SAND2022-5486C

Sandia National Laboratories

H_2FC Hydrogen and Fuel Cells Program

H_2 Fuel Cell Vessel Studies at Sandia National Laboratories

Lennie Klebanoff

Sandia National Laboratories

Livermore, CA 94551

Maritime Risk Symposium

Oak Ridge National Laboratory

November 15, 2018

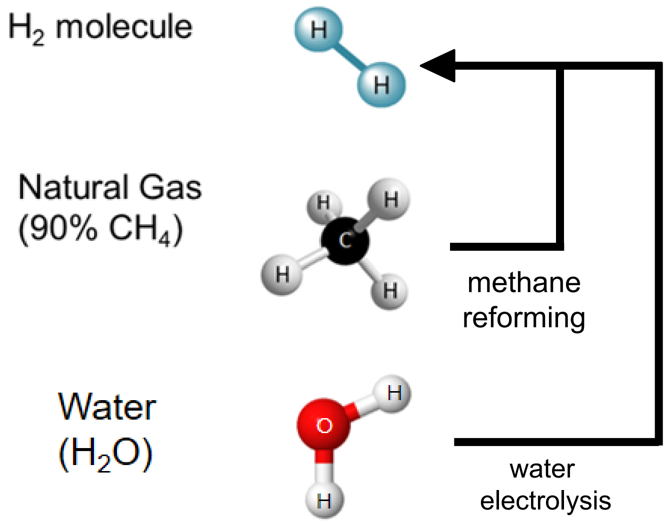
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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) ~12,000 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 do 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 a ignition source and the right H_2/air mixture.

Hydrogen safety follows the same approach as natural gas: eliminate ignition sources and leaks.

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 42 (2017) 757–774

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

International Journal of HYDROGEN ENERGY

Comparison of the safety-related physical and combustion properties of liquid hydrogen and liquid natural gas in the context of the SF-BREEZE high-speed fuel-cell ferry

CrossMark

L.E. Klebanoff [a,*], *J.W. Pratt* [a], *C.B. LaFleur* [b]

[a] *Sandia National Laboratories, Livermore, CA 94551, USA*
[b] *Sandia National Laboratories, Albuquerque, NM 87185, USA*

ARTICLE INFO

Article history:
Received 7 June 2016
Accepted 7 November 2016
Available online 25 November 2016

Keywords:
Liquid hydrogen
Liquid natural gas
Fuel cell ferry
Combustion properties
Safety properties

ABSTRACT

We review liquid hydrogen (LH_2) as a maritime vessel fuel, from descriptions of its fundamental properties to its practical application and safety aspects, in the context of the San Francisco Bay Renewable Energy Electric Vessel with Zero Emissions (SF-BREEZE) high-speed fuel-cell ferry. Since marine regulations have been formulated to cover liquid natural gas (LNG) as a primary propulsion fuel, we frame our examination of LH_2 as a comparison to LNG, for both maritime use in general, and the SF-BREEZE in particular. Due to weaker attractions between molecules, LH_2 is colder than LNG, and evaporates more easily. We describe the consequences of these physical differences for the size and duration of spills of the two cryogenic fuels. The classical flammability ranges are reviewed, with a focus on how fuel buoyancy modifies these combustion limits. We examine the conditions for direct fuel explosion (detonation) and contrast them with initiation of normal (laminar) combustion. Direct fuel detonation is not a credible accident scenario for the SF-BREEZE. For both fuels, we review experiments and theory elucidating the deflagration to detonation transition (DDT). LH_2 fires have a shorter duration than energy-equivalent LNG fires, and produce significantly less thermal radiation. The thermal (infrared) radiation from hydrogen fires is also strongly absorbed by humidity in the air. Hydrogen permeability is not a leak issue for practical hydrogen plumbing. We describe the chemistry of hydrogen and methane at iron surfaces, clarifying their impact on steel-based hydrogen storage and transport materials. These physical, chemical and combustion properties are pulled together in a comparison of how a LH_2 or LNG pool fire on the Top Deck of the SF-BREEZE might influence the structural integrity of the aluminum deck. Neither pool fire scenario leads to net heating of the aluminum decking. Overall, LH_2 and LNG are very similar in their physical and combustion properties, thereby posing similar safety risks. For ships utilizing LH_2 or LNG, precautions are needed to avoid fuel leaks, minimize ignition sources, minimize confined spaces, provide ample ventilation for required confined spaces, and to monitor the enclosed spaces to ensure any fuel accumulation is detected far below the fuel/air mix threshold for any type of combustion.

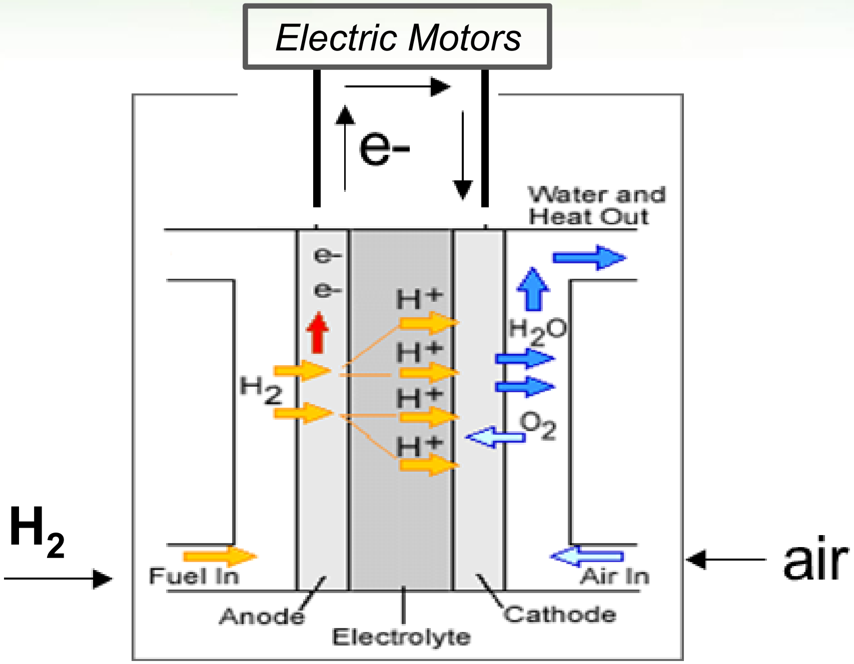
* *Corresponding author.*
E-mail address: lekleba@sandia.gov (L.E. Klebanoff).

http://dx.doi.org/10.1016/j.ijhydene.2016.11.024

More information about hydrogen gas (H_2) and liquid hydrogen (LH_2) can be found in:

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



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

Photos Courtesy Ryan Sookoo, Hydrogenics

Going In:

H_2 and air

Going Out:

Electricity

Waste Heat

Warm humidified air

-- commercially available

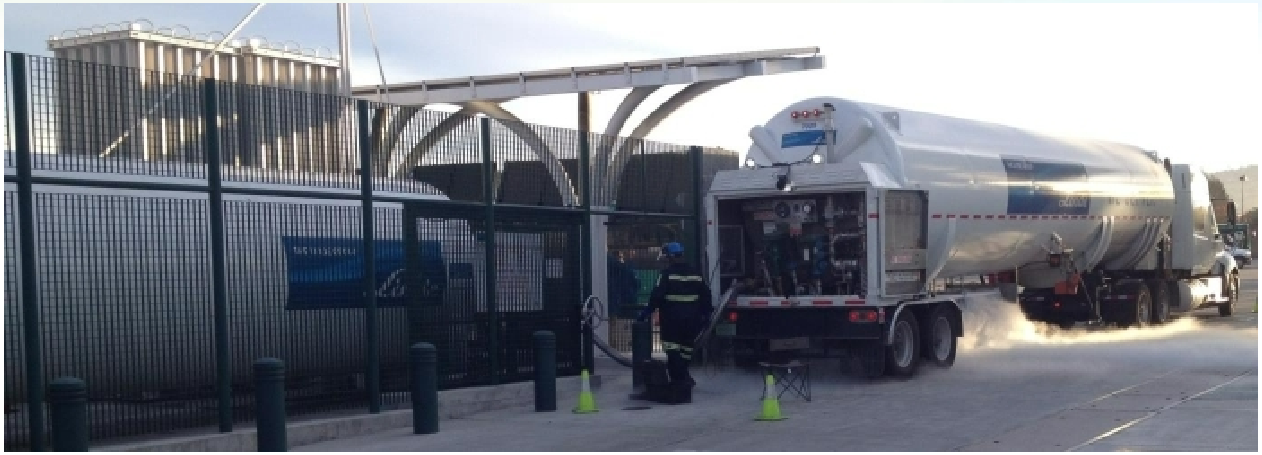
-- more energy efficient than diesel generators

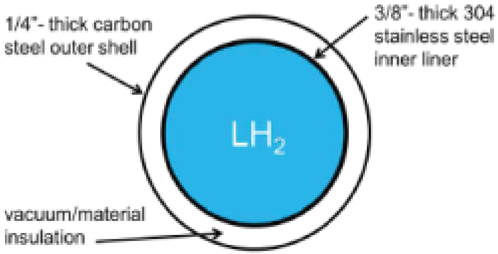
-- eliminates emissions at the point of use

-- eliminates polluting fuel spills, greatly reduces noise

-- emissions can only arise from H_2 production/delivery

H_2 Has Been Delivered and Used for Decades





Today: AC Transit Bus Station, Emeryville CA

1964 - 1973

1981 - 2011

A typical LH_2 trailer can deliver 4000 kg (~15,000 gallons) at a time.
(1 kg LH_2 occupies 3.72 gallons)

Trailer LH_2 tanks are DOT-approved and have never been breached in a road accident.

H_2 Fuel Cell Market Transformation

Bringing zero emission fuel cell technology into new applications, to improve energy efficiency and reduce emissions

Fuel Cell Cars

Fuel Cell Forklifts

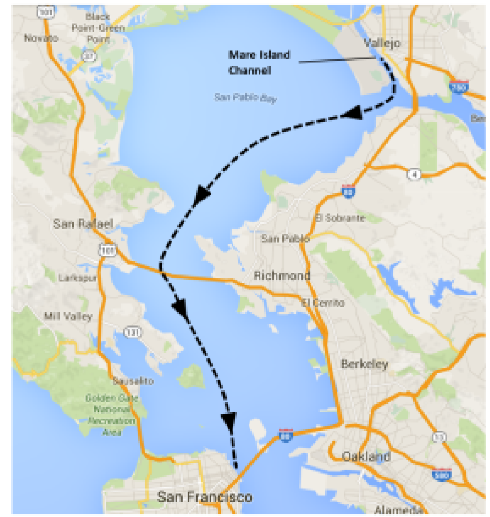
Fuel Cell Lighting

What about for watercraft?

Can H_2 fuel cell technology enable zero emission vessels?

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

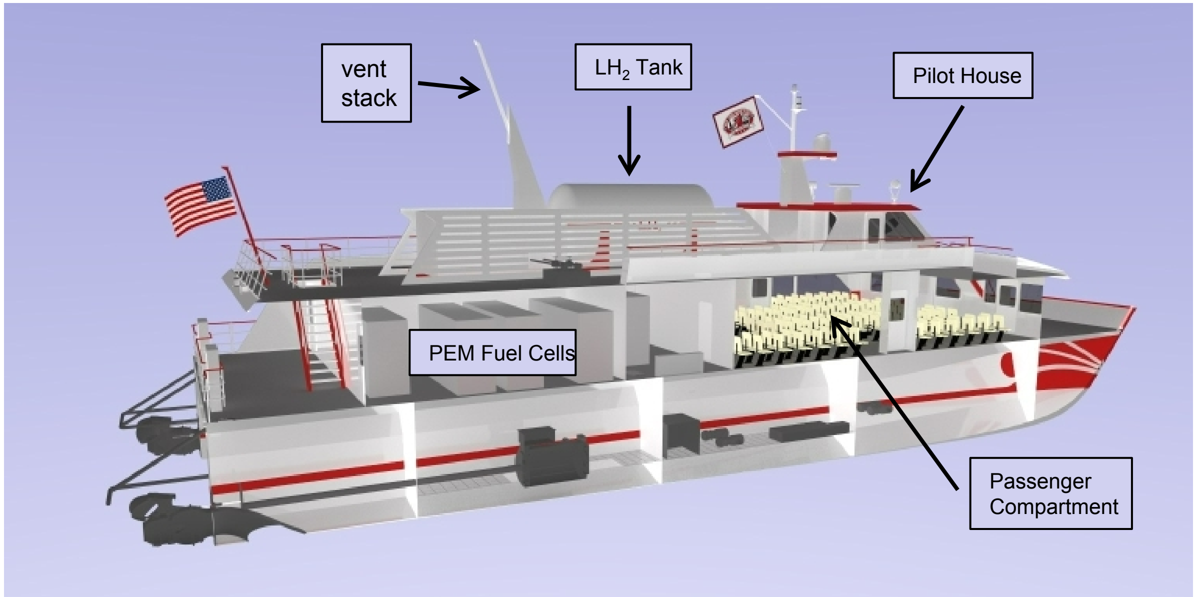
High-speed H_2 Ferry



Route:
San Francisco
to Vallejo, CA

	Ferry	H_2 Refueling
Technical	✓	✓
Regulatory	✓	✓
Economic	*Higher than conventional now, today's market acceptance to be determined*	

SF-Breeze Design: Catamaran

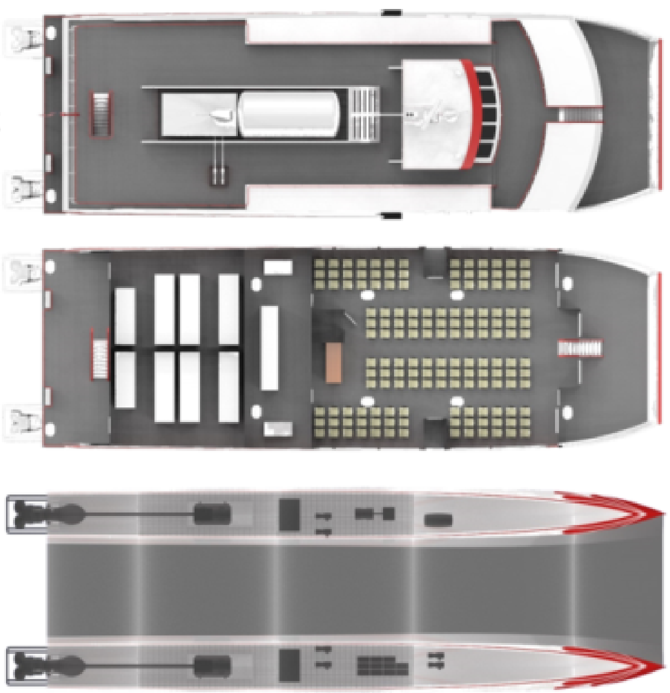


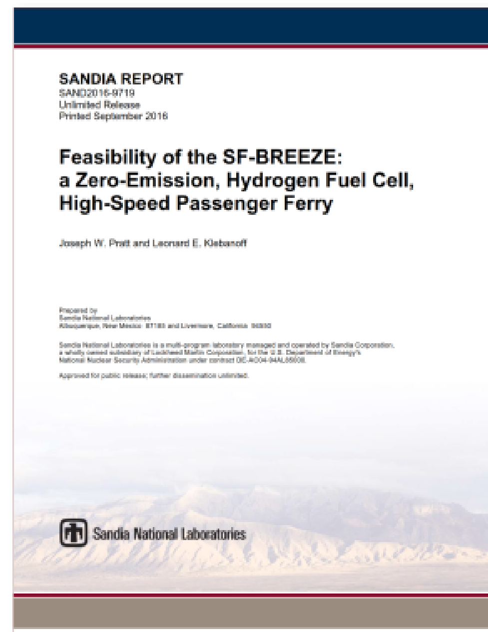
Elliott Bay Design Group

Design generated by Elliott Bay Design Group

SF-BREEZE details

- Fuel: ~2,000 kg LH_2 per day
- Propulsion power 4.4 MW, installed: 4.92 MW
- Passengers: 150
- Service Speed: 35 knots
- Length 109’ x Beam 33’ x Depth 11.25’
  Full Load Draft ~ 4.6’
- **Emissions: Zero**
- **Fuel Spills: Zero**





SANDIA REPORT
SAND2016-9719
Unlimited Release
Printed September 2016

Feasibility of the SF-BREEZE:
a Zero-Emission, Hydrogen Fuel Cell,
High-Speed Passenger Ferry

Joseph W. Pratt and Leonard E. Klebanoff

Sandia National Laboratories

maritime.sandia.gov

Project Integrates Ship Designers, Regulators, H_2 Experts and End Users

Elliott Bay Design Group

Sandia National Laboratories

Red and White Fleet – San Francisco Cruises

USCG MSC and Design and Eng. Stds.

USCG Sector San Francisco

USCG Liquid Gas Carrier NCOE

American Bureau of Shipping

Work Funded by The U.S. Department of Transportation (DOT), Maritime Administration (MARAD) through MARAD's Maritime Environmental and Technical Assistance (META) program.

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 <u>exceeds</u> the requirements of such vessels operating along U.S. coastlines?

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

Lennie Klebanoff
Sandia National Laboratories

Bruce Appelgate
Scripps Institution of Oceanography

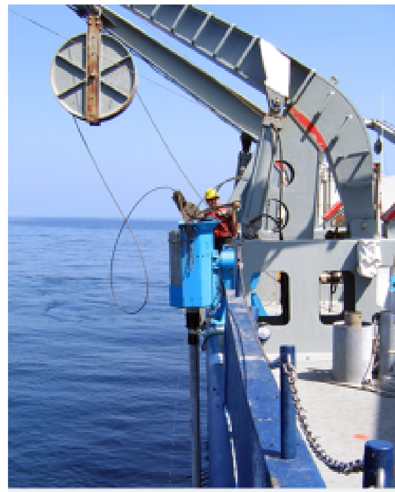
Zoltan Kelety
Scripps Institution of Oceanography

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

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

Deep ocean moorings and observation systems

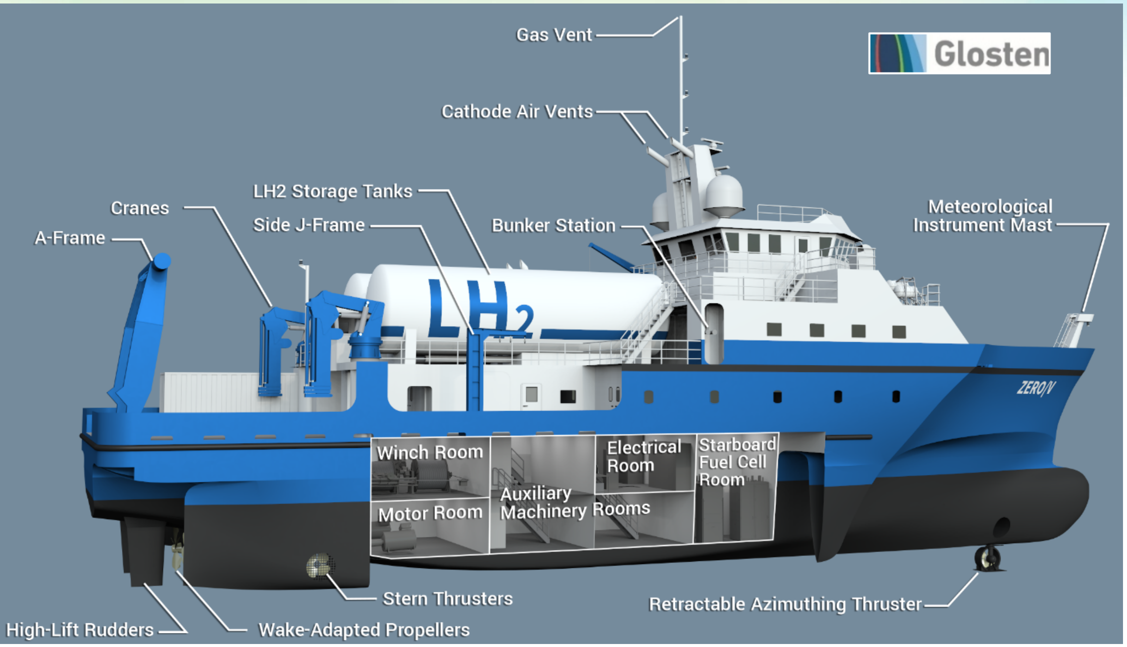
Surface mooring deployment

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).

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

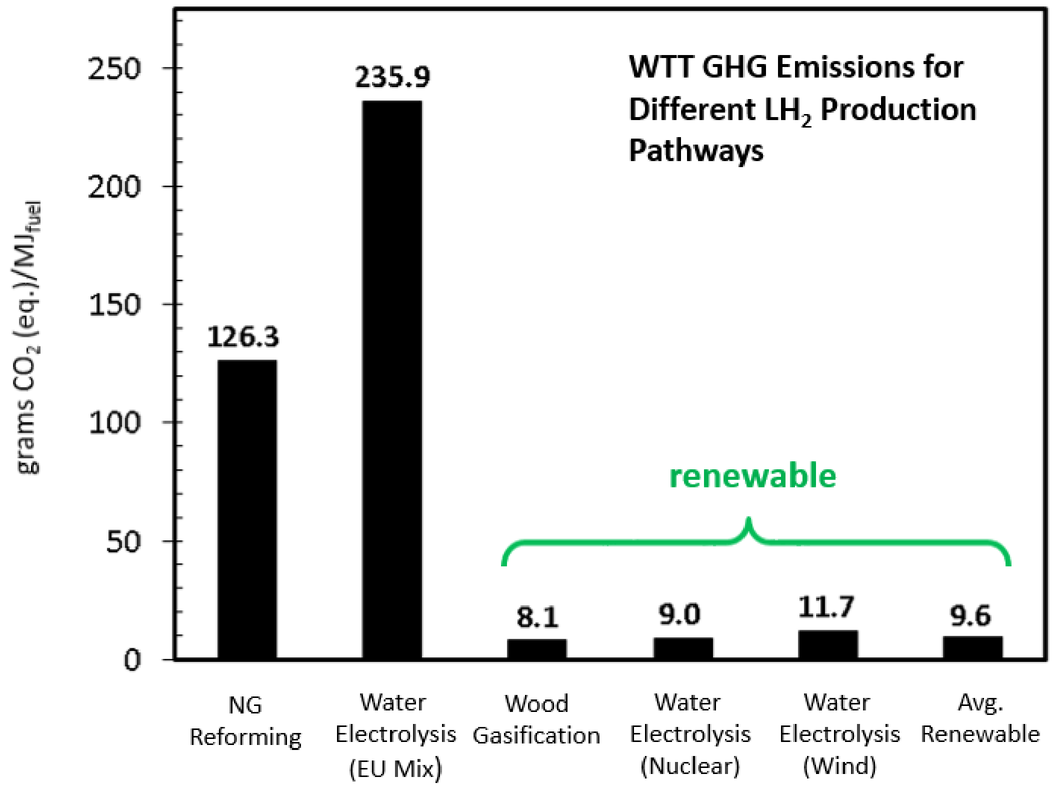


- Oceanographic research vessel for coastal / regional operations
- Uses clean hydrogen: **No fossil fuels!**
- Zero emissions: **Clean/no GHGs!**
- Carries no diesel: **No oil spills!**
- All-electric propulsion: **Quiet!**
- **FEASIBLE** with existing technology
- Outstanding scientific capabilities
- 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.

Well-to-Tank (WTT) Emissions Associated with H_2 Fuel Production and Delivery.

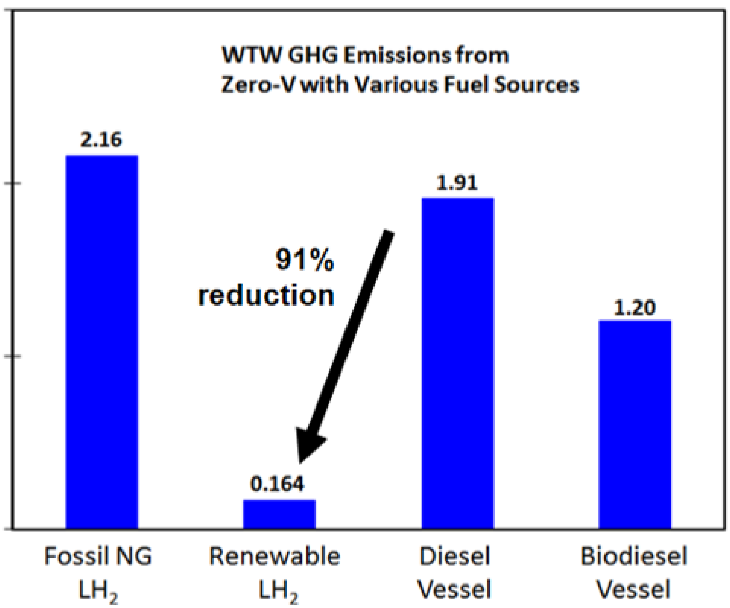


-- the equivalent GHG emissions for making diesel fuel is 87.4 grams CO_2 (eq.)/MJ_{fuel}

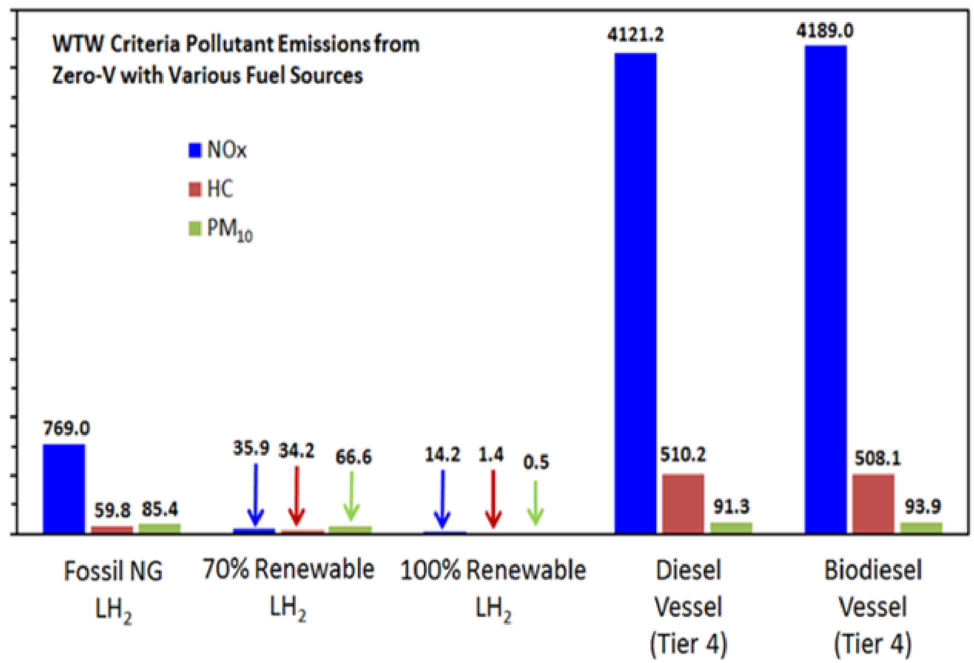
The GHG reduction from using H_2 technology REALLY depends on how the H_2 is made!

Emissions from LH_2 Production and Delivery (the Zero-V itself is zero-emissions):

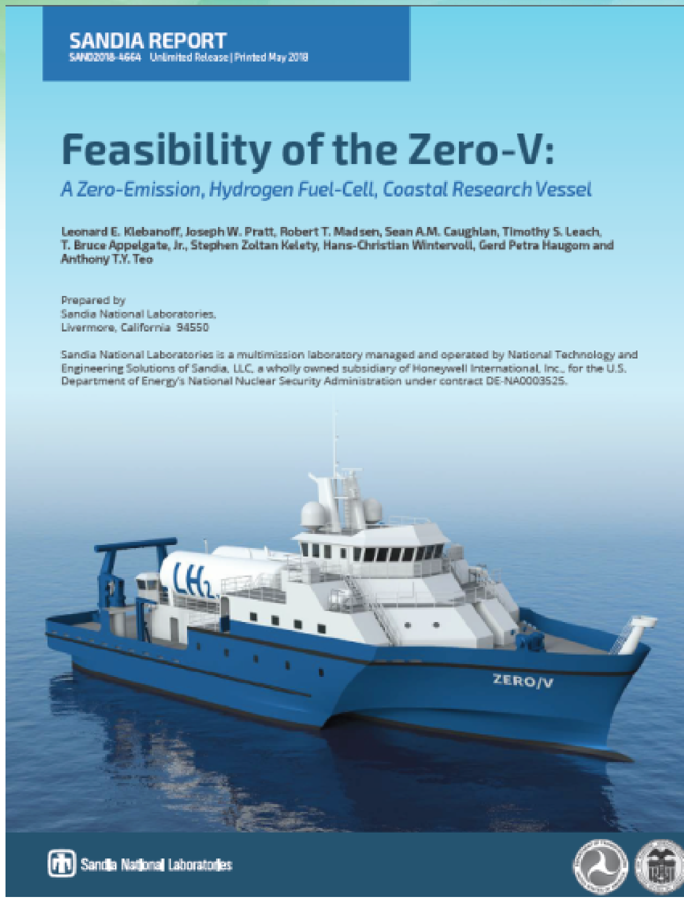
Well-to-Waves Greenhouse Gas Emissions (1,000 MT CO_2 equivalent / year)



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



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.



maritime.sandia.gov


Transportation Research Part D 54 (2017) 250–268

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

ELSEVIER

Comparison of the greenhouse gas and criteria pollutant emissions from the SF-BREEZE high-speed fuel-cell ferry with a diesel ferry

L.E. Klebanoff[a,*], J.W. Pratt[a], C.M. Leffers[b], K.T. Sonerholm[b], T. Escher[c], J. Burgard[c], S. Ghosh[d]

ABSTRACT

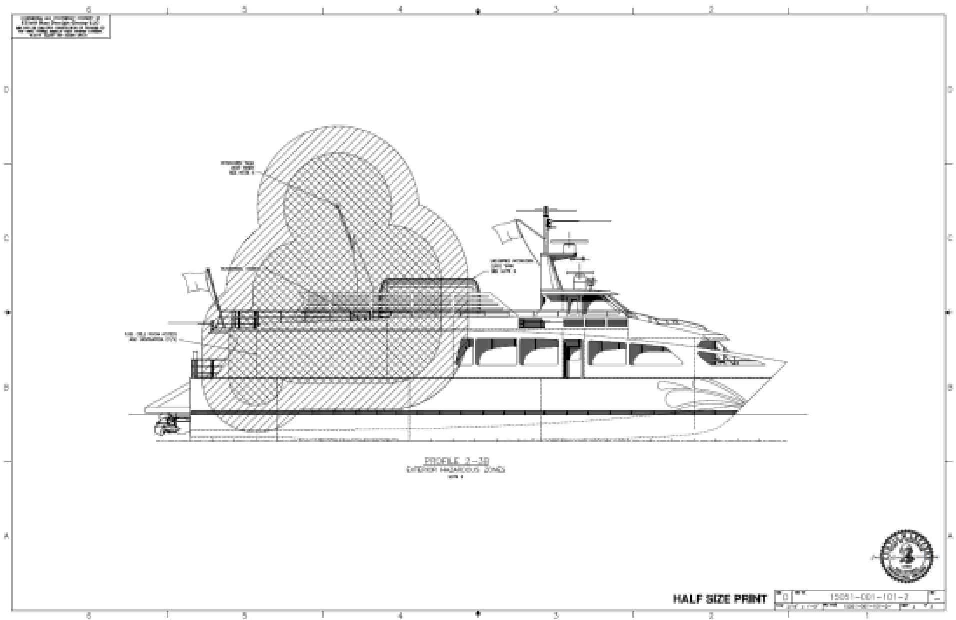
A theoretical comparison is made of the "well-to-waves" (WTW) greenhouse gas (GHG) and criteria pollutant emissions from the SF-BREEZE high-speed hydrogen PEM fuel-cell ferry and the VALLEJO ferry powered by traditional diesel engine technology but constrained to Tier 4 emissions standards. The emissions were calculated for a common maritime mission, the current ferry route between Vallejo CA and San Francisco CA. Calculations are made of the energy required for the SF-BREEZE and VALLEJO to perform the mission route profile. The SF-BREEZE requires more fuel energy than the VALLEJO, primarily due to the SF-BREEZE being heavier. Estimates are made for the SF-BREEZE GHG emissions associated with five LH_2 fuel production pathways including renewable and non-renewable (fossil-fuel based) methods. Estimates are also made for GHG emissions associated with fossil-diesel production and delivery as well as those for biodiesel, which can be considered a renewable "drop-in" fuel replacement for conventional diesel fuel. We find that the GHG emissions for the SF-BREEZE using non-renewable LH_2 are significantly higher than for the Tier 4 diesel-fueled VALLEJO on a per passenger basis. However, using renewable LH_2, the GHG emissions for the SF-BREEZE ferry are reduced compared to the diesel-fueled VALLEJO operating at Tier 4 emissions standards. We also compare the criteria pollutant emissions (NO_x, HC, PM_{10}) for the SF-BREEZE to that of the VALLEJO held to Tier 4 emissions standards fueled by diesel fuel or biodiesel. Hydrogen PEM fuel cell technology dramatically reduces NO_x and HC emissions below the most advanced Tier 4 criteria pollutant emissions requirements regardless of whether the LH_2 is made by NG reforming or via water electrolysis using renewable energy. Renewable LH_2 made with greater than renewable process energy is needed to also drop the SF-BREEZE PM_{10} emissions below that of Tier 4 for high-speed fuel cell ferry transportation. Overall, the results show that operating a hydrogen fuel cell ferry on nearly 100% renewable hydrogen provides the dramatic reduction in GHG and criteria pollutant emissions commensurate with the problems of global climate change and maritime air pollution worldwide.

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

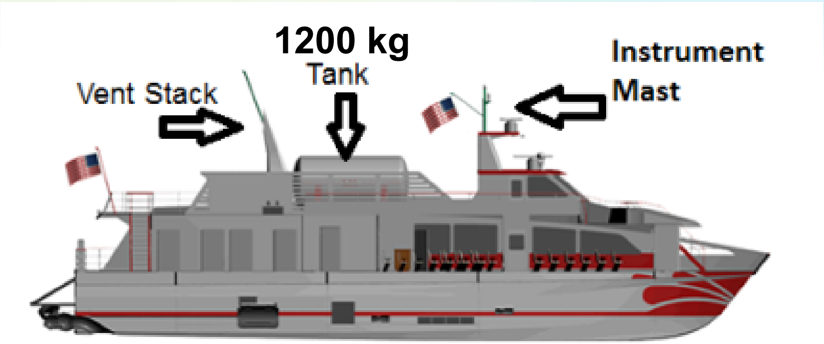
Work Funded by The U.S. Department of Transportation (DOT), Maritime Administration (MARAD) through MARAD's Maritime Environmental and Technical Assistance (META) program.

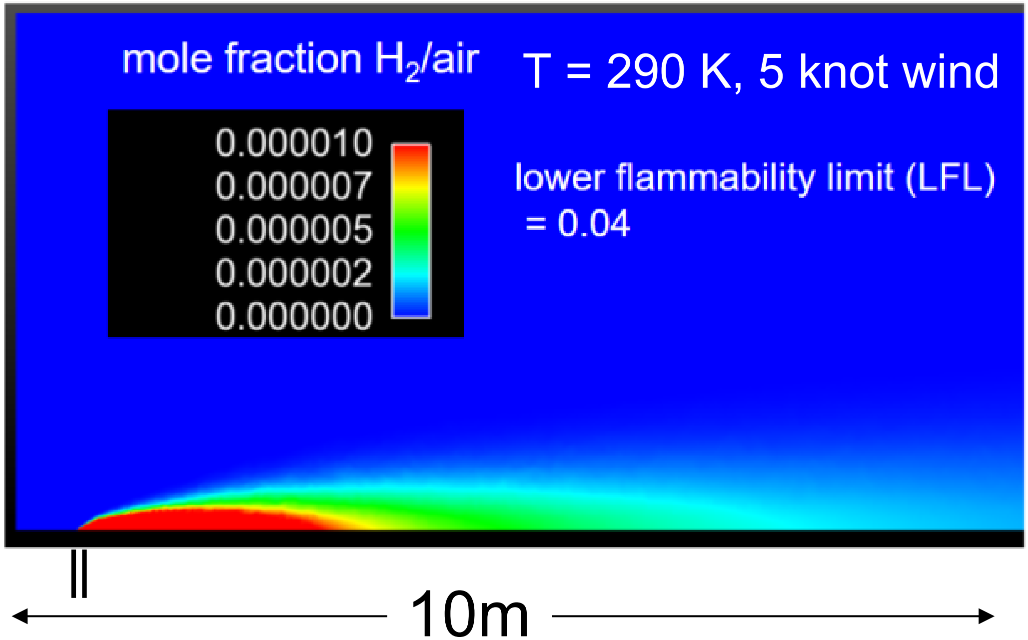
Gas Dispersion Analysis

- Overall Goal:
  - Inform accurate overall hazardous zone requirements for hydrogen so that H_2 fuel cell vessels can be safely operated.
- Benefit of defining hazardous zones for hydrogen:
  - Enable faster and easier approval by reducing the need for gas dispersion studies on every future vessel submitted for approval
  - Avoid placing undue burden on vessel design and layout
  - Avoid situations that are unsafe



Does Normal LH_2 Boil-off Represent a Safety Risk?





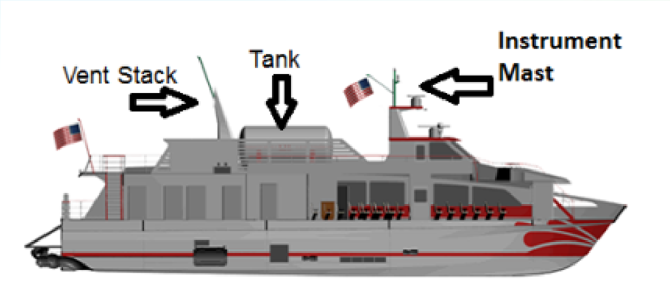
The H_2 concentrations out the vent stack during normal boil-off are 4000x smaller than the LFL for H_2/air mixtures.

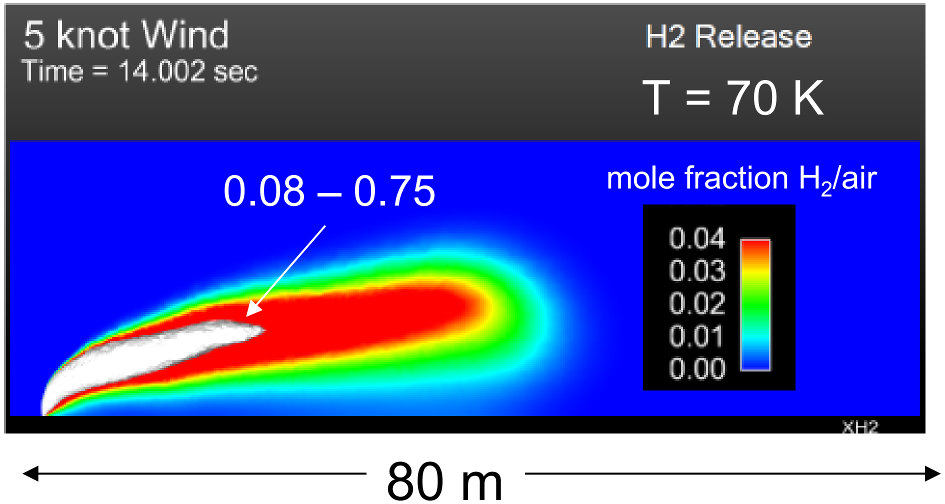
Venting H_2 from normal boil-off is not a safety risk.

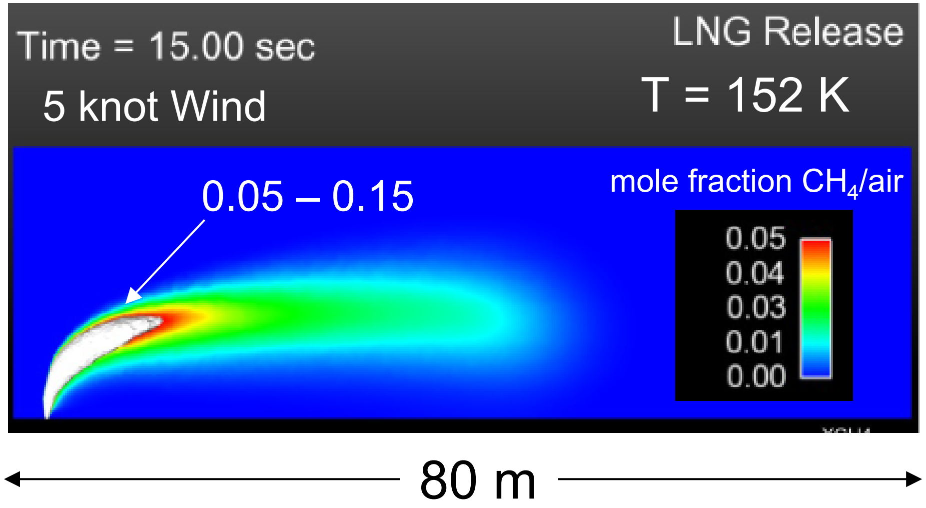
What if the Pressure Relief Valve on the LH_2 Tank Breaks?

Scenario: venting 150 psi hydrogen gas at 70K out the vent stack of the SF-BREEZE.

Assume the ~ 4500 gallon LH_2 tank is 10% LH_2, 90% vapor at 150 psi.







- Both H_2 and CH_4 (LNG) venting more buoyant than air.
- Greater initial penetration of CH_4 into the air (heavier).
- Venting completed in ~ 6 minutes.

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)? ✓

A H_2 Fuel Cell Ferry Will Soon Be Built!

-- Funded by the State of California Air Resources Board (CARB)

The world's first commercial hydrogen fuel cell ferry, and first hydrogen fuel cell vessel in the U.S.

- Aluminum catamaran
- 70' long
- 84 passenger (reconfigurable)
- 22 knot top speed

Project Lead

GOLDEN GATE ZERO EMISSION MARINE

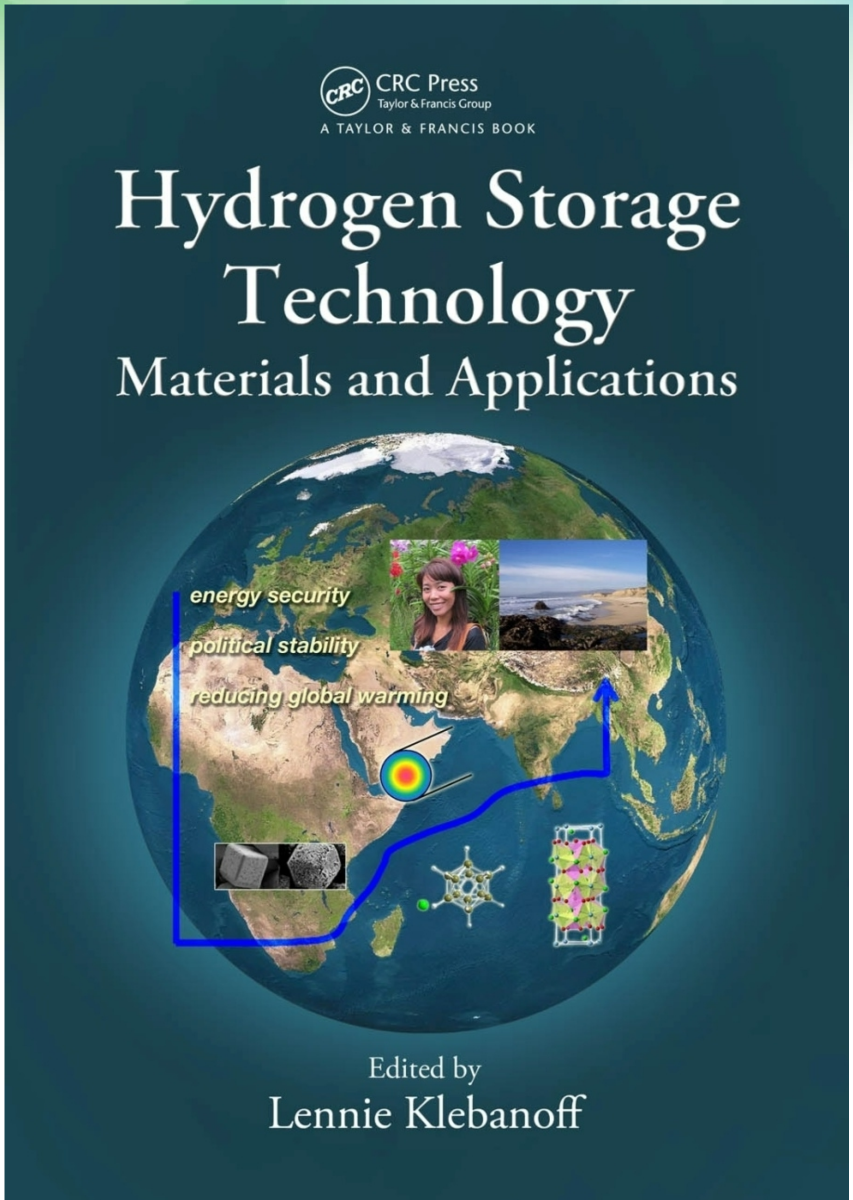
Funding & Administration

CALIFORNIA AIR RESOURCES BOARD

BAY AREA AIR QUALITY MANAGEMENT DISTRICT

CALIFORNIA CLIMATE INVESTMENTS — Cap and Trade Dollars at Work

This project is supported by the "California Climate Investments" (CCI) program

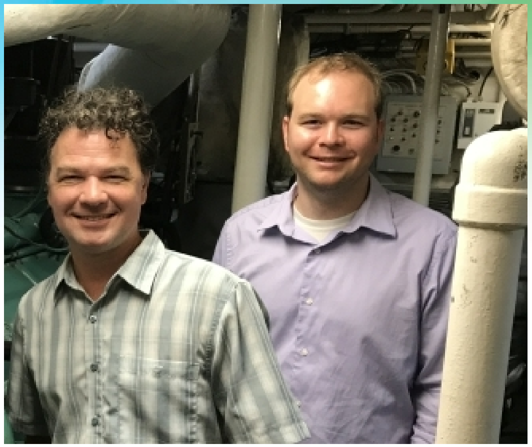


--published by CRC Press in 2012

Topics:

- Why we need H_2-based energy
- H_2 Energy Conversion Devices
- All methods of H_2 Storage
- Engineered H_2 Storage Systems
- H_2 Codes and Standards

-- available on Amazon



Thanks to all my friends and colleagues!

Sujit Ghosh, MARAD

An *extra special* <u>Thank You</u> to Sujit Ghosh and the US DOT / Maritime Administration (MARAD) for supporting these studies

For more information on H_2/Fuel Cell Maritime Projects visit:
https://maritime.sandia.gov

- Past and current maritime projects
- Download reports

Thank You!

Lennie Klebanoff
(925) 294-3471
lekleba@sandia.gov