SAND2021-11065PE

Sandia National Laboratories

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Safety Issues in Handling and Use of Hydrogen as a Fuel

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FRA Workshop “New Environmentally Sustainable Energy Technologies Powering the Future of Rail”

September 14, 2021

SAND2021-????

U.S. DEPARTMENT OF ENERGY

NNSA

Introduction to Sandia

Multi-Mission DOE NNSA Lab: ***"Exceptional Service in the National Interest"***

Federally Funded Research and Development Center (FFRDC)

- Government owned, contractor operated

Main sites: Albuquerque, NM and Livermore, CA

>**14,000 employees** (>12,000 in NM; >1,600 in CA)

Hydrogen and Fuel Cells Research Program

- Deep, quantitative understanding and a scientific basis for:
- **Materials** – for hydrogen production, storage and utilization
- **Safety** – risk analysis and the creation of risk-informed standards

Regulations

Hydrogen Regulatory Map

H2@Scale expanding into new sectors

- Transportation – vehicles, rail, maritime, aviation
- Production – distributed, SMR/renewable, offshore
- Storage – electrical grid storage, import/export
- Distribution – pipelines, transportation modes
- Use – heating, electricity, chemicals, transportation

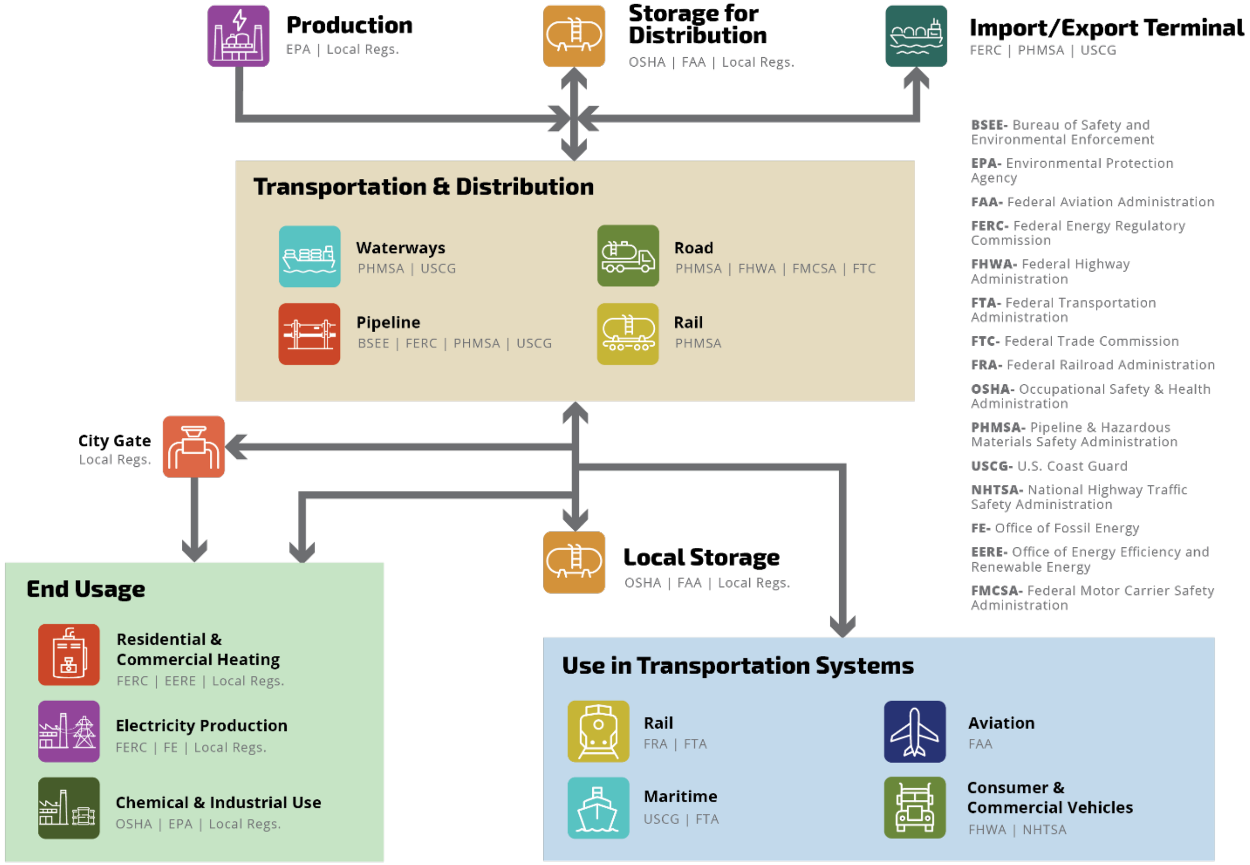
Regulated by federal, state, and local entities

- Current focus on federal oversight for future engagement

Large-scale natural gas infrastructure already exists in federal regs

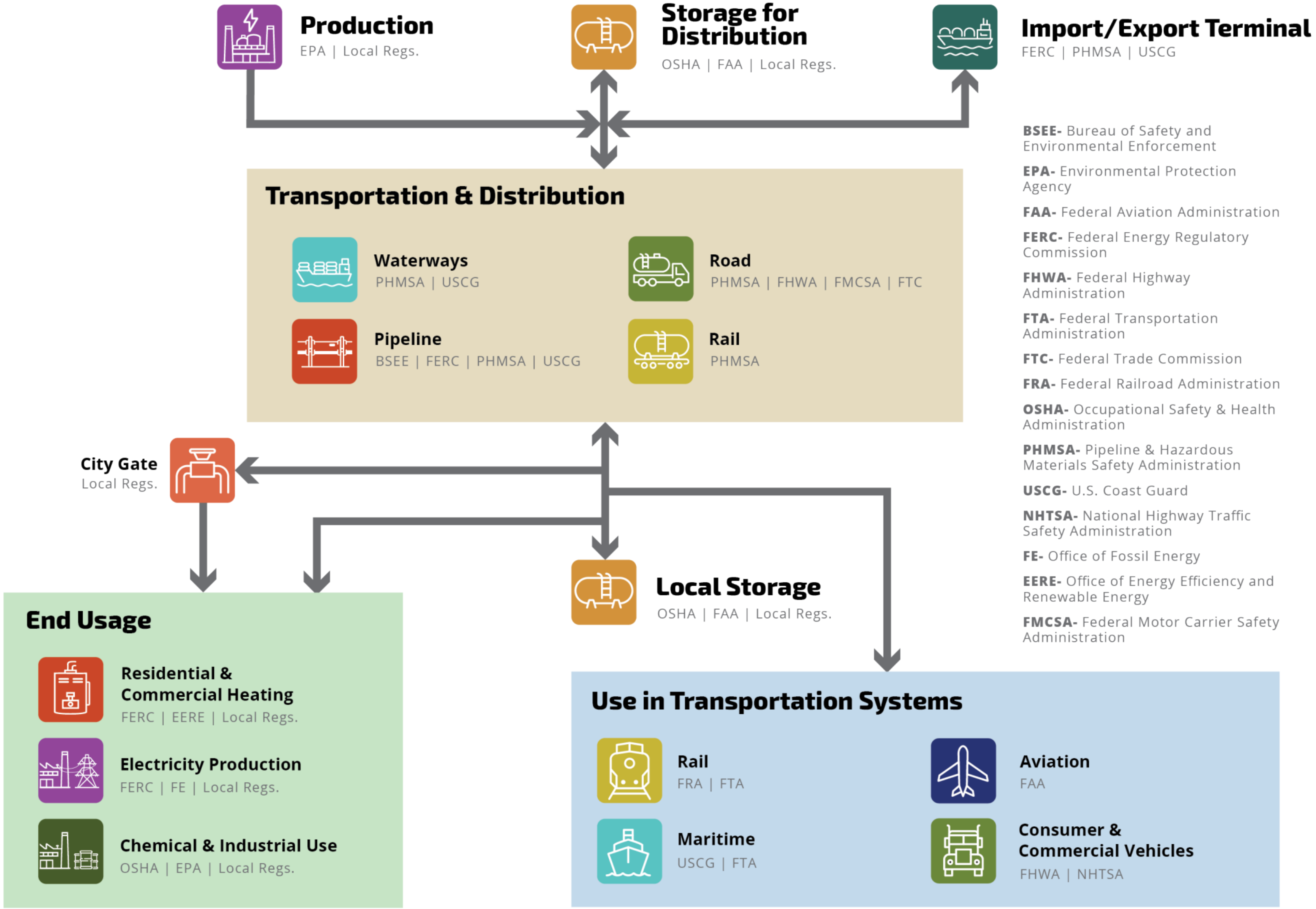
- Not always specific to hydrogen

Full Report: SAND2021-2955



Potential gaps in federal jurisdiction and opportunities for federal coordination identified

Hydrogen Regulatory Map



BSEE- Bureau of Safety and Environmental Enforcement

EPA- Environmental Protection Agency

FAA- Federal Aviation Administration

FERC- Federal Energy Regulatory Commission

FHWA- Federal Highway Administration

FTA- Federal Transportation Administration

FTC- Federal Trade Commission

FRA- Federal Railroad Administration

OSHA- Occupational Safety & Health Administration

PHMSA- Pipeline & Hazardous Materials Safety Administration

USCG- U.S. Coast Guard

NHTSA- National Highway Traffic Safety Administration

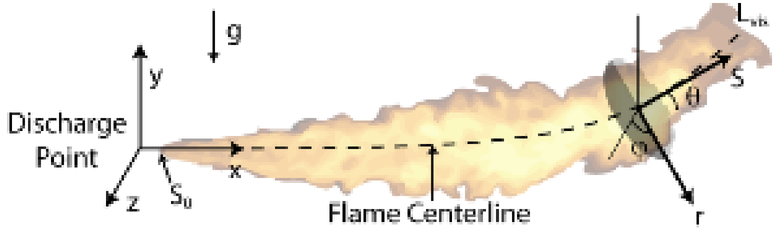
FE- Office of Fossil Energy

EERE- Office of Energy Efficiency and Renewable Energy

FMCSA- Federal Motor Carrier Safety Administration

Codes & Standards Reviews

Rail Propulsion - Gaps Identified in AAR Standards



- Liquid hydrogen (LH2) is **colder** than liquefied natural gas (LNG)
  - LNG tender can be purged with N_2 to remove oxygen, but LH2 would freeze N_2
- Hydrogen is less volumetrically dense than diesel or LNG
  - **Current flowrates** for diesel (300 gpm) or LNG (400 gpm) **likely too low** for fast fueling
- Hydrogen leaks/flames can be odorless and invisible (especially in daylight)
  - New **detection methods** and **inspection procedures** needed
- **Hydrogen is buoyant**, while diesel pools
  - Tanks likely better located at top of locomotives, rather than bottom (like diesel)
- **Shock and vibration** for rail environment needs to be considered for all hydrogen components
- Tank and piping design to account for **hydrogen embrittlement**

Report available online: DOT/FRA/ORD-21/20

Rail Refueling : Examples of Potential Gaps in NFPA 2 for Rail

- LH2 bulk storage setback distance table has maximum value of 75,000 gal (20,157 kg)
  - Rail facilities (and many other heavy-duty applications) can exceed this
- Outdoor Nonpublic Fueling requirements **do not currently exist** for GH2 or LH2
  - Sections are "reserved" for future use
- Requirements for concrete fueling pad **not applicable to rail**
  - Need to ensure these requirements are scoped appropriately
- **Vague requirement** for risk assessment for all LH2 refueling facilities
  - No specifics on methodology, acceptance criteria, etc.

Table 8.3.2.3.1.6(A) Minimum Distance from Bulk Liquefied Hydrogen [LH_2] Systems to Exposures

	Total Bulk Liquefied Hydrogen [LH_2] Storage					
	39.7 gal to 3500 gal	150 L to 13,250 L	3501 gal to 15,000 gal	13,251 L to 56,781 L	15,001 gal to 75,000 gal	56,782 L to 283,906 L
Type of Exposure	ft	m	ft	m	ft	m
Group 1						

10.5.3.2.3 Indoor Nonpublic Slow-Fill Fueling. (Reserved)

10.5.3.3 Outdoor Nonpublic Fueling.

10.5.3.3.1 General. Outdoor, nonpublic fueling installations shall meet the requirements of 10.5.2.2.1.

10.5.3.3.2 Outdoor Nonpublic Fast-Fill Fueling. (Reserved)

10.5.3.3.3 Outdoor Nonpublic Slow-Fill Fueling. (Reserved)

11.3.4 Outdoor Nonpublic Fueling.

11.3.4.1 General. (Reserved)

11.3.4.2 Outdoor Nonpublic Full-Service Fueling. (Reserved)

11.3.4.3 Outdoor Nonpublic Attended Self-Service Fueling. (Reserved)

11.3.4.4 Outdoor Nonpublic Unattended Self-Service Fueling. (Reserved)

10.5.2.2.1.3* The vehicle fueling pad shall be of concrete or a material having a resistivity not exceeding 1 megaohm as determined by an approved method unless the vehicle is grounded by other means, such as a grounding cable.

11.2 General.

11.2.1 Risk Assessment.

11.2.1.1 All hydrogen refueling station sites shall have a completed risk assessment prior to dispensing fuel.

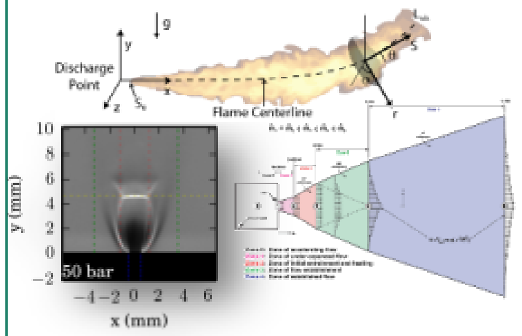
11.2.1.2 The risk assessment shall be updated when changes to the process affect operating limits or design specifications that were included as the basis for the original risk assessment.

Image: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=2

Safety Research Topics

Coordinated Activities to Enable Consistent, Rigorous, and Accepted Safety Analysis

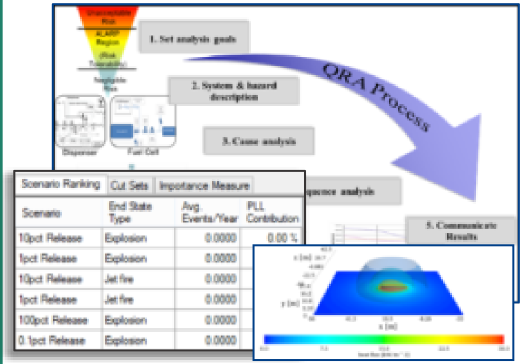
Behavior R&D



Develop and validate scientific models

to accurately predict hazards and harm from liquid releases, flames, etc.

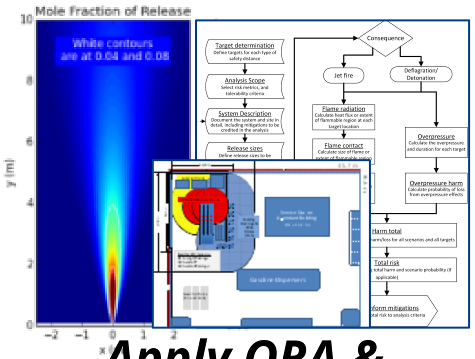
Risk R&D



Develop integrated methods and algorithms

for enabling consistent, traceable and rigorous QRA

Application in SCS



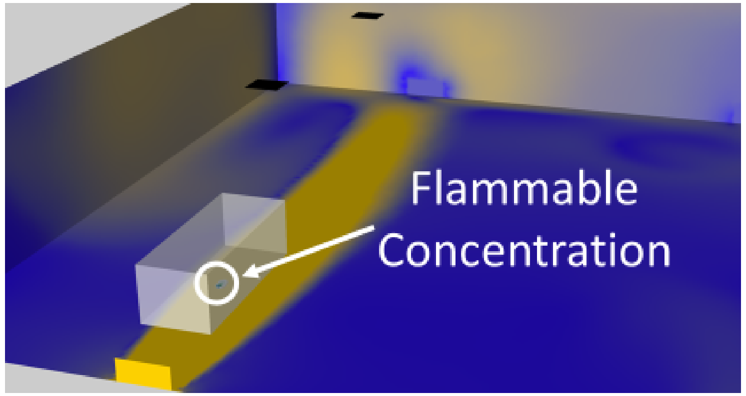
Apply QRA & behavior models to real problems

in hydrogen infrastructure and emerging technology

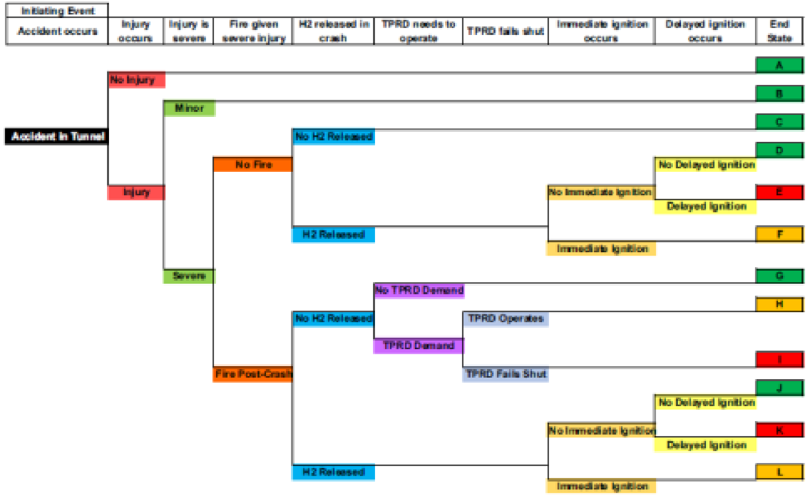
Developing methods, data, tools for H_2 safety codes and standards

Tool available online: HyRAM

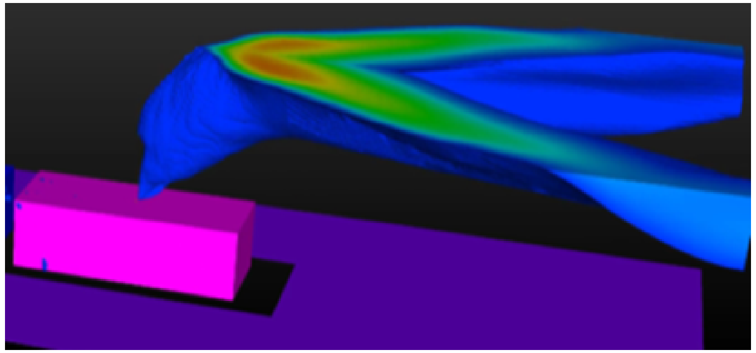
Hydrogen Risk Assessments and Consequence Modeling



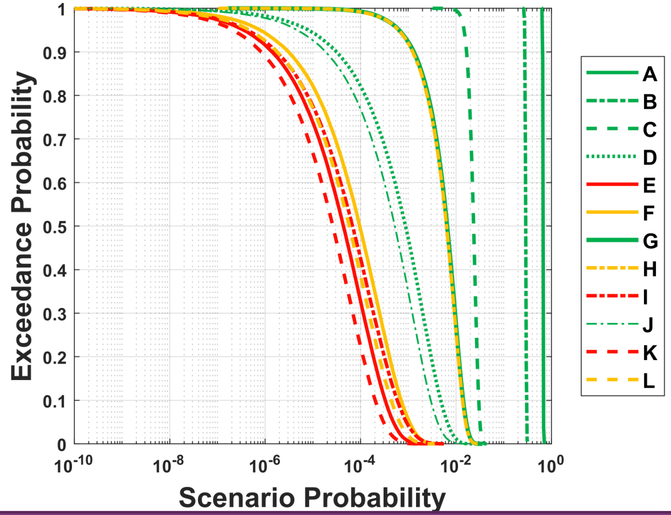
Dispersion modeling of leak with ventilation in repair garage



Event tree for hydrogen vehicle in crash



Jet fire modeling of effect of hydrogen leak on tunnel



Probability/likelihood of outcomes with uncertainty

https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/hydrogen-safety-codes-and-standards/quantitative-risk-assessment/

Current Work – Hydrogen Rail Safety Topics (DOT FRA)

Example LNG Fuel Tender Supplying 2 Locomotives [from Chart Industries]

Assessment of **post-crash outcomes** for passenger and freight rail

- Developing event sequence diagrams with uncertainty quantification for hydrogen on both freight and passenger rail
- Modeling of consequences scenarios (CFD and/or reduced-order)

Recommendations on **emergency response**

- Recommendations on the minimum evacuation times and distances for passenger or freight rail following accidental release of hydrogen fuel

Recommendations on best-practices for **human performance** to ensure and maintain safety **during refueling operations**

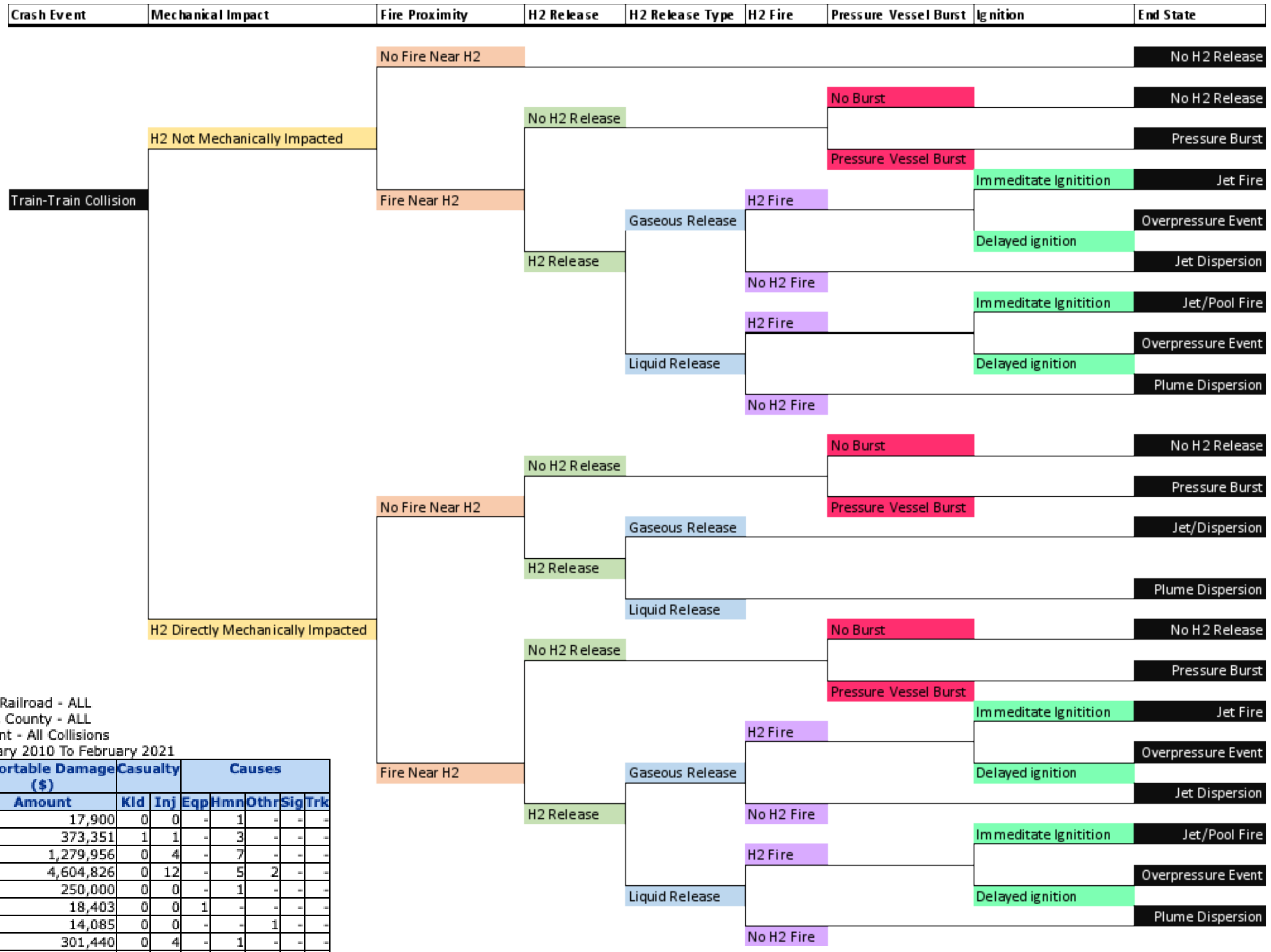
- Review of the human factor issues surrounding refueling of hydrogen fueled train
- Develop recommendations on best practices and procedures for refueling

Identify potential mechanical loading environments experienced in railroad operations that may lead to **hydrogen embrittlement** concerns

- Literature review to identify where existing hydrogen studies overlap the mechanical loading conditions experienced in normal railroad operations and identify potential areas where further experimental research would be beneficial

Rail Crash Risk Assessment – Approach

- Planning on separate event sequence diagrams for:
  - Main line vs. yard crashes
  - Passenger vs. freight crashes
- FRA Crash Database
  - Considering rear-end/head-on/side collisions and fires as possible initiating events
  - Crash severity can be categorized by speed, tonnage, derailments



ACCIDENTS IN DESCENDING FREQUENCY BY TYPE

Selections: Railroad Group - ALL RAILROADS SELECTED
State - All States County - All Counties
All Regions
All Causes / All Types of Accidents / All Track Types
January through February, 2021

	Total		Total Year Counts			YTD Counts Jan - Feb		% Change Over Time		
	Accs	Pct of Total	2018	2019	2020	2020	2021	2018 to 2020	2019 to 2020	To Feb 2020 2021
GRAND TOTAL.......	5,755	100.0	1,988	1,978	1,554	289	235	-21.8	-21.4	-18.7
01 Derailments	3,927	68.2	1,375	1,334	1,069	196	149	-22.3	-19.9	-24.0
12 Other impacts	649	11.3	224	215	177	32	33	-21.0	-17.7	3.1
13 Other events	430	7.5	133	179	104	26	14	-21.8	-41.9	-46.2
09 Obstruction impact	253	4.4	81	80	77	15	15	-4.9	-3.8	.
04 Side collision	186	3.2	42	69	63	11	12	50.0	-8.7	9.1
11 Fire/violent rupture	170	3.0	76	56	33	7	5	-56.6	-41.1	-28.6
05 Raking collision	74	1.3	31	26	15	1	2	-51.6	-42.3	100.0
03 Rear end collision	40	0.7	16	12	10	1	2	-37.5	-16.7	100.0
06 Broken train collision	13	0.2	4	5	3	.	1	-25.0	-40.0	.
02 Head on collision	12	0.2	6	2	2	.	2	-66.7	.	.
10 Explosion/detonation	1	0.0	.	.	1	.	.	.	.	.

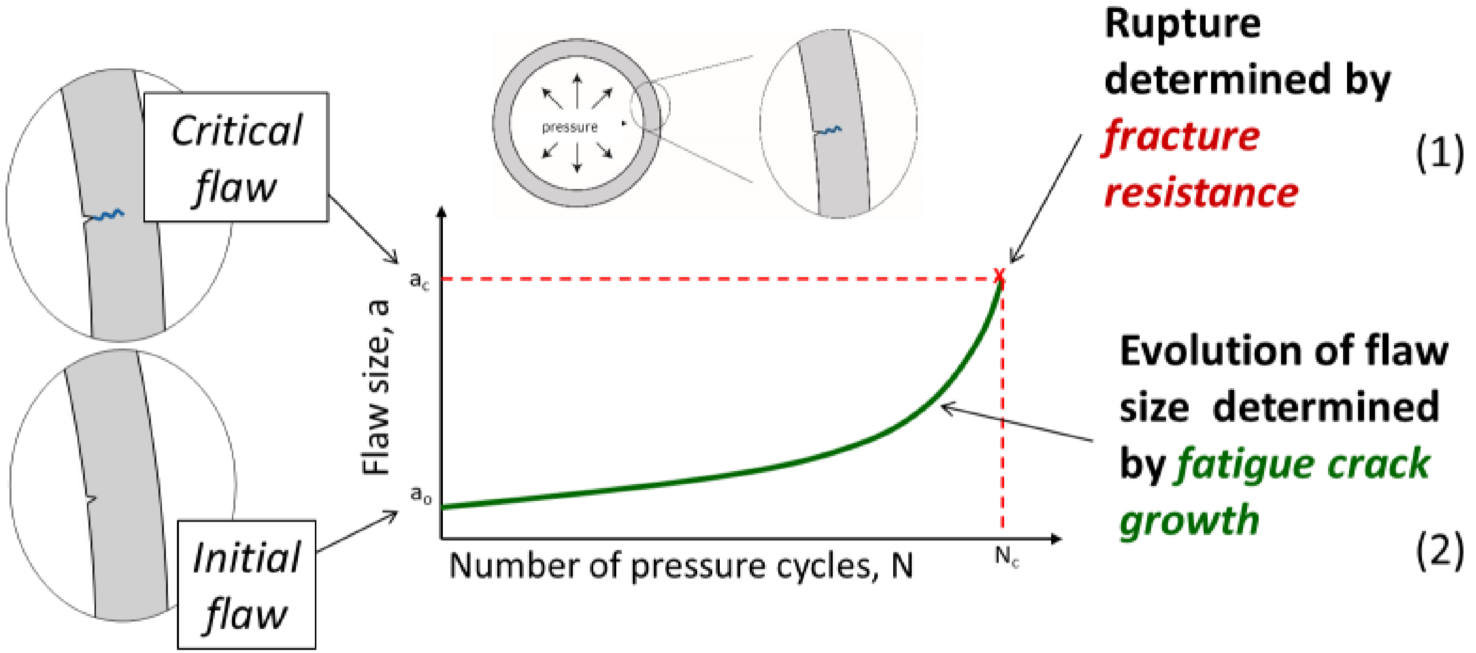
2010

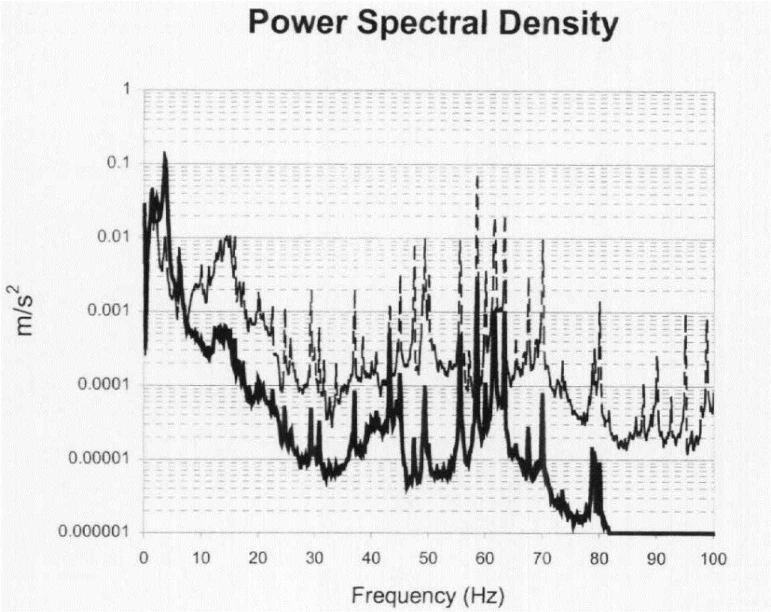
Selections: Railroad - ALL
State - ALL, County - ALL
Type of Accident - All Collisions
Time Frame - From January 2010 To February 2021

Trk - Spd Rng		Total		Type of Accident	Reportable Damage ($)	Casualty		Causes				
		Cnt	%	Coll	Amount	Kld	Inj	Eqp	Hmn	Othr	Sig	Trk
Main	**?**	1	0.1	1	17,900	0	0	-	1	-	-	-
	1 - 9	3	0.2	3	373,351	1	1	-	3	-	-	-
	10-19	7	0.5	7	1,279,956	0	4	-	7	-	-	-
	20-29	7	0.5	7	4,604,826	0	12	-	5	2	-	-
	30-39	1	0.1	1	250,000	0	0	-	1	-	-	-
	40-49	1	0.1	1	18,403	0	0	1	-	-	-	-
	50-59	1	0.1	1	14,085	0	0	-	-	1	-	-
	60-69	1	0.1	1	301,440	0	4	-	1	-	-	-
	>= 70	1	0.1	1	10,377	0	0	-	-	1	-	-
	--Sub	23	1.7	23	6,870,338	1	21	1	18	4	-	-
Yard	**?**	3	0.2	3	134,567	0	1	-	3	-	-	-
	1 - 9	74	5.4	74	4,261,857	0	2	1	63	4	4	2
	10-19	11	0.8	11	1,249,522	0	7	1	9	1	-	-
	40-49	1	0.1	1	10,000	0	0	-	-	1	-	-
	--Sub	89	6.5	89	5,655,946	0	10	2	75	6	4	2
Siding	**10-19**	2	0.1	2	471,394	0	0	-	2	-	-	-
	--Sub	2	0.1	2	471,394	0	0	-	2	-	-	-
Industry	**1 - 9**	13	1.0	13	794,486	0	0	-	13	-	-	-
	--Sub	13	1.0	13	794,486	0	0	-	13	-	-	-
Total		127	9.3	127	13,792,164	1	31	3	108	10	4	2

Hydrogen Embrittlement in Rail Shock/Vibration – Approach

- Estimating tank/pipe lifetimes based on g-forces from coupling shocks and rolling vibrations
  - Different g-forces and different frequencies
- Compare to lifetimes from pressure cycling





Cabin floor vibration (dotted line) and Seat level vibration (solid line) (from Johanning et al. AIHA Journal, 2020)

ASME B31.12 describes rules for hydrogen pipelines with reference to ASME BPVC Section VIII, Division 3, Article KD-10

Thank You!
Questions?

Maritime Feasibility and Safety Analyses

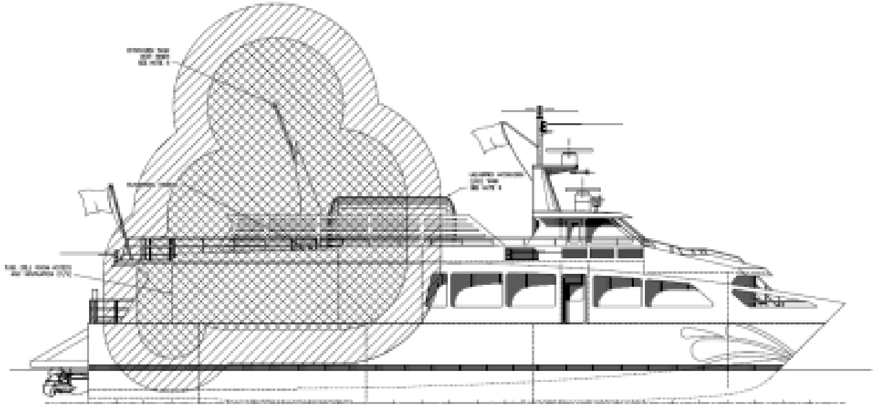
Feasibility studies funded by DOT/MARAD

SF-BREEZE high-speed hydrogen fuel cell ferry

- 1,000+ kg/day hydrogen demand

Zero-V hydrogen fuel cell coastal research vessel

- 2,400 nautical mile range
- Refueled with ~11,000 kg of LH_2



https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/market-transformation/maritime-fuel-cells/