SAND2020-4618PE

Assessing safety requirements for hydrogen fuel cell use in maritime applications using computational fluid dynamics

Myra Blaylock, Ph. D.

Sandia National Laboratories

UC Davis Seminar Series

April 30, 2020

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and 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. SAND No. 2020-

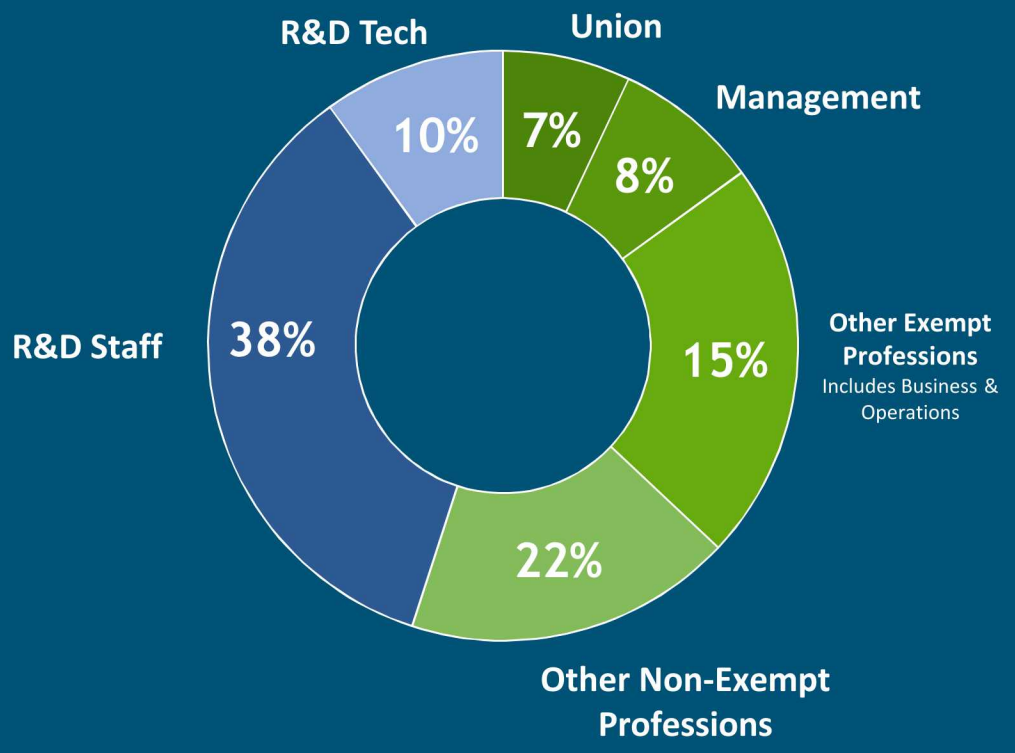
17 U.S. National Laboratories

Our Workforce ~14,100 employees

~12,300 Regular employees
~1,800 Temporary employees, students & postdoctoral appointees

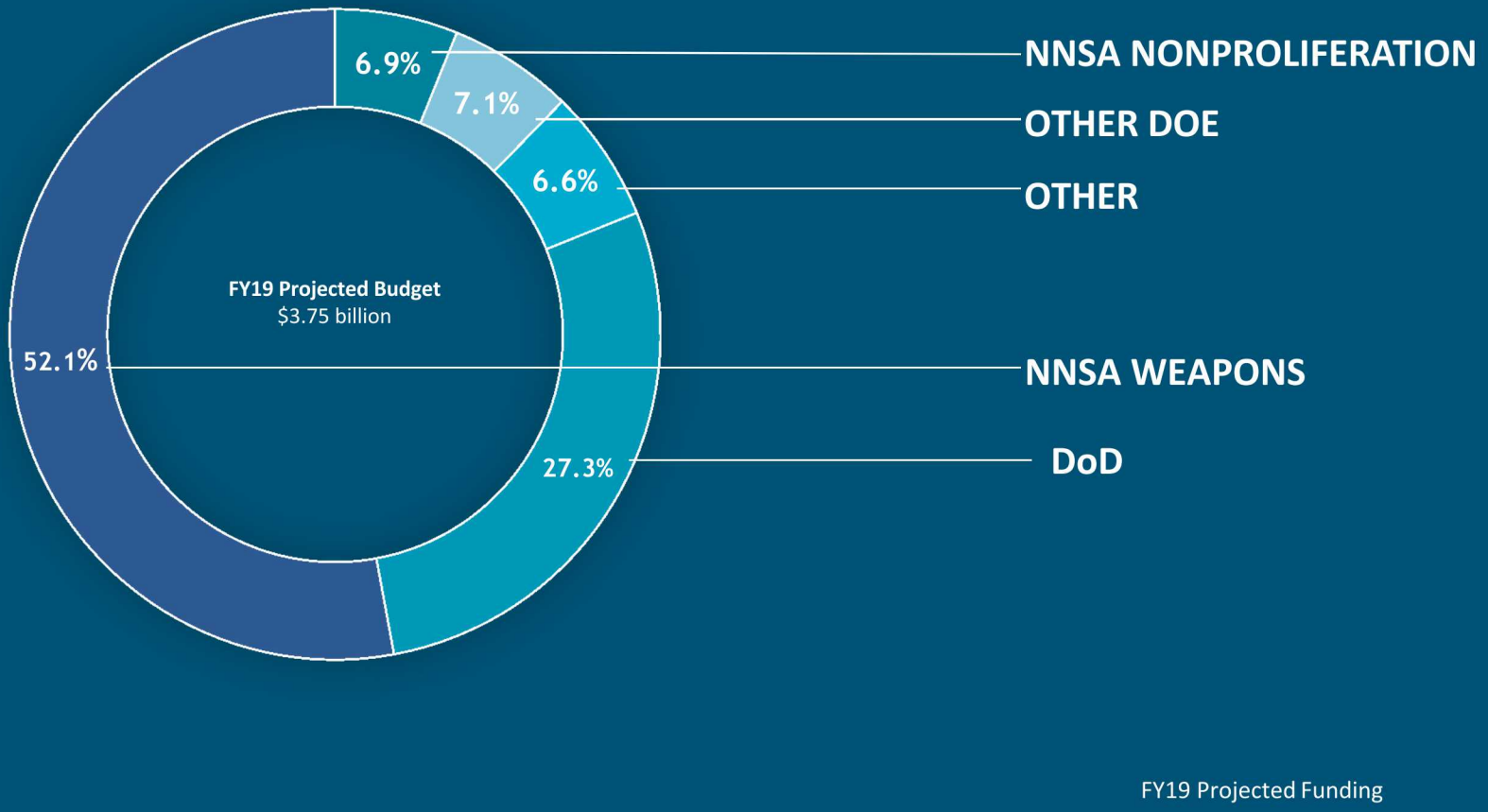
New Mexico Site: *(see breakout)*
Workforce: ~12,500
R&D employees: ~4,200
(R&D Staff & Technologists)

California Site: *(see breakout)*
Workforce : ~1,600
R&D employees: ~650
(R&D Staff & Technologists)



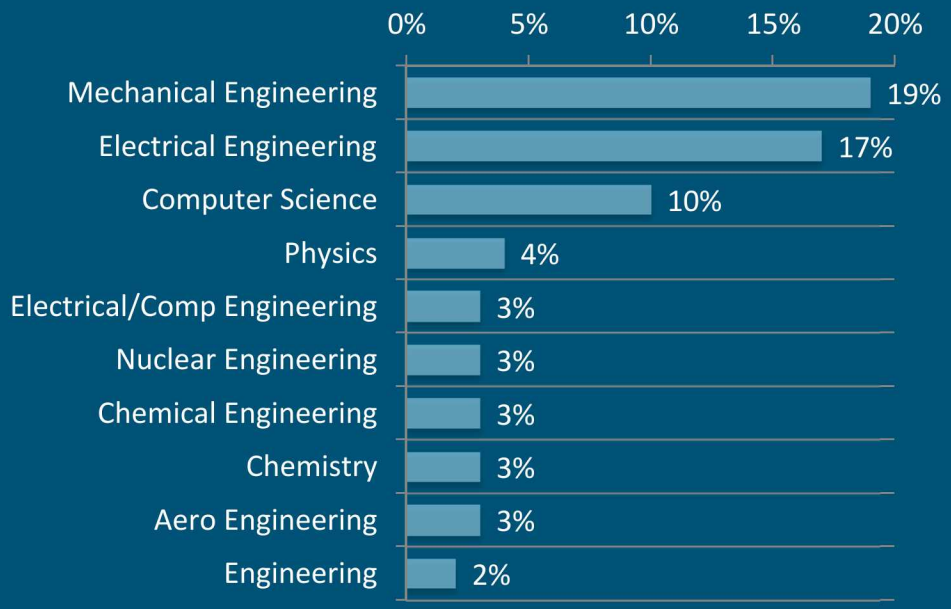
Data as of July 2019

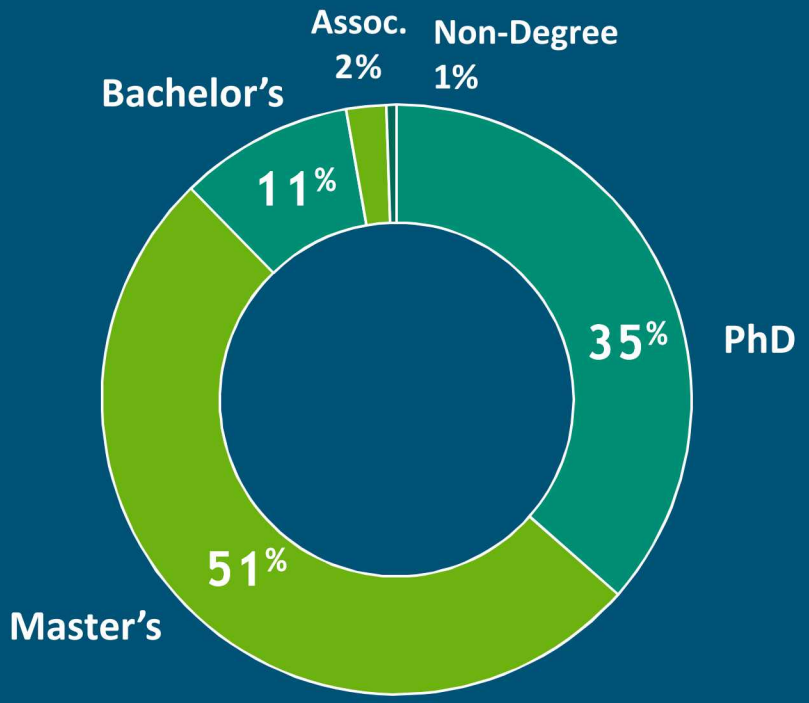
Sandia's Funding ~ $3.75 Billion



FY19 Projected Funding

R&D by Discipline & Degree



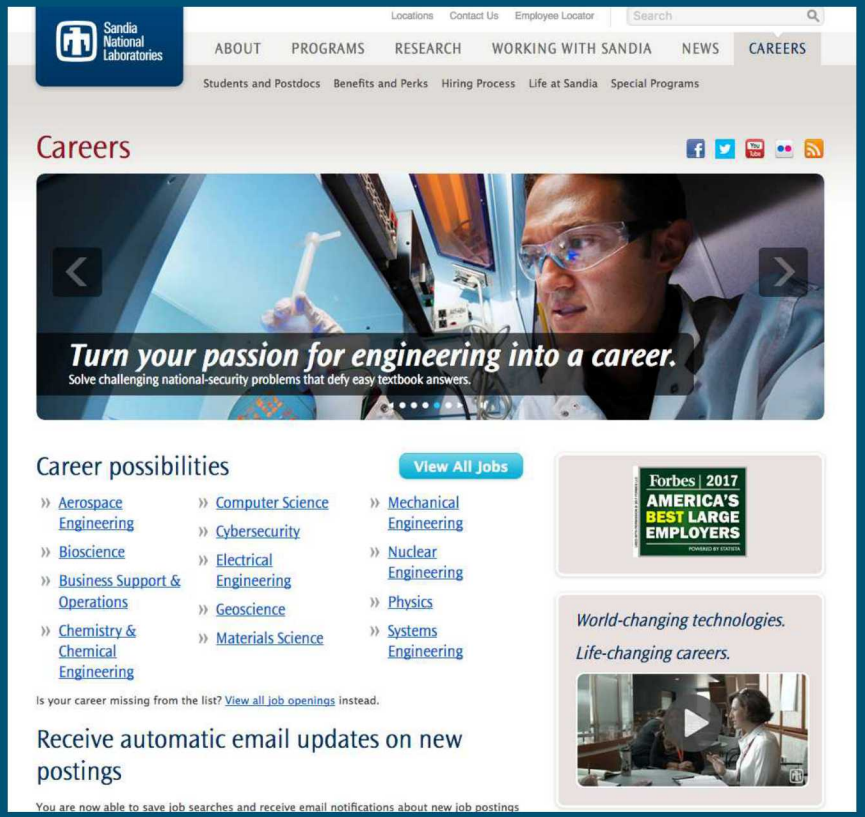


Top 10 job descriptions shown, Regular exempt non-management employees only

Data as of July 2019

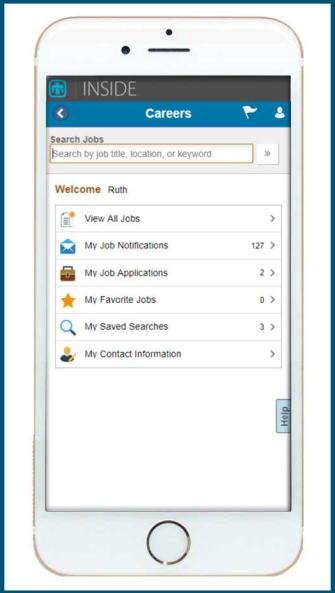
Apply Online! sandia.gov/careers

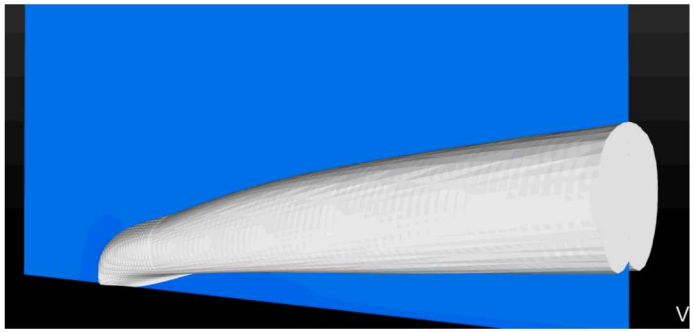
Internships, Post Docs, Fellowships, Full Time Staff

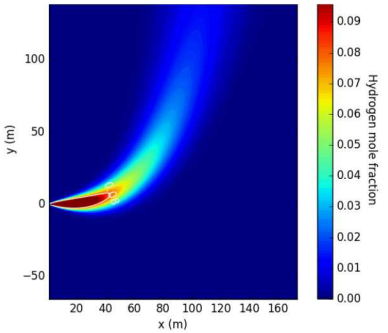


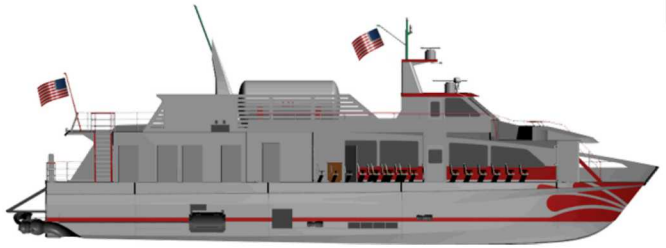
Sign up for Automated Job Notifications!

Mobile Job Applications







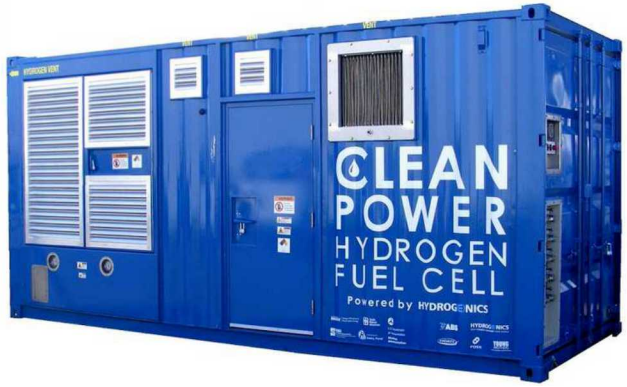


Informing Hazardous Zones for On-Board Hydrogen Liquid and Gas Systems

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and 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. SAND No. 2020-

Sandia's *Zero Emission Maritime* Program

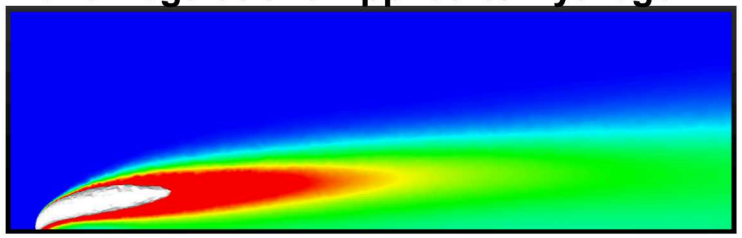
Maritime Hydrogen Fuel Cell Project (MarFC)



San Francisco Bay Renewable Energy Electric vessel with Zero Emissions (SF-BREEZE)

Zero Emissions Research Oceanographic Vessel (ZERO/V)

IMO code development Examination of Maritime Hazardous Zone Regulations Applied to Hydrogen



And more…

Visit: maritime.sandia.gov

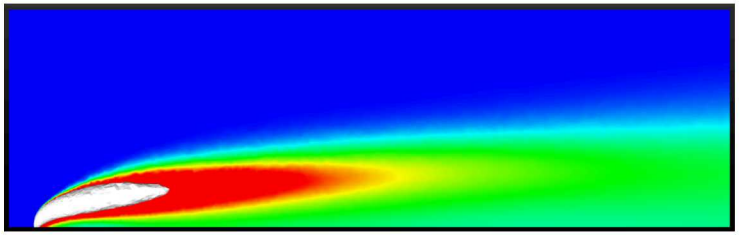
Project Scope

- SF-BREEZE Feasibility Study
  - Why H2
  - Initial design

- Gas Dispersion Analysis
  1. Abnormal Blowdown from LH_2 Tank
  2. Normal “Boil-off”
  3. Leak in Fuel Cell Room

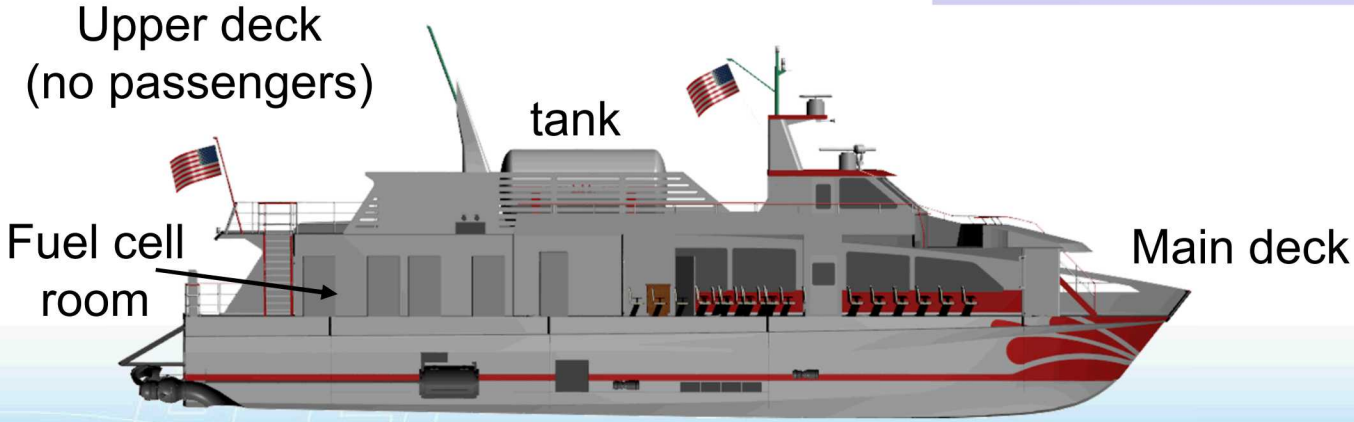
San Francisco Bay Renewable Energy Electric vessel with Zero Emissions (SF-BREEZE)

Examination of Maritime Hazardous Zone Regulations Applied to Hydrogen



SF-BREEZE by the numbers

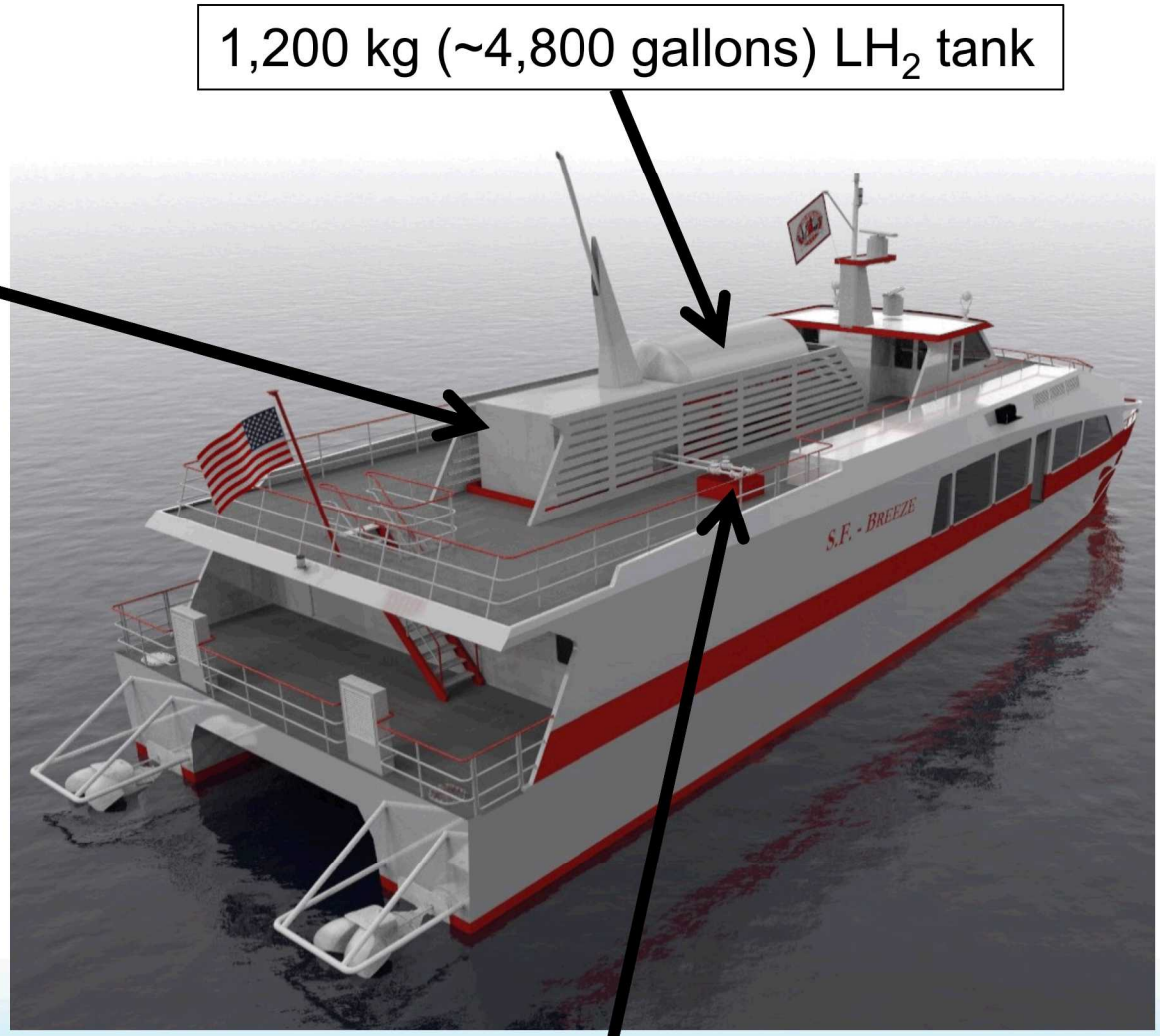
- Length 109’ x Beam 33’ x Depth 11.25’
- Passengers: 150
- Service Speed: 35 knots
- Passenger Cabin Forward, Fuel Cells Aft



Water jet and electric motors (no H_2 in the hulls)

Elliott Bay Design Group

SF-BREEZE Fueling Characteristics



Each round trip uses about **400 kg** of LH_2

Red and White Fleet

- Founded in 1892
- Offers over 5,000 sightseeing trips/yr under the Golden Gate Bridge.
- Fleet: 4 passenger vessels, steel mono hulls, 350 to 600 passengers
- Run 6 Tier III engines and 10 Tier II engines across their fleet to provide a service with the highest level of environmental responsibility
- In 2014, Mr. Escher made a commitment to providing their services on a **zero emission vessel**

A comprehensive regulatory assessment was performed by all partners.

USCG:

- Office of Design and Engineering Standards
- Marine Safety Center
- Sector San Francisco
- Liquid Gas Carrier National Center of Expertise

American Bureau of Shipping

Elliott Bay Design Group

Sandia National Labs

MARAD

Red and White Fleet

Findings:

- No regulatory show-stoppers
- 62 of 68 design aspects found covered by design basis documents
- *Gas dispersion analyses required for suggested hazardous zone exceptions*

H_2 Fuel Cell Ferry In Production!

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

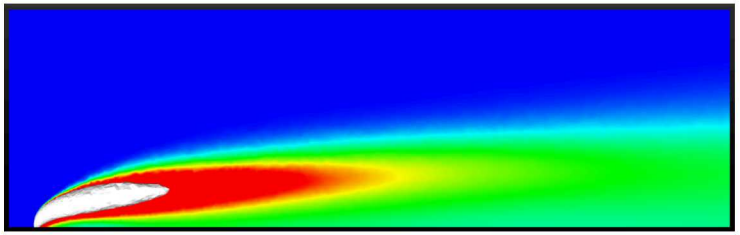
Project Scope

- SF-BREEZE Feasibility Study
  - Why H2
  - Initial design

- **Gas Dispersion Analysis**
  1. Abnormal Blowdown from LH_2 Tank
  2. Normal "Boil-off"
  3. Leak in Fuel Cell Room

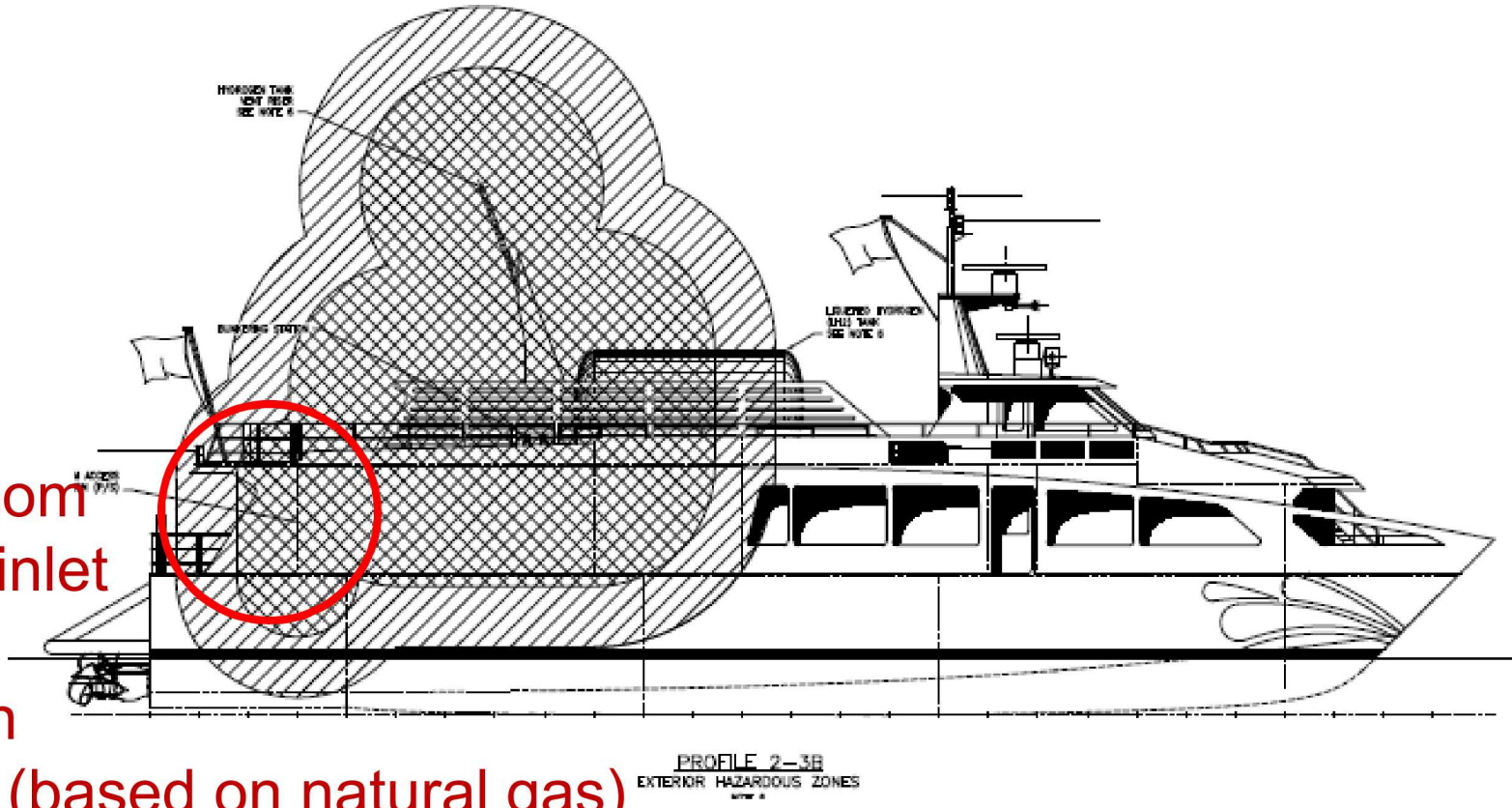
San Francisco Bay Renewable Energy Electric vessel with Zero Emissions (SF-BREEZE)

Examination of Maritime Hazardous Zone Regulations Applied to Hydrogen



Example hazardous zone exception

Hydrogen

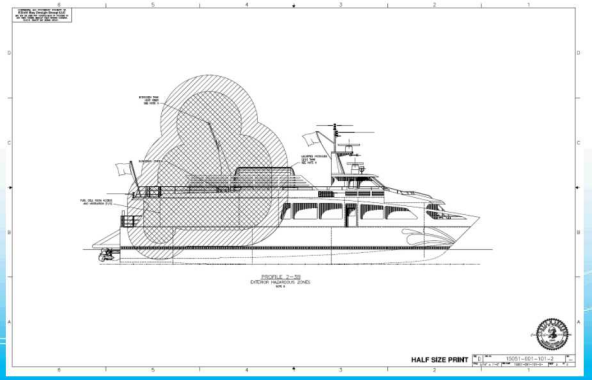


Fuel cell room ventilation inlet location in conflict with IGF 13.3.5 (based on natural gas)

- Qualitatively, it appears that the high buoyancy of hydrogen precludes the need for a hazardous zone to extend lower than the elevation of release.
- Quantitative gas dispersion analysis is required for Class and Flag approval.

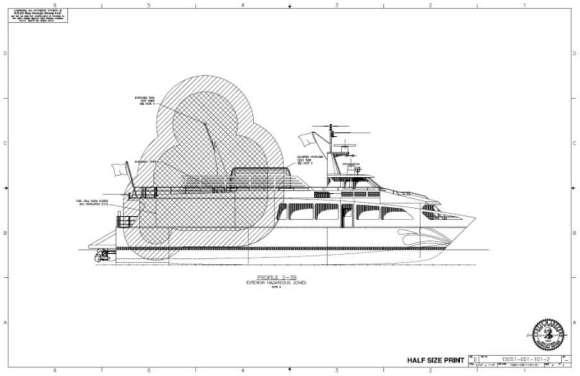
Gas Dispersion Analysis

- Goal
  - Inform accurate overall hazardous zone requirements for hydrogen
- 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
- Approach
  - Define most significant leak scenarios with stakeholders: US Coast Guard, American Bureau of Shipping, DNV-GL
  - Perform detailed modeling of these initial scenarios



Gas Dispersion Analysis for H_2 Release Scenarios

1. Abnormal Blowdown from LH_2 Tank
   - Are the Hazardous Zones in the right place?
   - Maximum release
   - Wind speeds:
     - 0 knots – calm day at docks
     - 5 knots – normal wind at docks
     - 30 knots – moving or very windy at docks
2. Normal "Boil-off"
   - Release pressure due to normal heating
3. Leak in Fuel Cell Room
   - Concerned about ventilation, overpressure and fire.
   - Sensors will shut off supply quickly



©Hydrogenics Corp.

Computational Fluid Dynamics (CFD)

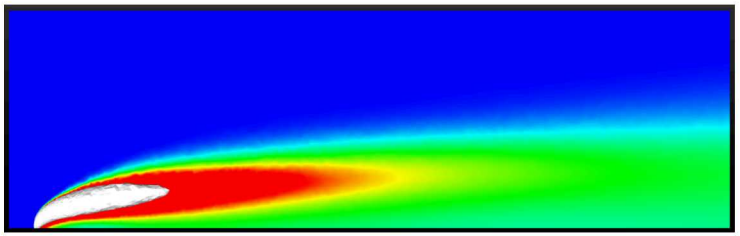
- Sandia's Sierra Suite: Fuego – incompressible flow solver
  - Reynolds' Averaged Navier-Stokes (RANS)
  - Small scale turbulence is averaged, so **dissipation is under predicted**
- Meshes: 60,000-2 million nodes
- HPC : 64 to 160 cores – 10 to 20 days of running
- Wind is assumed **constant laminar flow** for entire length of the release
  - Conservative results, especially for long-length releases and high-wind speeds

Outline

- **Gas Dispersion Analysis**
  1. Abnormal Blowdown from LH_2 Tank
  2. Normal "Boil-off"
  3. Leak in Fuel Cell Room

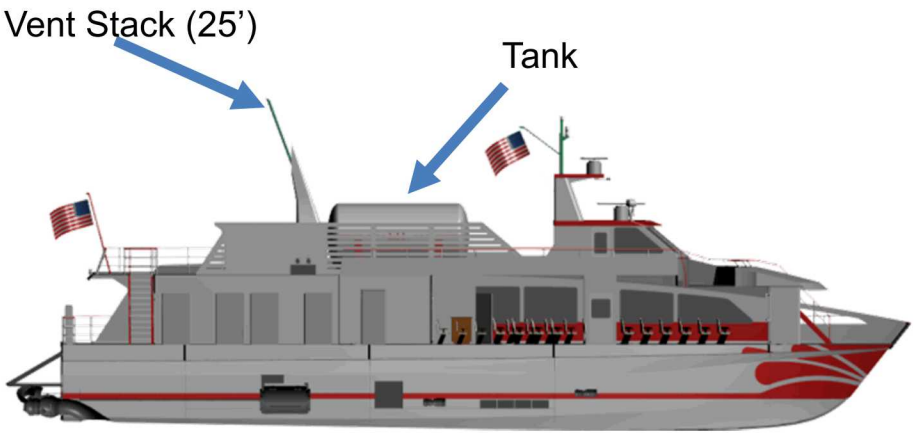
San Francisco Bay Renewable Energy Electric vessel with Zero Emissions (SF-BREEZE)

Examination of Maritime Hazardous Zone Regulations Applied to Hydrogen



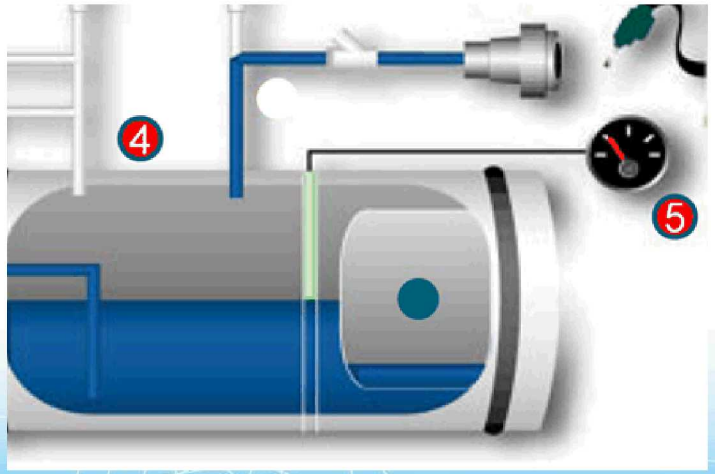
Scenario 1: Abnormal Blowdown Opened Pressure Relief Device from Large LH_2 Tank

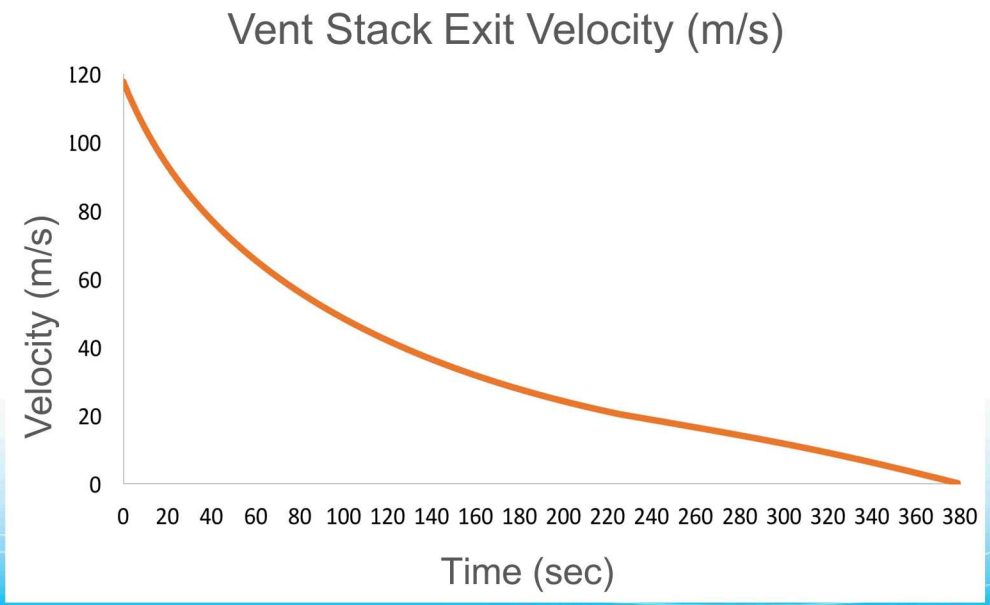
- Full Blowdown of LH_2 tank through a Vent Stack due to valve failure (worst case, not likely)
  - Tank Dimensions
    - 150 PSI
    - ~4500 gallons
    - 1 inch leak through valve
    - ~ 6 minutes to empty
    - 70 K = -203 C at exit
  - Vent Stack
    - ~7 inch internal diameter
    - 25 feet tall (7.5 m)
    - Modeled as straight up



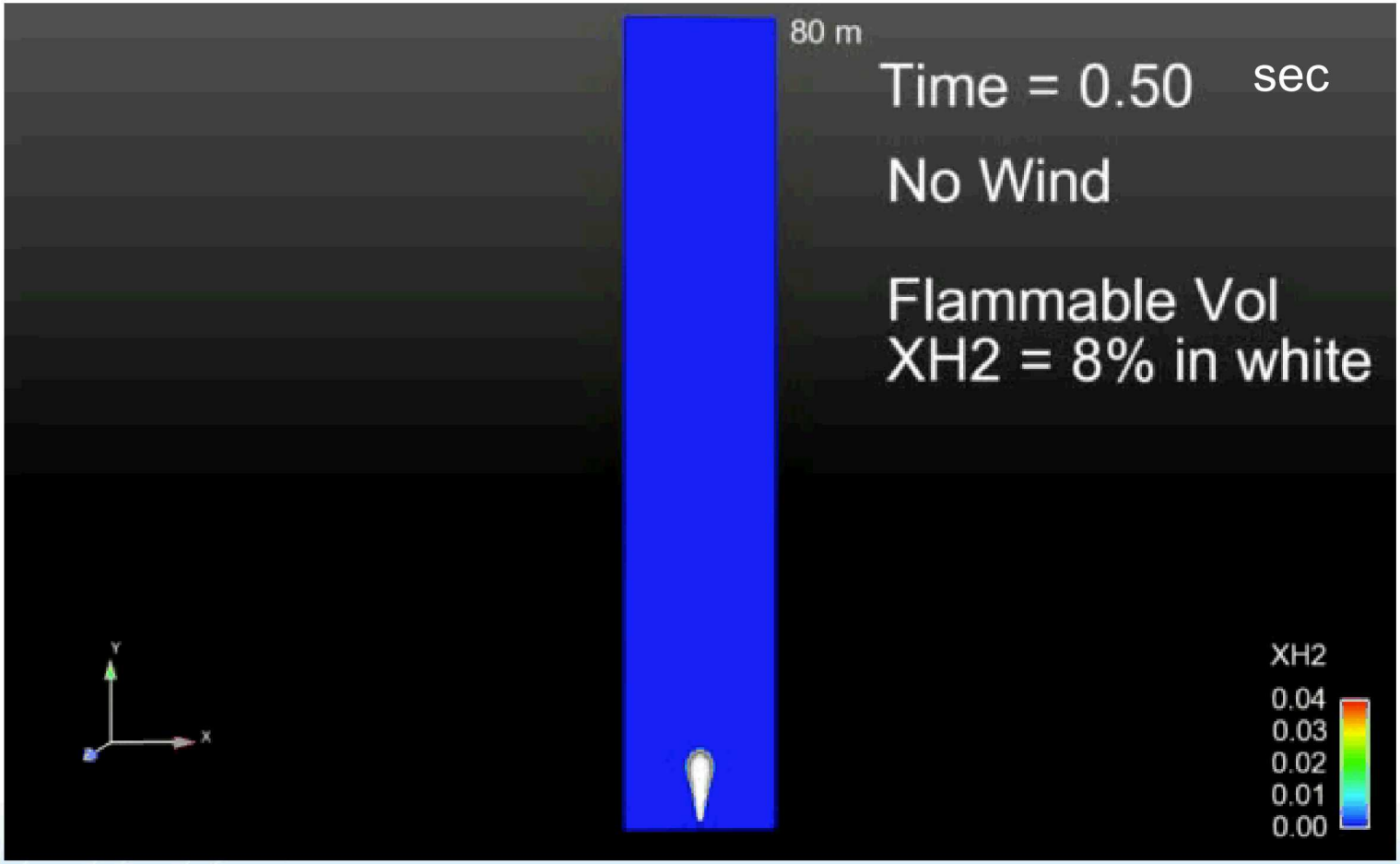
Worst Case: Blowdown when tank is 90% vapor

- Two phases in tank: liquid and vapor
- Leak will dump vapor quickly, then be limited to “boil-off” amounts
  - Only modelled the vapor release
- Biggest H_2 release comes from tank with mostly vapor
  - 10% liquid for cases shown
- Tank empties vapor in ~6 minutes



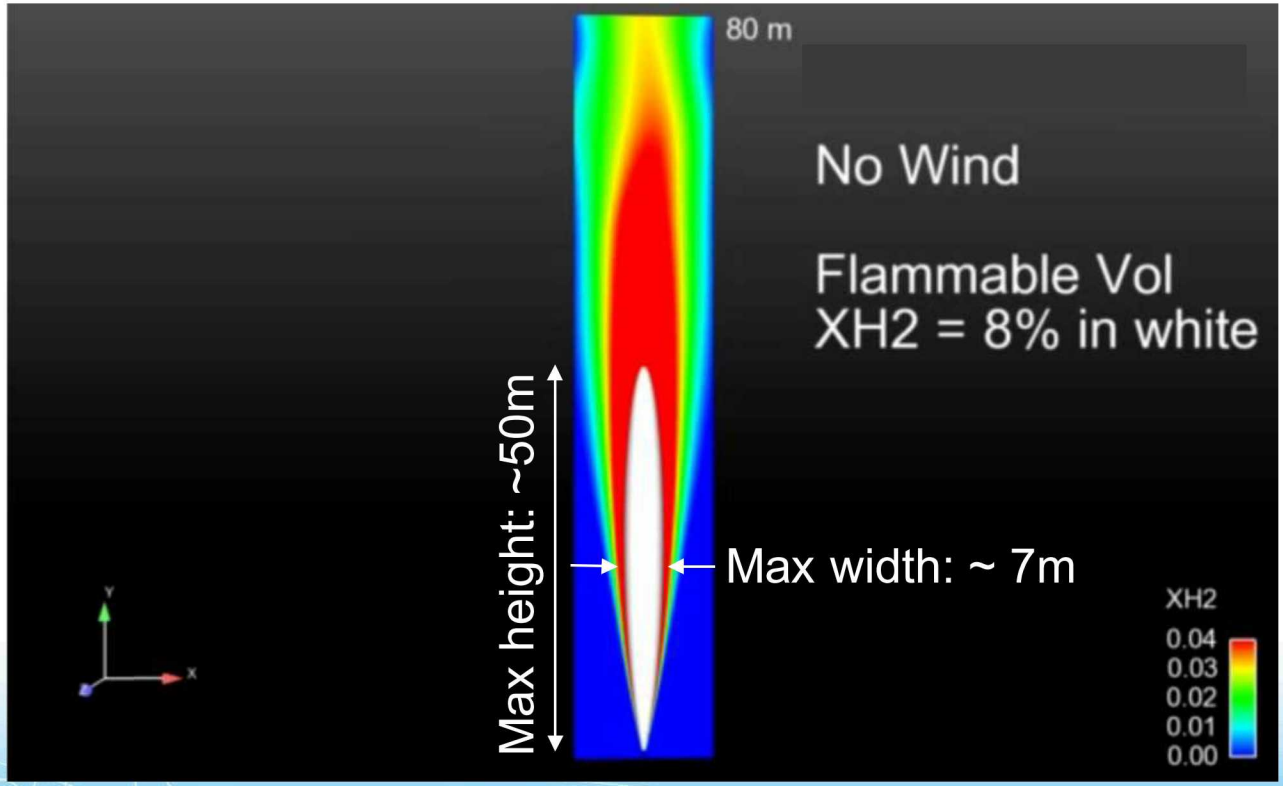


CFD of SF-BREEZE H_2 Release Without Wind



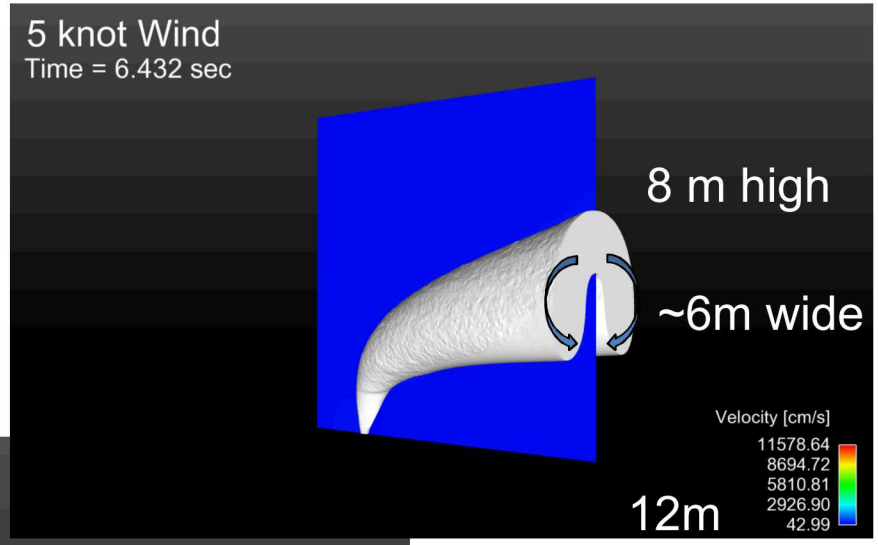
CFD of SF-BREEZE LH_2 Release Without Wind

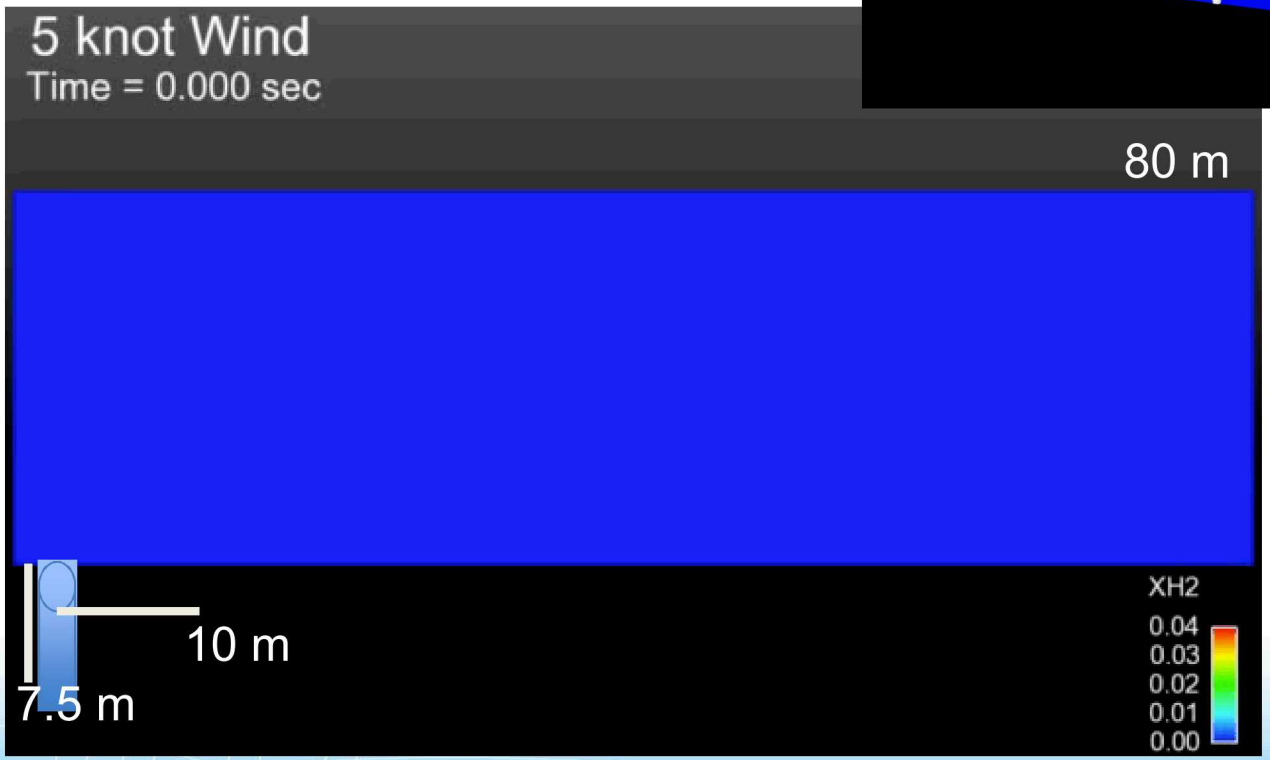
- White shows flammable mass with volumetric concentration between 8%-75%
- Flammable Region Reaches ~50 m high
  - Max Height at about 20 sec



CFD of SF-BREEZE LH_2 Release With 5 knot Wind

- White shows flammable mass with volumetric concentration between 8%-75%

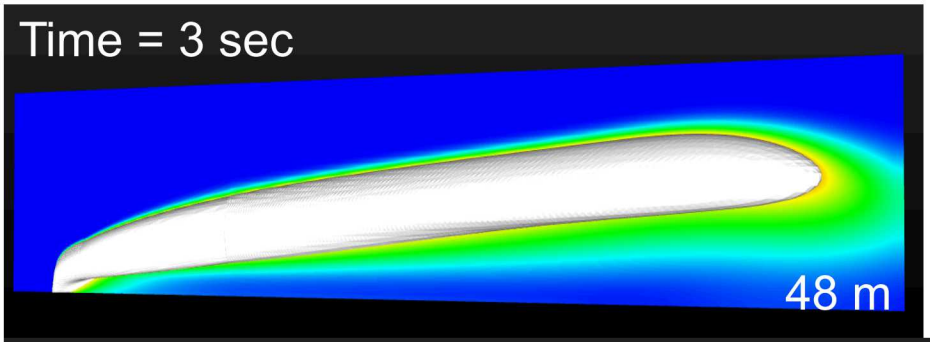


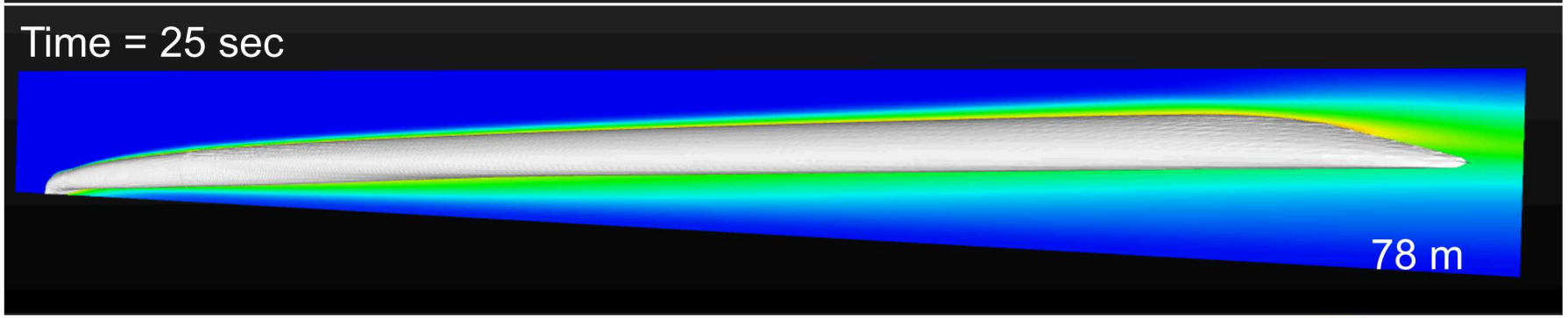


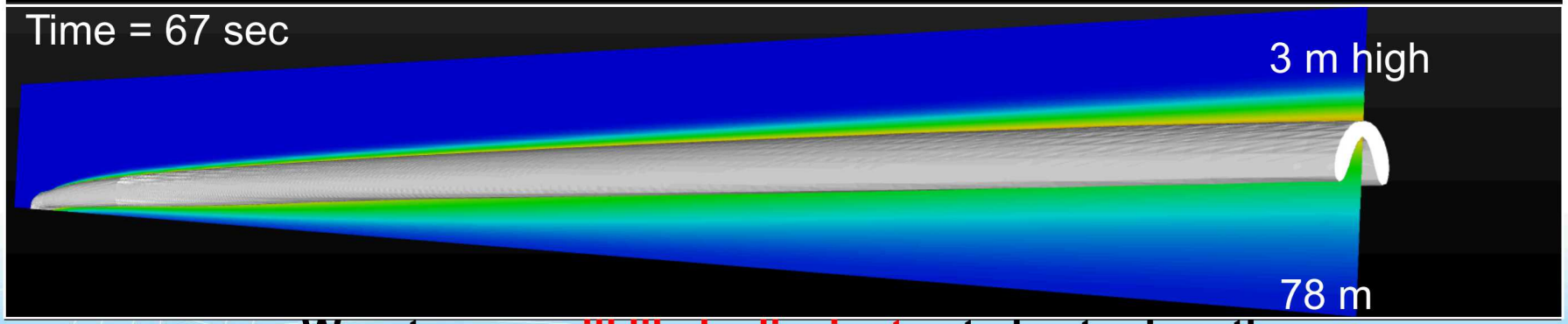
- Jet-in-Crossflow creates counter-rotating vortices
- Light weight H_2 pushed by wind
- Max: 20 m long, 8 m high @ 14 sec

45 m long

CFD of SF-BREEZE LH_2 Release With 30 knot Wind



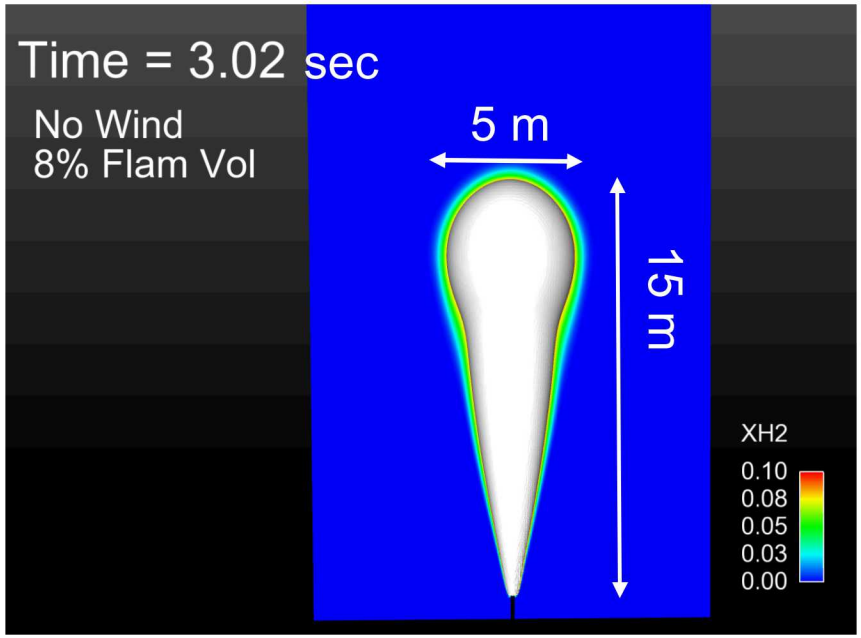


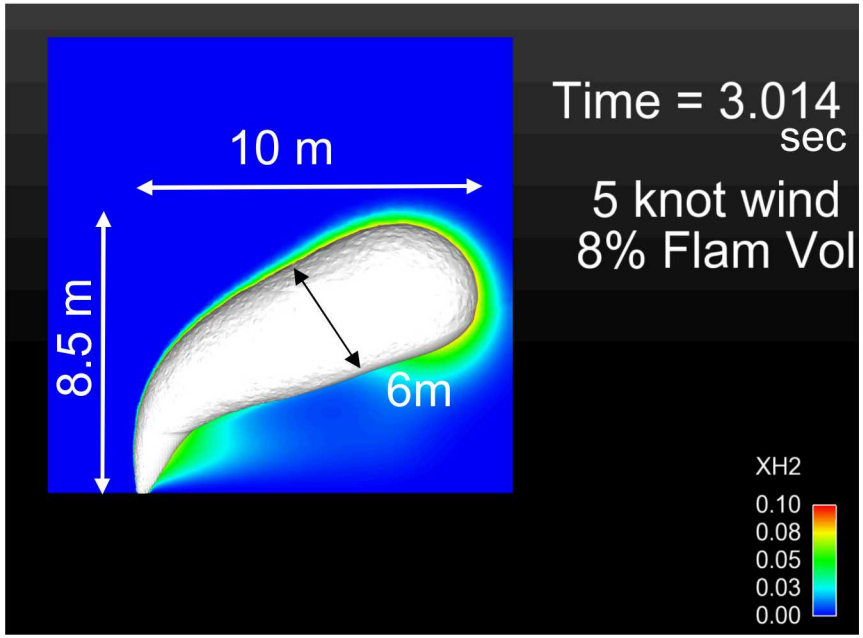


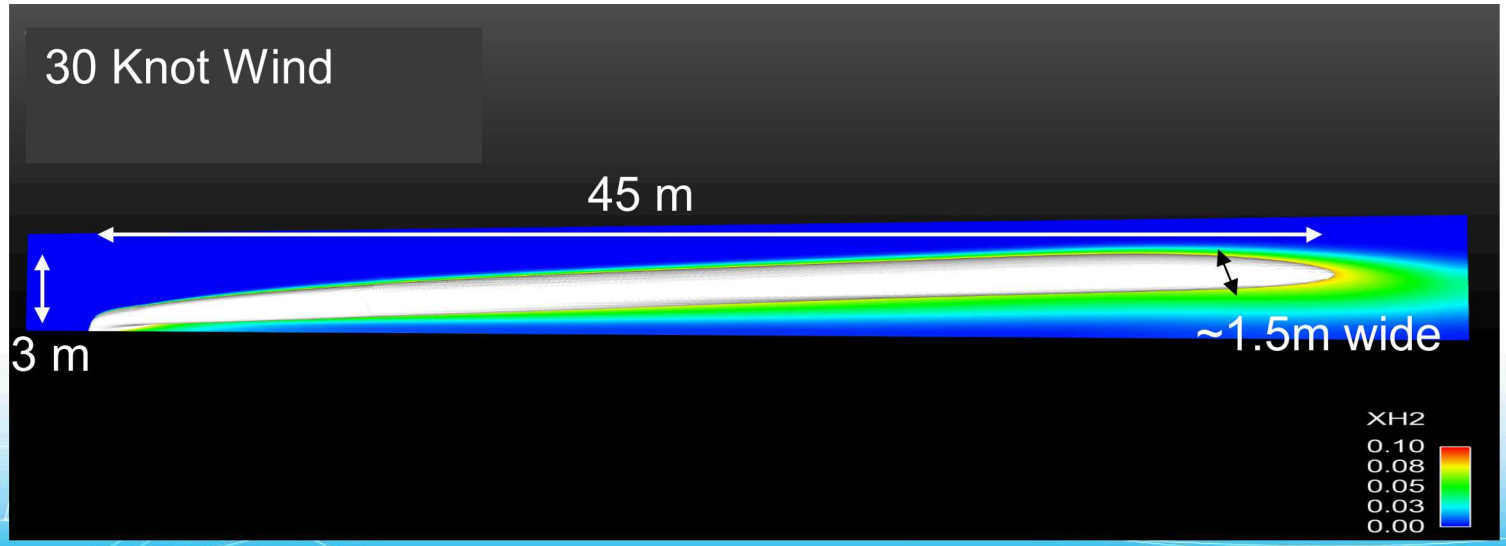
Worst case, will likely dissipate at shorter lengths

Does not include effect of downstream air disturbances/turbulence

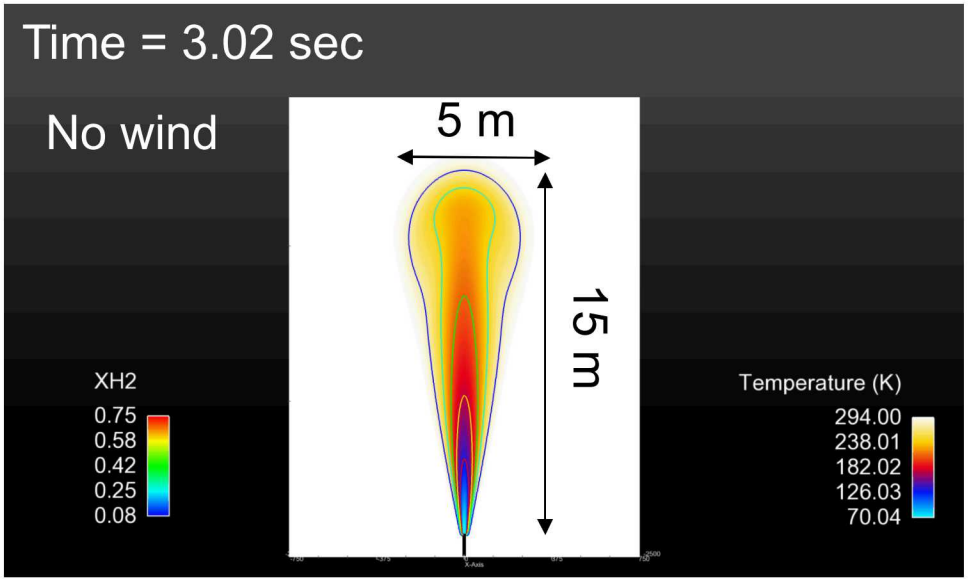
Shape of Plume Depends on Wind

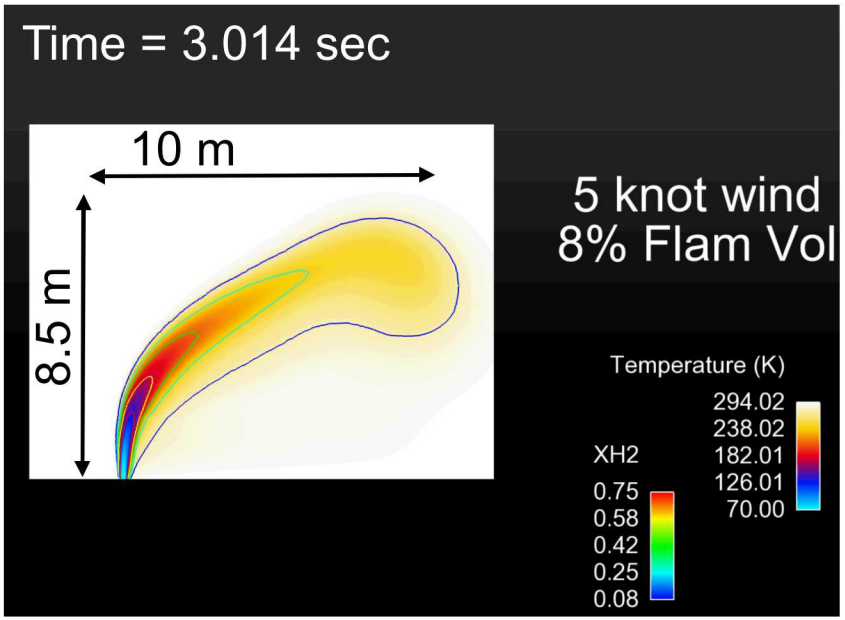


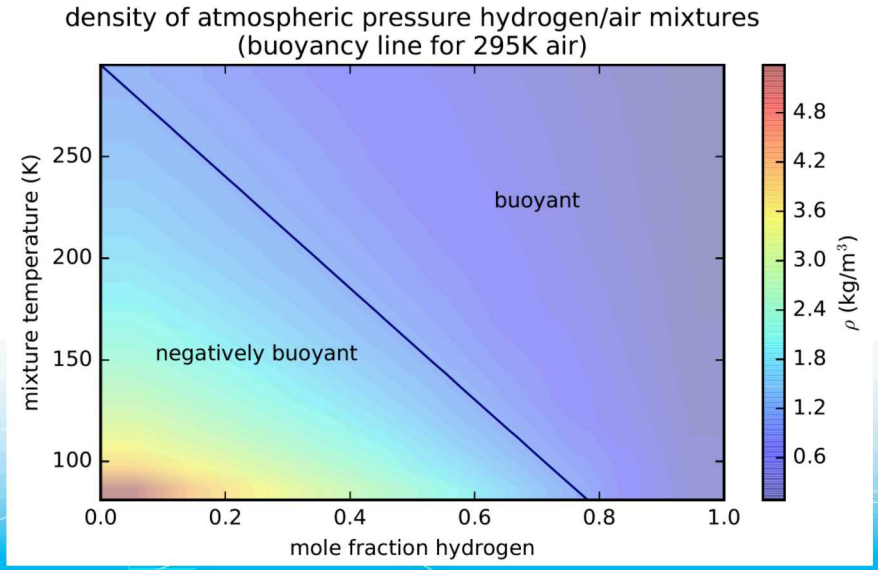


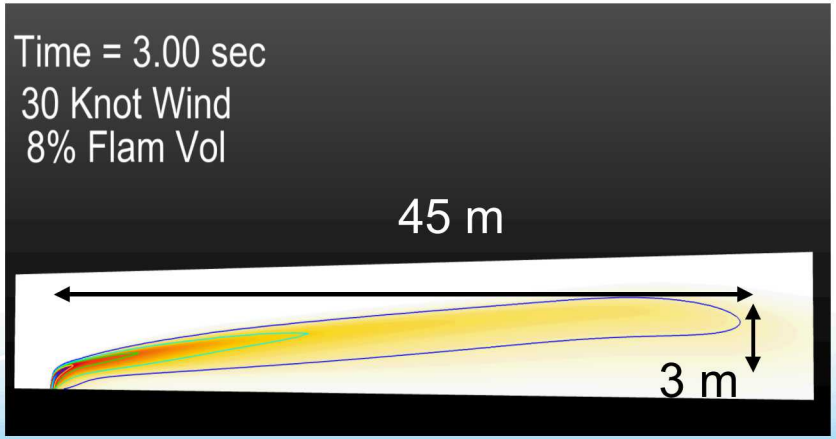


Positively Buoyant: Cold at high concentrations









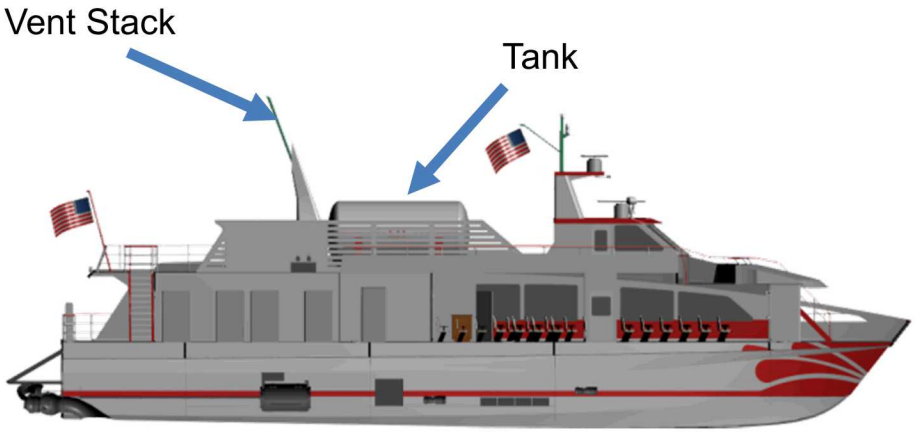
70 K = -203 ºC = -333 ºF

Outline

- **Gas Dispersion Analysis**
  1. Abnormal Blowdown
  2. **Normal Boil-off**
  3. Fuel cell room

Scenario 2: Normal Venting due to Boil-off

- Pressure will build up if LH_2 tank is not used for several days
  - Tank Dimensions
    - 150 PSI
    - ~4500 gallons
  - Vent Stack
    - ~7 inch internal diameter
    - 25 feet tall (7.5 m)

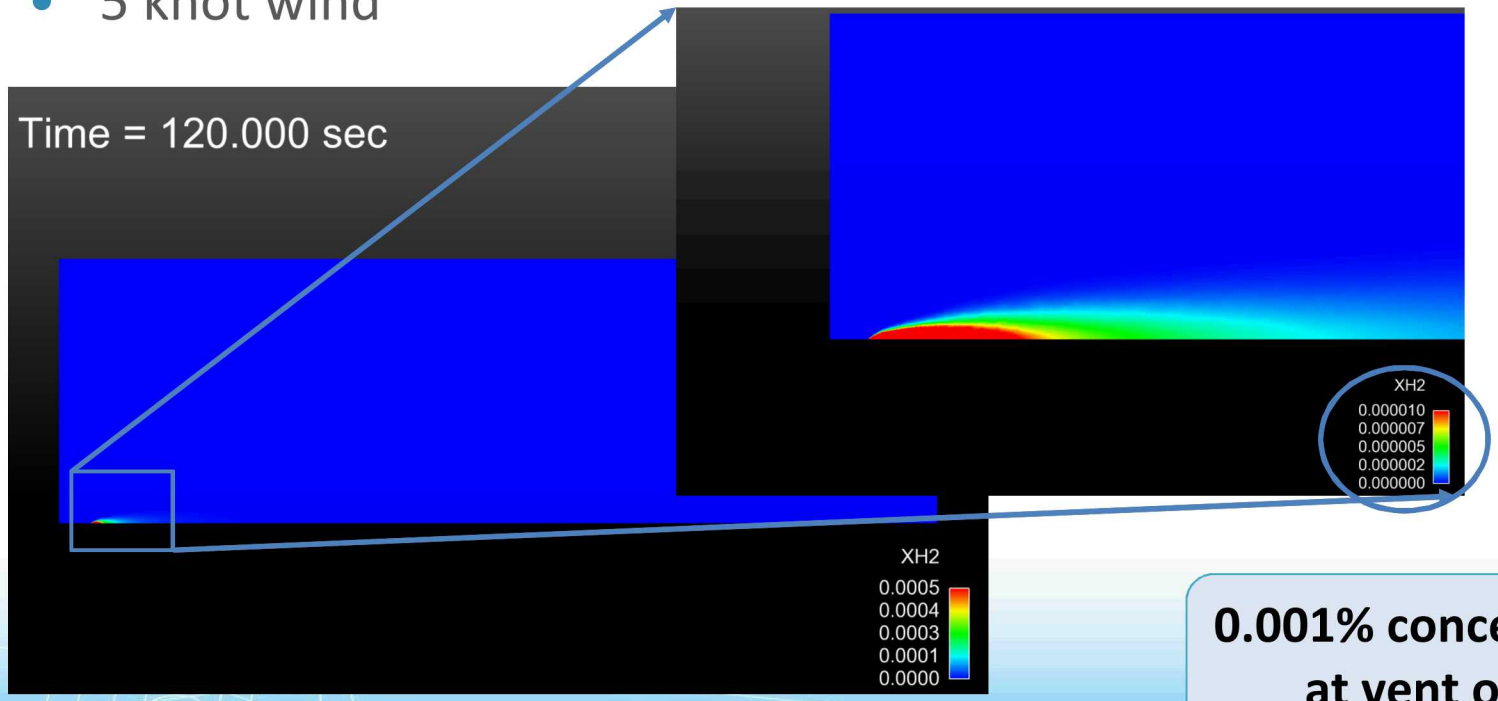


  - 1% of tank per day assumed (0.6% is expected)
    - 1200 kg tank -> 12 kg/day boil-off
  - Currently intentional releases of H_2 are not allowed while docked
    - Turn on fuel cells or some other way of reducing pressure needed

Scenario 2: Boil-off

Boil-off produces no flammable mass

- Steady state in tank – release limited by liquid hydrogen boiling to vapor and escaping
- 1% of tank per day assumed (0.6% is expected)
- 1200kg tank -> 12 kg/day boil-off through a 2” valve
- 5 knot wind



0.001% concentration at vent outlet

Outline

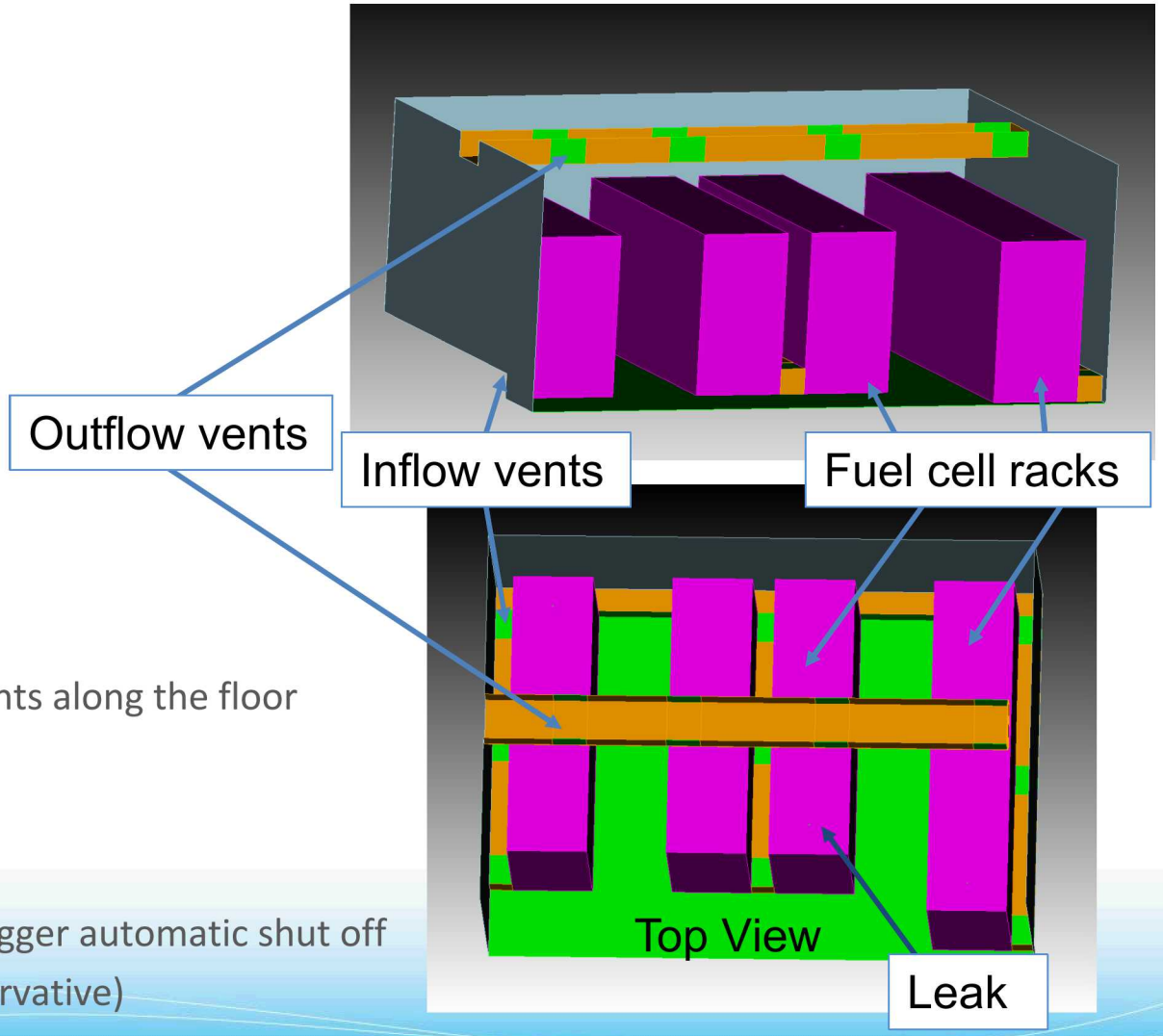
- **Gas Dispersion Analysis**
  1. Abnormal Blowdown from LH2 Tank
  2. Normal “Boil-off”
  3. Leak in Fuel Cell Room

San Francisco Bay Renewable Energy Electric vessel with Zero Emissions (SF-BREEZE)

©Hydrogenics Corp.

Scenario 3: Leak inside a fuel cell room

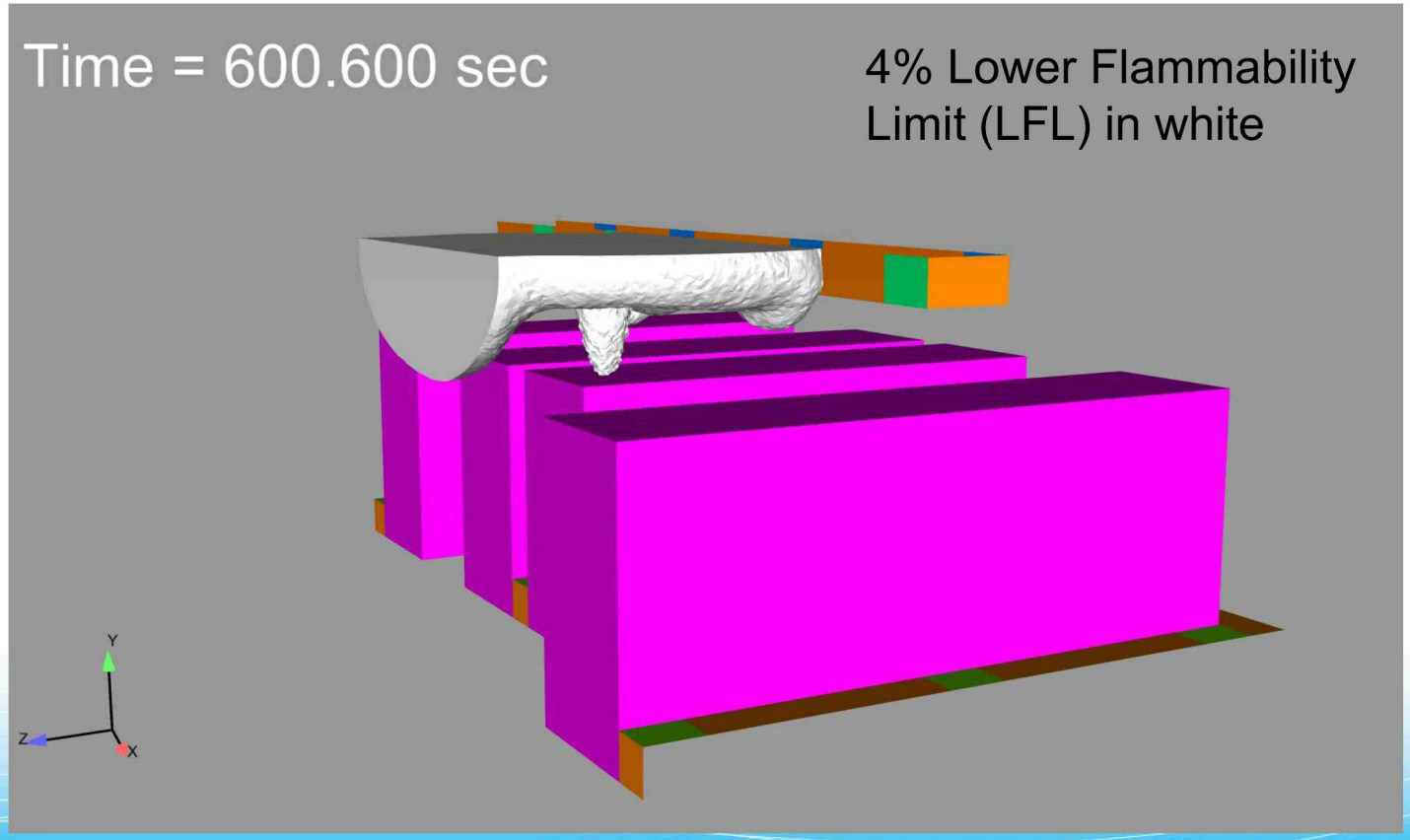
©Hydrogenics Corp.



- Ventilation:
  - 200 cfm from each of 9 vents along the floor
    - 30 ACH
  - Outflow vents near ceiling
- Leak from top of one rack
  - Pressure sensors would trigger automatic shut off
  - Stopped after 2 sec (conservative)

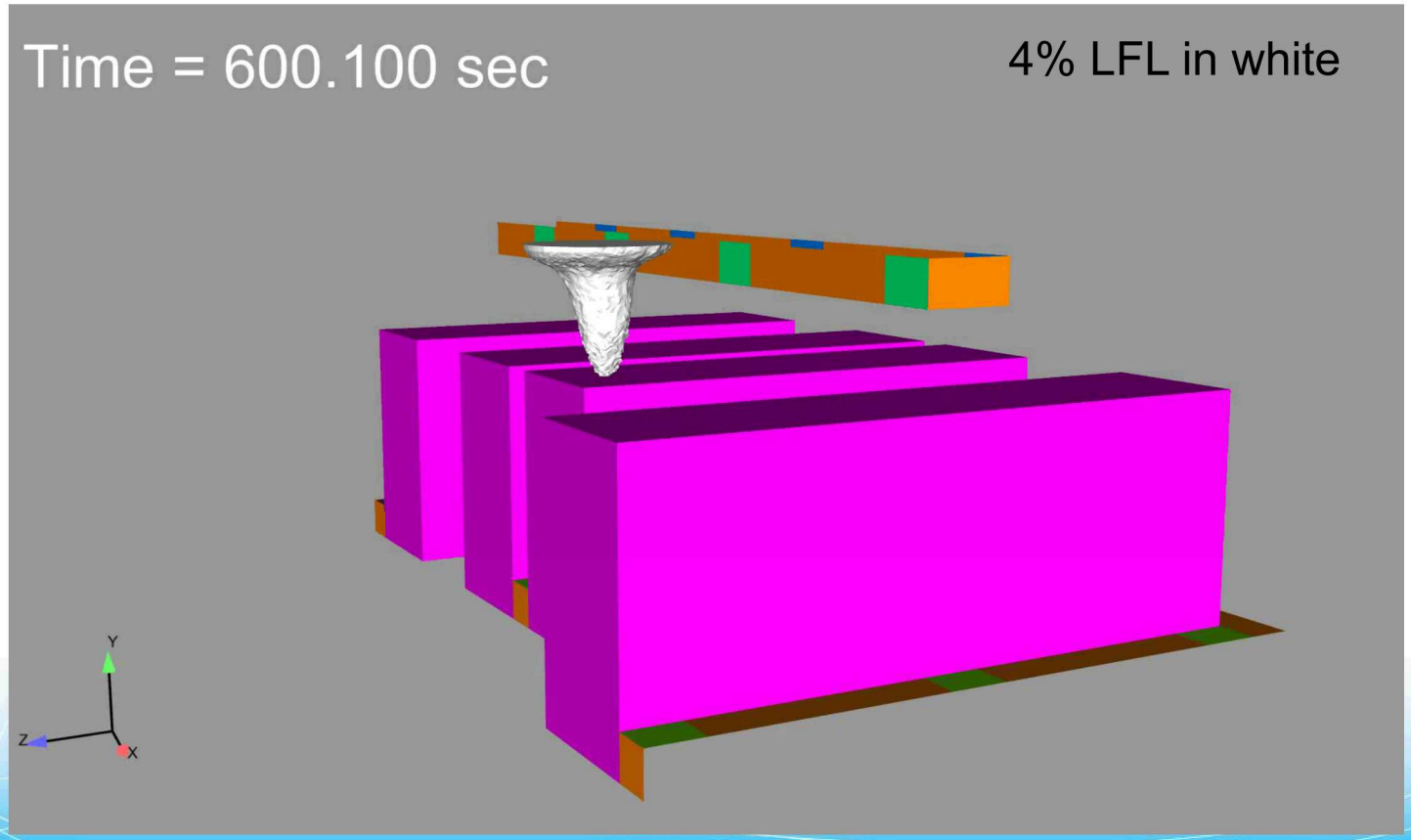
Fuel Cell Room : 2.0 sec Leak Cutoff

- Leak
  - Pressure = 100psi, 1” leak diameter
  - Starts at 600 sec (10 min to set up ventilation)
  - Stopped after 2 sec



Fuel Cell Room: 0.5 sec Leak Cutoff

- Leak
  - Pressure = 100psi, 1” leak diameter
  - Starts at 600 sec (10 min to set up ventilation)
  - Stopped after 0.5 sec



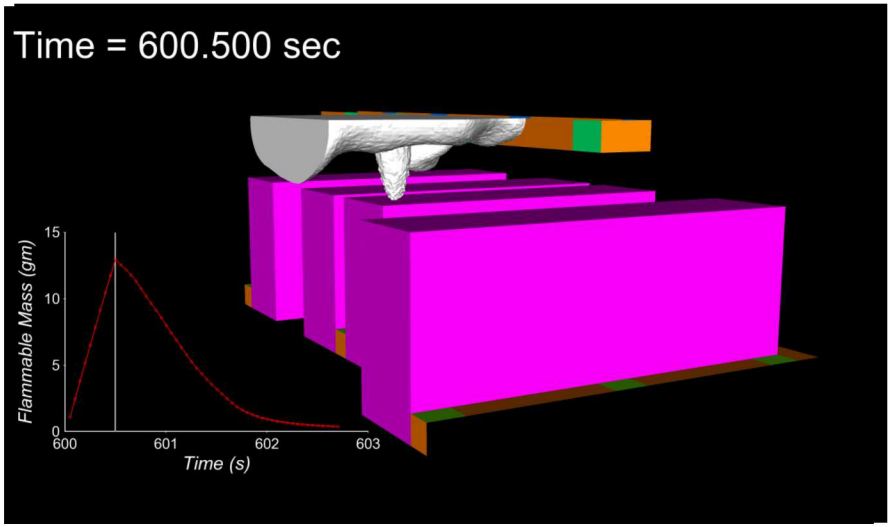
Flammable volume of H_2 can be used to determine potential overpressure hazard

Flammable mass : Cumulative fuel mass mixed into flammable concentrations (mixtures between 4% and 75% by volume for H_2-air)

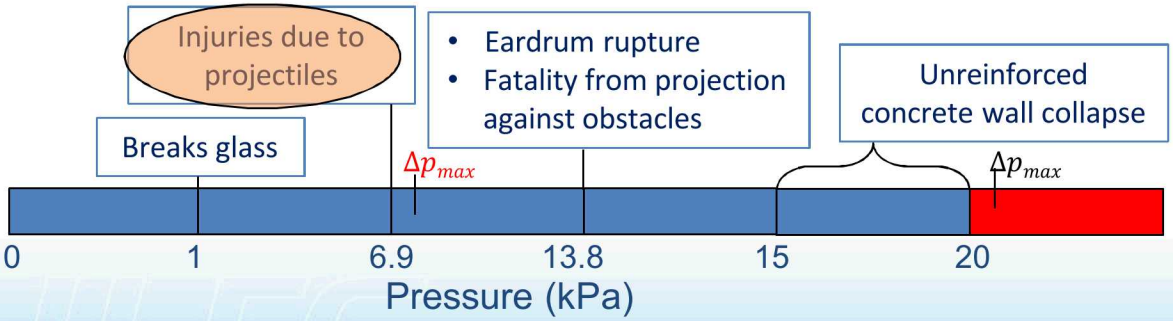
$$\Delta p = p_0 \left\{ \left[\frac{V_T + V_H}{V_T} \frac{V_T + V_{stoich}(\sigma - 1)}{V_T} \right]^{\gamma} - 1 \right\}$$

C. R. Bauwens, S. Dorofeev, Proc. ICHS, 2013.

p_0: Ambient pressure
V_T: Facility volume
V_H: Expanded volume of pure H_2
V_{stoich}: Stoichiometric consumed H_2 volume
σ: Stoichiometric H_2 expansion ratio
γ: Air specific heat ratio (1.4)



Potential Consequences:



$2.0\ sec \Rightarrow \Delta p_{max} = 21\ kPa$

$0.5\ sec \Rightarrow \Delta p_{max} = 7.0 kPa$

Chance of small injuries from overpressure — Local blast waves not considered

American Institute of Chemical Engineers, 1998.

Summary of Results

Scenario 1: Abnormal Blowdown

- Hydrogen plume shape is greatly influenced by the wind due to large density difference compared to air
- Plume is always positively buoyant even when very cold H_2 (70 K)
- Plume of flammable H_2 will be longer than plume of flammable natural gas (details in paper)

Scenario 2: Normal Boil-off

- During "boil-off" venting there is no flammable concentration of gas

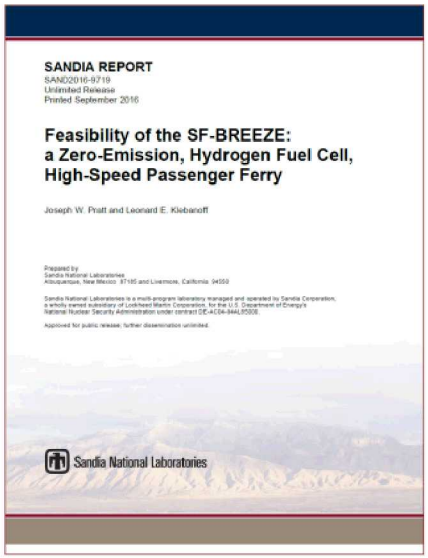
Scenario 3: Fuel cell room leak

- Large leak in fuel cell room will have flammable concentrations for only a very short period of time after source is shut off
- If ignited, will produce moderate overpressures
- Ventilation and safety system designs will have a large impact

Thank You!

For more information visit:

maritime.sandia.gov



Contact Information

Myra Blaylock

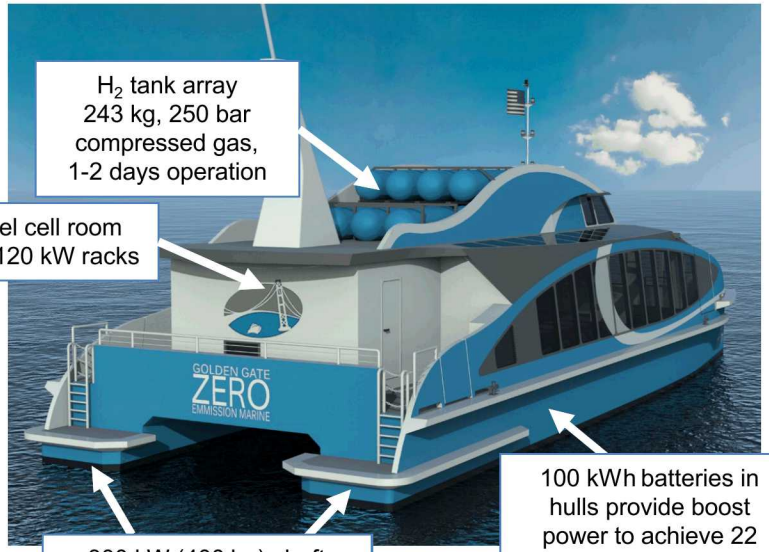
mlblayl@sandia.gov

Work funded by **US DOT / Maritime Administration** through the ***Maritime Environmental and Technical Assistance (META) program***

BACK-UP SLIDES

Elliott Bay Design Group Naval Architecture by Elliott Bay Design Group

Water-Go-Round Details



H_2 tank array 243 kg, 250 bar compressed gas, 1-2 days operation

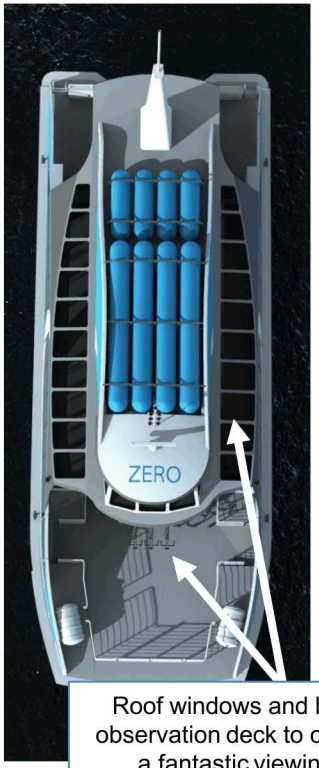
Fuel cell room 3 x 120 kW racks

100 kWh batteries in hulls provide boost power to achieve 22 knots

300 kW (400 hp) shaft motors (1 in each demi-hull)

84 passengers with high visibility window arrangement

Boarding from sides and bow for maximum flexibility

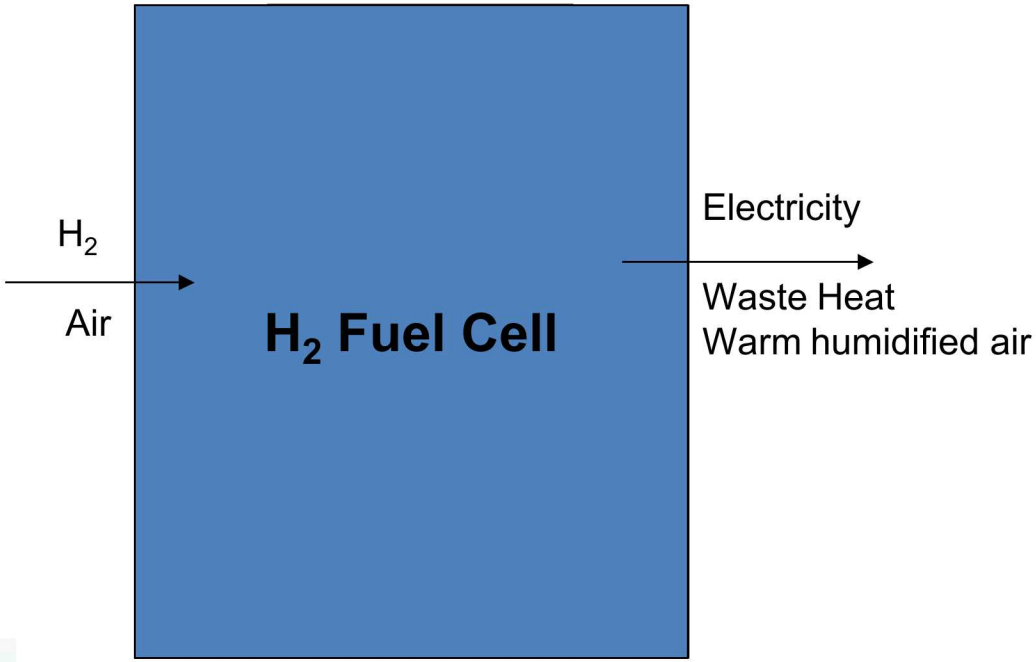


Roof windows and bow observation deck to create a fantastic viewing experience

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

Hydrogen Fuel Cell

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



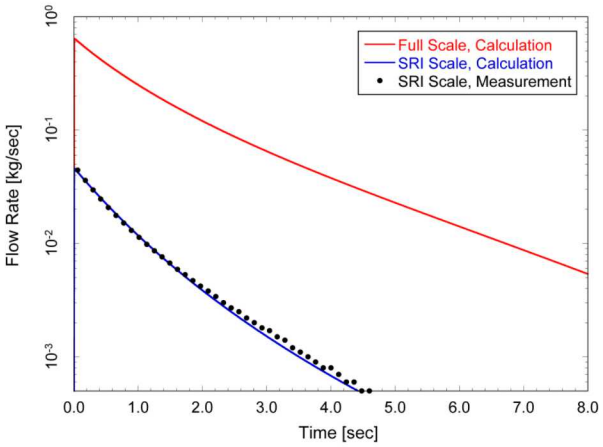
Hydrogen Fuel Cell Room

Photos Courtesy Ryan Sookoo, Hydrogenics

Conservative assumptions

1. Under-predicted dissipation due to RANS
2. Laminar flow of wind
3. Complete valve failure
4. 90% vapor in tank
5. 70 K as release temperature

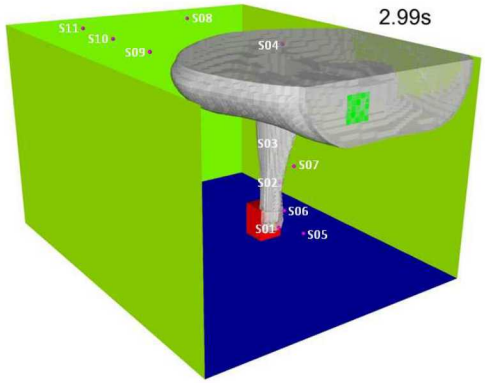
Simulation Validations

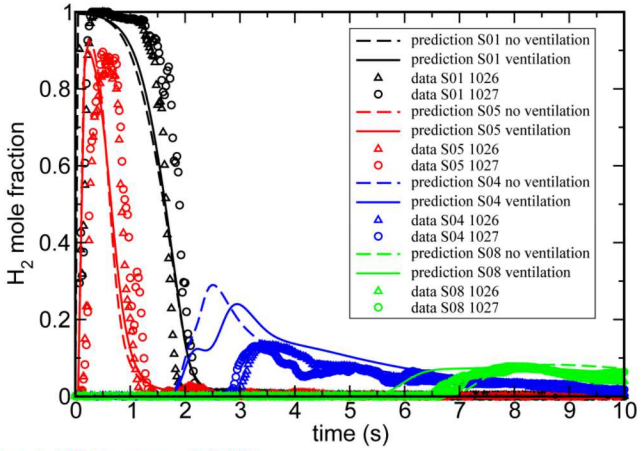


Blowdown release rates calculated via Sandia network flow solver (NETFLOW/MassTran) Winters, SAND Report 2009-6838.

Sandia "FUEGO" CFD flow solver

- Finite volume
- Compressible Navier-Stokes
- k-ε turbulence model





Houf et al., Int J H2Energy, 2013.

Methodology previously validated against large-scale hydrogen blowdown release experiments