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Sandia National Laboratories

H2FC Hydrogen and Fuel Cells Program

Hydrogen Fuel Cell Maritime Work at Sandia National Laboratories

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SNAME Meeting

Tacoma, WA

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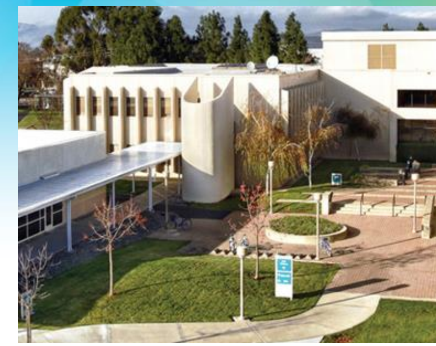
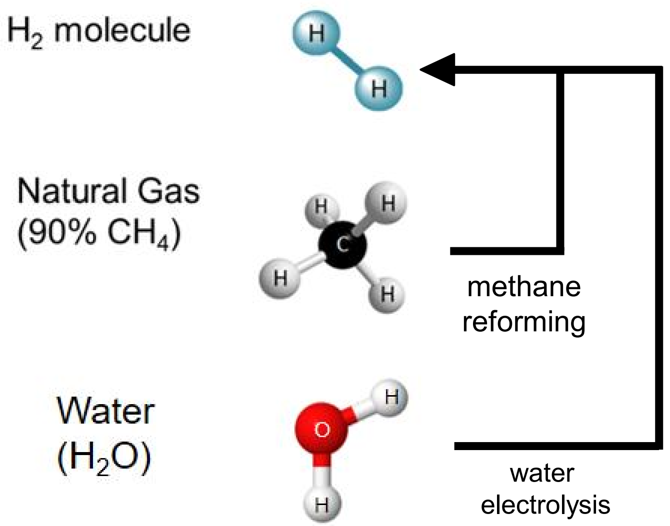


Livermore CA (SF Bay Area)

- 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).

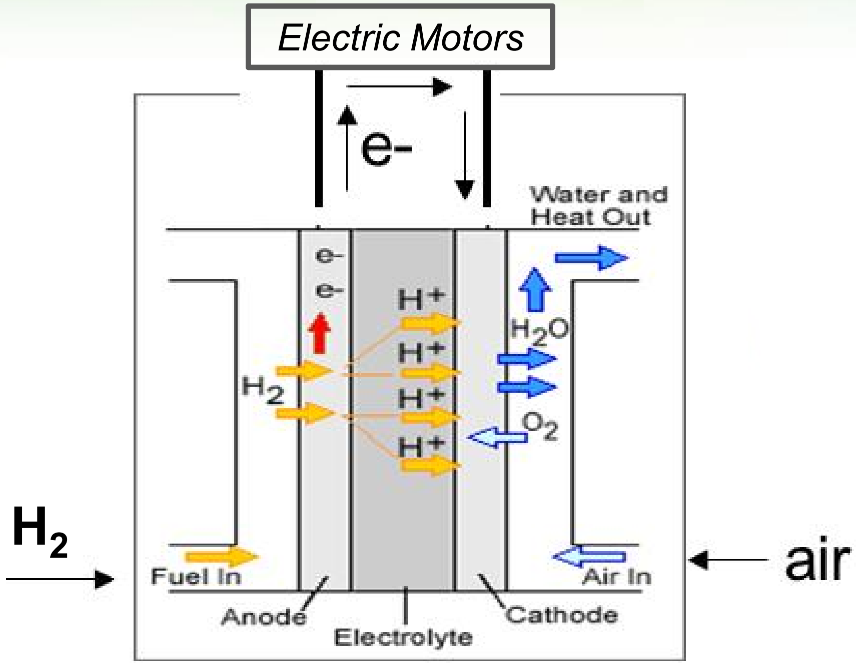
H_2 is NOT a Greenhouse Gas, unlike natural gas which is a potent GHG.

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 about the same energy as a gallon of diesel fuel.

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



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

- -- 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

Photos Courtesy Ryan Sookoo, Hydrogenics

Going In:
H_2 and air

Going Out:
Electricity
Waste Heat
Warm humidified air

Physical Properties of LH_2 and LNG

Note: 75 ºF = 297 K

LH_2:

Liquid Normal Boiling Point = 20 K (-253 ºC).
Liquid Density = 71 g/L
Lower Heating Value = 120 MJ/kg

LNG (LCH_4):

Liquid Normal Boiling Point = 111 K (-162 ºC).
Liquid Density = 422 g/L
Lower Heating Value = 45 MJ/kg

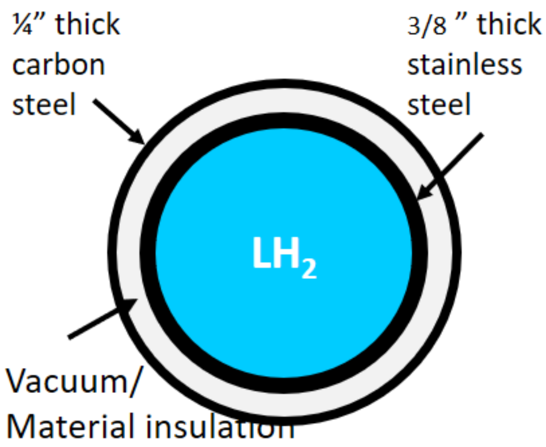
LH_2 has 0.38 times the mass of LNG, but has 2.4 times the volume, per unit of energy (LHV).

LH_2 has 0.36 times the mass of diesel, but has 4.2 times the volume, per unit of energy (LHV).

LH_2 and LNG are stored in similar ways:

LH_2 Storage Tank on Trailer

LNG Storage Tank on Trailer



Gaseous Flammability of H_2 vs NG

Both H_2 and NG (methane) mixtures with air are easily ignited by “Weak (Heat) Ignition Sources” such as: sparks, hot surfaces, open flames (< 50 mJ).

The flammability range for H_2 is wider than for NG: Lower Flammability Limit (LFL) to Upper Flammability Limit (UFL) for H_2 = 4.0 – 75.0 % and for NG = 5.3 – 15.0 %.

The lower explosion limit (LEL) of H_2 at room temperature (% by volume) - upper explosion limit (UEL) = 18.3 – 59.0 % at RT. The LEL to UEL of methane is = 6.3 – 13.5 % at room temperature.

Fires are dangerous and need to be prevented. Preventing fires eliminates other more dangerous combustion events like deflagrations and explosions.

Since H_2 and NG are so similar, the IGF code (written for NG), with only minor modifications, will serve the H_2 vessel community well. The NG codes have been great!: As of 2004 (from the SAND2004-6258 Report by Mike Hightower):

“During the past 40 years, more than 80,000 LNG carrier voyages have taken place, covering more than 100 million miles, without major accidents or safety problems, either in port or on the high seas.... No LNG shipboard fatalities from spills have occurred.”

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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

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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.

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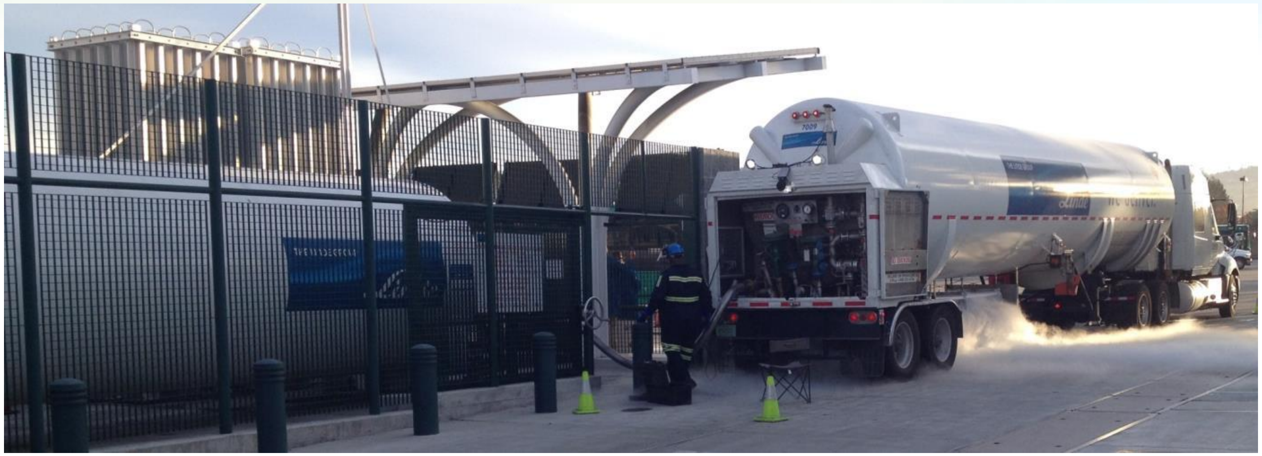
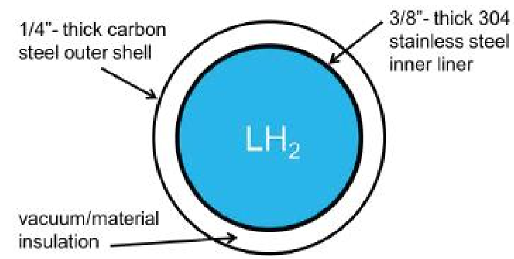
More information about hydrogen gas (H_2) and liquid hydrogen (LH_2) can be found in:

L.E. Klebanoff et al., International Journal of Hydrogen Energy **42**, 757 (2017).

H_2 Has Been Delivered and Used for Decades





Today: AC Transit Bus Station, Emeryville CA

1964 - 1973

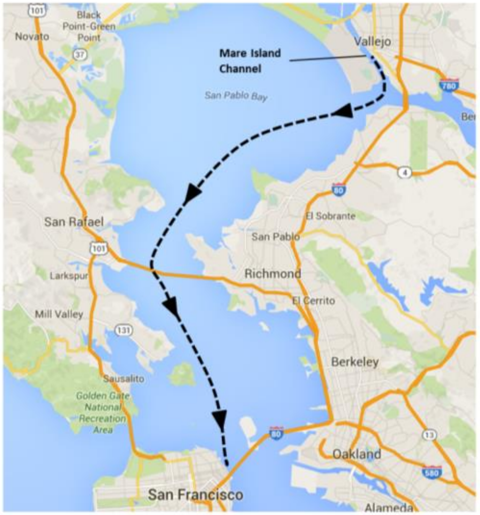
1981 - 2011

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

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

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

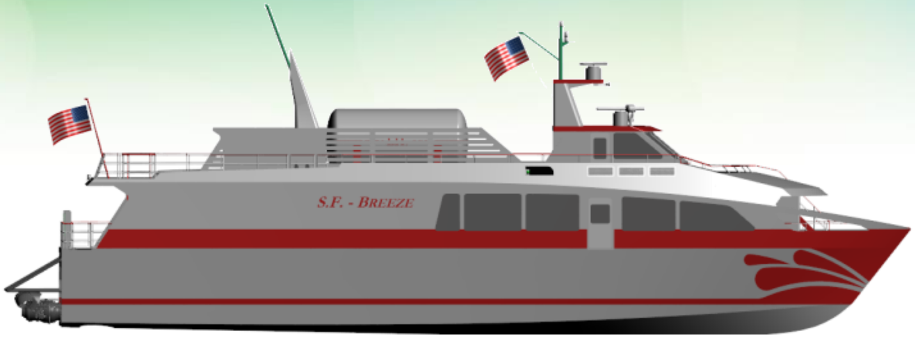
High-speed H_2 Ferry



Route:
San Francisco to Vallejo, CA

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

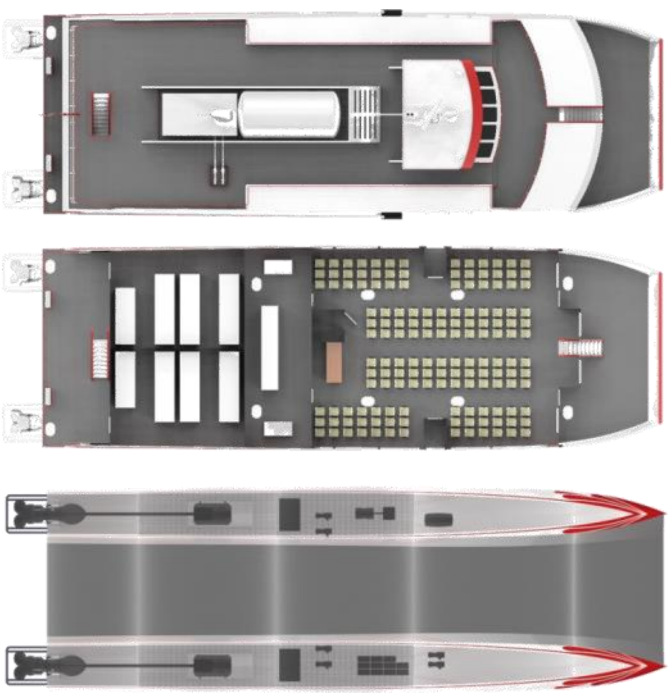
SF-BREEZE details



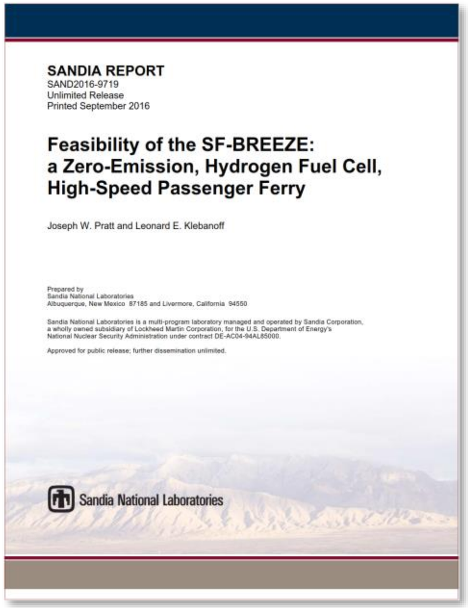
Upper Deck

Main Deck

Hulls



- 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**



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

Joseph W. Pratt and Leonard E. Klebanoff

Prepared by
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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?

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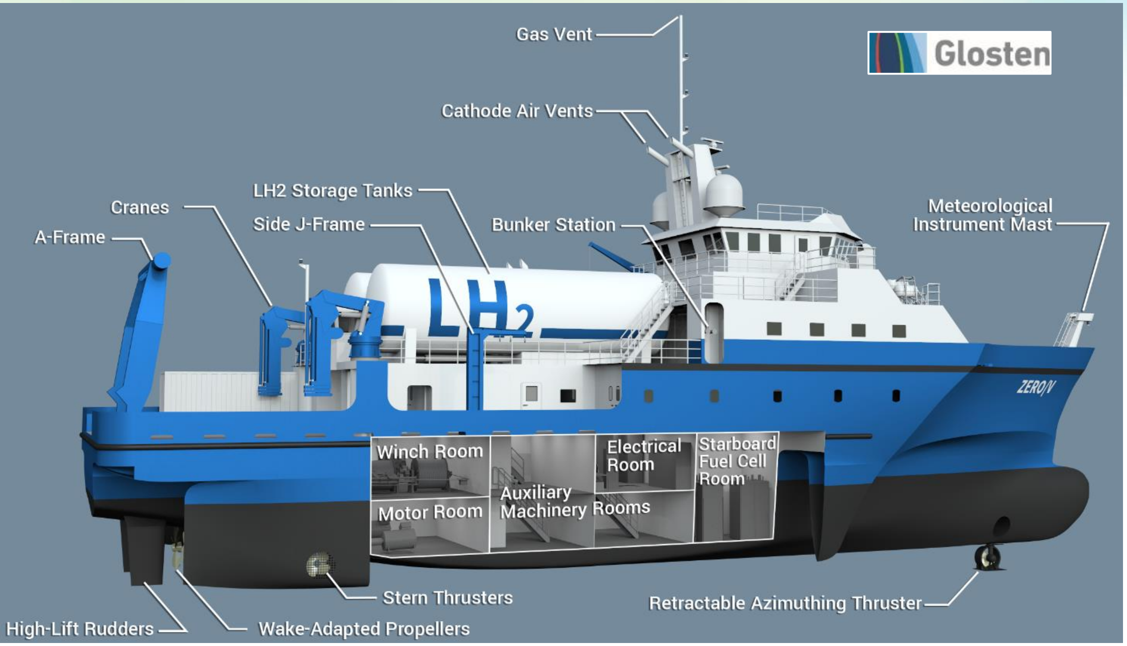
Glosten Participants: (L-R) Ian McCauley, Sean Caughlan, Robin Madsen and Catherine Farish.

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.

A H_2 Fuel Cell Ferry Is Under Construction!

-- 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

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)? ✓

And it's not just vessels!

20 foot containerized, 100 kW PEM fuel cell

Mobile Zero-emission Power

Powering Reefers in Hawaii

- ✓**Lower the technology risk**
- ✓**Lower the investment risk**
- ✓**Enable easier permitting and acceptance**
- ✓**Engage potential adopters/end users**

Will be used starting next month to provide shore power for Scripps research vessel.

Sandia National Laboratories

Scripps Institution of Oceanography UC San Diego

Cummins

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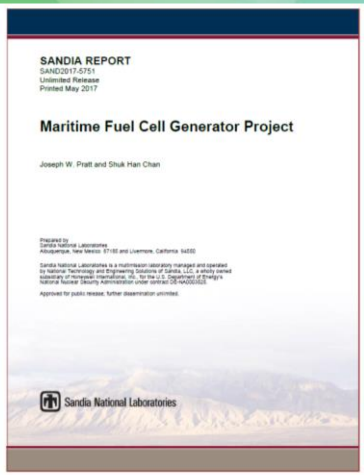
SHIFT POWER | ENERGIZE YOUR WORLD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Maritime Fuel Cell Generator Project

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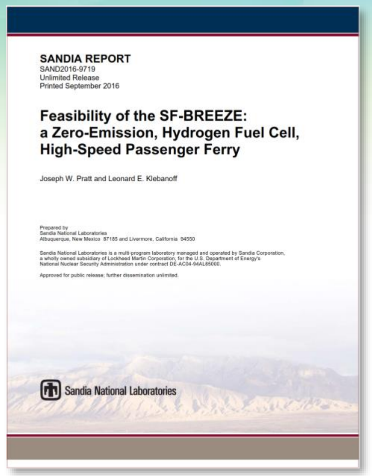
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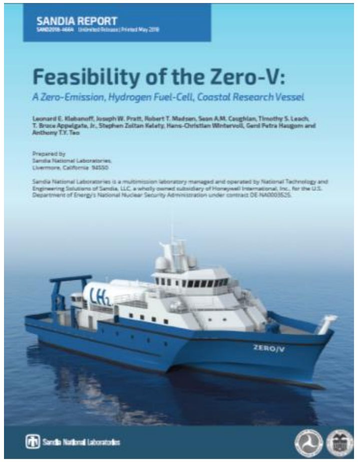
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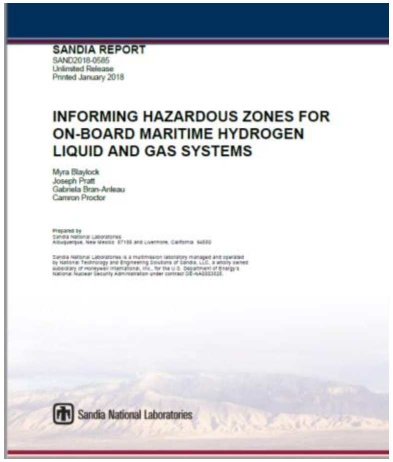
Feasibility of the Zero-V:

A Zero-Emission, Hydrogen Fuel-Cell, Coastal Research Vessel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INFORMING HAZARDOUS ZONES FOR ON-BOARD MARITIME HYDROGEN LIQUID AND GAS SYSTEMS

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Gabriela Bran-Anleau
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Thank You!!