Hydrogen Fuel Cell Technology for Ships
From Feasibility Studies to First H_2 Vessels

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ONLINE WEBINAR

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- Speaker
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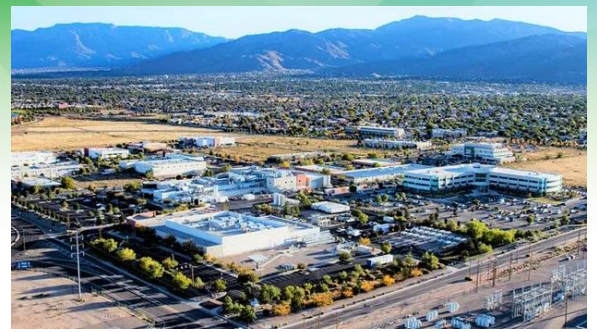


Sandia HQ: Albuquerque NM

Livermore CA, (SF Bay Area)

- Sandia is the largest National Lab in the U.S.
  - U.S. Department of Energy (DOE) ~15,000 employees
  - ~ US $4.4B/yr from DOE, other federal agencies, and private industry
  - H_2 Program in Livermore, CA (SF Bay Area)
- Hydrogen program: 70+ 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:

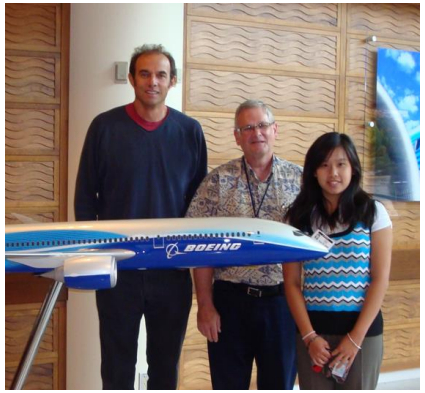
We Have Been Evaluating the Feasibility of Using H_2 Fuel Cells in Different Applications -- "Fuel Cell Market Transformation"

I founded the Sandia Fuel Cell Market Transformation Program in 2005.

2003

- (2003) Served on Governor Schwarzenegger's H_2 HWY Team
- (2007) H_2 Fuel Cells at Emergency Power System for Commercial Aircraft (Boeing)
- (2008) Modular Fuel Cell Power for Airplanes (Boeing)
- (2010) H_2 Mobile Lighting System (Boeing and DOE)
- (2010) H_2 Fuel Cells for Auxiliary Power on Airplanes (DOE)
- (2011) Man-portable H_2 Fuel Cell Applications (DOE)
- (2012) Fuel Cell Range Extender for Electric Work Trucks (DOE)
- (2016) Feasibility of a Fuel Cell High Speed Ferry (DOT/MARAD)
- (2017) Feasibility of a Fuel Cell Coastal Research Vessel (DOT/MARAD)
- (2022) Feasibility of a H_2 Hybrid Research Vessel (DOT/MARAD)
- (2022) H_2 Gas Dispersion Studies for a Fuel Cell Vessel (DOT/MARAD)
- (2024) Exploring LH_2 Tank Technology for ZE Fuel Cell Vessels (DOT/MARAD)
- (2024) Advanced Vent Mast Designs for H_2 Fuel Cell Vessels (DOT/MARAD)

2024



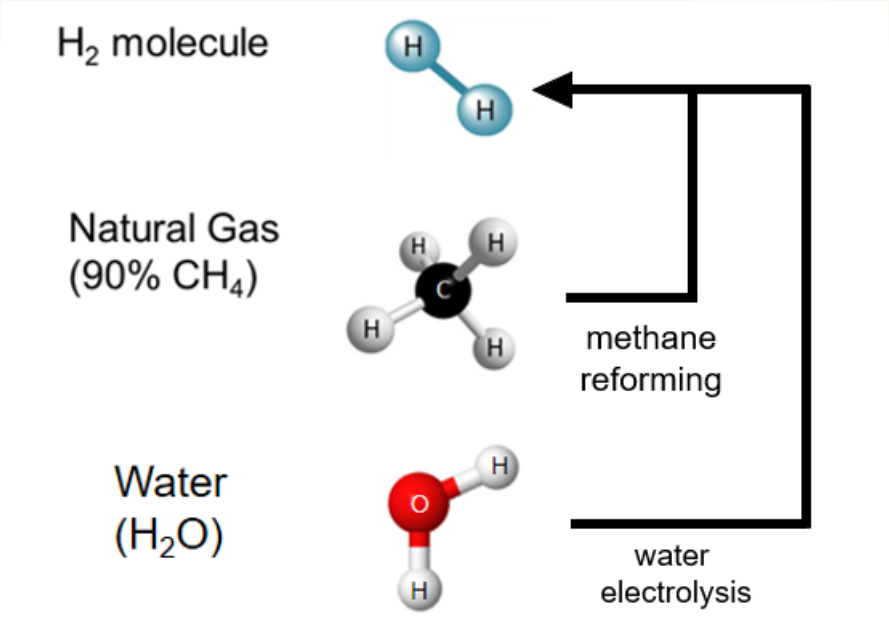
Joe Breit, Boeing

California Department of Transportation


Joe Pratt, ZEI


Scripps, Glosten and Hydrogenics (Cummins)

Properties of Hydrogen

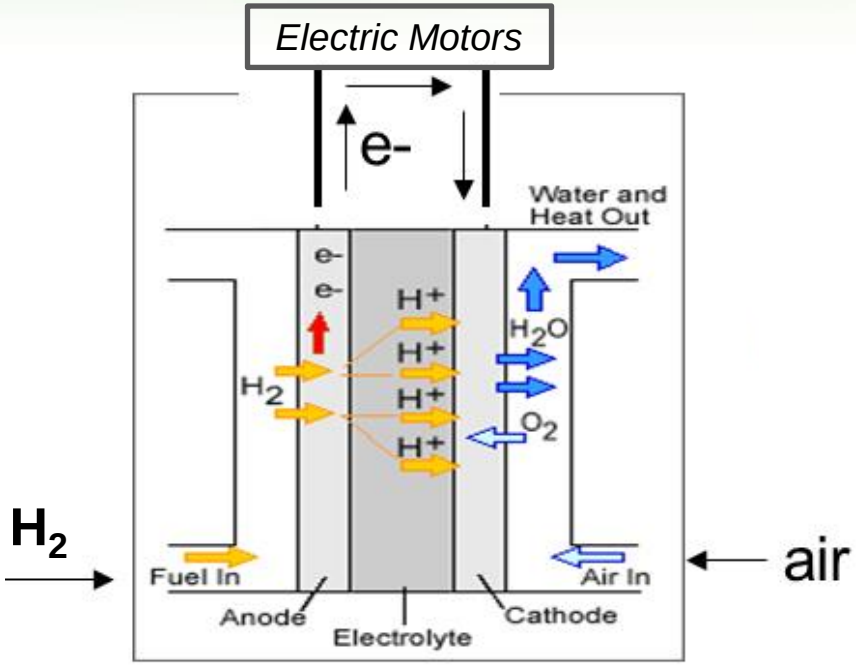


- Is typically a gas, but can be a liquid (LH_2) if made very cold (20 K).
- LH_2 evaporates very fast (4,000 gallons will evaporate in ~ 7 seconds).
- Is more buoyant than helium, will go straight up at ~ 40 mph if released.

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

- ✓ Overall, H_2 is very similar to natural gas (which is ~ 90% methane, CH_4)
- ✓ H_2 is not a direct greenhouse gas (GHG), but its photolytic properties are being studied.
- ✓ If spilled, LH_2 evaporates from the water leaving no residue.
- ✓ H_2 can be ignited given an ignition source and a combustible H_2/air mixture (4 – 75% mix with air).
- ✓ Hydrogen safety follows the same approach as natural gas: eliminate ignition sources and H_2 leaks.

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

Going In:
H_2 and air

Going Out:
Electricity
Waste Heat
Warm humidified air

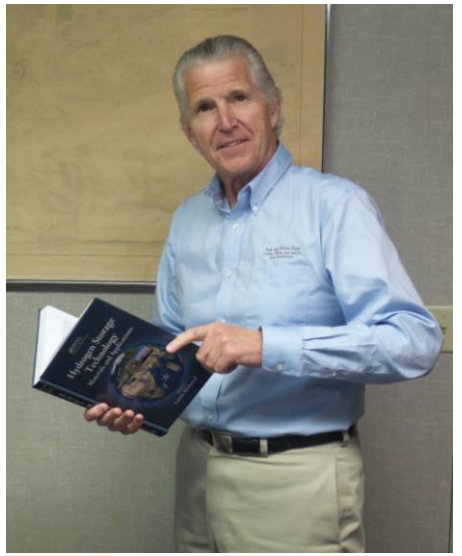
The Sandia Work on H_2 Vessels Originated with Tom Escher of the R&W Fleet in 2015

A forward-thinking maritime passenger transportation company offering sightseeing cruises, ferries and charter service in San Francisco.

The R&W Fleet is concerned about the effect of their vessels, and that of all maritime vessels, on the environment and on human health.

Tom approached Sandia with the question: Can H_2/fuel cell technology reduce vessel emissions to zero? What would be involved?

Our initial answer was:
We don't know, let's take a look at it!"

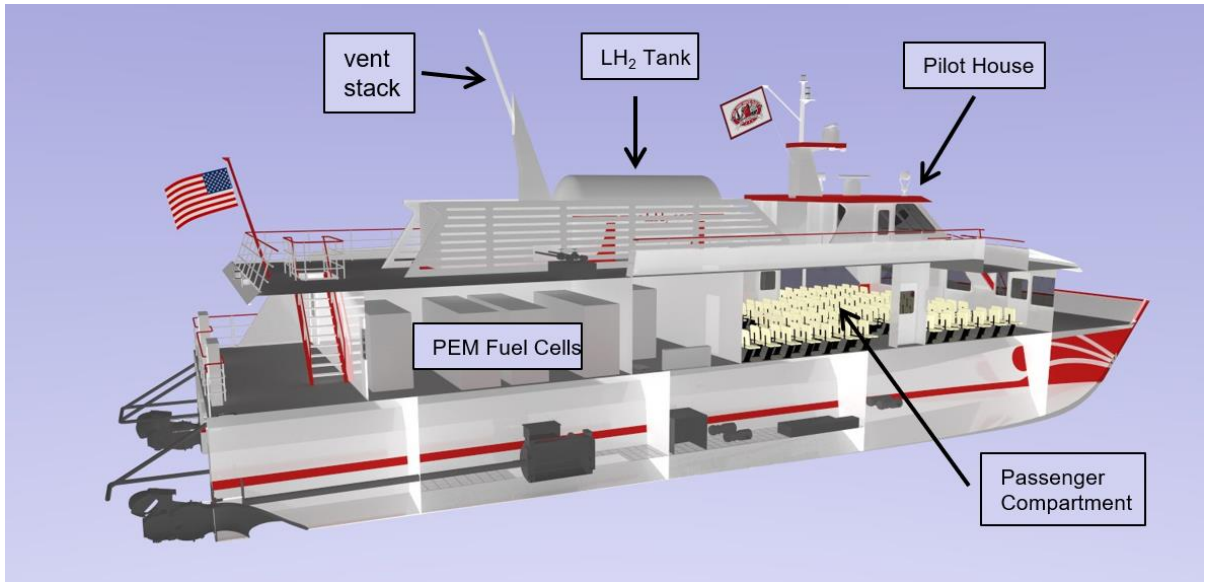


Tom Escher
President of R&W Fleet

SF-BREEZE Feasibility Design (2016)

- Fuel: ~2,400 kg LH_2 per day
- Propulsion power 4.4 MW
  Total installed Power: 4.92 MW
- Passengers: 150
- Range: 100 nautical miles (nm).
- Service Speed: 35 knots
- Length 109’ x Beam 33’ x Depth 11.25’
  Full Load Draft ~ 4.6’

Report: www.maritime.sandia.gov



ABS

Elliott Bay Design Group

Funded by DOT/MARAD’s META program

Status: SF-BREEZE vessel still a concept, but this work informed the design of the “Sea Change,” to be discussed. The SF-BREEZE also encouraged building the MF Hydra vessel in Norway!

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?

Gerd Petra Haugom (L) and Hans-Christian Wintervoll
DNV GL

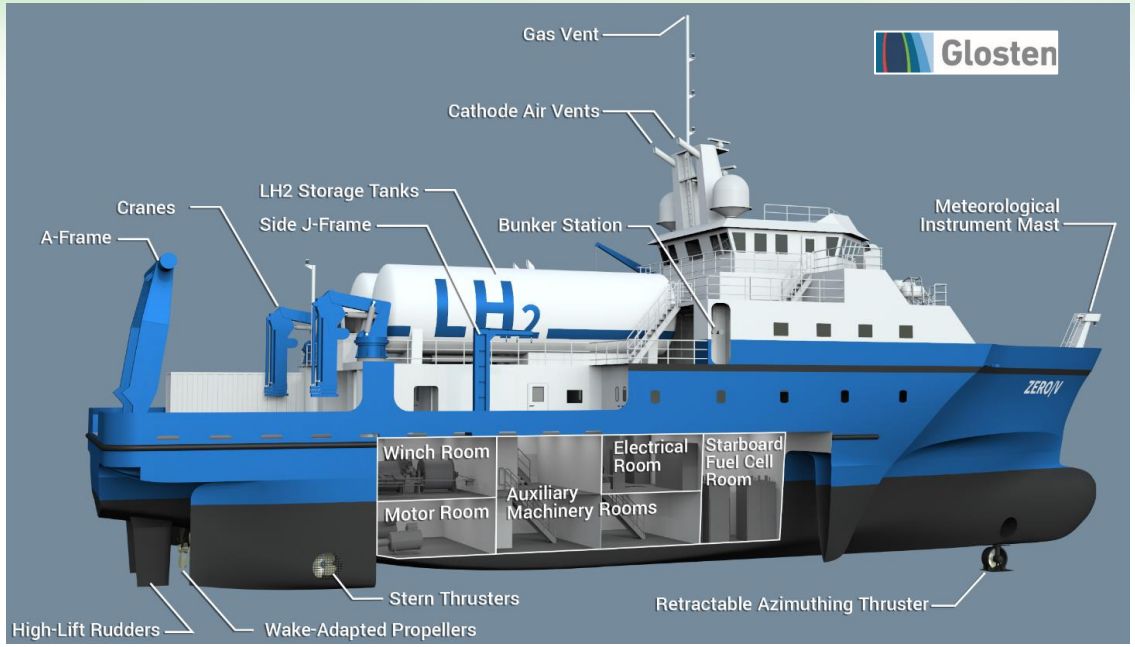
Lennie Klebanoff
Sandia National Laboratories

Bruce Appelgate
Scripps Institution of Oceanography

Zoltan Kelety
Scripps Institution of Oceanography

(L-R) Ian McCauley, Sean Caughlan, Robin Madsen and Catherine Farish, Glosten.

(2018) A Zero-emission Research Vessel is Feasible



Work Funded by DOT/MARAD's META program.

- All H_2 Coastal Research Vessel.
- 10 kts speed, 2400 NM range, 2-week endurance.
- 10,900 kg of consumable LH_2.
- 1.8 MW PEM fuel cell power.
- All-electric propulsion: **Quiet!**
- **FEASIBLE** with existing technology.
- Outstanding scientific capabilities.
- Advanced instrumentation.
- Designed for California's educational and R&D needs.

Status: Zero-V still a concept vessel. Scripps is interested in raising money to build it. Funding TBD.

R.T. Madsen, L.E. Klebanoff, et al., International Journal of Hydrogen Energy **45** (2020) 25328-25343.

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. Anticipated cost to build: $80 M.

(2020) What if H_2/Fuel Cells Provide Partial Vessel Power, in a Hybrid Arrangement? What Would That Look Like?

R/V Robert Gordon Sproul

Hydrogen Hybrid Sproul Replacement Vessel

Work Funded by DOT/MARAD's META Program.

Scripp's coastal/local research vessel, the *R/V Robert Gordon Sproul,* is nearing the end of its service life and will soon require replacement. We compared three potential "variants" for an *R/V Sproul* replacement vessel (SRV): a Baseline SRV consisting of a traditional diesel-electric powertrain, a Battery Hybrid SRV (battery/diesel-electric) and a Hydrogen Hybrid SRV (hydrogen fuel cell/diesel-electric).

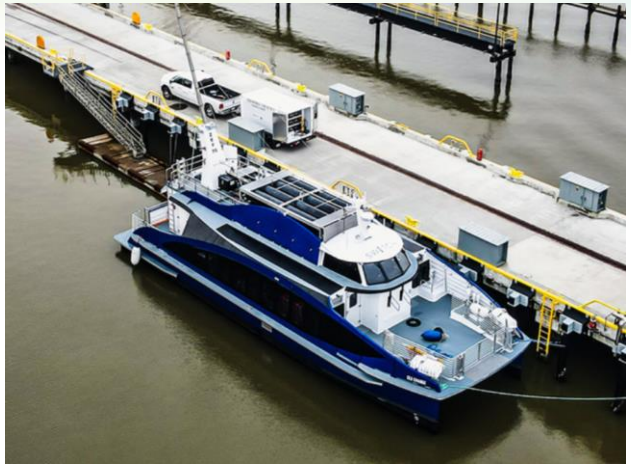
- LH_2 Storage: 733 kg
- Diesel Engines: ~ 1200 kW; Fuel Cells: ~ 800 kW
- Capital Cost: ~ $34M
- ~ 27% annual reduction in GHG emissions (renewable LH_2).
- 75% of the Sproul Missions can be performed on H_2 alone.
- H_2 Fuel Cells are 9X better energy density than Li-ion batteries

Status: H_2 Hybrid Vessel served as the basis for a proposal to the State of CA for funding, which was successful, to be discussed.

L.E. Klebanoff, et. al., International Journal of Hydrogen Energy **46** (2021) 38051 – 38072.

(2022) Sea Change: First Commercial H_2 Ferry in the US!

Out of the shipyard
(2022)



First H_2 fueling
(2023)

At Pier 9 in San Francisco
(2024)

SWITCH

ZERO EMISSION INDUSTRIES

Funding & Administration
CALIFORNIA AIR RESOURCES BOARD
BAY AREA AIR QUALITY MANAGEMENT DISTRICT
This project is supported by the "California Climate Investments" (CCI) program

The first hydrogen fuel cell vessel in the U.S.

- Aluminum catamaran
- 70’ long
- 80 passenger (reconfigurable)
- 13 knot top speed
- 242 kg of 250 bar H_2, up to 2 full days of operation
- 360 kW of H_2 PEM fuel cells
- Has passed USCG Sea Trials, is on the San Francisco Bay!

Status: About to enter service with the San Francisco Ferry Fleet, carrying passengers from the Ferry Building to Fisherman’s Wharf

SF-BREEZE and Zero-V Projects Inspire the MF *Hydra* in Norway

Hjelmeland, Norway

Email from Camilla Rohme, funder of the MF *Hydra* on 10/28/22 to L.E. Klebanoff

"And I also must thank you for your great work on the San Francisco Ferry. The meeting with you at DNV late 2016 or early 2017 and the sharing of your report gave me a good basis and lots of needed courage to take on the responsibility to procure the hydrogen ferry that ended up as Hydra….Your presentation in Florø made Edvard Sandvik believe a hydrogen ferry was possible."

July 23, 2021: Scripps Announces $35M in Funding of the H_2 Hybrid by the State of California

UC San Diego

Bruce Appelgate, Scripps Institution of Oceanography, at Press Conference

Length overall	49.9 m (164 feet)
Beam	11.0 m (36 feet)
Range (hydrogen)	400 nm
Range (diesel)	6,500 nm
Range (methanol)	2,400 nm
Endurance	11 days
Cruising speed	10 knots
Azimuthing thruster power	Two L-Drives, 500 kW each
Crew berths	7
Scientist berths	16 (on overnight trips)
Students	40 (on day trips)
Stationkeeping	Dynamic positioning
Main crane	2,400 lbs SWL
Stern A-Frame	21,000 lbs SWL
Side Frame	10,000 lbs SWL
Winches	Trawl, CTD/Hydro
Scientific instrumentation: sonar suite, GPS, motion reference, satcom broadband, network	

- ✓ Hydrogen Capacity: ~ 2100 kg LH_2
- ✓ 5-Year Design/Build/Qualify Program
- ✓ Project began October 2021
- ✓ 75% of all missions can be run entirely on H_2
- ✓ Initial operation H_2/diesel, but designed to readily convert to H_2/Methanol when appropriate.

Scripps Institution of Oceanography

UC San Diego

H_2 Hybrid Research Vessel (CCRV)

- ✓ Funding from the State of CA: $35M.
- ✓ Funding from ONR: $4M.
- ✓ Pending funding from ARCHES H_2 Hub.
- ✓ 5-Year Design/Build/Deploy Program.
- ✓ Project began October 2021.

CCRV project timeline

Detailed engineering, design, review, and construction preparation

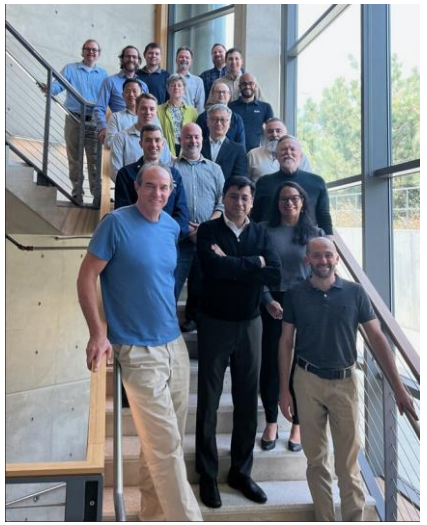
- 2021: Scripps issued RFI and RFP for design
- 2022: Development of detailed vessel engineering and design
- 2023: Engineering review, HAZID workshop and regulatory Approval In Principle

Construction

- 2024: Shipyard selection and preparation
- 2025: Keel laying, begin construction
- 2026: Construction

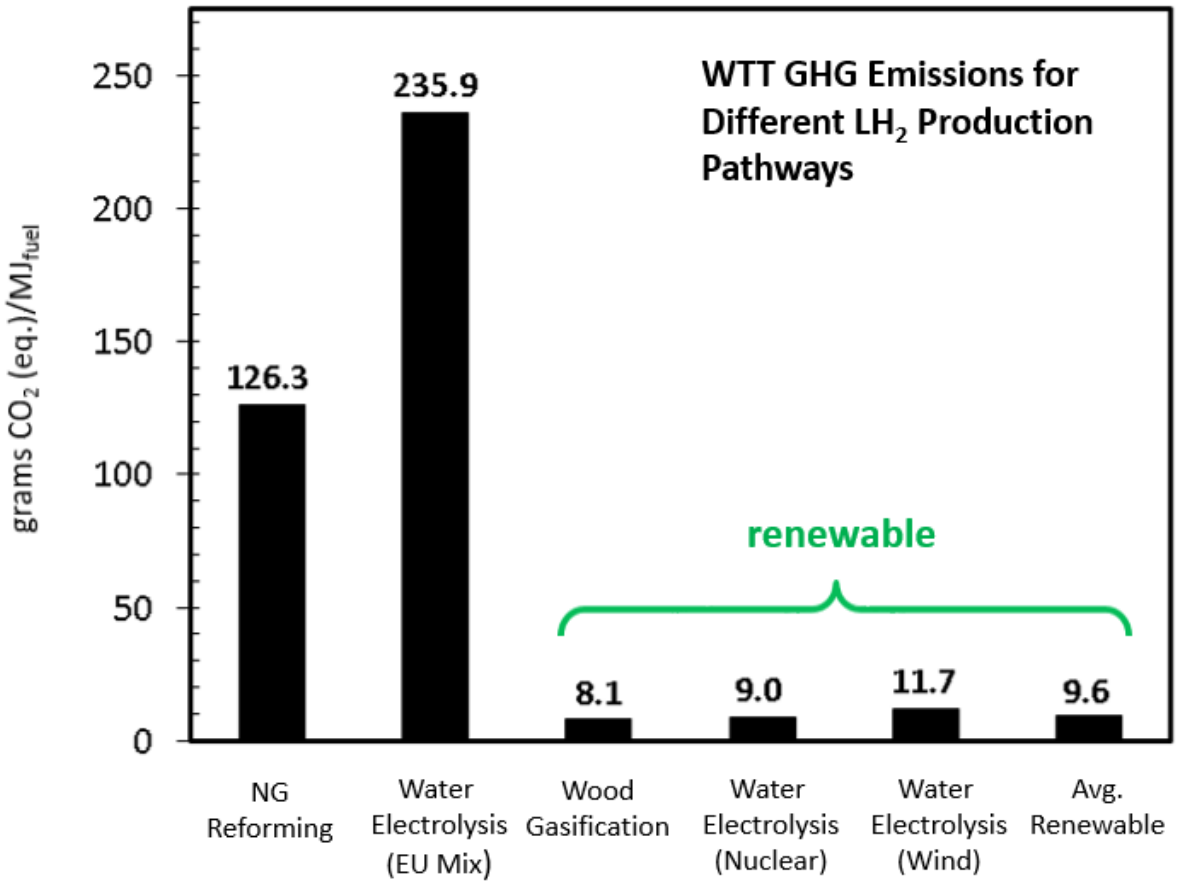
Commission and operate

- 2027: Commissioning & science verification trials
- 2028: Operational for science missions
- 2033: Convert alt fuel from diesel to methanol



HazID Workshop at Scripps with USCG Sector San Diego, USCG HQ December 11, 2023

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



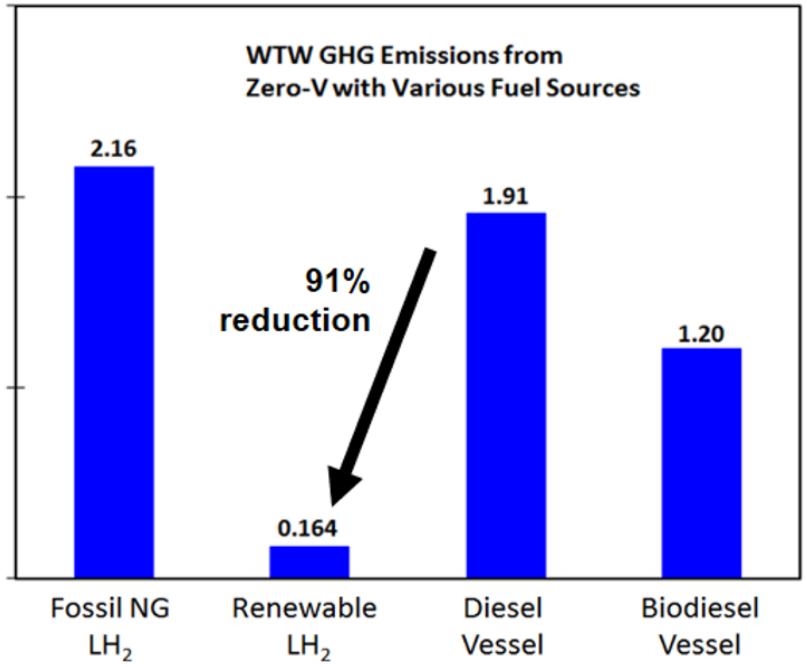
-- the equivalent GHG emissions for diesel fuel is 87.4 grams CO_2 (eq.)/MJ_{fuel}

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

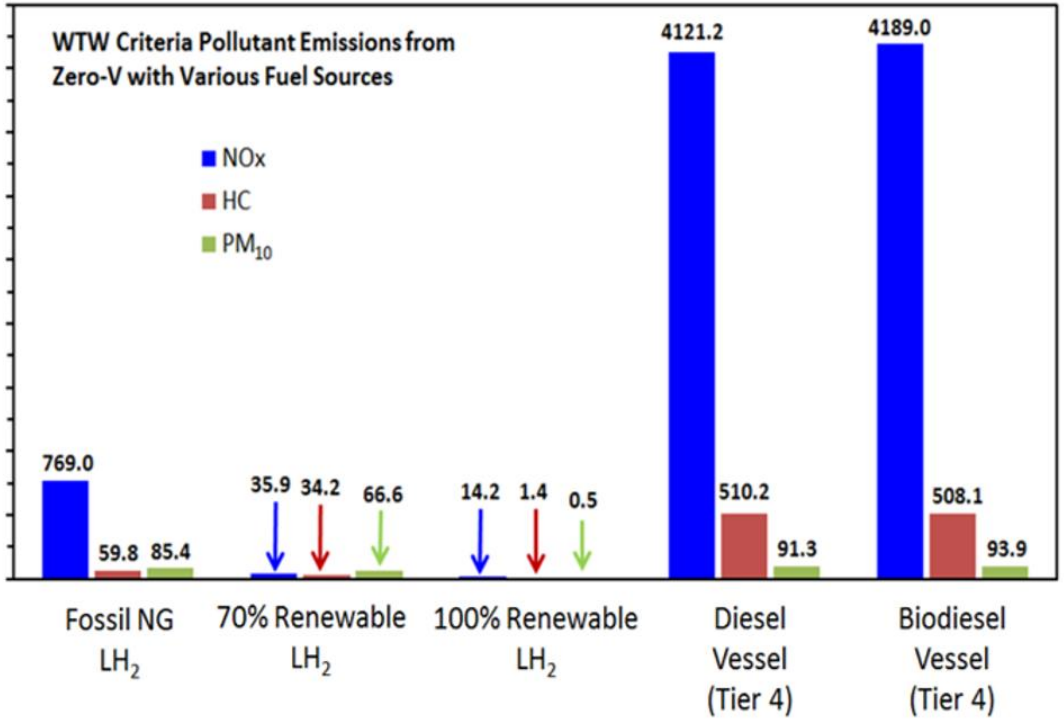
15

Well-to-Waves Emissions from the Zero-V (LH_2 fuel)

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



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



Note: Tier 4 specifies the most stringent regulations of the United States Environmental Protection Agency (EPA) on criteria pollutant emissions from diesel engines.

R.T. Madsen, L.E. Klebanoff, et al., International Journal of Hydrogen Energy **45** (2020) 25328-25343.

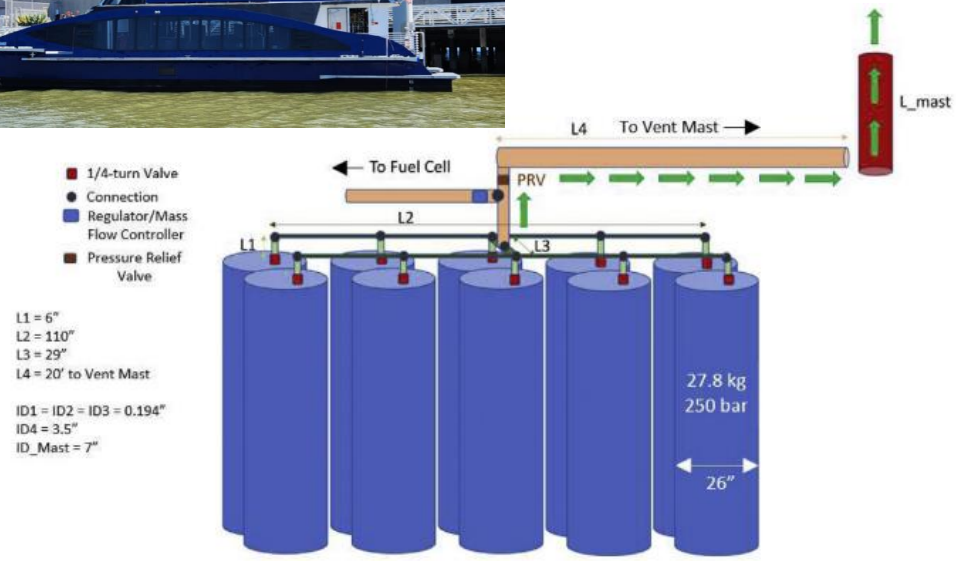
Using H_2 from any source, dramatic reductions in criteria pollutants below Tier 4 are provided. Using renewable hydrogen, a 91% reduction in CO_2 (eq.) emissions is obtained. Dramatic reductions are needed to survive growth in the fleet.

16

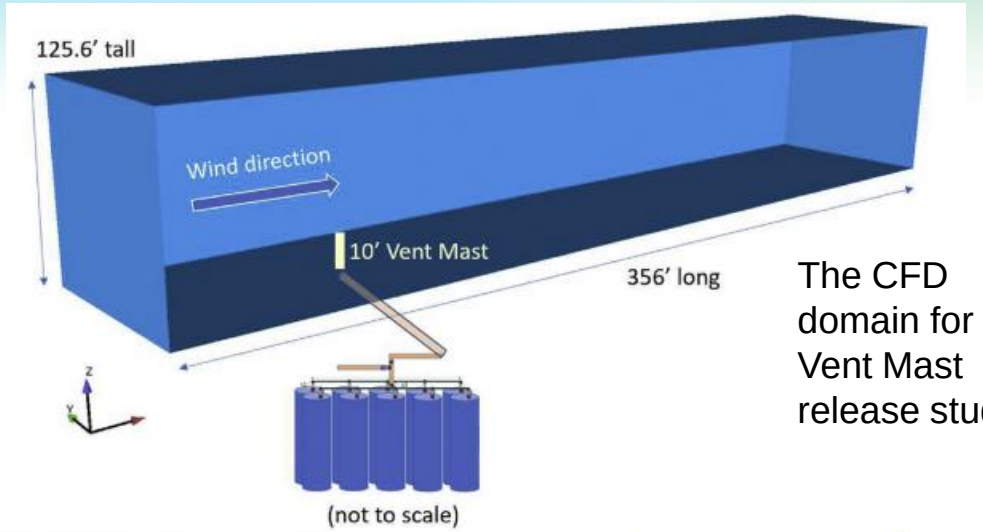
Sandia H_2 Gas Dispersion Studies for H_2 Vessel Releases

Vent Mast Releases

Work Funded by DOT/MARAD's META Program

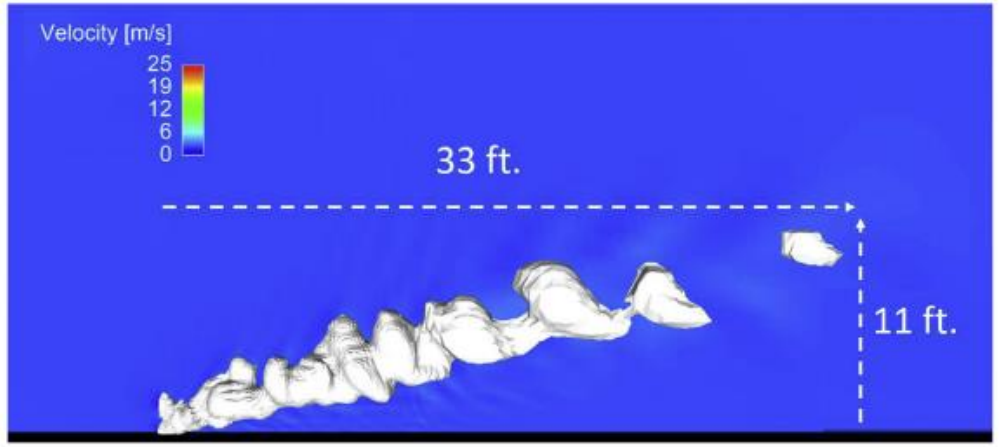


Layout of a 10-tank assembly similar to that on the Sea Change. Tanks are based on Type IV Hexagon Purus tanks with capacity 27.8 kg and 250 bar each.



The CFD domain for the Vent Mast release study.

CFD Studies by Myra Blaylock, Sandia



H_2 release with a constant 30 mph hydrogen exit velocity in a 5-knot cross wind. The white color encompasses H_2 concentrations from 4 – 75% (the flammability range).

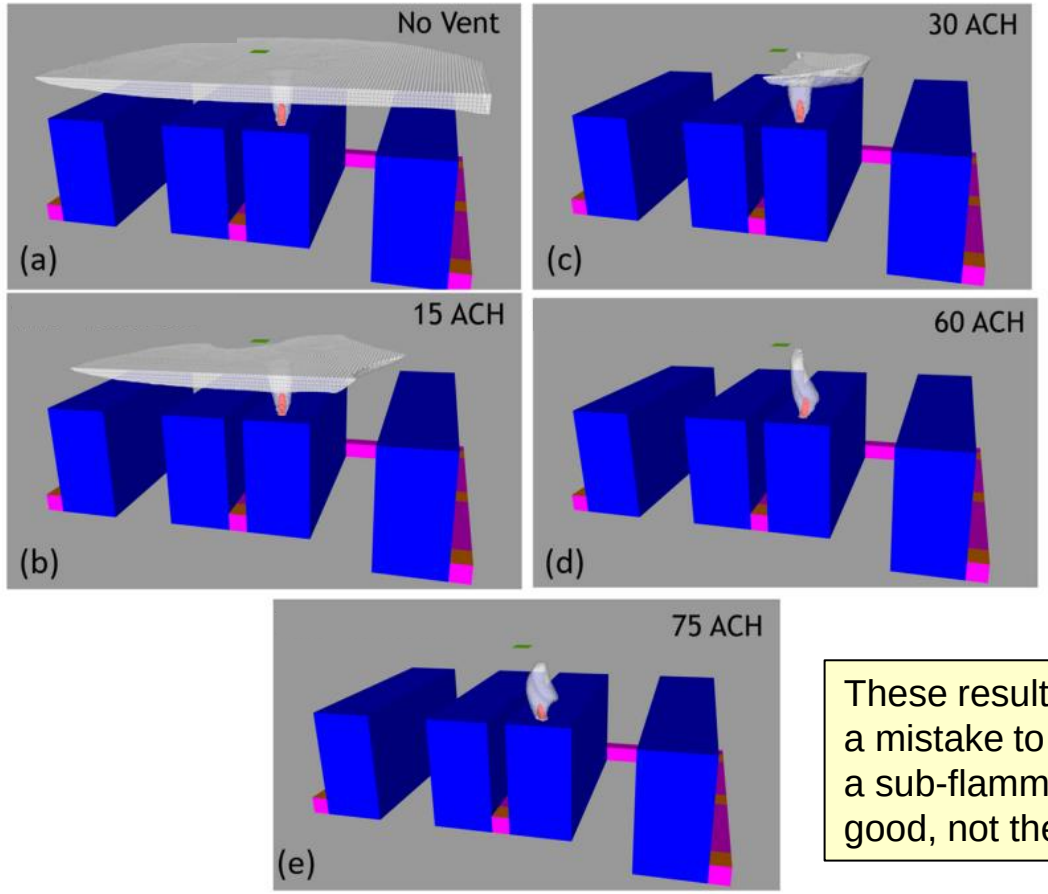
M.L. Blaylock and L.E. Klebanoff, International Journal of Hydrogen Energy **47** (2022) 21506 – 21516.

Sandia H_2 Gas Dispersion Studies for H_2 Vessel Releases

Fuel Cell Room Releases

Work Funded by DOT/MARAD's META Program

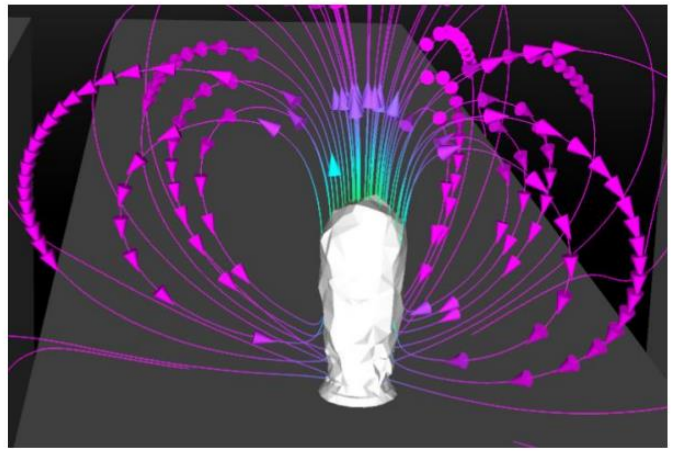
150 s into the leak, 3 x 10^{-5} kg/s
White = detectable H_2 by a H_2 alarm (0.4 – 4%)
Red is flammable (4 - 75%)



150 s into leak, 3 x 10^{-5} kg/s
White = flammable (4 – 75%)

Leak	0 ACH
1.0 x 10^{-5} kg/s (Leak 2)	
3.0 x 10^{-5} kg/s (Leak 3)	

CFD Studies by Kevin Gitushi, NC State University



For short times, the flammable H_2 envelope is self-limited, even in the absence of ventilation.

These results indicate it might be a mistake to over-ventilate, as you want to be able to detect a sub-flammable leak in the Fuel Cell Room. 15 ACH looks good, not the typically recommended 30 ACH.

K.M. Gitushi, M.L. Blaylock and L.E. Klebanoff, International Journal of Hydrogen Energy **47** (2022) 21492 - 21505.

Summary: 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 SF 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)? ✓

Acknowledgements

Sujit Ghosh, MARAD (retired)

Bryan Vogel, MARAD

Pete Devlin, DOE

An *extra special* Thank You to Sujit Ghosh, Bryan Vogel, Michael Carter and Dan Yuska of the US DOT / Maritime Administration (MARAD) and Pete Devlin of the US DOE for supporting our H_2/maritime work at Sandia.

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Praxair: Lauren Moser, Mark Wattanapanom, Roger Han, Rick Craighead

Red and White Fleet: Tom Escher and Joe Burgard

North Carolina State University: Kevin Gitushi

For more information on H_2/Fuel Cell Maritime Projects

visit: **https://maritime.sandia.gov**

- Past and current maritime projects
- Download reports

Thank You!

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