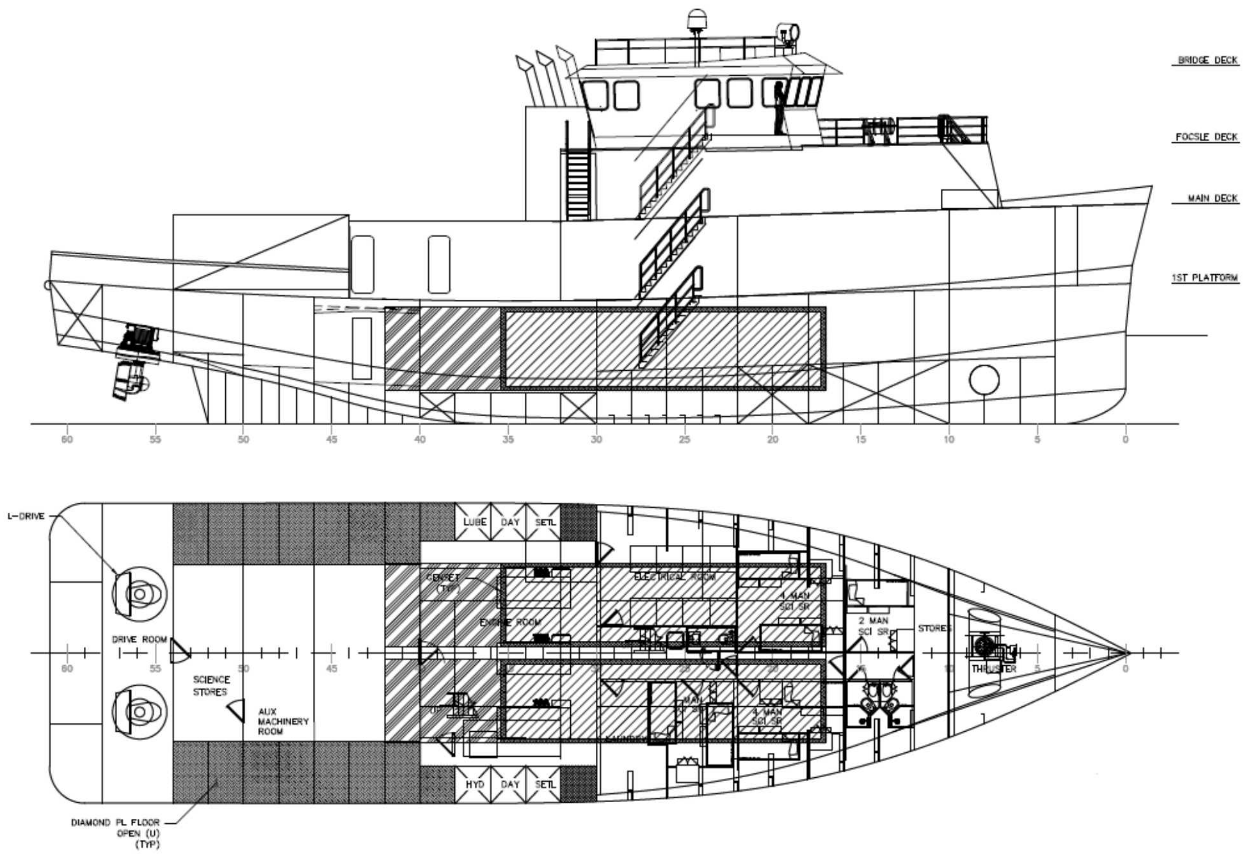


Figure 20 Arrangement of two 15,000 gallon LH_2 tanks below the main deck

As can be seen in Figure 20, tanks of this size occupy approximately 2/3 of the deck area on which they are installed. Two fuel cell rooms will also be required (not shown). Weight, stability, and watertight subdivision considerations were not considered at this stage but would also be drivers in any further design. Though not shown, the tanks need to be in ventilated compartments with room all around for tank inspection. The main deck would have to be raised to accommodate the tanks which would further affect stability. Accommodating the tanks would also result in an exceptional long single watertight compartment for a vessel of this size. While not evaluated, such a long compartment is likely to have detrimental effects to the floodable length and survivability of the vessel in a damaged condition. The tanks eliminate space needed for science quarters and auxiliary machinery below deck. Finding additional space for quarters and auxiliary machinery would require removing space on the main deck for science, and/or increasing the density of the accommodation spaces on the 01 deck. Altogether, accommodating the tanks and having a vessel that meets the Science Mission Requirements would only be possible with significant redesign and a larger and more costly vessel.

Discussion with Scripps and Sandia on the impracticality of these arrangements above indicated that tanks of this size would not be acceptable as the loss of capability would be too great, even without considering the probable weight and stability issues the tanks would cause. It was therefore determined that a fully hydrogen powered vessel of similar size and capability to the R/V *Sproul* would not be feasible. The arrangement derived for the *Zero-V* project had a much larger hullform than the SRV, and its trimaran hull greatly increased the width and available space onboard, enabling it to store sufficient hydrogen. While a vessel similar to the *Zero-V* would be capable of meeting all of the required mission capabilities, its cost would be significantly higher than the budget assumed in this report for the SRV. On a budget-limited vessel the size of the SRV, a fully hydrogen powered design is not feasible. No further investigation or design work was done on the fully hydrogen powered variant.

Section 8 Vessel Type Comparison Summary

8.1 Mission Compliance

The SRV variants (excluding the fully hydrogen variant) all meet the minimum SMR (Science Mission Requirements) and exceed in several categories. The vessel requirements are largely based on the RV *Robert Gordon Sproul*, plus additional requirements imposed by Scripps for the new vessel. In addition to the items noted in Table 25, it is assumed that all of the science equipment noted in Table 1 are accommodated on all three variants.

Table 25 Comparison of Science Mission Requirements to SRV Variants

Science Mission Requirements		Sproul Replacement Vessel (SRV)		
Vessel Requirements		**Diesel-Electric**	**Battery-Hybrid**	**H2-Hybrid**
Cruise Speed (calm water)	10 knots	Yes		
Speed in Seaway (calm water)	12 knots	Yes		
Cruise Range (NM)	2,400	2,880	2,908	3,156
Endurance (days)	10	Yes		
Sewage Holding (gallons)	Minimum 2000	7500		
Laboratory Area	Minimum 340 ft2	855	855	725
Students	Minimum 30 (40 desired)	40		
Crew Berths	Minimum 5	5 single staterooms		
Science Berths	Minimum 12	14 + 1 tech (3 quads, 1 double, 1 single)		
Portable Vans	Minimum 2	2		
Station Keeping	DP (desired)	Yes		
Deck Tie Down	UNOLS Compliant	Aft deck, forward bridge deck, all labs		
Science Support Equipment				
Main Crane	2,400 lbs SWL	~3500 lbs at max reach (29.5 ft)		
Stern A-Frame	SWL 10,000 to 21,000 lbs	19' 8" Height w/o block, 15' width, SWL 21,250 lbs		
Trawl Winch	Yes	Yes		
CTD/Hydro Winch	Yes	Yes		
Side Frame	Desired	17' clearance w/o block, 8'3" width, SWL 7,000 lbs		

8.2 Energy Requirements

A key goal of this study was to compare the performance of a Battery Hybrid to a Hydrogen Fuel Cell Hybrid with all else being equal. Both hybrids have complete diesel electric plants and carry the same quantity of diesel fuel. Both the Battery Hybrid SRV and the H_2 Hybrid SRV require special accommodations to support the additional equipment (batteries, fuel cells, LH_2 tank). With the exception of the additional vent stack and the LH_2 tank on the aft deck of the H_2 Hybrid SRV, the arrangements are very similar.

8.2.1 Zero Emissions Range

Key questions regarding these variants are what can be accommodated within the available volume and weight limits, and what are the zero emission benefits. If we just look at the range differences, it is evident that the LH_2 provides a substantial amount of energy storage and zero emissions range. The Battery Hybrid SRV has usable battery energy storage of 1410 kWh (60% DOD) which provides 25 nautical miles of range at 10 knots and 37 NM at 9 knots (SS4). By comparison the H_2 Hybrid SRV has a zero-emission range of 234 NM at 10 knots and 330 NM at 9 knots with 5% reserve in the tank (SS4). The results are summarized in Table 26.

Table 26 Zero emission range comparison between Battery and Hydrogen Hybrid SRVs

Cruise Speed	Range (NM)	
	Battery Hybrid	Hydrogen Hybrid
9 knots	37	330
10 knots	25	234

The difference in zero emission range between the battery and the fuel cell SRV variants are significant. The Hydrogen Hybrid SRV has nearly 10 times the zero-emission range, and additionally the Hydrogen Hybrid SRV is able to accomplish all of the missions under 24 hours in length with only LH_2 as fuel.

8.2.2 Fuel Consumption

A comparison of annual fuel consumption between the three variants is presented in Table 27. Compared to the baseline Diesel Electric SRV, both the Battery Hybrid and Hydrogen Hybrid have significant diesel fuel savings. The Battery Hybrid reduces fuel consumption by approximately 9% and the Hydrogen Hybrid by approximately 30%.

Table 27 Annual Fuel Consumption Comparison all Variants

Mission	Missions Per Year	Diesel Electric SRV	Battery Hybrid SRV		Hydrogen Hybrid SRV	
		Diesel	Diesel	Shore	Diesel	LH2
		kg/year	kg/year	kWh/year	kg/year	kg/year
Class Cruise: Biology of Fishes	2	1,671	1,375	2,820	0	392
Class Cruise: Biology (Typ)	11	12,242	10,464	15,510	0	2,903
Class Cruise: Marine Geology & Invertibrates	4	4,656	4,000	5,640	0	1,110
Class Cruise: AUV Ops	2	3,280	2,904	2,820	0	788
Physical Oceanography	1	1,780	1,585	1,410	0	417
Coastal Mooring	5	13,368	12,169	7,050	0	3,207
Geology Sampling (Multicore)	1	11,452	10,773	1,410	9,400	733
Deep Moorings (4000m) & Towed Sonar II	1	13,096	12,335	1,410	11,044	733
AUV Ops II	1	14,459	13,630	1,410	12,407	733
Deep Moorings (4000m) & Towed Sonar I	1	16,856	15,907	1,410	14,804	733
Coastal Physical Oceanography	1	17,981	16,976	1,410	15,929	733
AUV Ops I	1	18,357	17,334	1,410	16,305	733
Cyanobacteria: CTDs and Incubations	2	37,297	35,220	2,820	33,193	1,466
Geology: Vibracore & Box Core	1	24,045	22,737	1,410	21,993	733
Total	**34**	**190,541**	**177,410**	**47,940**	**135,075**	**15,413**

8.2.3 Energy Efficiency

Based on the calculations from Table 27 it is possible to sum the total annual energy consumption and compare the efficiencies of the three SRV variants.

Table 28 shows the calculated annual energy use for each variant in units of megajoules per year (MJ/yr). The values were calculated based on a lower heating values for MDO and Hydrogen as noted below.

Table 28 Comparison of Efficiencies between SRV Variants based on annual fuel consumption

Variant	MJ/year[1]	Reduction from Baseline
Diesel Electric SRV (Baseline)	8,383,795	N/A
Battery Hybrid SRV	7,978,640	4.8%
Hydrogen Hybrid SRV	7,794,378	7.0%

Comparing the variants on efficiency, the Battery hybrid is approximately 5% more efficient than the baseline and the Hydrogen Hybrid is approximately 7% more efficient than the baseline

[1] LHV for MDO assumed to be 44MJ/kg. LHV for Hydrogen assumed to be 120.1 MJ/kg. 3.6MJ = 1kWh

based on total annual fuel consumption of both hydrogen, diesel, and shore power. Annual shore power in kWh was converted to MJ for comparison.

8.3 Arrangements

The primary difference in arrangements between the three variants is below the main deck where the Fuel Cells and Batteries are housed. Additionally, the Hydrogen Hybrid SRV has the large LH_2 tank on the 01 level aft deck. Additionally, the LH_2 bunkering station on the main deck reduces the space in the main lab.

8.4 Cost

A side by side cost comparison is provided in Table 29. As noted in the previous sections, the increasing costs of the Battery and Hydrogen Hybrid variants are driven not only from increased equipment and engineering costs, but also from increased contingency costs that have been added to account for the increased risk and uncertainty for the novel designs. The enhanced performance of the Hydrogen Hybrid SRV does indeed come at a higher cost over the battery hybrid, and significantly over the baseline diesel electric.

Table 29 SRV Variant Cost Comparison

SRV Variant	Low Labor Cost	High Labor Cost
Diesel Electric SRV	$20,666,734	$22,227,842
Battery Hybrid SRV	$25,101,522	$26,997,622
H2 Hybrid SRV	$33,126,402	$35,628,679

8.5 Emissions Comparison

Sandia National Labs estimated the greenhouse gas (GHG) and criteria emissions for the three variants. The full results are presented in the Sandia Report in Appendix C. Both 'fossil' diesel and biodiesel are considered. Also, both conventionally made hydrogen (from natural gas) and renewable hydrogen (hydrogen made from renewable energy) are considered.

Summarizing the main results, the best performing hybrid vessel from an emissions reduction is the Hydrogen Hybrid SRV using 100% renewable hydrogen, because of the superior stored energy available with hydrogen fuel as compared to batteries. The annual WTW (well-to-waves) GHG emissions from the Hydrogen Hybrid SRV using renewable LH_2 in combination with fossil diesel fuel yields a 26.7% GHG reduction. By contrast the Battery Hybrid SRV using 100% renewable electricity and fossil diesel reduces GHG by 6.9% compared to the Diesel Electric SRV (see Figure 21).

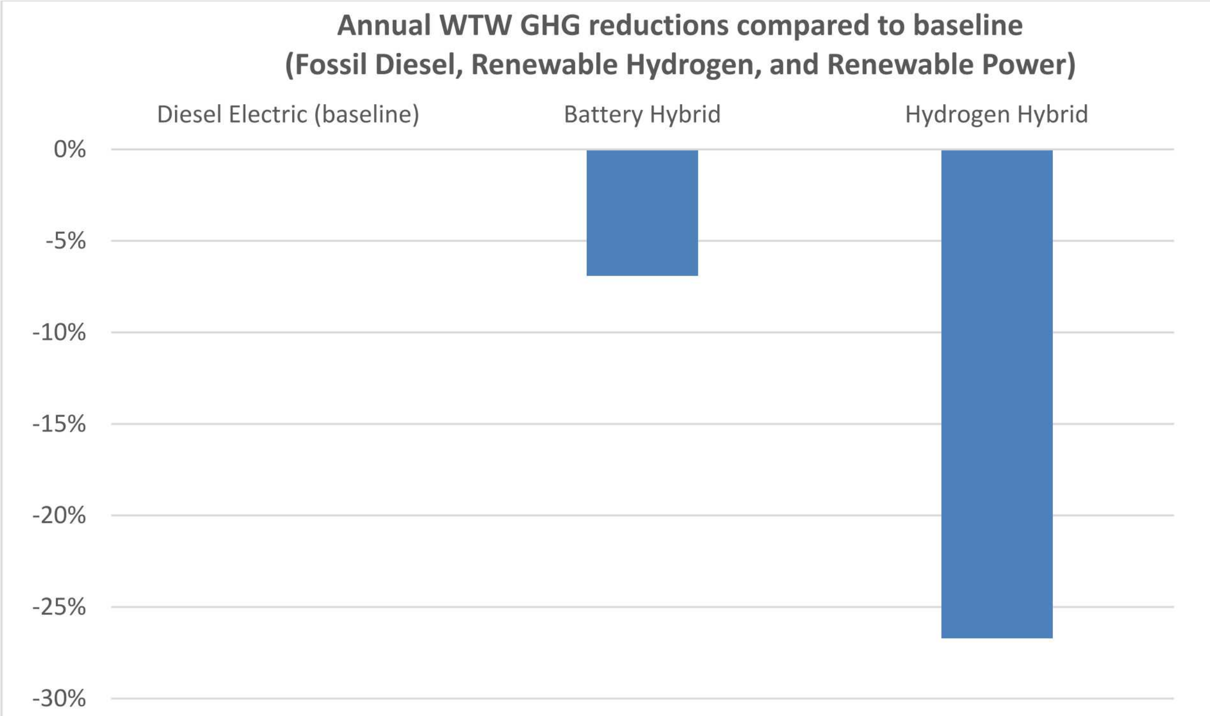


Figure 21 Comparison of GHG Emissions for SRV Variants

For criteria pollutants the Hydrogen Hybrid SRV with renewable hydrogen in combination with fossil diesel fuel will see reductions (compared to the Diesel Electric SRV) of 32.7% in NO_x, 32.4% in HC and 32.6% in PM_{10}. By comparison the Battery Hybrid SRV using fossil diesel and 100% renewable electricity will see reductions (compared to the Diesel Electric SRV) of 5.9% in NO_x, 5.9% in HC and 6.0% in PM_{10} (Figure 22).

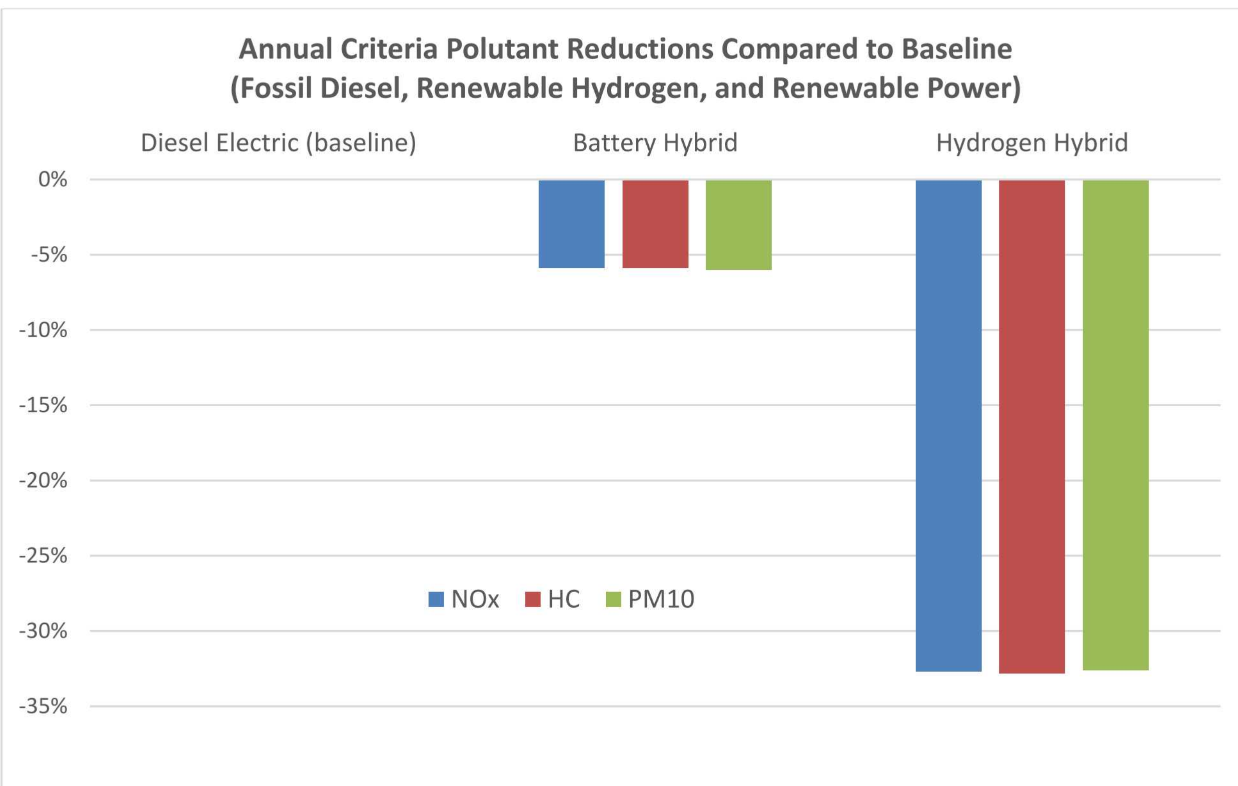


Figure 22 Comparison of Criteria Pollution for SRV Variants

Section 9 Future Work

The vessel design process is often described as a design spiral. The project starts at the outside of the spiral and works around through the vessel requirements, design, and performance. Each trip around the spiral takes the outcomes of the prior cycle and refines them. In this manner the project works inward through the spiral in ever increasing detail and rigor until the final design is achieved.

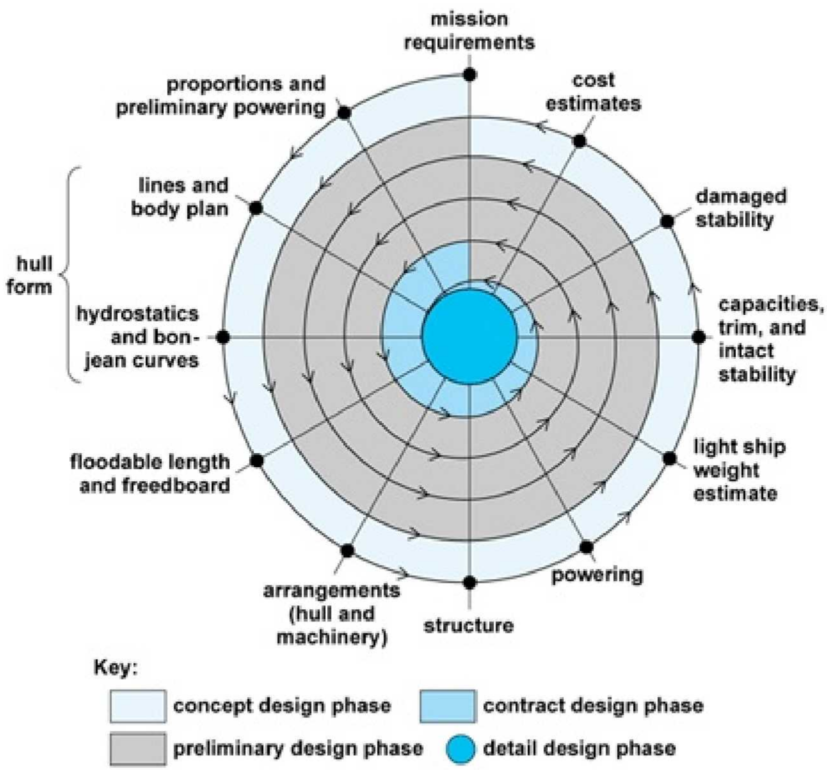


Figure 23 J. Evans visualized the ship design spiral in "Basic Design Concepts," Naval Engineers Journal, 1959

This project represents the first trip around the design spiral, providing a fundamental design basis to evaluate the feasibility of the vessel concept and comparing between potential variants. Significant additional work is required to flesh out and refine the design, especially in the areas peculiar to the gas system for the hydrogen variants and the battery system for the battery variant. This section discusses some next steps required to further develop the design.

9.1 Gas System Development and Risk Assessment for the Hydrogen Hybrid SRV

A key step to moving the project forward is to conduct a gas systems risk assessment. Because the vessel must be developed and reviewed under the regulatory framework of an alternative design, both the US Coast Guard and classification societies will require a comprehensive and detailed risk assessment of gas systems and related fire and safety systems to demonstrate an equivalent level of operability and safety to a conventionally fueled vessel. The first step of this is a comprehensive design of the systems. Following this, a hazard identification (HAZID) workshop involving major project and regulatory stakeholders would need to be held to identify potential risks and hazards. This would likely result in many specific areas requiring further analysis to further asses the level of risk. It is anticipated that at a minimum the following analysis would be required:

- Failure modes and effects analysis (FMEA) of the gas system, fuel cells, propulsion electrical/control systems, gas detection systems, fire detection systems, ventilation systems, fire suppression systems, and emergency shutdown systems.
- Gas dispersion modeling of gas releases from the vent mast and leaks in enclosed spaces (i.e. fuel cell rack, Fuel Cell Room, tank connection space), and in the weather.
- Explosion analysis of the Fuel Cell Room.
- Probabilistic damage assessment of gas system.
- Fire risk assessment especially in way of the storage tanks.

9.2 Hullform and Arrangement

The hull form and basic arrangement was held constant in all variants. Once a specific variant is chosen, the hull form requires iterative development to balance the weights and centers with the buoyancy. The arrangement of the vessel also requires iterative design to tailor to one specific variant.

9.3 Structural Design

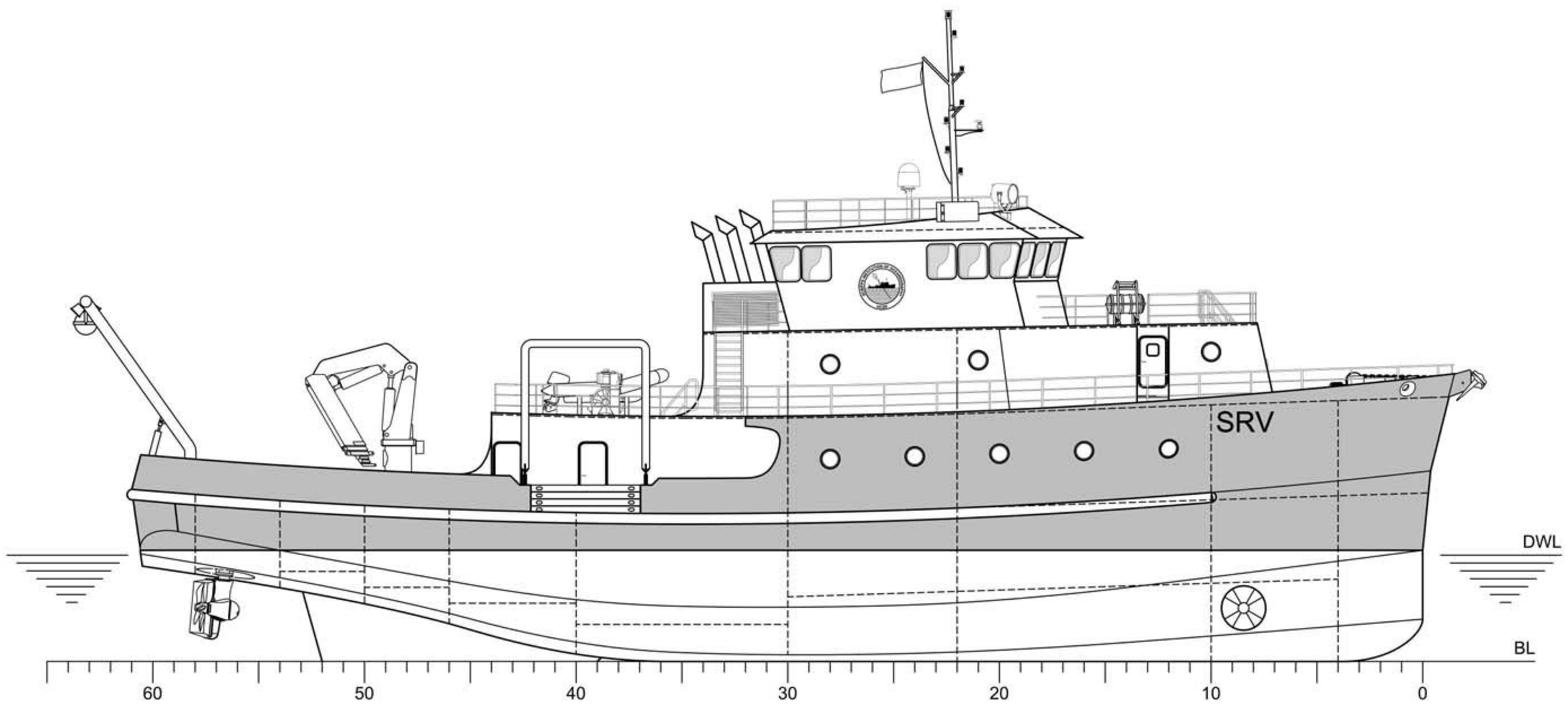
A structural design is required to take the design to the next phase of development. Because the hull structure is a significant driver of both the vessel weight and construction cost, developing a comprehensive hull structural arrangement would greatly improve accuracy of both estimates.

9.4 Vessel Systems Design and Energy Optimization

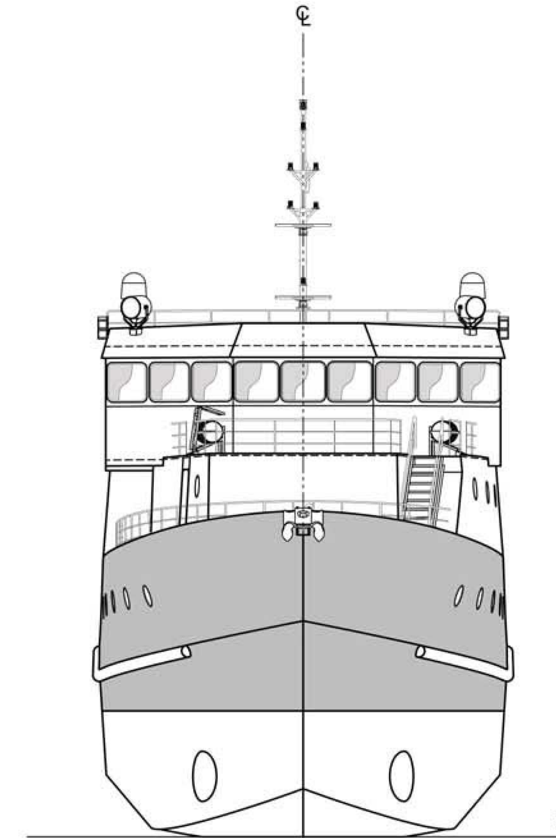
This feasibility study only examined vessel systems that are directly affected by or unique to the use of hydrogen fuel, fuel cells, and batteries. Additionally, these systems were only examined at a high level to assess feasibility, not to develop the full system details. To take the vessel design forward, all vessel systems would require a preliminary level of design to develop the system requirements and sizing. Additionally, optimizing the energy efficiency to minimize the vessel's ship service electrical loads will be very important. Through a rigorous focus on reducing electrical energy use, it may be possible to significantly improve range or reduce required fuel storage tank or battery size.

Appendix A Drawings

- Baseline
    - General Arrangement
    - Electrical One-Line Diagram
- Hydrogen Hybrid
    - General Arrangement
    - Electrical One-Line Diagram
    - Concept Gas System
- Battery Hybrid
    - General Arrangement
    - Electrical One-Line Diagram



ELEVATION 1-6B
OUTBOARD PROFILE
1/16"=1'-0"



SECTION 1-3B
BOW
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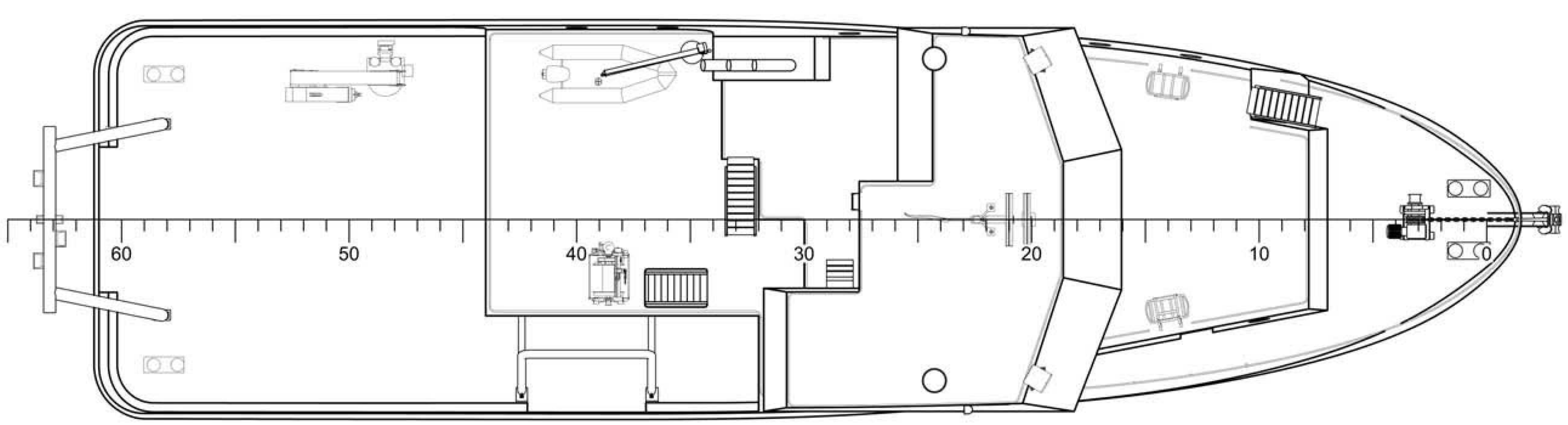
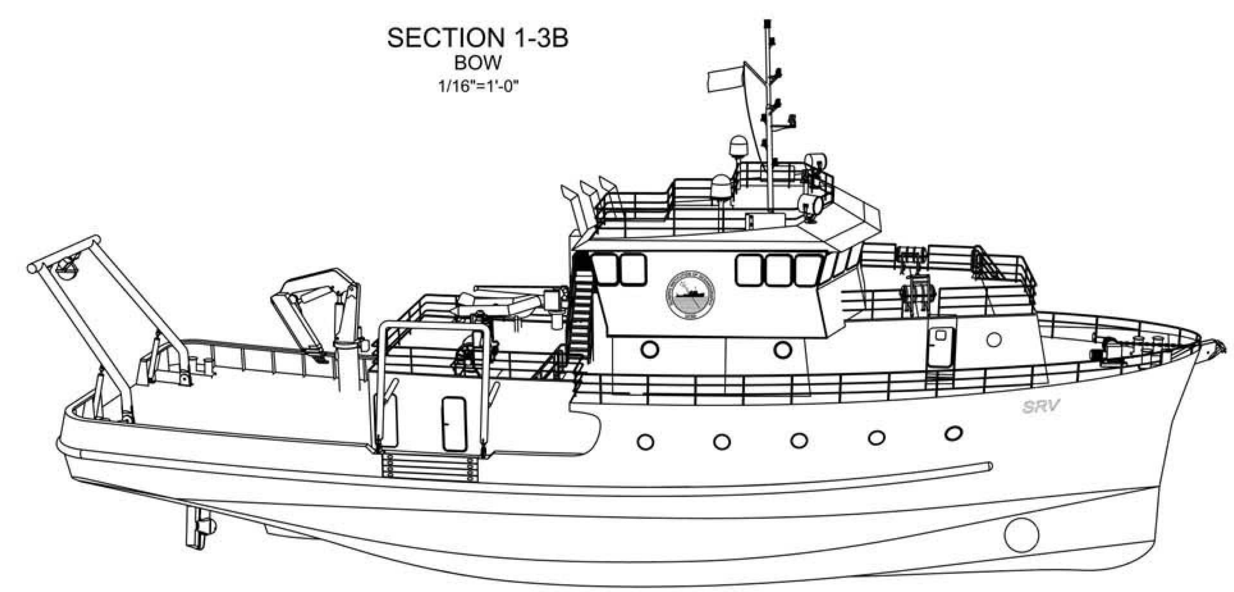


PLAN 1-6A
WEATHER DECKS
1/16"=1'-0"



NTS

GENERAL NOTES

REFERENCES

REVISIONS				
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SPROUL REPLACEMENT VESSEL
BASELINE GENERAL ARRANGEMENT
01 OUTBOARD PROFILE TOP & END VIEWS

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SB	SAC	TSL	05/20/2020

Scale	Drawing Number	Sheet	of	Revision
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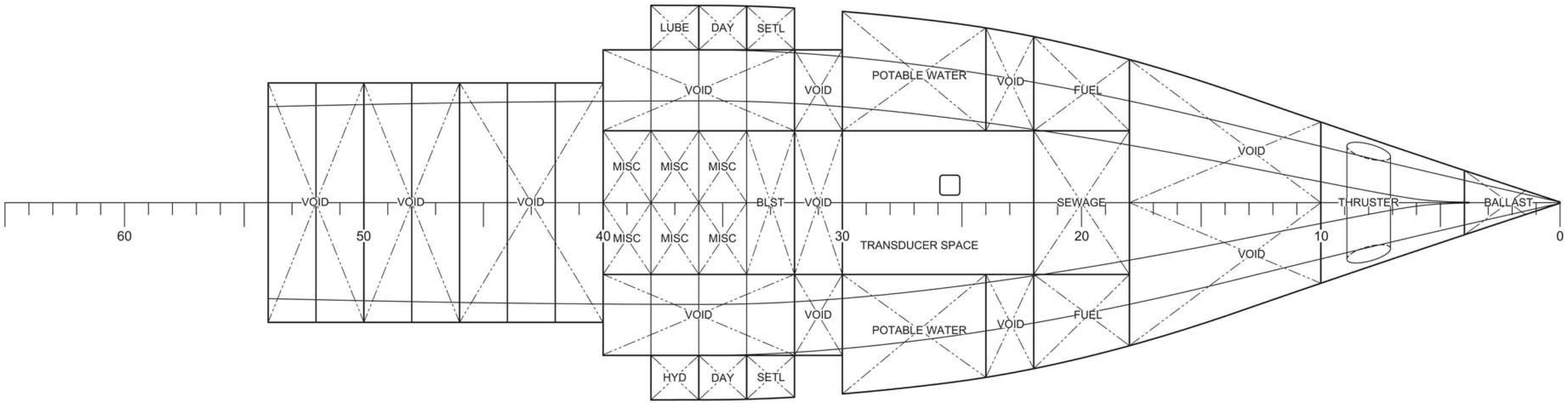
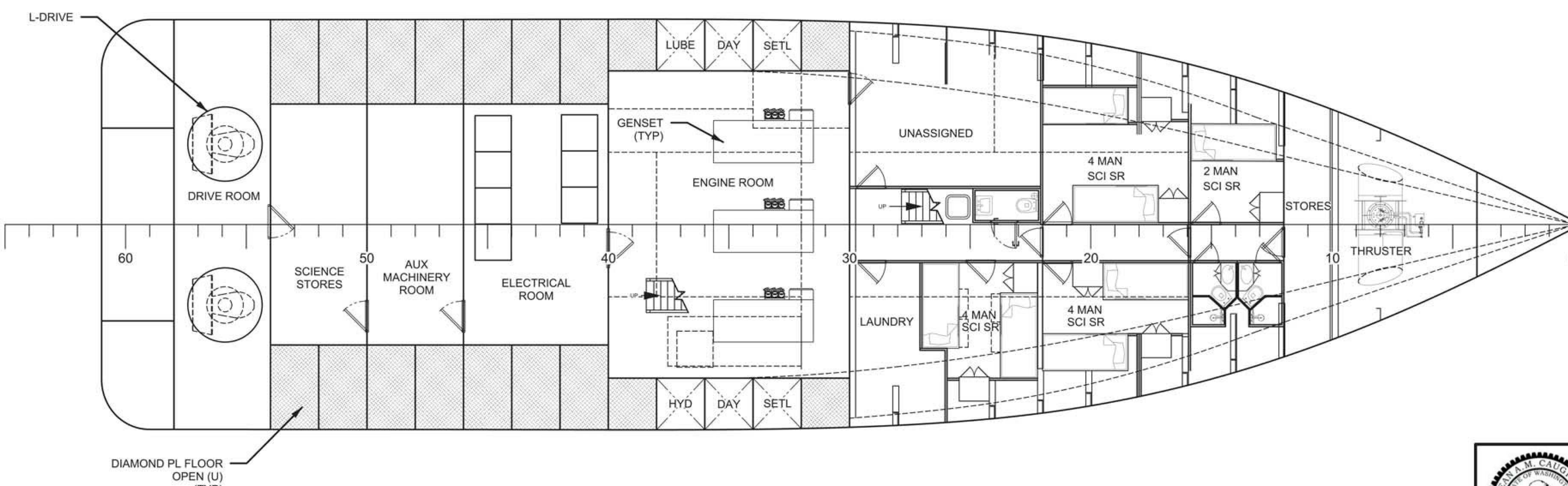


PLAN 2-5C
TANK PLAN
3/32"=1'-0"



PLAN 2-5A
1ST PLATFORM
3/32"=1'-0"

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BASELINE GENERAL ARRANGEMENT
02 LOWER DECKS

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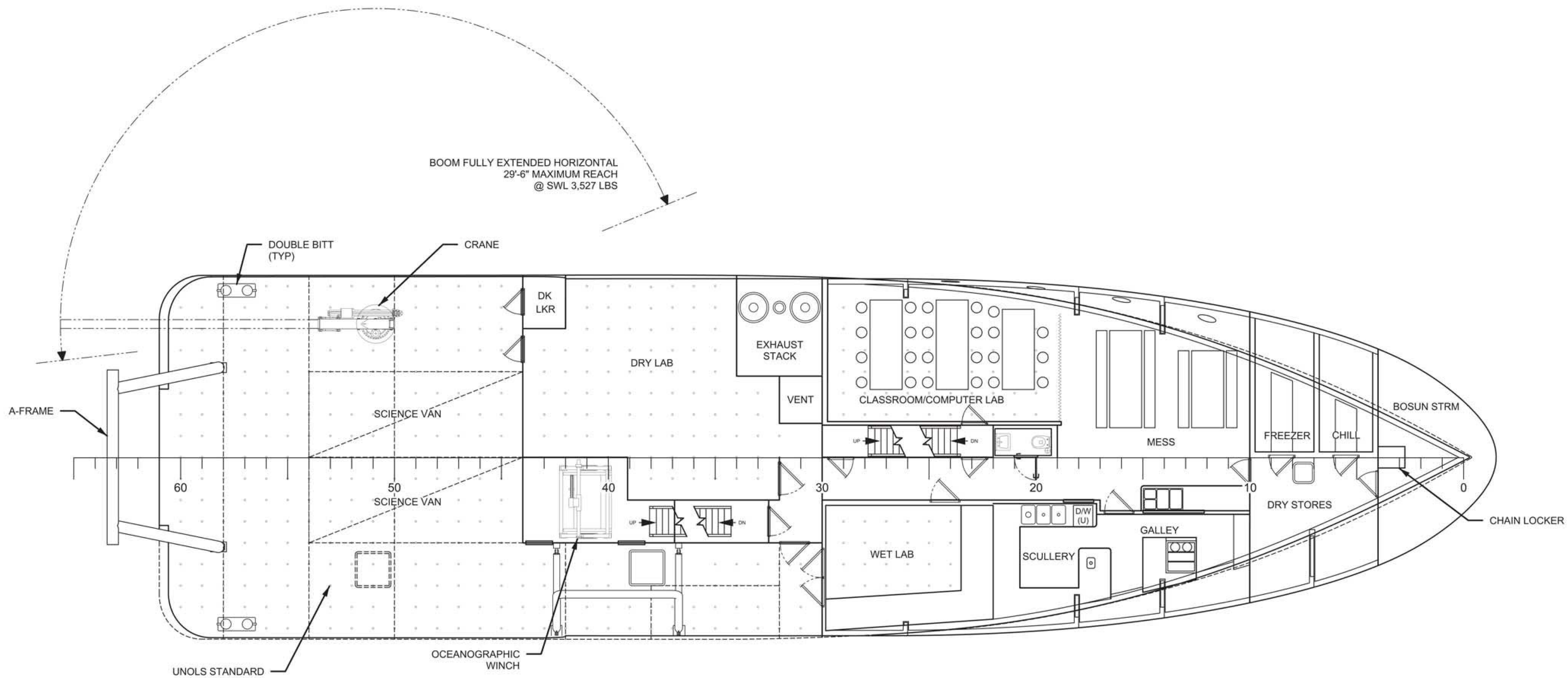

PLAN 3-5B
MAIN DECK
3/32"=1'-0"

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03 MAIN DECK

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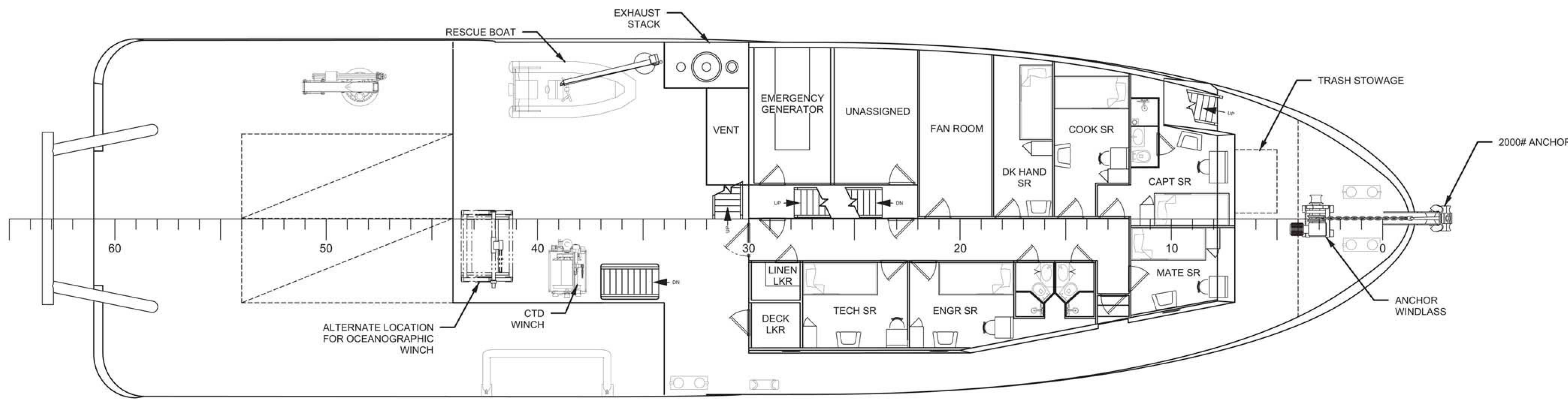

PLAN 4-5B
FOCSLE DECK
3/32"=1'-0"

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BASELINE GENERAL ARRANGEMENT
04 FOCSLE DECK

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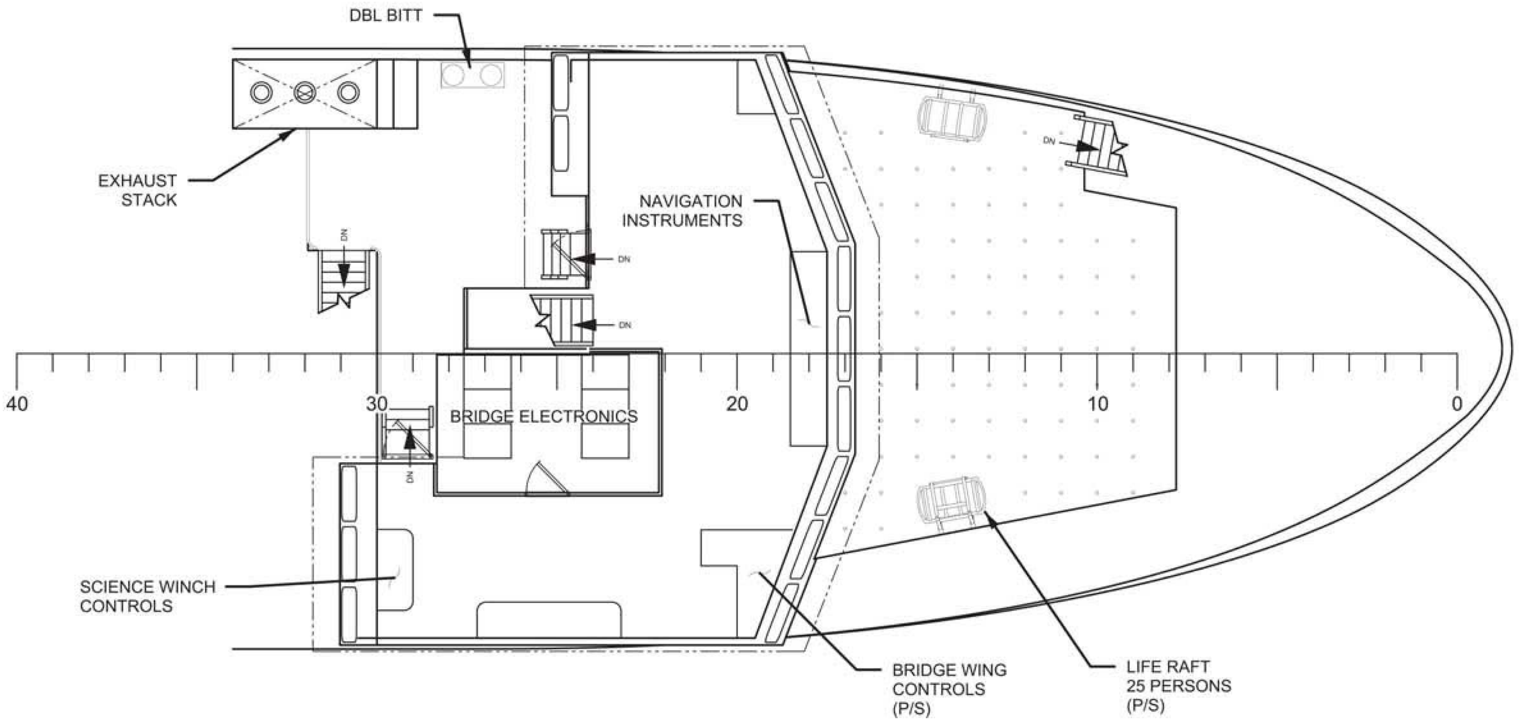
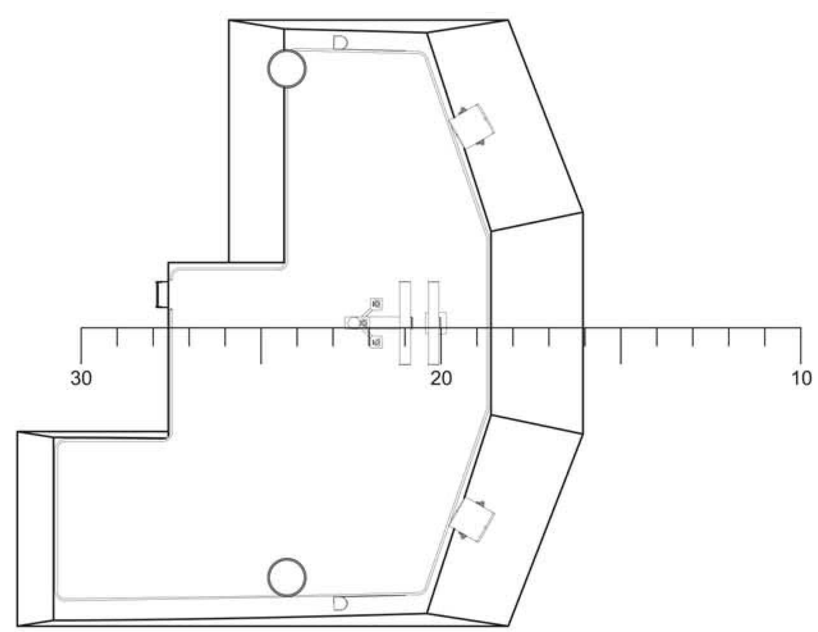


PLAN 5-5C
BRIDGE DECK
3/32"=1'-0"



PLAN 5-5A
BRIDGE HOUSE TOP
3/32"=1'-0"

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SPROUL REPLACEMENT VESSEL BASELINE GENERAL ARRANGEMENT 05 BRIDGE DECK AND HOUSE TOP				
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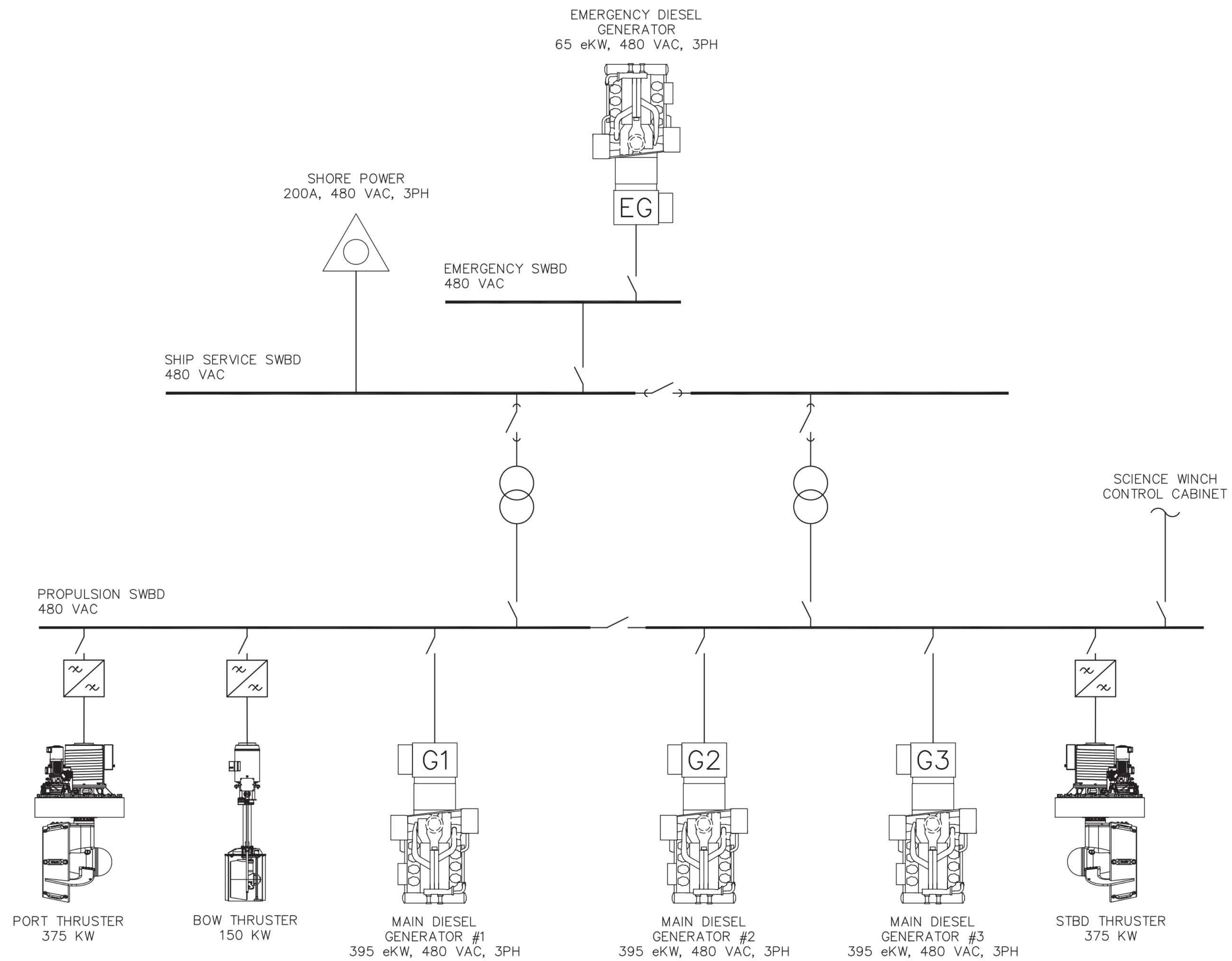

DIAGRAM 1–5A
CONCEPT SYSTEM
ARCHITECTURE

GENERAL NOTES

1. THIS DRAWING IS A BASELINE ELECTRICAL ONE–LINE DRAWING TO FACILITATE A FUNDAMENTAL ELECTRICAL SYSTEM ARCHITECTURE COMPARISON BETWEEN SEVERAL ELECTRICAL PLANT OPTIONS. THIS DRAWING IS NOT MEANT TO REPRESENT A COMPLETE ELECTRICAL SYSTEM WHICH WOULD BE A REQUIRED ON A VESSEL.
2. ALL EQUIPMENT AND DESIGNS SHALL COMPLY WITH, BUT NOT BE LIMITED TO, THE REQUIREMENTS OF THE US COAST GUARD (USCG), DNVGL, AND THE RECOMMENDATIONS OF THE INSTITUTE OF ELECTRICAL AND ELECTRONIC ENGINEERS (IEEE) STANDARD 45.

REFERENCES

1. GLOSTEN, DRAWING 19112.01–070–01, BASELINE GENERAL ARRANGEMENT

REVISIONS

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	–	INITIAL RELEASE	06/19/20	TSL

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SPROUL REPLACEMENT VESSEL
BASELINE ELECTRICAL ONE–LINE DIAGRAM
CONCEPT SYSTEM ARCHITECTURE

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Scale	Drawing Number	Sheet	of	Revision
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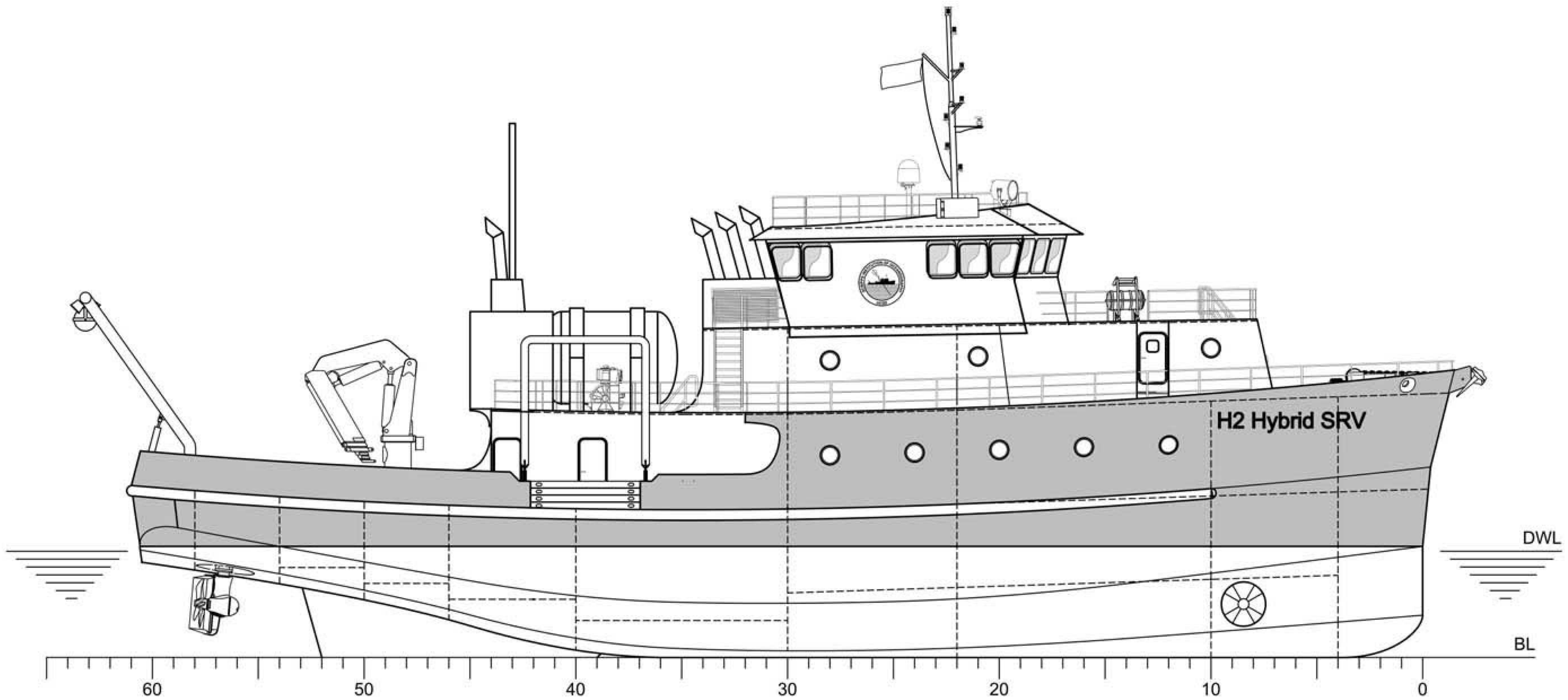
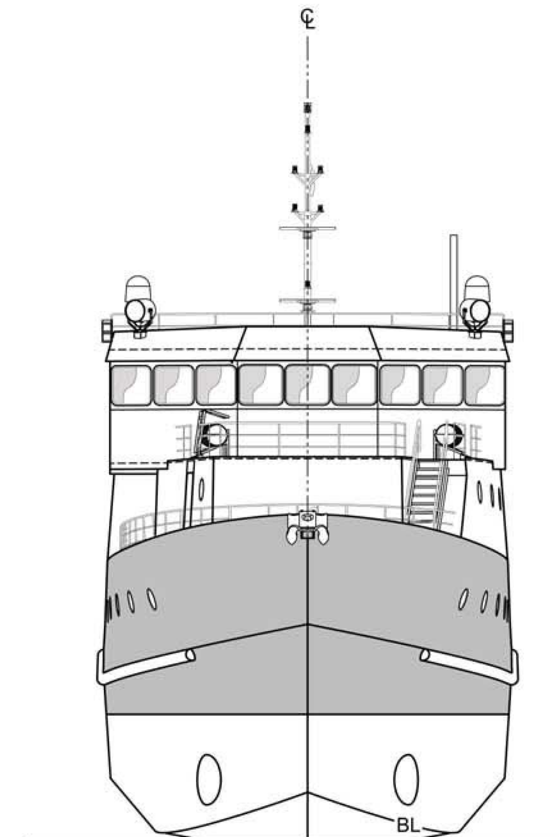
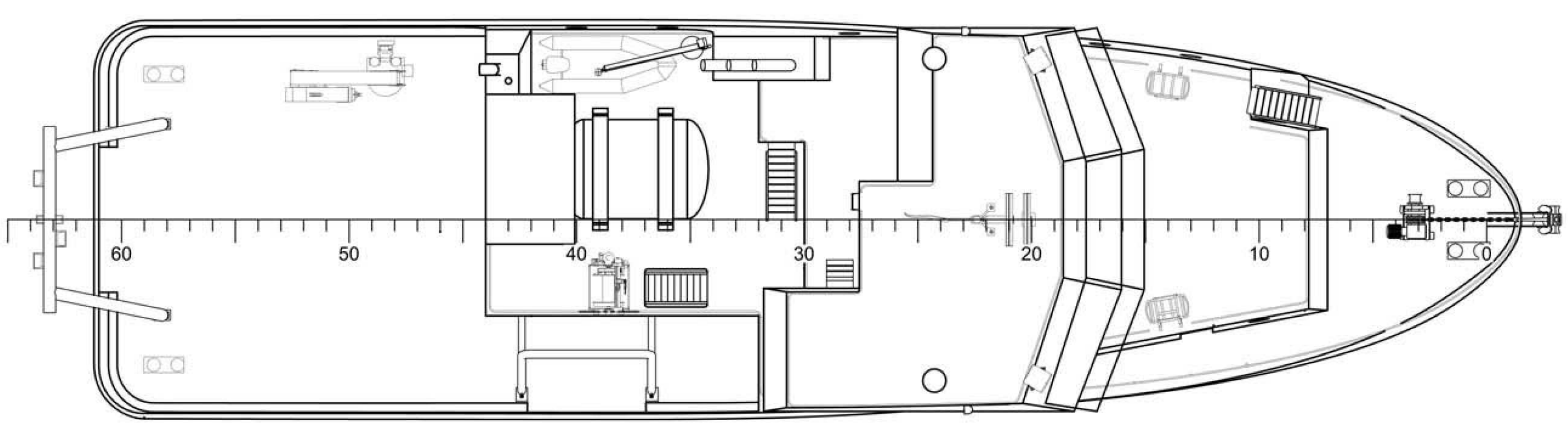


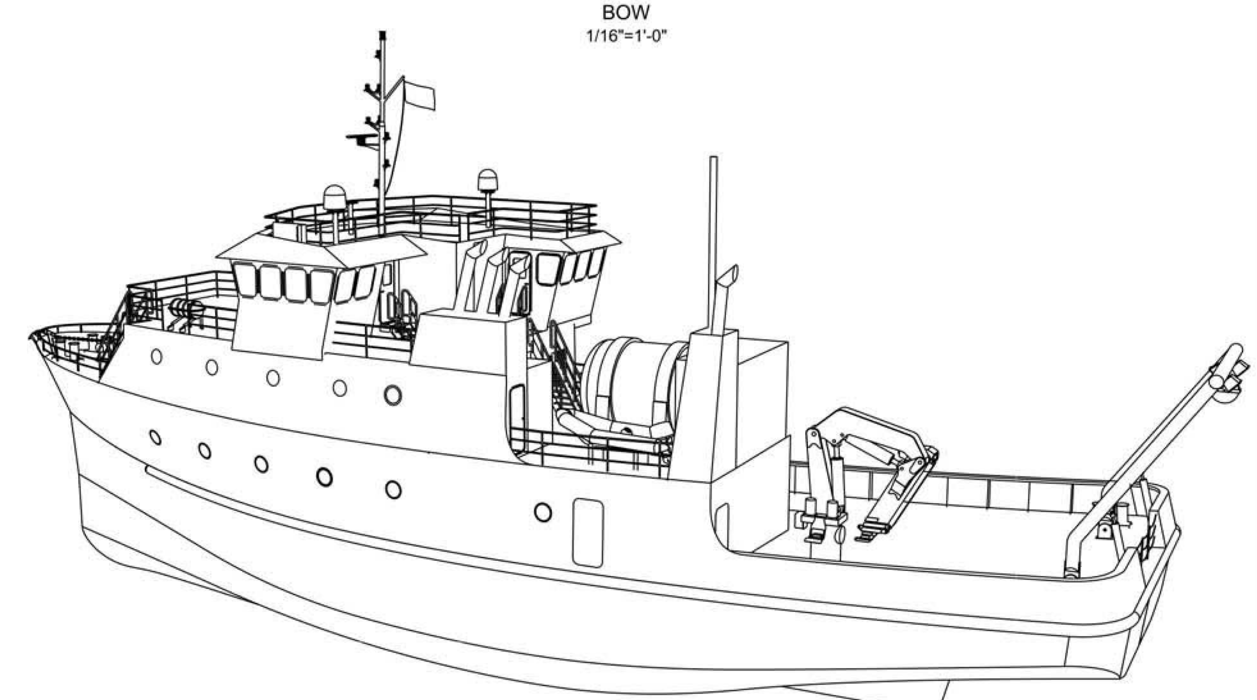
ELEVATION 1-6B
OUTBOARD PROFILE
1/16"=1'-0"



SECTION 1-3B
BOW
1/16"=1'-0"



PLAN 1-6A
WEATHER DECKS
1/16"=1'-0"



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GENERAL NOTES	REFERENCES

REVISIONS

ZONE	REV	DESCRIPTION	DATE	APPD

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HYDROGEN HYBRID GENERAL ARRANGEMENT
01 OUTBOARD PROFILE TOP & END VIEWS

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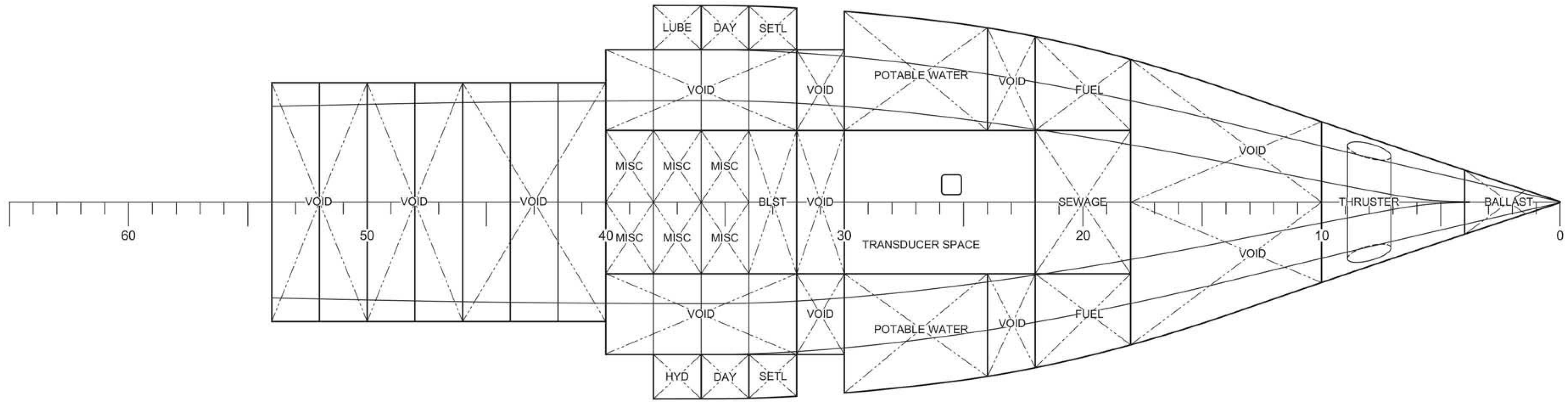
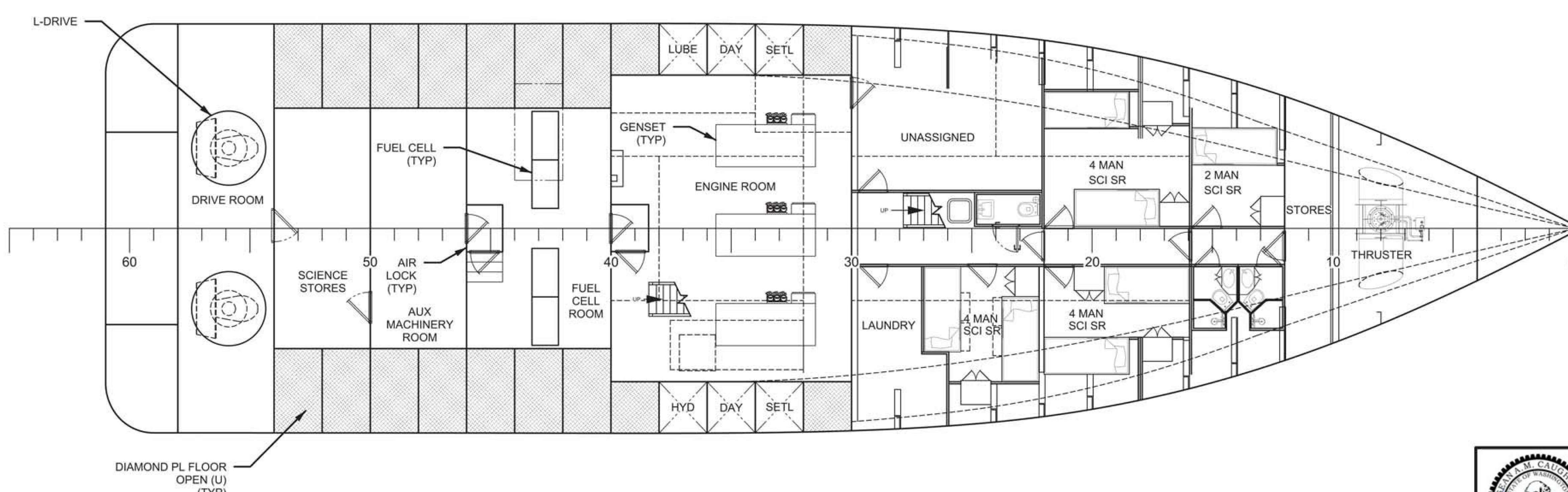


PLAN 2-5C
TANK PLAN
3/32"=1'-0"



PLAN 2-5A
1ST PLATFORM
3/32"=1'-0"

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HYDROGEN HYBRID GENERAL ARRANGEMENT
02 LOWER DECKS

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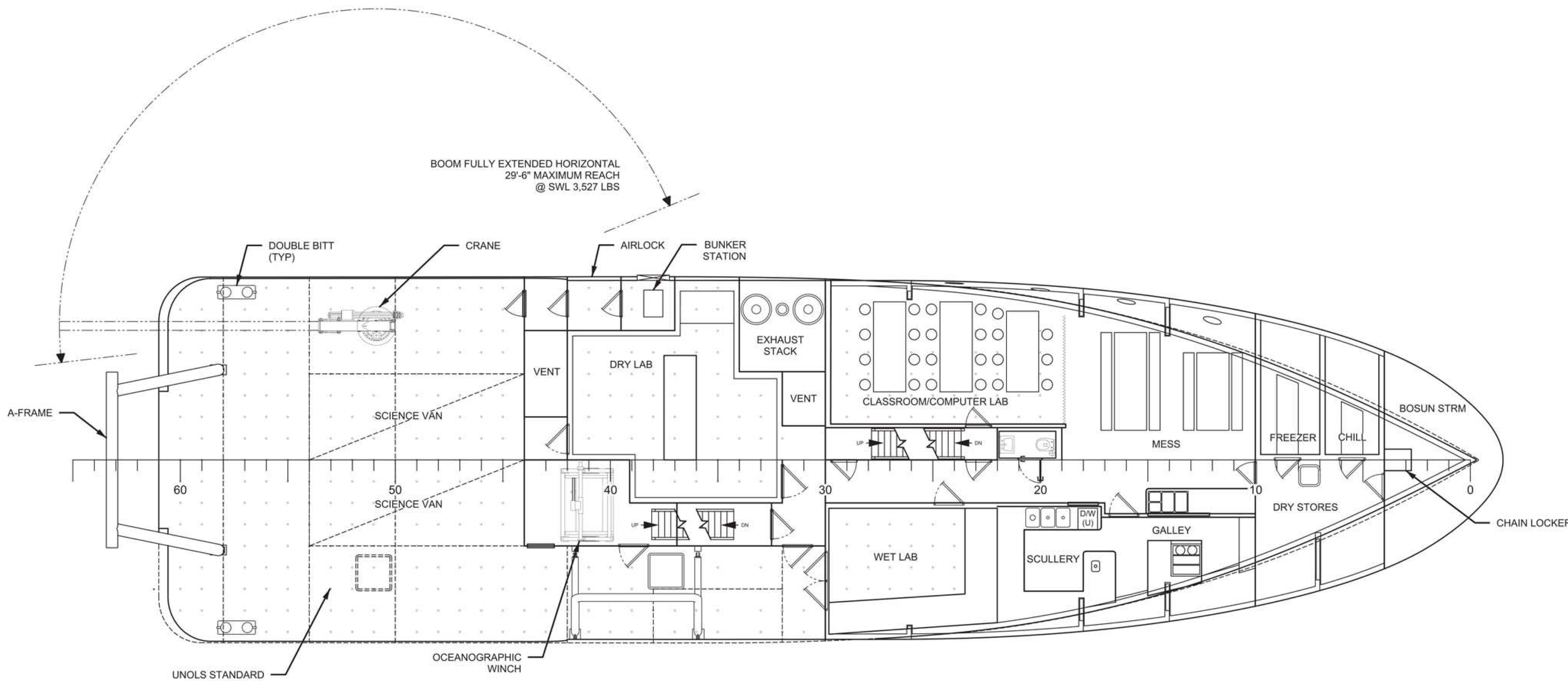

PLAN 3-5B
MAIN DECK
3/32"=1'-0"

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HYDROGEN HYBRID GENERAL ARRANGEMENT
03 MAIN DECK

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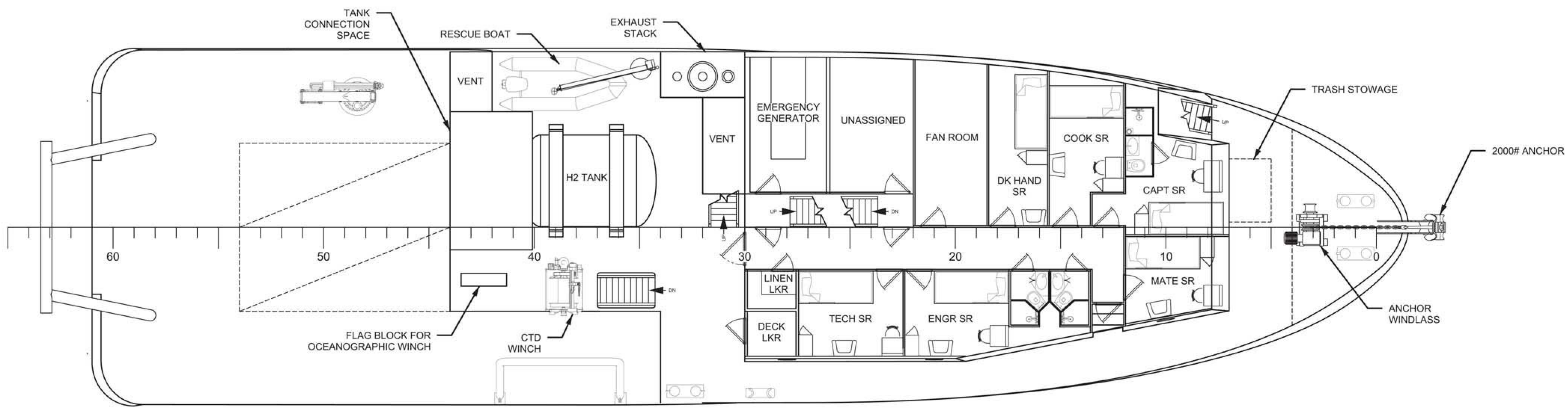

PLAN 4-5B
FOCSLE DECK
3/32"=1'-0"

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SPROUL REPLACEMENT VESSEL
HYDROGEN HYBRID GENERAL ARRANGEMENT
04 FOCSLE DECK

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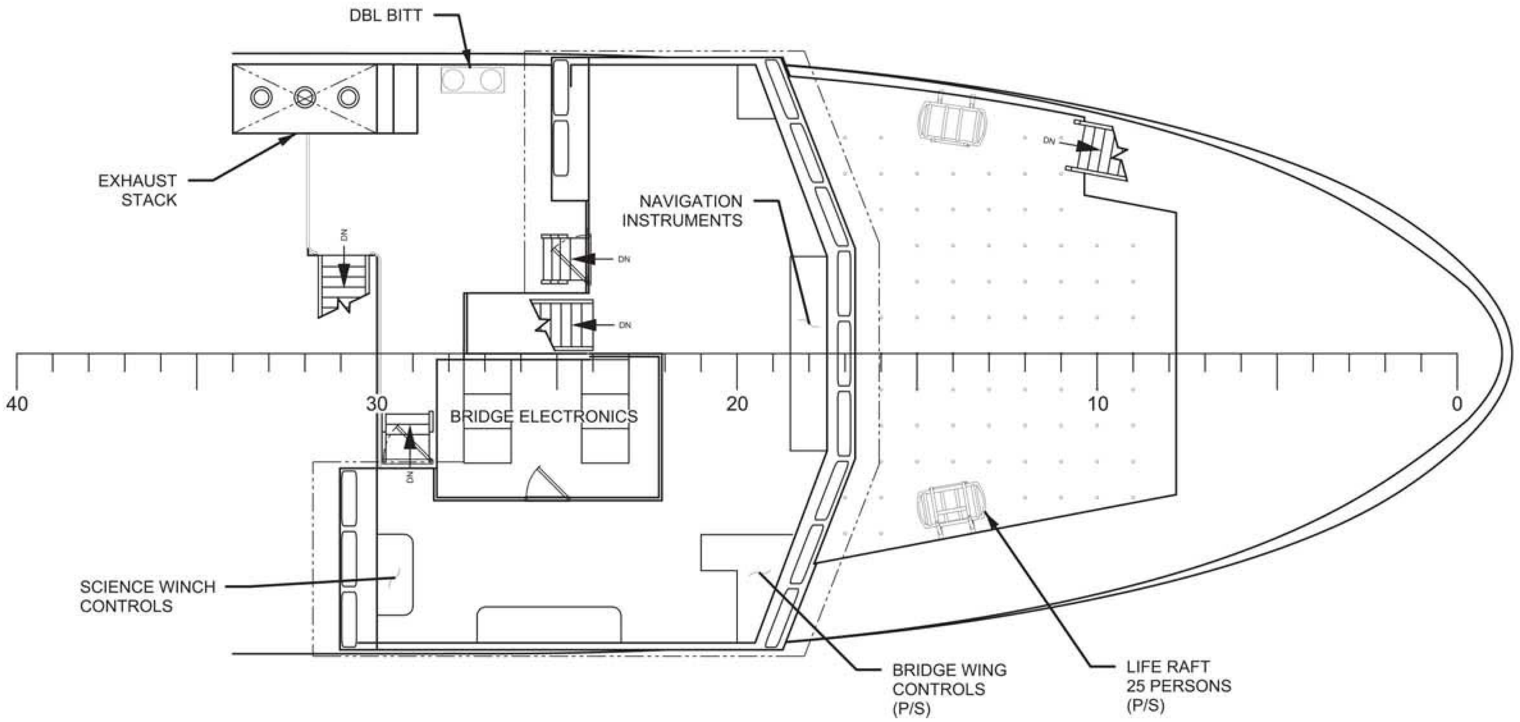
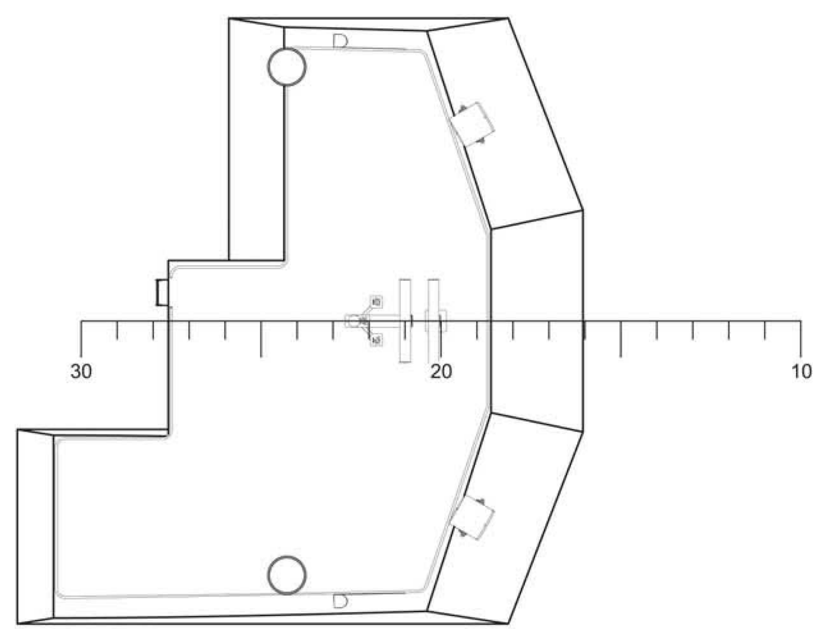


PLAN 5-5C
BRIDGE DECK
3/32"=1'-0"



PLAN 5-5A
BRIDGE HOUSE TOP
3/32"=1'-0"

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SPROUL REPLACEMENT VESSEL
HYDROGEN HYBRID GENERAL ARRANGEMENT
05 BRIDGE DECK AND HOUSE TOP

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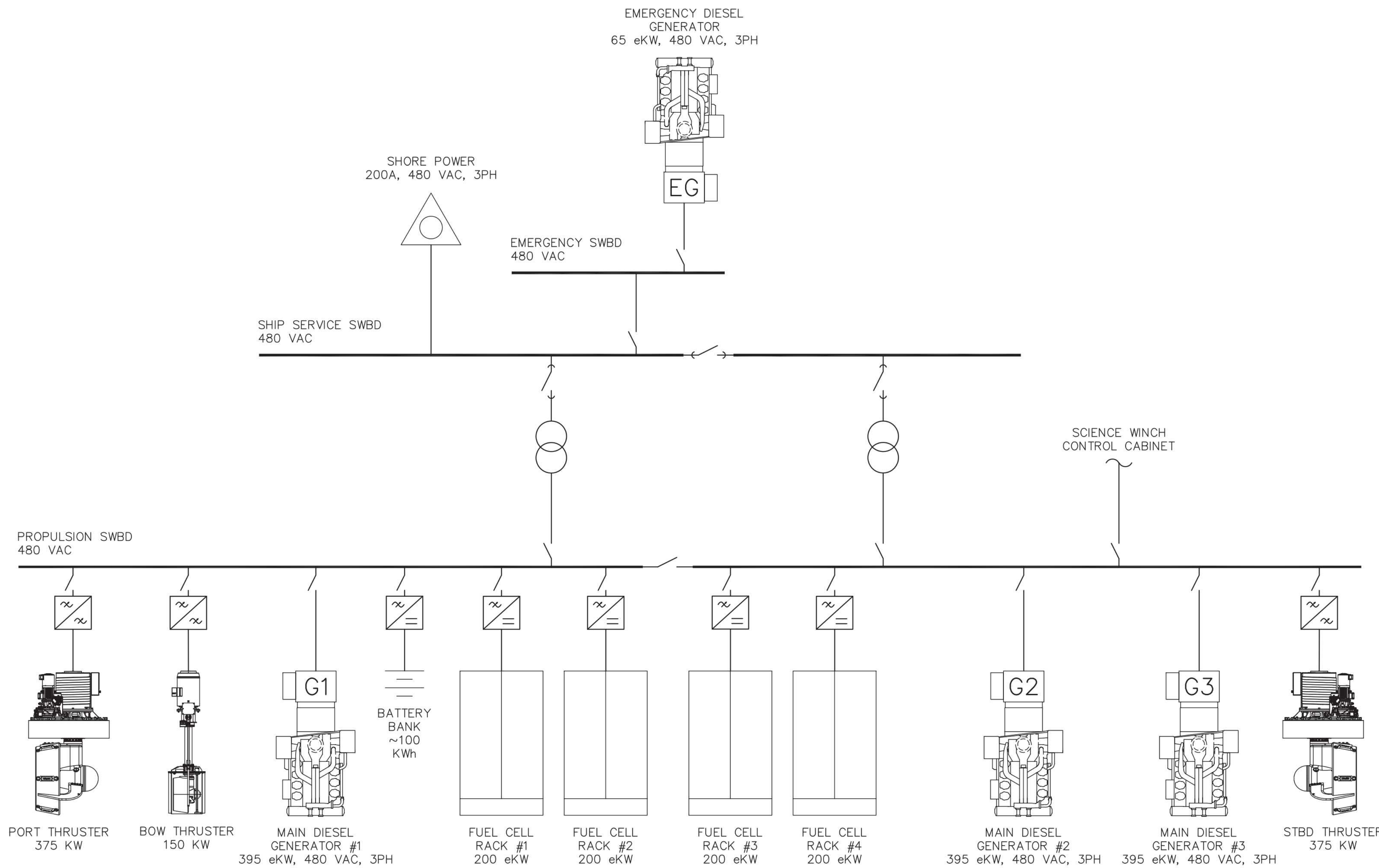

DIAGRAM 1–5A

CONCEPT SYSTEM ARCHITECTURE

GENERAL NOTES

1. THIS DRAWING IS A PRELIMINARY ELECTRICAL ONE–LINE DRAWING TO FACILITATE A FUNDAMENTAL ELECTRICAL SYSTEM ARCHITECTURE COMPARISON BETWEEN SEVERAL ELECTRICAL PLANT OPTIONS. THIS DRAWING IS NOT MEANT TO REPRESENT A COMPLETE ELECTRICAL SYSTEM WHICH WOULD BE A REQUIRED ON A VESSEL.
2. MARINE HYDROGEN FUEL CELL INSTALLATIONS ARE AN EMERGING TECHNOLOGY AND CURRENTLY THERE IS NO APPLICABLE REGULATORY REVIEW PROCESS IN PLACE IN THE UNITED STATES. THIS DRAWING IS TO TO FACILITATE A REGULATORY FEASIBILITY DISCUSSION OF THE FUNDAMENTAL ELECTRICAL SYSTEM ARCHITECTURE.
3. ALL EQUIPMENT AND DESIGNS SHALL COMPLY WITH, BUT NOT BE LIMITED TO, THE REQUIREMENTS OF THE US COAST GUARD (USCG), DNVGL, AND THE RECOMMENDATIONS OF THE INSTITUTE OF ELECTRICAL AND ELECTRONIC ENGINEERS (IEEE) STANDARD 45.
4. ELECTRICAL EQUIPMENT AND INSTALLATIONS WITHIN THE HAZARDOUS ZONES SHALL BE INTRINSICALLY SAFE, EXPLOSION–PROOF, FLAMEPROOF OR ANOTHER ACCEPTED PROTECTION METHOD IN ACCORDANCE WITH APPLICABLE USCG AND DNV–GL REQUIREMENTS PARTICULAR TO EACH ZONE'S HAZARD DESIGNATION.
5. FUEL CELL ROOMS ARE PROTECTED BY EMERGENCY SHUTDOWN SYSTEMS (ESD). THEY ARE CONSIDERED NON–HAZARDOUS UNDER NORMAL CONDITIONS. ANY NON ESSENTIAL ELECTRICAL EQUIPMENT AND LIGHTING SHALL IN THE SPACE OR WITHIN THE HAZARDOUS AREAS ASSOCIATED WITH THE SPACE SHALL BE DE–ENERGIZED UPON DETECTION OF A GAS LEAK. ANY ESSENTIAL EQUIPMENT AND LIGHTING REQUIRED TO OPERATE FOLLOWING DETECTION OF GAS LEAKAGE SHALL BE SUITABLE FOR USE IN ZONE 1.

REFERENCES

1. GLOSTEN, DRAWING 19112.01–300–01, BASELINE ELECTRICAL ONE–LINE DIAGRAM
2. GLOSTEN, DRAWING 19112.01–070–02, HYDROGEN HYBRID GENERAL ARRANGEMENT

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SPROUL REPLACEMENT VESSEL
HYDROGEN HYBRID ELECTRICAL ONE–LINE DIAGRAM
CONCEPT SYSTEM ARCHITECTURE

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PIPING SYMBOL LIST

SYMBOL	DESCRIPTION	SYMBOL	DESCRIPTION
→	DIRECTION OF FLOW ARROW	PT	PRESSURE TRANSMITTER
— GS —	PIPE – GAS SUPPLY	P	PRESSURE GAUGE
— SW —	PIPE – SEAWATER	AF	AXIAL FAN
— LB —	PIPE – LIQUID BUNKERING		GAS DETECTOR
— NS —	PIPE – NITROGEN SUPPLY		AIR INLET / OUTLET
— VD —	DUCT – VENTILATION DUCT		VALVE, SOLENOID OPERATED
— GV —	PIPE – GAS VENT	M	VALVE, MOTOR OPERATED
	VALVE, GLOBE	NC	VALVE, NORMALLY CLOSED
			SPRAY NOZZLE
	VALVE, ANGLE, PRESSURE RELIEF (SELF ACTUATED)		
	VALVE, MANUAL OVERRIDE		

ACRONYM LIST

GSU – GAS SUPPLY UNIT
PBU – PRESSURE BUILD UNIT
LH2 – LIQUEFIED HYDROGEN GAS
ACH – AIR CHANGES PER HOUR

GENERAL NOTES

1. MARINE HYDROGEN FUEL CELL INSTALLATIONS ARE AN EMERGING TECHNOLOGY AND CURRENTLY THERE IS NO APPLICABLE REGULATORY REVIEW PROCESS IN PLACE IN THE UNITED STATES. THIS DRAWING IS TO BE USED ONLY TO FACILITATE A REGULATORY FEASIBILITY DISCUSSION OF THE FUNDAMENTAL GAS SYSTEMS ARCHITECTURE FOR THE SUBJECT VESSEL. THIS DRAWING IS NOT TO BE USED FOR THE DESIGN, CONSTRUCTION, MAINTENANCE OR OPERATION OF ANY MARINE, INDUSTRIAL OR OTHER GAS SYSTEM OR RELATED VENTILATION, GAS DETECTION OR SAFETY SYSTEMS.
2. PIPING SYSTEM DESIGN, MATERIAL, INSTALLATION, TESTING AND WORKMANSHIP WILL BE IN ACCORDANCE WITH REGULATORY BODY REQUIREMENTS OF U.S. COAST GUARD AND DNVGL
3. BULKHEAD AND DECK PIPING PENETRATIONS SHALL MAINTAIN THE WATERTIGHT, FUMETIGHT AND FIRE RATING OF THE BOUNDARY PER REGULATORY BODY REQUIREMENTS.
4. GAS SUPPLY, BUNKERING, AND PRESSURE RELIEF/VENT LINES SHALL BE CONTAINED IN A GAS TIGHT VENTILATED DUCT WHEN RUN THROUGH ENCLOSED SPACES.
5. LIQUID BUNKERING LINES SHALL BE DOUBLE–WALLED VACUUM INSULATED.
6. VENTILATION DUCTING SHALL BE A36 STEEL WELDED GAS TIGHT ALONG THE ENTIRE LENGTH.
7. ALL LIQUEFIED HYDROGEN PIPING SHALL BE SUFFICIENTLY INSULATED WHERE LOCATED WITHIN REACH OF PERSONNEL.
8. ALL PIPING CONTAINED IN TANK ROOMS SHALL BE CRYOGENIC COMPATIBLE.
9. ELECTRIC FAN MOTORS SHALL NOT BE LOCATED IN VENTILATION DUCTS FOR HAZARDOUS SPACES. FANS SHALL BE NON–SPARKING WITH EXPLOSION PROOF MOTORS SUITABLE FOR USE IN A HYDROGEN GAS ATMOSPHERE.
10. THE NUMBER AND POWER OF THE VENTILATION FANS SHALL BE SUCH THAT THE CAPACITY IS NOT REDUCED BY MORE THAN 50%, IF A FAN WITH A SEPARATE CIRCUIT FROM THE MAIN SWITCHBOARD OR EMERGENCY SWITCHBOARD OR A GROUP OF FANS WITH COMMON CIRCUIT FROM THE MAIN SWITCHBOARD OR EMERGENCY SWITCHBOARD, IS OUT OF SERVICE.
11. ALL TANKS, PIPING, GASKETED PIPE JOINTS, AND HOSE CONNECTIONS SHALL BE ELECTRONICALLY BONDED TO THE SHIP'S STRUCTURE.

REFERENCES

1. GLOSTEN, DRAWING 19112.01–070–02, HYDROGEN HYBRID GENERAL ARRANGEMENT
2. DNV RULES FOR CLASSIFICATION OF SHIPS PART 6 CHAPTER 2 SECTION 3 "FUEL CELL INSTALLATIONS"
3. DNV RULES FOR CLASSIFICATION OF SHIPS PART 6 CHAPTER 2 Section 5 "GAS FUELED SHIP INSTALLATIONS"
4. IMO INTERNATIONAL CODE OF SAFETY FOR SHIPS USING GASES OR OTHER LOW–FLASHPOINT FUELS (IGF CODE), 2017

REVISIONS

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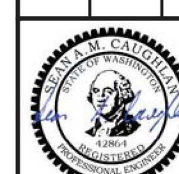

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SPROUL REPLACEMENT VESSEL
CONCEPT GAS SYSTEM ARCHITECTURE SKETCH
REFERENCES NOTES AND SYMBOLS

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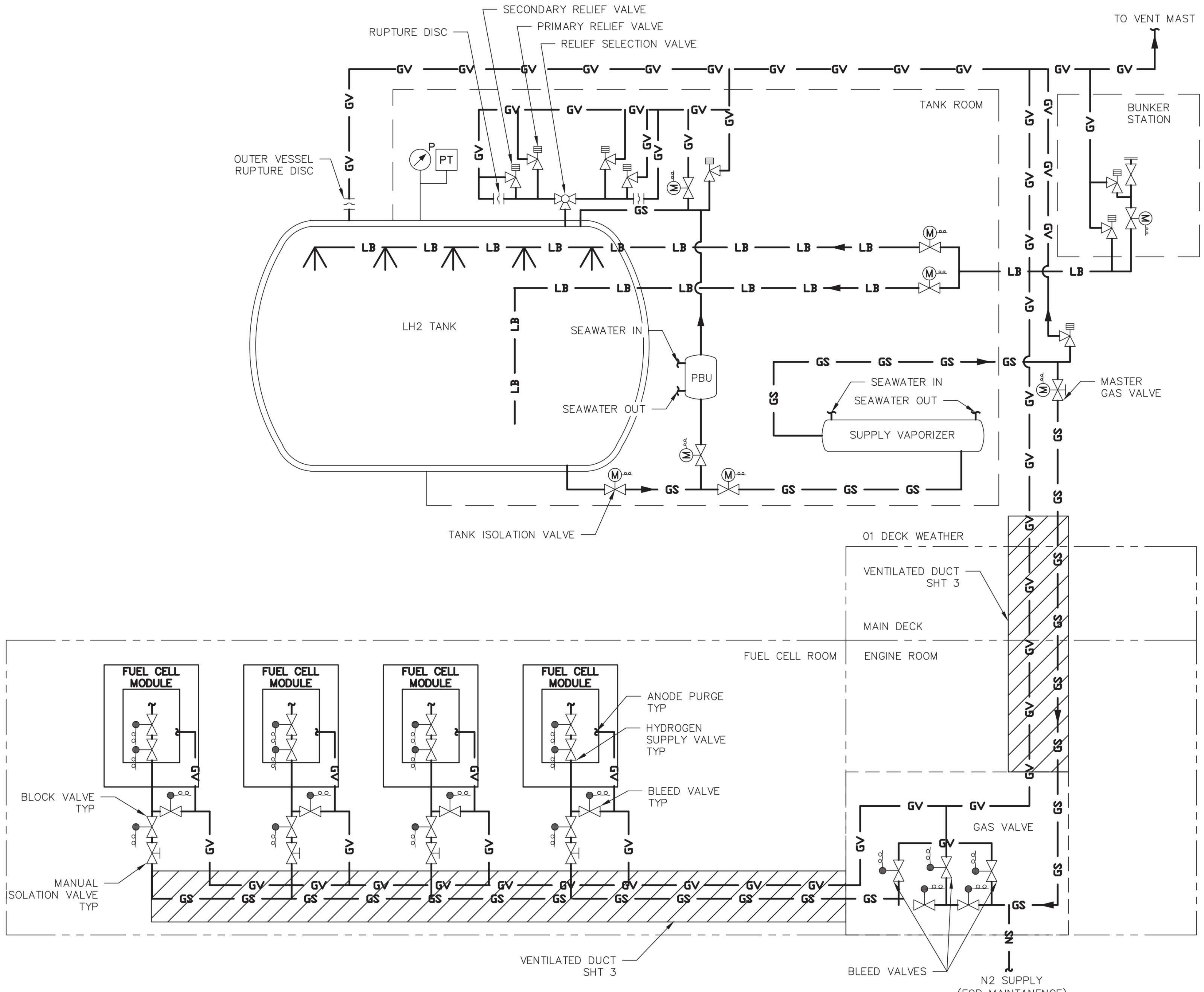

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SPROUL REPLACEMENT VESSEL
CONCEPT GAS SYSTEM ARCHITECTURE SKETCH
CONCEPT GASEOUS FUEL SYSTEM

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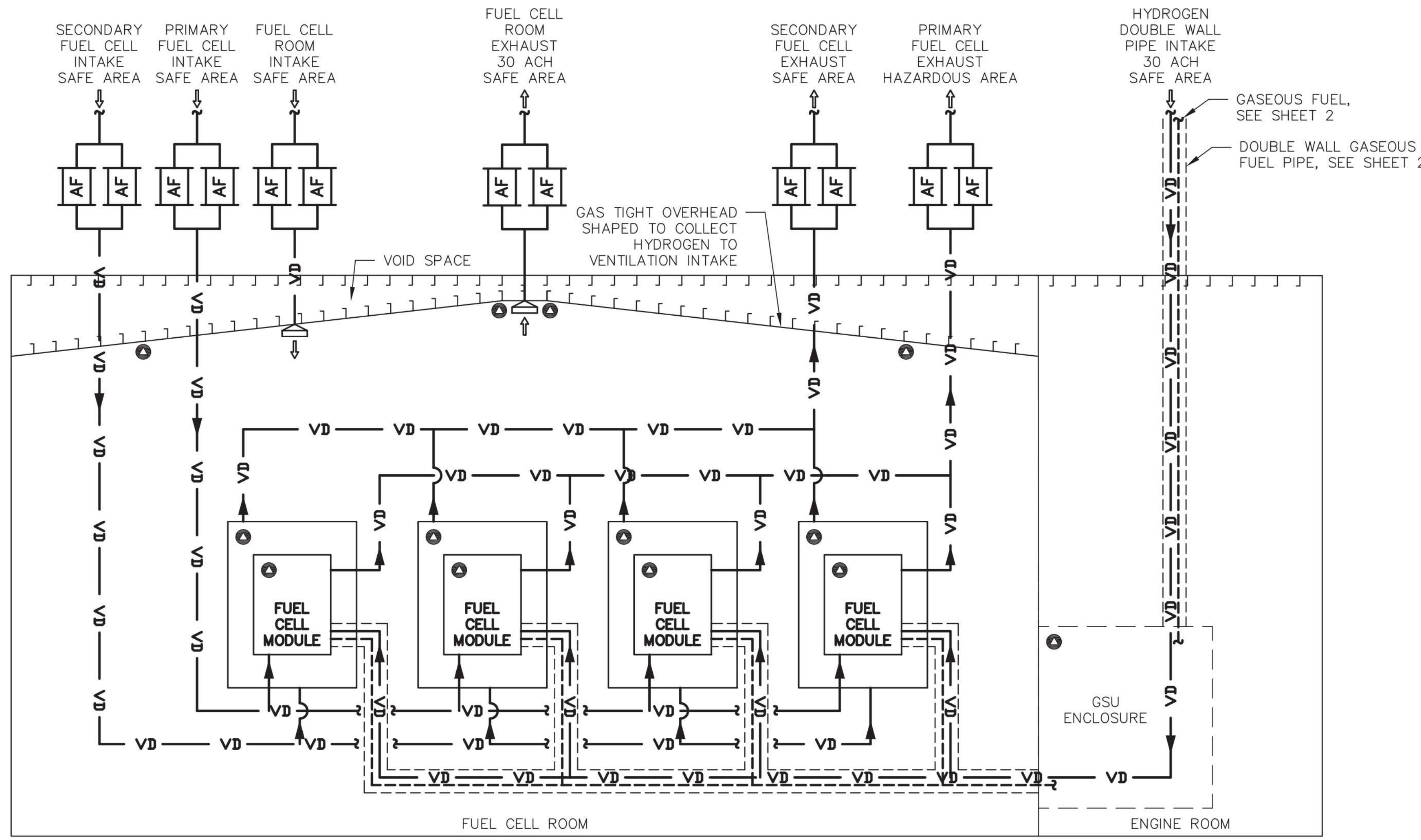

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SPROUL REPLACEMENT VESSEL
CONCEPT GAS SYSTEM ARCHITECTURE SKETCH
CONCEPT VENTILATION SYSTEM

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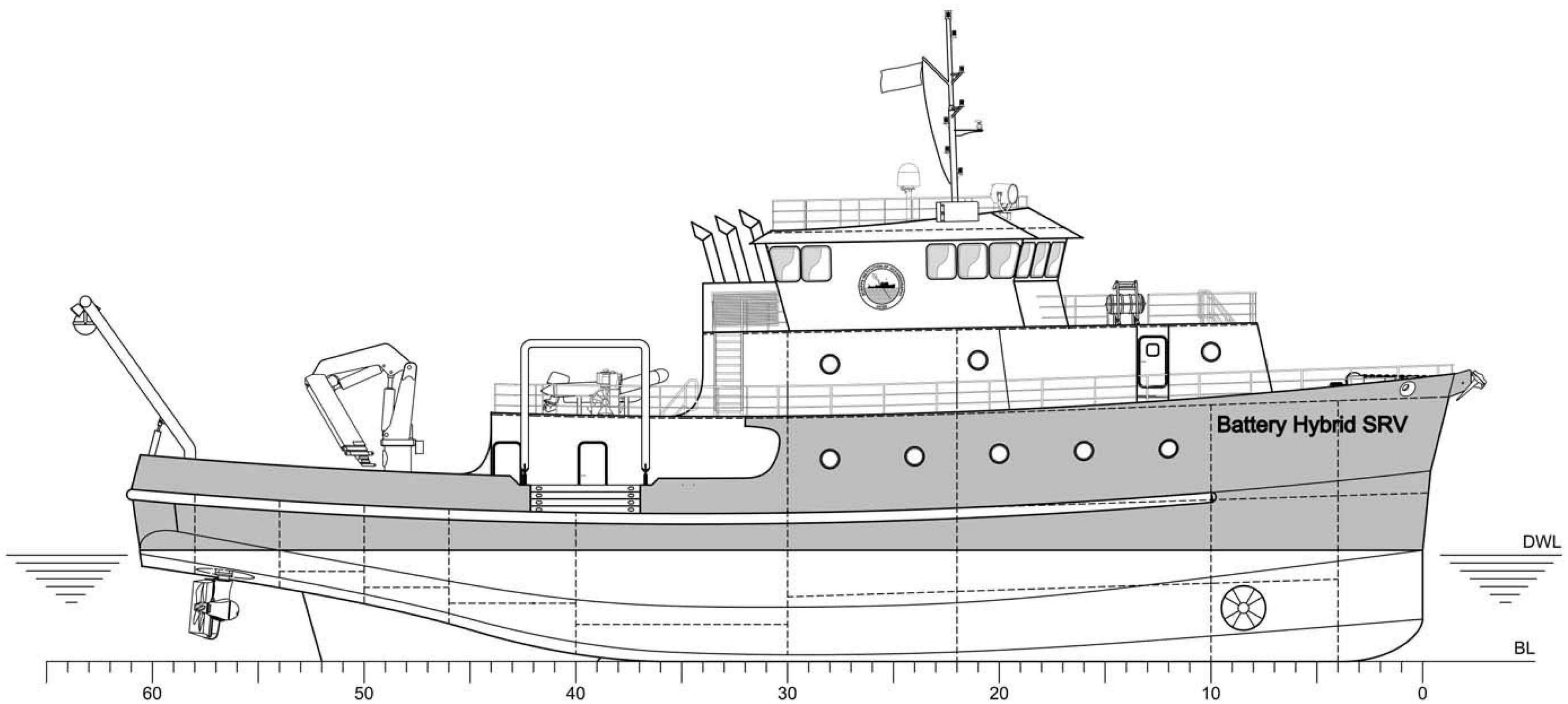
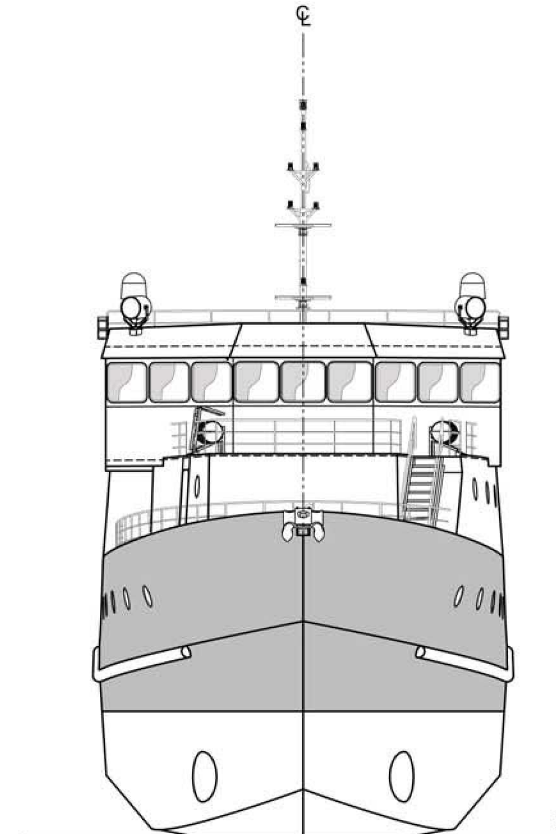
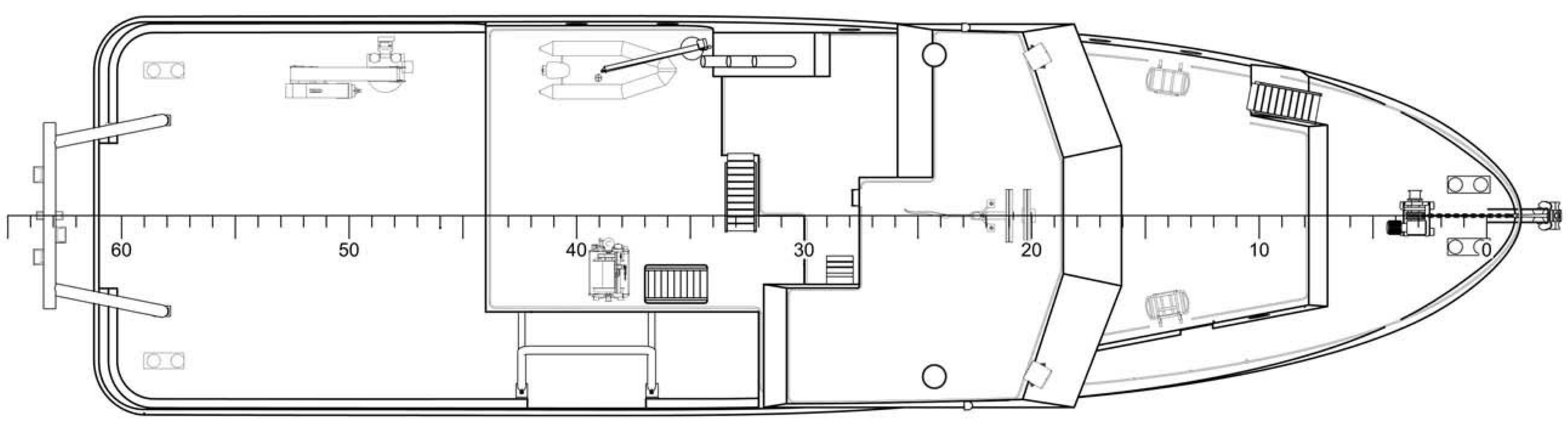


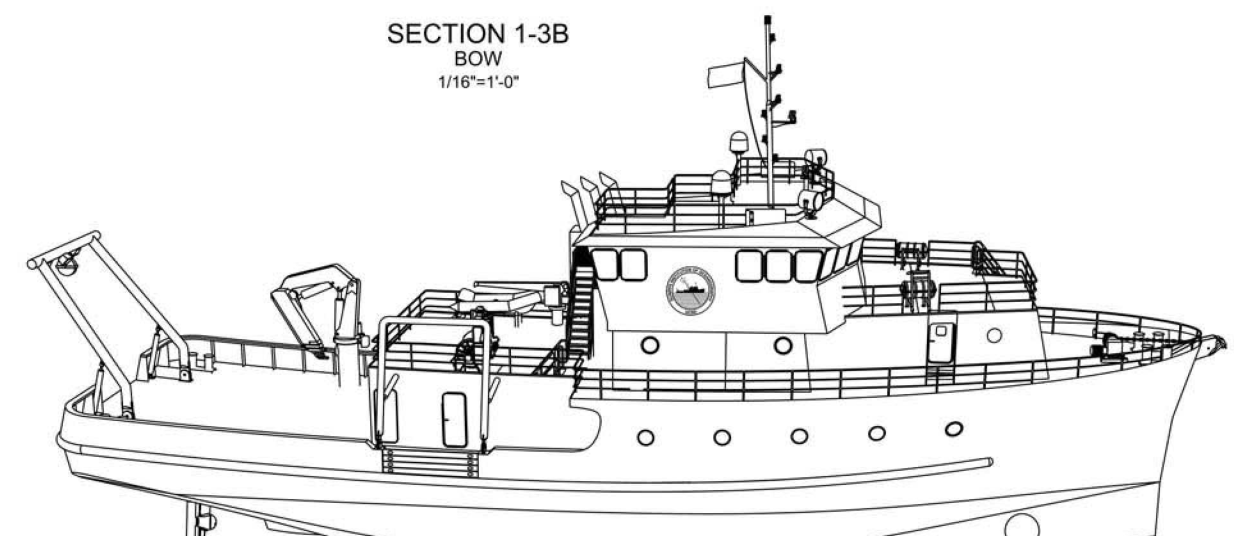
ELEVATION 1-6B
OUTBOARD PROFILE
1/16"=1'-0"



SECTION 1-3B
BOW
1/16"=1'-0"



PLAN 1-6A
WEATHER DECKS
1/16"=1'-0"



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GENERAL NOTES

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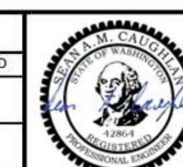

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BATTERY HYBRID GENERAL ARRANGEMENT
01 OUTBOARD PROFILE TOP & END VIEWS

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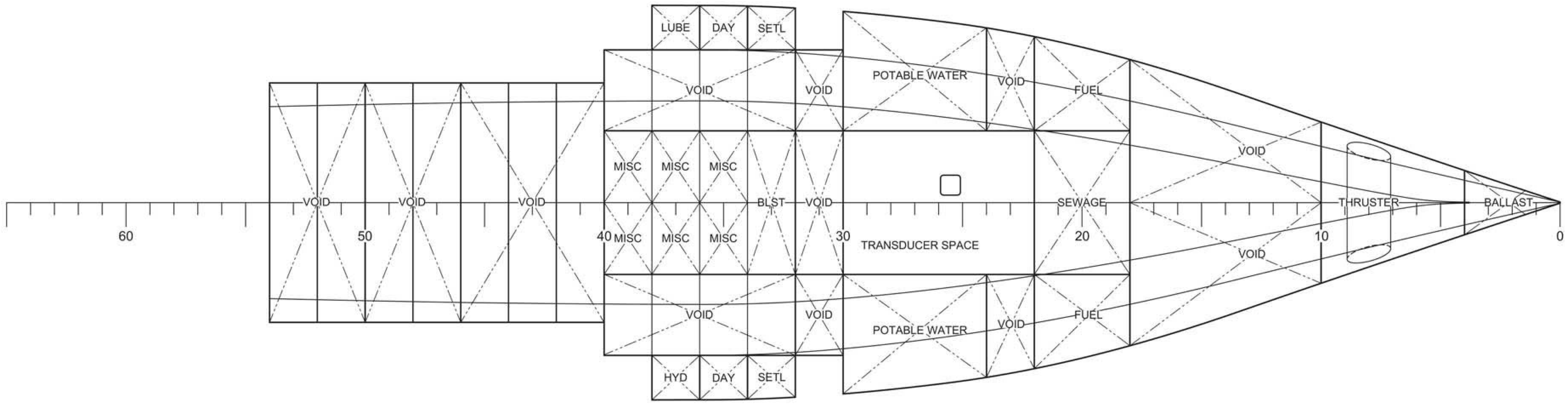
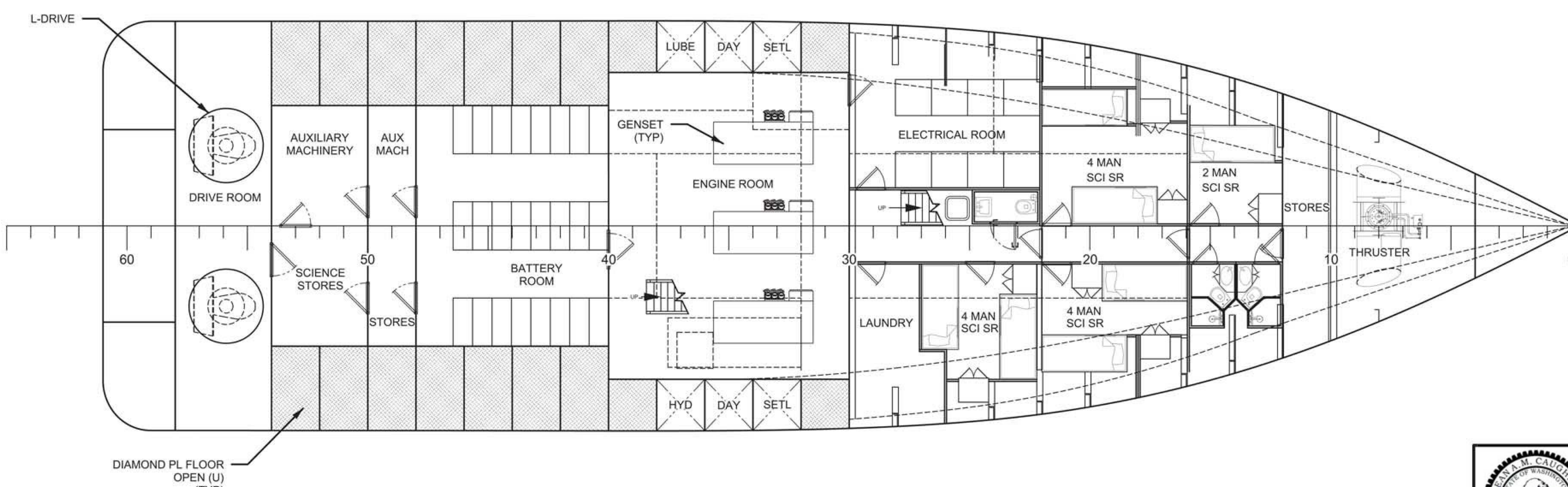


PLAN 2-5C
TANK PLAN
3/32"=1'-0"



PLAN 2-5A
1ST PLATFORM
3/32"=1'-0"

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LIVERMORE, CALIFORNIA

SPROUL REPLACEMENT VESSEL
BATTERY HYBRID GENERAL ARRANGEMENT
02 LOWER DECKS

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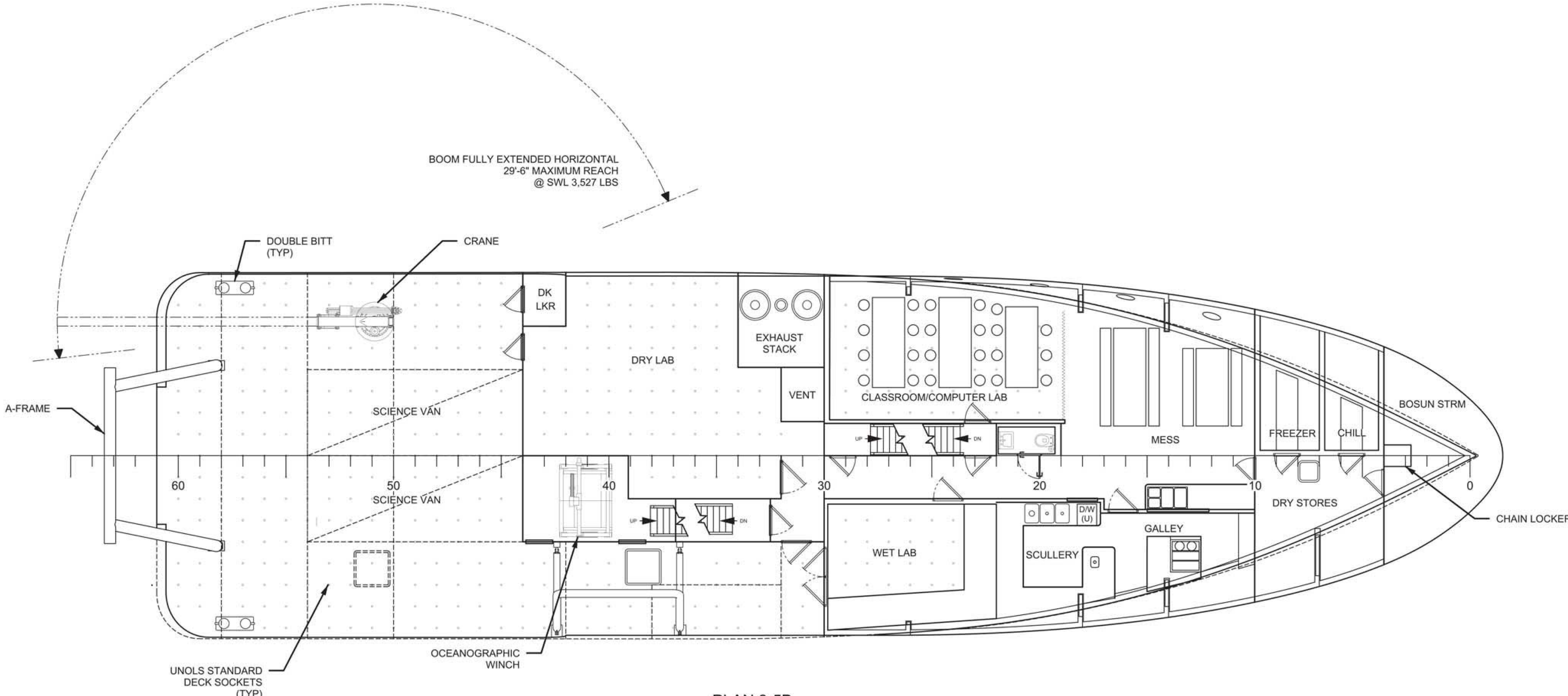

PLAN 3-5B
MAIN DECK
3/32"=1'-0"

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BATTERY HYBRID GENERAL ARRANGEMENT
03 MAIN DECK

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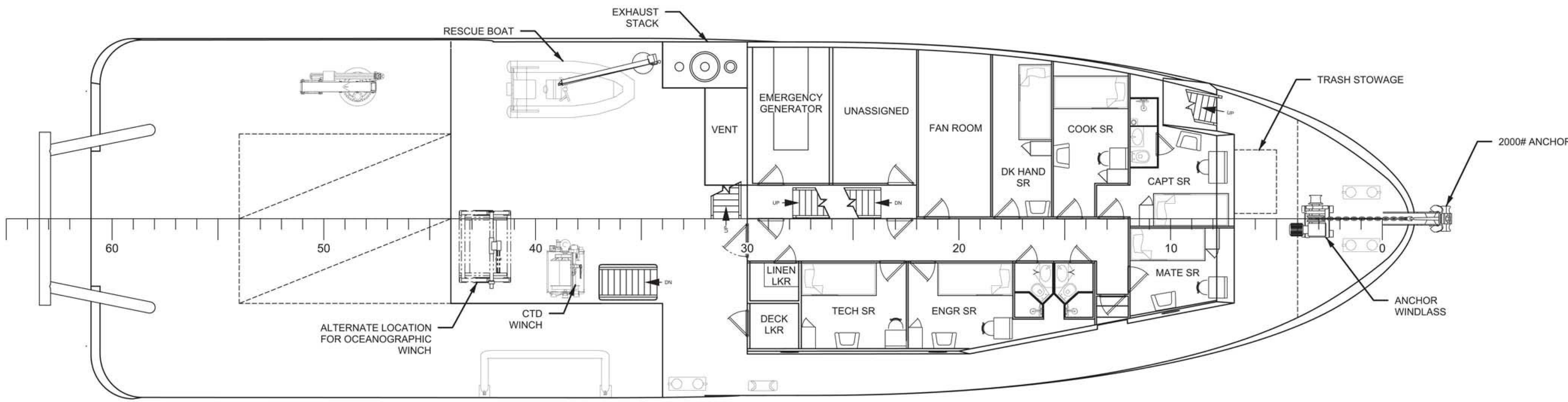

PLAN 4-5B
FOCSLE DECK
3/32"=1'-0"

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SPROUL REPLACEMENT VESSEL BATTERY HYBRID GENERAL ARRANGEMENT 04 FOCSLE DECK			
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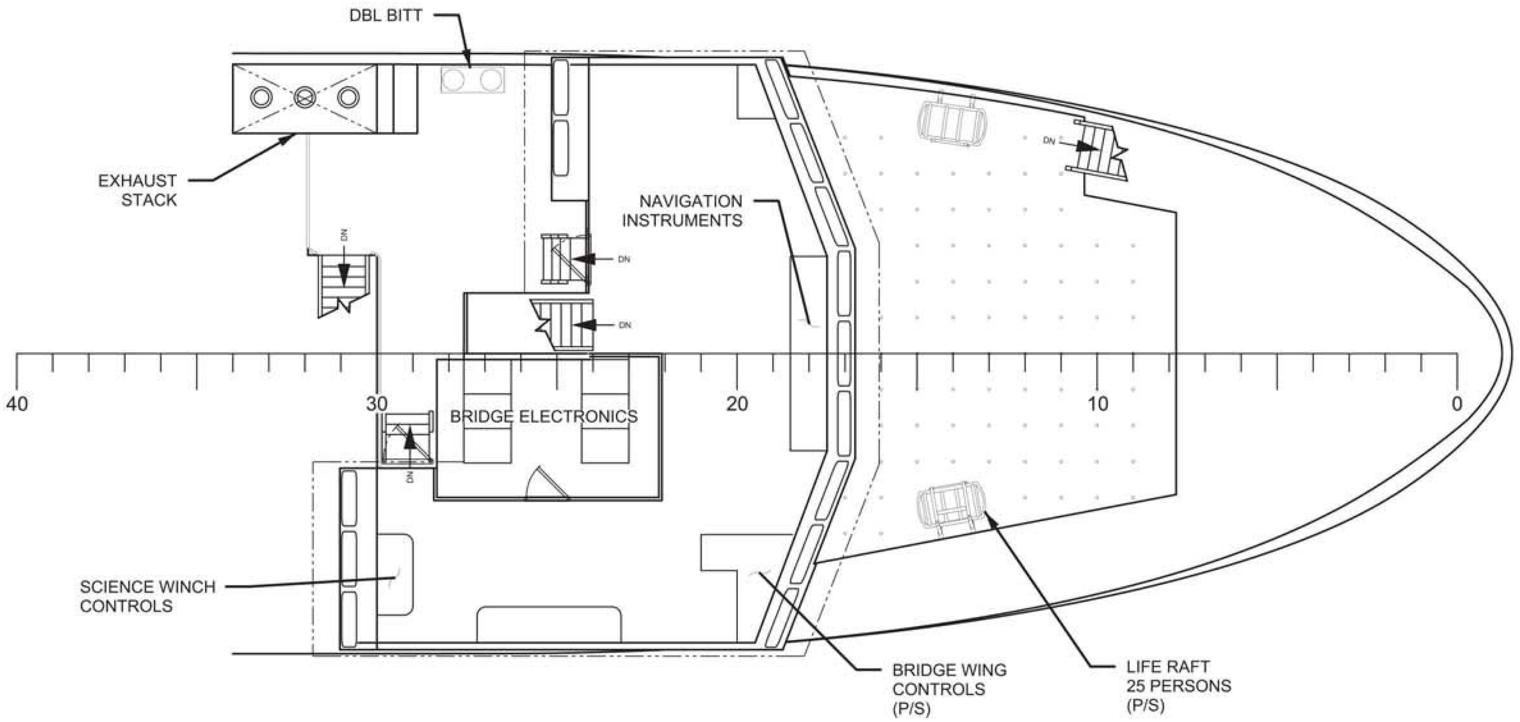
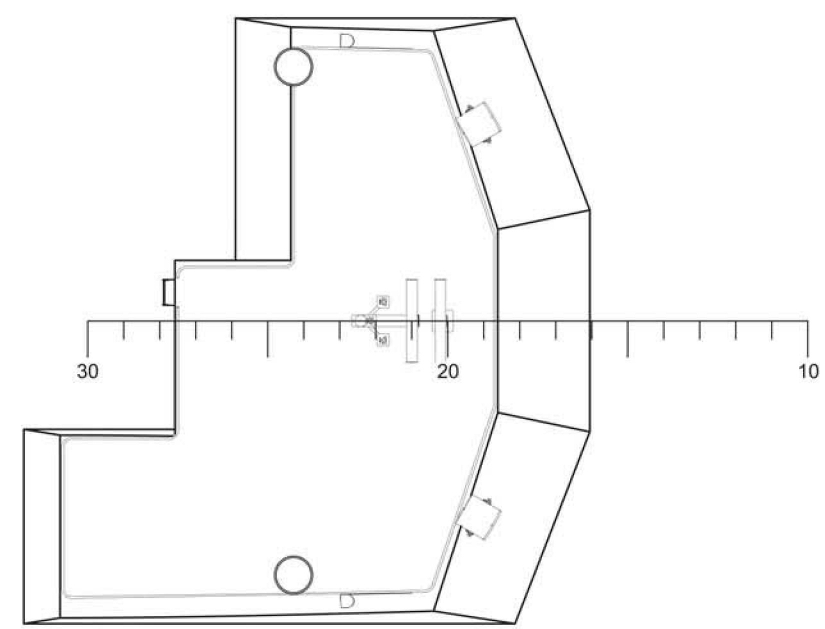


PLAN 5-5C
BRIDGE DECK
3/32"=1'-0"



PLAN 5-5A
BRIDGE HOUSE TOP
3/32"=1'-0"

SEAN A. M. CAUGHLAN
STATE OF WASHINGTON
42864
REGISTERED PROFESSIONAL ENGINEER
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BATTERY HYBRID GENERAL ARRANGEMENT
05 BRIDGE DECK AND HOUSE TOP

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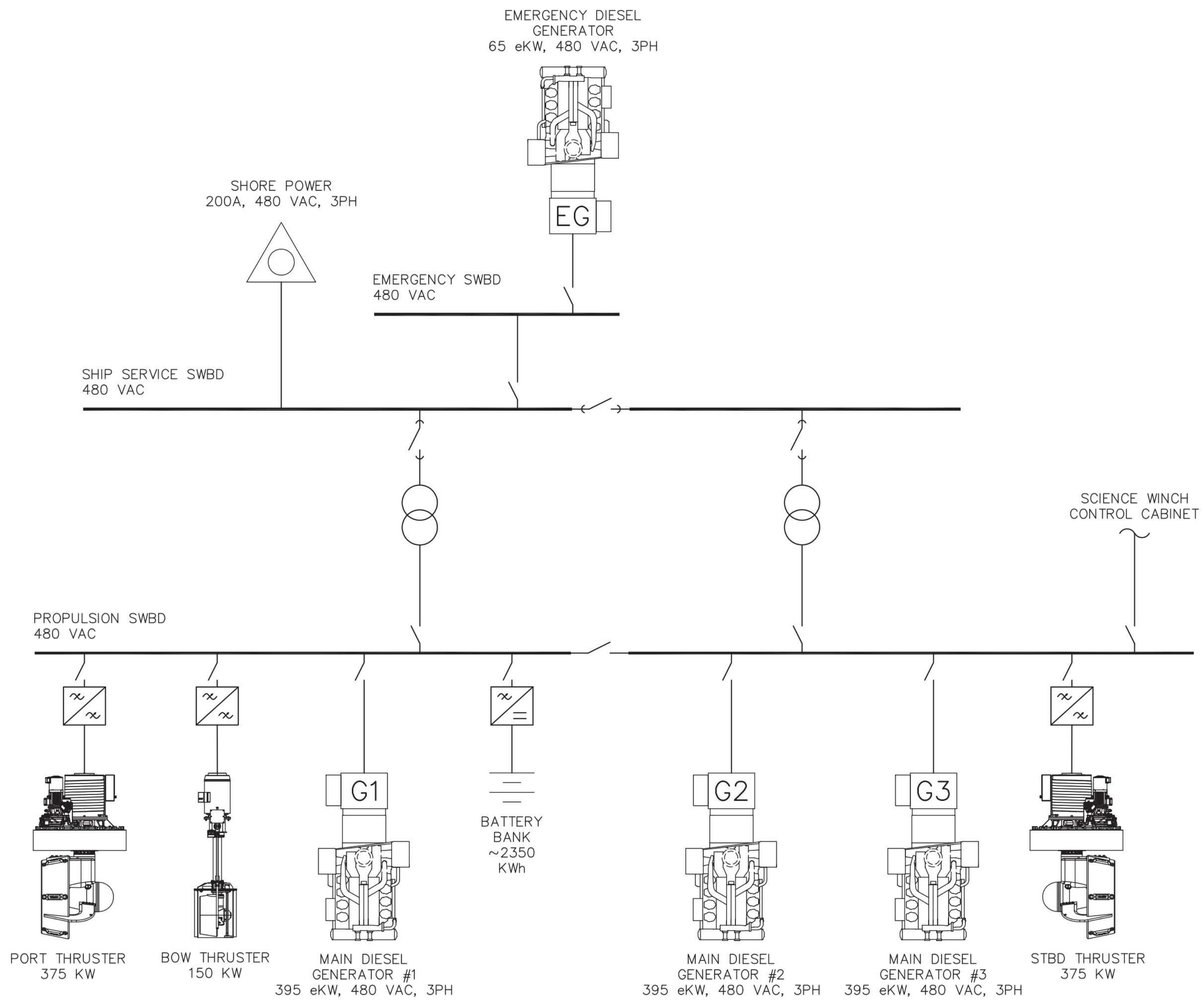

DIAGRAM 1–5A

CONCEPT SYSTEM ARCHITECTURE

GENERAL NOTES

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REFERENCES

1. GLOSTEN, DRAWING 19112.01–070–01, BASELINE GENERAL ARRANGEMENT
2. GLOSTEN, DRAWING 19112.01–300–01, BASELINE ELECTRICAL ONE–LINE DIAGRAM
3. GLOSTEN, DRAWING 19112.01–070–03, BATTERY HYBRID GENERAL ARRANGEMENT

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LIVERMORE, CALIFORNIA

SPROUL REPLACEMENT VESSEL
BATTERY HYBRID ELECTRICAL ONE–LINE DIAGRAM
CONCEPT SYSTEM ARCHITECTURE

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Drawn	Checked	Approved	Size	Issue Date
CJC	SAC	TSL	B	06/19/2020

Scale	Drawing Number	Sheet	of	Revision
NOT TO SCALE	19112.01–300–03	1	1	–

Appendix B Calculations

- Range and Endurance (all variants)
- Fuel Consumption Comparison (all variants)
- Electrical Loads Analysis (all variants)
- Stability (Hydrogen Hybrid)

Sandia National Laboratories
Sproul Replacement
Diesel_Battery_H2 Comparison

By: CJC
Checked: RTM/SAC
Date: June 16, 2020
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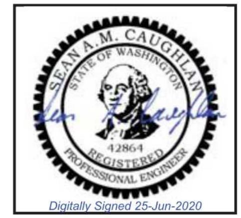
Propulsion Motor Efficiency	0.950	**Veth Integrated L-Drive (96% Motor, 1% Gear)**
Switchgear Efficiency	0.960	**Estimate**
Tank Relief Valve Setting	9.00	**bar g**
Fuel Reserve (Heel)	5%	
Consumable Tank Volume	69.0%	
CH2 Gas Density	0.08998	**g/L @ standard conditions (0°C, 1 atm)**
CH2 Gas Density	0.002548	**kg/ft3**
LH2 Density	70.85	**kg/m3**
Battery Efficiency	0.95	
Battery Size	2350	**kWh**
Battery Depth of Discharge	60.0%	
Diesel Generator efficiency	0.94	
Generator Set Size, kWe	395	**kW**

Condition	Sprint	Transit	Survey	Towing	Loiter	On Station Science Ops
Speed (knots)	12	10	8	2	0-2	0
Propulsion Power (shaft kW)	500	214	87	60	15	100
Propulsion (kWe)	1053	451	184	126	32	211
Bow Thrusters (kWe)	0	0	0	0	30	100
Science Loads (kWe)	0	0	37.5	37.5	0	75
Ship Service (kWe)	70	70	70	70	70	70
Total Electrical (kWe)	1169	542	303	244	137	475
Fuel Cells Online	-	4	4	4	2	4
Electrical Load per Fuel Cell (kWe)	-	136	76	61	69	119
Fuel Consumption per Fuel Cell (g/s)	-	2.18	1.15	0.92	1.04	1.86
Fuel Consumption (kg/hr)	-	31.4	16.5	13.2	7.5	26.8
Fuel Consumption (SCF/hr)	-	12308	6493	5189	2925	10531
Fuel Consumption (m3/hr)	-	0.44	0.23	0.19	0.11	0.38
Time on Battery (hr)	-	2.47	4.41	5.50	9.77	2.82
# of Diesel Generators Online	-	2	2	1	1	2
Diesel Generator Load (kWe)	-	271	152	244	137	237
Engine Load (kWm)	-	288	161	259	146	252
BSFC, Synchronous Speed (g/kWh)	-	223	223	223	235	223
Diesel Fuel Consumption (kg/hr)	-	129	72	58	34	113

Missions	Sprint	Transit	Survey	Towing	Loiter	On Station Science Ops	Totals	
	0	3	0	6	3	0	12	Hours
	0	386	0	347	103	0	835	kg (DG)
	0	1712	0	1538	433	0	3683	kWh (Bat)
Class Cruise: Biology of Fishes	0	94	0	79	22	0	196	kg (H2)
	0	3	3	3	0	3	12	Hours
	0	386	216	173	0	338	1113	kg (DG)
	0	1712	958	769	0	1498	4938	kWh (Bat)
Class Cruise: Biology (Typ)	0	94	50	40	0	80	264	kg (H2)
	0	3	0	0	3	6	12	Hours
	0	386	0	0	103	675	1164	kg (DG)
Class Cruise: Marine Geology &	0	1712	0	0	433	2997	5142	kWh (Bat)
Invertebrates	0	94	0	0	22	161	277	kg (H2)
	0	4	0	0	0	10	14	Hours
	0	515	0	0	0	1126	1640	kg (DG)
	0	2283	0	0	0	4995	7278	kWh (Bat)
Class Cruise: AUV Ops	0	125	0	0	0	268	394	kg (H2)
	0	4	0	18	0	2	24	Hours
	0	515	0	1040	0	225	1780	kg (DG)
	0	2283	0	4615	0	999	7897	kWh (Bat)
Physical Oceanography	0	125	0	238	0	54	417	kg (H2)
	0	8	0	0	2	14	24	Hours
	0	1029	0	0	69	1576	2674	kg (DG)
	0	4566	0	0	289	6993	11847	kWh (Bat)
Coastal Mooring	0	251	0	0	15	376	641	kg (H2)
	0	20	20	0	20	60	120	Hours
	0	2573	1440	0	685	6754	11452	kg (DG)
	0	11415	6388	0	2886	29969	50657	kWh (Bat)
Geology Sampling (Multicore)	0	627	331	0	149	1610	2717	kg (H2)
	0	48	6	0	12	54	120	Hours
	0	6174	432	0	411	6079	13096	kg (DG)
	0	27396	1916	0	1731	26972	58016	kWh (Bat)
Deep Moorings (4000m) & Towed Sonar II	0	1505	99	0	89	1449	3143	kg (H2)
	0	16	8	0	56	88	168	Hours
	0	2058	576	0	1919	9906	14459	kg (DG)
	0	9132	2555	0	8079	43954	63721	kWh (Bat)
AUV Ops II	0	502	132	0	417	2361	3413	kg (H2)
	0	48	6	30	12	72	168	Hours
	0	6174	432	1733	411	8105	16856	kg (DG)
	0	27396	1916	7691	1731	35963	74698	kWh (Bat)
Deep Moorings (4000m) & Towed Sonar I	0	1505	99	397	89	1932	4023	kg (H2)
	0	24	0	0	12	132	168	Hours
	0	3087	0	0	411	14859	18357	kg (DG)
	0	13698	0	0	1731	65931	81361	kWh (Bat)
AUV Ops I	0	753	0	0	89	3542	4384	kg (H2)
	0	64	0	30	30	68	192	Hours
	0	8232	0	1733	1028	7655	18649	kg (DG)
	0	36528	0	7691	4328	33965	82512	kWh (Bat)
Cyanobacteria I: CTDs and Incubations	0	2007	0	397	224	1825	4452	kg (H2)
	0	64	0	30	30	68	192	Hours
	0	8232	0	1733	1028	7655	18649	kg (DG)
	0	36528	0	7691	4328	33965	82512	kWh (Bat)
Cyanobacteria II: CTDs and Incubations	0	2007	0	397	224	1825	4452	kg (H2)
	0	48	24	24	96	48	240	Hours
	0	6174	1728	1387	3289	5403	17981	kg (DG)
	0	27396	7666	6153	13850	23975	79040	kWh (Bat)
Coastal Physical Oceanography	0	1505	397	317	715	1288	4223	kg (H2)
	0	36	18	0	36	150	240	Hours
	0	4631	1296	0	1234	16885	24045	kg (DG)
	0	20547	5749	0	5194	74922	106412	kWh (Bat)
Geology: Vibracore & Box Core	0	1129	298	0	268	4025	5720	kg (H2)
	0	240	0	0	0	0	240	Hours
	0	30872	0	0	0	0	30872	kg (DG)
	0	136981	0	0	0	0	136981	kWh (Bat)
Range Endurance	0	7526	0	0	0	0	7526	kg (H2)

Sandia National Laboratories
Sproul Replacement
Fuel Consumption Comparison - All Variants



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Constants/Assumptions

Propulsion Motor Efficiency	0.95	Veth Integrated L-Drive
Switchgear Efficiency	0.96	
Tank Relief Valve Setting	9.00	bar g
Fuel Reserve (Heel)	5%	
Consumable Tank Volume	69.0%	
CH2 Gas Density	0.08998	g/L @ standard conditions (0°C, 1 atm)
CH2 Gas Density	0.002548	kg/ft3
LH2 Density	70.85	kg/m3
Battery Efficiency	0.95	
Battery Size	2350	kWh
Battery Depth of Discharge	60.0%	
Diesel Generator efficiency	0.94	
Generator Set Size, kWe	395	kW

Mission	Missions Per Year	Baseline		Hydrogen Hybrid[1]				Battery Hybrid[2]			
		Diesel		Diesel		LH2		Diesel		Shore Power	
		kg/mission	kg/year	kg/mission	kg/year	kg/mission	kg/year	kg/mission	kg/year	kWh/mission	kWh/year
Class Cruise: Biology of Fishes	2	835	1,671	0	0	196	392	688	1,375	1,410	2,820
Class Cruise: Biology (Typ)	11	1,113	12,242	0	0	264	2,903	951	10,464	1,410	15,510
Class Cruise: Marine Geology & Invertibrates	4	1,164	4,656	0	0	277	1,110	1,000	4,000	1,410	5,640
Class Cruise: AUV Ops	2	1,640	3,280	0	0	394	788	1,452	2,904	1,410	2,820
Physical Oceanography	1	1,780	1,780	0	0	417	417	1,585	1,585	1,410	1,410
Coastal Mooring	5	2,674	13,368	0	0	641	3,207	2,434	12,169	1,410	7,050
Geology Sampling (Multicore)	1	11,452	11,452	9,400	9,400	733	733	10,773	10,773	1,410	1,410
Deep Moorings (4000m) & Towed Sonar II	1	13,096	13,096	11,044	11,044	733	733	12,335	12,335	1,410	1,410
AUV Ops II	1	14,459	14,459	12,407	12,407	733	733	13,630	13,630	1,410	1,410
Deep Moorings (4000m) & Towed Sonar I	1	16,856	16,856	14,804	14,804	733	733	15,907	15,907	1,410	1,410
Coastal Physical Oceanography	1	17,981	17,981	15,929	15,929	733	733	16,976	16,976	1,410	1,410
AUV Ops I	1	18,357	18,357	16,305	16,305	733	733	17,334	17,334	1,410	1,410
Cyanobacteria: CTDs and Incubations	2	18,649	37,297	16,596	33,193	733	1,466	17,610	35,220	1,410	2,820
Geology: Vibracore & Box Core	1	24,045	24,045	21,993	21,993	733	733	22,737	22,737	1,410	1,410
Range Endurance (Not a Mission)	0	30,872	0	28,820	0	733	0	29,222	0	1,410	0
Total	**34**		**190,541**		**135,075**		**15,413**		**177,410**		**47,940**

1. Hydrogen hybrid fuel consumption is calculated assuming that one day missions are completed using only hydrogen fuel and longer missions are complete utilizing the enter usable capacity of hydrogen supplementing diesel fuel. Diesel fuel reductions were calculated via energy comparison with hydrogen fuel.

2. Battery hybrid fuel consumption is calculated assuming that 60% of the total battery is consumed from shore power on every mission along with a 5% diesel fuel consumption reduction on the remaining fuel usage for hybrid operation.

Electrical Load Analysis Sandia National Laboratories Sproul Replacement Vessel	BY: CJC CHECKED: RTM/SAC APPROVED: TSL	
PREPARED FOR Sandia National Laboratories Livermore, California	FILE: 19112.01 DOCUMENT: 19112.01-300-04 REVISION: -	
Glosten INNOVATIVE MARINE SOLUTIONS 1201 WESTERN AVENUE, SUITE 200 SEATTLE, WASHINGTON 98101-2953 T 206.624.7850 GLOSTEN.COM	DATE: 4/30/2020	Digitally Signed 25-Jun-2020

GENERAL NOTES

1. This document has been developed from information in References 1,2, and 3.

2. Definitions and acronyms
   DF: Demand Factor, defined as the fraction of time that the load is operational in an operational profile.
   ekW: Electrical kilowatts
   FLA: Full Load Amperes
   HP: Horsepower
   kVA: Kilo Volt-Amperes
   Utilization Factor: the fraction of the connected load rating that is utilized during normal operation.
   V: Voltage
   ϕ: Number of phases

3. Calculation procedure: Profile Load = Connected * Utilization Factor * Demand Factor

4. This electrical load analysis is preliminary. It represents anticipated loads and demand factors for the Sproul Replacement research vessel.

5. The main propulsion and ship service loads are supplied with power from four 200kW fuel cell modules. The fuel cells provide a total of 800 kW.

6. The fuel cell stacks supply DC power to the main propulsion switchboard at 350VDC - 720VDC. The propulsion switchboard supplies power to the propulsion motors, thrusters and ship service switchboard through an inverter and transformer.

7. There are seven operating profiles considered in the analysis. The In Transit scenario is applicable when the vessel is transiting between stations, and not performing science operations. The towing scenario represents when the vessel is moving at slow speed (2 knots) and using the towing winch. The Loitering and On Station profiles represent light and heavy DP respectively. In these scenarios, the bow and stern thrusters are being utilized, along with heavy science equipment demands. The In Port scenario represents the vessel's electrical demands while on shore power.

8. The 2250 kWh battery in the Batter Electric Hybrid is capable of a 3C continuous rating. For this analysis a 0.5C loading (1125 kW) is assumed.

REFERENCES

1. Baseline Electrical One-Line Diagram, Glosten, File No. 19112.01-300-01
2. Hydrogen Hybrid Electrical One-Line Diagram, Glosten, File No. 19112.01-300-02
3. Batery Hybrid Electrical One-Line Diagram, Glosten, File No. 19112.01-300-03

REVISIONS

REV.	SECTION	DESCRIPTION
-	ALL	ORIGINAL RELEASE

Electrical Load Analysis	FILE:	19112.01	BY:	CJC
Sandia National Laboratories	REVISION:	-	CHECKED:	RTM/SAC
Sproul Replacement Vessel	DATE:	30-Apr-20	APPROVED:	TSL
DOCUMENT: 19112.01-300-04				

DRIVETRAIN TYPE	**Diesel-Electric (Baseline)**

LOAD DATA

SWBS #	Load Description	V	Φ	HP	FLA	Power Factor	Connected ekW	Connected kVA	Utilization Factor	Utilized ekW	Utilized kVA	Load Notes
	Propulsion											
	Port Propulsion Motor	480	3		563.84	0.80	375.00	468.75	1.00	375.00	468.75	
	Stbd Propulsion Motor	480	3		563.84	0.80	375.00	468.75	1.00	375.00	468.75	
	Bow Thruster	480	3		225.53	0.80	150.00	187.50	1.00	150.00	187.50	
	Loads											
	Ship Service Loads	480	3		267.30	0.90	200.00	222.22	1.00	200.00	222.22	
	Science Loads	480	3		225.53	0.80	150.00	187.50	1.00	150.00	187.50	
	Sub-Total						*1250.00*	*1534.72*		*1250.00*	*1534.72*	
	Design Ship Service Margin	10%					125.00	153.47		125.00	153.47	
	Growth Margin	10%					125.00	153.47		125.00	153.47	
	Total						1500.00	1841.67		1500.00	1841.67	

OPERATING PROFILES

Load Description	Sprint DF	Sprint ekW	Sprint kVA	Transit 10 knots DF	Transit 10 knots ekW	Transit 10 knots kVA	Survey 8 knots DF	Survey 8 knots ekW	Survey 8 knots kVA
Propulsion									
Port Propulsion Motor	1.00	375.00	468.75	0.61	226.88	283.59	0.27	99.38	124.22
Stbd Propulsion Motor	1.00	375.00	468.75	0.61	226.88	283.59	0.27	99.38	124.22
Bow Thruster	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Loads									
Ship Service Loads	0.35	70.00	77.78	0.35	70.00	77.78	0.35	70.00	77.78
Science Loads	0.00	0.00	0.00	0.00	0.00	0.00	0.25	37.50	46.88
Sub-Total		*820.00*	*1015.28*		*523.75*	*644.97*		*306.25*	*373.09*
Design Ship Service Margin		82.00	101.53		52.38	64.50		30.63	37.31
Growth Margin		82.00	101.53		52.38	64.50		30.63	37.31
Total		984.00	1218.33		628.50	773.96		367.50	447.71

Load Description	Towing DF	Towing ekW	Towing kVA	Loitering (Light DP) DF	Loitering (Light DP) ekW	Loitering (Light DP) kVA	On Station (DP) DF	On Station (DP) ekW	On Station (DP) kVA	In Port DF	In Port ekW	In Port kVA
Propulsion												
Port Propulsion Motor	0.16	58.13	72.66	0.02	7.50	9.38	0.28	103.13	128.91	0.00	0.00	0.00
Stbd Propulsion Motor	0.16	58.13	72.66	0.02	7.50	9.38	0.28	103.13	128.91	0.00	0.00	0.00
Bow Thruster	0.00	0.00	0.00	0.20	30.00	37.50	0.67	99.90	124.88	0.00	0.00	0.00
Loads												
Ship Service Loads	0.35	70.00	77.78	0.35	70.00	77.78	0.35	70.00	77.78	0.25	50.00	55.56
Science Loads	0.25	37.50	46.88	0.00	0.00	0.00	0.50	75.00	93.75	0.00	0.00	0.00
Sub-Total		*223.75*	*269.97*		*115.00*	*134.03*		*451.15*	*554.22*		*50.00*	*55.56*
Design Ship Service Margin		22.38	27.00		11.50	13.40		45.12	55.42		5.00	5.56
Growth Margin		22.38	27.00		11.50	13.40		45.12	55.42		5.00	5.56
Total		268.50	323.96		138.00	160.83		541.38	665.06		60.00	66.67

	Generators	PF		ekW	kVA
	Generator #1	0.80		395.00	493.75
	Generator #2	0.80		395.00	493.75
	Generator #3	0.80		395.00	493.75
	Total Ship Generating Power			1185.00	1481.25

	Loading	ekW	kVA	Sprint	Transit 10 knots	Survey 8 knots	Towing	Loitering (Light DP)	On Station (DP)	In Port
	1 Generator Online	395.00	493.75	249%	159%	93%	68%	35%	137%	15%
	2 Generators Online	790.00	987.50	125%	80%	47%	34%	17%	69%	8%
	3 Generators Online	1185.00	1481.25	83%	53%	31%	23%	12%	46%	5%

Electrical Load Analysis	FILE: 19112.01	BY: CJC
Sandia National Laboratories	REVISION: -	CHECKED: RTM/SAC
Sproul Replacement Vessel	DATE: 30-Apr-20	APPROVED: TSL
DOCUMENT: 19112.01-300-04		

DRIVETRAIN TYPE	
	Diesel-Battery Electric Hybrid

LOAD DATA

SWBS #	Load Description	V	Φ	HP	FLA	Power Factor	Connected ekW	Connected kVA	Utilization Factor	Utilized ekW	Utilized kVA	Load Notes
	Propulsion											
	Port Propulsion Motor	480	3		563.84	0.80	375.00	468.75	1.00	375.00	468.75	
	Stbd Propulsion Motor	480	3		563.84	0.80	375.00	468.75	1.00	375.00	468.75	
	Bow Thruster	480	3		225.53	0.80	150.00	187.50	1.00	150.00	187.50	
	Loads											
	Ship Service Loads	480	3		267.30	0.90	200.00	222.22	1.00	200.00	222.22	
	Science Loads	480	3		225.53	0.80	150.00	187.50	1.00	150.00	187.50	
	Sub-Total						*1250.00*	*1534.72*		*1250.00*	*1534.72*	
	Design Ship Service Margin	10%					125.00	153.47		125.00	153.47	
	Growth Margin	10%					125.00	153.47		125.00	153.47	
	Total						1500.00	1841.67		1500.00	1841.67	

OPERATING PROFILES

Load Description	Sprint DF	Sprint ekW	Sprint kVA	Transit 10 knots DF	Transit 10 knots ekW	Transit 10 knots kVA	Survey 8 knots DF	Survey 8 knots ekW	Survey 8 knots kVA	Towing DF	Towing ekW	Towing kVA	Loitering (Light DP) DF	Loitering (Light DP) ekW	Loitering (Light DP) kVA	On Station (DP) DF	On Station (DP) ekW	On Station (DP) kVA	In Port DF	In Port ekW	In Port kVA
Propulsion																					
Port Propulsion Motor	1.00	375.00	468.75	0.61	226.88	283.59	0.27	99.38	124.22	0.16	58.13	72.66	0.02	7.50	9.38	0.28	103.13	128.91	0.00	0.00	0.00
Stbd Propulsion Motor	1.00	375.00	468.75	0.61	226.88	283.59	0.27	99.38	124.22	0.16	58.13	72.66	0.02	7.50	9.38	0.28	103.13	128.91	0.00	0.00	0.00
Bow Thruster	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	30.00	37.50	0.67	99.90	124.88	0.00	0.00	0.00
Loads																					
Ship Service Loads	0.35	70.00	77.78	0.35	70.00	77.78	0.35	70.00	77.78	0.35	70.00	77.78	0.35	70.00	77.78	0.35	70.00	77.78	0.25	50.00	55.56
Science Loads	0.00	0.00	0.00	0.00	0.00	0.00	0.25	37.50	46.88	0.25	37.50	46.88	0.00	0.00	0.00	0.50	75.00	93.75	0.00	0.00	0.00
Sub-Total		*820.00*	*1015.28*		*523.75*	*644.97*		*306.25*	*373.09*		*223.75*	*269.97*		*115.00*	*134.03*		*451.15*	*554.22*		*50.00*	*55.56*
Design Ship Service Margin		82.00	101.53		52.38	64.50		30.63	37.31		22.38	27.00		11.50	13.40		45.12	55.42		5.00	5.56
Growth Margin		82.00	101.53		52.38	64.50		30.63	37.31		22.38	27.00		11.50	13.40		45.12	55.42		5.00	5.56
Total		984.00	1218.33		628.50	773.96		367.50	447.71		268.50	323.96		138.00	160.83		541.38	665.06		60.00	66.67

	Generators/Batteries	PF		ekW	kVA
	Generator #1	0.80		395.00	493.75
	Generator #2	0.80		395.00	493.75
	Battery #1 (see GN #8)	1.00		1125.00	1125.00
	Total Ship Generating Power			1915.00	2112.50

	Loading			ekW	kVA		Sprint	Transit 10 knots	Survey 8 knots	Towing	Loitering (Light DP)	On Station (DP)	In Port
	1 Generator Online			395.00	493.75		249%	159%	93%	68%	35%	137%	15%
	2 Generators Online			790.00	987.50		125%	80%	47%	34%	17%	69%	8%
	1 Generator + Battery			1520.00	1618.75		75%	48%	28%	20%	10%	41%	4%
	2 Generators + Battery			1915.00	2112.50		58%	37%	21%	15%	8%	31%	3%
	Battery Only			1125.00	1125.00		108%	69%	40%	29%	14%	59%	6%

Electrical Load Analysis	FILE:	19112.01	BY:	CJC
Sandia National Laboratories	REVISION:	-	CHECKED:	RTM/SAC
Sproul Replacement Vessel	DATE:	30-Apr-20	APPROVED:	TSL
DOCUMENT: 19112.01-300-04				

DRIVETRAIN TYPE	Diesel-Hydrogen Fuel Cell Hybrid

LOAD DATA

SWBS #	Load Description	V	Φ	HP	FLA	Power Factor	Connected ekW	Connected kVA	Utilization Factor	Utilized ekW	Utilized kVA	Load Notes
	Propulsion											
	Port Propulsion Motor	480	3		563.84	0.80	375.00	468.75	1.00	375.00	468.75	
	Stbd Propulsion Motor	480	3		563.84	0.80	375.00	468.75	1.00	375.00	468.75	
	Bow Thruster	480	3		225.53	0.80	150.00	187.50	1.00	150.00	187.50	
	Loads											
	Ship Service Loads	480	3		267.30	0.90	200.00	222.22	1.00	200.00	222.22	
	Science Loads	480	3		225.53	0.80	150.00	187.50	1.00	150.00	187.50	
	Sub-Total						*1250.00*	*1534.72*		*1250.00*	*1534.72*	
	Design Ship Service Margin	10%					125.00	153.47		125.00	153.47	
	Growth Margin	10%					125.00	153.47		125.00	153.47	
	Total						1500.00	1841.67		1500.00	1841.67	

OPERATING PROFILES

Load Description	Sprint DF	Sprint ekW	Sprint kVA	Transit 10 knots DF	Transit 10 knots ekW	Transit 10 knots kVA	Survey 8 knots DF	Survey 8 knots ekW	Survey 8 knots kVA	Towing DF	Towing ekW	Towing kVA	Loitering (Light DP) DF	Loitering (Light DP) ekW	Loitering (Light DP) kVA	On Station (DP) DF	On Station (DP) ekW	On Station (DP) kVA	In Port DF	In Port ekW	In Port kVA
Propulsion																					
Port Propulsion Motor	1.00	375.00	468.75	0.61	226.88	283.59	0.27	99.38	124.22	0.16	58.13	72.66	0.02	7.50	9.38	0.28	103.13	128.91	0.00	0.00	0.00
Stbd Propulsion Motor	1.00	375.00	468.75	0.61	226.88	283.59	0.27	99.38	124.22	0.16	58.13	72.66	0.02	7.50	9.38	0.28	103.13	128.91	0.00	0.00	0.00
Bow Thruster	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	30.00	37.50	0.67	99.90	124.88	0.00	0.00	0.00
Loads																					
Ship Service Loads	0.35	70.00	77.78	0.35	70.00	77.78	0.35	70.00	77.78	0.35	70.00	77.78	0.35	70.00	77.78	0.35	70.00	77.78	0.25	50.00	55.56
Science Loads	0.00	0.00	0.00	0.00	0.00	0.00	0.25	37.50	46.88	0.25	37.50	46.88	0.00	0.00	0.00	0.50	75.00	93.75	0.00	0.00	0.00
Sub-Total		*820.00*	*1015.28*		*523.75*	*644.97*		*306.25*	*373.09*		*223.75*	*269.97*		*115.00*	*134.03*		*451.15*	*554.22*		*50.00*	*55.56*
Design Ship Service Margin		82.00	101.53		52.38	64.50		30.63	37.31		22.38	27.00		11.50	13.40		45.12	55.42		5.00	5.56
Growth Margin		82.00	101.53		52.38	64.50		30.63	37.31		22.38	27.00		11.50	13.40		45.12	55.42		5.00	5.56
Total		984.00	1218.33		628.50	773.96		367.50	447.71		268.50	323.96		138.00	160.83		541.38	665.06		60.00	66.67

	Generators/Fuel Cells	PF		ekW	kVA
	Generator #1	0.80		395.00	493.75
	Generator #2	0.80		395.00	493.75
	Generator #3	0.80		395.00	493.75
	Fuel Cell Rack #1 (see GN #5)	1.00		200.00	200.00
	Fuel Cell Rack #2	1.00		200.00	200.00
	Fuel Cell Rack #3	1.00		200.00	200.00
	Fuel Cell Rack #4	1.00		200.00	200.00
	Total Ship Generating Power			1985.00	2281.25

	Loading	ekW	kVA	Sprint	Transit 10 knots	Survey 8 knots	Towing	Loitering (Light DP)	On Station (DP)	In Port
	1 Generator Online	395.00	493.75	249%	159%	93%	68%	35%	137%	15%
	2 Generators Online	790.00	987.50	125%	80%	47%	34%	17%	69%	8%
	3 Generators Online	1185.00	1481.25	83%	53%	31%	23%	12%	46%	5%
	1 Fuel Cell Racks	200.00	200.00	609%	387%	224%	162%	80%	333%	33%
	2 Fuel Cell Racks	400.00	400.00	305%	193%	112%	81%	40%	166%	17%
	3 Fuel Cell Racks	600.00	600.00	203%	129%	75%	54%	27%	111%	11%
	4 Fuel Cell Racks	800.00	800.00	152%	97%	56%	40%	20%	83%	8%

TANK STATUS

Trim: zero, Heel: zero

Part	Gals.	SpGr	Weight(LT)	LCG	TCG	VCG	FSM
SEWAGE.C	7539.0	1.025	28.79	37.96a	0.00	3.39	58.3*
FODB2.P	2295.2	0.870	7.44	38.71a	8.82p	4.23	6.3*
FODB2.S	2295.2	0.870	7.44	38.71a	8.82s	4.23	6.3*
POTABLE.P	3778.6	1.000	14.08	54.15a	10.10p	3.56	20.7*
POTABLE.S	3778.6	1.000	14.08	54.15a	10.10s	3.56	20.7*
MISCDB3.P	657.7	1.025	2.51	70.00a	3.19p	1.75	2.4*
MISCDB3.S	657.7	1.025	2.51	70.00a	3.19s	1.75	2.4*
MISCDB4.P	638.2	1.025	2.44	73.98a	3.19p	1.80	2.4*
MISCDB4.S	638.2	1.025	2.44	73.98a	3.19s	1.80	2.4*
MISCDB5.P	573.1	1.025	2.19	77.95a	3.19p	1.97	2.4*
MISCDB5.S	573.1	1.025	2.19	77.95a	3.19s	1.97	2.4*
FOSET.P	1233.0	0.870	4.00	66.02a	14.56p	8.63	0.6*
FOSET.S	1233.0	0.870	4.00	66.02a	14.56s	8.63	0.6*
FODAY.P	1261.7	0.870	4.09	70.00a	14.60p	8.59	0.6*
FODAY.S	1261.7	0.870	4.09	70.00a	14.60s	8.59	0.6*
LO.P	1249.5	0.924	4.30	73.99a	14.61p	8.69	0.7*
HYDRO.S	1249.5	0.924	4.30	73.99a	14.61s	8.69	0.7*
Total Tanks--------->			110.87	53.97a	0.00	4.52	131.6*

Distances in FEET.--Moments in Ft-LT.

Note: FSM values marked with an asterisk (*) are formal values which are not the same as the true values in the present condition.

Condition Graphic

Tanks

	8 FODB2.S	20 MISCDB3.P	23 MISCDB4.S	28 FOSET.P	31 FODAY.S
4 SEWAGE.C	13 POTABLE.P	21 MISCDB3.S	24 MISCDB5.P	29 FOSET.S	32 LO.P
7 FODB2.P	14 POTABLE.S	22 MISCDB4.P	25 MISCDB5.S	30 FODAY.P	33 HYDRO.S

******* INTACT STABILITY ANALYSIS *******
170.173(C) INTACT STABILITY CRITERIA

Condition 1: Minimum Operational Weight
Intact; No Damage

WEIGHT STATUS
Trim: Aft 2.02/115.00, Heel: zero

Part	Weight(LT)	LCG	TCG	VCG	FSM
LIGHT SHIP	475.01	64.18a	0.00	15.03	
FIXED BALLAST	22.00	42.50a	0.00	2.00	
Total Weight-------->	497.01	63.22a	0.00	14.45	
Load-----SpGr	Weight(LT)	LCG	TCG	VCG	
Total Tanks--------->	--- Included in Fixed Weight ---				131.6*
Total Weight-------->	497.01	63.22a	0.00	14.45	
Free Surface Adjustment---------->				0.26	
Adjusted CG---------------------->		63.22a	0.00	14.72	

Distances in FEET.--Moments in Ft-LT.

Note: FSM values marked with an asterisk (*) are formal values which are not the same as the true values in the present condition.

FREEBOARD STATUS
Baseline draft: 7.435 @ 0.00, 9.460 @ 115.00a
Trim: Aft 2.02/115.00, Heel: zero
Least freeboard is 5.26 Ft located at 87.57a
Least extra freeboard (to margin line) is 5.01 Ft located at 87.57a

Condition 1: Minimum Operational Weight
Intact; No Damage

HYDROSTATIC PROPERTIES
Trim: Aft 2.02/115.00, No Heel, VCG = 14.45

LCF Draft	Displacement Weight(LT)	Buoyancy-Ctr. LCB	VCB	Weight/ Inch	LCF	Moment/ In trim	GML	GMT
8.673	497.01	63.39a	5.05	7.28	70.30a	49.28	136.8	3.31

Distances in FEET.-------Specific Gravity = 1.025.-----------Moment in Ft-LT.
Trim is per 115.00Ft
Draft is from Baseline. Formal Free Surface included.

Note: GMT includes the formal free surface moment 131.6 Ft-LT

HYDROSTATIC PROPERTIES
Trim: Aft 2.02/115.00, No Heel, Fixed VCG = 14.45

LCF Draft	Displacement Weight(LT)	Buoyancy-Ctr. LCB	VCB	Weight/ Inch	LCF	Moment/ In trim	KML	KMT
8.673	497.01	63.39a	5.05	7.28	70.30a	49.28	151.3	18.03

Distances in FEET.-------Specific Gravity = 1.025.-----------Moment in Ft-LT.
Trim is per 115.00Ft
Draft is from Baseline.

HYDROSTATIC PROPERTIES
Trim: Aft 2.02/115.00, No Heel

Origin Depth	Displacement Weight(LT)	Center of Buoyancy LCB	TCB	VCB	WPA	LCF	BML	BMT
7.434	497.01	63.39a	0.00	5.05	3058	70.30a	146.2	12.71

Distances in FEET.----Specific Gravity = 1.025.---Formal Free Surface included.

Note: BMT includes the formal free surface moment 131.6 Ft-LT

"DRAFT AT FWD MARKS" 7.576
"DRAFT AT MIDSHIP" 8.492
"DRAFT AT AFT MARKS" 9.407

Condition 1: Minimum Operational Weight
Intact; No Damage

CRITICAL POINT STATUS
Baseline draft: 7.435 @ 0.00, 9.460 @ 115.00a
Trim: Aft 2.02/115.00, Heel: zero

	Critical Points		LCP	TCP	VCP	Height
(1)	ER LOUVER	FLOOD	64.00a	4.50p	24.96	16.40
(1)	ER LOUVER	FLOOD	64.00a	4.50s	24.96	16.40
(2)	EMGEN LOUVER	FLOOD	60.00a	9.76s	25.00	16.51
(2)	EMGEN LOUVER	FLOOD	60.00a	9.76p	25.00	16.51
(3)	WET LAB DOOR	TIGHT	60.00a	13.71s	15.11	6.62
(3)	WET LAB DOOR	TIGHT	60.00a	13.71p	15.11	6.62
(4)	DRY LAB DOOR	TIGHT	84.00a	12.23s	15.27	6.35
(4)	DRY LAB DOOR	TIGHT	84.00a	12.23p	15.27	6.35
(5)	FAN ROOM DOOR	TIGHT	64.00a	7.12s	24.09	15.53
(5)	FAN ROOM DOOR	TIGHT	64.00a	7.12p	24.09	15.53
(9)	BOW		2.49f	0.00	24.98	17.59
(10)	MS AT SIDE		60.00a	15.83s	14.03	5.54
(10)	MS AT SIDE		60.00a	15.83p	14.03	5.54
(11)	TRANSOM AT CL		122.00a	0.00	16.25	6.67

Distances in FEET.

Condition 1: Minimum Operational Weight
Intact; No Damage

RIGHTING ARMS vs HEEL ANGLE

Total CG: LCG = 63.22a TCG = 0.00 VCG = 14.45
Free Surface Adjustment: 0.26
Adjusted CG: LCG = 63.22a TCG = 0.00 VCG = 14.72

Origin Depth	Degrees of Trim	Heel	Displacement Weight(LT)	Righting Arms in Trim	in Heel	Area	Flood Pt Height
7.432	1.01a	0.00	497.01	0.00	0.000	0.00	6.35(4)
7.437	0.96a	5.00s	497.00	0.00	0.291	0.73	15.61(2)
7.451	0.81a	10.00s	496.90	0.00	0.567	2.88	14.63(2)
7.447	0.57a	15.00s	497.01	0.00	0.803	6.32	13.57(2)
7.384	0.28a	20.00s	497.01	0.00	0.976	10.80	12.48(2)
7.265	0.01a	24.46s	497.01	0.00	1.028	15.31	11.44(2)
7.244	0.02f	25.00s	497.01	0.00	1.027	15.86	11.31(2)
7.099	0.16f	27.93s	497.01	0.00	1.003	18.84	-0.00(3)
6.965	0.25f	30.00s	497.01	0.00	0.968	20.87	10.07(2)
6.524	0.41f	35.00s	497.01	0.00	0.830	25.40	8.78(2)
5.907	0.49f	40.00s	497.01	0.00	0.638	29.09	7.48(2)
5.121	0.50f	45.00s	497.01	0.00	0.434	31.78	6.18(2)
4.187	0.45f	50.00s	497.01	0.00	0.223	33.42	4.87(2)
3.339	0.37f	54.20s	497.01	0.00	0.000	33.91	3.76(2)
3.171	0.36f	55.00s	497.01	0.00	-0.048	33.89	3.55(2)
2.095	0.23f	60.00s	497.02	0.00	-0.372	32.86	2.20(2)
0.970	0.08f	65.00s	496.99	0.00	-0.727	30.13	0.83(2)
0.265	0.04a	68.03s	497.03	0.00	-0.952	27.59	-0.00(2)
-0.203	0.11a	70.00s	496.99	0.00	-1.104	25.56	-0.53(2)

Distances in FEET.------Specific Gravity = 1.025.-----------Area in Ft-Deg.

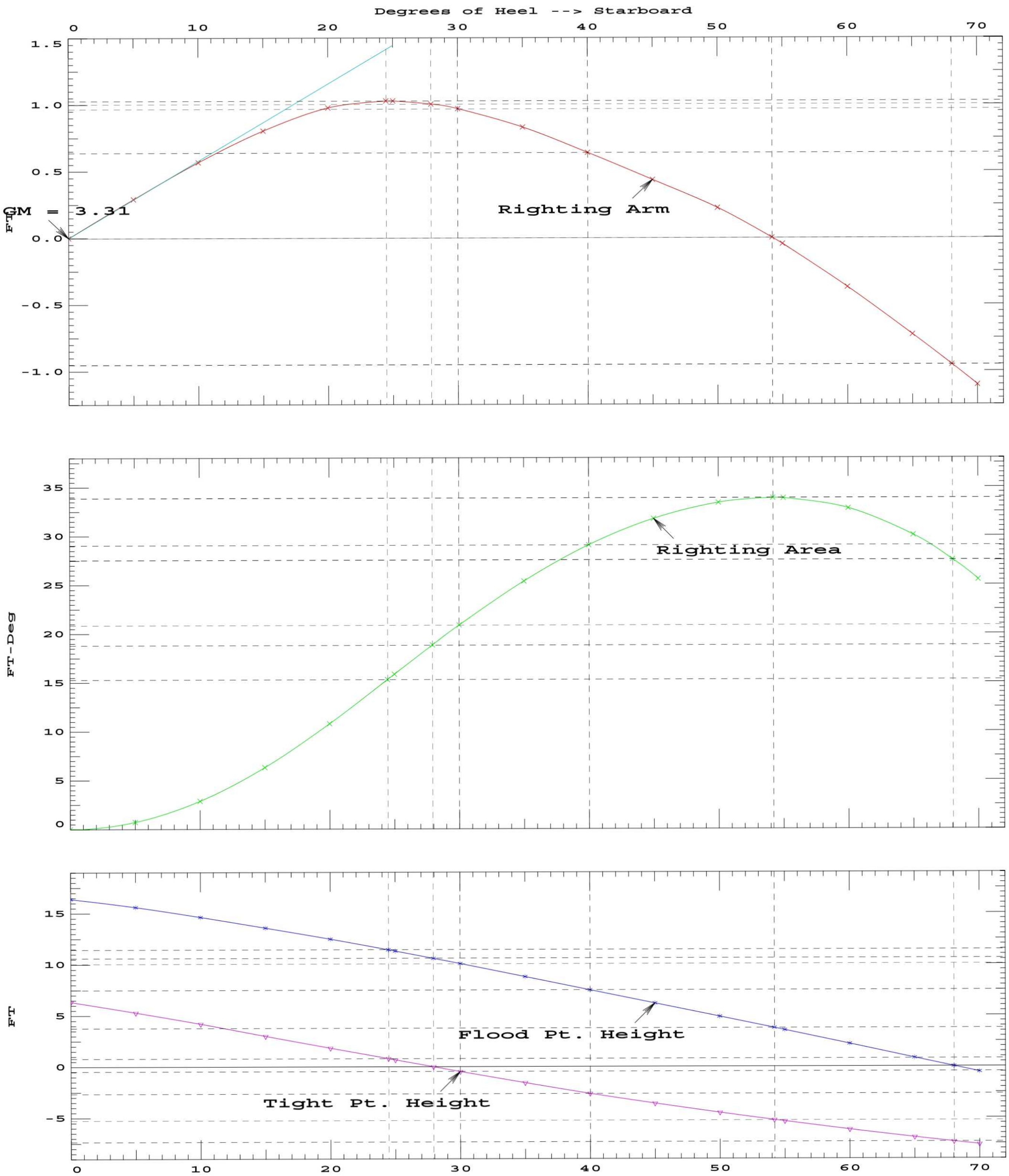
Note: No tank loads are present.

	Critical Points		LCP	TCP	VCP
(2)	EMGEN LOUVER	FLOOD	60.00a	9.76	25.00
(3)	WET LAB DOOR	TIGHT	60.00a	13.71	15.11
(4)	DRY LAB DOOR	TIGHT	84.00a	12.23	15.27

LIM	46 CFR 170.173(c) CRITERION		Min/Max		Attained	
(1)	GM Upright	>	0.49	Ft	3.31	P
(2)	Absolute Angle at MaxRA	>	15.00	deg	24.46	P
(3)	Area from abs 0.000 deg to 40 or Flood	>	16.90	Ft-deg	29.09	P
(4)	Area from 30 deg to 40 or Flood	>	5.60	Ft-deg	8.22	P
(5)	Area from abs 0.000 deg to MaxRA at 15	>	13.10	Ft-deg	17.69	P
(6)	Area from abs 0.000 deg to MaxRA at 30	>	10.30	Ft-deg	13.91	P

--------------------Relative angles measured from 0.000 --------------------

Condition 1: Minimum Operational Weight
Intact; No Damage



Condition 2: Departure without SLM
Intact; No Damage

WEIGHT STATUS
Trim: 0.00/115.00, Heel: zero

Part	Load	SpGr	Weight (LT)	LCG	TCG	VCG	FSM
LIGHT SHIP			475.01	64.18a	0.00	15.03	
CREW & EFFECTS			1.34	34.00a	0.00	27.75	
SCI & EFFECTS			2.13	36.00a	0.00	10.50	
DRY STORES			2.37	13.83a	0.00	20.17	
CHILL STORES			1.20	13.83a	0.00	20.17	
FREEZER STORES			1.69	13.83a	0.00	20.17	
GENERAL STORES			3.50	60.00a	0.00	15.00	
ENGINEERS STORES			1.00	78.33a	0.00	9.17	
SCIENCE LABS			2.00	63.08a	0.00	18.92	
SCIENCE STORES			4.00	100.00a	0.00	11.25	
SCIENCE AFT DECK			9.00	98.00a	0.00	19.17	
SCIENCE VAN 1			7.50	93.92a	0.00	19.50	
SCIENCE VAN 2			7.50	93.92a	0.00	19.50	
FIXED BALLAST			22.00	42.50a	0.00	2.00	
LH2 FUEL			0.70	78.00a	0.00	27.68	
Total Fixed--------->			540.94	64.29a	0.00	14.75	
	Load	SpGr	Weight (LT)	LCG	TCG	VCG	FSM
FP.C	0.885	1.025	7.79	5.33a	0.00	9.26	2.7
SEWAGE.C	0.100	1.025	2.88	38.18a	0.00	0.37	57.6
FODB2.P	1.000	0.870	7.44	38.71a	8.82p	4.23	0.0
FODB2.S	1.000	0.870	7.44	38.71a	8.82s	4.23	0.0
POTABLE.P	1.000	1.000	14.08	54.15a	10.10p	3.56	0.0
POTABLE.S	1.000	1.000	14.08	54.15a	10.10s	3.56	0.0
MISCDB3.P	0.500	1.025	1.26	70.00a	3.19p	0.87	2.4
MISCDB3.S	0.500	1.025	1.26	70.00a	3.19s	0.87	2.4
MISCDB4.P	0.500	1.025	1.22	73.96a	3.19p	0.95	2.4
MISCDB4.S	0.500	1.025	1.22	73.96a	3.19s	0.95	2.4
MISCDB5.P	0.500	1.025	1.09	77.90a	3.19p	1.21	2.4
MISCDB5.S	0.500	1.025	1.09	77.90a	3.19s	1.21	2.4
FOSET.P	1.000	0.870	4.00	66.02a	14.56p	8.63	0.0
FOSET.S	1.000	0.870	4.00	66.02a	14.56s	8.63	0.0
FODAY.P	1.000	0.870	4.09	70.00a	14.60p	8.59	0.0
FODAY.S	1.000	0.870	4.09	70.00a	14.60s	8.59	0.0
LO.P	0.500	0.924	2.15	73.98a	14.41p	5.94	0.5
HYDRO.S	0.500	0.924	2.15	73.98a	14.41s	5.94	0.5
Total Tanks--------->			81.32	51.61a	0.00	5.02	131.6*
Total Weight-------->			622.26	62.63a	0.00	13.48	
Free Surface Adjustment---------->						0.21	
Adjusted CG---------------------->				62.63a	0.00	13.69	

Distances in FEET.--Moments in Ft-LT.

Note: FSM values marked with an asterisk (*) are formal values which are not the same as the true values in the present condition.

Condition 2: Departure without SLM
Intact; No Damage

FREEBOARD STATUS
Baseline draft: 10.083 @ 0.00, 10.079 @ 115.00a
Trim: 0.00/115.00, Heel: zero
Least freeboard is 4.16 Ft located at 87.57a
Least extra freeboard (to margin line) is 3.91 Ft located at 87.57a

Condition 2: Departure without SLM
Intact; No Damage

HYDROSTATIC PROPERTIES
Trim: 0.00/115.00, No Heel, VCG = 13.48

LCF Draft	Displacement Weight(LT)	Buoyancy-Ctr. LCB	VCB	Weight/ Inch	LCF	Moment/ In trim	GML	GMT
10.080	622.26	62.63a	5.90	7.55	70.17a	53.44	118.5	3.35

Distances in FEET.-------Specific Gravity = 1.025.-----------Moment in Ft-LT.
Trim is per 115.00Ft
Draft is from Baseline. Formal Free Surface included.

Note: GMT includes the formal free surface moment 131.6 Ft-LT

HYDROSTATIC PROPERTIES
Trim: 0.00/115.00, No Heel, Fixed VCG = 14.75

LCF Draft	Displacement Weight(LT)	Buoyancy-Ctr. LCB	VCB	Weight/ Inch	LCF	Moment/ In trim	KML	KMT
10.080	622.26	62.63a	5.90	7.55	70.17a	52.91	132.1	17.04

Distances in FEET.-------Specific Gravity = 1.025.-----------Moment in Ft-LT.
Trim is per 115.00Ft
Draft is from Baseline.

HYDROSTATIC PROPERTIES
Trim: 0.00/115.00, No Heel

Origin Depth	Displacement Weight(LT)	Center of Buoyancy LCB	TCB	VCB	WPA	LCF	BML	BMT
10.083	622.26	62.63a	0.00	5.90	3170	70.17a	126.1	10.92

Distances in FEET.----Specific Gravity = 1.025.---Formal Free Surface included.

Note: BMT includes the formal free surface moment 131.6 Ft-LT

"DRAFT AT FWD MARKS" 10.082
"DRAFT AT MIDSHIP" 10.081
"DRAFT AT AFT MARKS" 10.079

Condition 2: Departure without SLM
Intact; No Damage

CRITICAL POINT STATUS
Baseline draft: 10.083 @ 0.00, 10.079 @ 115.00a
Trim: 0.00/115.00, Heel: zero

	Critical Points		LCP	TCP	VCP	Height
(1)	ER LOUVER	FLOOD	64.00a	4.50p	24.96	14.88
(1)	ER LOUVER	FLOOD	64.00a	4.50s	24.96	14.88
(2)	EMGEN LOUVER	FLOOD	60.00a	9.76s	25.00	14.92
(2)	EMGEN LOUVER	FLOOD	60.00a	9.76p	25.00	14.92
(3)	WET LAB DOOR	TIGHT	60.00a	13.71s	15.11	5.03
(3)	WET LAB DOOR	TIGHT	60.00a	13.71p	15.11	5.03
(4)	DRY LAB DOOR	TIGHT	84.00a	12.23s	15.27	5.19
(4)	DRY LAB DOOR	TIGHT	84.00a	12.23p	15.27	5.19
(5)	FAN ROOM DOOR	TIGHT	64.00a	7.12s	24.09	14.01
(5)	FAN ROOM DOOR	TIGHT	64.00a	7.12p	24.09	14.01
(9)	BOW		2.49f	0.00	24.98	14.90
(10)	MS AT SIDE		60.00a	15.83s	14.03	3.95
(10)	MS AT SIDE		60.00a	15.83p	14.03	3.95
(11)	TRANSOM AT CL		122.00a	0.00	16.25	6.17

Distances in FEET.

Condition 2: Departure without SLM
Intact; No Damage

RIGHTING ARMS vs HEEL ANGLE

Total CG: LCG = 62.63a TCG = 0.00 VCG = 13.48
Free Surface Adjustment: 0.21
Adjusted CG: LCG = 62.63a TCG = 0.00 VCG = 13.69

Origin Depth	Degrees of Trim	Heel	Displacement Weight(LT)	Righting Arms in Trim	in Heel	Area	Flood Pt Height
10.082	0.00	0.00	622.26	0.00	0.000	0.00	5.03(3)
10.066	0.04f	5.00s	622.26	0.00	0.295	0.74	14.03(2)
10.012	0.13f	10.00s	622.23	0.00	0.584	2.94	13.05(2)
9.912	0.29f	15.00s	622.23	0.00	0.859	6.55	12.01(2)
9.756	0.46f	20.00s	622.30	0.00	1.031	11.32	10.88(2)
9.710	0.49f	20.97s	622.27	0.00	1.049	12.33	-0.00(3)
9.449	0.55f	25.00s	622.27	0.00	1.080	16.65	9.66(2)
8.959	0.55f	30.00s	622.29	0.00	1.056	22.03	8.39(2)
8.295	0.46f	35.00s	622.26	0.00	1.005	27.19	7.06(2)
7.465	0.30f	40.00s	622.24	0.00	0.952	32.09	5.72(2)
6.489	0.08f	45.00s	622.25	0.00	0.868	36.65	4.38(2)
5.437	0.15a	50.00s	622.24	0.00	0.704	40.61	3.00(2)
4.348	0.37a	55.00s	622.23	0.00	0.475	43.59	1.61(2)
3.245	0.56a	60.00s	622.23	0.00	0.201	45.30	0.22(2)
3.073	0.59a	60.78s	622.26	0.00	0.155	45.44	-0.00(2)
2.498	0.67a	63.37s	622.26	0.00	0.000	45.64	-0.72(2)
2.136	0.72a	65.00s	622.26	0.00	-0.099	45.56	-1.17(2)

Distances in FEET.------Specific Gravity = 1.025.-----------Area in Ft-Deg.

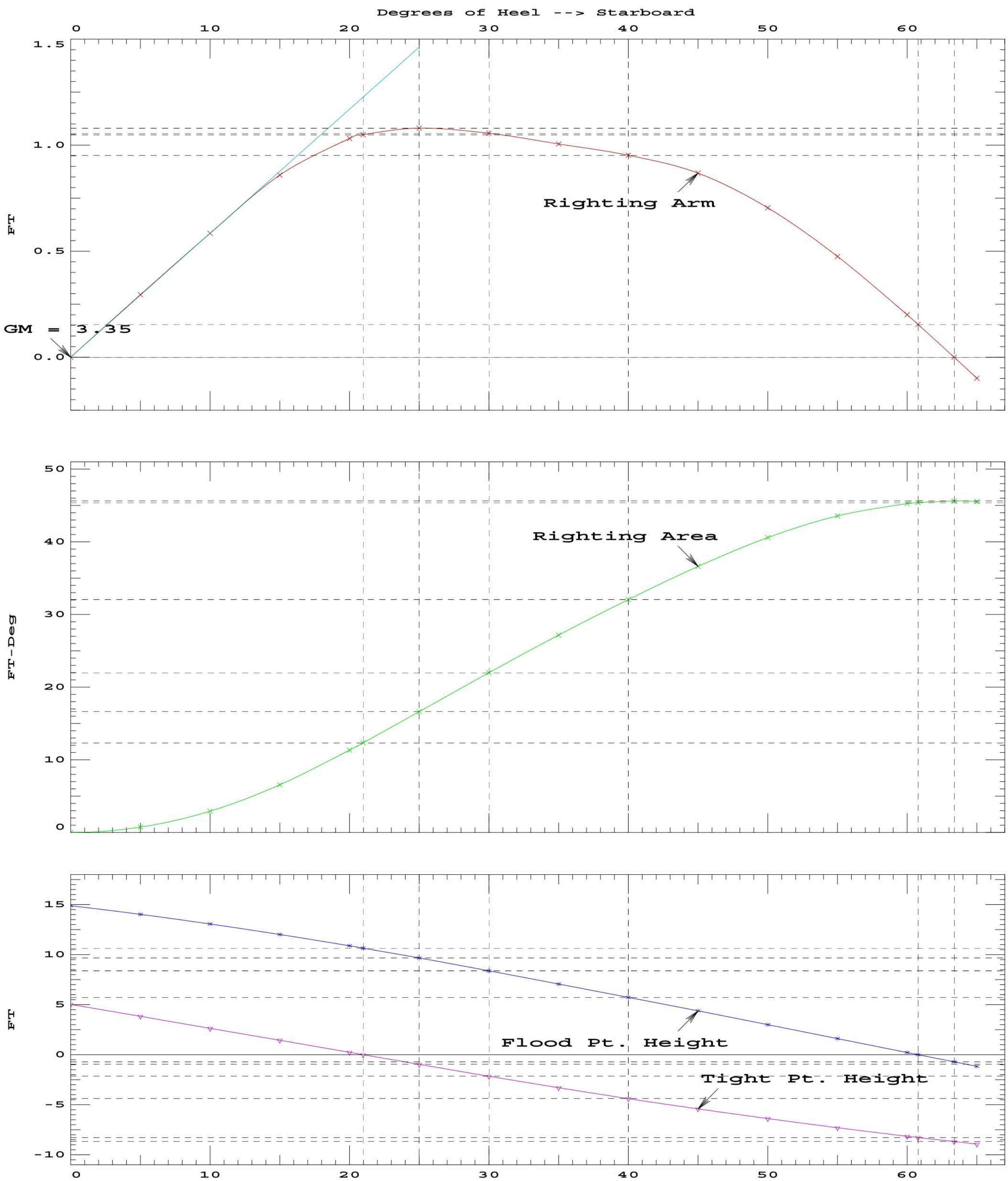
Note: The Weight and Center of Gravity used for the righting arms above include tank loads. However, the tank load centers were NOT ALLOWED TO SHIFT with heel and trim changes. Rather, a constant Free Surface Moment of 131.6 Ft-LT was applied to artificially modify the CG.

	Critical Points		LCP	TCP	VCP
(2)	EMGEN LOUVER	FLOOD	60.00a	9.76	25.00
(3)	WET LAB DOOR	TIGHT	60.00a	13.71	15.11

LIM	46 CFR 170.173(c) CRITERION		Min/Max		Attained
(1)	GM Upright	>	0.49	Ft	3.35 P
(2)	Absolute Angle at MaxRA	>	15.00	deg	25.00 P
(3)	Area from abs 0.000 deg to 40 or Flood	>	16.90	Ft-deg	32.09 P
(4)	Area from 30 deg to 40 or Flood	>	5.60	Ft-deg	10.06 P
(5)	Area from abs 0.000 deg to MaxRA at 15	>	13.10	Ft-deg	19.41 P
(6)	Area from abs 0.000 deg to MaxRA at 30	>	10.30	Ft-deg	15.26 P

--------------------Relative angles measured from 0.000 --------------------

Condition 2: Departure without SLM
Intact; No Damage



Condition 3: Mid Voyage without SLM
Intact; No Damage

WEIGHT STATUS
Trim: Aft 0.15/115.00, Heel: zero

Part	Weight (LT)	LCG	TCG	VCG
LIGHT SHIP	475.01	64.18a	0.00	15.03
CREW & EFFECTS	1.34	34.00a	0.00	27.75
SCI & EFFECTS	2.13	36.00a	0.00	10.50
DRY STORES	2.37	13.83a	0.00	20.17
CHILL STORES	1.20	13.83a	0.00	20.17
FREEZER STORES	1.69	13.83a	0.00	20.17
GENERAL STORES	3.50	60.00a	0.00	15.00
ENGINEERS STORES	1.00	78.33a	0.00	9.17
SCIENCE LABS	2.00	63.08a	0.00	18.92
SCIENCE STORES	4.00	100.00a	0.00	11.25
SCIENCE AFT DECK	9.00	98.00a	0.00	19.17
SCIENCE VAN 1	7.50	93.92a	0.00	19.50
SCIENCE VAN 2	7.50	93.92a	0.00	19.50
FIXED BALLAST	22.00	42.50a	0.00	2.00
LH2 FUEL	0.37	78.00a	0.00	27.68
Total Fixed--------->	540.61	64.28a	0.00	14.74

Part	Load	SpGr	Weight (LT)	LCG	TCG	VCG	FSM
FP.C	0.885	1.025	7.79	5.33a	0.00	9.26	2.7
SEWAGE.C	0.600	1.025	17.27	38.03a	0.00	2.05	58.3
FODB2.P	0.250	0.870	1.86	39.18a	8.00p	1.94	1.7
FODB2.S	0.250	0.870	1.86	39.18a	8.00s	1.94	1.7
POTABLE.P	0.500	1.000	7.04	54.30a	9.51p	2.13	12.8
POTABLE.S	0.500	1.000	7.04	54.30a	9.51s	2.13	12.8
VOID3.C	1.000	1.025	5.02	66.00a	0.00	1.75	0.0
MISCDB3.P	0.500	1.025	1.26	70.00a	3.19p	0.87	2.4
MISCDB3.S	0.500	1.025	1.26	70.00a	3.19s	0.87	2.4
MISCDB4.P	0.500	1.025	1.22	73.96a	3.19p	0.95	2.4
MISCDB4.S	0.500	1.025	1.22	73.96a	3.19s	0.95	2.4
MISCDB5.P	0.500	1.025	1.09	77.90a	3.19p	1.21	2.4
MISCDB5.S	0.500	1.025	1.09	77.90a	3.19s	1.21	2.4
FOSET.P	0.750	0.870	3.00	66.02a	14.48p	7.26	0.5
FOSET.S	0.750	0.870	3.00	66.02a	14.48s	7.26	0.5
FODAY.P	0.750	0.870	3.07	70.00a	14.52p	7.22	0.5
FODAY.S	0.750	0.870	3.07	70.00a	14.52s	7.22	0.5
LO.P	0.300	0.924	1.29	73.97a	14.23p	4.73	0.5
HYDRO.S	0.300	0.924	1.29	73.97a	14.23s	4.73	0.5
Total Tanks--------->			69.74	49.94a	0.00	3.74	131.6*
Total Weight-------->			610.35	62.64a	0.00	13.48	
Free Surface Adjustment---------->						0.22	
Adjusted CG--------------------->				62.64a	0.00	13.70	

Distances in FEET.--Moments in Ft-LT.

Note: FSM values marked with an asterisk (*) are formal values which are not the same as the true values in the present condition.

Condition 3: Mid Voyage without SLM
Intact; No Damage

FREEBOARD STATUS
Baseline draft: 9.858 @ 0.00, 10.006 @ 115.00a
Trim: Aft 0.15/115.00, Heel: zero
Least freeboard is 4.27 Ft located at 87.57a
Least extra freeboard (to margin line) is 4.02 Ft located at 87.57a

Condition 3: Mid Voyage without SLM
Intact; No Damage

HYDROSTATIC PROPERTIES
Trim: Aft 0.15/115.00, No Heel, VCG = 13.48

LCF Draft	Displacement Weight(LT)	Buoyancy-Ctr. LCB	VCB	Weight/ Inch	LCF	Moment/ In trim	GML	GMT
9.949	610.35	62.65a	5.82	7.52	70.18a	52.99	119.8	3.40

Distances in FEET.-------Specific Gravity = 1.025.-----------Moment in Ft-LT.
Trim is per 115.00Ft
Draft is from Baseline. Formal Free Surface included.

Note: GMT includes the formal free surface moment 131.6 Ft-LT

HYDROSTATIC PROPERTIES
Trim: Aft 0.15/115.00, No Heel, Fixed VCG = 14.74

LCF Draft	Displacement Weight(LT)	Buoyancy-Ctr. LCB	VCB	Weight/ Inch	LCF	Moment/ In trim	KML	KMT
9.949	610.35	62.65a	5.82	7.52	70.18a	52.54	133.5	17.10

Distances in FEET.-------Specific Gravity = 1.025.-----------Moment in Ft-LT.
Trim is per 115.00Ft
Draft is from Baseline.

HYDROSTATIC PROPERTIES
Trim: Aft 0.15/115.00, No Heel

Origin Depth	Displacement Weight(LT)	Center of Buoyancy LCB	TCB	VCB	WPA	LCF	BML	BMT
9.858	610.35	62.65a	0.00	5.82	3160	70.18a	127.5	11.06

Distances in FEET.----Specific Gravity = 1.025.---Formal Free Surface included.

Note: BMT includes the formal free surface moment 131.6 Ft-LT

"DRAFT AT FWD MARKS" 9.868
"DRAFT AT MIDSHIP" 9.935
"DRAFT AT AFT MARKS" 10.003

Condition 3: Mid Voyage without SLM
Intact; No Damage

CRITICAL POINT STATUS
Baseline draft: 9.858 @ 0.00, 10.006 @ 115.00a
Trim: Aft 0.15/115.00, Heel: zero

	Critical Points		LCP	TCP	VCP	Height
(1)	ER LOUVER	FLOOD	64.00a	4.50p	24.96	15.02
(1)	ER LOUVER	FLOOD	64.00a	4.50s	24.96	15.02
(2)	EMGEN LOUVER	FLOOD	60.00a	9.76s	25.00	15.06
(2)	EMGEN LOUVER	FLOOD	60.00a	9.76p	25.00	15.06
(3)	WET LAB DOOR	TIGHT	60.00a	13.71s	15.11	5.17
(3)	WET LAB DOOR	TIGHT	60.00a	13.71p	15.11	5.17
(4)	DRY LAB DOOR	TIGHT	84.00a	12.23s	15.27	5.30
(4)	DRY LAB DOOR	TIGHT	84.00a	12.23p	15.27	5.30
(5)	FAN ROOM DOOR	TIGHT	64.00a	7.12s	24.09	14.15
(5)	FAN ROOM DOOR	TIGHT	64.00a	7.12p	24.09	14.15
(9)	BOW		2.49f	0.00	24.98	15.13
(10)	MS AT SIDE		60.00a	15.83s	14.03	4.10
(10)	MS AT SIDE		60.00a	15.83p	14.03	4.10
(11)	TRANSOM AT CL		122.00a	0.00	16.25	6.23

Distances in FEET.

Condition 3: Mid Voyage without SLM
Intact; No Damage

RIGHTING ARMS vs HEEL ANGLE

Total CG: LCG = 62.64a TCG = 0.00 VCG = 13.48
Free Surface Adjustment: 0.22
Adjusted CG: LCG = 62.64a TCG = 0.00 VCG = 13.70

Origin Depth	Degrees of Trim	Degrees of Heel	Displacement Weight(LT)	Righting Arms in Trim	Righting Arms in Heel	Area	Flood Pt Height
9.860	0.07a	0.00	610.42	0.00	0.000	0.00	5.17(3)
9.844	0.04a	5.00s	610.34	0.00	0.299	0.75	14.17(2)
9.796	0.06f	10.00s	610.31	0.00	0.593	2.98	13.20(2)
9.704	0.23f	15.00s	610.30	0.00	0.873	6.65	12.16(2)
9.560	0.41f	20.00s	610.38	0.00	1.054	11.51	11.03(2)
9.486	0.46f	21.60s	610.35	0.00	1.084	13.21	-0.00(3)
9.269	0.53f	25.00s	610.35	0.00	1.109	16.96	9.82(2)
8.800	0.55f	30.00s	610.35	0.00	1.088	22.50	8.54(2)
8.159	0.48f	35.00s	610.35	0.00	1.036	27.82	7.22(2)
7.350	0.34f	40.00s	610.33	0.00	0.977	32.85	5.89(2)
6.387	0.15f	45.00s	610.34	0.00	0.892	37.53	4.54(2)
5.345	0.07a	50.00s	610.33	0.00	0.729	41.62	3.18(2)
4.263	0.27a	55.00s	610.32	0.00	0.499	44.72	1.79(2)
3.165	0.46a	60.00s	610.33	0.00	0.221	46.54	0.40(2)
2.842	0.50a	61.46s	610.35	0.00	0.134	46.80	-0.00(2)
2.359	0.57a	63.64s	610.35	0.00	0.000	46.94	-0.60(2)
2.058	0.61a	65.00s	610.34	0.00	-0.084	46.89	-0.97(2)

Distances in FEET.------Specific Gravity = 1.025.-----------Area in Ft-Deg.

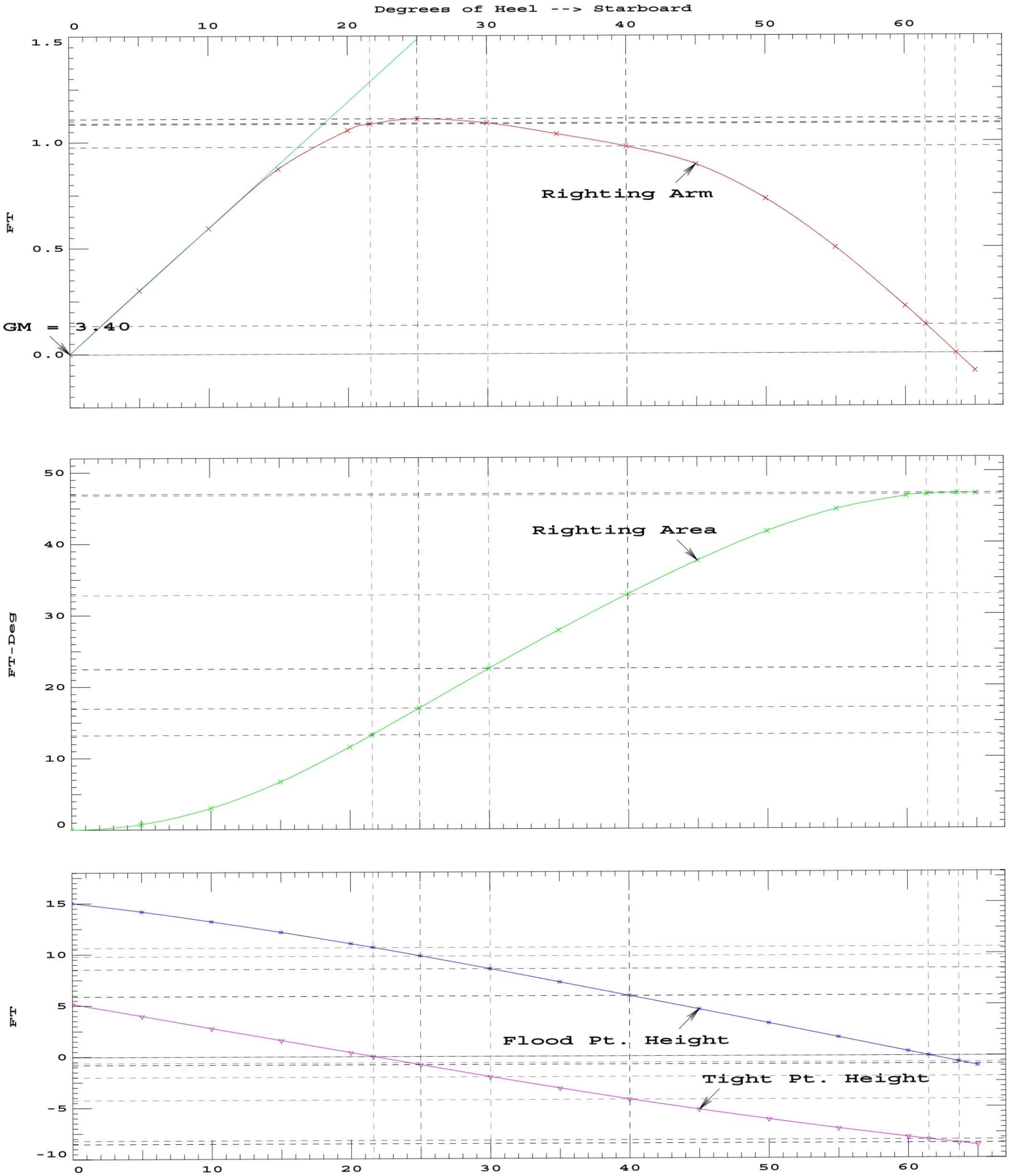
Note: The Weight and Center of Gravity used for the righting arms above include tank loads. However, the tank load centers were NOT ALLOWED TO SHIFT with heel and trim changes. Rather, a constant Free Surface Moment of 131.6 Ft-LT was applied to artificially modify the CG.

Critical Points		LCP	TCP	VCP
(2) EMGEN LOUVER	FLOOD	60.00a	9.76	25.00
(3) WET LAB DOOR	TIGHT	60.00a	13.71	15.11

LIM	46 CFR 170.173(c) CRITERION		Min/Max		Attained	
(1)	GM Upright	>	0.49	Ft	3.40	P
(2)	Absolute Angle at MaxRA	>	15.00	deg	25.00	P
(3)	Area from abs 0.000 deg to 40 or Flood	>	16.90	Ft-deg	32.85	P
(4)	Area from 30 deg to 40 or Flood	>	5.60	Ft-deg	10.36	P
(5)	Area from abs 0.000 deg to MaxRA at 15	>	13.10	Ft-deg	19.78	P
(6)	Area from abs 0.000 deg to MaxRA at 30	>	10.30	Ft-deg	15.55	P

--------------------Relative angles measured from 0.000 --------------------

Condition 3: Mid Voyage without SLM
Intact; No Damage



Condition 4: Arrival without SLM
Intact; No Damage

WEIGHT STATUS
Trim: Aft 0.04/115.00, Heel: zero

Part	Weight (LT)	LCG	TCG	VCG
LIGHT SHIP	475.01	64.18a	0.00	15.03
CREW & EFFECTS	1.34	34.00a	0.00	27.75
SCI & EFFECTS	2.13	36.00a	0.00	10.50
DRY STORES	2.37	13.83a	0.00	20.17
CHILL STORES	1.20	13.83a	0.00	20.17
FREEZER STORES	1.69	13.83a	0.00	20.17
GENERAL STORES	3.50	60.00a	0.00	15.00
ENGINEERS STORES	1.00	78.33a	0.00	9.17
SCIENCE LABS	2.00	63.08a	0.00	18.92
SCIENCE STORES	4.00	100.00a	0.00	11.25
SCIENCE AFT DECK	9.00	98.00a	0.00	19.17
SCIENCE VAN 1	7.50	93.92a	0.00	19.50
SCIENCE VAN 2	7.50	93.92a	0.00	19.50
FIXED BALLAST	22.00	42.50a	0.00	2.00
LH2 FUEL	0.04	78.00a	0.00	27.68
Total Fixed--------->	540.28	64.27a	0.00	14.73

Part	Load	SpGr	Weight (LT)	LCG	TCG	VCG	FSM
FP.C	0.885	1.025	7.79	5.33a	0.00	9.26	2.7
SEWAGE.C	1.000	1.025	28.79	37.96a	0.00	3.39	0.0
POTABLE.P	0.100	1.000	1.41	54.52a	8.63p	0.69	4.8
POTABLE.S	0.100	1.000	1.41	54.52a	8.63s	0.69	4.8
VOID3.C	1.000	1.025	5.02	66.00a	0.00	1.75	0.0
MISCDB3.P	0.500	1.025	1.26	70.00a	3.19p	0.87	2.4
MISCDB3.S	0.500	1.025	1.26	70.00a	3.19s	0.87	2.4
MISCDB4.P	0.500	1.025	1.22	73.96a	3.19p	0.95	2.4
MISCDB4.S	0.500	1.025	1.22	73.96a	3.19s	0.95	2.4
MISCDB5.P	0.500	1.025	1.09	77.90a	3.19p	1.21	2.4
MISCDB5.S	0.500	1.025	1.09	77.90a	3.19s	1.21	2.4
FOSET.P	0.250	0.870	1.00	66.04a	14.10p	4.26	0.4
FOSET.S	0.250	0.870	1.00	66.04a	14.10s	4.26	0.4
FODAY.P	0.250	0.870	1.02	69.99a	14.14p	4.23	0.4
FODAY.S	0.250	0.870	1.02	69.99a	14.14s	4.23	0.4
LO.P	0.100	0.924	0.43	73.94a	13.66p	3.19	0.2
HYDRO.S	0.100	0.924	0.43	73.94a	13.66s	3.19	0.2
Total Tanks--------->			56.46	44.01a	0.00	3.68	131.6*
Total Weight-------->			596.74	62.35a	0.00	13.69	
Free Surface Adjustment---------->						0.22	
Adjusted CG---------------------->				62.35a	0.00	13.91	

Distances in FEET.--Moments in Ft-LT.

Note: FSM values marked with an asterisk (*) are formal values which are not the same as the true values in the present condition.

Condition 4: Arrival without SLM
Intact; No Damage

FREEBOARD STATUS
Baseline draft: 9.776 @ 0.00, 9.811 @ 115.00a
Trim: Aft 0.04/115.00, Heel: zero
Least freeboard is 4.44 Ft located at 87.57a
Least extra freeboard (to margin line) is 4.19 Ft located at 87.57a

Condition 4: Arrival without SLM
Intact; No Damage

HYDROSTATIC PROPERTIES
Trim: Aft 0.04/115.00, No Heel, VCG = 13.69

LCF Draft	Displacement Weight(LT)	Buoyancy-Ctr. LCB	VCB	Weight/ Inch	LCF	Moment/ In trim	GML	GMT
9.797	596.74	62.36a	5.73	7.48	70.03a	52.34	121.0	3.22

Distances in FEET.-------Specific Gravity = 1.025.-----------Moment in Ft-LT.
Trim is per 115.00Ft
Draft is from Baseline. Formal Free Surface included.

Note: GMT includes the formal free surface moment 131.6 Ft-LT

HYDROSTATIC PROPERTIES
Trim: Aft 0.04/115.00, No Heel, Fixed VCG = 14.73

LCF Draft	Displacement Weight(LT)	Buoyancy-Ctr. LCB	VCB	Weight/ Inch	LCF	Moment/ In trim	KML	KMT
9.797	596.74	62.36a	5.73	7.48	70.03a	51.93	134.8	17.13

Distances in FEET.-------Specific Gravity = 1.025.-----------Moment in Ft-LT.
Trim is per 115.00Ft
Draft is from Baseline.

HYDROSTATIC PROPERTIES
Trim: Aft 0.04/115.00, No Heel

Origin Depth	Displacement Weight(LT)	Center of Buoyancy LCB	TCB	VCB	WPA	LCF	BML	BMT
9.776	596.74	62.36a	0.00	5.73	3143	70.03a	129.0	11.18

Distances in FEET.----Specific Gravity = 1.025.---Formal Free Surface included.

Note: BMT includes the formal free surface moment 131.6 Ft-LT

"DRAFT AT FWD MARKS" 9.778
"DRAFT AT MIDSHIP" 9.794
"DRAFT AT AFT MARKS" 9.810

Condition 4: Arrival without SLM
Intact; No Damage

CRITICAL POINT STATUS
Baseline draft: 9.776 @ 0.00, 9.811 @ 115.00a
Trim: Aft 0.04/115.00, Heel: zero

	Critical Points		LCP	TCP	VCP	Height
(1)	ER LOUVER	FLOOD	64.00a	4.50p	24.96	15.17
(1)	ER LOUVER	FLOOD	64.00a	4.50s	24.96	15.17
(2)	EMGEN LOUVER	FLOOD	60.00a	9.76s	25.00	15.21
(2)	EMGEN LOUVER	FLOOD	60.00a	9.76p	25.00	15.21
(3)	WET LAB DOOR	TIGHT	60.00a	13.71s	15.11	5.32
(3)	WET LAB DOOR	TIGHT	60.00a	13.71p	15.11	5.32
(4)	DRY LAB DOOR	TIGHT	84.00a	12.23s	15.27	5.47
(4)	DRY LAB DOOR	TIGHT	84.00a	12.23p	15.27	5.47
(5)	FAN ROOM DOOR	TIGHT	64.00a	7.12s	24.09	14.29
(5)	FAN ROOM DOOR	TIGHT	64.00a	7.12p	24.09	14.29
(9)	BOW		2.49f	0.00	24.98	15.21
(10)	MS AT SIDE		60.00a	15.83s	14.03	4.24
(10)	MS AT SIDE		60.00a	15.83p	14.03	4.24
(11)	TRANSOM AT CL		122.00a	0.00	16.25	6.44

Distances in FEET.

Condition 4: Arrival without SLM
Intact; No Damage

RIGHTING ARMS vs HEEL ANGLE

Total CG: LCG = 62.35a TCG = 0.00 VCG = 13.69
Free Surface Adjustment: 0.22
Adjusted CG: LCG = 62.35a TCG = 0.00 VCG = 13.91

Origin Depth	Degrees of Trim	Heel	Displacement Weight(LT)	Righting Arms in Trim	in Heel	Area	Flood Pt Height
9.778	0.02a	0.00	596.84	0.00	0.000	0.00	5.31(3)
9.764	0.02f	5.00s	596.74	0.00	0.283	0.71	14.31(2)
9.724	0.13f	10.00s	596.70	0.00	0.560	2.82	13.34(2)
9.645	0.31f	15.00s	596.66	0.00	0.825	6.29	12.30(2)
9.513	0.51f	20.00s	596.76	0.00	1.002	10.89	11.18(2)
9.415	0.59f	22.25s	596.75	0.00	1.039	13.19	-0.00(3)
9.249	0.67f	25.00s	596.75	0.00	1.054	16.08	9.98(2)
8.809	0.72f	30.00s	596.75	0.00	1.027	21.32	8.72(2)
8.196	0.69f	35.00s	596.74	0.00	0.964	26.31	7.41(2)
7.412	0.59f	40.00s	596.74	0.00	0.888	30.95	6.08(2)
6.466	0.42f	45.00s	596.74	0.00	0.792	35.15	4.75(2)
5.434	0.23f	50.00s	596.73	0.00	0.619	38.71	3.40(2)
4.359	0.04f	55.00s	596.72	0.00	0.376	41.23	2.02(2)
3.265	0.13a	60.00s	596.74	0.00	0.085	42.40	0.64(2)
2.967	0.18a	61.35s	596.76	0.00	0.000	42.46	0.27(2)
2.751	0.21a	62.33s	596.74	0.00	-0.062	42.43	-0.00(2)
2.157	0.28a	65.00s	596.75	0.00	-0.236	42.03	-0.73(2)
1.035	0.42a	70.00s	596.78	0.00	-0.566	40.03	-2.09(2)

Distances in FEET.------Specific Gravity = 1.025.-----------Area in Ft-Deg.

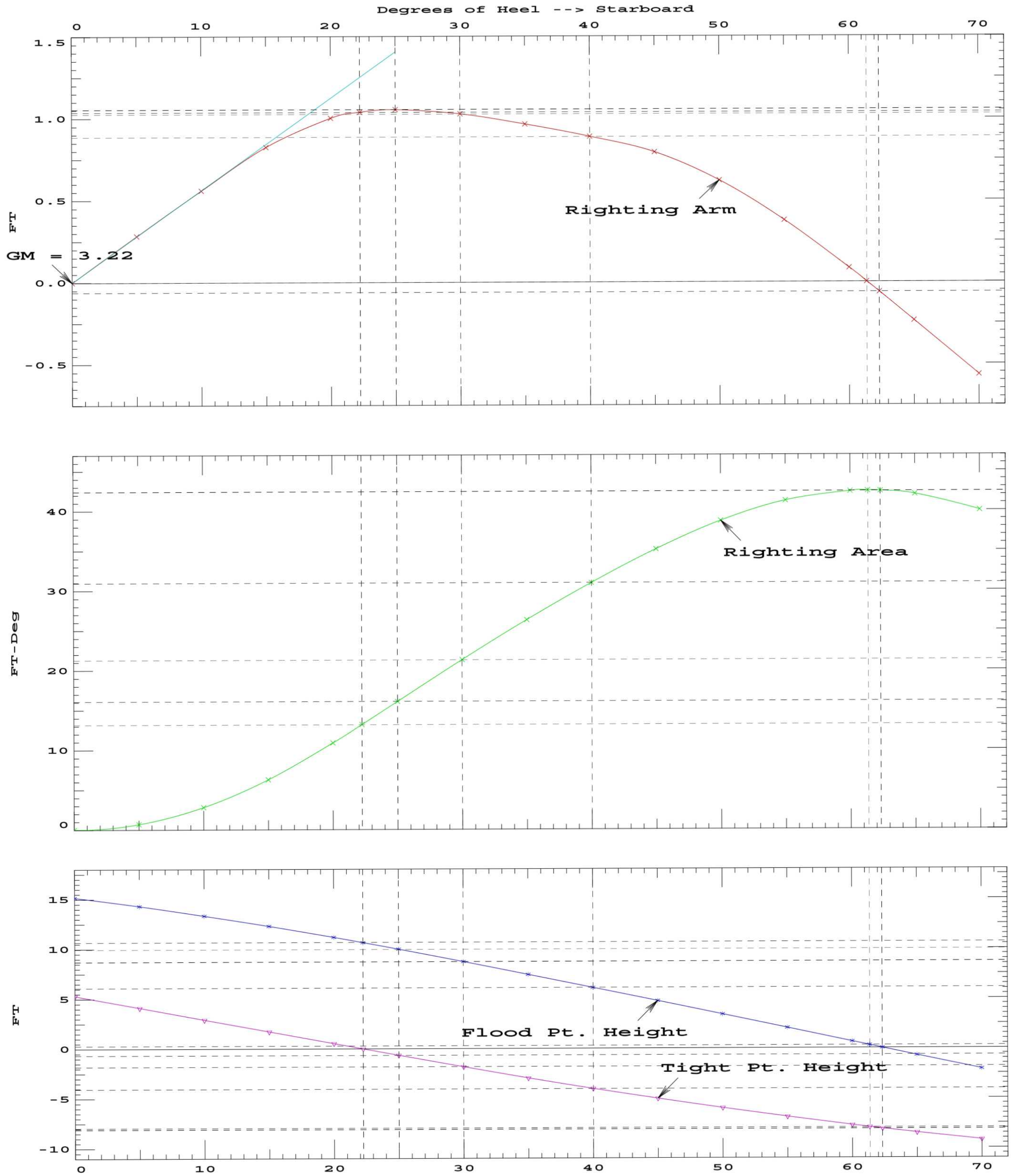
Note: The Weight and Center of Gravity used for the righting arms above include tank loads. However, the tank load centers were NOT ALLOWED TO SHIFT with heel and trim changes. Rather, a constant Free Surface Moment of 131.6 Ft-LT was applied to artificially modify the CG.

	Critical Points		LCP	TCP	VCP
(2)	EMGEN LOUVER	FLOOD	60.00a	9.76	25.00
(3)	WET LAB DOOR	TIGHT	60.00a	13.71	15.11

LIM	46 CFR 170.173(c) CRITERION		Min/Max		Attained	
(1)	GM Upright	>	0.49	Ft	3.22	P
(2)	Absolute Angle at MaxRA	>	15.00	deg	25.00	P
(3)	Area from abs 0.000 deg to 40 or Flood	>	16.90	Ft-deg	30.95	P
(4)	Area from 30 deg to 40 or Flood	>	5.60	Ft-deg	9.63	P
(5)	Area from abs 0.000 deg to MaxRA at 15	>	13.10	Ft-deg	18.75	P
(6)	Area from abs 0.000 deg to MaxRA at 30	>	10.30	Ft-deg	14.74	P

--------------------Relative angles measured from 0.000 --------------------

Condition 4: Arrival without SLM
Intact; No Damage



Appendix C Sandia Emissions Report

Emission of Greenhouse Gases and Criteria Pollutants

Lennie Klebanoff, Sandia National Laboratories

Here we assesses the emission of greenhouse gases (GHG) and criteria pollutants from the baseline vessel fueled with diesel fuel ("the Diesel Baseline vessel"), the same baseline vessel fueled with biodiesel as a drop-in replacement fuel ("the Biodiesel Baseline vessel"), the Hydrogen Hybrid vessel and the Battery Hybrid vessel. All vessel emissions are compared for the vessels performing the same suite of Scripps science missions over the course of a year.

GHG emissions (CO_2, N_2O, CH_4) for the Hydrogen Hybrid vessel are calculated for hydrogen sourced from natural gas (NG), water electrolysis using the European Union (EU) grid mix (similar to the grid mix of California) and for hydrogen made from renewable (low-carbon) sources such as electrolysis using nuclear, solar or wind based electricity sources. GHG emissions for the Battery Hybrid are calculated assuming shore power characteristic of the EU grid or 100% renewable electricity. For both the Hydrogen Hybrid and Battery Hybrid vessels, emissions coming from the companion carbon-based fuel (either diesel or biodiesel) are calculated as well. Three criteria pollutants were evaluated: Nitrogen oxides (NO_x), hydrocarbons (HC) and particulate matter of diameter 10 microns or less (PM_{10}). For the Hydrogen Hybrid these are calculated for NG-sourced hydrogen and 100% renewable hydrogen, with the diesel generators running on either fossil diesel fuel or biodiesel. The Battery Hybrid vessel criteria emissions are calculated with shore power sourced from the CA grid and 100% renewable electricity, with the companion diesel propulsion generators running on either diesel fuel or biodiesel.

Water is the only product of proton exchange membrane (PEM) fuel cell operation. There is no formation of CO_2, NO_x, SO_x, or particulate matter (PM), making the PEM fuel cell a zero-emissions power plant for the Hydrogen Hybrid vessel. As a result, the GHG emissions associated with the use of a PEM fuel cell on the Hydrogen Hybrid only arise from emissions associated with the production and transport of liquid hydrogen (LH_2) to the vessel. This fuel pathway is referred to as "well-to-tank" (WTT). The Hydrogen Hybrid also has a diesel propulsion component, and GHG emissions arise from the production and delivery of diesel fuel to the vessel. If the diesel fuel originates from petroleum (i.e. fossil diesel), then there is the additional GHG emissions associated with its combustion in the propulsion engines. Thus, GHG emissions from the Diesel Baseline vessel, and emissions from the use of fossil diesel in the Hydrogen Hybrid and Battery Hybrid vessels, arise from two sources: 1) the WTT production and delivery of the diesel fuel and 2) the combustion of the fuel. This is also true for the criteria pollutants. For our maritime application, we refer to this pathway from well to end use on the vessel as "well-to-waves" (WTW).

Our GHG estimates rely on the WTT GHG analysis conducted by the European Commission for automotive fuels in 2007 [1], which were updated in 2013 [2]. These studies considered a wide variety of pathways (both fossil fuel and renewable) for generating hydrogen. As described in Reference 2, the WTT analysis considers the process of producing, transporting, manufacturing and distributing a number of fuels, including hydrogen, diesel, and biodiesel fuel. The study covers all steps in producing and delivering a final fuel product to the storage tank of an end use (e.g., vessel) with the steps defining a WTT pathway. Energy costs and GHG emissions are assessed along various fuel production/delivery pathways. The study assumes the infrastructure for fuel production and delivery already exists, hence it does not consider GHG emissions associated with construction or decommissioning of plants (which are relatively negligible anyway). For fuels of biomass origin, such as biodiesel or hydrogen from wood gasification, the predicted GHG emissions do not include emissions caused by land use change but do include N_2O emissions from use of fertilizer and N_2O release from agricultural lands.

The prior SF-BREEZE project report [3] and a recent publication [4] reviews the 4 general categories defining a WTT pathway. The *Production and Conditioning at Source* category captures all operations required to extract, capture or cultivate the primary energy source at its point of capture. The *Transportation to Processing Plant* category captures the transportation of the primary energy carrier to the processing plant where the primary energy carrier is refined into finished fuel. The *Processing at Plant* category captures the energy and GHG emissions involved in processing and transforming the product into a final fuel to an agreed upon specification near the final market. Furthermore, if the hydrogen needs to be liquefied (as it does for the Hydrogen Hybrid), liquefaction also takes place at the centralized plant and involves significant energy input with associated GHG emissions. The *Distribution* category captures the energy and GHG emissions associated with transport to the final customer end use. While hydrogen may one day be delivered by pipeline, for the Hydrogen Hybrid application, we consider LH_2 to be initially delivered by road tanker. Taken together, the emissions associated with these four categories are added together to form the WTT pathway emissions, which are the emissions already released by the time the fuel is delivered to the vessel. If in using the fuel the vessel has emissions, then these need to be added to the WTT emissions to form the WTW emissions, which capture the entire emissions associated with fuel production and delivery as well as use to power the vessel.

The major GHGs accounted for [2 - 4] are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Natural gas is ~ 90% methane. The results are expressed as "CO_2 equivalence" (CO_2 (eq.)) and each gas is assigned a CO_2 (eq.) "weighting factor." CO_2 has a weighting factor of 1, whereas CH_4 has a factor of 23. Thus, methane is 23 times more potent a GHG than carbon dioxide. Thus, leaks of NG are of significant environmental concern. Nitrous oxide emission derives primarily from nitrogen fertilizer production and release from open agricultural fields. Although produced in relatively smaller amounts, N_2O is an important GHG because of its very large weighting factor of 296. In contrast to CO_2, CH_4, and N_2O, H_2 is not a GHG, so leaks of hydrogen, while an economic loss and a safety concern, have no environmental impact.

The LH_2 WTT pathways considered in this study are depicted in Figure 1 and have also been presented elsewhere [1 - 4]. Approximately 90% of the hydrogen used today comes from the steam methane reforming of fossil NG. Steam methane reforming (SMR) to LH_2 is identified in the EU Commission study as pathway GPLH1b. The NG is conditioned at the source, transported via NG pipeline 4000 km, reformed into hydrogen at a central reforming facility, with the hydrogen liquefied at the plant and then transported as a liquid in a road tanker a distance of 300 km. Since all of the carbon in fossil-based NG is released into the atmosphere during pathway GPLH1b, we anticipate large GHG emissions from the hydrogen fuel-cell component of the Hydrogen Hybrid propulsion system using NG-based LH_2.

A second LH_2 production pathway is electrolysis of water using grid electricity. For the GHG emissions estimates we use the grid mix of the European Union (EU), since this was used in the GHG study from the EU Commission Study [1,2]. This pathway is indicated in Figure 1 and identified in the EU Commission report as pathway EMEL1/LH1. Table 1 compares the 2007 EU grid mix assumed for the study [1], and that of the State of California in 2018 [5]. There are distinct differences between the two grid mixes. The EU has more low-carbon nuclear, while the State of CA has considerably less high-carbon coal. The State of CA has more low-carbon wind, but less zero-carbon hydroelectric power. Overall, we judge these two grid mixes to be comparable as bases for GHG calculations. Indeed, electrolysis pathway GHG emission estimates using either the EU grid [2] or the CA grid [6] are within ~ 13% of each other. More recent assessments of the EU grid mix in 2013 show only small variations from the grid mix of 2007 [2].

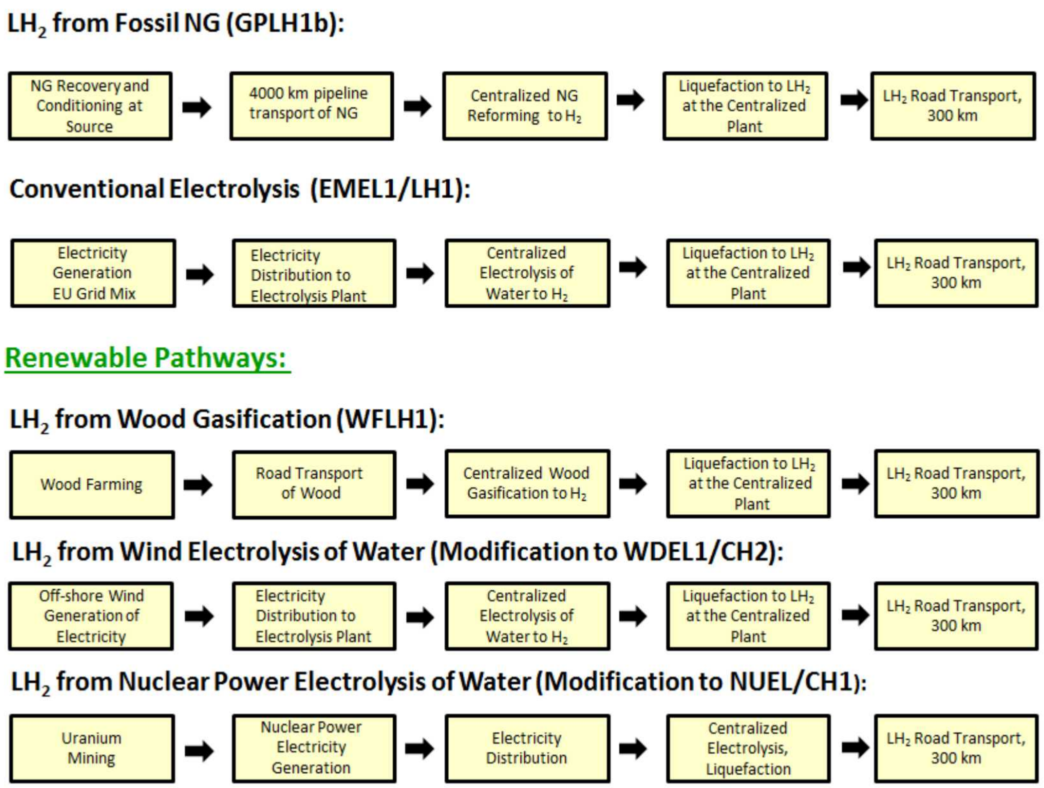


Figure 1: WTT LH_2 pathways considered in the GHG analysis. Pathway codes in parenthesis identify the pathway described in detail in the European Commission reports [1, 2].

Table 1: A comparison of the 2007 EU grid mix assumed in the studies of References 1 and 2 with the 2018 State of California grid mix described in Reference 5.

Grid Resource	2007 EU Mix (%)	2018 State of CA (%)
Nuclear	37.5	9.0
Coal	22.4	3.3
Oil	9.6	0
Natural Gas	15.5	34.9
Hydroelectric	12.4	10.8
Wind	0.4	11.5
Waste	1.8	0.10
Other Renewables	0.3	19.9
Other	0.1	10.5

"Renewable Pathways" of hydrogen production are those that don't involve the release of carbon, or if carbon is released, then it came recently from CO_2 in the air, making the pathway "carbon neutral." The EU commission studies [1, 2] incorporated one renewable pathway that led directly to LH_2, namely wood gasification (WFLH1). Other renewable pathways to hydrogen include using offshore wind to electrolyze water (WDEL1/CH2) and using nuclear generated electricity to electrolyze water (NUEL/CH1), as depicted in Figure 1. For these latter two pathways, compressed hydrogen gas was produced, not LH_2. To estimate a GHG emission number for the pathway that would have led to LH_2, we modified the compressed-gas path to include a hydrogen liquefaction step, and increased the GHG emissions reported by the EU Commission for the renewable compressed hydrogen product by a factor of 1.286 to reflect increased emissions associated with liquefaction using renewable energy. This factor was determined by taking the ratio of the GHG emissions reported for making LH_2 by fossil NG reforming (GPLH1b), 126.3 g CO_2 (eq.)/MJ_{fuel} to the GHG emissions reported for making compressed hydrogen by fossil NG reforming (GPCH2b), 98.2 g CO_2 (eq.)/MJ_{fuel}. That ratio is 1.286 and is used to correct renewable pathway GHG emission reported for compressed gas to obtain the GHG emission for producing LH_2 via the same production method.

The results for the EU Commission report for total WTT GHG emissions in CO_2 (eq.) for the LH_2 production pathways of Figure 1 are reported in Figure 2. The EU Commission reports [1, 2] can be consulted for the breakdown in the GHG emissions according to each

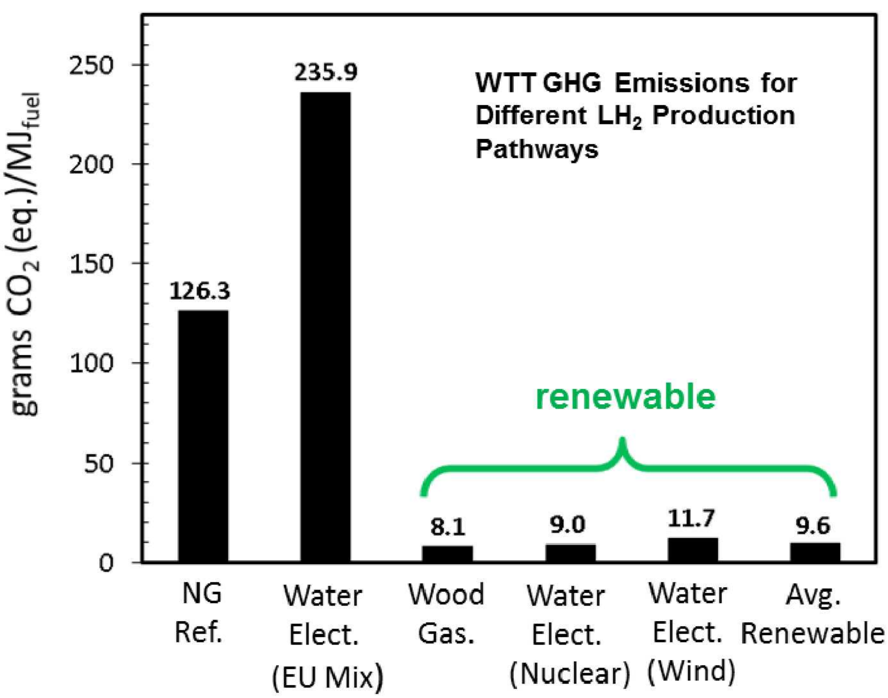


Figure 2: Total fuel pathway (WTT) GHG emissions in grams CO_2 (eq.)/MJ_{fuel} for the LH_2 production pathways considered in this study: (L-R); NG reforming, electrolysis of water using the EU grid mix, wood gasification, water electrolysis using nuclear-based electricity, water electrolysis using wind-based electricity, and the average of the renewable paths. The figure reports the GHG emissions from making one MJ of finished fuel on a LHV basis, MJ_{fuel}.

pathway step (production at source, transportation to processing plant, processing to fuel, and fuel transport to market).

Figure 2 shows that the current commercial method of making LH_2, namely NG reforming to hydrogen followed by liquefaction (GPLH1b) produces 126.3 grams of CO_2 (eq.) per megajoule of LH_2 on a lower-heating-value (LHV) basis. The LHV of hydrogen is 119.96 MJ/kg. Thus, 15.1 kg of CO_2 (eq.) emissions are released in the production of 1 kg of LH_2.

Water electrolysis using conventional grid power comprised of the EU mix produces 235.9 grams of CO_2 (eq.)/MJ_{fuel}, significantly worse than the fossil NG reforming route. This is because water electrolysis is very energy intensive. The EU Commission reports that it takes 1.13 MJ of process energy for every 1.0 MJ of LH_2 fuel produced by NG reforming. In contrast, it takes 4.22 MJ of process energy to make 1.0 MJ of LH_2 via water electrolysis. Thus, if the current carbon-rich electrical grid is used to perform the electrolysis, LH_2 production via water electrolysis is not competitive from a GHG perspective with steam methane reforming.

Figure 2 shows that when renewable sources of hydrogen are available, then fuel pathway GHG emissions are dramatically reduced. Wood gasification (WFLH1) yields 8.1 grams of CO_2(eq.) for every 1.0 MJ (LHV) of LH_2 produced. Electrolysis of water using low-carbon electricity sources such as nuclear power or wind also yield very low GHG emission values of 9.0 and 11.7 g CO_2 (eq.)/MJ_{fuel}, respectively. Taking the average of these renewable paths, we get an average renewable GHG emissions for the production and delivery of renewable LH_2 as 9.6 grams CO_2(eq.)/MJ_{fuel}. Since PEM fuel cells produce no emissions of any kind at the point of use, these WTT LH_2 production numbers provide the entire basis for estimating GHG emissions from the fuel-cell portion of the Hydrogen Hybrid vessel propulsion system.

For the use of diesel fuel in the Diesel Baseline, the Hydrogen Hybrid and Battery Hybrid vessels, there are two components of GHG emission. The first component lies in the production and delivery of diesel fuel. The EU Commission study reports that GHG emissions associated with diesel production is 14.2 g CO_2 (eq.)/MJ_{fuel}. Recalling the LHV of diesel is 43.4 MJ/kg and noting the density of marine diesel fuel is 0.890 kg/L, making one gallon of diesel fuel releases 2.1 kg CO_2 (eq.) per gallon produced. This figure is significantly less than the 15.1 kg of CO_2 (eq.) emissions released in the production of 1 kg of LH_2 by fossil NG reforming. The emissions for manufacture of diesel fuel are less because there is dramatically less process energy used in refining petroleum to diesel fuel than in steam reforming NG to hydrogen. The EU Commission reports that it takes 0.16 MJ of process energy to make 1.0 MJ of diesel fuel. This can be compared to the 1.13 MJ of process energy it takes to make 1.0 MJ of LH_2 fuel by NG reforming. Only a portion of the process energy is tied up in liquefaction of hydrogen. The EU reports that to make and deliver 1.0 MJ of hydrogen compressed to 880 bar (pathway GPCH2b) still requires 0.72 MJ of process energy. Summarizing, making LH_2 is more energy intensive than making diesel fuel, even when using the least-energy-intensive pathway for making hydrogen, namely SMR of NG.

Since the carbon atoms in fossil diesel fuel came from the atmosphere millions of years ago, its combustion represents a significant addition to CO_2 already in the atmosphere. The EU commission reports that burning diesel fuel produces 73.2 g CO_2 (eq.)/MJ_{fuel}. This is nearly all produced as CO_2, assuming the average chemical formula for diesel fuel is $C_{12}H_{23}$. Thus, the total WTW GHG emissions from making and burning (to completion) 1.0 MJ (LHV) of fossil-derived diesel fuel is 14.2 g CO_2 (eq.) + 73.2 g CO_2 (eq.) = 87.4 g CO_2 (eq.)/MJ_{fuel}.

We consider "biodiesel fuel," specifically fatty acid methyl ester (FAME), to be the "renewable" carbon-based fuel that could be used as a "drop-in fuel" for a baseline biodiesel vessel, or for use in the hybrid variants (hydrogen, battery). The EU Commission reports [1, 2] the energy and GHG emissions associated with making and delivering biodiesel fuel, with the most updated figures from the 2013 EU report [2]. In Europe, biodiesel is mostly produced from rapeseed with some production using sunflower seeds as the feedstock. Since the carbon in these living materials came recently from atmospheric CO_2, burning biodiesel with CO_2 release is considered carbon neutral, and the WTW GHG emissions equal the WTT GHG emissions for biodiesel. However, the WTT GHG emissions for making and delivering biodiesel are not zero, since significant process energy is needed for farming the seeds and converting the biomass to fuel. Making biofuels from these seeds takes 1.20 MJ of process energy for every megajoule of biodiesel fuel produced. This is 7.5 times more process energy than it takes to make the energy equivalent of diesel fuel from petroleum (0.16 MJ/MJ_{fuel}). The WTT GHG emissions associated with making biodiesel fuel by the rapeseed and sunflower pathways is (taking the average of the two feedstocks) 55.0 g CO_2 (eq.)/MJ_{fuel} [2]. Although burning biodiesel does not release net CO_2, criteria pollutants are created, such as NO_x, HC and PM.

The fuel and electricity consumption utilized by the vessels to perform the equivalent suite of annual Scripps science missions determines the overall emissions from the vessels. Those fuel consumption details are presented in Table 2. The important figures for the annual emissions analysis are the total consumption numbers per year.

Table 2: Breakdown of the fuel and electrical energy usage for the Baseline Diesel, Hydrogen Hybrid and Battery Hybrid variants. For the emission calculations, the fuel usage for the Baseline Biodiesel vessel is assumed to the same on a kg basis as for the Diesel Baseline vessel.

Mission	Missions Per Year	Baseline		Hydrogen Hybrid[1]				Battery Hybrid[2]			
		Diesel		Diesel		LH2		Diesel		Shore Power	
		kg/mission	kg/year	kg/mission	kg/year	kg/mission	kg/year	kg/mission	kg/year	kWh/mission	kWh/year
Class Cruise: Biology of Fishes	2	835	1,671	0	0	196	392	688	1,375	1,410	2,820
Class Cruise: Biology (Typ)	11	1,113	12,242	0	0	264	2,903	951	10,464	1,410	15,510
Class Cruise: Marine Geology & Invertibrates	4	1,164	4,656	0	0	277	1,110	1,000	4,000	1,410	5,640
Class Cruise: AUV Ops	2	1,640	3,280	0	0	394	788	1,452	2,904	1,410	2,820
Physical Oceanography	1	1,780	1,780	0	0	417	417	1,585	1,585	1,410	1,410
Coastal Mooring	5	2,674	13,368	0	0	641	3,207	2,434	12,169	1,410	7,050
Geology Sampling (Multicore)	1	11,452	11,452	9,400	9,400	733	733	10,773	10,773	1,410	1,410
Deep Moorings (4000m) & Towed Sonar II	1	13,096	13,096	11,044	11,044	733	733	12,335	12,335	1,410	1,410
AUV Ops II	1	14,459	14,459	12,407	12,407	733	733	13,630	13,630	1,410	1,410
Deep Moorings (4000m) & Towed Sonar I	1	16,856	16,856	14,804	14,804	733	733	15,907	15,907	1,410	1,410
Coastal Physical Oceanography	1	17,981	17,981	15,929	15,929	733	733	16,976	16,976	1,410	1,410
AUV Ops I	1	18,357	18,357	16,305	16,305	733	733	17,334	17,334	1,410	1,410
Cyanobacteria: CTDs and Incubations	2	18,649	37,297	16,596	33,193	733	1,466	17,610	35,220	1,410	2,820
Geology: Vibracore & Box Core	1	24,045	24,045	21,993	21,993	733	733	22,737	22,737	1,410	1,410
Range Endurance (Not a Mission)	0	30,872	0	28,820	0	733	0	29,222	0	1,410	0
Total	**34**		**190,541**		**135,075**		**15,413**		**177,410**		**47,940**

1. Hydrogen hybrid fuel consumption is calculated assuming that one day missions are completed using only hydrogen fuel and longer missions are complete utilizing the enter usable capacity of hydrogen supplementing diesel fuel. Diesel fuel reductions were calculated via energy comparison with hydrogen fuel.
2. Battery hybrid fuel consumption is calculated assuming that 60% of the total battery is consumed from shore power on every mission along with a 5% diesel fuel consumption reduction on the remaining fuel usage for hybrid operation.

Greenhouse Gas (GHG) Emissions:

With this information in Table 2, we can now compare and contrast the WTW GHG emissions from the Diesel Baseline, Biodiesel Baseline, Hydrogen Hybrid (using companion diesel and biodiesel fuel for the diesel engines) and Battery Hybrid (using companion diesel and biodiesel fuel) vessels, all in performing the same Scripps science mission in a given year. The results are shown in Figure 3.

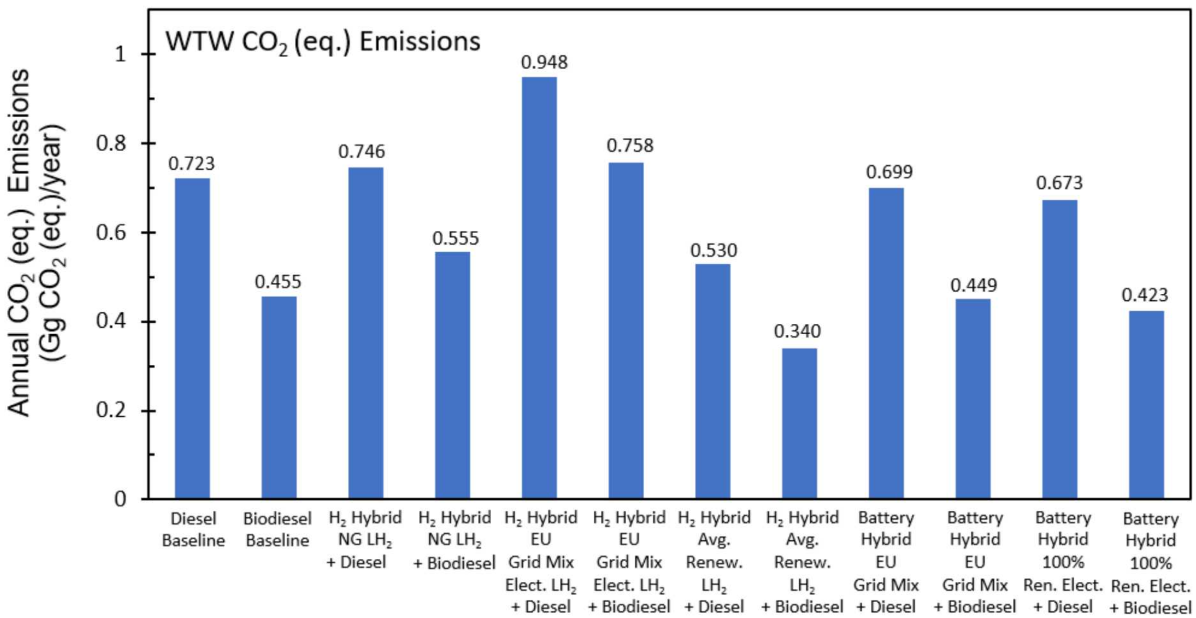


Figure 3: Predicted well-to-waves (WTW) GHG annual emissions for the Diesel Baseline, Biodiesel Baseline, the Hydrogen (H_2) Hybrid (with varying types of hydrogen and diesel and biodiesel), and the Battery Hybrid (with varying types of electricity combined with diesel and biodiesel). For the hydrogen production by grid electrolysis and the shore power supplied to the Battery Hybrid, the EU grid is assumed [1, 2]. Also shown is the Battery Hybrid using 100% renewable electricity for the shore power with presumed zero GHG emissions. 1 Gg = 1 x 10^9 grams.

Figure 3 shows that the annual WTW GHG emissions from the Diesel Baseline would be 0.723 Gigagrams (Gg) of CO_2 (eq.) per year. Recall that a "Gigagram" is 1x10^9 grams. One could consider using biodiesel to power an "equivalent biodiesel baseline vessel." Figure 3 shows that the WTW GHG emissions are indeed reduced to 0.455 Gg CO_2 (eq.)/year for biodiesel. This represents a 37% reduction in GHG emissions. The reduction is not as large as one might expect from a biofuel because making biodiesel is energy intensive. We note here that the analysis does not consider that more biodiesel would have to be stored to execute the same science missions because the LHV of biodiesel is ~ 37 MJ/kg [7], down from 43.4 MJ/kg for diesel fuel. The extra biodiesel fuel would increase the weight of the vessel, thereby increasing the energy demand. Without additional fuel to account for the reduced LHV of biodiesel, the Baseline Biodiesel Vessel would not make the 2400 nm range required of the SRV. The biodiesel results are for the biodiesel productions paths considered in Reference 2. Biodiesel production paths can vary considerably, especially regarding the fertilizer and water requirements. The GHG emissions for a biodiesel pathway differing from those of Reference 2 would have to be evaluated separately.

The GHG emissions for the Hydrogen Hybrid depend on how the LH_2 is produced, and whether fossil diesel or biodiesel is used as the companion fuel in the hybrid arrangement. For the case where the LH_2 is sourced from NG, and diesel fuel is the companion fuel, the GHG emissions (0.746 Gg CO_2 (eq.)/year) are slightly worse than the equivalent vessel running on fossil diesel (0.723 Gg CO_2 (eq.)/year). This increase is due to the energy intensiveness of making hydrogen in the first place. Also, the hydrogen liquefaction involves significant energy and associated GHG emissions even when the hydrogen is sourced from NG, which is the least energy intensive production path. These effects conspire to produces undesirable GHG emissions for the Hydrogen Hybrid along the fuel production and delivery path. Using biodiesel in combination with NG-sourced hydrogen ameliorates this GHG increase, producing emissions of 0.555 Gg CO_2 (eq.)/year, a 23% reduction from the fossil Diesel Baseline vessel. The GHG emissions for the Hydrogen Hybrid are even larger if the LH_2 is produced from water electrolysis, due to the high process energy (and associated grid GHG emissions) for this production path.

The Hydrogen Hybrid GHG emissions are reduced using renewable hydrogen. Taking the average value of the renewable production pathways, 9.6 g CO_2 (eq.)/MJ_{fuel} in Figure 2, Figure 3 shows the annual WTW GHG emissions from the Hydrogen Hybrid using renewable LH_2 in combination with fossil diesel in the hybrid arrangement becomes 0.530 Gg CO_2 (eq.)/year. This is a 26.7% reduction from the Diesel Baseline vessel. When using biodiesel as the companion fuel to renewable hydrogen, the GHG emissions drop to 0.340 Gg CO_2 (eq.)/year, a 53.0% reduction from the Diesel Baseline vessel. Figure 3 thus shows that the real potential in hydrogen technology to reduce GHG lies in using renewable hydrogen. The renewable hydrogen considered for Figure 3 is nearly 100% renewable. In our discussions with the gas suppliers (e.g. Air Products), renewable LH_2 can be made available to the Hydrogen Hybrid today in the quantities required and are currently working to make renewable hydrogen more broadly available.

Turning to the Battery Hybrid vessel operating on shore power electricity combined with fossil diesel or biodiesel companion fuels, we see that the GHG emissions are only slightly less than the unhybridized Diesel Baseline or Biodiesel Baseline vessels. For example, the Battery Hybrid vessel with electricity from the EU grid mix combined with diesel fuel provides a 3.3% reduction in GHG emissions compared to the Diesel Baseline vessel. This is a consequence of there being comparatively little stored energy in the battery bank of the Battery Hybrid vessel. The Baseline

Diesel vessel uses 190,541 kg of diesel fuel annually (Table 2). This corresponds to 8.27 x 10^6 MJ of LHV fuel energy. In contrast, the Battery Hybrid vessel consumes 47,940 kWh of electricity in a year (172,584 MJ). Thus, the annual electrical energy stored in the Battery Hybrid is only 2.1% of the annual LHV value of the Diesel Baseline vessel. As a result, the ability to influence the vessel emissions through battery hybridization is very limited due to the poor energy storage density of battery technology. In addition, electricity from the EU grid mix has GHG emissions associated with it [1, 2], 150 g CO_2(eq.)/MJ, which is higher than GHG emissions associated with the production and use of a MJ of diesel fuel (87.4 g CO_2(eq.)/MJ_{fuel}). If 100% renewable electricity is used for the shore power (with no associated GHG emissions), then the GHG emission savings for the Battery Hybrid arise entirely from the avoided diesel fuel use, producing a 6.9% GHG reduction as shown in Figure 3.

In comparison, the Hydrogen Hybrid utilizes 15,413 kg of hydrogen in a year (Table 2). This corresponds to a LHV of 1.85 x 10^6 MJ, or 22.4% of the LHV of the Diesel Baseline vessel. The higher energy storage density of hydrogen allows it to have a larger influence on the overall Hybrid Vessel GHG emissions, as shown in Figure 3.

Traditional biodiesel is the fatty acid methyl ester product that results from the transesterification of vegetable oil or animal fats with methanol. The oils themselves are not compatible with diesel engine operation due to their higher viscosities, thus requiring the transesterification processing. In the ~2010 timeframe, there emerged alternative methods of oil processing that produced fuels whose composition more closely resembled fossil diesel. These products are called "renewable diesel" or "green diesel." Renewable diesel is produced primarily by "hydrodeoxygenation" in which the oil or fat feedstock is treated with hydrogen at elevated temperatures and pressures to produce long chain alkanes (not the esters of biodiesel) that resemble the components of fossil diesel fuel. In Europe, the product is called "hydrotreated vegetable oil" (HVO) [1, 2]. The 2013 EU commission study [2] reports that the WTT GHG emissions (grams CO_2 (eq.)/MJ_{fuel}) for HVO and biodiesel are essentially the same. This means that the WTW GHG emissions results in Figure 3 would be essentially the same if renewable diesel replaced biodiesel in the analysis. Green or renewable diesel is less dense (0.8 kg/L) than marine diesel fuel but has a similar LHV [8].

Criteria Pollutant Emissions:

Criteria pollutant emissions from the combustion of fossil fuels, among them NO_x, HC and PM continues to be of concern due to their immediate adverse health effects. Since the PEM fuel cell does not involve combustion, it is incapable of producing criteria pollutants at the point of use. As a result, any criteria pollutant emissions associated with the use of hydrogen on the Hydrogen Hybrid arise entirely from the production and transport of LH_2 to the vessel, namely the WTT criteria pollutant emissions. Criteria pollutant emissions can arise from combustion used to create the process heat needed to heat the reactants for the SMR process or as a byproduct of the

SMR process. Alternatively, combustion could be used to generate the electricity used in hydrogen liquefaction.

Analogously, criteria pollutant emissions are associated with the production and delivery of diesel fuel. For example, the diesel-fueled tanker truck delivering diesel fuel is a source of diesel pathway criteria pollutant emissions. If the diesel fuel originates from petroleum ("fossil diesel"), then there are the additional criteria pollutant emissions associated with burning the fuel in the vessel propulsion diesel engines. As a result, criteria pollutant emissions arising from the use of fossil-diesel involve two sources: (1) production and delivery of the diesel fuel and (2) combustion of the fuel onboard the vessel. If the diesel fuel originates from biomass ("biodiesel"), there are still criteria pollutant emissions released on the vessel, even though biodiesel reduces GHG emissions because the carbon released on the vessel originated recently from CO_2 in the air.

The European Commission WTT analysis for automotive fuels in 2007 [1], updated in 2013 [2], were used as the basis for our GHG analysis. However, these studies did not provide information on criteria pollutant WTT emissions. For WTT fuel pathway criteria pollutant emissions, we use a 2007 analysis conducted by Unnasch and Pont of TIAX LLC for the California Energy Commission (CEC) [6]. The TIAX WTT study provides estimates for criteria pollutant emissions based on the energy consumption of various fuel paths, including the production and delivery of LH_2, diesel fuel and biodiesel. Combustion energy consumption is the principle source of criteria emission in these fuel pathways. The study reports emissions from the perspective of California.

The TIAX study generally follows the spirit of the pathways indicated in Figure 1. The pathway for production of LH_2 from fossil NG is similar to that in Figure 1 (labeled GPLH1b from the European Commission study), except that the distance for LH_2 road transport was assumed to be 80.5 km (50 miles) instead of 300 km. Using 100% renewable electricity for the fuel manufacturing, the WTW criteria pollutant emissions for the Hydrogen Hybrid would collapse to those for LH_2 trailer transport operating on diesel fuel. The TIAX report provided the appropriate pathway criteria emission values for tanker transport of LH_2. Note that if the LH_2 trailer ran on 100% renewable hydrogen instead of diesel fuel, the criteria pollutant emissions could be essentially eliminated.

Table 3 reports the WTT criteria pollutant emissions associated with the fuel pathways for LH_2 produced by SMR of fossil NG, 100% renewable LH_2 (with diesel truck transport), fossil diesel fuel, biodiesel fuel, the CA Grid and 100% renewable electricity pathways. The results are reported in terms of grams of pollutant emitted per gigajoule (LHV) of the fuel energy. The criteria pollution associated with electricity production is also taken from the TIAX study [6], appropriate for the CA grid. We also add criteria emissions (zero) assuming an optimal 100% renewable electricity path for consideration as shore power for the Battery Hybrid Vessel.

Table 3: WTT criteria pollutant emissions for fuel and electricity pathways on a LHV basis. GJ_{fuel} represents the lower heating value (LHV) of the indicated fuel in gigajoules (GJ). 1 GJ = 1 x 10^9 J. The 100% Renewable LH_2 fuel pathway assumes the hydrogen is delivered 80.5 km (50 miles) in a diesel-fueled trailer.

Fuel Pathway	NO_x (g/GJ_{fuel})	HC (g/GJ_{fuel})	PM (g/GJ_{fuel})
Fossil NG LH_2 Fuel Pathway	45.0	3.5	5.0
100% Renewable LH_2 Fuel Pathway	0.83	0.083	0.029
Fossil Diesel Fuel Pathway	1.4	3.5	0.06
Biodiesel Fuel Pathway	4.5	3.4	0.18
Electricity (CA NG/RPS mix)	1.30	1.82	6.00
100% Renewable Electricity	0.00	0.00	0.00

The "Fossil NG LH_2 Fuel Pathway" has sizeable criteria pollutant emissions. This is due to the use of combustion (typically of NG) to heat the SMR reactor to the required ~ 900 °C. In addition, combustion is used to provide electricity for the process equipment via the California grid (of which 38% is derived from burning NG or coal, see Table 1), and combustion is used to power the LH_2 tanker truck as it drives 80.5 km in delivering LH_2. In the TIAX study [6] it was noted for this fuel pathway that there exist somewhat high PM emissions for natural gas combined cycle power plants which constitute 34.9%. of the California grid mix. The origin is not the increased (~2x) PM emissions associated with LH_2 trailer transport compared to diesel fuel transport. Indeed, the PM release from trailer transport of 4000 kg of LH_2 a distance of 80.5 km is predicted [6] to be only 0.029 g/GJ_{fuel} ; ~0.6% of the overall WTT PM emissions of 5.0 g/GJ_{fuel} for the Fossil NG LH_2 Fuel Pathway reported in Table 3. It is the energy intensity of H_2 production, not transport, which drives the associated WTT criteria pollutant emissions.

Using 100% renewable electricity for the LH_2 fuel manufacturing, the WTT criteria pollutant emissions collapse to those for LH_2 trailer transport operating on diesel fuel and are listed in Table 3. It is conceivable that hydrogen-powered trailers, running on 100% renewable hydrogen, will one day be the preferred delivery method for hydrogen. For this case, the emissions associated with 100% Renewable LH_2 would essentially vanish. Table 3 also lists the WTT criteria pollutants associated with making and delivering fossil diesel and biodiesel. The criteria pollutant emissions for biodiesel are generally higher than for fossil diesel because of the increased process energy needed to make biodiesel fuel, as mentioned earlier.

Using these values in Table 3, we can calculate the annual WTW criteria pollutant emissions for the Diesel Baseline and Biodiesel Baseline vessels, as presented in Table 4.

Table 4: Annual WTW criteria pollutant emissions for the Diesel Baseline and the Biodiesel Baseline vessels, with the diesel generators constrained to Tier 3 operation.

	NO_x (kg/year)	HC (kg/year)	PM_{10} (kg/year)
Diesel Baseline Fuel Pathway, WTT	11.58	28.94	0.50
Biodiesel Baseline Fuel Pathway, WTT	37.21	28.11	1.49
Diesel/Biodiesel Baseline Tier 3 Engine	4304	430.4	84.56
Diesel Baseline Tier 3 Total (Pathway + Engine), WTW	4316	459.3	85.06
Biodiesel Baseline Tier 3 Total (Pathway + Engine), WTW	4341	458.5	86.05

For Table 4, we constrain the diesel engine emissions (using fossil diesel or biodiesel) to be at the U.S. EPA Tier 3 emission limits [9] appropriate for the engine size (395 kWe) and cylinder displacement (2.25 L/cylinder) of the assumed diesel generators. For this engine, the Tier 3 regulations are: NO_x + HC = 5.6 g/kWh, PM = 0.10 g/kWh. Note how the NO_x and HC emissions are lumped together into a single specification. For comparison to our WTW analysis which estimates NO_x and HC separately, we re-interpret the Tier 3 regulations so that HC emissions are one-tenth the NO_x emissions (as specified in the Tier 4 regulations), subject to the condition that HC and NO_x sum to 5.6 g/kWh as specified by the Tier 3 regulations.

The annual WTW emissions for the Hydrogen Hybrid are reported in Table 5. Here, the WTW criteria pollutant emissions (pathway + engine) for the fuel cell portion of the hybrid propulsion system are equal to the LH_2 well-to-tank (WTT) fuel pathway emissions because the PEM fuel cell criteria pollutant emissions are zero. For the diesel generator portion of the propulsion system, the generators are presumed operating at the Tier 3 emission limits, with pathway emissions associated with the production of diesel and biodiesel fuels explicitly captured.

Table 5: Annual WTW criteria pollutant emissions for the Hydrogen Hybrid vessel for NG-derived hydrogen and 100% renewable hydrogen fueling the fuel cell, accompanied by diesel generator power fueled with either fossil diesel or biodiesel. The diesel generators are assumed to be operating at the Tier 3 emission limits for criteria pollution.

	NO_x (kg/year)	HC (kg/year)	PM_{10} (kg/year)
Fossil NG LH_2 Fuel Pathway, WTT	83.16	6.47	9.24
100% Renewable LH_2 Fuel Pathway, WTT	1.53	0.153	0.054
H_2 Hybrid Fuel Cell Engine	0.00	0.00	0.00
Fossil NG LH_2 Total (Pathway + Engine), WTW	83.16	6.47	9.24
100% Renewable LH_2 Total (Pathway + Engine), WTW	1.53	0.153	0.054
Diesel Fuel Pathway, WTT	8.20	20.51	0.351
Biodiesel Fuel Pathway, WTT	26.38	19.93	1.05
Diesel/Biodiesel Tier 3 Engine	2896	289.6	56.90
Diesel Tier 3 Total (Pathway + Engine), WTW	2904	310.1	57.25
Biodiesel Tier 3 Total (Pathway + Engine), WTW	2922	309.5	57.95
H_2 Hybrid Fossil NG LH_2/Diesel Total, WTW	2987	316.6	66.49
H_2 Hybrid Fossil NG LH_2/Biodiesel Total, WTW	3005	316.0	67.19
H_2 Hybrid 100% Renewable LH_2/Diesel Total, WTW	2905	310.3	57.30
H_2 Hybrid 100% Renewable LH_2/Biodiesel Total, WTW	2924	309.6	58.00

The annual WTW criteria emissions associated with Battery Hybrid vessel are shown in Table 6.

Table 6: Annual WTW criteria pollutant emissions for the Battery Hybrid vessel calculated for Shore Power consisting of the NG/RPS CA Grid Electricity from Reference 6 and 100% Renewable Electricity. The battery drive is accompanied by diesel generator power fueled with either fossil diesel or biodiesel. The diesel generators are assumed to be operating at the Tier 3 emission limits for criteria pollution.

	NO_x (kg/year)	HC (kg/year)	PM_{10} (kg/year)
Battery "Engine" Emissions	0.00	0.00	0.00
Electricity Pathway, WTT CA Mix NG/RPS	0.224	0.314	1.04
Electricity Pathway, WTT 100% Renewable Electricity	0.00	0.00	0.00
Battery Emissions (Pathway + Engine), CA Mix, WTW	0.224	0.314	1.04
Battery Emissions (Pathway + Engine), 100% Ren., WTW	0.00	0.00	0.00
Diesel Fuel Pathway, WTT	10.77	26.94	0.462
Biodiesel Fuel Pathway, WTT	34.64	26.18	1.386
Diesel/Biodiesel Tier 3 Engine Emissions	4049	404.9	79.57
Diesel Tier 3 Total (Pathway + Engine), WTW	4060	431.8	80.03
Biodiesel Tier 3 Total (Pathway + Engine), WTW	4084	431.1	80.96
Battery Hybrid /Diesel Total, CA Mix, WTW	4060.2	432.1	81.07
Battery Hybrid /Biodiesel Total, CA Mix, WTW	4084.2	431.4	82.00
Battery Hybrid /Diesel Total, 100% Renewable, WTW	4060	431.8	80.03
Battery Hybrid /Biodiesel Total, 100% Renewable, WTW	4083	431.1	80.96

The results for the annual WTW criteria pollutant emissions shown in Tables 4 - 6 are presented graphically in Figures 4 – 6 for NO_x, HC and PM_{10} emissions, respectively. Figure 7 shows all the criteria pollution results on a single bar chart.

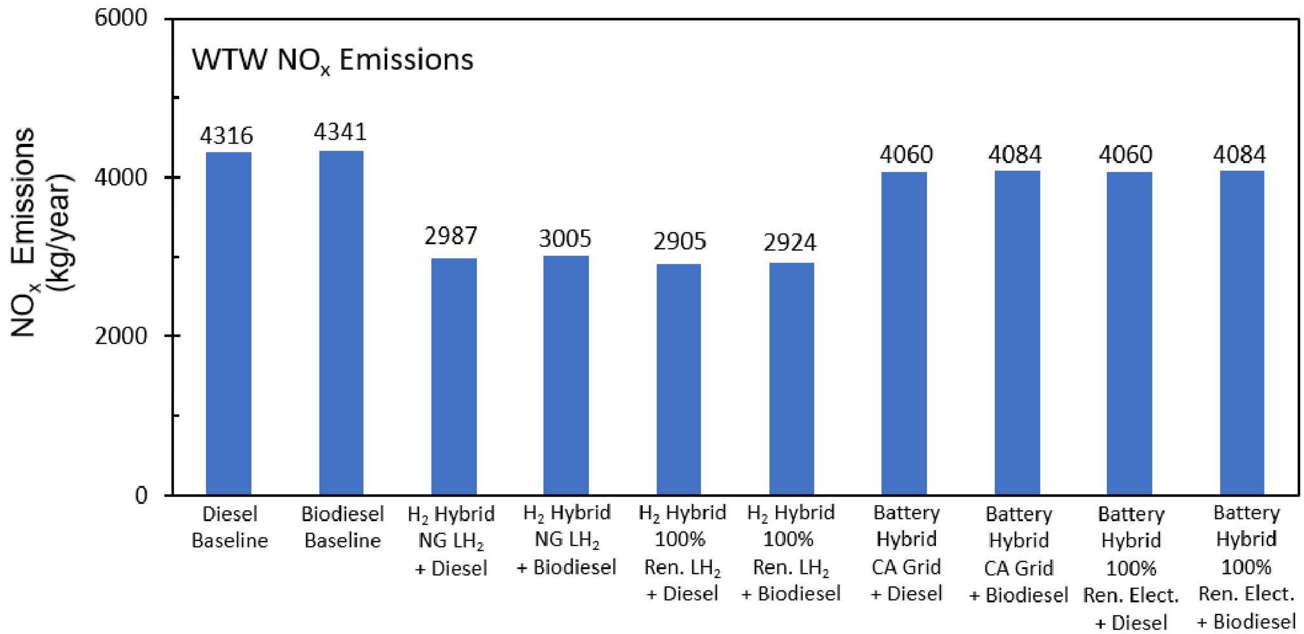


Figure 4: Predicted annual well-to-waves (WTW) NO_x emissions for the Diesel Baseline vessel, Biodiesel Baseline vessel and the Hydrogen (H_2) Hybrid vessel, with NG LH_2 and 100% renewable LH_2 accompanied by diesel power from fossil diesel and biodiesel. Also shown are the predicted annual NO_x emissions for the Battery Hybrid with CA Grid and 100% Renewable shore power accompanied by diesel and biodiesel fuel for the diesel generator portion of the hybrid propulsion system. The diesel and biodiesel engine emissions are constrained to the Tier 3 limits.

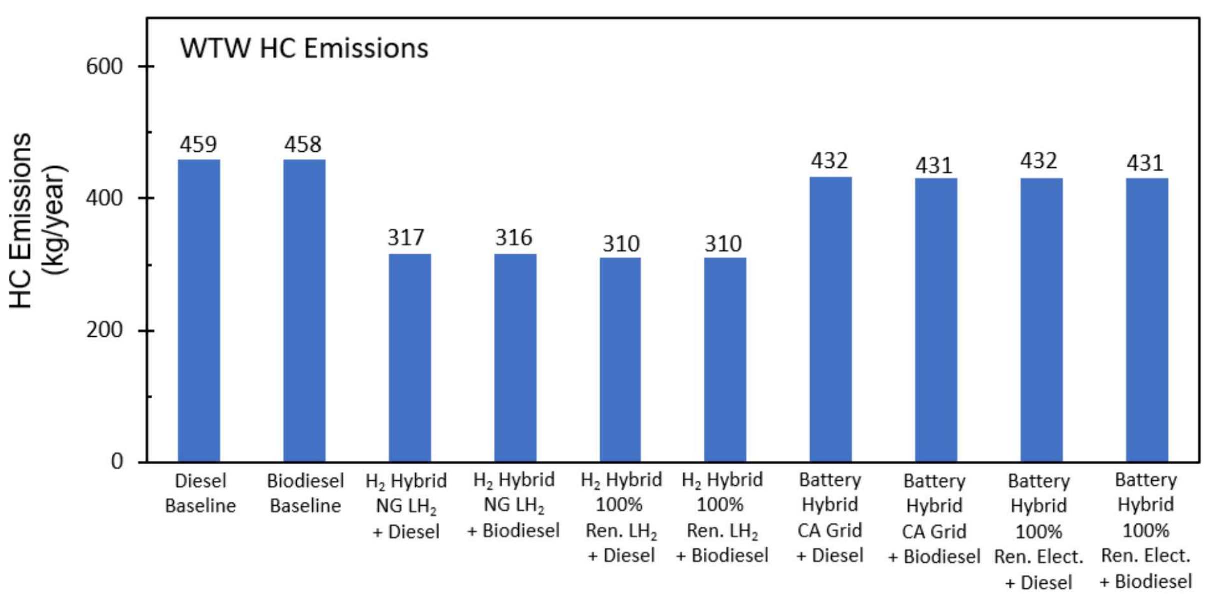


Figure 5: Predicted annual well-to-waves (WTW) HC emissions for the Diesel Baseline vessel, Biodiesel Baseline vessel and the Hydrogen (H_2) Hybrid vessel, with NG LH_2 and 100%

renewable LH_2 accompanied by diesel power from fossil diesel and biodiesel. Also shown are the predicted annual HC emissions for the Battery Hybrid with CA Grid and 100% renewable shore power accompanied by diesel and biodiesel fuel for the diesel generator portion of the hybrid propulsion system. The diesel and biodiesel engine emissions are constrained to the Tier 3 limits.

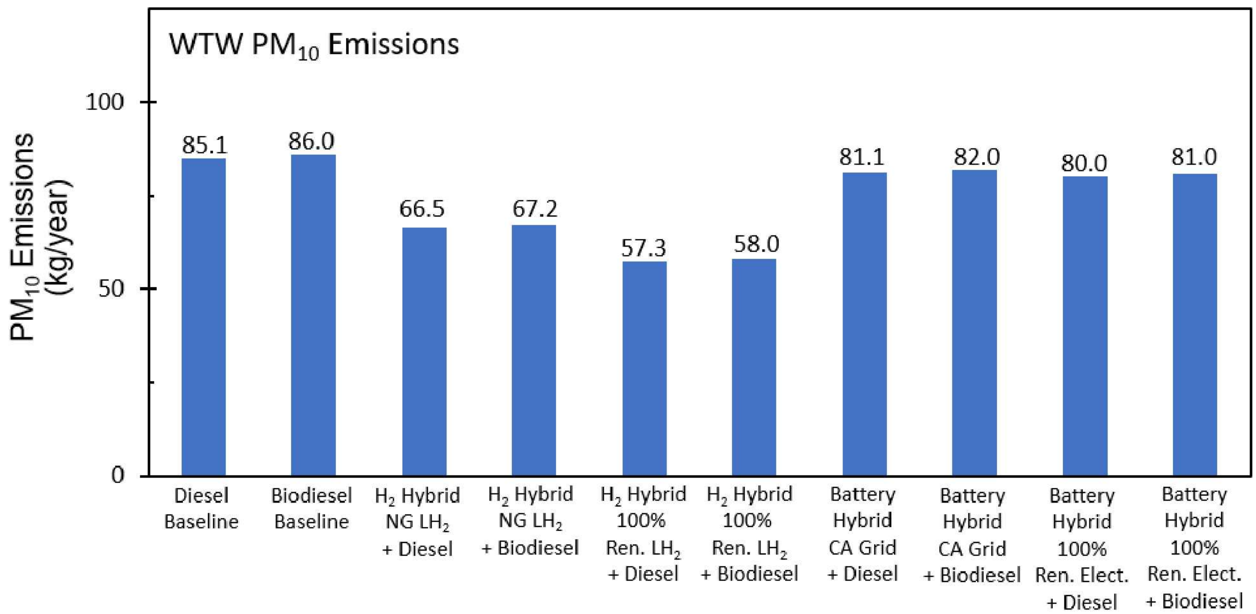


Figure 6: Predicted annual well-to-waves (WTW) PM_{10} emissions for the Diesel Baseline vessel, Biodiesel Baseline vessel and the Hydrogen (H_2) Hybrid vessel, with NG LH_2 and 100% renewable LH_2 accompanied by diesel power from fossil diesel and biodiesel. Also shown are the predicted annual PM_{10} emissions for the Battery Hybrid with CA Grid and 100% Renewable shore power options accompanied by diesel and biodiesel fuel for the diesel generator portion of the hybrid propulsion system. The emissions for the diesel and biodiesel engines are constrained to the Tier 3 limits.

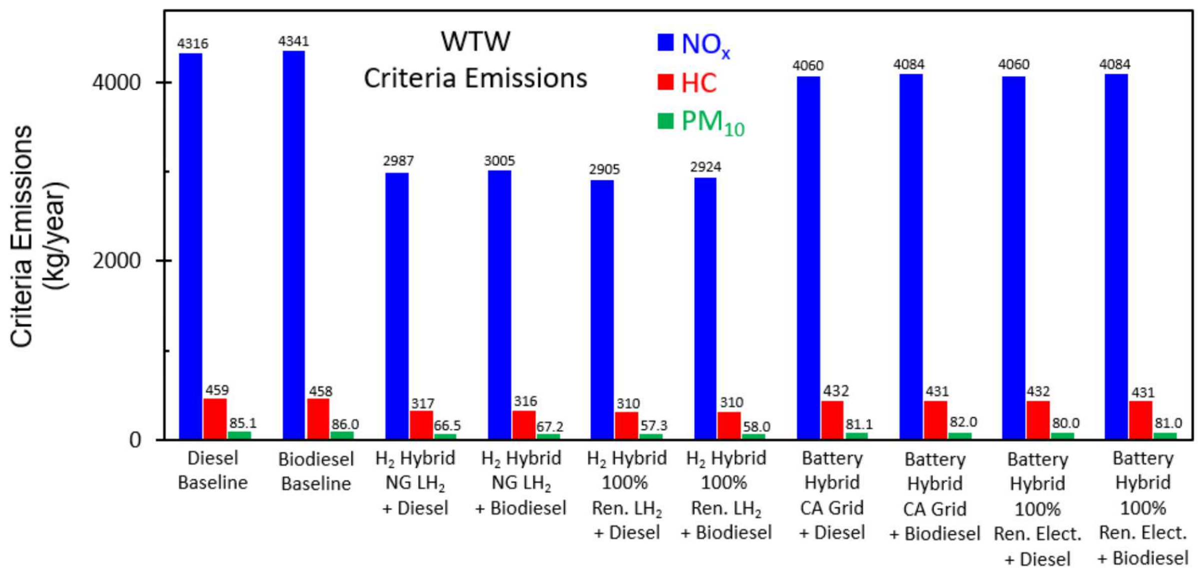


Figure 7: Predicted annual well-to-waves (WTW) criteria pollutant emissions for the Diesel Baseline vessel, Biodiesel Baseline vessel and the Hydrogen (H_2) Hybrid vessel, with NG LH_2 and 100% renewable LH_2 accompanied by diesel power from fossil diesel and biodiesel. Also shown are the predicted annual criteria pollutant emissions for the Battery Hybrid with CA Grid and 100% renewable shore power accompanied by diesel and biodiesel fuel for the diesel generator portion of the hybrid propulsion system. The emissions for the diesel and biodiesel engines are constrained to the Tier 3 limits. This figure is a summary of Figures 4 – 6.

Examining these figures, summarized in Figure 7, we see that the WTW NO_x, HC and PM emissions for the Diesel Baseline and Biodiesel Baseline vessels are very similar. Although the WTT criteria emissions for the production and delivery of biodiesel are higher than those for fossil diesel due to the increased process energy required, these pathway emissions are only a small fraction (6% or less) of the overall WTW criteria pollutant emissions (see Table 4). This finding, combined with the engine emissions for the fossil diesel and biodiesel vessels set equal at the Tier 3 limits, produce the similarities seen in Figures 4 –7 for the Diesel Baseline and Biodiesel baseline vessel criteria emissions.

The criteria emissions for the Hydrogen Hybrid are all lower than for the Diesel Baseline and Biodiesel Baselines, regardless of how the hydrogen is made or what the companion fuel (diesel, biodiesel) is. In addition, the criteria emissions for the Hydrogen Hybrid are lower using 100% renewable hydrogen than using NG-sourced LH_2. These reductions can be traced to relatively less criteria pollutants being produced when NG is burned for SMR process heat, and dramatically less NO_x associated with electrolysis of water using renewable electricity [6]. Using the Hydrogen Hybrid with 100% renewable LH_2 combined with diesel fuel as the companion fuel, we see reductions (compared to the Diesel Baseline vessel) of 32.7% in NO_x, 32.4% in HC and 32.6% in PM_{10}.

Turning to the Battery Hybrid vessel, operating with fossil diesel or biodiesel companion fuels, we see that the criteria emissions are only marginally less than the unhybridized Diesel Baseline or Biodiesel Baseline vessels, regardless whether or not the CA Grid or 100% renewable electricity is used for shore power. This is a consequence of there being comparatively little stored energy in the battery bank of the Battery Hybrid vessel as was discussed previously in connection with the GHG emission results of Figure 3. As a result, the ability to influence the vessel criteria emissions through battery hybridization is very limited due to the poor energy storage density of battery technology. Using the Battery Hybrid with 100% renewable electricity (with assumed zero criteria emissions) combined with diesel fuel as the companion fuel, we see reductions (compared to the Diesel Baseline vessel) of 5.9% in NO_x, 5.9% in HC and 6.0% in PM_{10}.

The TIAX report [6] did not examine criteria emissions from renewable diesel because it was a barely emerging technology at the time of the report. There have been no published analyses of the WTT criteria pollutant emissions associated with the production and delivery of renewable diesel. However, the 2013 EU Commission study [2] reports that the WTT energy required to make HVO (renewable diesel) and biodiesel are very nearly the same. This suggests that the WTW criteria pollutant emissions from using renewable diesel would be very similar to the results using biodiesel as shown in Figures 4 - 7. This finding is analogous to the similarity of renewable diesel and biodiesel in the WTW GHG emissions discussed previously in connection with Figure 3.

Summarizing the main results, GHG and criteria pollutant emissions were estimated for the Diesel Baseline, Biodiesel Baseline, Hydrogen Hybrid (using various sources of LH_2 with companion diesel and biodiesel fuel for the diesel engines) and Battery Hybrid (using various sources of shore power with companion diesel and biodiesel fuel) vessels, all in performing the same Scripps science mission in a given year. The best performing hybrid vessel is the Hydrogen Hybrid variant using 100% renewable hydrogen, because of the superior stored energy available with hydrogen fuel cell technology. The Hydrogen Hybrid can store 22.4% of the fuel energy as hydrogen compared to the Baseline Diesel vessel. The annual WTW GHG emissions from the Hydrogen Hybrid using renewable LH_2 in combination with fossil diesel in the hybrid arrangement yields a 26.7% GHG emissions reduction from the Diesel Baseline vessel. When using biodiesel as the companion fuel to renewable hydrogen, the GHG emissions are reduced 53.0% from the Diesel Baseline vessel. In contrast, the Battery Hybrid variant can only provide ~ 2% of the stored energy as electricity compared to the baseline Diesel Vessel, minimizing its impact on the hybrid vessel GHG emissions. For example, the Battery Hybrid vessel with 100% renewable electricity combined with diesel fuel provides a 6.9% reduction in GHG emissions. Similar results are seen for the criteria pollutant emissions. Using the Hydrogen Hybrid with 100% renewable LH_2 combined with diesel fuel as the companion fuel, we see reductions (compared to the Diesel Baseline vessel) of 32.7% in NO_x, 32.4% in HC and 32.6% in PM_{10}. Using the Battery Hybrid with 100% renewable electricity combined with diesel fuel as the companion fuel, we see reductions (compared to the Diesel Baseline vessel) of 5.9% in NO_x, 5.9% in HC and 6.0% in PM_{10}.

References:

[1]. R. Edwards, J.-F. Larive, V. Mahieu and P. Rouveirolles, "*Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context: Well-to-Tank Report*", Version 2C, Technical Report by the Joint Research Center of the European Commission March 2007.

[2]. R. Edwards, J.-F. Larive, D. Rickeard and W. Weindorf, "*Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context: Well-to-Tank Report,*" Version 4, Technical Report by the Joint Research Center of the European Commission, July 2013.

[3]. The SF-BREEZE final report can be downloaded at: www.maritime.sandia.gov

[4]. L.E. Klebanoff, J.W. Pratt, C.M. Leffers, K.T. Sonerholm, T. Escher, J. Burgard and S. Ghosh, *"Comparison of the Greenhouse Gas and Criteria Pollutant Emissions from the SF-BREEZE High-speed Fuel-cell Ferry with a Diesel Ferry,"* Transportation Research Part D **54** (2017) 250-268.

[5]. Information on the CA Grid Mix used in this study can be found at:

https://ww2.energy.ca.gov/almanac/electricity_data/total_system_power.html

[6]. S. Unnasch and J. Pont, *"Full Fuel Cycle Assessment Well to Tank Energy Inputs, Emissions and Water Impacts,"* California Energy Commission Report CEC-600-2007-002-D, 2007. Available at: http://www.energy.ca.gov/2007publications/CEC-600-2007-002/CEC-600-2007-002-D.PDF

[7] P.S. Mehta and K. Anand, "*Estimation of a Lower Heating Value of Vegetable Oil and Biodiesel Fuel,*" Energy and Fuels **23**, 3893 (2009).

[8]. S. Bezergianni and A. Dimitriadis, *"Comparison Between Different Types of Renewable Diesel,"* Renewable and Sustainable Energy Reviews **21** (2013) 110 - 116.

[9]. The Tier 3 U.S. EPA regulations can be found at: https://www.ecfr.gov/cgi-bin/text-idx?SID=a8a469920cf35098c9f7bcd496ab758a&mc=true&node=pt40.36.1042&rgn=div5#se40.36.1042_1101

Appendix D Supplier References

- Ballard Power FCwave Fuel Cell Module
- MAN LH2 Fuel Gas Supply System Technical Specifications
- MAN Marine Fuel Gas Supply System Process Flow Diagram

Ballard – FCwave

- 24-06-2020

COMMERCIAL CONFIDENTIAL

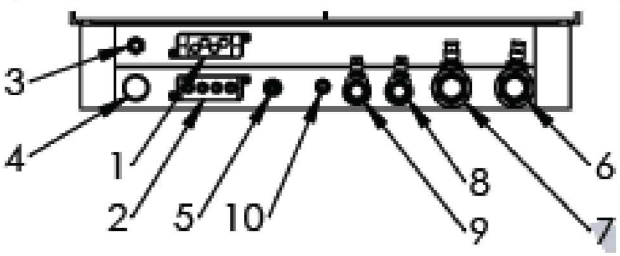
Marine system

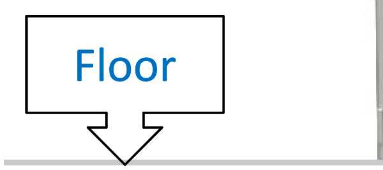
Item	FCwave™		
Performance			Units
Rated power - BOL		200	kW
Minimum power		30	kW
Peak fuel Efficiency		56%	
Operating voltage		350 - 720	V DC
Rated current[1]	2x 300	1 x 550	A
System cooling output		Max 65	°C
Stack technology			
Heat management	Liquid cooled		
Targeted B50 lifetime2		34,000	hrs.
H2 Pressure		3,5 - 5	Barg
Physical			
Dimensions (l x w x h)[3]		1228 x 672 x 2120	mm
Weight (estimate)[4]		875	kg
Reactants & cooling			
Type	Gaseous hydrogen		
Composition	As per SAE spec. J2719*		
Oxidant	Air		
Composition	Particulate, Chemical and Salt filtered*		
Coolant[5]	Water or 50/50 glycol		
Flow Rates			
Hydrogen flow rate @200 kW BOL		3.5	g/s
Design criteria		4.9	g/s
Safety Compliance			
Certifications	DNV-GL compliant		
Enclosure	Hydrogen safe enclosure		
Monitoring			
Control interface	Ethernet, Can		
Emissions			
Exhaust	Zero emission		

- ”Fjord” mode (Norway)
- Zero emissions
- Silent / Safer operations
- Scalable from 200kW –
- Remote Monitoring
- Low Life cycle cost

Marine system

Pos	Description	Connection
1	Control and communication	Harting Han 24HPR
2	DC out +/- A & +/- B SM12	Harting Han 24HPR
3	H2 Supply	HyLok tube fitting 22M
4	H2 enclosure ventilation inlet	ISO 7/1 - R 2"
5	Process water drain	
6	HT Coolant out	ISO 7/1 - Rp 2"
7	HT Coolant in	ISO 7/1 - Rp 2"
8	LT Coolant in/out	ISO 7/1 - Rp 1 1/4"
9	LT Coolant in/out	ISO 7/1 - Rp 1 1/4"
10	HT Coolant drain/fill	Quick connector
11	Process exhaust	Pipe OD Ø88,9 mm
12	H2 enclosure ventilation outlet	Pipe OD Ø60 mm





Ballard has chosen to build the System as an already known technology. Battery rack has the same structure with all connections in the bottom.

The requirements with connectors below floor come from our VOC

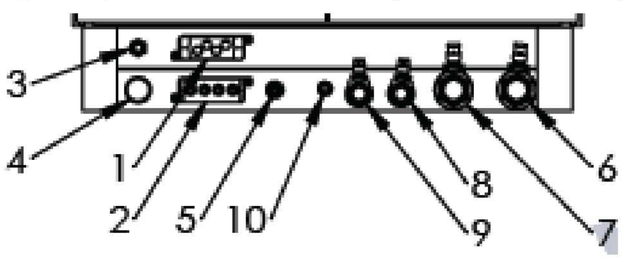
Slide 3

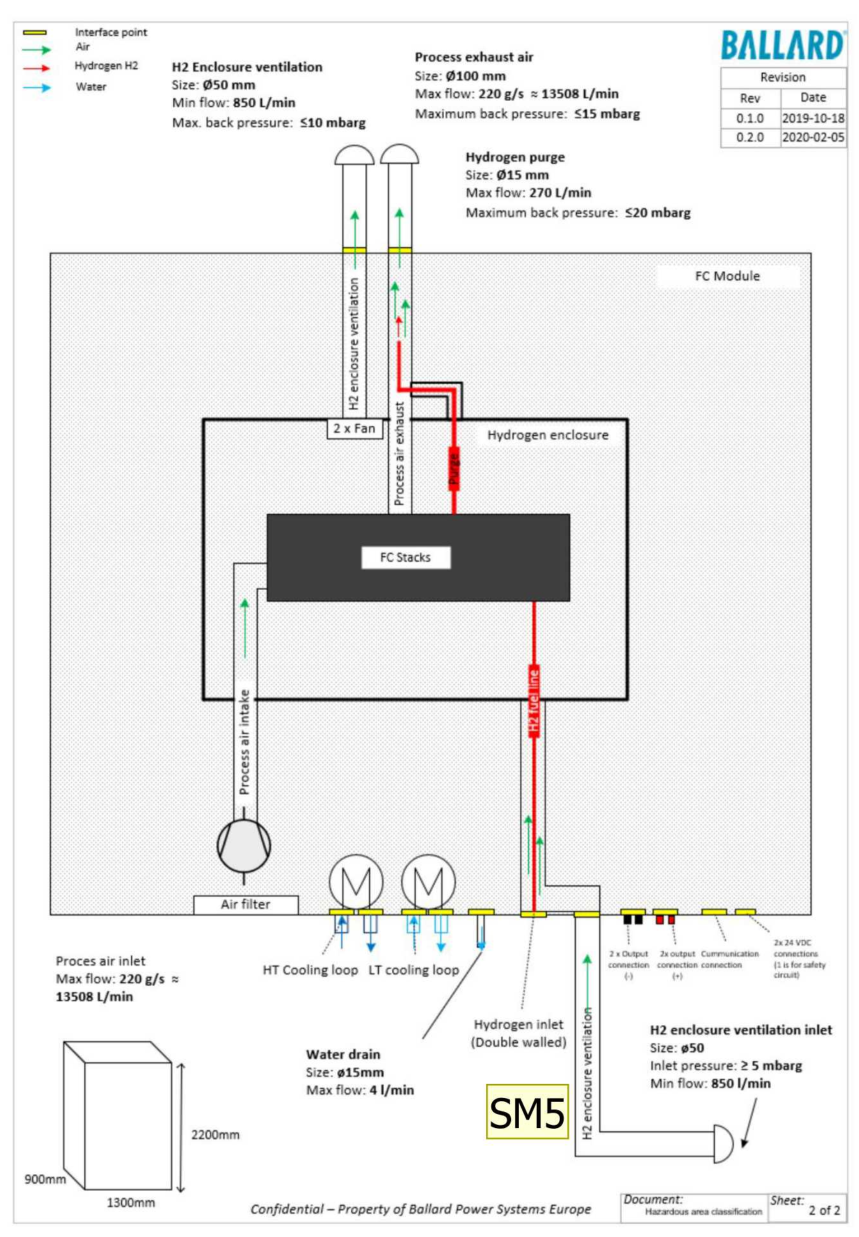
SM12 9/76: double wall shall be indicated for the H_2 supply
Schmidt, Matthias, 3/26/2020

General arrangement

- H2 enclosure to secure all hydrogen components in a small area

Pos	Description	Connection
1	Control and communication	Harting Han 24HPR
2	DC out +/- A & +/- B	Harting Han 24HPR
3	H2 Supply	HyLok tube fitting 22M
4	H2 enclosure ventilation inlet	ISO 7/1 - R 2"
5	Process water drain	
6	HT Coolant out	ISO 7/1 - Rp 2"
7	HT Coolant in	ISO 7/1 - Rp 2"
8	LT Coolant in/out	ISO 7/1 - Rp 1 1/4"
9	LT Coolant in/out	ISO 7/1 - Rp 1 1/4"
10	HT Coolant drain/fill	Quick connector
11	Process exhaust	Pipe OD Ø88,9 mm
12	H2 enclosure ventilation outlet	Pipe OD Ø60 mm





Slide 4

SM5 10/76: double walled connection should be indicated outside the FC module

Schmidt, Matthias, 3/26/2020

Technical Specification

MAN Energy Solutions
Future in the making

Customer

Glosten

Application

LH2 Fuel Gas Supply System

MAN Cryo quotation number

E-SE-2020-87165

Revision & date

Rev01/2020-02-14

TABLE OF CONTENTS

Revision	Date	Comments
03		
02		
01	2020-02-12	First issue

1.1 ATTACHED DOCUMENTS

Document	Revision	Date	Description

1.2 REFERENCE DOCUMENTS

Document	Revision	Date	Description

2 GENERAL INFORMATION

The purpose of the SYSTEM, herein referred to as Fuel Gas Supply System (FGSS), is to bunker, store and vaporize LH2 supplying gaseous hydrogen to the consumers onboard the vessel. Gaseous hydrogen consumers are generally considered as fuel cells.

The data in the below tables in this chapter are to be considered as preliminary.

2.1 RULES AND REGULATIONS

IGF code

EN codes where applicable

Classification Society Rules

The system is delivered according to the rules and regulations at the date of quotation. If the rules and regulations change after the quotation date MAN Cryo has the right to adjust the price accordingly.

Recommendations from the already performed HAZID will be followed and the system shall comply with the requirements from the approval in principle of the complete hydrogen fuel cell system.

2.2 AMBIENT CONDITIONS

Ambient conditions		
Ambient temperature (inside ship structure)	Min-Max	0°C to +47,5°C
Ambient temperature (open deck)	Min-Max	-5°C to +35°C
Sea water design temperature	Min-Max	0°C to +32°C
Relative Humidity	Min-Max	0 to 80%
Type of atmosphere		Salty Sea (Marine)

2.3 QUALITY OF HEATING MEDIA

Fresh heating media water shall be treated according MAN Energy Solutions quality requirements - see manual. Heating media is considered clean and free from any impurities.

Heating media		
Heating media temperature	Min-Max	+40 to +70°C

2.4 UTILITIES

Description/Media	Operational Data	Design Data	Remark
Electrical power	Two independent 220-240 VAC, (one UPS)	1000W	For supply to PCS
Electrical power	220-240 VAC, (UPS)	200W	For supply to operator stations (2x)
Electrical power	230 V		For TCS Lighting
Electrical power	400 V		For HEU water pumps and Air compressor to N2 system
Heating Water to Heat Exchanger Unit	70 m3/h Min: +40°C Max: +70ºC	5 barg +35ºC /+75°C 450 kW	Design assumption is that heating water will be taken from the yacht heat recovery system.
Instrument air	Flow: 25 Nm3/h Max: 10 barg Min: 6.5 barg Temperature: ambient	10 barg 0ºC /+35 °C	Air quality according to ISO8573-1:2010 Class 2.2.1
Nitrogen for inerting blow-off piping in TCS and vent mast	Flow: max 30 Nm3/h Max: 0.1 barg Min: 0.05 barg Temperature: ambient	0.2 barg 5ºC /+35 °C	A continuous flow rate of 25 Nm3/h is needed for keeping the vent mast inerted. (equals to 30 air changes / h)
Nitrogen for inerting of pipe in TCS and bunkering pipe (maintenance)	Volume requirement: 5 Nm3 Max: 9 barg Min: 7 barg		Five times total process pipe volume
Ventilation air for TCS, air lock and bunker space	Flow: 1500 m3/h[1)] Temperature: -5°C to +35°C		Based on TCS volume 50 m3

1) Depends on dispersion analysis

2.5 GENERAL

All supplied hardware tested and approved as required by the classification society.

Designed using SI-system if not otherwise stated.

Given values are theoretical until design and (or construction) is finalized.

Language: English.

Engineering unit of pressure in “bar(g)”.

Engineering unit of temperature in °C.

Piping and pipe fittings according to ISO EN standard.

2.6 PACKING AND PRESERVATION

The equipment is packed and preserved according to MAN Energy Solutions standard.

Tank & Equipment will be delivered with an overpressure. This should be maintained by Client to prevent ingress of moisture. Equipment is delivered to be stored in an inside environment. If the equipment is to be stored for long periods it should be stored equal to those intended for use.

Client can ask for postponement of shipping of equipment up until 4 weeks prior to planned shipping

2.7 PLATE LETTERING AND INDICATOR SCALES

Plate lettering in English.

Indicator scales according to SI unit system.

3 PROJECT SPECIFIC DETAILS

Ship details	
Classification Society	DNVGL or LR
Flag state	TBD
Location of tank	Below deck
Position of tank	Midship
Orientation of tank	Longitudinal

3.1 STRUCTURAL BASIS OF DESIGN / LOAD SPECIFICATION

The following loads below are the loads considered for the tank system (i.e. tank and tank connection space).

3.1.1 Wind loading on equipment

No wind loading considered for the design.

3.1.2 Snow and ice loading

No snow or ice loading considered for the design.

3.1.3 Vibration loads

TBD

3.1.4 Green seas

The system is foreseen not to be exposed to green sea loading.

3.1.5 Protection structure requirements

None

3.1.6 Acceleration loads

TBD

3.2 LH2 CONSUMER DATA

Fuel cell consumption	Fuel cell output	Flow rate of GH2	pressure	Temperature	Remark
Maximum	-	60 kg/h	4 - 7 barg	0°C - 50°C	

4 PROCESS DESCRIPTION

LH2 is filled to the storage tank via the bunker station on the ships side. The LH2 flow can be directed to vapor phase or liquid phase to control the tank pressure.

LH2 is evaporated by the dedicated product vaporizer and sent to the consumer. It can supply gas to consumer at the correct flow rate and temperature thanks to heat supplied from a heat exchanger. The Pressure Buildup Unit (PBU) maintains the tank pressure ensuring LH2 supply to the vaporizer.

4.1 BUNKERING MODE

During bunkering LH2 is received at the Bunker Station and transferred to the tank. The tank can be bottom filled or top filled depending on tank pressure and temperature. This is automated by the control system. The bunker station that is not in operation stays inerted and segregated.

4.2 OPERATING MODE

LH2 is evaporated by the dedicated product vaporizer and sent to the consumers. It can supply gas to consumers at the correct flow rate and temperature thanks to heat supplied from a heat exchanger. This process does not require rotating equipment for gas supply minimizing OPEX and spare parts.

4.3 BOG ACCUMULATING MODE

The tank is designed for a holding time of 30 days without any additional boil off gas handling equipment. The combination of vacuum insulation and inner vessel design pressure of 9 bar(g) makes it possible to accumulate boil off gas for an extended period of time without the need for venting or any losses. The system design allows for BOG to be superheated in the vaporizer for consumer supply.

5 SCOPE OF SUPPLY

MAN Cryo Scope of Supply includes all designed items necessary in order to ensure a safe and reliable operation of the system.

5.1 VACUUM INSULATED TANK

MAN Cryo´s vacuum insulated IMO type C independent tanks are designed to store and feed gas to consumers in a safe and environmentally friendly way. The tank consists of an inner and an outer vessel. The inner vessel is designed as a pressure vessel with capacities to handle low temperature liquids while the outer vessel is designed as a secondary barrier to handle low temperature liquids as well as necessary vacuum pressures. Both the inner and outer vessel are made of austenitic stainless steel.

The tank has one sliding and one fixed tank support in order to allow thermal movements. The tank supports are designed for installation on a flat and level deck throughout the length of the tank.

The inner vessel is wrapped with multilayer insulation and the annular space between the inner and outer vessel is evacuated to high vacuum pressure for best possible insulation. The suspension of the inner vessel to the outer vessel is designed for low heat transfer between vessels.

The outer vessel is covered with a 100 mm layer of insulation in order to protect the ship’s hull structure and surrounding equipment from the cold environment in case of a leakage of LH2 into the annular space.

The inner vessel is cleaned, dried and sealed with an over pressure before shipment and a tank cleanliness certificate is issued as well. Cleanliness according to EN 12300 ANNEX A.

The tank is delivered with lifting instructions. Weight and center of gravity are clearly marked on drawings.

The tanks are completely welded and all welds (100%) are x-rayed, tightness tested and hydrostatic pressure tested according to IGF code requirements.

Vacuum tank technical data	
Quantity	1
Type	T15
Gross volume	15 m^3
Orientation	Horizontal
Insulation type, annular space	Vacuum/Multilayer
Insulation type, outer vessel	Thermal insulation, mineral wool
Insulation protection	Lining
Design pressure (MARVS)	9 barg
Design temperature	-253°C, according to IGF code
Working temperature	-253°C
Loading limit	According to IGF code
Weight	15 tons
Outer vessel diameter	2500
Height	2800
Length including TCS	6000
Width	2800

The final design accelerations may influence the footprint dimensions. Change of the design load and design collision load may influence the design specification. Tank loading limit is dependent on design criteria, tank orientation and position, safety valves etc.

5.2 TANK CONNECTION SPACE (TCS)

MAN Cryo TCS is the central part of the Fuel Gas Supply System and contains all necessary functions for supplying gas to consumer from the LH2 tank. The TCS is designed as one complete unit handling all functions for tank control and vaporization. It receives LH2 from Bunker Station, routes LH2 to vaporizer and Pressure Build-up Unit and discharges gas at correct temperature and pressure to consumers. It has a stainless steel gas-tight enclosure which, in case of system failure, can handle cryogenic spillage without hazard to other parts of the ship. The TCS includes systems for nitrogen, instrument air and vent headers. Stress calculations are conducted for both piping as well as structural steel.

All equipment in the TCS is installed to give room for maintenance and service. The TCS is attached to the tank and is a safety barrier where personnel are normally not to be present. The enclosure is designed to handle cryogenic temperatures and insulated with A-60 Fire insulation to protect equipment within the TCS. Furthermore the TCS is prepared for ventilation to prevent build up of gaseous hydrogen. Capacity to be agreed.

All remote operated valves are fail safe pneumatically operated and use an instrument air system.

The TCS contains the following equipment:

- Bunker line with valves and connections to vapor and liquid phase of tank
- Master gas fuel valve for safe separation of fuel gas supply system from fuel cell room if fuel cells are not in operation.
- Vaporizer
- Pressure build-up unit
- Tank safety valves with associated interlock valves on inlet and discharge side. Enables for safe maintenance of safety valves without the need to gas-free the complete system
- Nitrogen lines for purging and inerting of all media pipes inside TCS
- Double block and bleed arrangement for nitrogen supply
- Tank instrumentation consisting of pressure gauge, level measurement, high alarm and overloading protection
- Leakage detection consisting of temperature measurement and level measurement to detect liquid leakage or water in the bilge. The bilge is not connected to any other drainage system. Possible LH2 leakage will evaporate and be extracted through the vent mast. Possible glycol water leakage will have to be removed manually.
- Pneumatic valves equipped with a "fail safe close" spring return and limit switches for indication of open/closed
- Pneumatic connections routed to pneumatic header for only one single tie in point for easy installation
- System for stripping and inerting of bunkering lines
- Connections for shielding gas for welding close to tie-in points to facilitate installation.
- Vacuum insulated process pipes

- Leakage collection system, in order to collect any possible leakage from the vacuum insulated process pipes inside the TCS and lead it to vent mast.

TCS technical data	
Quantity	1
Type	TCS36
Length	1600
Width (without air lock and entrance room)	4000
Height	2700
Gas distribution pipe to fuel cells	DN100 preliminary
Heating media pipe	DN100 preliminary
Vaporizer	Tube and shell
Pressure Build-up Unit (PBU) type	Tube and shell
Maximum gas flow at TCS outlet	60 kg/h
Material (Box)	Type 304/304L
Material (Piping)	Type 316/316L
Tie in points	TBS
Connection flanges	EN1092-1
Weld connections	Butt weld EN-ISO piping
Threaded connections	NPT
Ventilation air	TBD

5.2.1 Lighting inside TCS

The TCS, air lock and entrance room are supplied with lighting and wiring as per class requirement. Number of lighting fixtures to be decided during detailed design face. Light fixtures are Ex-proof LED type.

5.2.2 Fire detection inside TCS

The TCS is prepared with brackets for fire detection equipment inside the TCS.

5.2.3 A60 insulation

The TCS is covered with a 100 mm layer of A60 insulation in order to protect the ship's hull structure and surrounding equipment from the cold environment in case of a leakage of LH2 into the TCS.

5.2.4 Air lock with entrance room

Air lock for safe entrance without creating hazardous area in tank hold space. The air lock consists of two separate compartments attached to TCS. Both compartments are prepared with connection points for ventilation and gas tight doors. A bolted hatch serves as entrance between the inner compartment and TCS. Light and sound alarms are installed on the outside of air lock to signal and alert if gas is detected inside TCS or if the gas tight doors are not properly closed.

5.3 BUNKER STATION

The bunker station is used to bunker the storage tank via one hose system without gas return.

The bunker station includes systems for nitrogen, instrument air and vent headers and all equipment is located bearing service and maintenance in mind. Stress calculations are conducted for both piping as well as structural steel on the Bunker Station. The bunker station is built on a robust framework in order to be able to handle the forces that comes from the bunker hoses while bunkering.

The bunker station contains the following equipment:

- Valves, piping & instrumentation needed for safe operation
- Pneumatic valves equipped with a "fail safe close" spring return and limit switches for indication of open/closed
- Pressure indication and transmitters located on a panel for easy reading during operation
- Pneumatic connections routed to pneumatic header for only one single tie in point for easy installation.
- Safety valves with blow off lines routed to common header for easy installation
- Strainer at battery limit of liquid line
- Nitrogen lines for stripping and inerting of transfer hoses/bunkering line. (alternatively helium may be used as inert gas instead of nitrogen)
- Drip trays below skid with connections for safe disposal of liquid
- Blind flanges for preservation of cleanliness
- Ex-proof solenoid valves installed on valve actuator allowing for a quick valve response
- Instrument and electrical cabling terminated in junction boxes for easy installation
- All pipe sections where liquid can be trapped are equipped with thermal relief valves
- Connection type compatible with Air Products standard truck LH2 supply system.

Bunker station technical data	
Quantity	1
Type	BS32
Bunkering capacity	25 m^3/h
Liquid line nominal diameter	DN32
Nitrogen connection size	DN15 preliminary
Design pressure Bunker line	20 bar(g)
Design pressure vent mast line	5 bar(g)
Material structure	Type 316/316L
Material piping	Type 316/316L

The bunker station is assumed to be installed on deck on an elevation higher that the storage tank. Bunkering pressure shall be at least same as the tank operating pressure plus pressure drop in connecting piping in order to deliver maximum design flow.

The bunker station is pickled, passivated and painted in order to give a more corrosion resistant surface to withstand the corrosive environment where the bunker station is located.

5.3.1 Bunker station control panel

Bunker panel to control pneumatic valves for bunkering operation locally. Showing related indication (tank pressure, tank level, high level alarm indicator) and alarm information. Connected to the alarm and control system by Modbus. The cabinet consist of one control cabinet with emergency stop push button. To be placed in safe area according to discussions with client and classification society.

5.4 HEAT EXCHANGER UNIT

The MAN Cryo heat exchanger units are designed to exchange heat from the ships hot water system to the vaporizer and pressure build up unit. The heat exchanger unit is not EX classified and should be placed in safe area.

The heat exchanger unit supplies heat to the FGSS system to vaporize the LH2. The heat exchanger unit is equipped with two circulation pumps of which one is a standby. The pumps are all single suction, single stage, vertical inline centrifugal pumps. Pumps are supplied with class certificates according to specific society rules. All heavy components, above 25 kg, are equipped with lifting devices where handling is expected during the lifetime of the system. The heat exchanger unit is furnished with lifting brackets for safe material handling. The piping is marked with media and flow direction at each inlet and outlet of the heat exchanger unit and each inlet and outlet of the heat exchanger.

The heat exchanger unit consists of the following equipment:

- 2x100% centrifugal circulation pumps for reliable operation (One pump stand-by). Pumps to be mounted on vibration dampers
- Easily accessible suction strainers for each pump (1,6 mm mesh area)
- Plate heat exchanger, clip-on type, with small footprint and easy maintenance
- Temperature indicators at heat exchanger inlet and outlet
- Pressure indicators at both pumps and strainers
- Manual valves for easy maintenance and at all battery limits
- Junction boxes for instruments and power cabling
- Safety valve for thermal expansion in glycol water circuit

Heat exchanger unit technical data	
Quantity	1
Type	HEU65

5.4.1 Glycol water Expansion drum

An expansion tank is included in the Glycol Water System to accommodate expansion. The expansion drum must be installed as the high point in the glycol water system and is designed so it can be bolted on a bulkhead. The expansion tank will be installed inside the TCS.

The expansion tank is equipped with the following equipment supplied by MAN Cryo:

- Gas detection
- Level switches

5.5 CONTROL SYSTEM

MAN Cryo standalone control systems are designed to handle all functionality needed for high availability and safe operation of gas supply to the consumers. Sub-systems such as bunkering stations etc. are also controlled. The control system is supplied in one cabinet which includes all necessary equipment and software and is delivered preconfigured, tested and approved by the classification society. The electrical installation is in accordance with the recommendations of the international Electrotechnical Commission (IEC) in, particular publications IEC 60092 and IEC60079. Furthermore also the EMC directive 89/336 EEC is followed. As far as possible the electrical equipment and components are designed and located readily accessible for repair and maintenance. Colour marking of busbars, conductors and signal lights are in accordance with IEC. All cable ends ad conductors are adequately marked at each connection terminal. Marking is on accordance with drawings and international standards. All components inside cabinets are marked by label. The control system receives signals from instruments on the equipment of the fuel gas supply system and performs activities depending on which “mode” of operation is chosen.

Two operating stations, typically on Bridge and in Engine Control Room (ECR) are included. Transfer of signals / information to Integrated Automation System (IAS) by MODBUS TCP or RTU connection/RS485. The interface at the two operating stations is via 24 inch screens with track ball and English key board. The screens can be flush mounted. The operating station on bridge is for viewing alarms and monitoring the Fuel Gas Supply System while the operating station in the engine room/Engine Control Room can also adjust variables such as set pressure control parameters and alarm limits.

- Fuel gas control system assembled in one cabinet
- All relevant sub equipment needed for the Control and monitoring system such as Ethernet switches, ex barriers, relays and internal cables inside cabinets and on skids
- Control cabinet to be located outside hazardous area for example in engine control room, electrical equipment room or other suitable place
- All internal cables and buses are connected
- Pre-tested and approved in workshop for fast and easy installation and start-up on the vessel
- Two independent 230 VAC power supply cables are needed.
- The control system can be provided with UPS as option

Control system cabinet	
Quantity	1
Location	Below deck, safe area
Supply voltage	2 x 230 VAC
Power consumption (max/normal)	1800/750W
Preliminary cabinet size (WxHxD)	1200x2000x400mm
CPUs	Siemens S7 1500-series PLC
I/O system	Siemens ET 200-series
Max temperature	40°C
UPS time	>30 minutes as option
Protection class	IP54
Location	Safe area

Cabinet locks are provided with standard double bar (DIN 43668) closing device (double-bit key no.5). The cabinets are equipped with holders to keep the door open during service work and there is also internal lighting inside the control cabinets.

5.5.1 Operating stations

The control and monitoring interface is used for operating, control and monitoring of the fuel gas system such as:

- Selecting gas modes and bunkering
- ESD system reset and status
- Alarm management and logging
- Monitoring/Control of levels, pressures as well as temperatures
- Control of gas pressure to the consumers
- Start/stop of gas supply
- Manual operation of valves(if required)
- Alarm logging

5.6 SAFETY SYSTEM (EMERGENCY SHUT DOWN SYSTEM)

The redundant ESD System has power supply and I/O modules that are separated from the control system. The ESD system safely shuts down equipment if the process values are outside design range or instruments fails. The ESD system is installed in the control system cabinet.

The ESD system handles signals from the MAN Cryo scope of supply. External systems such as gas detection, fire detection, ventilation surveillance etc. shall be connected. There are 16 digital I/O's reserved for CUSTOMER external systems included as standard, more can be supplied as option if requested by customer.

ESD push button(s) are provided in FGSS area and other locations on board, in alignment with the rules. ESD push buttons are supplied by MAN Cryo and mounted by CUSTOMER for the following locations:

ESD button locations	
Bunker station	1 pc
Fuel storage hold space	1 pc
ECR	1 pc
Wheelhouse	1 pc

The ESD system will close automatic valves inside the TCS and bunker station according to rules and regulations.

5.7 GAS DETECTORS

A gas detection system is included, equipped with separate independent sensors for detection of combustible gases and vapors in the range below the lower explosive limit (LEL). In case of high values, a visible and audible alarm will occur in wheel house and engine control room and necessary safety actions will take place.

Preliminary, 15 pcs of gas detectors are considered, to be located in strategical places such as bunker station and TCS.

5.8 INTERCONNECTING PIPING DESIGN

MAN Cryo will use supplied preliminary routing to make pipe stress analysis. Modified routing or supports will be suggested to comply with design requirement from class and IGF code.

Output: Analysis report (which can be used for class approval) and modifications of supplied isometric drawing.

Required input from customer:

- Isometric drawing with preliminary routing for each pipe + 3D cad model showing the pipe with the surrounding structure. Preliminary support points and positions for deck penetrations to be included.
- Design data for piping
- Ship data for calculation of acceleration level
- Hog and sag data
- Material to be used for media piping and outer pipe of double wall piping

5.9 INTERCONNECTING PIPING SUPPLY

Upon request MAN Cryo are also able to procure, supply and install the interconnecting piping according to “Request For Price Indication Hydrogen fuel system”, ver. 1, Ch. 6.6.

N.B: Interconnecting piping supply is currently not a part of MAN Cryo scope of supply.

5.10 INSTRUMENTATION

All necessary instrumentation for a safe and reliable operation of the system is included.

This includes, but not limited to:

- Level monitoring LH2 tank
- Level alarm LH2 tank
- Level alarm glycol water expansion drum
- Level alarms in drip trays
- Pressure alarm/monitoring LH2 tank
- Bunkering pressures
- Leakage measurements at bunker station
- Gas pressures and temperatures
- Glycol water pressures and temperatures

Instrument cables are routed to junction boxes on equipment units. Cabling between units and control system through ship to be done by CUSTOMER.

All remote operated valves are pneumatically operated. Instrument air is supplied from the onboard instrument air system supplied by CUSTOMER. All equipment units containing remote operated valves are fitted with one single instrument air connection point.

The instruments installed in hazardous area are IEC Ex certified and installation complies with IEC standards and class requirements.

High quality class approved instruments are used to ensure high performance and accuracy.

Skids are delivered with instruments mounted and connected to the skid junction boxes.

Junction boxes on skids are prepared for multicore cable entry for connection to C&M and ESD systems.

All field instruments have ingress protection compliant with IEC 60092-507:2015 and of at least IP54, on deck IP56.

Instrument	Measuring principle	Signal
Level monitoring (preliminary)	Hydrostatic pressure by dP (LH2 Tank), Radar (to be confirmed)	Analog 4..20mA HART
Level alarm	Temperature sensing (LH2 Tank) Vibrating fork (Water expansion tank)	Analog 4..20mA HART Digital NAMUR
Pressure	Ceramic-capacitive	Analog 4..20mA HART
Temperature	Platinum resistance type PT-100 with smart transmitter	Analog 4..20mA HART
Valve and door position	Inductive proximity switch	Digital NAMUR

5.11 LABLING & MARKING

Valves, pipes, and instruments will be equipped with stainless steel tags or plastic labels for identification according to MAN Cryo standard is included.

Typical signs to be included:

- TAG no
- Media coding
- Safety marking
- Information marking

6 DOCUMENTATION

6.1 PRELIMINARY DOCUMENT TYPES

Below table lists document types that are typical for MAN Cryo standard design scope.

All deviations regarding design scope and set-up for order execution affect the content of this list as well as the planned submittal weeks after contract signature date.

The document status for this list remains preliminary until the design scope is set and set-up for order execution incl. a preliminary time schedule is established.

After contract award, the relevant documents and or document types are transferred to a master document list (MDL) where additional metadata for each document is identified in the beginning of order execution. The MDL is distributed to the customer for information.

Preliminary Document Types-standard design scope
Tank support loads
Process and safety documentation
Layouts
Quality documentation
Automation documentation
Operating and maintenance documentation
Commissioning Documentation

6.2 DOCUMENT CONTROL

After contract award, the customer receives a document package including below listed instructions and templates.

1. 600355180 How to guide for access and utilization of Nexus for externals
2. 600376139 How to guide Communication and Document Management for Externals
3. Template transmittal letter
4. Template comment form

6.3 DOCUMENT DISTRIBUTION SET-UP (NEXUS)

Document distribution is performed via Nexus, MAN-ES extranet platform. After contract award, the customer will receive an invitation to Nexus.

Both MAN Cryo and customer utilize Nexus for document distribution.

6.4 DOCUMENT FORMAT

MAN Cryo documentation listed in the MDL is in the English language and is presented in pdf format. When possible, drawings are generated in A3 format for optimal detail level.

6.5 FINAL DOCUMENTATION

MAN Cryo compiles a final documentation in accordance with the design scope. It consists of the following sections:

- A. Operating manual
- B. Automation documentation
- C. Maintenance manual
- D. Drawings
- E. Class Society certificates (no CE, ATEX or Class certificates for equipment)

The final documentation is made accessible via Nexus.

7 QUALITY MANAGEMENT

Quality at MAN Cryo is based on a process approach from an integrated management system.

Quality control through the project execution process includes:

- Perform audit of suppliers
- Perform qualification of suppliers
- Verification of correct material through material certificates according to traceability requirements
- Managing the project ITP
- Perform FAT
- Review and compile production documentation

The Integrated Management System of MAN Cryo is certified by an accredited third party and complies with the following quality standards:

- ISO 9001:2015
- ISO 14001:2015
- OHSAS 18001:2017
- ISO 3834-2:2005

8 SERVICES AND COMMISSIONING

8.1 KICK OFF MEETING

MAN Cryo will attend a kick off meeting at customer premises a few weeks after contract effectiveness. MAN Cryo to be notified by Customer minimum 2 weeks before Kick off meeting. Accommodation, living expenses, transportation and daily allowance are included in the offer, meeting is planned for one day.

8.2 HAZOP/HAZID/FMEA

MAN Cryo will attend HAZOP/HAZID/FMEA meeting with two (2) qualified personnel at customer premises for 2 consecutive days to participate during HAZOP meeting. MAN Cryo to be notified by Customer minimum 2 weeks before HAZOP. Accommodation, living expenses, transportation and daily allowance are included in the offer.

8.3 INTERFACE MEETING

Despite all documentation and work scope splits etc our experience tells us that an integration meeting a few months into the project is necessary. MAN Cryo to be notified by Customer minimum 2 weeks before the meeting. Accommodation, living expenses, transportation and daily allowance are included in the offer, meeting is planned for two consecutive days at customer premises.

8.4 PRE-COMMISSIONING & COMMISSIONING

MAN Cryo commissioning team are delegated for technical assistance during installation and initial start-up at. The shipyard should provide necessary support/assistance during the pre-commissioning and commissioning. The shipyard should provide 14 days' notice before the start of pre-commissioning and commissioning activities so resources and transport can be arranged. MAN Cryo "Pre-commissioning" and "Commissioning Checklist" are to be signed by the shipyard and sent to MAN Cryo 3 working days before requested start date. In case where the system as such is not ready for commissioning despite signed, "Pre-commissioning" and "Commissioning Checklist", travel expenses and hours spent shall be fully reimbursed by the CUSTOMER towards MAN Cryo. Costs incurred due to cancelled visits (within 7 days before agreed start) will be logged as commissioning activities.

Total time for commissioning is estimated to 40 man days on basis of 10 hours per day and free undisturbed access during this period. The commissioning is based on maximum three round trips.

The commissioning budget price includes accommodation, living expenses, transportation and daily allowance for the quoted man-days as well as a sufficient amount of travel. Total time for commissioning also includes cool-down and training of staff(one day).

In case the number of quoted man-days are spent, additional time and expense will be charged separately in accordance with MAN Cryo standard day rate.

MAN Cryo will log and record commissioning activities providing a commissioning report and weekly timesheets for shipyard signature. Commissioning budget will be managed and monitored by MAN Cryo, when the commissioning budget is close to expended MAN Cryo will notify CUSTOMER.

With exception to working hours included in the commissioning budget, MAN Cryo's commissioning budget excludes any costs associated to Sea Trial such as accommodation, living expenses, transfer costs (between place of commissioning & vessel) etc. All costs associated with Sea Trial are understood to be at “Customer” expense and therefore Free of Charge to MAN Cryo. Responsibilities according to below table.

	Responsible	Supporting	Supply pf consumables	Arrangement and accommodation cost
Pre-commissioning				
Start-up of utilities	Shipyard	Shipyard	Shipyard	Shipyard
Cleaning and drying	shipyard	MAN Cryo	Shipyard	MAN Cryo
Loop testing	MAN Cryo	Shipyard	Shipyard	MAN Cryo
Commissioning of rotating equipment	MAN Cryo	Shipyard	Shipyard	MAN Cryo
Inerting of piping	MAN Cryo	Shipyard	Shipyard	MAN Cryo
Commissioning				
Cause & Effect test with class	MAN Cryo	MAN Cryo/Shipyard	Shipyard	MAN Cryo
Cool down with Liquid Nitrogen (LIN)	MAN Cryo	Shipyard	Shipyard	MAN Cryo
Functional test of system with LIN	MAN Cryo	Shipyard	Shipyard	MAN Cryo
Emptying system of LIN	MAN Cryo	Shipyard	Shipyard	MAN Cryo
Any tests witnessed by class	Shipyard	MAN Cryo	Shipyard	MAN Cryo
First bunkering and quay trial				
LH2 Bunkering	MAN Cryo	Shipyard	Shipyard	MAN Cryo
Quay side testing	MAN Cryo	Shipyard	Shipyard	MAN Cryo
Sea Trial				
Test program	Shipyard	MAN Cryo	Shipyard	MAN Cryo
Gas trial testing	Shipyard	MAN Cryo	Shipyard	MAN Cryo

9 AFTER SALES SERVICE

In the MAN Group the worldwide organization MAN PrimeServ delivers customized service solutions for increasing service life, improving availability, reducing emissions, or simply for delivering the right spare parts and manpower.

MAN PrimeServ has an experienced group of service technicians and workshops specialized in service of cryogenic equipment. Their main focus is to support customers with spare parts, inspection, maintenance and repair works.

9.1 SERVICE AGREEMENTS

MAN PrimeServ service agreements allow customers to estimate maintenance costs in advance. Based on a modular concept our service contracts are customized to individual demands and expectations. In this close partnership customers and MAN PrimeServ mutually agree on the scope of services employed. For example:

- The desired response time
- The duration of the contract
- Spare parts to be held in stock
- Sharing of responsibilities and risk

10 WORK SCOPE SPLIT

	General	MAN	Shipyard
1.1	External Hazid Responsible Project Schedule Dependent		X
1.2	External Hazid Attendance 2 x personnel 1 day	X	
1.3	External Risk Analysis (HAZOP/FMEA) 2 x personnel 1 day Project Schedule Dependent		X
1.4	External Risk Analysis (HAZOP/FMEA) 2 x personnel 1 day	X	
1.5	Internal HAZOP of MAN Cryo SYSTEM.	X	
1.6	MAN Cryo design documentation and final equipment markings in SI metric system.	X	
1.7	Classification Society and Flag Approval assistance for MAN Cryo Supplied Items. Rules applicable at time of Contract Award.	X	
1.8	Flag Approval and Classification Society at Shipyard and at Sea (inc during commissioning and sea/gas trial)		X
1.9	Any additional state or independent approvals relating to MAN Cryo Scope of Supply		X
1.10	Confirmation of Structural Loads (Acceleration, Collision, Vibration, Wind, Ice, Green Seas, Protective Structure etc.) Project Schedule Dependent - Confirmation at contract award		X
1.11	Hog and sag details for the ship. Project Schedule Dependent - Confirmation at contract award		X
1.12	Supply of Tie In Point Design Data to shipyard (Structural Loads, Mechanical Interface, Manufacturing Tolerances, Media Type & Temperature etc).	X	
1.13	System Design Integration/Compatibility with FGSS skids and consumers	X	
1.14	Suitable Placement of equipment and physical integration into the ship		X
1.15	Skids pre-piped & pre-wired to designated skid Tie In Point	X	
1.16	Foundations, Structural & Secondary supports, Frames, Brackets etc. required for installation, including any necessary strengthening, reinforcement, structural steel/grout, resin blocks, vibration absorption, protective materials, etc.		X
1.17	All Installation incl lifting, lifting equipment, etc. (If not specified below)		X
1.18	Access & egress to MAN Cryo equipment (if not specified below).		X
1.19	Protective coverings, shields or diffusers (For operating media, noise, weather, mechanical protection, etc.)		X
1.20	SYSTEM surface treatment according to MAN Cryo standard. Equipment supplied for inside environment. All other (additional) surface treatment performed by Shipyard at Shipyard	X	X
1.21	Utility supply systems to designated Tie In Point on skids & equipment (Electric, UPS, network, Instrument Air (IA), water, glycol water, brine, oil, etc.)		X
1.22	Brackets for TCS, Airlock & Entrance room lighting and cabling	X	
1.23	TCS, Airlock & Entrance room lighting and cabling	X	

1.24	Flow meter and/or any fuel cell or system efficiency measuring		X
1.25	All ventilation incl. control, measuring, power equipment, dampers, etc.		X
1.26	Preservation & storage of skids & equipment after delivery from MAN Cryo, according MAN Cryo Instruction. (Delivery until in service)		X
1.27	FGSS operating media (LH2)		X
1.28	Commissioning, Sea Trial & Training. As per contract	X	
1.29	Arrangement of Onboard Personal Accommodation, Onboard Food, Local Transport/Transfers etc during sea trial for MAN Cryo personnel & sub-supplier free of charge		X
1.30	Additional Pre Commissioning, Commissioning, Start-up, Sea Trial & Training		X
1.31	Final Documentation - Operating Manual and Maintenance Manual uploaded to NEXUS	X	
1.32	Operating manual regarding MAN Cryo Scope of supply	X	
1.33	Overall operating manual for entire fuel gas system (including engines, GVU, utilities, ventilation etc.)		X
1.34	Operating maintenance manual regarding MAN Cryo Scope of supply	X	
1.35	Overall maintenance manual for entire fuel gas system (including engines, GVU, utilities, etc.)		X
1.36	Counter flanges		X
1.37	Interconnecting piping		X
1.38	Operating supply media, nitrogen, electricity, instrument air, water, LH2 etc,		X
1.39	Integration design and installation of the equipment on-board the vessel		X
1.40	Vent mast		X
2	**LH2 Tank (Technical Specification 5.1)**	**MAN**	**Shipyard**
2.1	LH2 C Type Tank	X	
2.2	TCS	X	
2.3	TCS Piping System	X	
2.4	TCS with Entrance Room (Bolted Hatch) and Air Lock	X	
2.5	TCS insulation (A60)	X	
2.6	Vaporizer	X	
2.7	PBU	X	
2.8	Saddles	X	
2.9	TCS and Tank thermal calculations	X	
2.10	Integration and design of tank room after thermal calculation		X
2.11	Installation		X

3	Bunker station (Technical Specification 5.3)	MAN	Shipyard
3.1	MAN Cryo Custom made Bunker Station	X	
3.2	Water curtain		X
3.3	Ship shore link		X
3.4	Connection type compatible with Air Products standard truck LH2 supply system	X	
3.5	Guard rails around bunkering station (if required)		X
3.6	Weather Protection		X
3.7	Installation		X
4	**Heat Exchanger Unit (Technical Specification 5.4)**	**MAN**	**Shipyard**
4.1	MAN Cryo's HEU Skid (Not for EX Zone)	X	
4.2	GWA Circulation Pumps (2 pcs)	X	
4.3	Pressure Indicators	X	
4.4	Direct on Line Starters for GWA Circulation Pumps (Supplied loose)	X	
4.5	GWA Plate Heat Exchanger (1 pc)	X	
4.6	Design of expansion tank	X	
4.7	Expansion Tank (1pc)	X	
4.8	Installation of HEU and Expansion tank		X
4.9	Shunt valves for temperature regulation (If required)		X
5	**Nitrogen Generation System (Technical Specification 5.5)**	**MAN**	**Shipyard**
5.1	Design, procurement, supply & commissioning	X	
5.2	Installation		X
6	**Instrument air**	**MAN**	**Shipyard**
6.1	Instrument Air (IA) distribution manifold TCS (TCS IA battery limit)	X	
6.2	Instrument Air (IA) distribution manifold Bunker station (BS IA battery limit)	X	
6.3	On-skid instrument air tubing between manifolds and pneumatic acturators	X	
6.4	Instrument air supply system (compressors, dryers, buffer tank, etc.)		X
6.5	Piping between TCS/BS IA battery limits and IA supply system		X
6.6	Commissioning of IA system		X
7	**Control system (Technical Specification 5.6)**	**MAN**	**Shipyard**
7.1	MAN Cryo FGSS Functional Description	X	
7.2	Control cabinet, PLC system, programming	X	
7.3	Operator Stations; one for navigation bridge, one for Engine control room	X	
7.4	Screen for flush mounting; one for navigation bridge, one for ECR	X	

7.5	Installation of Screen for flush mounting		X
7.6	UPS and UPS Control System Cabinet		X
7.7	UPS Control Operator stations and other		X
7.8	230VAC Power Supply		X
7.9	Network Switch for redundant fiberoptic connection to bridge operating station	X	
7.10	Control Function in Vessel IAS		X
7.11	Instruments on skids pre-wired to on-skid junction box	X	
7.12	TCS pre-wired to adjoining junction box	X	
7.13	Installation & final connection of interconnecting cables		X
7.14	Installation and connection of loose supplied equipment (if applicable)		X
7.15	Installation of cabinet		X
8	**Safety System (Technical Specification 5.7)**	**MAN**	**Shipyard**
8.1	ESD System (Installed in Control Cabinet), PLC system, OP stations, programming	X	
8.2	Available Digital I/O's available for external signals (16 pcs)	X	
8.3	Emergency Stop Push Buttons (4 pcs)	X	
8.4	Cause & Effect Diagram	X	X
8.5	Pre-wired system cabinet	X	
8.6	TCS leakage detection (low temp & level)	X	
8.7	Tank overfill protection	X	
8.8	Gas supply pressure and low temperature protection	X	
8.9	Fire Fighting and Detection System		X
8.10	Ventilation Monitoring System		X
8.11	Safe Engine shutdown signals		X
8.12	Installation & final connection of interconnecting cables		X
8.13	Installation and connection of loose supplied equipment (if applicable)		X
8.14	Installation of cabinet		X
9	**Instrumentation (Technical Specification 5.11)**	**MAN**	**Shipyard**
9.1	Installation & Final Connection of Supply and Interconnecting cables		X
9.2	Electrical Testing of Supply and Interconnecting cables (Hot and Cold)		X
9.3	Attendance during electrical testing of important functions	X	X
9.4	Instruments on skids pre-wired to On Skid Connection Point (Starter, Isolator, Junction Box etc.)	X	
9.5	Electrical Testing of On Skid Wiring	X	
9.6	Uninterruptible Power Supply (UPS)		X

10	Gas detection system (Technical Specification 5.8)	MAN	Shipyard
10.1	IR Detector including Gas detectors	X	
10.2	Installation and cabling		X
11	**Documentation and Engineering**	**MAN**	**Shipyard**
11.1	For documentation, see above	X	
11.2	Spare parts list	X	
11.3	Signal diagram	X	
11.4	Alarm list	X	
11.5	Cable layout	X	
11.6	Electrical Connections drawing	X	
11.7	Installation check list	X	
11.8	Handover document after commissioning	X	

11 DIVISION OF SCOPE

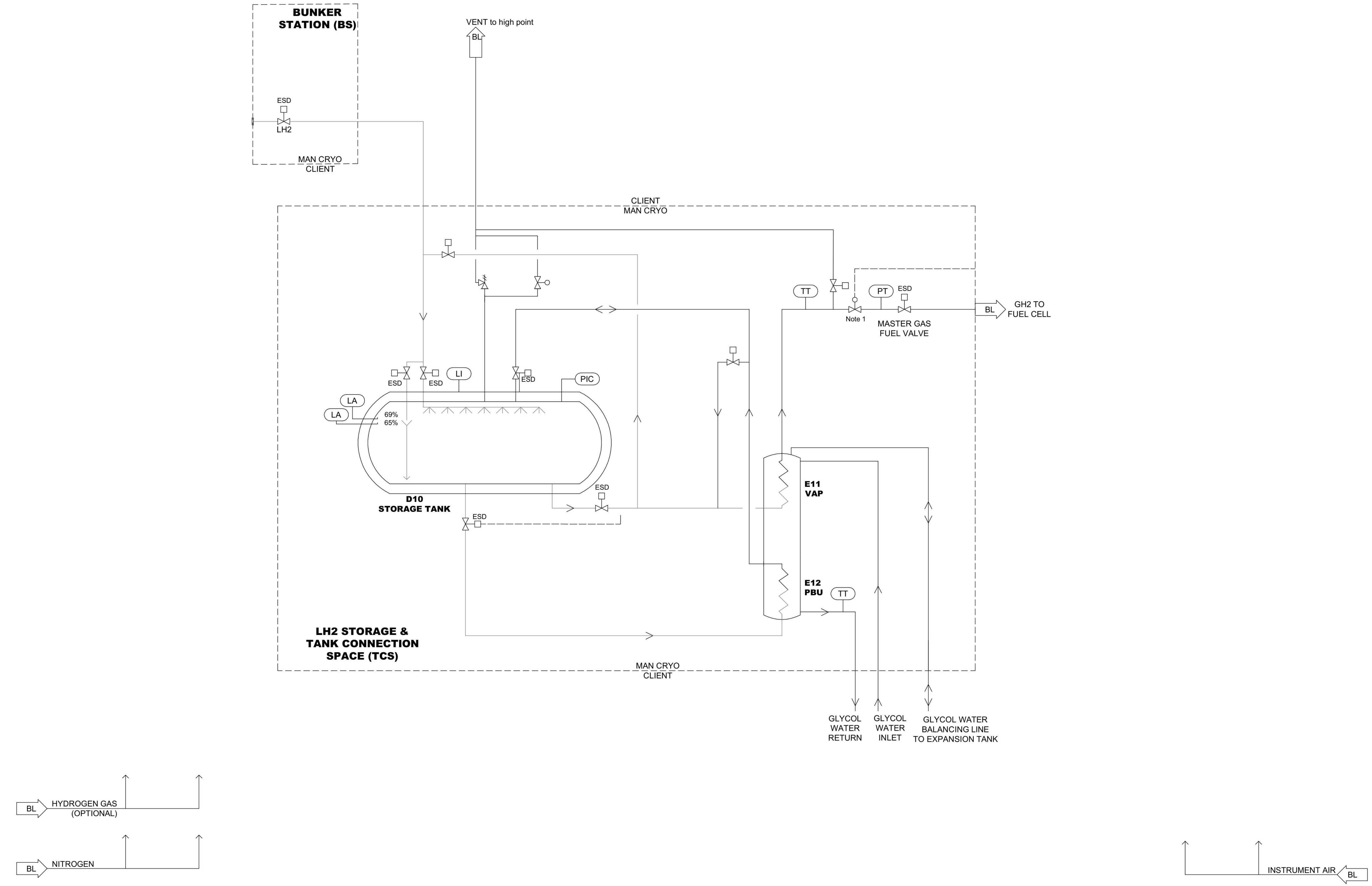
Ref.	Item	Comments
1	**General**	
1.1	Technical specification	Included (E-SE-2019-82301_Rev01)
1.2	Training	Included
1.3	Design and Detail Engineering	Included for equipment which is part of main scope
2	**Vacuum insulated tank**	
2.1	Components	Included
2.2	Installation onsite	Not Included
2.3	Commissioning	Included
2.4	Warranty/service setup	Included
2.5	Transportation	Included
3	**Tank Connection Space**	
3.1	Components	Included
3.2	Installation onsite	Not Included
3.3	Commissioning	Included
3.4	Warranty/service setup	Included
3.5	Transportation	Included Note: Air lock and entrance room not attached to the TCS during transportation. Needs to be welded on to the TCS at site.
4	**Bunker station**	
4.1	Components	Included
4.2	Installation onsite	Not Included
4.3	Commissioning	Included
4.4	Warranty/service setup	Included
4.5	Transportation	Included
5	**Glycol water system**	
5.1	Components	Included
5.2	Installation onsite	Not Included
5.3	Commissioning	Included
5.4	Warranty/service setup	Included
5.5	Transportation	Included
6	**Nitrogen generating system**	
6.1	Components	Included
6.2	Installation onsite	Not Included
6.3	Commissioning	Included
6.4	Warranty/service setup	Included
6.5	Transportation	Included

7	**Interconnecting Piping**	
7.0	Design	Included
7.1	Components	Not Included
7.2	Installation onsite	Not Included
7.3	Commissioning	Not Included
7.4	Warranty/service setup	Not Included
7.5	Transportation	Not Included
8	**Instrumentation**	
8.1	Components	Included
8.2	Installation onsite	Not Included
8.3	Commissioning	Included
8.4	Warranty/service setup	Included
8.5	Transportation	Included

12 EXCLUSION LIST

The following services and items are excluded from MAN Cryo scope of supply:

- Any kind of installation at shipyard/site
- Deck reinforcements
- Fuel preparation room structure and piping
- Vent masts outside of MAN Cryo battery limits
- Ventilation system for TCS, bunker station and double wall piping. Fans, ventilation monitoring, fire dampers etc
- Interface engineering to Integrated Automation System (IAS)
- Local authority engineering or approvals
- 3rd part associated costs on site/at yard
- Costs for discussion with flag state
- Fire protection system
- Electrical cables between junction boxes on equipment skids and control & safety system cabinets.
- Operating supply item e.g. nitrogen, electricity, instrument air or water for fire protection etc.
- Nitrogen system
- Nitrogen distribution system outside of MAN Cryo equipment. (However, Tank Connection Space and Bunker station are prepared for N2 Purge)
- Liquid nitrogen for cooling of tank during cool down and inerting
- LH2, flares or other equipment needed for bunkering
- Integration design for the equipment on board the vessel
- NDT work at CUSTOMER'S premises
- Any kind of engineering and supply not explicitly mentioned
- Counter flanges
- Ship to shore link while bunkering
- Interconnecting piping; bunker line, gas supply piping, GWA piping, vent mast, , nitrogen and instrument air (offered as optional))
- Process fluids (for heat exchangers, glycol water)
- Water curtains at bunker stations
- UPS



Note 1: Placement of fuel cell control valve to be evaluated.

Date	Prepared	Checked	Approved	Description	Status	Issue
2019-10-07	JOHE	MAPA		Concept PFD	A	01

PROCESS FLOW DIAGRAM

MARINE FUEL GAS SUPPLY SYSTEM

LH2 STORAGE AND VAPORIZATION

Client Job No.	N/A
Client Job Code	N/A
Client Doc. No.	N/A
Proj. No.	Glosten
Proj. Name	LH2
Doc. No.	600XXXXXX