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

Dr. Joe Pratt
Sandia National Laboratories

SNAME Norcal Chapter

January 18, 2017

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

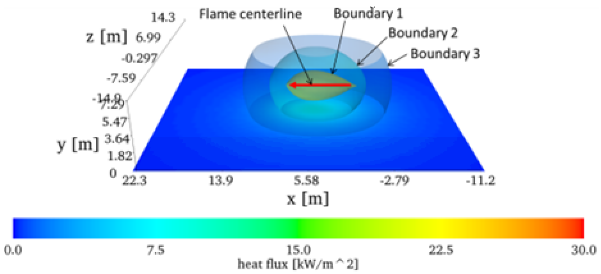
Sandia National Laboratories
"Exceptional service in the national interest"

- Largest National Lab in U.S.
  - U.S. Department of Energy (DOE)
  - ~12,000 employees
  - ~US$2.3B/yr from DOE, other federal agencies, and private industry
  - H2 Program in Livermore, CA (HQ in Albuquerque, NM)
- Hydrogen program: 60+ years technical depth in a wide range of areas, which we apply to enable impactful clean energy solutions




Sandia's *Zero Emission Maritime* Work (since 2012)

- **Cold ironing** with hydrogen fuel cells (study)
- **Fuel cell generator** for ports and ships (deployment)
- **SF-BREEZE** ferry (feasibility study and optimization)
- **IMO hydrogen code** development (invited part of US delegation)
- **ZERO/V** ocean going research vessel (feasibility study)
- **Zero Emission Hydrogen Vessel Working Group** lead



Project Concept

High-speed H_2 Ferry

Engineering model of the SF-BREEZE

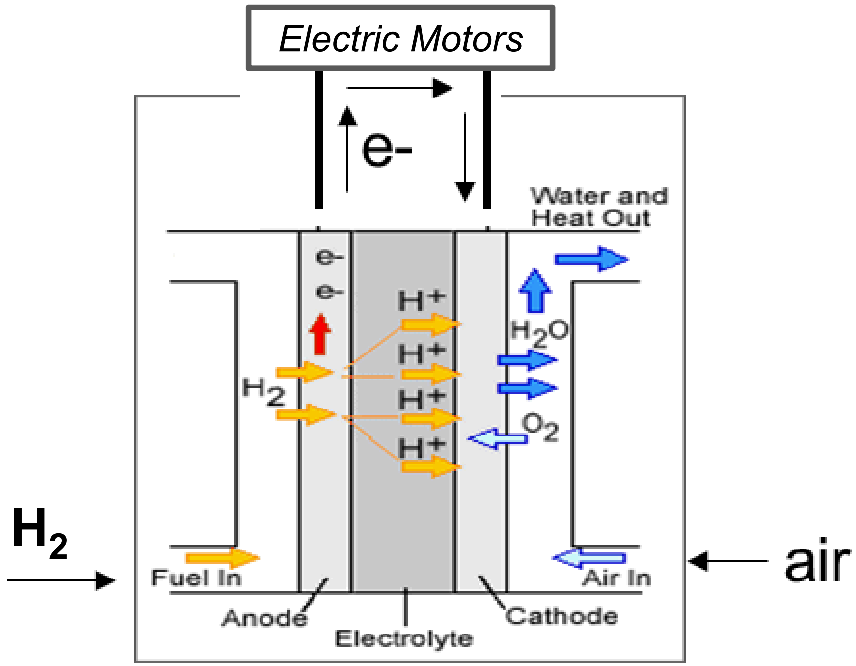
Dockside Fueling Station

Example existing dockside hydrogen station in Hamburg, Germany

Technically Possible? ***Accepted by Regulators?*** ***Commercially Viable?***

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

Hydrogen Fuel Cell



$2 H_2 + O_2 \rightarrow 2 H_2O$

Photos Courtesy Ryan Sookoo, Hydrogenics

Going In:

H_2 and air

Going Out:

Electricity
Waste Heat
Warm humidified air

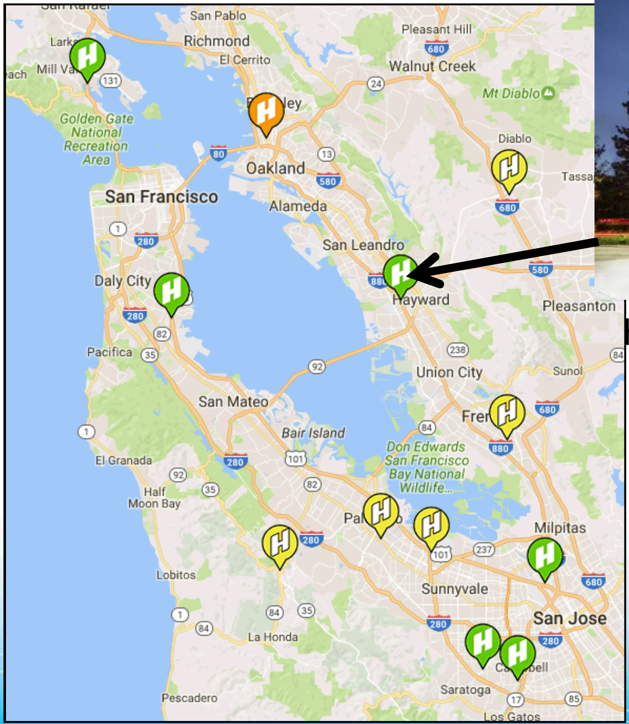
Hydrogen fueling stations and fuel cell electric vehicles are in the Bay Area today

Hyundai Tucson

Toyota Mirai

Honda Clarity

AC Transit buses

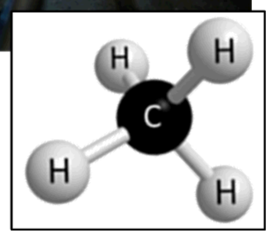


Hayward hydrogen fueling station (A St. @ 880)

Hydrogen is a combustible fuel, very similar to natural gas, but does not contain *carbon.*

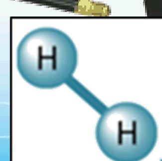
H_2O
CO
CO_2

Natural gas

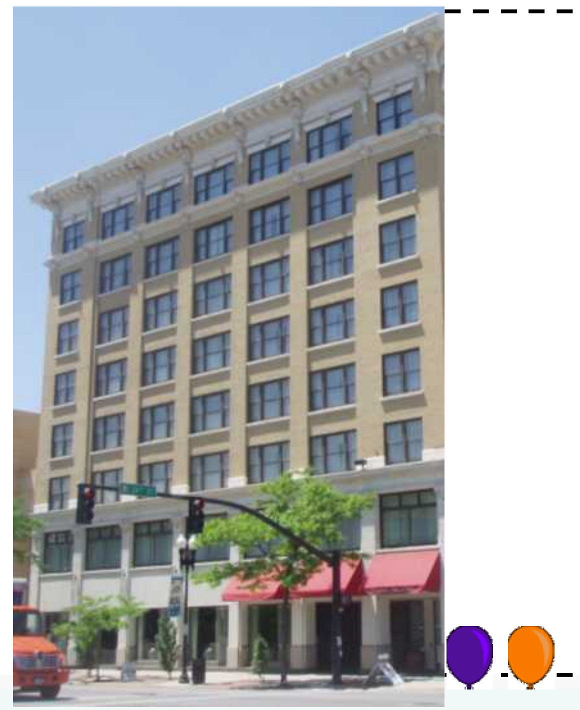


H_2O

Hydrogen



Hydrogen is the lightest gas



NG H_2

Ways to Store Hydrogen on the SF-BREEZE

Gaseous tanks

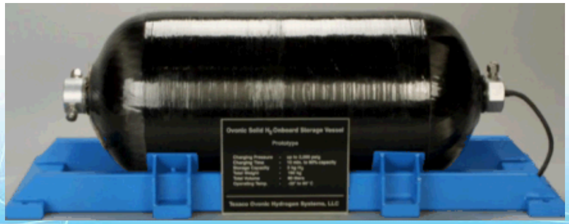
~2,000 psi steel or aluminum

5,000-10,000 psi carbon fiber composite assemblies

Liquid hydrogen

✓

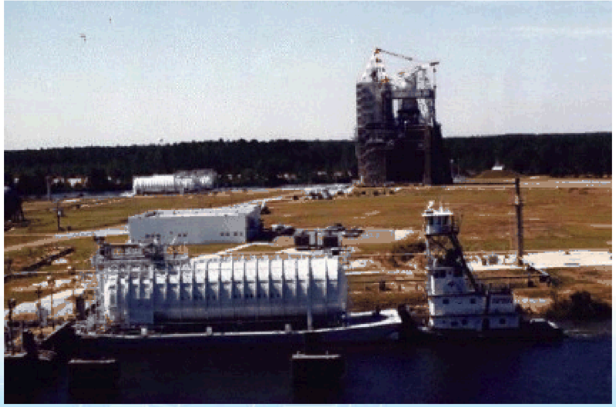
Metal Hydride



Liquid hydrogen is the lightest option for the SF-BREEZE

LH_2 has been safely used for decades


AC Transit bus fueling facility, Emeryville



LH_2 tanks are double walled vacuum insulated stainless steel tanks with steel shell.

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

LH_2 and LNG are similar cryogenic fuels

LH_2:

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

LNG (LCH_4):

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

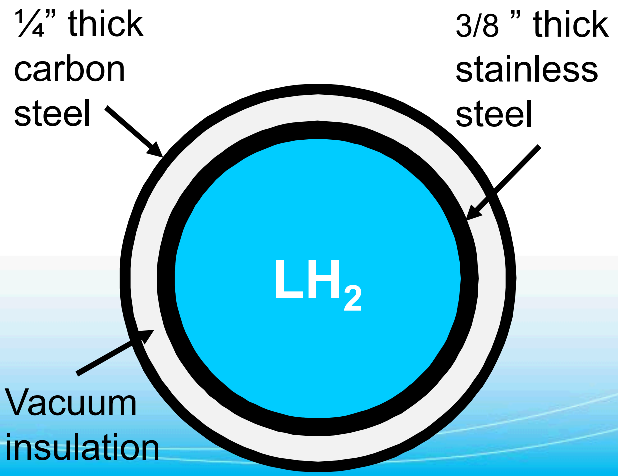
For the same amount of stored energy:

- **LH_2 is lighter** (m = 0.38 x LNG)
- **LH_2 is bigger** (V = 2.4 x LNG)

LNG and LH_2 are stored in similar ways:

LH_2 Storage Tank on Trailer

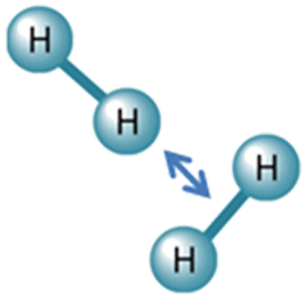
LNG Storage Tank on Trailer



Vessel design with LH_2 is similar to that with LNG

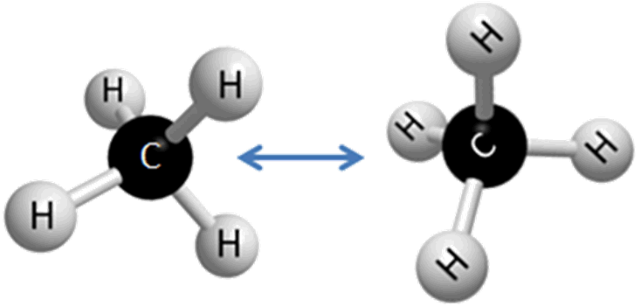
Commonalities

- Similar combustion properties
- Same safety design method:
  - Leak avoidance and monitoring
  - Minimize ignition sources
  - Provide ventilation



Major Differences

- H_2 is much more buoyant than CH_4 - even when very cold.
- LH_2 is colder and can condense/freeze air.



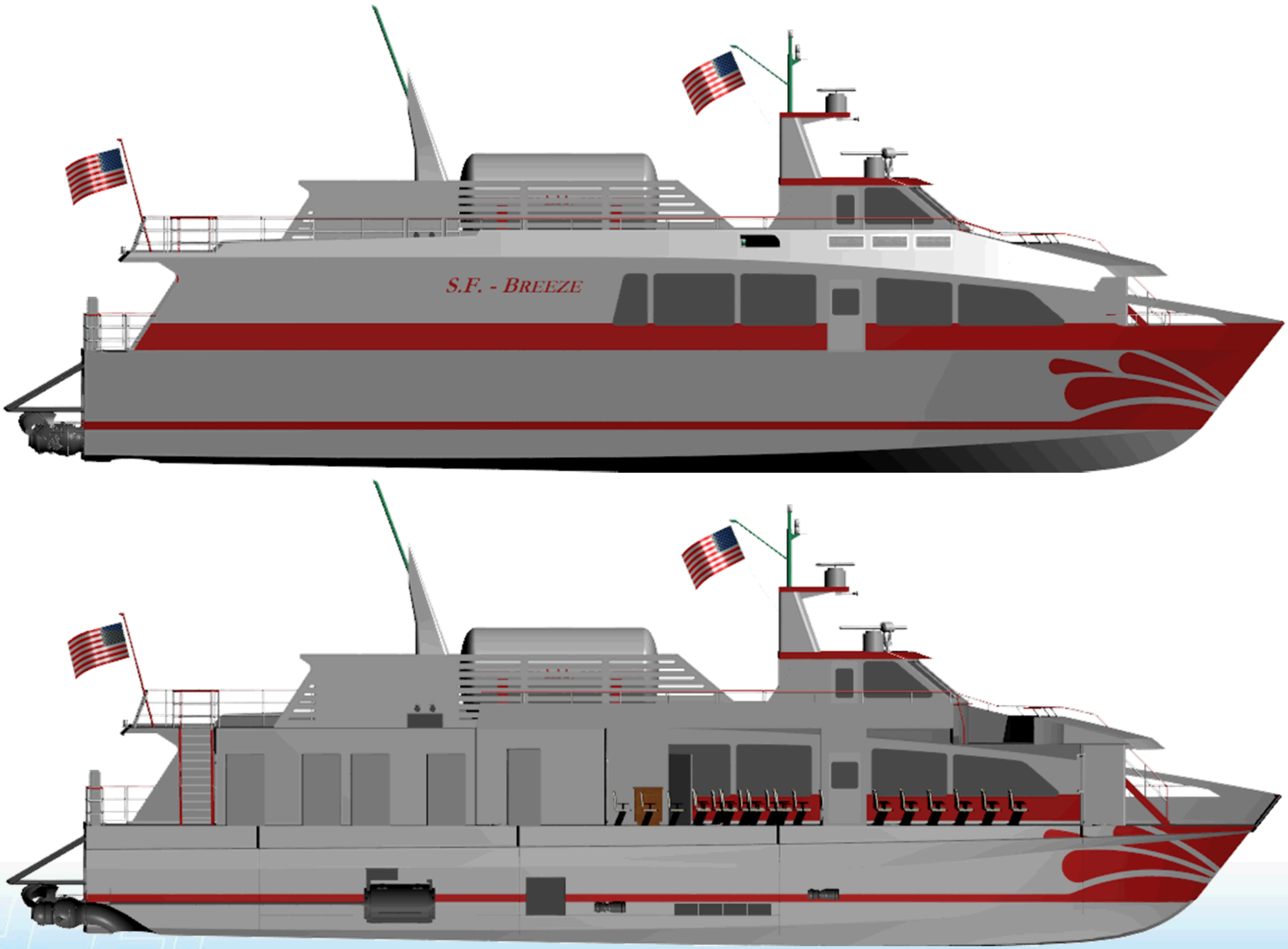
The current use of LNG as a maritime propulsion fuel is paving the way for use of LH_2 for vessels.

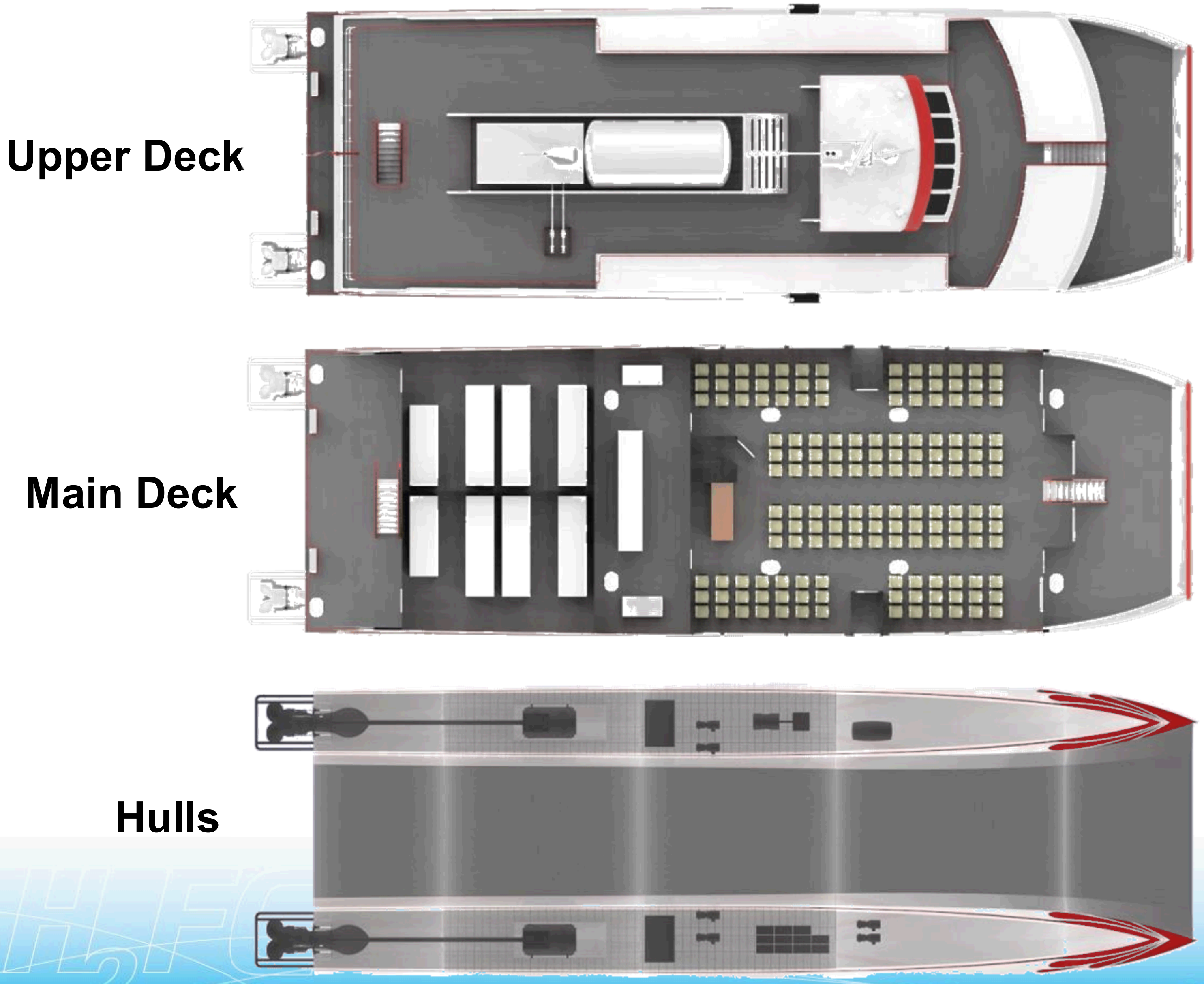
SF-BREEZE Operating Requirements

- High-speed commuter ferry in an ocean bay environment
- Must be competitive with other modes of transportation (car, bus, train, other ferries)
- 35 kts top speed, 23 nm one-way
- Daily logistics:
    1. Two morning round trips (~100 nm)
    2. Refuel in less than 1 hr at midday
    3. Two afternoon round trips (~100 nm)
    4. Refuel again at night
- Each round trip uses about 400 kg LH_2

The final SF-BREEZE design meets all requirements

Elliott Bay Design Group Naval Architecture by Elliott Bay Design Group


S.F. - BREEZE



Elliott Bay Design Group

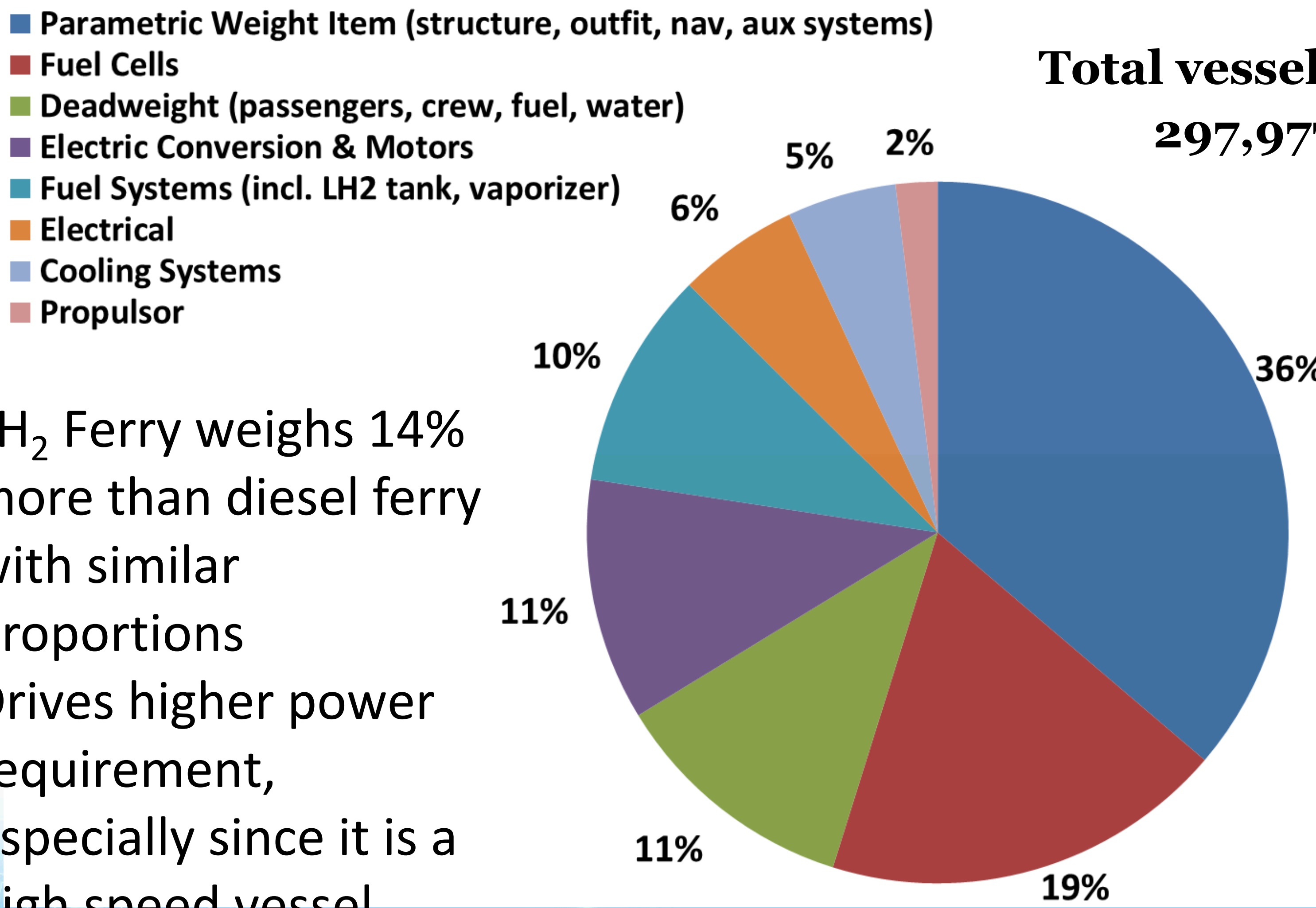
SF-BREEZE by the numbers

- LOA 109’ x Beam 33’ x Depth 11.25’
- Full Load Draft ~ 4.6’
- Full Load Displacement ~133 LT
- Passengers: 150
- Service Speed: 35 knots
- Tonnage: 79.86 GRT
- Passenger Cabin Forward, Fuel Cells Aft
- LH_2 tank located on centerline (>B/5 from side)
- Propulsion power 4.4 MW, installed power 4.92 MW

Propulsion system architecture

1. Fuel cells feed DC-DC power converter to regulate voltage
   - 41 Fuel cell units – 120 kW x 41 = 4.92 MW
     - 4.6 MW for propulsion, 120 kW for other loads, remainder is margin
2. DC-DC power converters feed DC-AC power inverters
3. DC-AC power inverters feed AC PM propulsion motors (2 x 2 MW Permanent Magnet AC motors)
4. AC PM propulsion motors feed linear jet or water jet propellers (2 x 2.6 MW)

Vessel Weight



Total vessel weight: 297,977 lb

- LH_2 Ferry weighs 14% more than diesel ferry with similar proportions
- Drives higher power requirement, especially since it is a high speed vessel

Regulatory Design Basis

Principle regulation governing the design of the vessel:

- **46 CFR Subchapter T – Small Passenger Vessels**

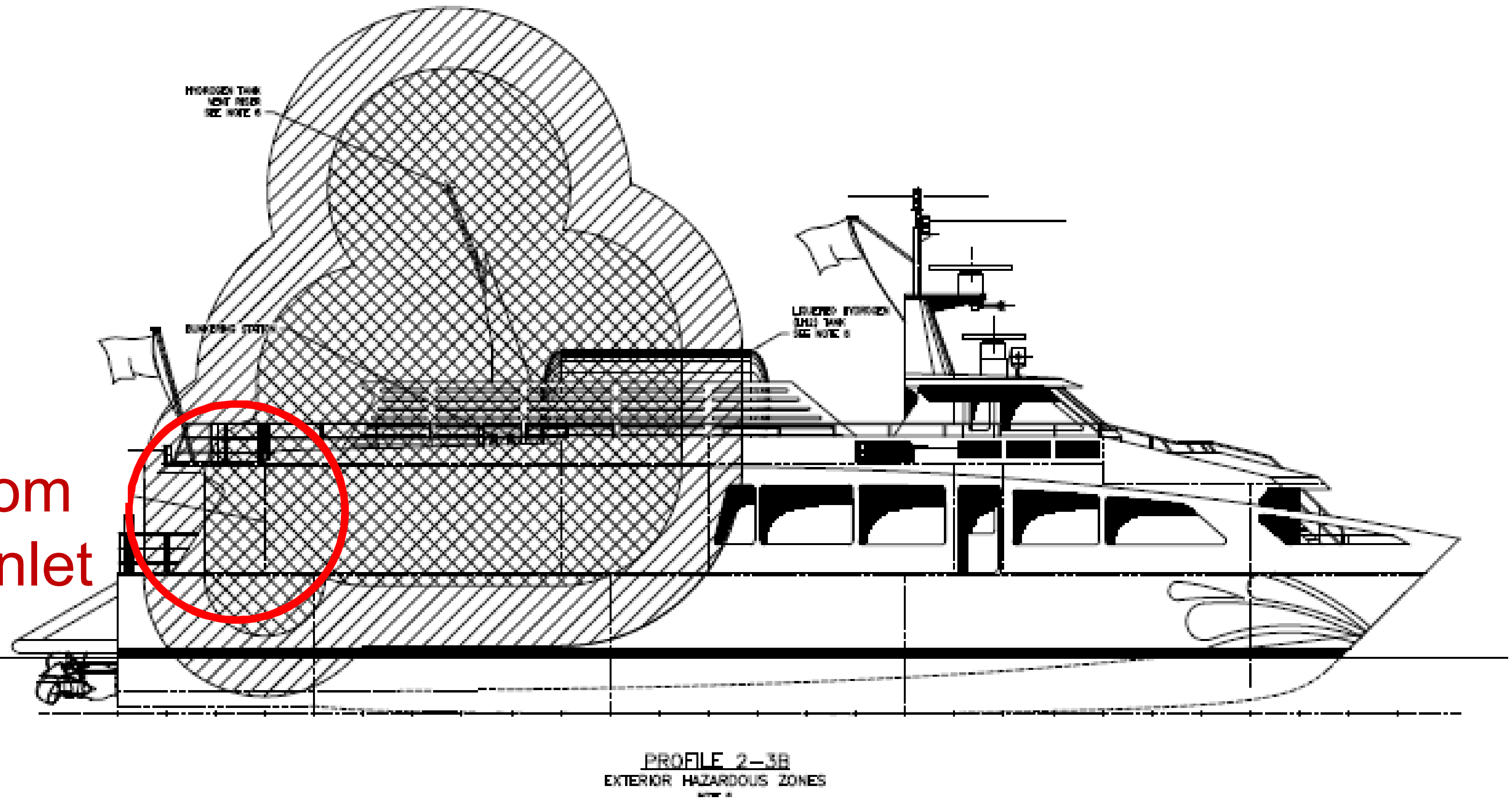
Other documents are used as guidance, since no official regulations yet exist which specifically apply to a hydrogen powered, high speed, aluminum ferry.

- **IMO MSC 95/22/Add.1 (Adopted IGF Code)**
- IMO CCC 2/3/1 (IGF Code with Fuel Cell Additions)
- ABS Guide for Propulsion and Auxiliary Systems for Gas Fueled Ships
- ABS Rules for Building and Classing High-Speed Craft
- IEC 60092-502 Electrical Installations on Ships
- IEC 60079-10 Electrical Apparatus for Explosive Gas Atmospheres
- 46 CFR Subchapter J – Electrical Engineering
- 46 CFR Subchapter F – Marine Engineering
- ASME B31.12 Hydrogen Piping and Pipelines
- ANSI/CSA America FC1-2004 Stationary Fuel Cell Power Systems

Hazardous Zones Philosophy

- Based on guidance for LNG in IGF code
  - USCG recommendation
  - Comparison of LH_2 and LNG Properties With a Focus on Safety – Sandia
- Emergency Shut Down (ESD) arrangement
  - Two independent fuel cell rooms provide redundancy
- LH_2 tank and fuel delivery components located on open deck
- Bunkering station located on open deck

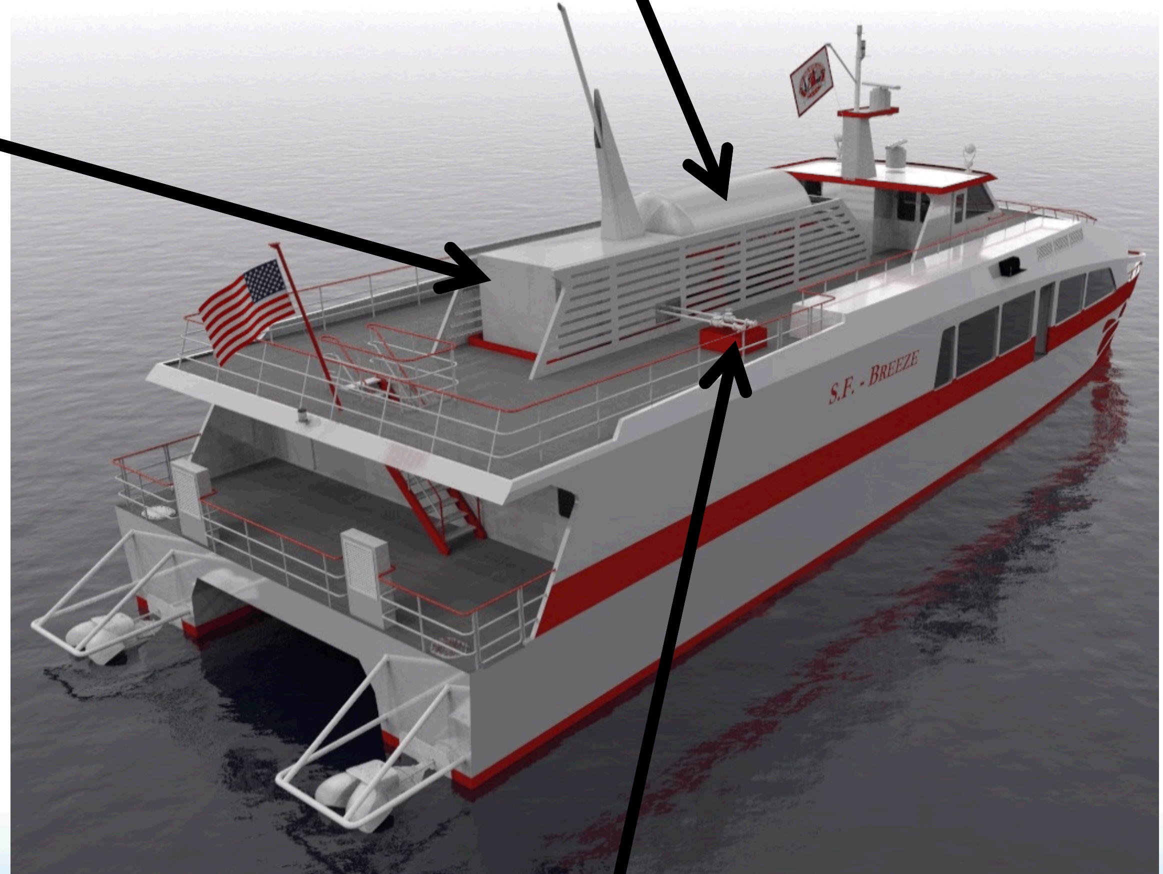
Example proposed Exception: Hazardous Zones



Fuel cell room ventilation inlet location in conflict with IGF 13.3.5

Based on the buoyant and evaporative properties of hydrogen, it isn't practical for the hazardous zones from equipment on the upper deck to extend down to the main deck.

SF-BREEZE Fueling Characteristics



Refueling process will be similar to LNG bunkering

(1) Shoreside storage tank (or refuel directly from truck).

(2) Piping and connecting the fueling arm

(3) Transferring the fuel

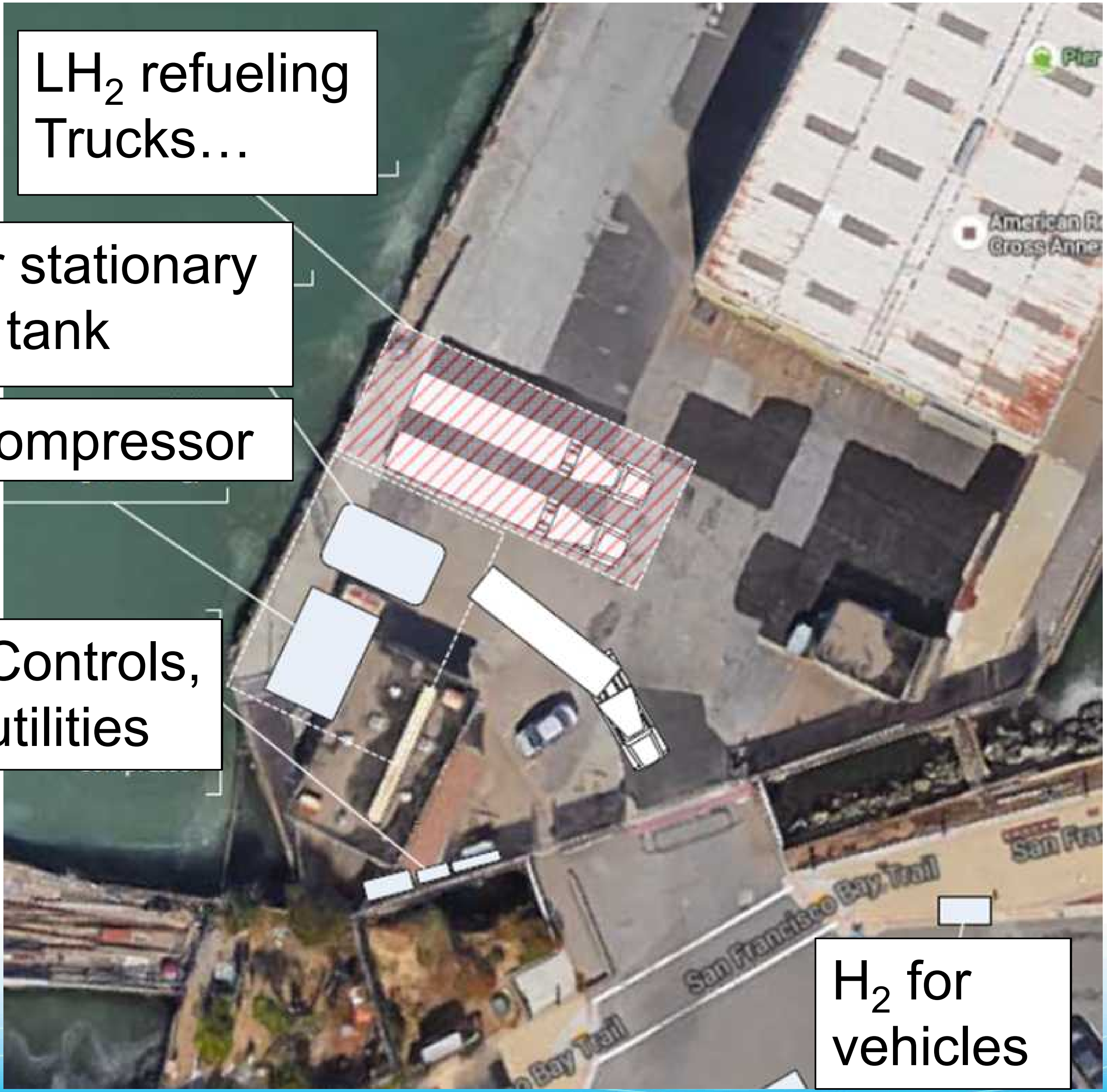
(4) Underway

See complete video at: youtu.be/oZWuTWtp5Rs

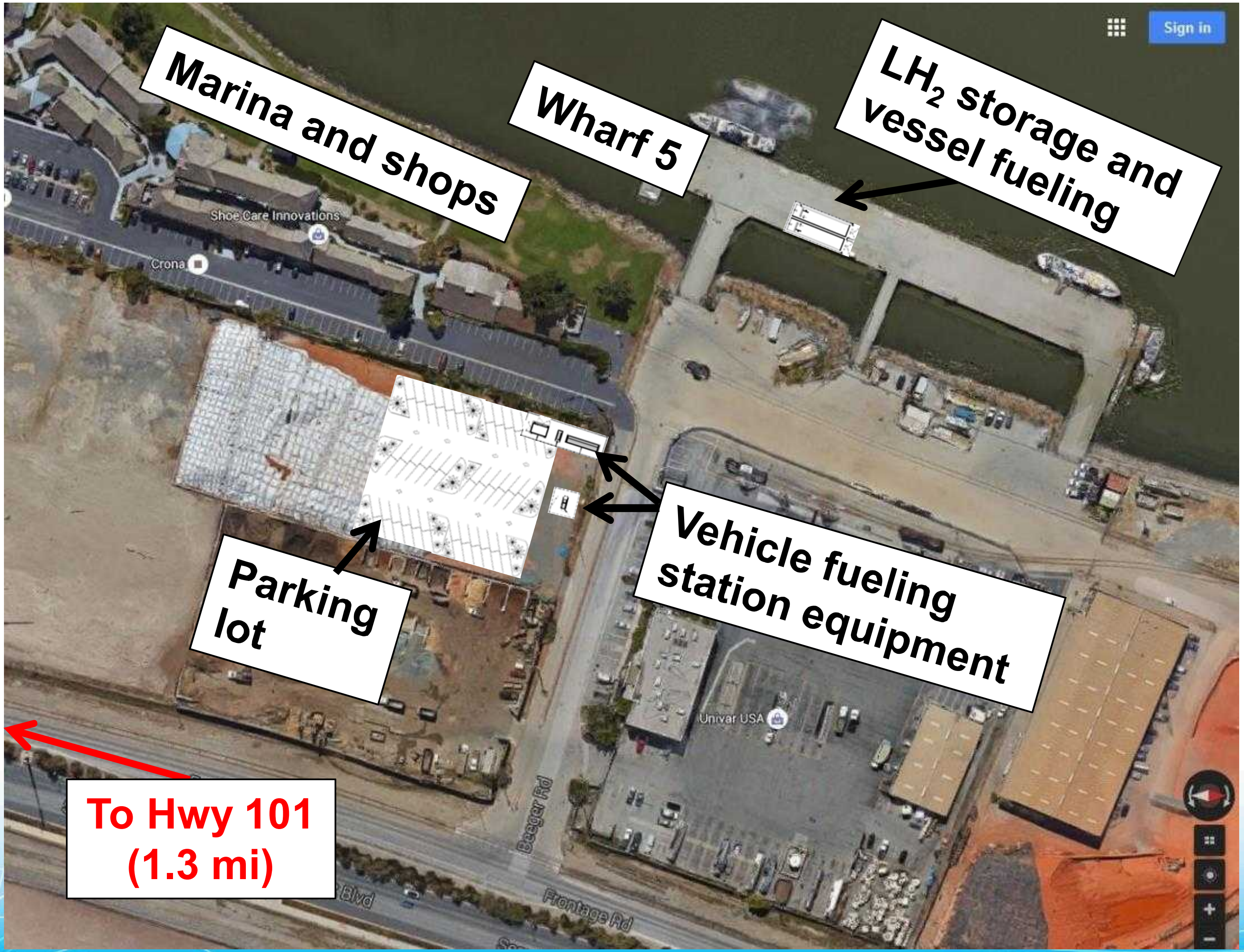
Important difference between LH_2 and LNG:
<u>Hydrogen is non-toxic and is not a greenhouse gas.</u> If vented or spilled it quickly and completely evaporates with no harm to personnel or the environment.

The Port of San Francisco prefers Pier 54 for fueling both the SF-BREEZE and fuel cell electric vehicles.

A viable hydrogen fueling complex designed by Linde at the Port of San Francisco



The Port of Redwood City identified Wharf 5 and nearby lots as ideal for fueling vessels and vehicles.



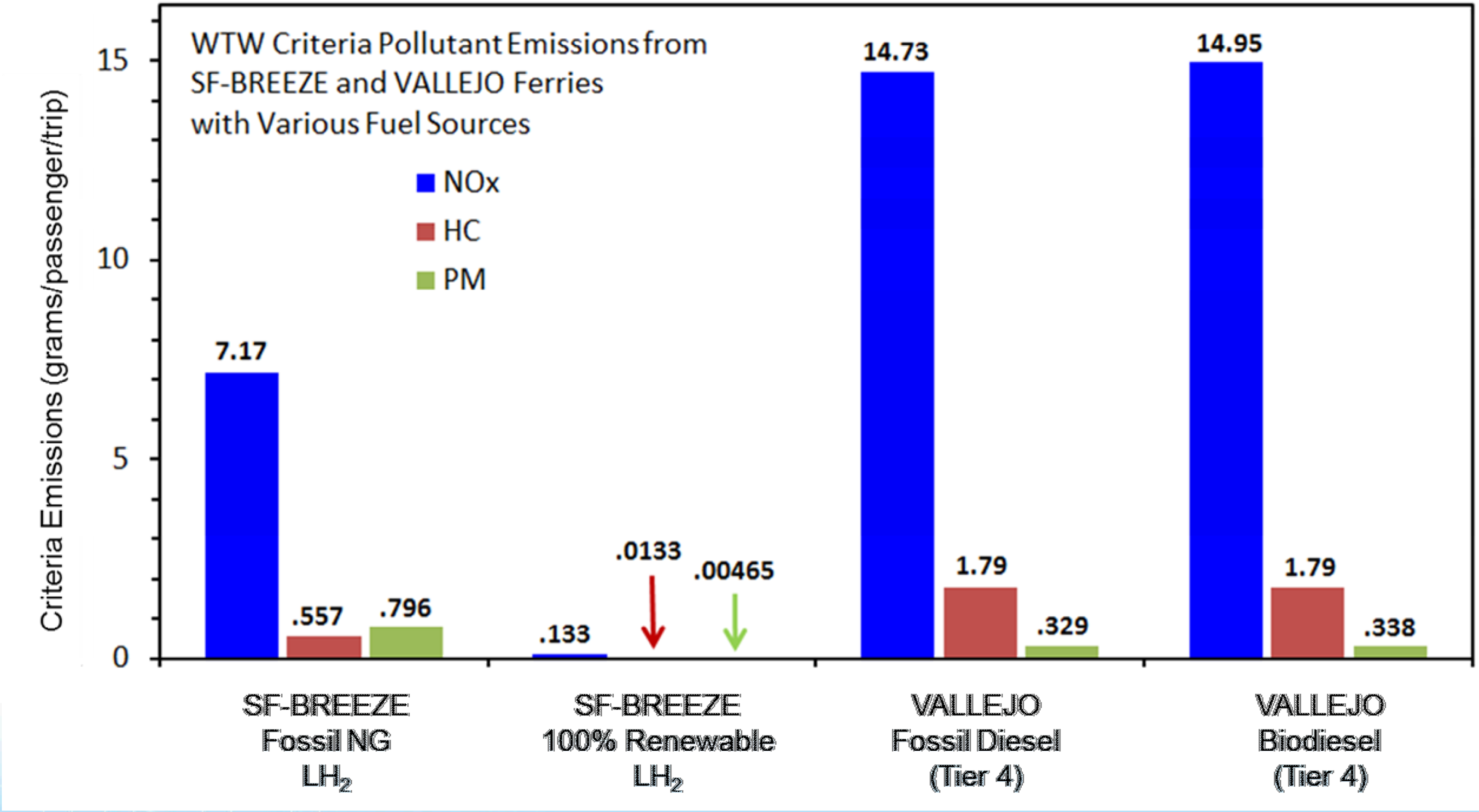
Air Emissions: Analysis, with comparison to the existing, similar sized ferry on the same route

SF-BREEZE
Top Speed: 35 knots
Power Plant: PEM fuel cells
Fuel: Liquid Hydrogen
Passenger Capacity: 150

Vallejo
Top Speed: 35 knots
Power Plant: Diesel engine
Fuel: Ultra low sulfur diesel
Passenger Capacity: 300

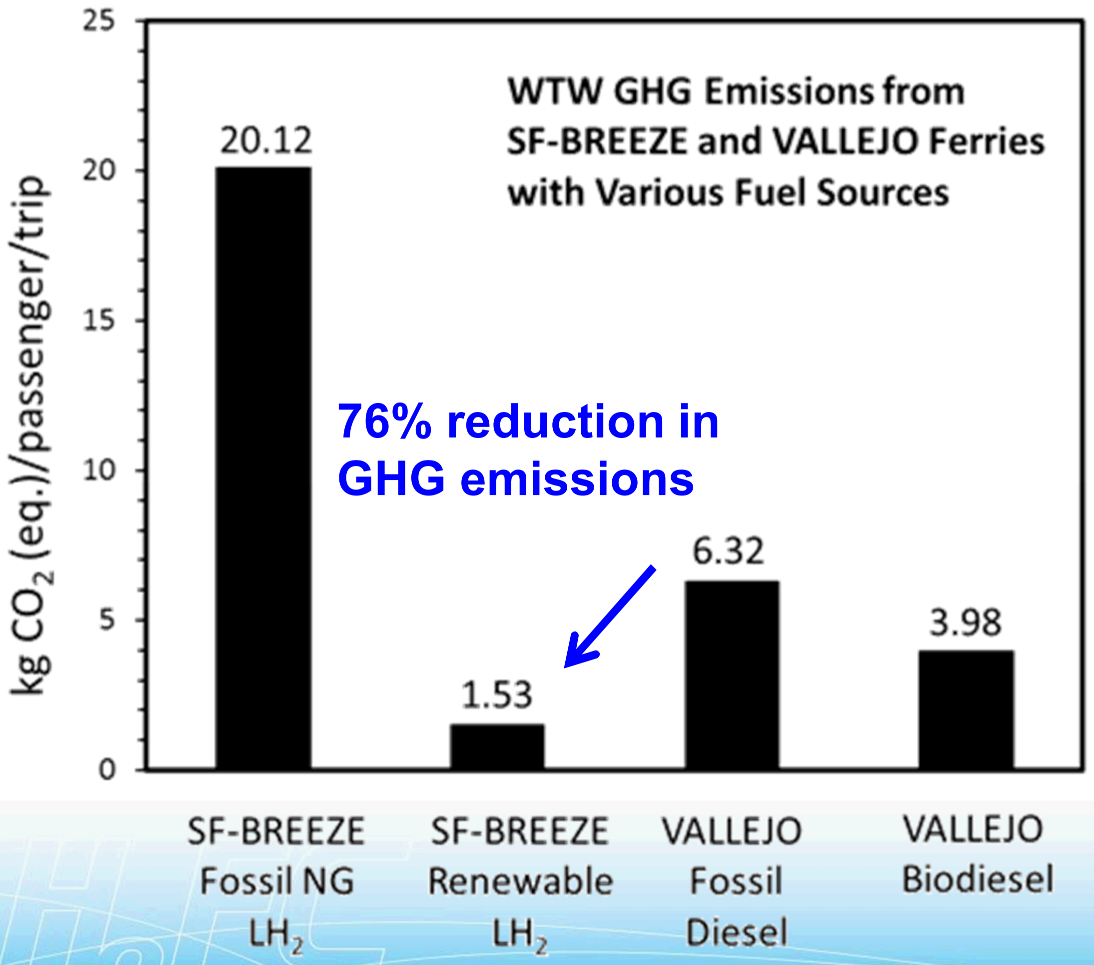
For this comparision, assume a "new-build" Vallejo diesel vessel held to Tier 4 criteria pollutant emission constraints.

The SF-BREEZE drastically reduces "Well-to-Waves" pollutant emissions compared to the most advanced (Tier 4) marine diesel ferries.



The SF-BREEZE has zero criteria pollutant emissions at the point of use

SF-BREEZE can achieve dramatic Well-to-Waves greenhouse gas (GHG) reduction with *renewable* LH_2



All SF-BREEZE emissions are due to the LH_2 production path; the SF-BREEZE is zero emission at the point of use

Renewable liquid hydrogen is available

Renewable methane

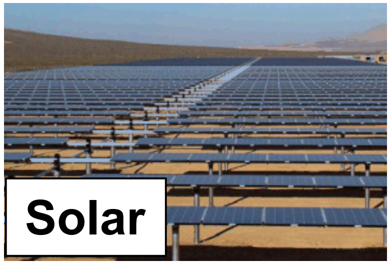
→ Reformation

H_2 ↓

Liquefaction → Renewable liquid hydrogen

H_2 ↑

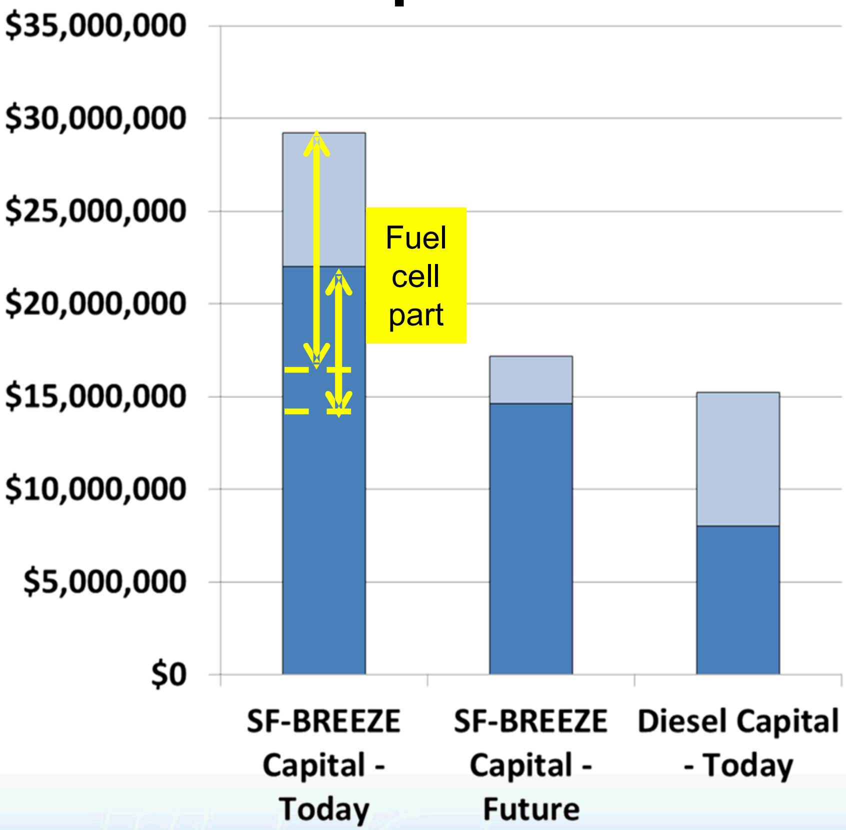
Renewable electricity



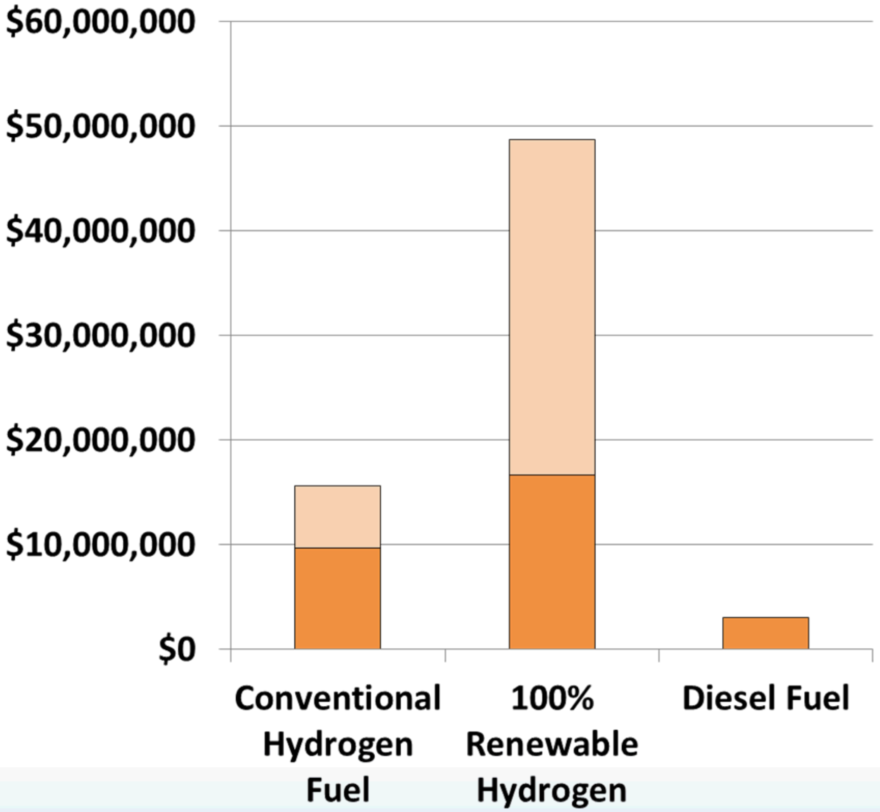
→ Electrolysis

The costs are currently higher than diesel with projected cost decreases ahead

Capital Cost



5-Year Fuel Cost

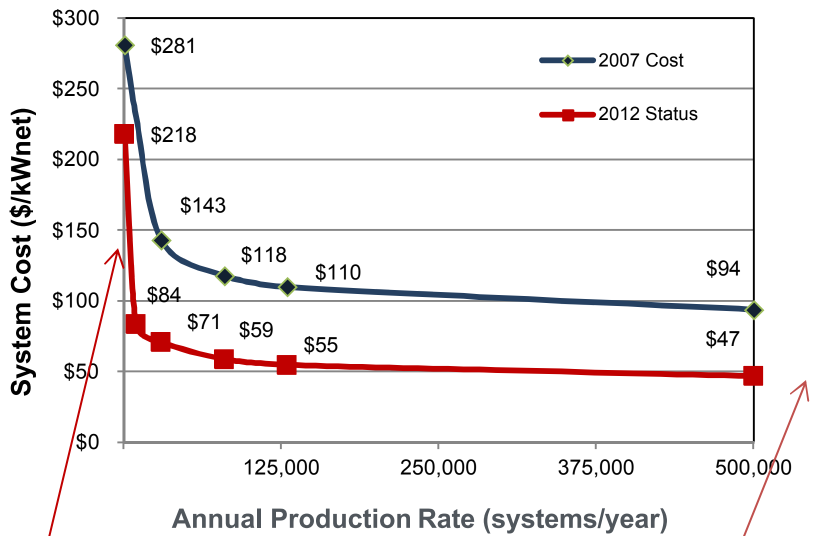


The decreased health risks and lower environmental impact saves our region **$2.6M - $11M** for each SF-BREEZE ferry built instead of a Tier 4 diesel ferry.

PEM fuel cell costs will come down as they are deployed in automobiles and elsewhere

Cost of Automotive PEM Fuel Cells*

Projected Costs at Different Manufacturing Rates



**Based on state-of-the-art lab scale technology projection to high-volume manufacturing (500,000 units/year).- Strategic Analysis*

Estimated cost of a 120 kW module today: **$2,500/kW** → Estimated cost of 100-1,000 units in 3 years: **$1,000/kW** → Longer term cost: **$100-$200/kW** for auto PEM fuel cell at 10,000 units year → Long term DOE high-volume cost target: **$30/kW**

Customers are already willing to pay more for zero emission fuel cell technology

Toyota Camry (gasoline engine)
MSRP: ~$25,000
Fuel price: ~$2.80/gallon

Lease: $259/mo
Fuel price: ~$2.80/gallon

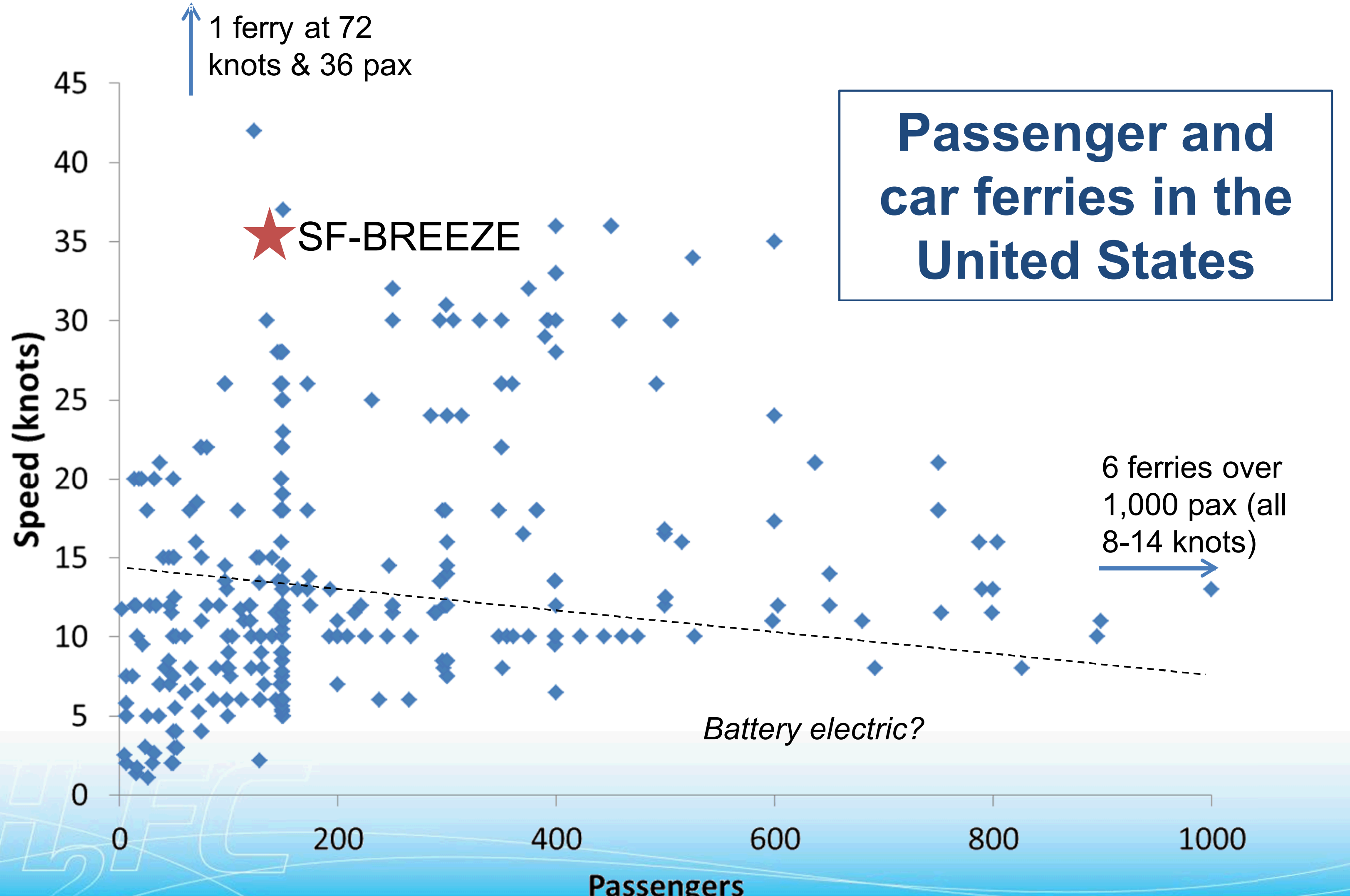
Toyota Mirai (H_2 Fuel Cell)
MSRP: $45,000 (after gov't incentives)
Fuel price: $10-$14/kg*

Lease: $349/mo
Fuel price: included for 3 yrs

What cost premium is allowable for consumer acceptance?

*only half the hydrogen is needed for the same range because a fuel cell is ~2-times more efficient than a gasoline engine

Optimization: What is the best type of zero emission ferry to build today?



Summary

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

Next Steps

Six project phases

Phase 1: Feasibility study (complete)*

Phase 2: Optimization of the vessel (underway)*

Phase 3: Detailed design of the H_2 ferry and station

Phase 4: Build the H_2 ferry and station

Phase 5: Operate the H_2 ferry and station

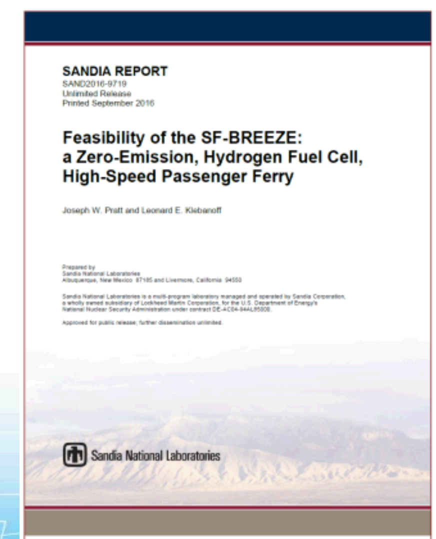
Phase 6: Extend to H_2 cars, buses and trucks

*Phases 1 and 2 funded by US DOT / Maritime Administration

Thank you!

SF-BREEZE Feasibility Study Final Report - Download from: **maritime.sandia.gov**

- All ferry design documents and drawings
- LH_2 fuel assessment (with comparison to LNG)
- Emissions
- Regulations
- Bunkering
- Economics


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

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.

Sandia National Laboratories

Sandia

Joe Pratt

(925) 294-2133

jwpratt@sandia.gov

Red and White Fleet

Joe Burgard

(415) 901-5248

jburgard@redandwhite.com

Elliott Bay Design Group

Curt Leffers

(206) 204-1346

cleffers@ebdg.com