SAND2021-11021PE

Sandia National Laboratories

Exceptional service in the national interest

Insights from Sandia's Hydrogen Projects

Presenter: Benjamin Schroeder

Contributors: Brian Ehrhart, Chris LaFleur, Ethan Hecht, Austin Glover, Austin Baird, Jamal Mohmand, Cianan Sims (SI), Myra Blaylock, Gabriela Anleu, Leonard Klebanoff, Cheri Markt

ARPA-E: LOCOMOTIVES Kickoff Meeting

September 13, 2021

SAND2021-????

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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

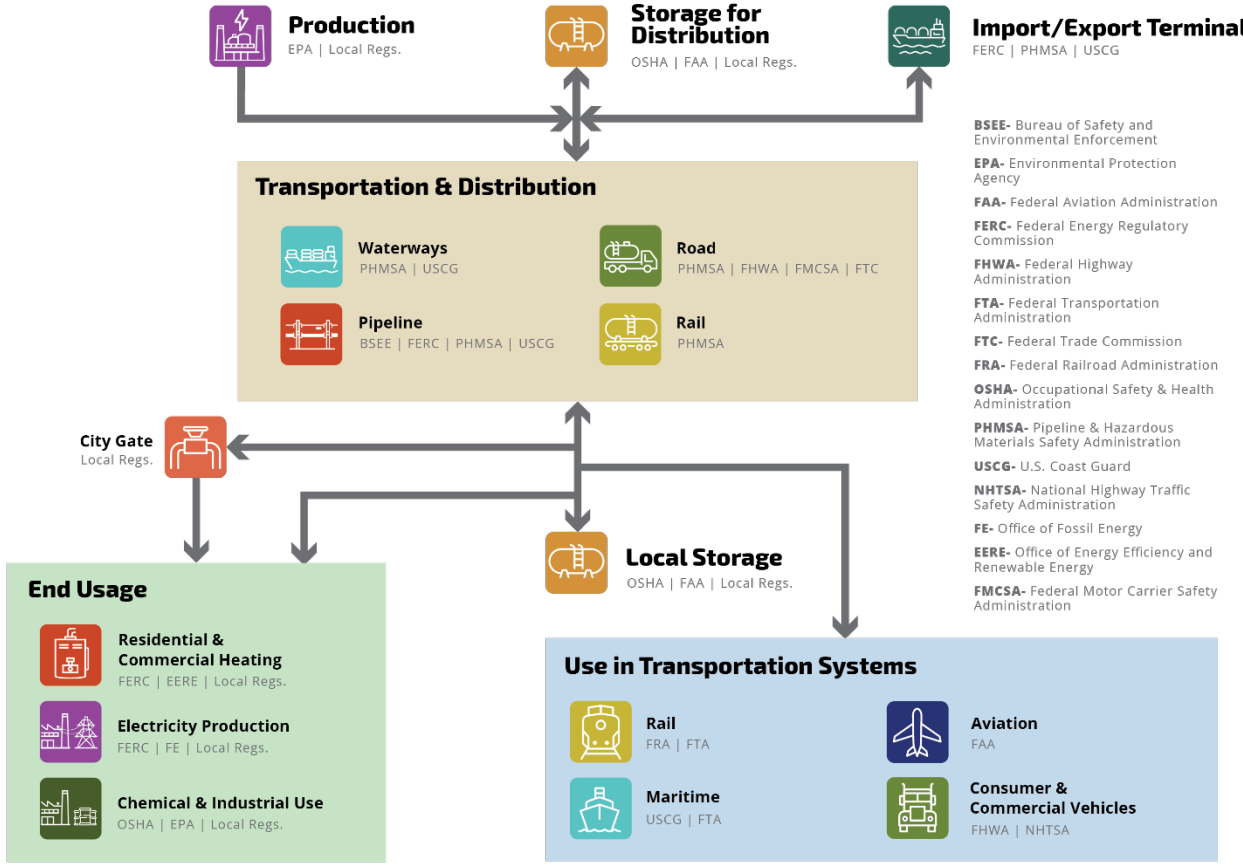
Regulated by federal, state, and local entities

- Current focus on federal oversight for future engagement

Large-scale natural gas infrastructure already exists in federal regs

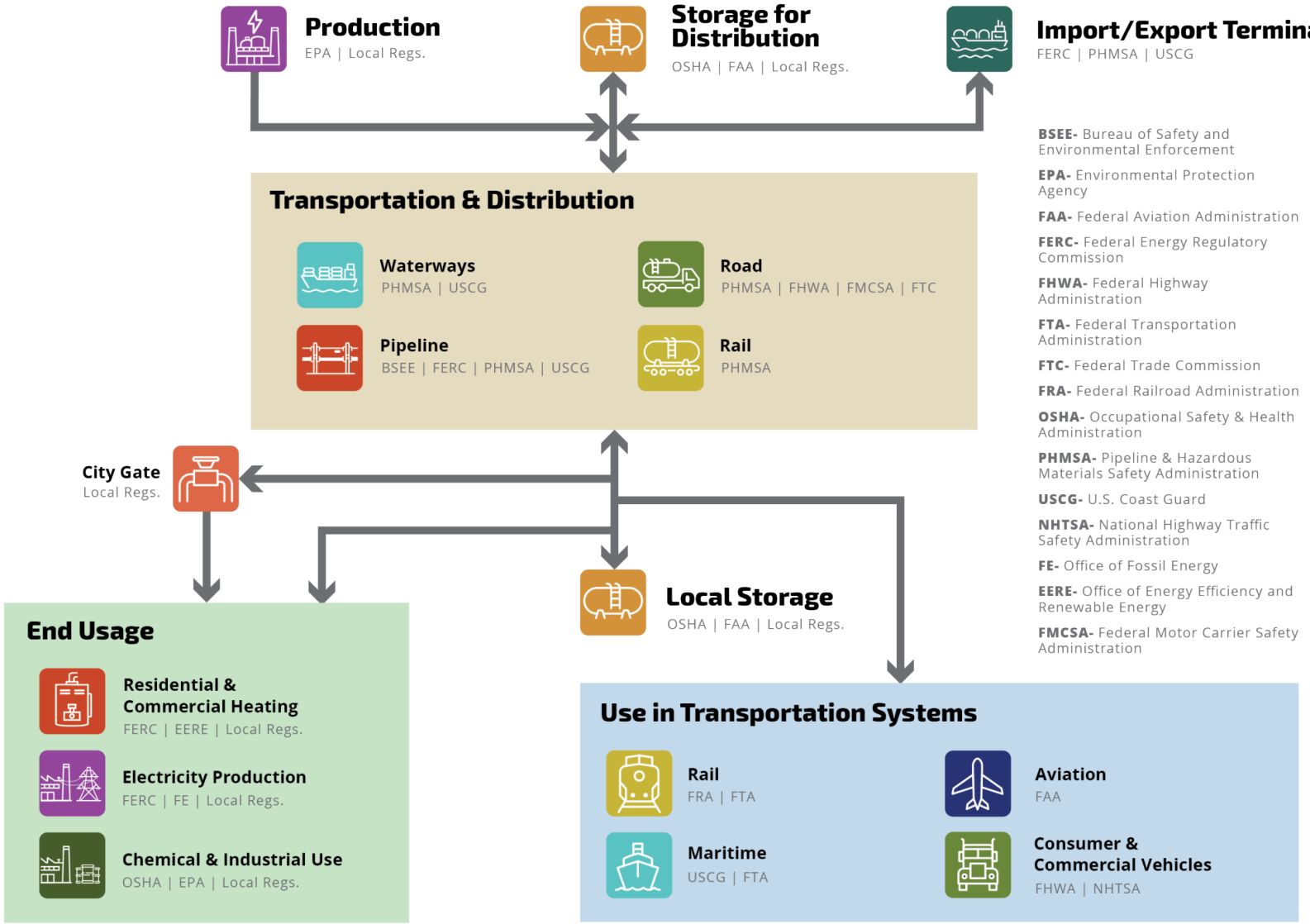
- Not always specific to hydrogen

Full Report: [SAND2021-2955]



Potential gaps in federal jurisdiction and opportunities for federal coordination identified

Hydrogen Regulatory Map



Codes & Standards Reviews

Safety Codes and Standards (DOT FRA)

Gaps identified in AAR standard for future revisions:

- 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 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 forms 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 need to be designed to account for **hydrogen embrittlement**

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

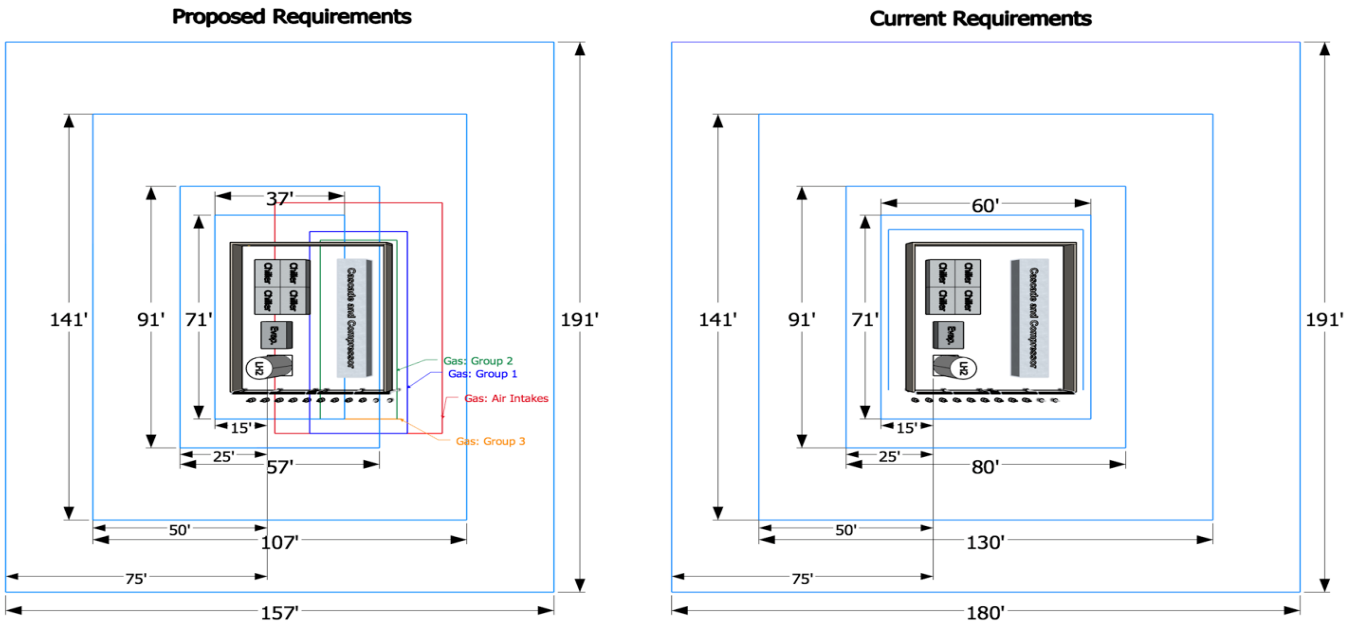
Refueling Infrastructure Assessments

Light-Duty Vehicle Infrastructure Studies

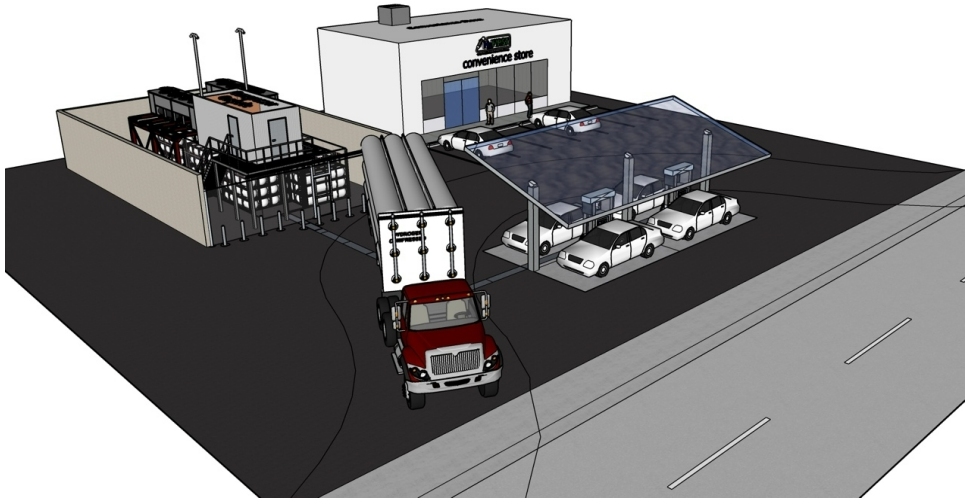
H2FIRST
Hydrogen Fueling Infrastructure Research and Station Technology

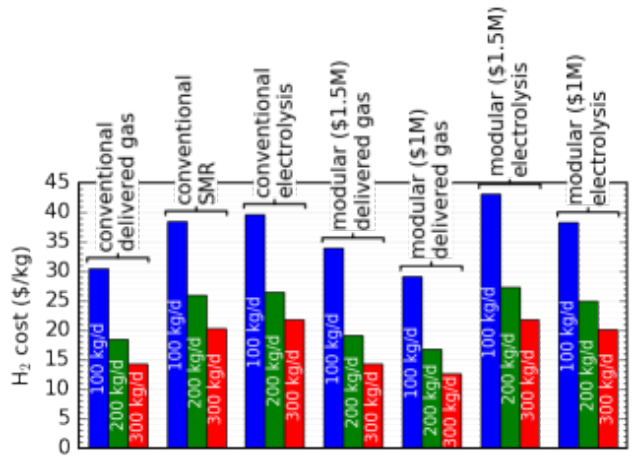
Publicly available system designs for stakeholders

Focusing on NFPA 2 code



Layout footprint quantification and comparison





Economic

https://www.osti.gov/biblio/1604872
https://www.hydrogen.energy.gov/pdfs/review17/pd139_hecht_2017_o.pdf

Rail Refueling Assessment Approach: Bottom-Up Example Designs

Reference designs, not complete enumeration/optimization

- Individual real-world needs will differ

Illustrate trade-offs **between designs**

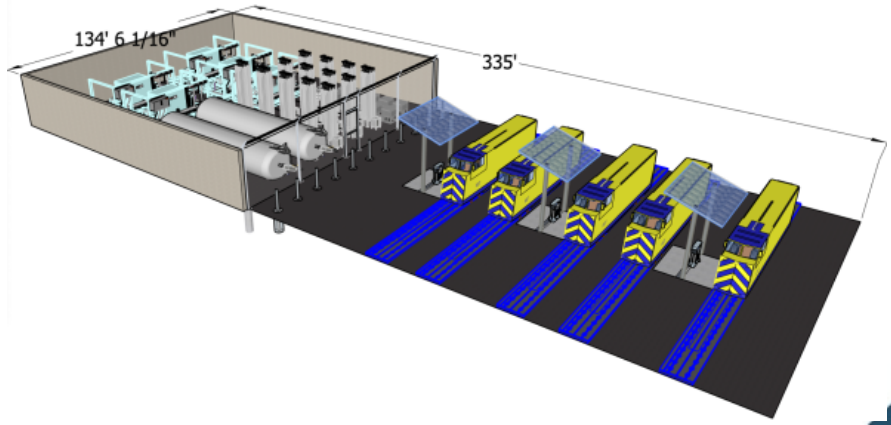
- Gaseous vs. liquid hydrogen
- Large vs. small (economies of scale)
- Passenger vs. freight rail (operational needs)

Identify **key metrics** for each design

- Scale – conditions, flowrates, number of components
- Footprint – physical layout of refueling facility
- Cost – approximate current capital cost estimates

Refueling Facility Design Scenarios

Design	Trains/Day	State	Config.
Multiple Units Passenger	10	GH2	MU Train
Locomotive Passenger	50	GH2	Loco-motive
Small Freight	5	LH2	Tender
Medium Freight	50	LH2	Tender
Large Freight	200	LH2	Tender



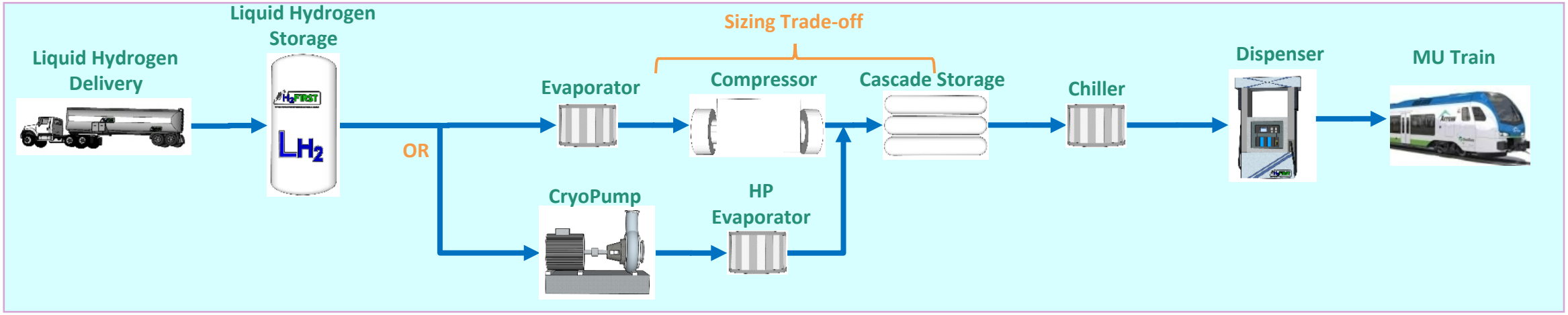
Design Options When Dispensing GH2

LH2 on-site storage, dispensing GH2

Assuming LH2 delivery; GH2 delivery trailers have much less capacity

- H2 could also be produced on-site or delivered via pipeline
- LH2 cryopump would need on-site liquefaction

Liquid H_2 storage with gaseous H_2 dispensing gives many options for sizing/optimization



Four Configurations for LH2 Storage

1. Compressor Refuels Directly
   - Larger compressor mass flow rate able to refuel directly
   - Very small cascade system only to stabilize the flow
2. Compressor Supplies Cascade System
   - Smaller compressor replenishes cascade system
   - Larger cascade system capacity supplies refueling
3. CryoPump/Evaporator Refuels Directly
   - Larger cryopump/evaporator flow rate able to refuel directly
   - Very small cascade system only to stabilize the flow
4. CryoPump/Evaporator Supplies Cascade System
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   - Larger cascade system capacity supplies refueling

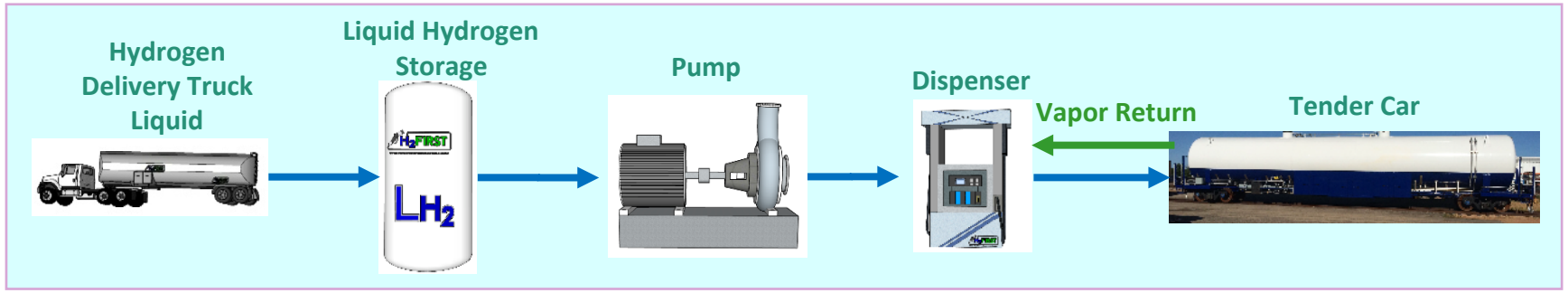
Liquid Hydrogen Refueling for Freight Rail

- LH2 on-site storage, dispensing LH2
- Assuming LH2 delivery
  - H2 could also be produced on-site or delivered via pipeline with on-site liquefaction
- Pressure-build loop could potentially replace cryopump
  - Adds heat to storage tank
- Direct refueling from pump; no cascade storage
- Vapor return line can be returned to tank or vented
  - Could potentially be used for other refueling

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



Storage and dispensing of LH2 more conceptually simple, but still multiple possible design options



Images:
https://www.energy.gov/sites/prod/files/2019/04/f62/fcto-h2-at-rail-workshop-2019-nason-larson.pdf

Liquid Hydrogen Freight Rail Preliminary Design Inputs

Assuming **7,500 kg** H_2 per fuel tender car (from ANL)

Filling Times

- **10 kg/min** (12.5 hours), **300 kg/min** (25 minutes), or **1,200 kg/min** (6.25 minutes)
- Higher flow rates depend on cost and pump availability

Multiple hypothetical designs

- **Small**: 5 trains per day → 37,500 kg/day dispensed capacity
- **Medium**: 50 trains per day → 375,000 kg/day dispensed capacity
- **Large**: 200 trains per day → 1,500,000 kg/day dispensed capacity
- Context: current LH2 liquefaction facilities ~10,000-30,000 kg/day; total ~370,000 kg/day in U.S.
  - Largest facilities likely far in future, would represent significant future capacity increase

Simultaneous fueling likely needed for larger stations

- Depends on refueling window (e.g., 24 hours/day or less)
- Individual pumps per dispenser or single variable-flow pump?

Submerged pumps can operate on-demand, no need for pre-cooling

Freight rail refueling is orders of magnitude greater capacity than vehicle refueling stations

Thank You!
Questions?

Multiple Units Passenger Rail Preliminary Design Inputs

Hypothetical Multiple Units Fleet

- **10 MU trains**
  - Actual single-train demonstrations likely to use direct-truck fueling
- Refueling **once per day**
- **260 kg** H_2 per MU at **350 bar** (per ANL)

Time per Refueling

- 15 minutes → 17.3 kg/min
- 30 minutes → 8.7 kg/min
  - Context: 10 kg/min DOE target for heavy-duty road vehicles
- Not counting connection/idle time

Total Facility Capacity:

- **2,600 kg/day**
  - Context: FirstElement Sunnyvale light-duty vehicle station total capacity: 1,600 kg/day

Example H_2 Multiple Units Trains





Small MU fleet refueling facility capacity ~2X capacity of current light -duty vehicle refueling stations

https://cafcp.org/blog/sunnyvale-hydrogen-station-opens

Images:
https://www.gosbcta.com/wp-content/uploads/2019/09/20191231_RPT_SBCTA_2019_Low_or_Zero_Emission_Multiple_Unit_Feasibility_Study.pdf
https://www.alstom.com/press-releases-news/2020/3/alstoms-hydrogen-train-coradia-ilint-completes-successful-tests

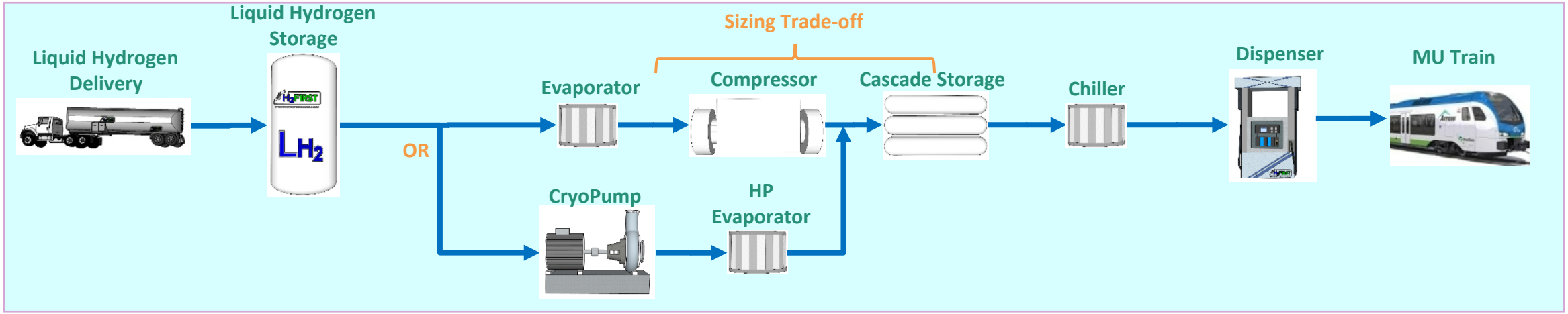
Pump vs. Compressor and Pressure Cascade Sizing Options

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Multiple Units Passenger Rail Preliminary Results

	Compressor Direct	Compressor Cascade	CryoPump Direct	CryoPump Cascade
Total Compressor/CryoPump Flow Rate [kg/hr]	520-1040*	108	520-1040*	108
Number of Compressors/CryoPumps	1-2	1	3-6	1
Number of Evaporators	3-6	1	3-6	1
Cascade Useable Capacity [kg]	22**	2058	22**	2058
Number of Cascade Storage Tanks	1	341	1	341

All systems dispense same flowrate of GH2: 520-1040* kg/hr

Example commercially-available components used for number needed to meet flow rate requirements

Evaporator pressures low for pre-compressor, high for post cryopump

* Flow rate ranges for 30 minute and 15 minute fill

** Cascade capacity for direct fill not strictly required, just to even out flow

Total cost depends on trade-off in component costs; optimum may be somewhere in between extremes

Locomotive Passenger Rail Preliminary Design Inputs

Hypothetical Passenger Locomotive Fleet

- **50 locomotives**
  - Actual single-train demonstrations likely to use direct-truck fueling
- Refueling **once per day**
- **400 kg** H2 per locomotive at **350 bar**

Time per Refueling

- 40 minutes → 10 kg/min
  - Context: 10 kg/min DOE target for heavy-duty road vehicles
- Not counting connection/idle time

Total Facility Capacity:

- **20,000 kg/day**
  - 7.7X more capacity than MU facility

Example Passenger Locomotives





Capacity of facility for larger locomotive fleet >10X larger than current light-duty vehicle refueling stations

Images:
https://ww2.arb.ca.gov/sites/default/files/2020-10/Day%201%20Ext%205%20Caltrans%2020201026.pdf

Locomotive Passenger Rail Preliminary Sizing Results

50 locomotives, minimum of 40 minutes to refuel each:
>33.3 hours of refueling per day

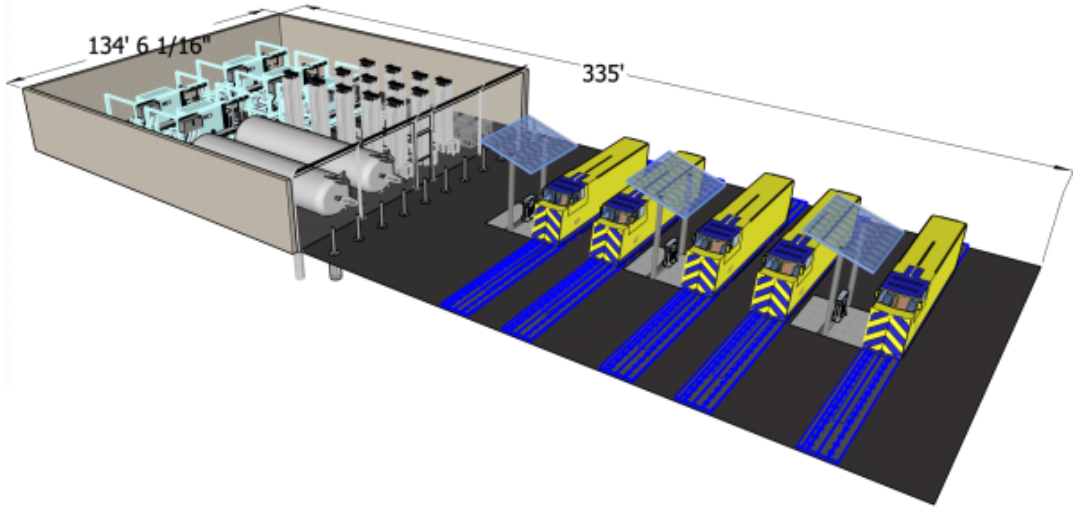
- Simultaneous refueling needed

Assuming **10 hours** to refuel **entire fleet**

- Overnight, passenger operation during the day
- 50 locomotives over 10 hours: **5 locomotives per hour**
- Gives 60 minutes total refueling time

Compressor/cryopump flowrate

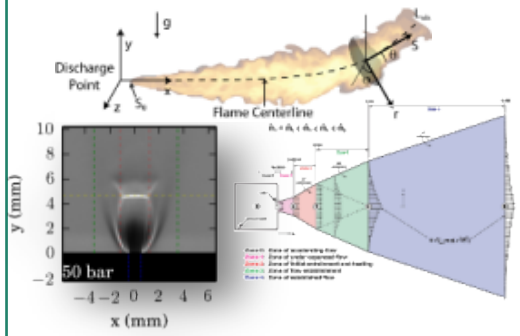
- LH2 storage, dispensing GH2
- Direct refueling:
  - 5 x 10 kg/min = 5 x **600 kg/hr** (individual compressor/pump per dispenser)
  - 50 kg/min = **3,000 kg/hr** for consolidated compressor/cryopump(s)
- Cascade refueling
  - 13.9 kg/min = **833.3 kg/hr** total to supply cascade over 24 hours (minimum flowrate)
    - Resulting cascade: >11,667 kg dispensed capacity



Larger fleet and more H_2 per train means higher capacity components needed for scale

Approach: ***Coordinated Activities*** to Enable Consistent, Rigorous, and Accepted Safety Analysis

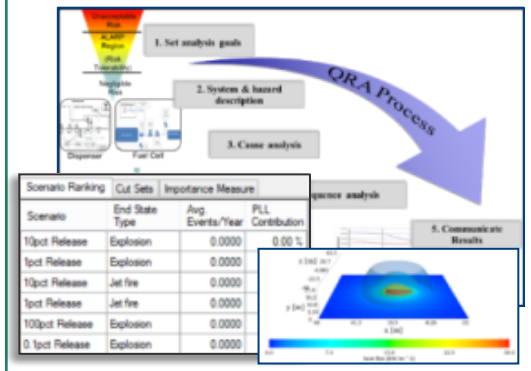
Behavior R&D



Develop and validate scientific models

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

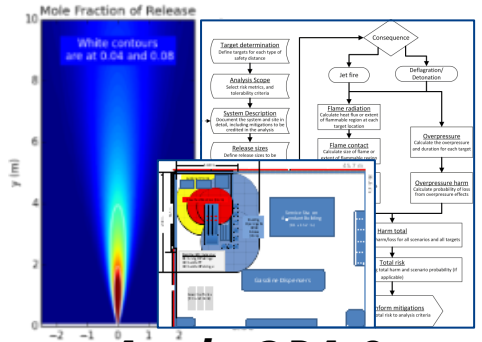
Risk R&D



Develop integrated methods and algorithms

for enabling consistent, traceable and rigorous QRA

Application in SCS

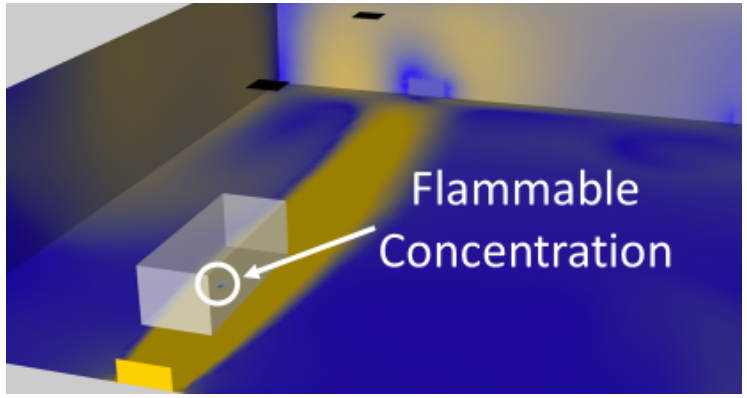


Apply QRA & behavior models to real problems

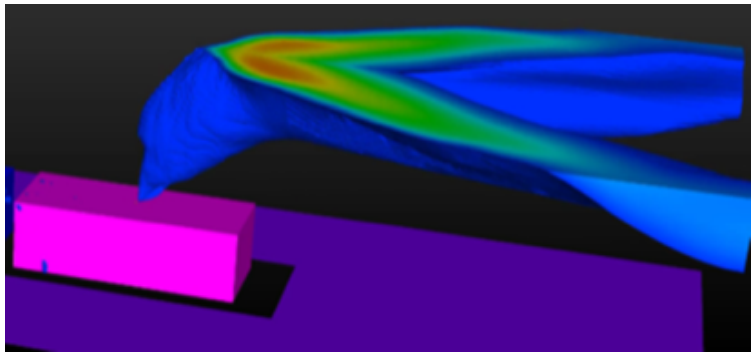
in hydrogen infrastructure and emerging technology

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

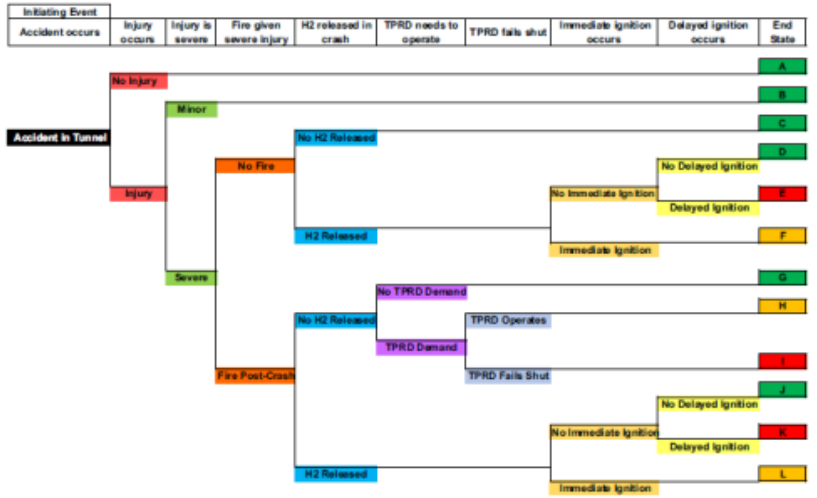
Hydrogen Risk Assessments and Consequence Modeling



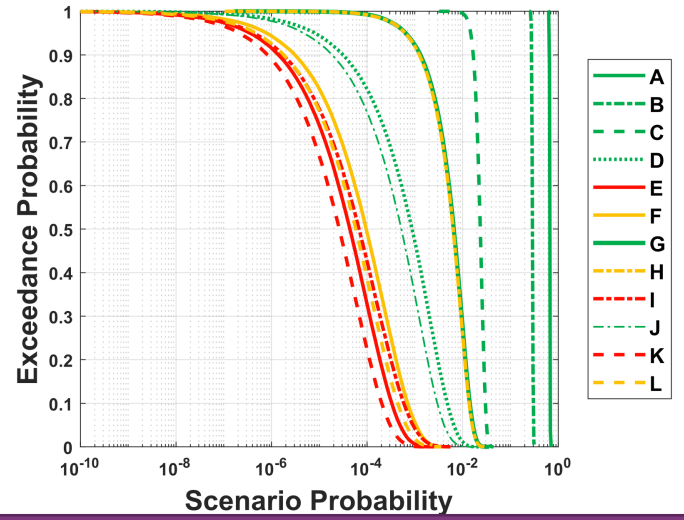
Dispersion modeling of leak with ventilation in repair garage



Jet fire modeling of effect of hydrogen leak on tunnel



Event tree for hydrogen vehicle in crash



Probability/likelihood of outcomes with uncertainty

https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/quantitative-risk-assessment/