A ZERO-EMISSION HYDROGEN FUEL CELL RESEARCH VESSEL

Bruce Appelgate, Scripps Institution of Oceanography

30 November 2017 - UNOLS Annual Meeting

Zero-V Hydrogen Fuel Cell Research Vessel

Team Members

Is it technically and economically possible to create a zero-emissions H_2 fuel cell research vessel that meets or exceeds the requirements of such vessels operating along U.S. coastlines?

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PRESENTATION OVERVIEW

Context: Need for new vessel

Why Carbon Pollution Must Stop

Mission Requirements

Vessel Particulars

Capabilities

Capability Comparison

Arrangements

Hydrogen Gas Systems

Hazardous Areas

Bunkering

Cost Estimates

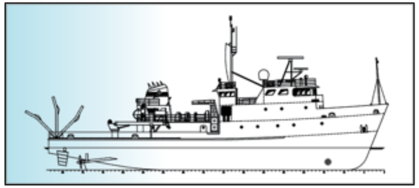
Emissions Estimates

CALIFORNIA NEEDS A COASTAL / LOCAL RESEARCH VESSEL

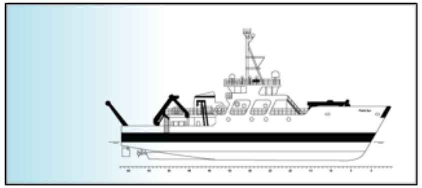
- California **society and economy** depend on the ocean for resources, commerce, defense, infrastructure, and quality of life.
- Growing need for **undergraduate and graduate education** involving instruction, research and practical training at sea.
- **California economy, 6th largest in world**, is strongly tied to the ocean and drives a growing demand for maritime research & development.
- *Roger Revelle* and *Sally Ride* have worldwide research portfolios, and will not predictably be available in California waters
- California universities require an **accessible, affordable, capable research vessel** for classes and student research projects, operating on time frames tailored to academic calendars.
- California needs the ability to mount **rapid response** missions to ephemeral events, with quick access to a capable, well-outfitted, professionally-staffed vessel

CALIFORNIA-BASED INTERMEDIATE CLASS & SMALLER SHIPS

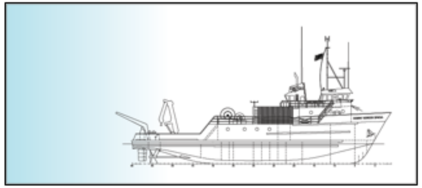
Research vessels able to carry out California's local research and education needs have decreased from 3 to 1, with the last remaining ship approaching the end of its service life. A new vessel is needed.



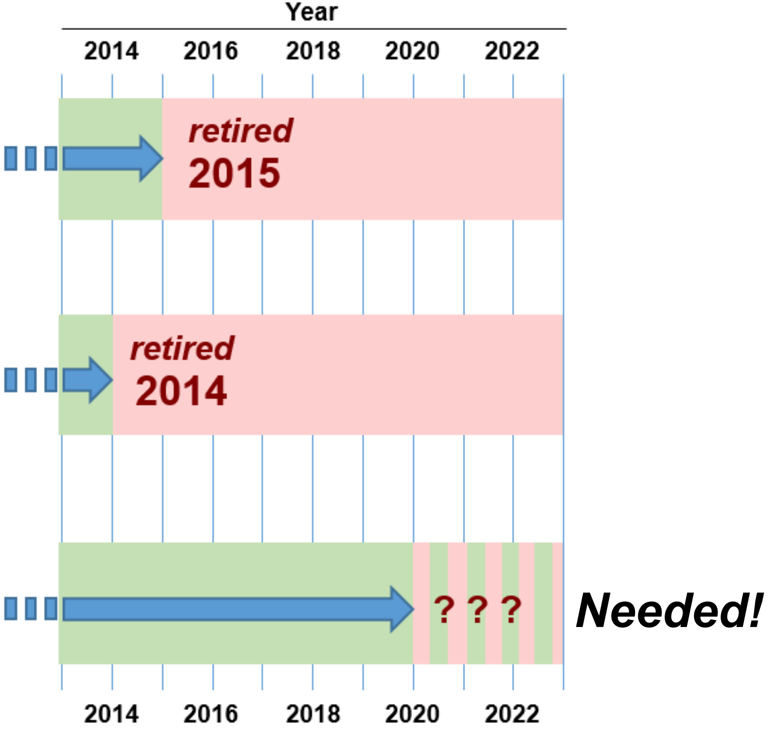
INTERMEDIATE
R/V *New Horizon*
170 feet / 40-day endurance
12 crew / 19 scientists



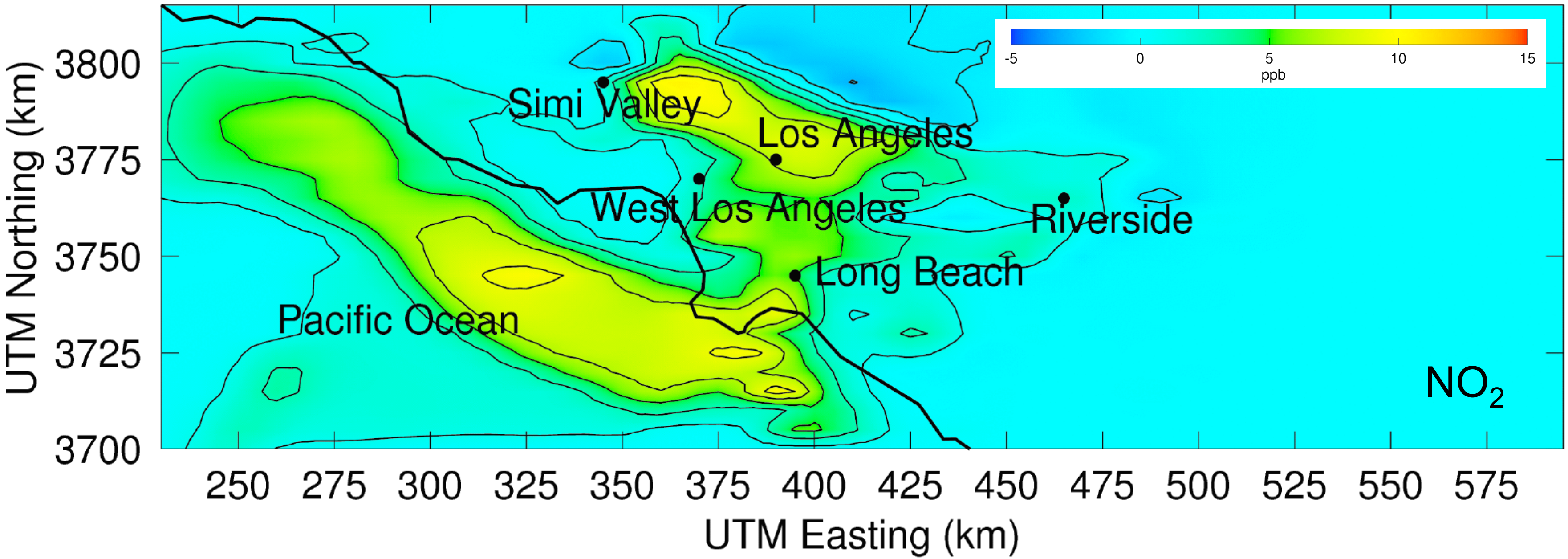
REGIONAL
R/V *Pt Sur*
135 feet / 21-day endurance
8 crew / 12 scientists



LOCAL / COASTAL
R/V Robert Gordon Sproul
125 feet / 14-day endurance
5 crew / 12 scientists

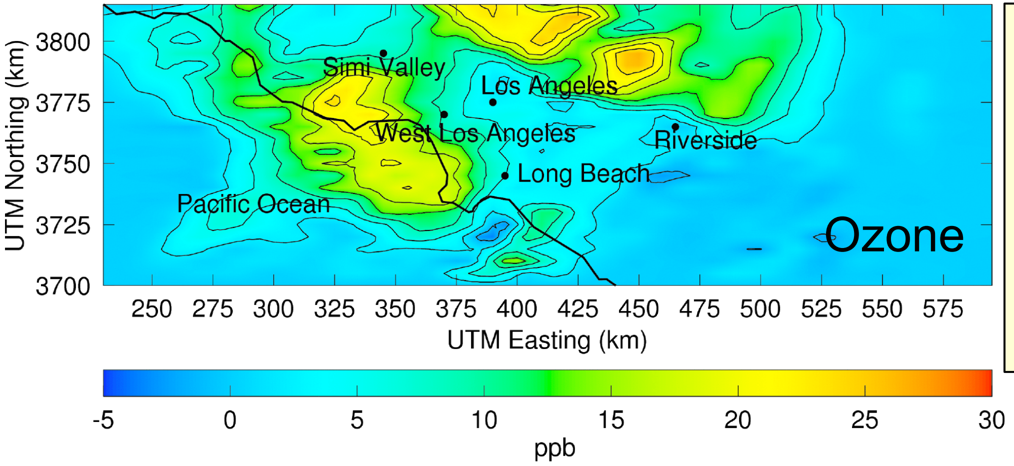


ENVIRONMENTAL IMPERATIVE

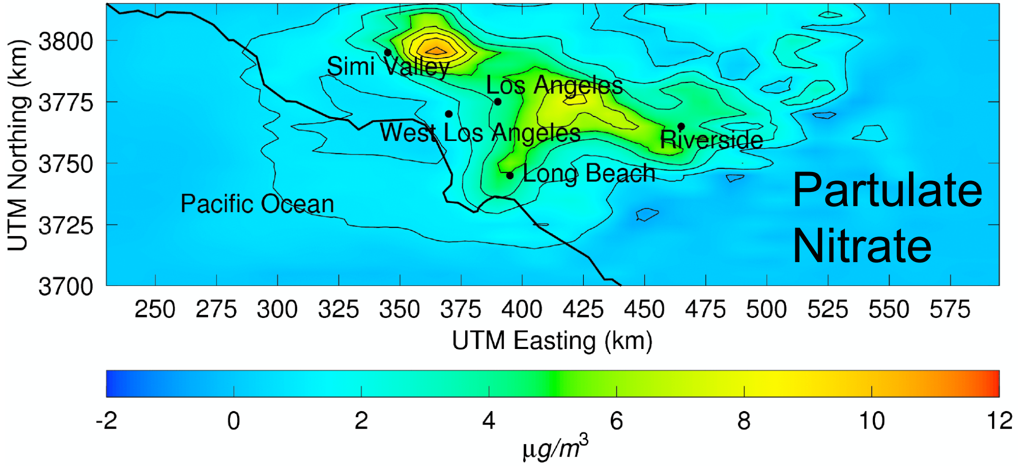


Difference between 24-hour average NO2 concentration (ppb) for year 2002 in the South Coast air basin of California between cases with and without ship emissions. **A positive value indicates an increase in the concentration due to ship emissions.**

Dabdub et al., 2008, Air Quality Impacts of Ship Emissions in the South Coast Air Basin of California



California Air Resources Board identifies DPM as a **toxic air contaminant** based on published evidence of a relationship between diesel exhaust exposure and lung cancer and other adverse health effects



"…diesel exhaust still poses substantial risks to public health and the environment."

AGU
American Geophysical Union

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Home / Worldwide ship traffic up 300 percent since 1992

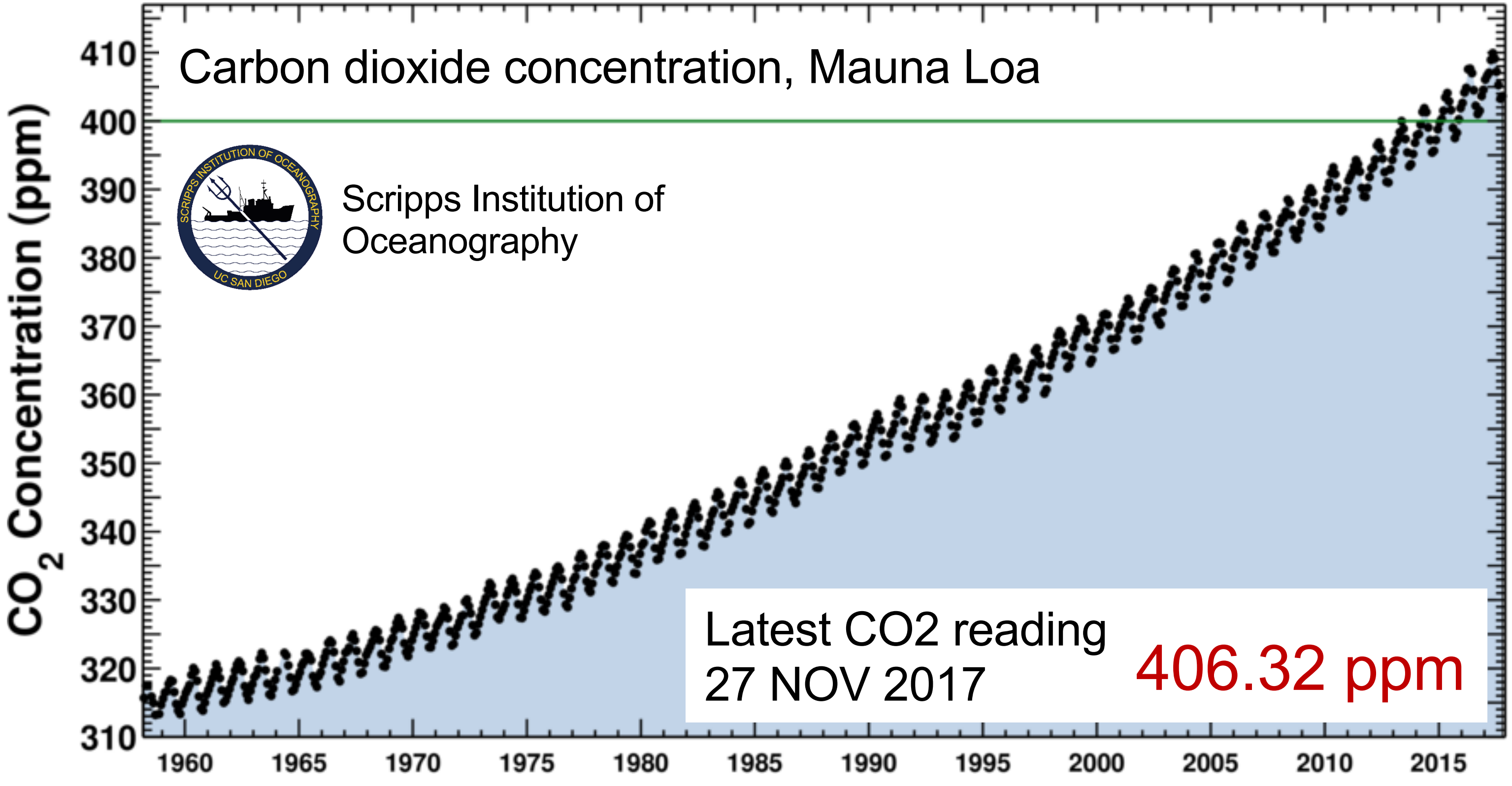
WORLDWIDE SHIP TRAFFIC UP 300 PERCENT SINCE 1992

NEW SATELLITE DATA REVEALS WHOPPING BOOST IN SHIPPING

17 November 2014

Like 0 Tweet G+ Share 21

ENVIRONMENTAL IMPERATIVE



WE NEED TO REDUCE GHG EMISSIONS BY > 75%

"There is evidence that the greatly increasing use of the fossil fuels, whose material contents after combustion are principally H_2O and CO_2, is seriously contaminating the earth's atmosphere with CO_2

Since CO_2 absorbs long- wavelength radiation, it is possible that this is already producing a secular climatic change in the direction of higher average temperatures. This could have profound effects both on the weather and on the ecological balances."

M. King Hubbert

from "Energy Resources", a 1962 Report to the Committee on Natural Resources of the US National Academy of Sciences, page 96

Increases in global temperature date back to ~ 1910

5^{TH} AVENUE AND 42^{ND} STREET, NEW YORK CITY 1910

Even here the train was coming off the tracks

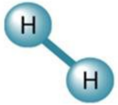
The world population was 1.75 billion in 1910, compared to today's population of 7.3 billion.

We need deep, deep cuts in GHG emissions to impact the global climate change problem.

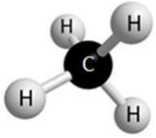
Zero-emission technology is needed for emission reductions to be stable against growth

We target zero-emissions maritime technology (vessels, power) using H_2 fuel cells.

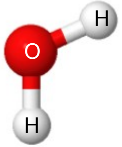
H_2 molecule



Natural Gas
(90% CH_4)



Water
(H_2O)



Hydrogen is typically made from natural gas, but "renewable H_2" derived from biogas or electrolyzing water (H_2O) with clean power is available. Renewable H_2 is preferred due to low GHG emissions from H_2 production.

HYDROGEN (H_2)

- **Is a gas at standard conditions (room T, atmospheric pressure)**
- **Liquefies (LH_2) at 20K (-424 °F, -253 °C)**
- **LH_2 evaporates rapidly (seconds)**
- **More buoyant than helium**

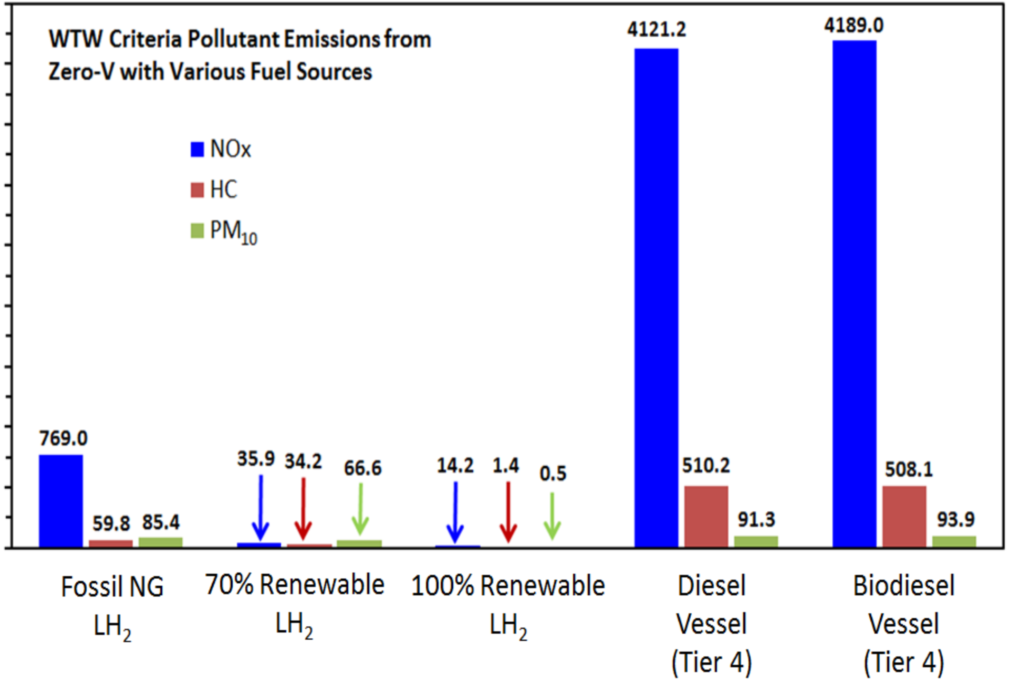
H_2 /LH_2 is similar to NG/LNG but there are differences

	Hydrogen	Natural Gas
Greenhouse Gas	No	Yes, potent
Ignitable	yes, given right mixture	yes, given right mixture
Lower Heating Value	120 MJ/kg	45 MJ/kg
Approach to Safety	Avoid leaks and ignition sources	Avoid leaks and ignition sources
Boiling point (liquid)	20K (-253 °C).	111K (-162 °C)
Density (liquid)	71 g/L	422 g/L

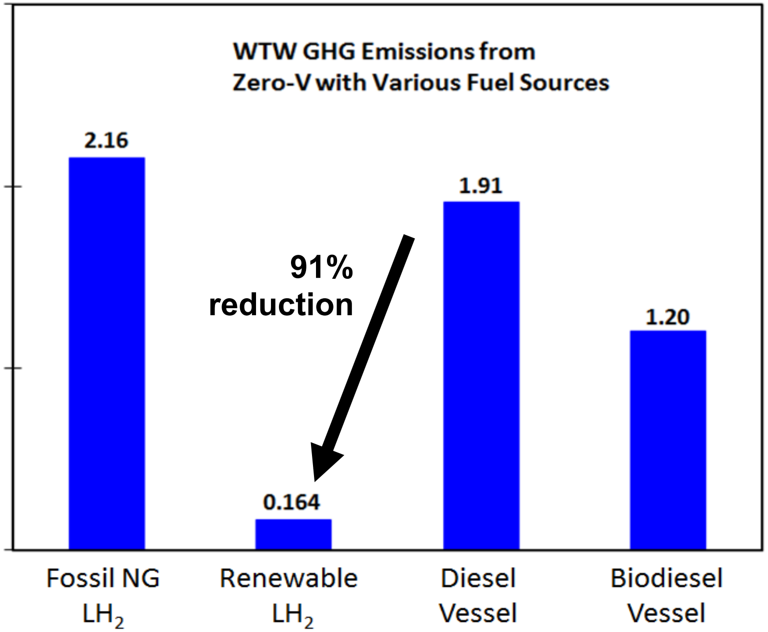
For the same amount of stored energy, LH_2 has 0.38 times the mass of LNG, but has 2.4 times the volume

EMISSIONS (FROM H_2 PRODUCTION)

Well-To-Waves Criteria Emissions (kg / year)



Well-to-Waves Greenhouse Gas Emissions (1,000 MT CO_2 equivalent / year)



Criteria pollutant emissions can be reduced using LH_2. Dramatic reductions in GHG can be achieved with ***renewable*** LH_2. Renewable LH_2 is available from the gas suppliers.

ZERO/V PROJECT GOALS

Assess technical feasibility of H_2 fuel cell research vessel

Vessel performance - Reduced emissions - Noise - Refueling - Affordability

Establish technology and know-how

- Increase H_2 technology expertise within the U.S. maritime industries, new jobs.
- Develop maritime regulations for H_2 vessel technology based on sound science.
- Promote class society capability for examining the safe operation of H_2 vessels.
- Promote the development of fuel cell technology for marine applications.

Improve the environment

- Eliminate vessel greenhouse gas (GHG) and smog emissions, eliminate polluting fuel spills.

Increase US energy independence

- Increase awareness among U.S. H_2 suppliers of maritime applications.
- Stimulate H_2 production and delivery in the U.S., especially renewable H_2.

ZERO-V SCIENCE MISSION REQUIREMENTS

Primary Vessel Requirements

Cruise	10 kts, calm water	Portable Vans	2
Speed	12 kts, calm water (sprint) 9 kts, SS4 7 kts, SS5	Crew Berths	11
Range	2400 nm	Scientist Berths	18
DP	2 kts beam current, 25 kts wind at best heading	A-Frame	12,000 ST SWL
Endurance	15 days	Main Crane	8,000 lbs @ 12' over the side
Main Lab	800 sq ft	Portable Crane	4,000 lbs SWL
Wet Lab	500 sq ft	Side Frame	5,000 lbs SWL
Computer Lab	120 sq ft	Trawl Winch	10,000m 3/8 3x19
Aft Deck	1200 sq ft	Hydro Winch	10,000m 0.322 EM, 10,000m 1/4 3x19

Operational Profiles

- Coastal mooring
- Deep moorings & towed sonar
- Mapping
- Class cruise: biology
- Class cruise: geology
- Class cruise: ROV
- ROV survey
- Geology sampling
- FLIP anchor handling
- UAV flight ops
- AUV ops
- Physical oceanography
- Biogeochemical survey

Primary Ports of Call

RANGE AND ENDURANCE

Operating Conditions

							On	On Station

Fu
Fu
Fu

Mission Profiles

Time (hours)

CCRV Ideal	Mission			Per Year
	Length	Participants		Number
Operational profiles	(days)	Science	Techs	missions
Coastal Mooring	1	15	1	6
Deep Moorings (4000 m) & towed sonar	5	13	2	2
Mapping (multibeam & towed CHIRP)	5	7	1	2
Class cruise: biology	1	40	4	6
Class cruise: geology	1	40	4	6
Class cruise: ROV	1	20	4	4
ROV survey	7	12	4	2
Geology sampling	5	10	2	2
FLIP anchor handling	3	2	2	6
UAV flight ops (aerial drones)	4	10	1	2
AUV ops (Remus, Wave glider, Spray etc)	4	10	1	5
Physical oceanography	8	14	1	4
Biogeochemical survey	8	14	1	2

LH_2 Consumed

Mission	Hydrogen Consumed, kg
Coastal Mooring	1,208
Deep Moorings (4000m) & towed sonar	5,352
Mapping (multibeam & towed CHIRP)	4,015
Class Cruise biology	492
Class Cruise geology	492
Class Cruise ROV	492
ROV Survey	7,670
Geology Sampling	5,979
FLIP Anchor Handling	2,605
UAV Flight Ops	3,000
AUV Ops (REMUS, Wave Flider, Spray etc)	2,279
Physical oceanography	8,243
Biochemical Survey	7,654
Endurance	10,664

Achieves all missions and 2400 nm range

VESSEL PARTICULARS – GENERAL

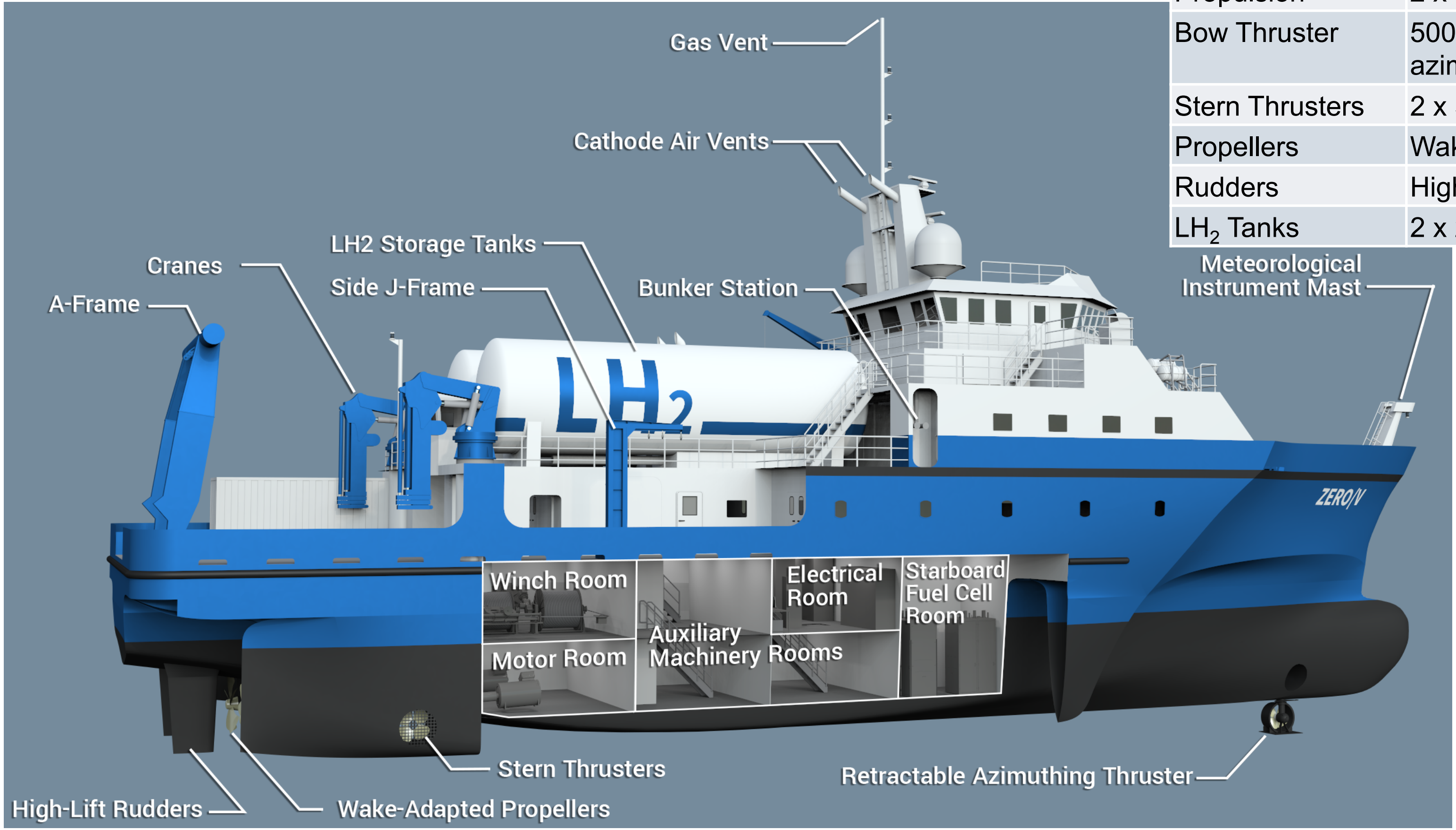
Hull Type	Trimaran
Material	Aluminum
Length	170 ft.
Beam	56 ft.
Draft	12 ft.
Freeboard	9 ft.
Displacement	1,175 LT
Cruise Speed	10 knots
Range	2,400 nm
Endurance	15 days
Station Keeping	Dynamic positioning
Berths	18 Science (8 double, 2 single) 11 Crew (single)
Air Emissions	Water vapor

VESSEL PARTICULARS – SCIENCE

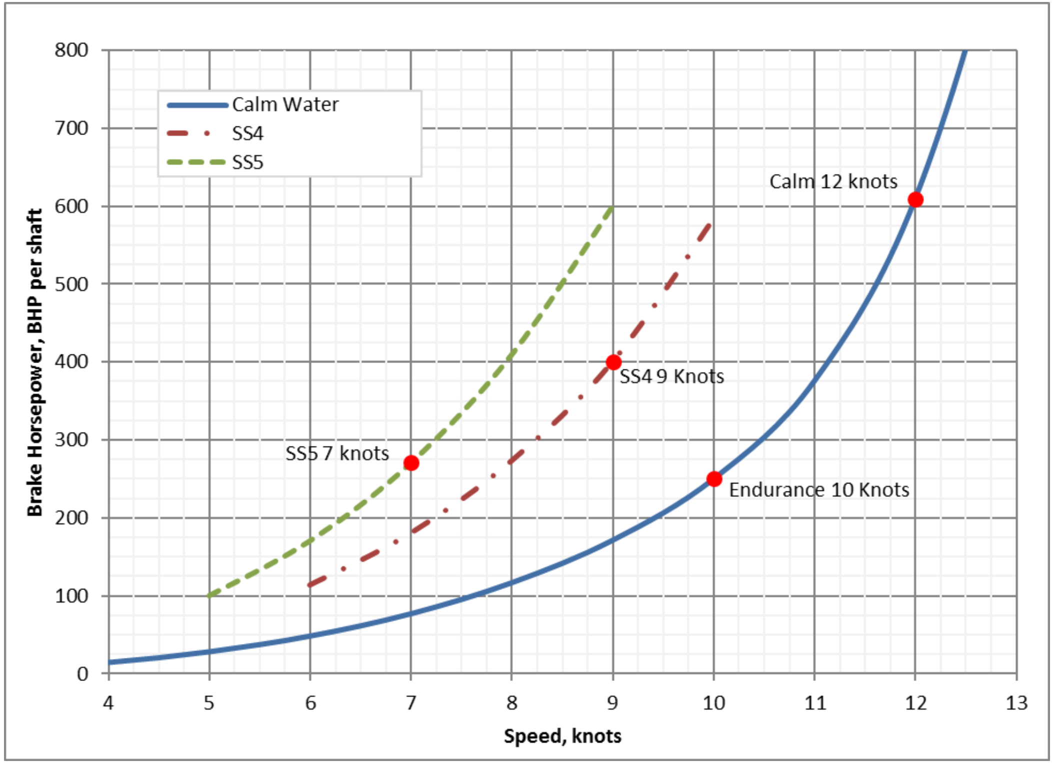
A-Frame	20,000 lbs SWL 20′ vertical clearance 12′ outboard reach
Main Cranes (2)	8,000 lbs SWL over the side
Portable Crane	8,000 lbs SWL
Side Frame	5,000 lbs SWL
Trawl Winch	10,000m 3/8 3x19 wire
Hydro Winch	10,000m 0.322 EM 10,000m ¼″ 3x19 wire
Multi Beam Sonar	Kongsberg EM712
Underwater Noise	ICES up 8 knots
Main Lab	825 ft^2
Wet Lab	575 ft^2
Computer Lab	175 ft^2
Aft Deck	1,775 ft^2
Side Deck	525 ft^2
Van Spaces	2
Science Payload	50 LT

VESSEL PARTICULARS – PROPULSION

Power	10 x 180 kW hydrogen fuel cell racks
Propulsion	2 x 500 kW PM motors
Bow Thruster	500 kW, retractable azimuthing
Stern Thrusters	2 x 500 kW tunnel
Propellers	Wake-adapted fixed pitch
Rudders	High-lift
LH_2 Tanks	2 x 28,800 gal type C



SPEED AND POWERING

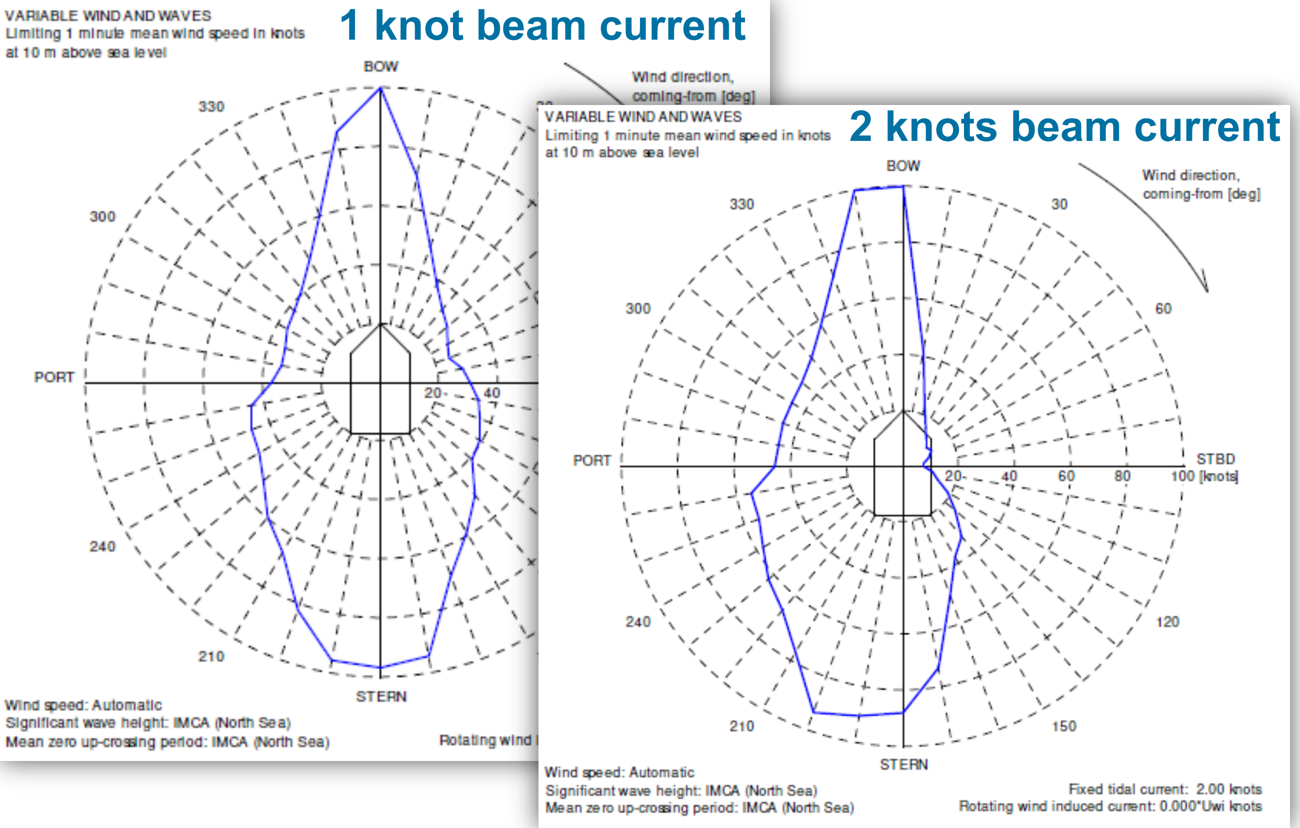


Zero-V achieves required 10 knot cruise speed

Methodology

- Parametric regression methods not available for low speed trimarans
- Calculated Resistance with ITTC Method
  - Resistance calculated for each hull separately
  - Frictional + residuary + appendage + air
- Speed in seaways extrapolated from calm water using added resistance from waves

CAPABILITIES - POSITION KEEPING



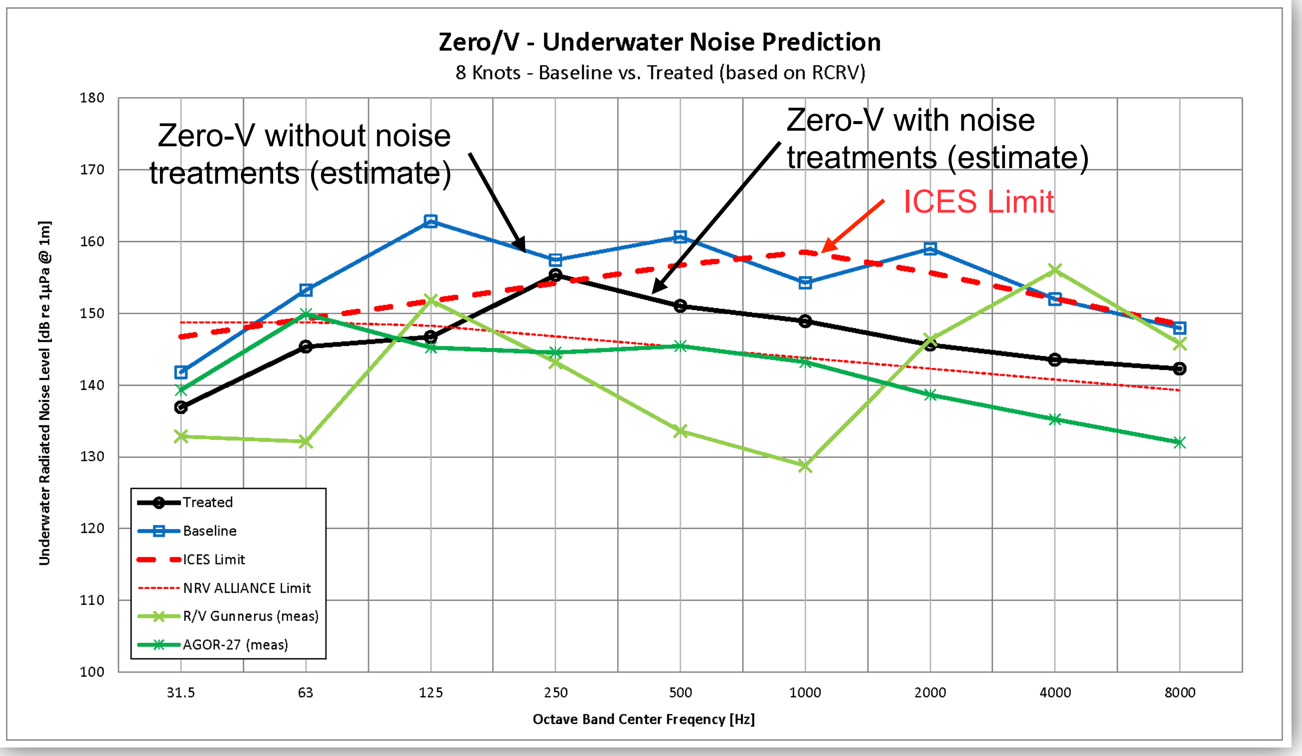
Maintain position with

1 kt beam current with 25 kt wind and waves from any direction

2 kts beam current with 25 knots wind and waves at best heading (up to 15 deg bow quarter and 45 deg stern quarter)

Station keeping performance meets science mission requirements

CAPABILITIES – UNDERWATER RADIATED NOISE (URN)



Expectation is Zero-V can meet ICES* limit at 8 knots

Initial assessment

- Used Regional Class R/V (monohull) URN analysis and removed noise from Z-drives & diesel engines
- Non-cavitating propellers

Considerations

- Trimaran has less noise radiating surface
- Aluminum may require more noise treatment than steel

Computational analysis is required for a more accurate assessment

*International Council for the Exploration of the Sea (ICES) Report 209 is an often used benchmark of R/V URN

CAPABILITIES – COMPARING OTHER VESSEL TO ZERO-V

	Zero-V	Sally Ride	RCRV	New Horizon	Sharp	Sproul
Length, ft.	170	238	192	170	146	125
Beam, ft.	56	50	41	36	32	32
Size	•	+	≈	-	-	--
Range	•	++	++	++	+	+
Science Berths	•	+	≈	≈	-	-
Lab Space	•	≈	-	-	--	--
Deck Space	•	+	-	-	-	-
Over Side Handling	•	+	≈	≈	-	--
Station Keeping	•	≈	≈	-	≈	-
Multibeam	•	+	≈	n/a	-	n/a
Payload	•	++	≈	+	-	--
Year Built	NA	2014	NA	1978	2005	1981

++ much greater + greater -- much less - less ≈ equivalent × none

Zero-V's capabilities (except range) are on par with a diesel fueled R/V of similar size but without air emissions or risk of fuel spills, and it has less machinery noise

R/V *Sally Ride*

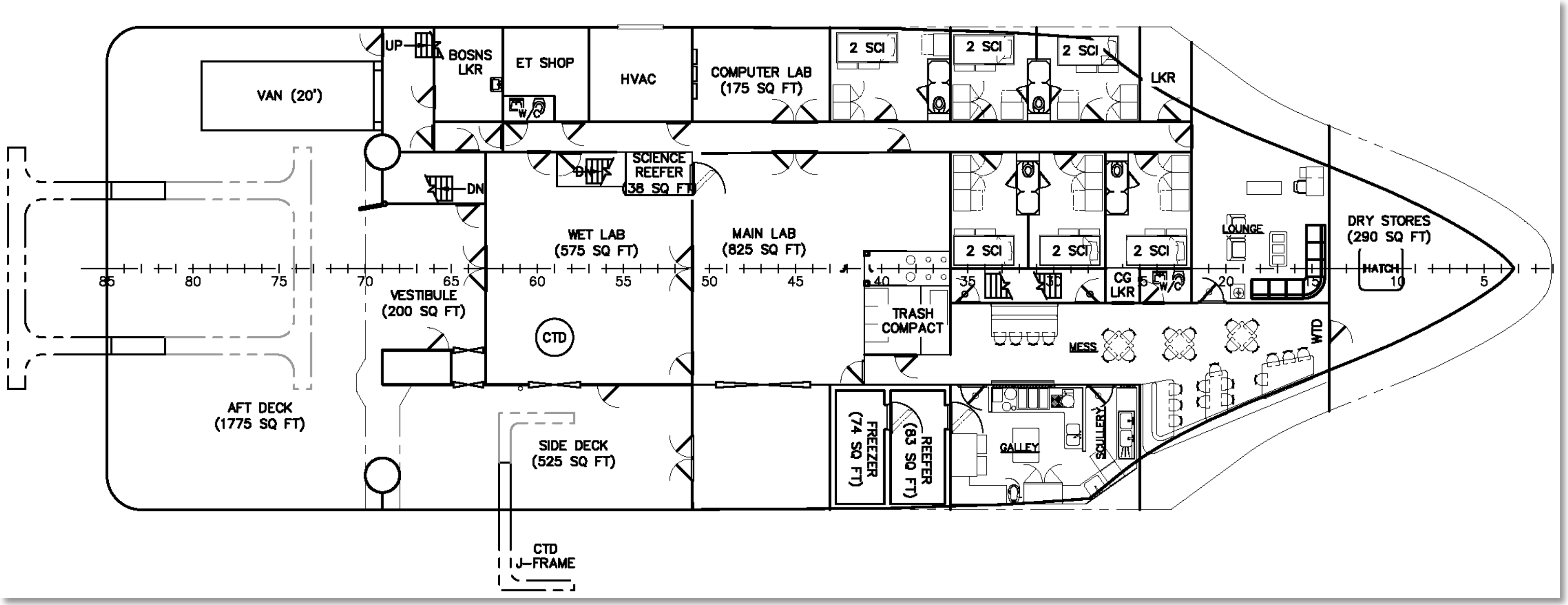
Region Class Research Vessel

R/V *New Horizon*

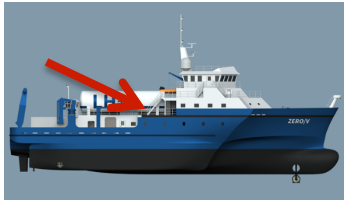
R/V *Hugh R. Sharp*

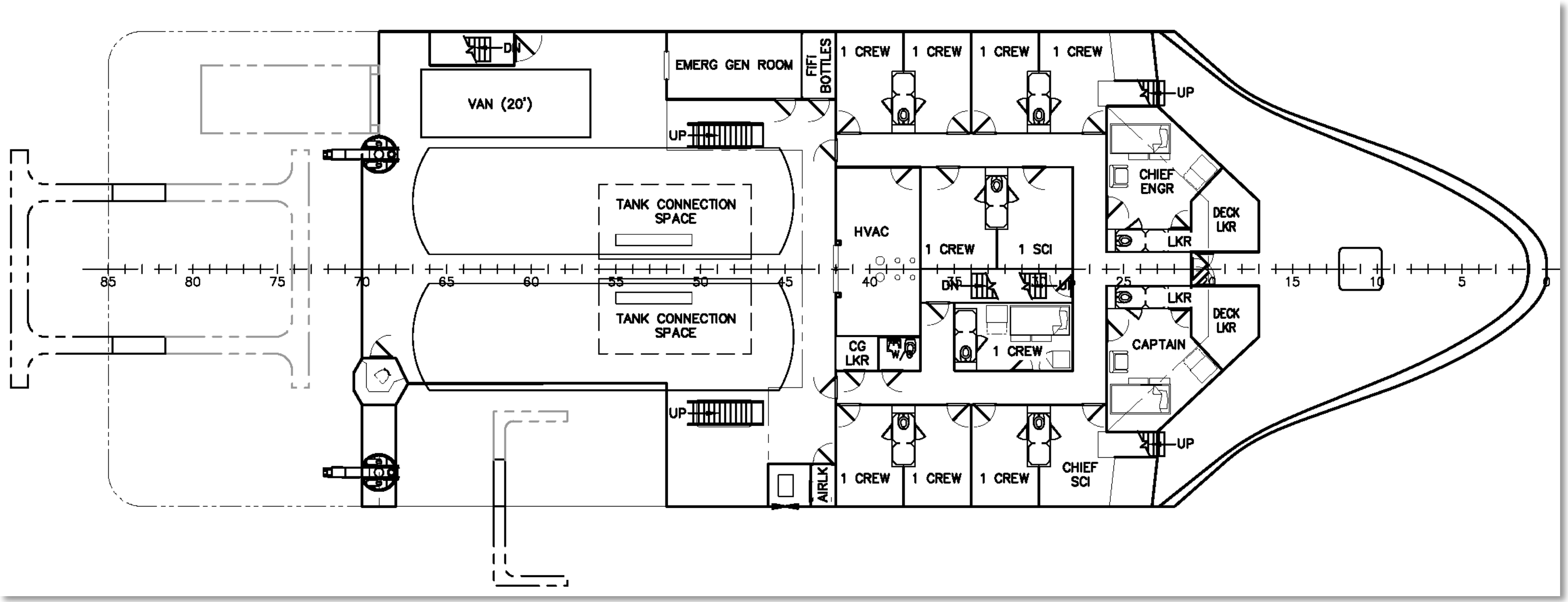
R/V *Robert Gordon Sproul*

ARRANGEMENTS – MAIN DECK

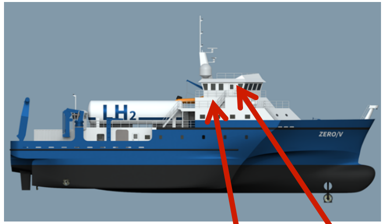


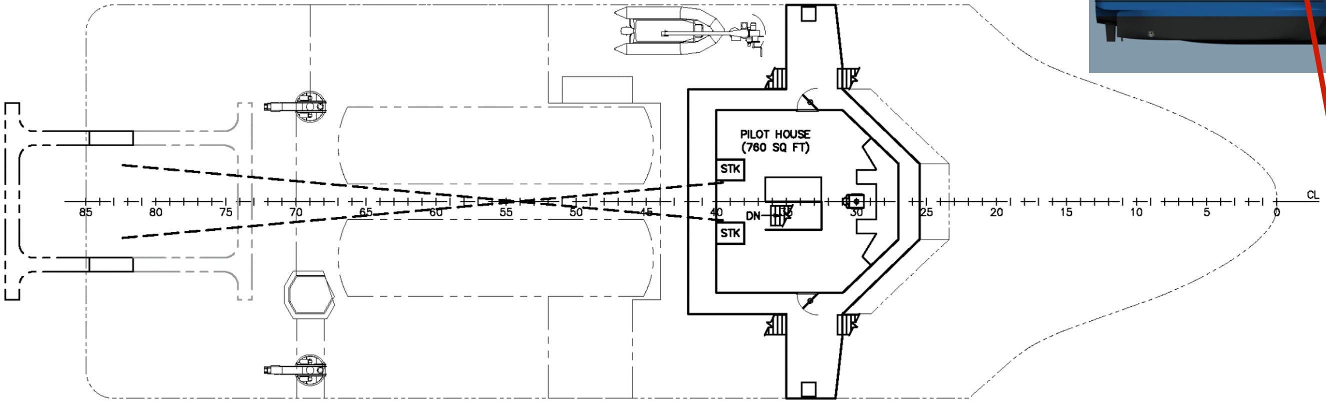
ARRANGEMENTS – 01 LEVEL



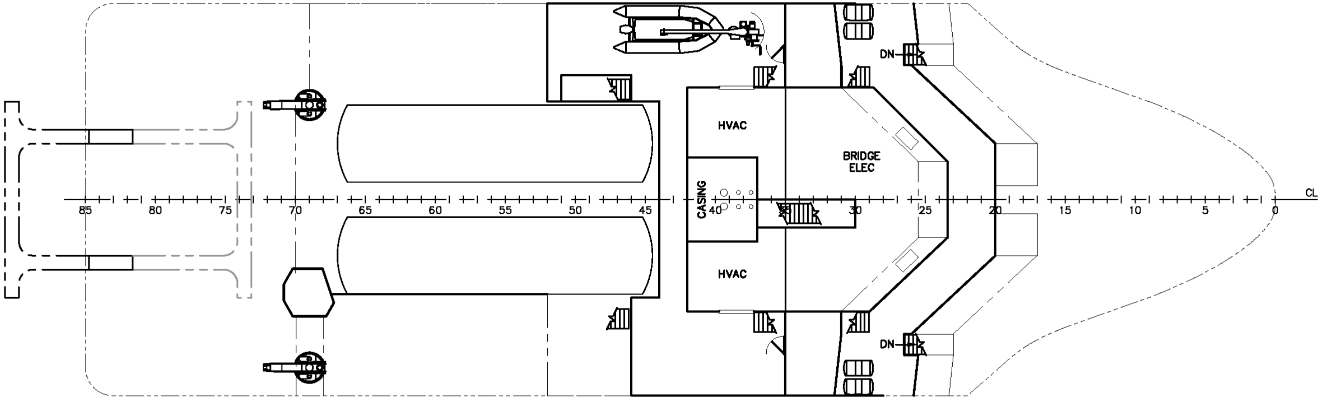


ARRANGEMENTS – 02 & 03 LEVELS



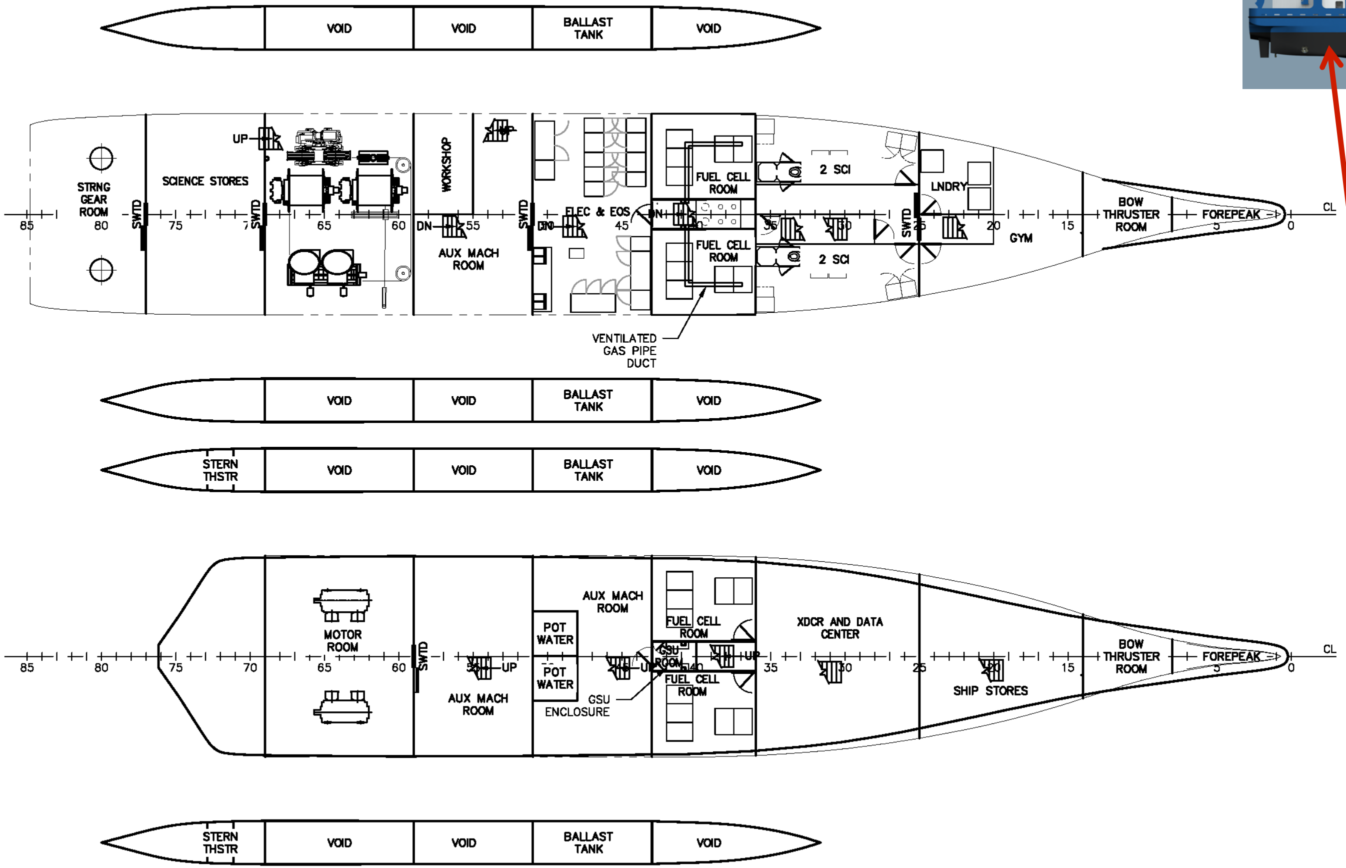


03 Level



02 Level

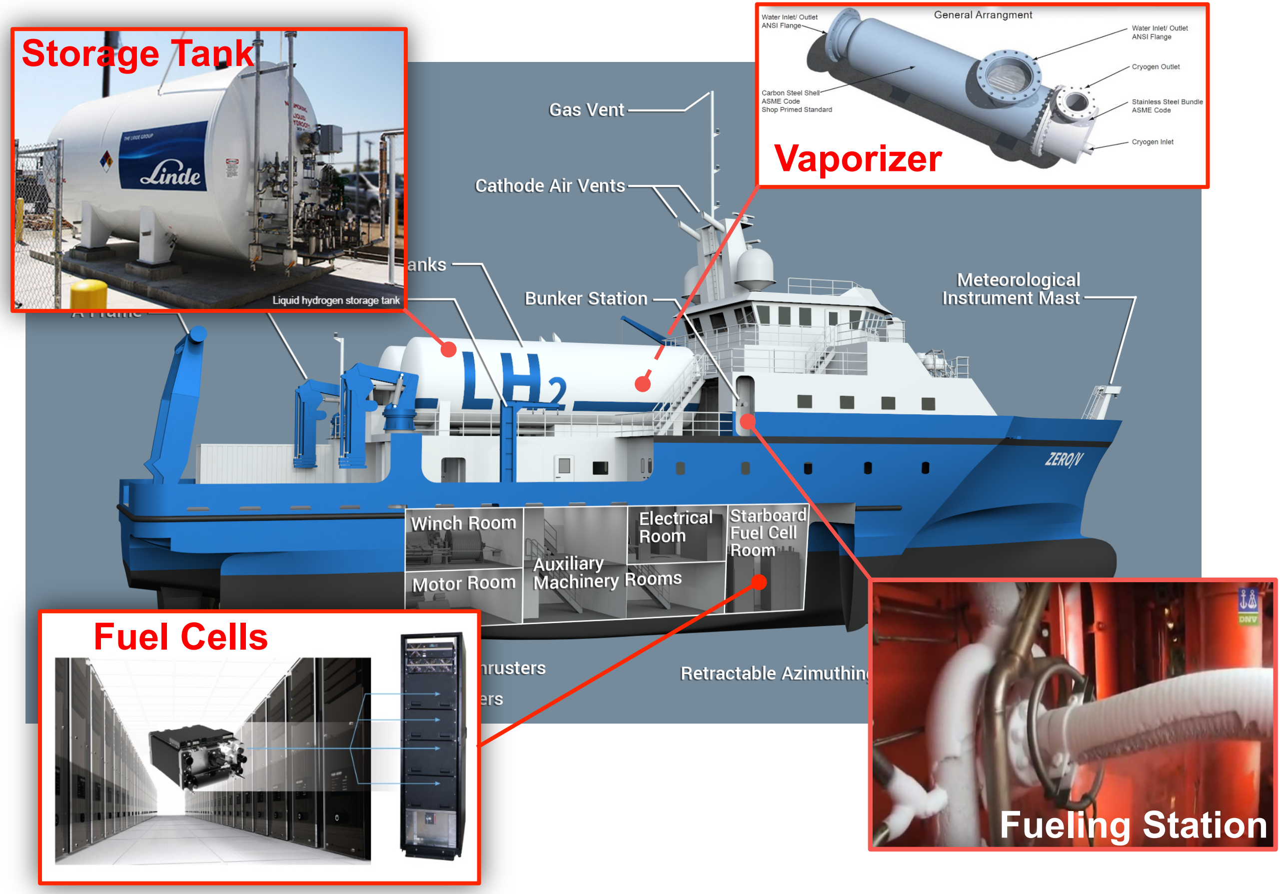
ARRANGEMENTS – TANK TOP & 1ST PLATFORM



1st Platform

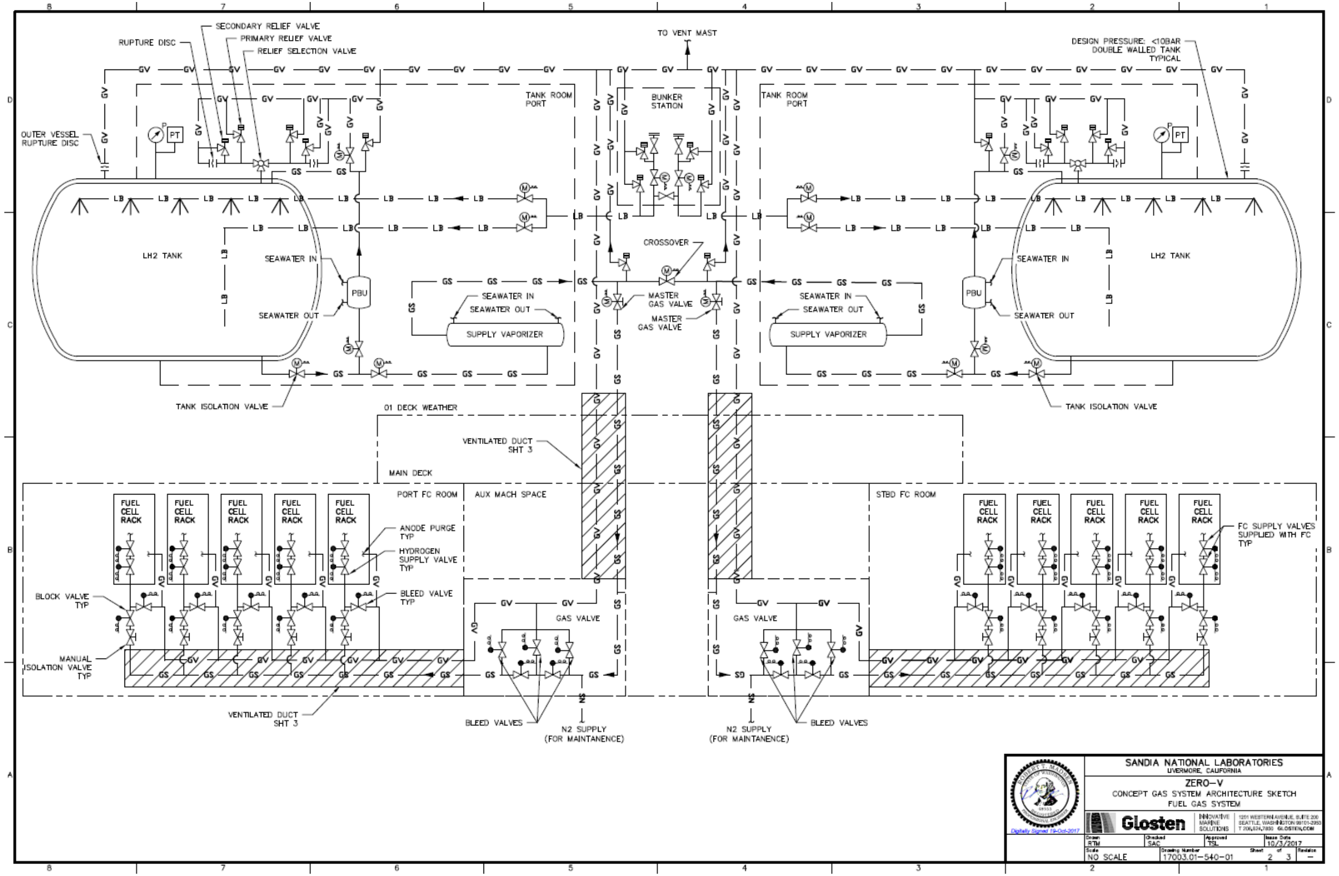
Tank Top

H_2 GAS SYSTEMS

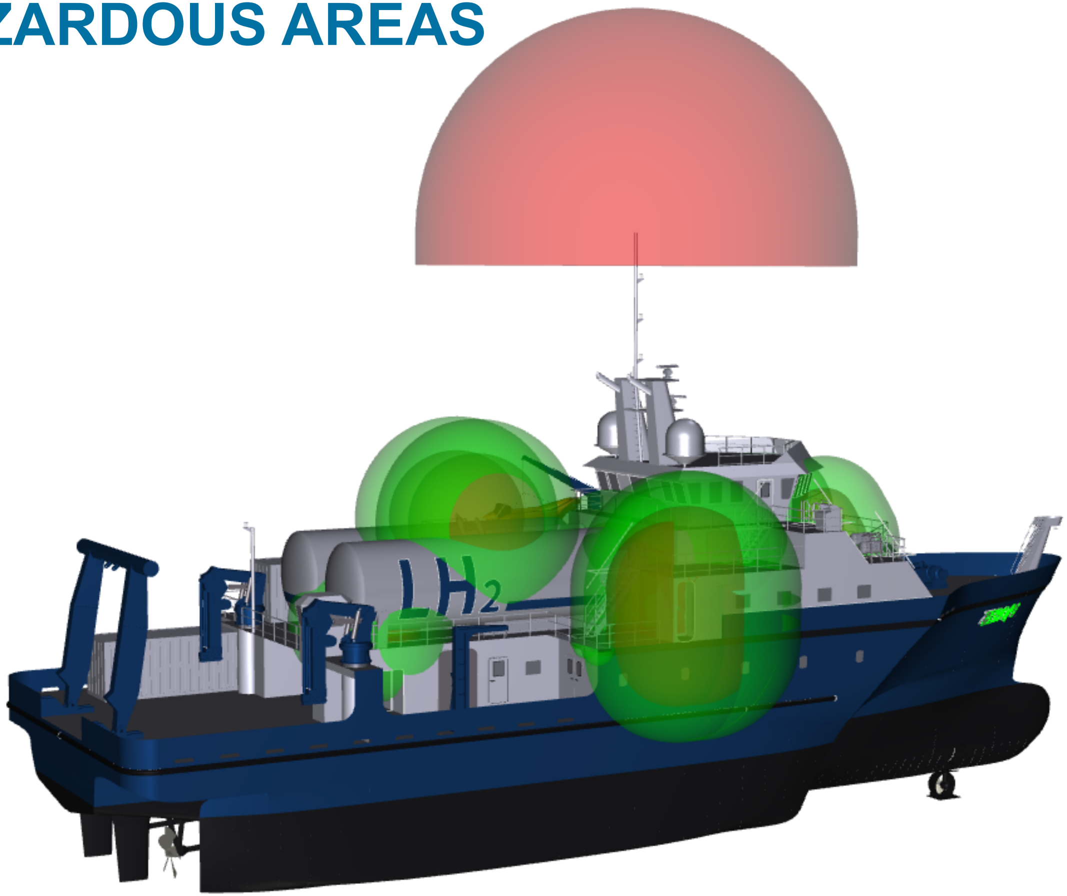


- **(2)** Type C vacuum insulated LH_2 tanks (5,830 kg capacity / tank)
- **(10)** Power racks with 6 Hydrogenics HyPM HD 30 fuel cell modules (180 kW/ rack)
- **(2)** Thermax cryogenic cold water evaporators
- Gas system full redundancy
- Fuel cell room has redundant ventilation and gas detection for each rack and emergency shutdown upon any failure
- Water deluge system protects areas around tank
- NOVEC clean agent fire extinguishing in fuel cell rooms

H_2 GAS SYSTEMS



HAZARDOUS AREAS



Locations where hydrogen vapors are expected to exist or may exist under normal or abnormal conditions

Sources

- Hydrogen vents
- Bunker station
- Valves and flanges in hydrogen pipes
- Tank connection space vents
- Fuel cell rooms
- Fuel cell room ventilation openings

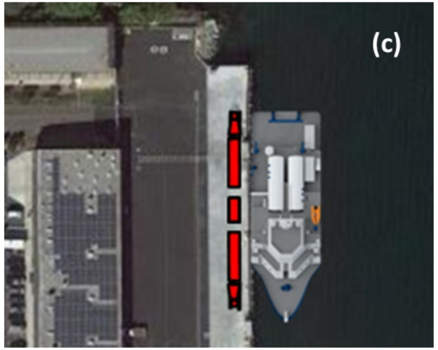
BUNKERING LH_2

Discussed bunkering with Linde and Air Products

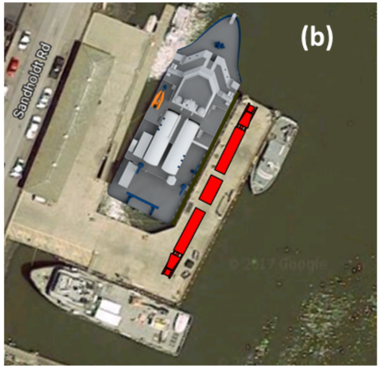
Bunker from trucks

- No shore infrastructure
- Currently used for filling LH_2 storage tanks across US
- Trailer delivers approximately 4,000 kg of LH_2
- 3 trailers to fully fuel. Typical bunkering with 1-2 trailers (most missions <8,000 kg)
- Full trailer deliver take 3.5 to 4 hours
- Use 2 trailers simultaneously, one bunkering each tank

BUNKERING – PORT ACCESS



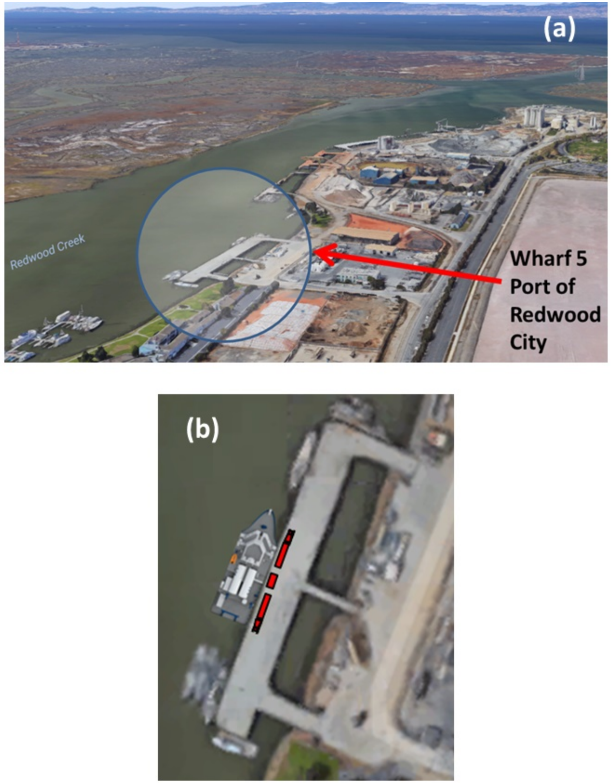
Nimitz Marine Facility (Mar-Fac) at the Scripps Institution of Oceanography, San Diego CA



Monterey Bay Aquarium Research Institute (MBARI), Moss Landing, CA

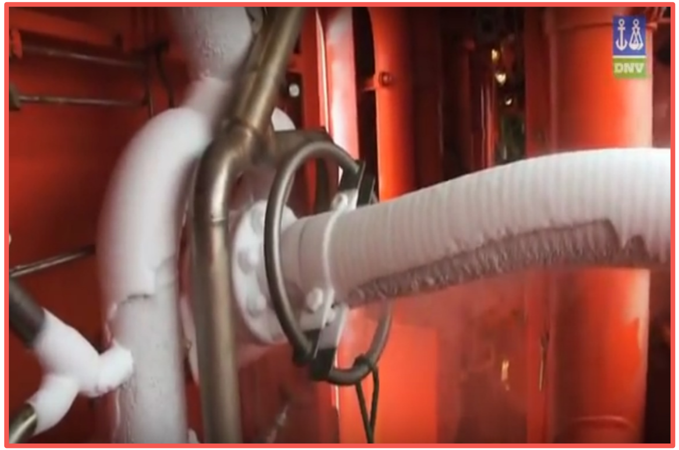
BUNKERING – PORT ACCESS

Location of Pier 54, San Francisco CA



Wharf 5, Port of Redwood City, Redwood City CA

BUNKERING - VESSEL



Bunker Station on 01 Deck starboard side

Bunker piping is doubled walled vacuum insulated stainless steel (304 or 316).

- **Provides secondary containment**
- **Minimize heat ingress into the LH2 during bunkering.**

Dedicated bunker flange/pipe for each tank

- **Simultaneous & independent bunkering**
- **Crossover between the two bunker lines allows a single bunker flange to be used to fill both tanks.**

VESSEL COST ESTIMATE

Capital Cost

Contract Design Engineering	$2.5M
Vessel Construction	$76M to $82M
Program Costs	$4M to $8M (5-10% of construction cost)

Operating Costs

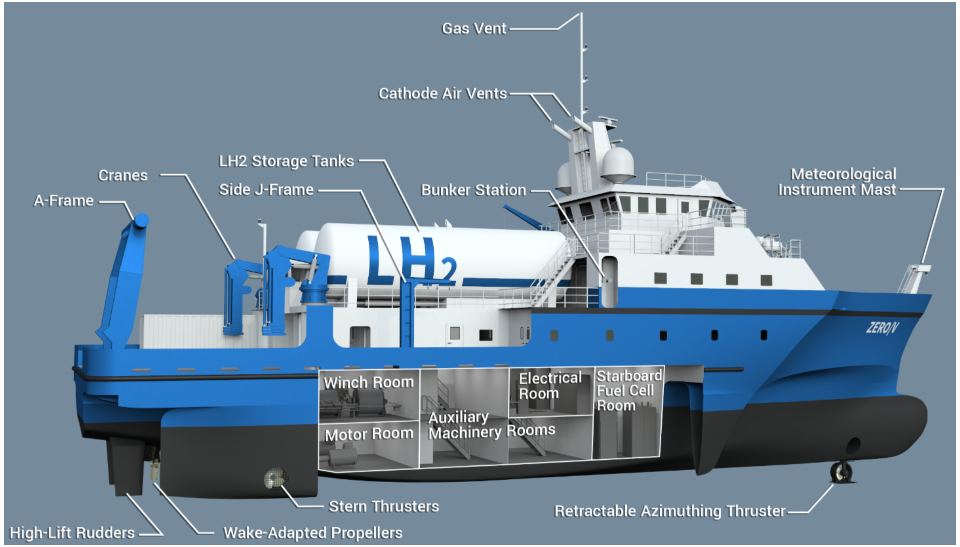
Using a comparison to annual operating costs for the R/V New Horizon (retired from Scripps), it is estimated that the Zero-V operating costs using conventional hydrogen would initially be ~7.7% higher than for an equivalent diesel fueled vessel.

Zero-emission research vessel feasibility study: ZERo/V

SCRIPPS INSTITUTION OF OCEANOGRAPHY UC SAN DIEGO

Sandia National Laboratories

Glosten



- Design study funded by MARAD for a new coastal / local vessel
- No fossil fuels required / no GHGs
- Zero emissions: **Clean!**
- Electric drives: **Quiet!**
- **FEASIBLE** with existing technology
- Outstanding scientific cabability
- Next: create affordable green design to replace *Robert Gordon Sproul*

The zero-emission research vessel (ZERo/V) concept vessel has a range of 2,400 nm with berths for up to 24 scientists, supporting general-purpose missions. Anticipated construction cost: $80 million.

end