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The Zero-V: Feasibility of a Liquid Hydrogen Fueled Coastal Research Vessel

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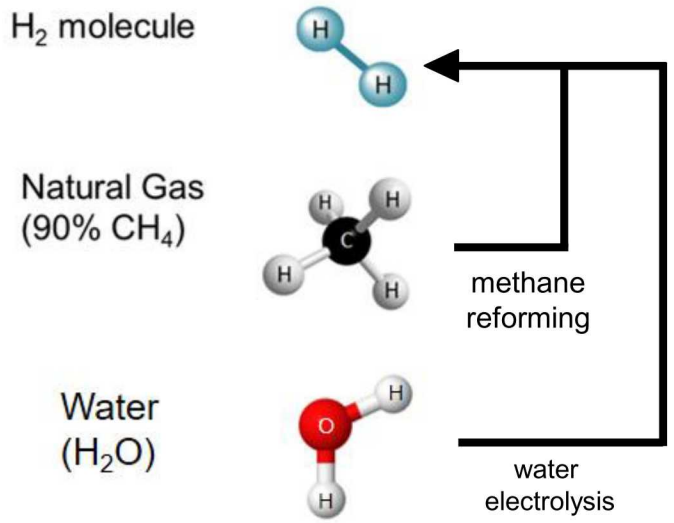
Sandia HQ:
Albuquerque NM

Livermore CA
(SF Bay Area)

- Sandia is the largest National Lab in the U.S.
  - U.S. Department of Energy (DOE) ~13,000 employees
  - ~ US $3.2B/yr from DOE, other federal agencies, and private industry
  - H_2 Program in Livermore, CA (SF Bay Area)
- Hydrogen program: 60+ years of work, in a wide range of areas (H_2 storage, production, delivery, development of regulations, market transformation), which we apply to enable impactful clean energy solutions
- Market Transformation: Zero Emission H_2/Fuel Cell Maritime Program:

Hydrogen Properties:



- Is typically a gas, but can be a liquid (LH_2) if made very cold (20 K).
- LH_2 evaporates very fast (4,000 gallons will evaporate in ~7 seconds)
- More buoyant than helium. Goes straight up at ~40 mph.

Overall, H_2 is very similar to natural gas (which is ~ 90% methane, CH_4).

H_2 is NOT a Greenhouse Gas, unlike natural gas which is a potent GHG.

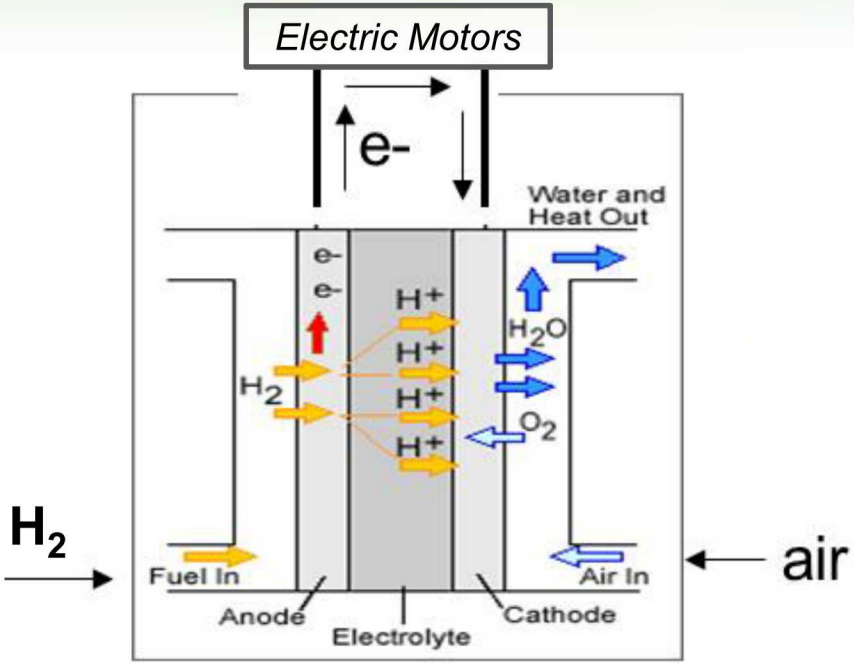
If spilled, LH_2 evaporates from the water leaving no residue.

H_2 can be ignited given an ignition source and the right H_2/air mixture.

Energetically, a kg of H_2 has ~ the same energy as a gallon of diesel.

For more information, see: L.E. Klebanoff, J.W. Pratt and C.B. LaFleur, International Journal of Hydrogen Energy **42**, 757 (2017).

When hydrogen is used in a *Fuel Cell* it produces ZERO pollution or greenhouse gas at point of use



Photos Courtesy Ryan Sookoo, Hydrogenics

$2\ H_2 + O_2 \rightarrow 2\ H_2O$

-- commercially available
-- more energy efficient than diesel generators
-- eliminates emissions at the point of use
-- eliminates fuel spills, greatly reduces noise
-- emissions can only arise from H_2 production/delivery
-- no "thermal runaway" possible

Going In:

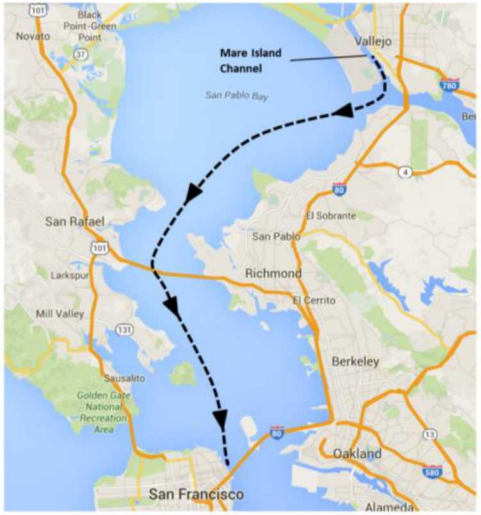
H_2 and air

Going Out:

Electricity
Waste Heat
Warm humidified air

SF-BREEZE: The first study to show that H_2 fuel cells can be used in maritime propulsion, and how to do it.

High-speed H_2 Ferry



Route:
San Francisco to Vallejo, CA

	Ferry	Hydrogen Station
Technical	✓	✓
Regulatory	✓	✓
Economic	*Higher than conventional now, today's market acceptance to be determined*	

The SF-BREEZE Project Led to the Zero-V Hydrogen Fuel Cell Research Vessel

Overall Feasibility Question: 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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13 Scripps Missions Define the Zero-V Performance

Unmanned underwater vehicles
After deployment, UUVs navigate underwater autonomously to conduct sampling, mapping, sensing and other missions

Sediment coring
Sediment samples from piston cores enable detailed geological histories to be determined

Surface mooring deployment
R/V Roger Revelle, Philippine Sea

The Zero-V has very different performance needs:

- Desired calm water speed: 10 knots (instead of 35 knots for the SF-BREEZE)
- Desired range: 2,400 nautical miles (instead of 100 nm for the SF-BREEZE)
- Endurance: 14 days (instead of 4 hours for the SF-BREEZE).

The larger range pushes us into large quantities of stored hydrogen, making the Zero-V a stepping stone to very large H_2 vessels.

The R/V Zero-V: General Characteristics

-- satisfies all 13 Scripps science missions for a coastal research vessel

Hull Type: Trimaran
Material: Aluminum
Length: 170 ft.
Beam: 56 ft.
Draft: 12 ft.
Freeboard: 9 ft.

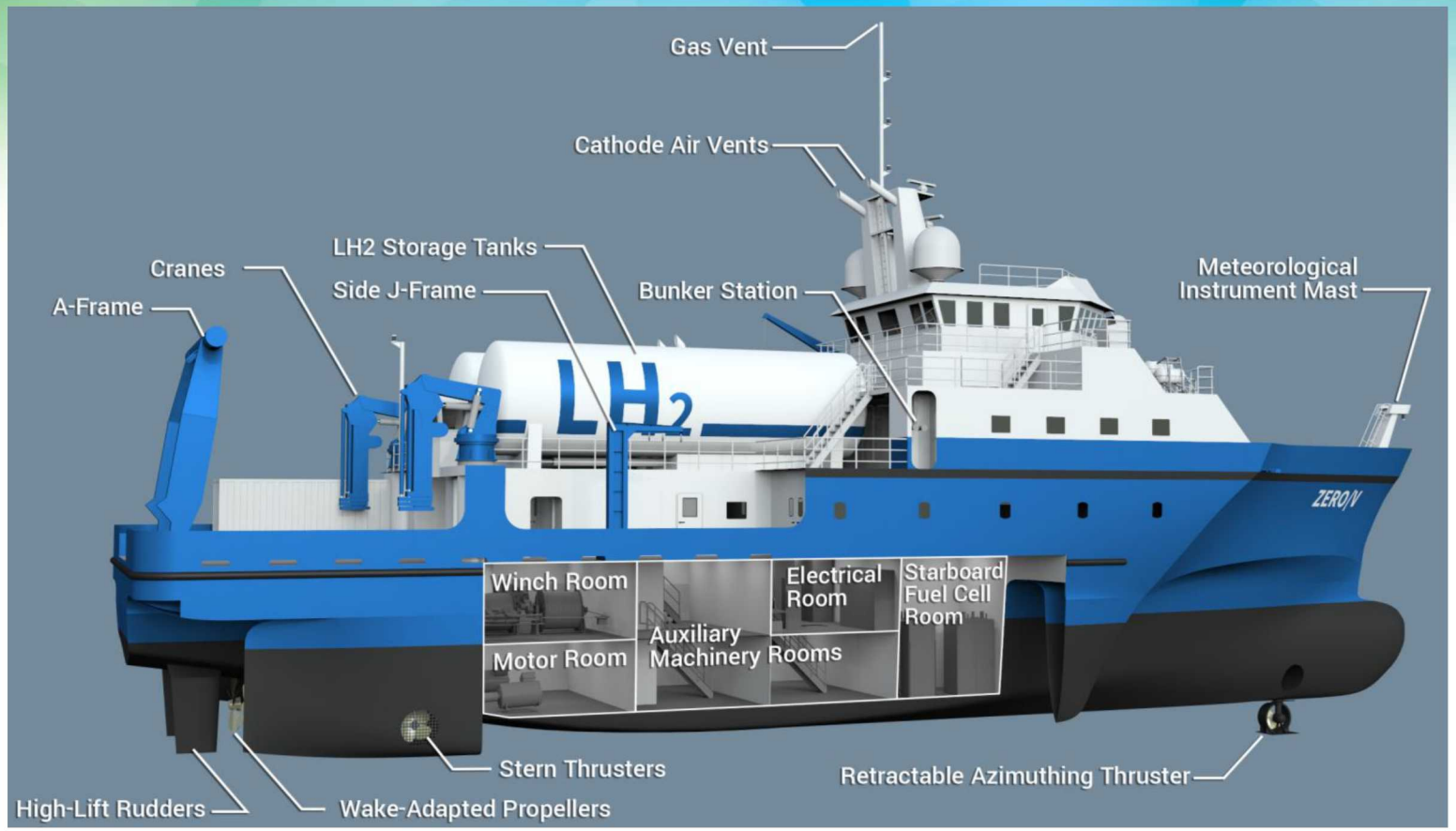
Displacement: 1,175 LT
Cruise Speed: 10 knots
Range: 2,400 nm
Endurance: 15 days
Station Keeping: Dyn. Positioning
Air Emissions: Water Vapor

Berths:
18 science
(8 double, 2 single)

11 crew (singles)

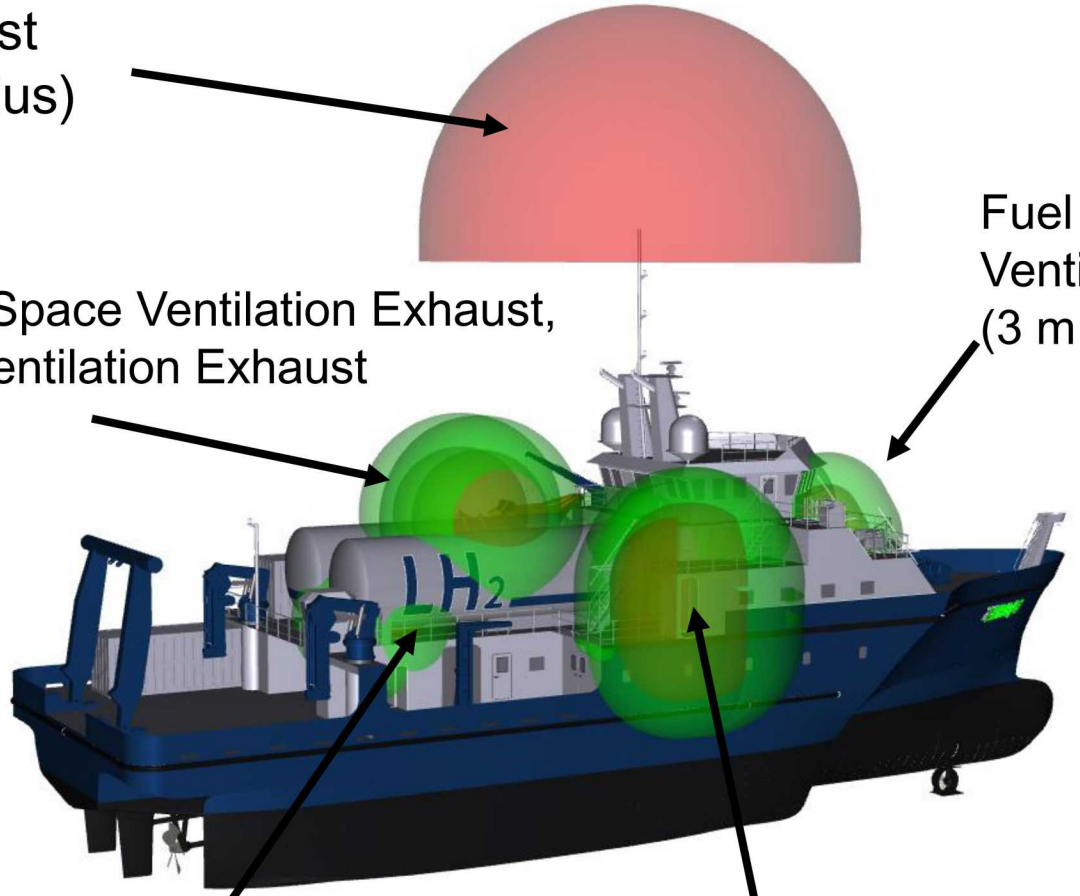
The R/V Zero-V: Science Capabilities

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



- LH_2 Tanks: 2 Type C tanks, ~5500 kg of LH_2 each
- Power: 10 x 180 kW PEM fuel cell racks (Hydrogenics)
- 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

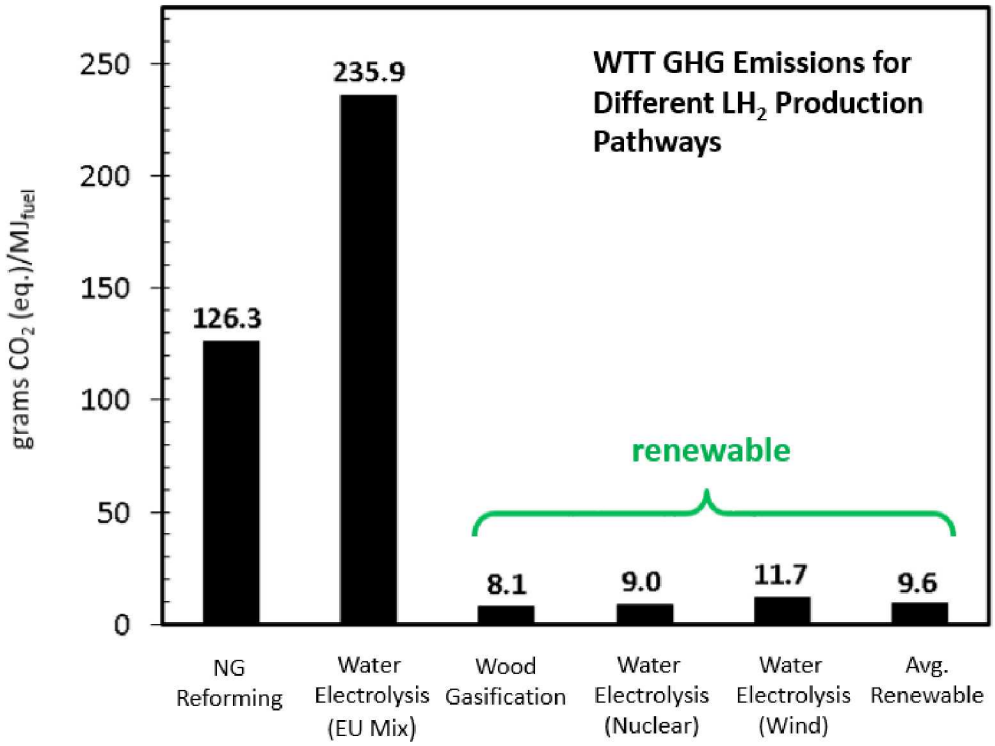
Hazardous Zone Plan for the Zero-V Influences The Design



Locations where H_2 vapors are expected to exist or may exist under normal or abnormal conditions. These spaces cannot have ignition sources or gas paths to safe areas.

The GHG Reduction from Using H_2 Technology REALLY Depends on How the H_2 is Made

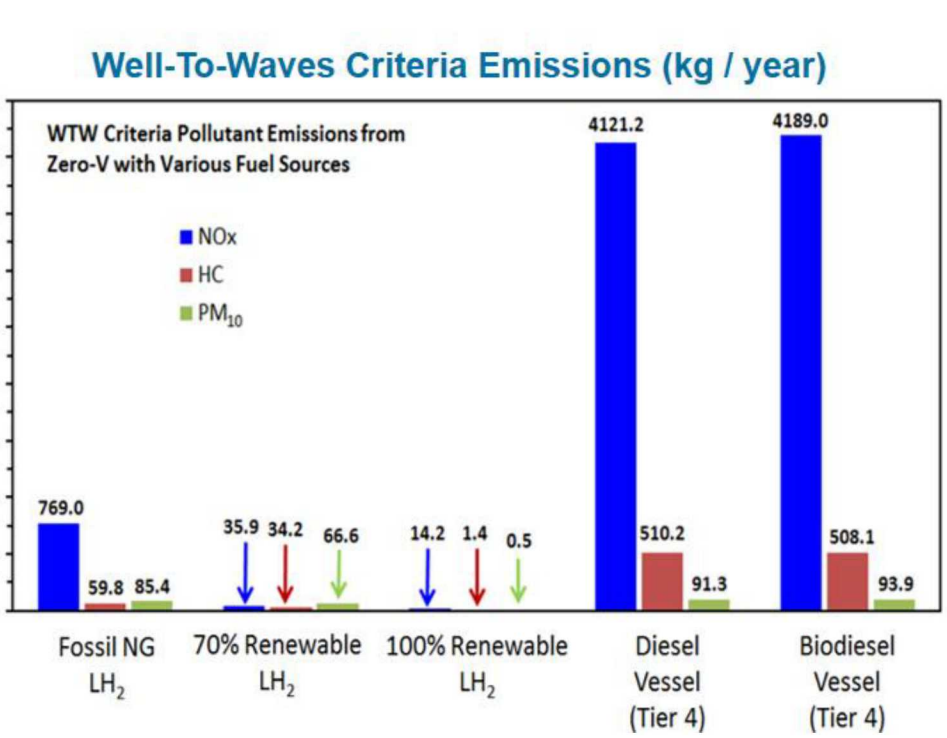
WTT: "Well-to-Tank" emissions associate with fuel production and delivery.

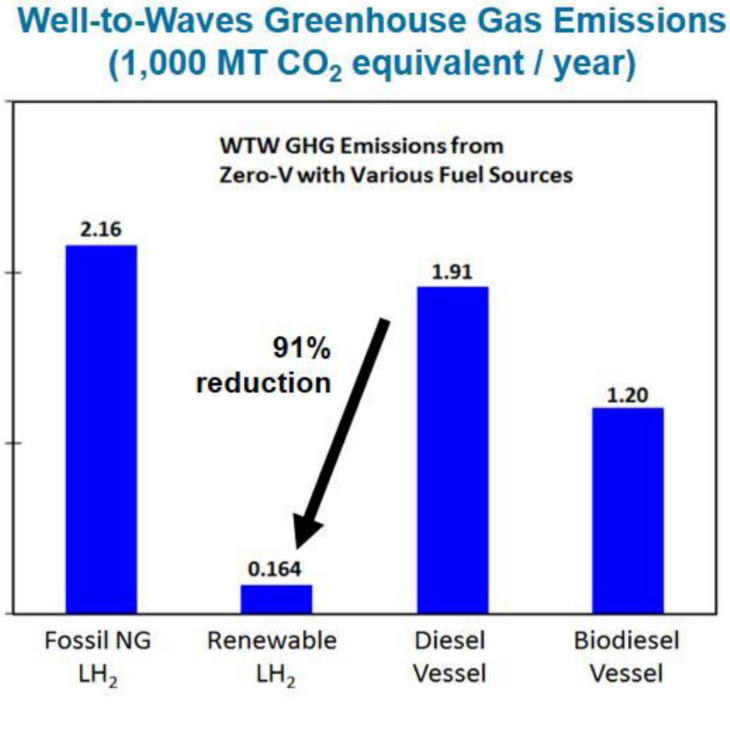


-- the equivalent GHG emissions for diesel fuel is 87.4 grams CO_2 (eq.)/MJ_{fuel}

More information on the calculation of GHG emissions from H_2 fuel cell technology can be found it: L.E. Klebanoff , J.W. Pratt et al., Transportation Research D **54**, 250 (2017).

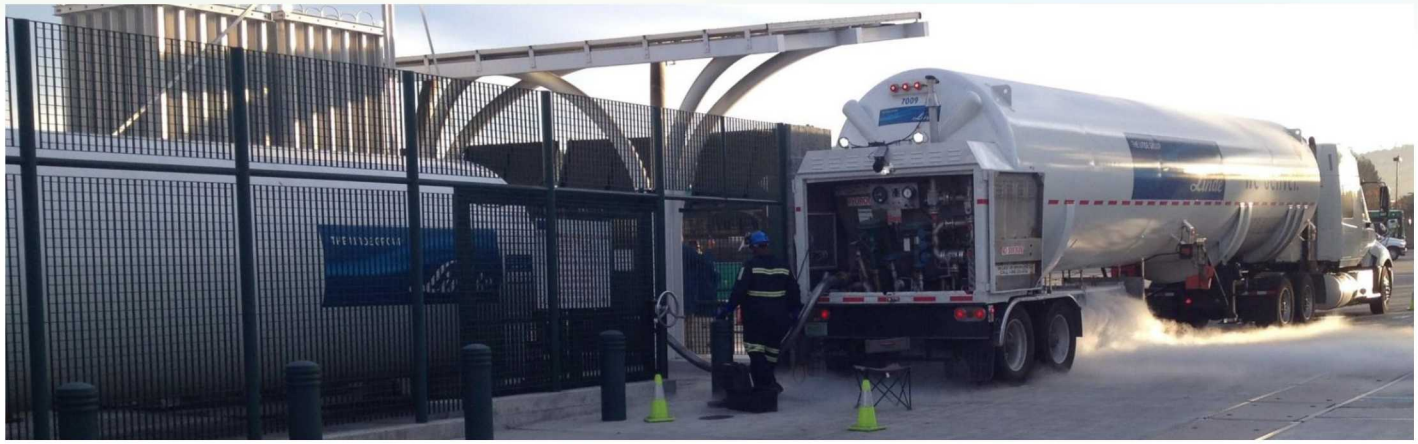
The Zero-V Dramatically Reduces Well-to-Waves Emissions





Using H_2 from any source, dramatic reductions in criteria pollutants below Tier 4 are provided. Using renewable hydrogen, a 91% reduction in CO_2 (eq.) emissions is obtained.

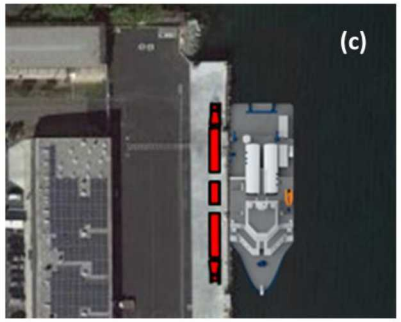
How Would the Zero-V Refuel?



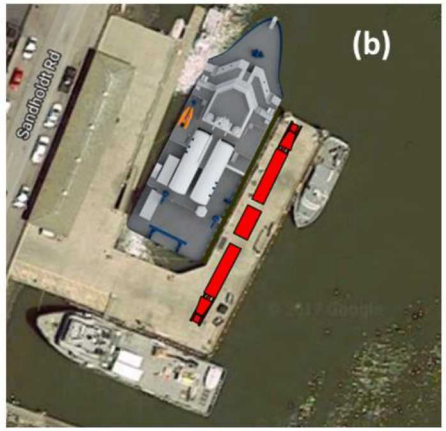
A.C. Transit Emeryville CA H_2 Station

- Discussed bunkering with Linde and Air Products. Both recommended mobile refueling of the Zero-V:
- 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 the Zero-V. Typical bunkering with 1-2 trailers (most missions <8,000 kg). Can fully refuel in 3.5-4 hours.
  - Use 2 trailers simultaneously, one bunkering each tank

Where Would the Zero-V Refuel?



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



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

We also confirmed refueling is possible
at Pier 54 of the Port of SF, and Wharf 5 at the Port of Redwood City

Vessel Cost Estimate

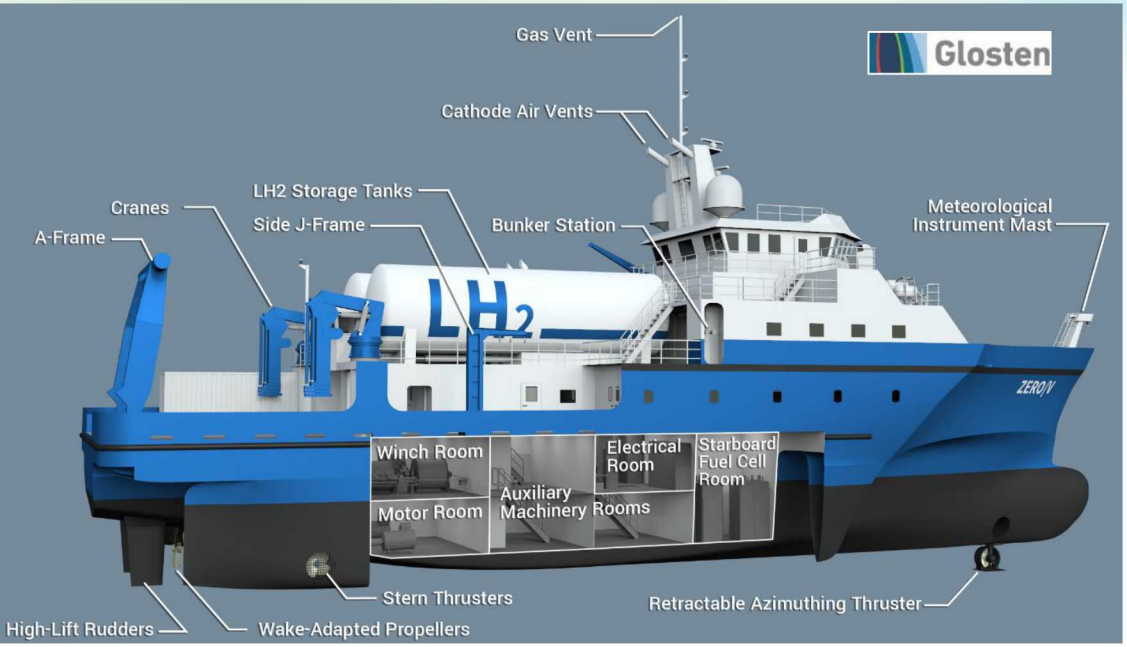
Capital Cost:

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

Operations and Maintenance (O&M) Cost:

- 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.

A zero-emission research vessel is feasible NOW using existing technology



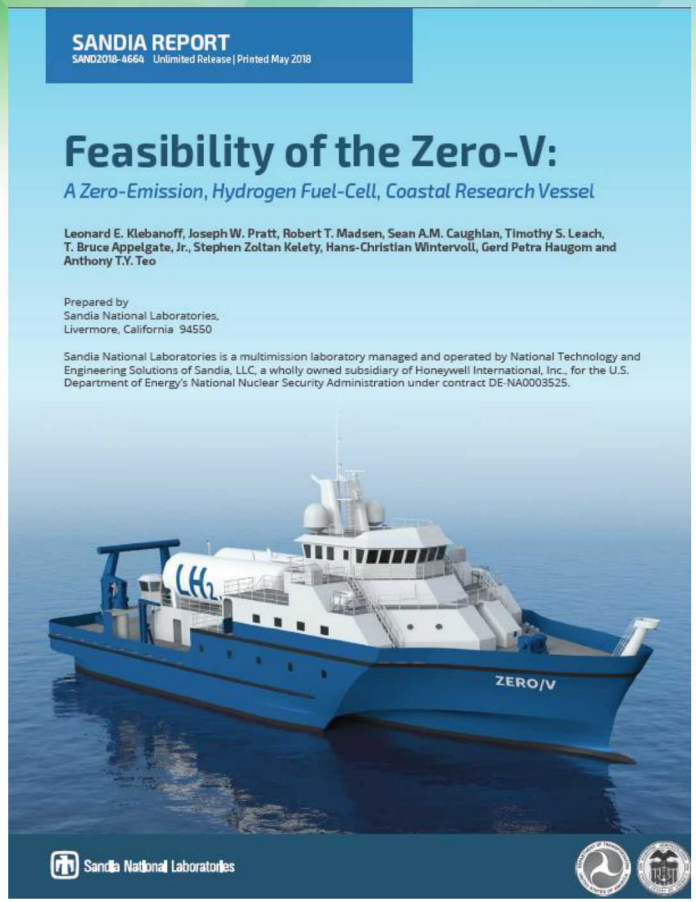
- Oceanographic research vessel for coastal / regional operations
- Uses clean hydrogen: **No fossil fuels!**
- Zero emissions: **Clean/no GHGs!**
- Carries no diesel: **No oil spills!**
- All-electric propulsion: **Quiet!**
- **FEASIBLE** with existing technology
- Outstanding scientific capabilities
- Advanced instrumentation
- Designed for California's educational and R&D needs

A bold, transformative game-changer

The zero-emission research vessel (Zero-V) concept vessel has a range of 2,400 nm, speed of 10 knots, with berths for up to 20 scientists, supporting general-purpose missions. Anticipated cost to build: $80 million.

H_2 Vessel Feasibility Questions Encountered and Passed

- Will they float? ✓
- Can they go fast enough, up to 35 knots? ✓
- Can they carry a decent number of people (~150)? ✓
- Do they have sufficient range before needing refueling? ✓
- Can the hydrogen suppliers provide 2500 kg of LH_2 per day? ✓
- Can the hydrogen suppliers provide renewable LH_2? ✓
- Can they be refueled fast enough for commuter service ? ✓
- Would the technology be supported by Bay Area Ports? ✓
- Are there deep cuts in well-to-waves (WTW) GHG emissions? ✓
- Are there deep cuts in WTW criteria pollutant emissions? ✓
- Can they satisfy regulatory requirements to gain an Approval in Principal? ✓
- Would the U.S. Coast Guard find any "show stopping" issues? ✓
- Would it be commercially attractive? **TBD**
- Can suitable refueling sites be found for these vessels? ✓
- Would there be support from local government (City Hall, others)? ✓



maritime.sandia.gov

Sujit Ghosh, MARAD

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Thank You!!

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