SAND2019-2422PE

Hydrogen Fueling Infrastructure Research and Station Technology

Hydrogen Stations for Urban Sites

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Overview

Timeline
- Task start date: March 2017
- Task end date: June 2019

Barriers (Delivery)
A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis
I. Other Fueling Site/Terminal Operations
K. Safety, Codes and Standards, Permitting

Budget
- FY19 DOE Funding: $125k (carryover)
    - SNL: $100k
    - NREL: $25k

Partners
- NREL

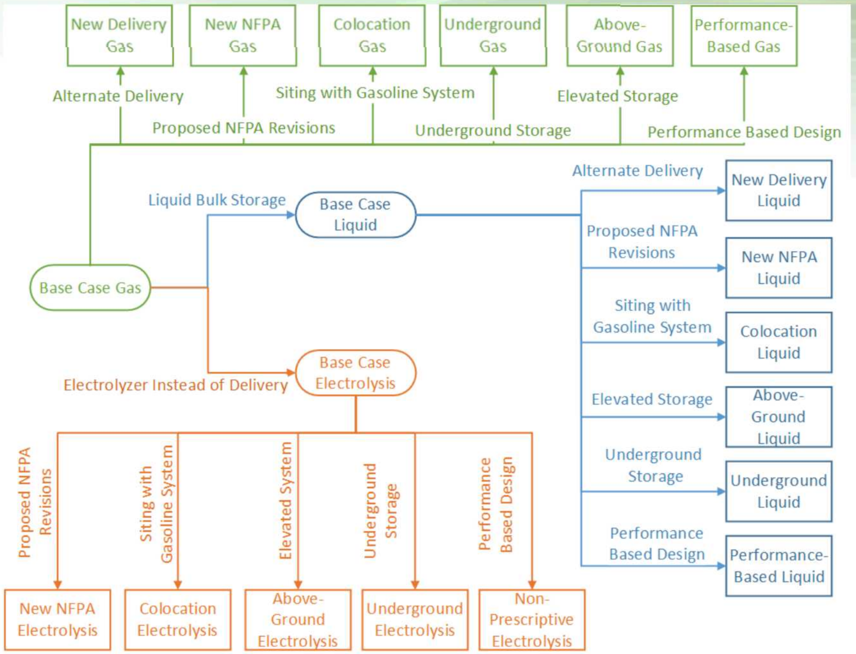
Relevance: Hydrogen Vehicle Fueling Infrastructure

- **FCTO Target: Reduce footprint of liquid stations by 40% by 2022, relative to 2016 baseline**
- Objective:
  - Create compact gaseous and liquid hydrogen reference station designs appropriate for urban locations, enabled by design changes and near-term technology and fire code changes

Barrier from Delivery MYRDD	Impact
A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis	Provide assessment of station footprint possibilities using current technologies and show possibilities for urban siting
I. Other Fueling Site/Terminal Operations	Show how to reduce station footprint within or equivalent to current requirements
K. Safety, Codes and Standards, Permitting	Identify main drivers of station footprint and requirements that do not contribute to reduced risk

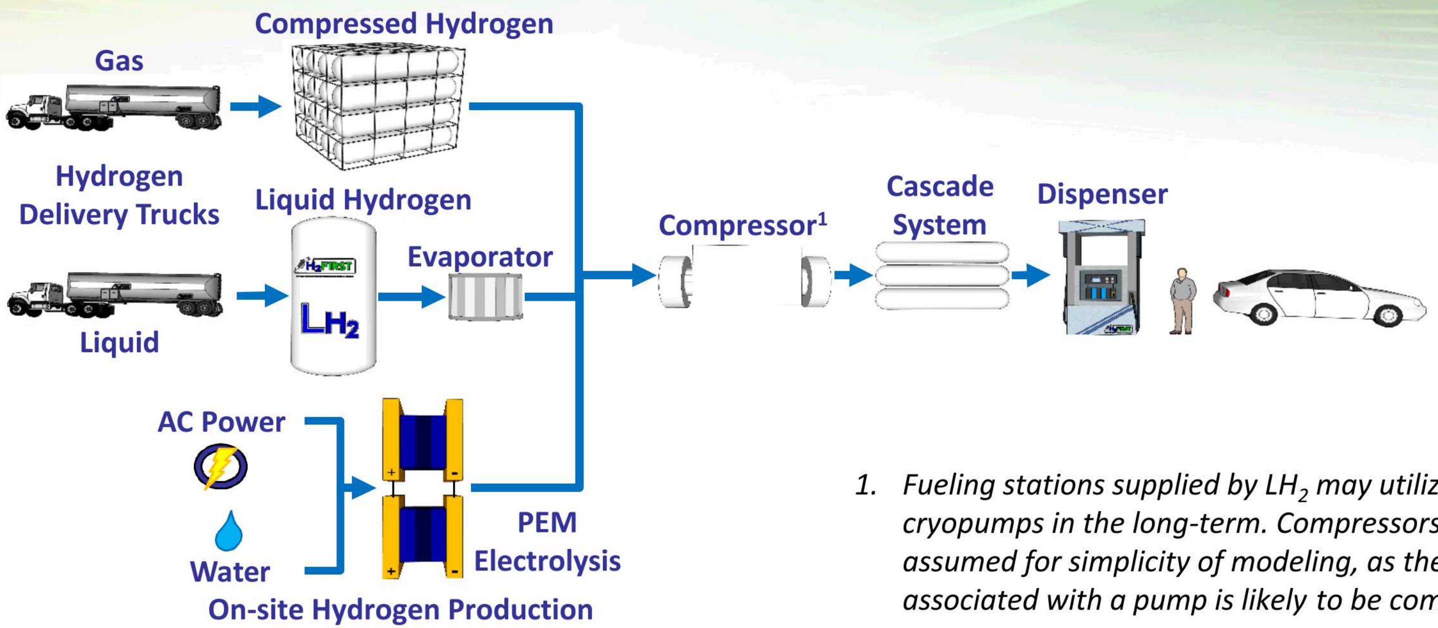
Approach: Develop base cases and assess relative impact of non-compliance/technology improvements

- Focus on **reducing station footprint**
  - Build on previous reference station analyses that examined system layout, physical footprint, and cost
- Make comparisons to base case designs for
  1. delivered gas,
  2. delivered liquid, and
  3. on-site production via electrolysis
  - Fully compliant, all requirements and setback distances
- Assess the impact of:
  - New code requirements
  - New delivery methods
  - Gasoline refueling station co-location
  - Underground storage
  - Roof-top storage
  - Performance-based designs



Milestone	Status
Complete a report based on workshop feedback and includes assessment of layout suitability in at least 3 cities	50% Complete Preliminary siting study complete, report in progress.
Provide designs for compact station concepts which enable siting on 3X the number of HFSs identified as "Potential" in the Harris et al. report for the dense urban example of San Francisco	90% Complete Preliminary siting study complete, including 7 sites identified in Harris et al. report

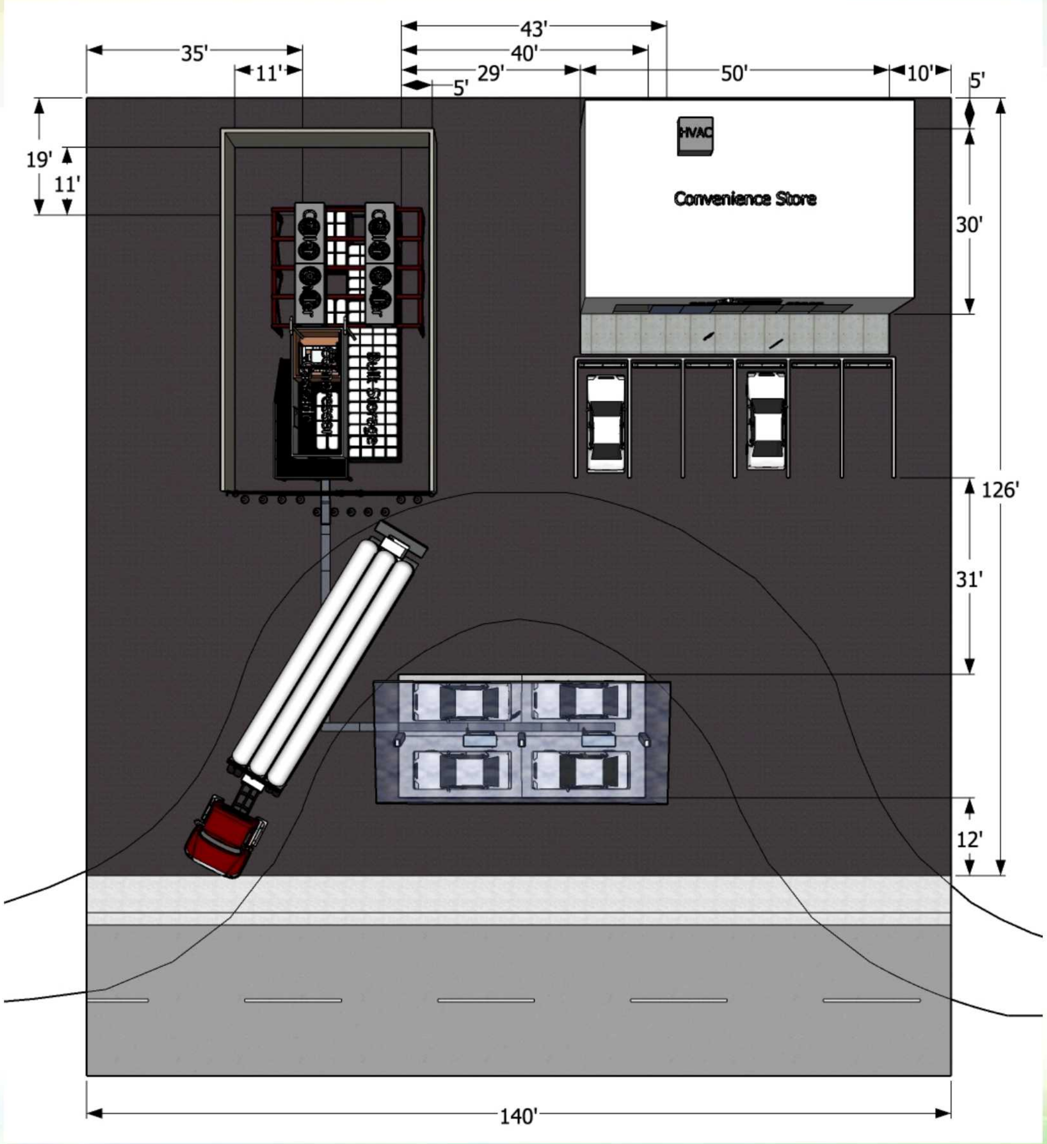
Accomplishment: Specified components needed for three methods of hydrogen supply



1. *Fueling stations supplied by LH_2 may utilize cryopumps in the long-term. Compressors were assumed for simplicity of modeling, as the footprint associated with a pump is likely to be comparable.*

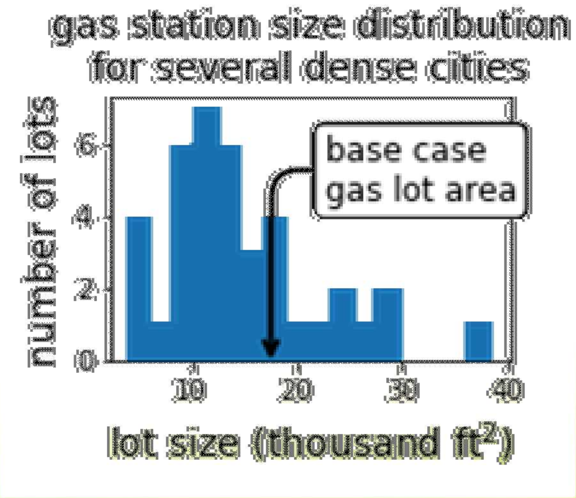
- Compressor
  - 25 kg/hr flow rate (constant 600 kg/day)
  - Outlet pressure of 94.4 MPa (13,688 psi)
- Chillers
  - 25.2 kW (7.2 tons) of refrigeration needed for each chiller
  - Aluminum cooling block of 1,330 kg (0.49 m^3) needed for each
- Cascade
  - 10 cascade units, each containing 5 (1:1:3) pressure vessels
  - Outlet flow rate 60 kg/hr to each dispenser
- Dispensing
  - 4 fueling positions, 70 MPa, -40°C

Accomplishment: Delivery truck path (rather than setback distances) extends lot in two dimensions for base case gas



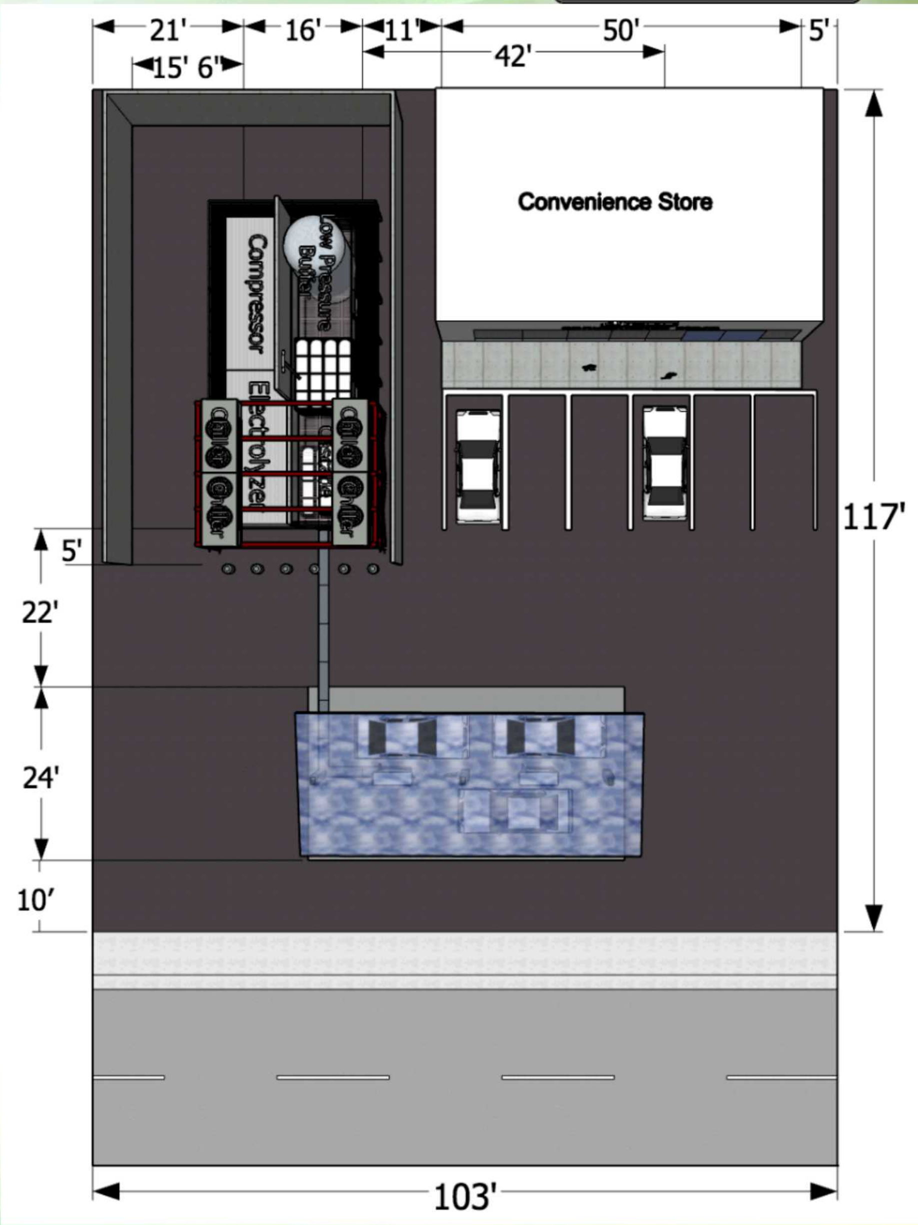
- Lot Size: 126 x 140 ft
- Total Area: 17,640 ft^2

(Slightly larger than median of [small sample of] existing urban gas stations)

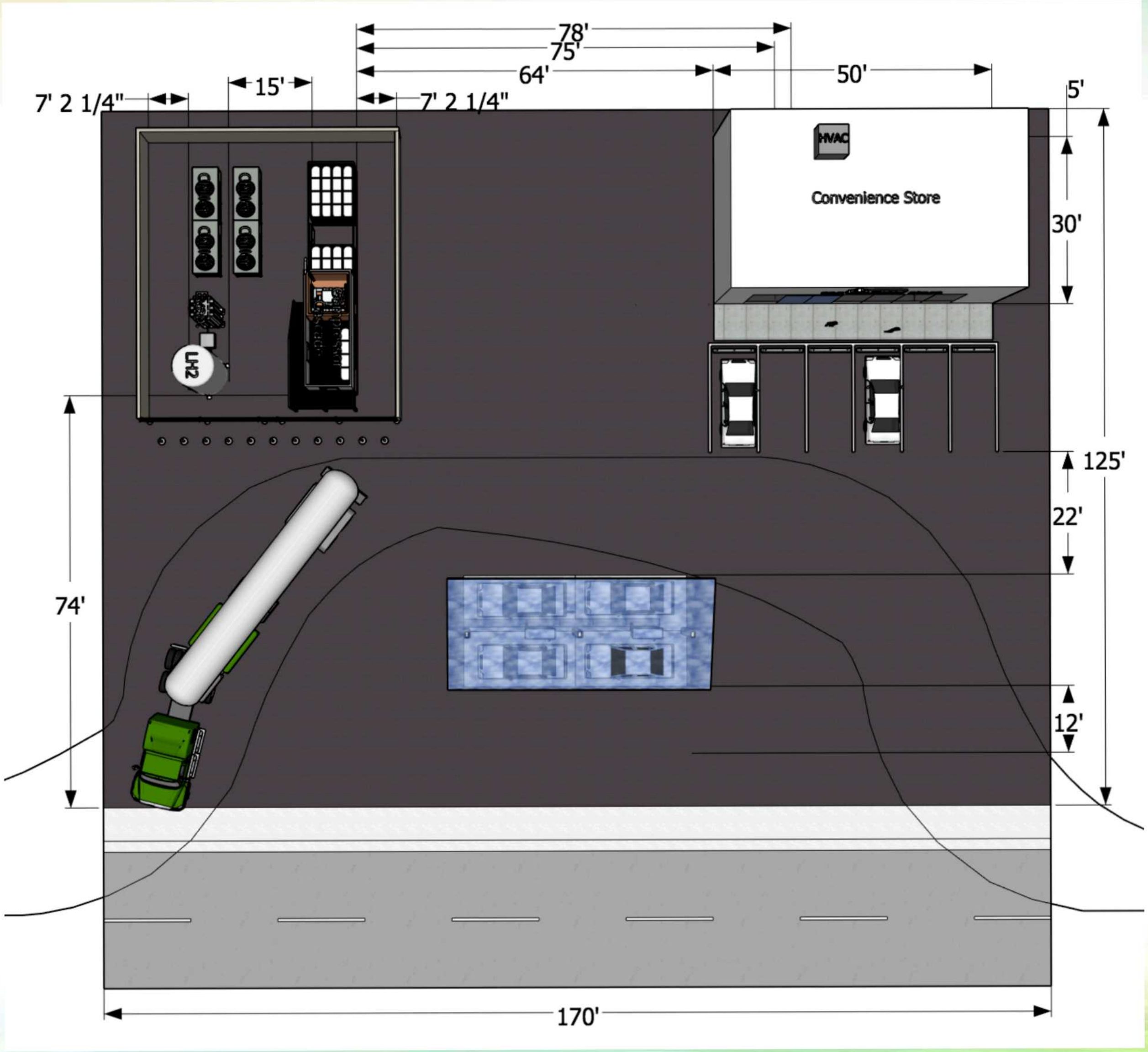


Accomplishment: Without delivery, on-site electrolysis base case has a small footprint

- PEM electrolyzer (nominal 2 MW)
  - Approximate footprint 40 ft + 20 ft container
  - Supplies 25 kg of GH_2 at 20 bar to compressor
  - Sized for 24 hour/day use
- GH_2 low pressure buffer (gas reservoir)
  - Used to smooth the flow from the electrolyzer to the compressor.
  - 90 kg of usable hydrogen at full capacity (50 bar)
- No delivery truck
  - Greatly reduces footprint
  - Could reduce resiliency
    - No direct way to delivery emergency hydrogen if electrolyzer is down
- Lot Size: 117 x 103 ft
- Total Area: 12,051 ft^2



Accomplishment: Base case liquid footprint is large due to delivery truck and non-reducible 75 ft. air intakes setback



- Bulk liquid storage
  - 800 kg, 11,299 L (2,985 gal)
- Lot size: 170 x 125 ft
- Total Area: 21,250 ft^2

Accomplishment: Identified challenges in interpretation and implementation of NFPA 2 leading to code updates

H2FIRST

Gaseous setback distances

- Large system can have "bulk storage" before and after compressor

- Complexity of system makes selection of single pressure and diameter challenging
  - Single system could take worst-case: maximum pressure from one area and maximum ID from other area
  - Could also calculate setback distances for each system section and select largest
    - This is specified in Appendix I, but nowhere else

Calculations for larger system may lead to unintended setback distances

Liquid setback distances

- Hybrid system (liquid-to-gas) analyzed as all-liquid system
  - ***Recently changed in 2020 Ed. of NFPA 55***
- Setback distances are different for most exposures, only a few able to be reduced

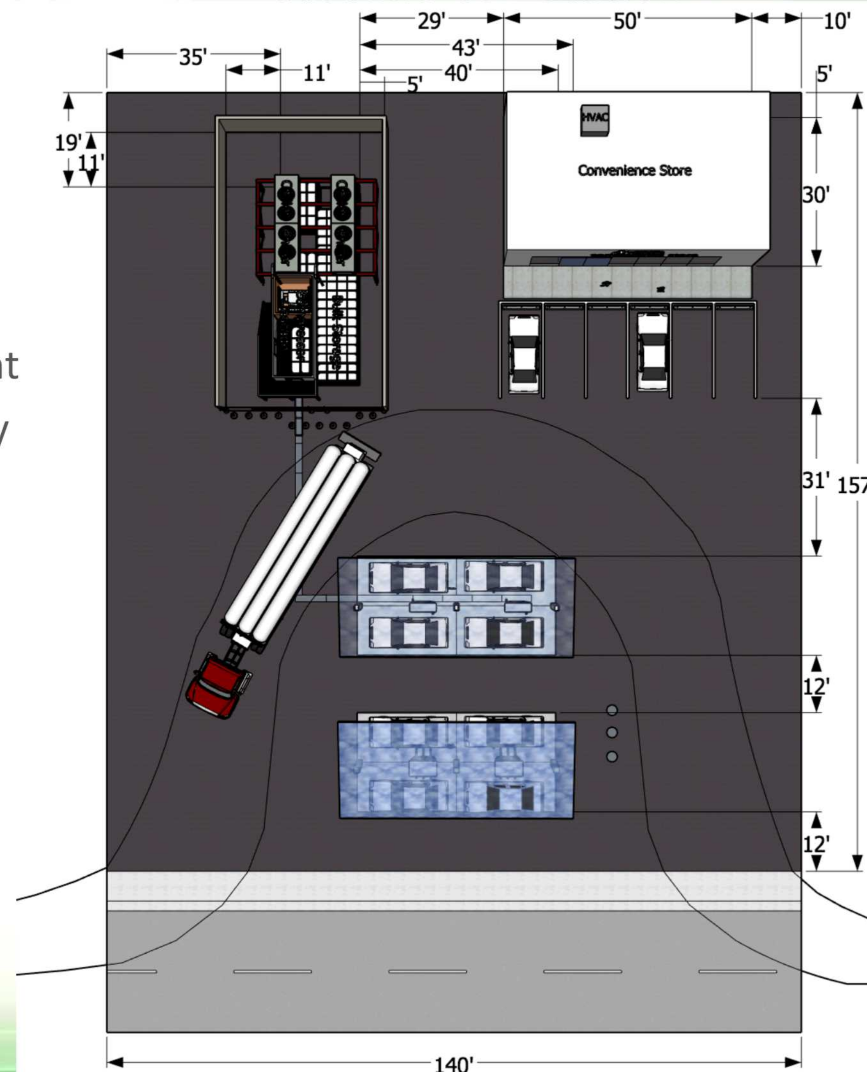
Group	Exposure	Reducible	Distance
1	1 Lot lines	Yes	15 m (50 ft)
	2 Air intakes		23 m (75 ft)
	3 Operable openings in buildings		23 m (75 ft)
	4 Ignition sources		15 m (50 ft)
2	5 Places of public assembly		23 m (75 ft)
	6 Parked cars		1.7 m (25 ft)
3	7(a)(1) Sprinklered non-combustible building	Yes	1.5 m (5 ft)
	7(a)(2)(i) Unsprinklered, without fire-rated wall	Yes	15 m (50 ft)
	7(a)(2)(ii) Unsprinklered, with fire-rated wall	Yes	1.5 m (5 ft)
	7(b)(1) Sprinklered combustible building	Yes	15 m (50 ft)
	7(b)(2) Unsprinklered combustible building	Yes	23 m (75 ft)
	8 Flammable gas systems (other than H2)	Yes	23 m (75 ft)
	9 Between stationary LH2 containers		1.5 m (5 ft)
	10 All classes of flammable and combustible liquids	Yes	23 m (75 ft)
	11 Hazardous material storage including LO2	Yes	23 m (75 ft)
	12 Heavy timber, coal	Yes	23 m (75 ft)
	13 Wall openings		15 m (50 ft)
	14 Inlet to underground sewers		1.5 m (5 ft)
	15a Utilities overhead: public transit electric wire		15 m (50 ft)
	15b Utilities overhead: other overhead electric wire		7.5 m(25 ft)
	15c Utilities overhead: hazardous material piping		4.6 m (15 ft)
	16 Flammable gas metering and regulating stations		4.6 m (15 ft)

Accomplishment: Developed new designs and compared them to base cases, based on a range of assumptions

- **Effects of future changes to NFPA 2**
  - Significant impact on minimum footprint, but other factors (traffic and delivery truck path) reduce impact on full layout
- **Alternate Delivery**
  - Smaller delivery trucks greatly reduce footprint
  - Higher pressure can maintain delivery capacity
- **Gasoline Co-Location**
  - Needs to meet NFPA 2/55 and NFPA 30/30A
  - Space for underground gasoline tanks and additional dispensers

Different design changes have different impacts on station footprints

Gasoline Co-Location



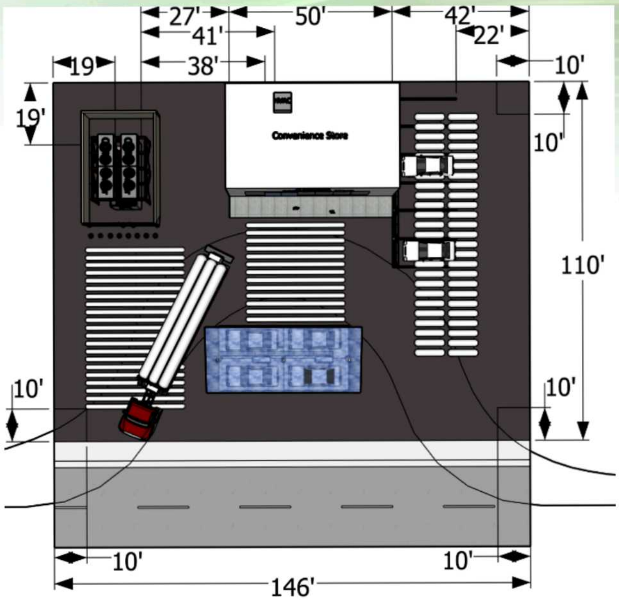
Accomplishment: Created elevated and underground storage station designs that reduce footprint

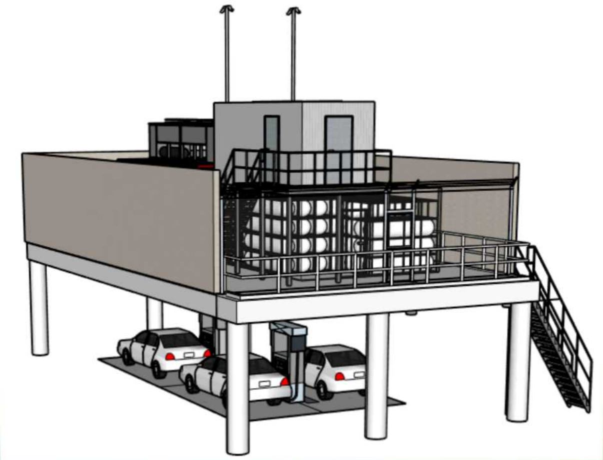
Underground Storage

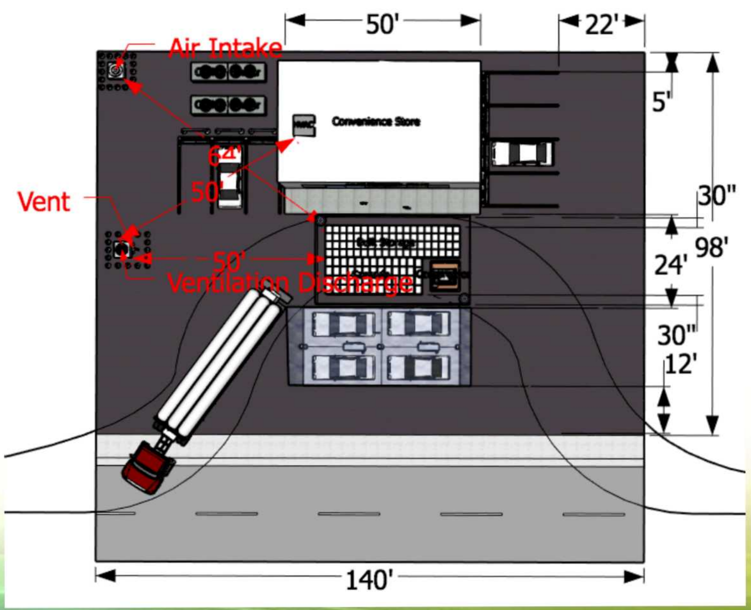
- Direct burial
- Vault

Elevated Storage

- Setback distances still apply to line-of-sight
- Storage/equipment on building (e.g., convenience store) induce many new and difficult requirements
- Storage and equipment could be ~140 tons
- Seismic loading and aesthetics are issues







Accomplishment: Summary of lot sizes for all cases

	Design	Total Lot Area (ft^2)	Reduction from Base Case
Delivered Gas	Base Case Gas	17,640	--
	New NFPA Separation Distances	17,640	0.00%
	New Delivery Single Truck	14,391	18.42%
	New Delivery Double Truck	15,875	10.01%
	Gasoline Co-Location	21,980	-24.60% (Increase)
	Underground Direct-Bury	16,060	8.96%
	Underground Vault	13,720	**22.22%**
	Rooftop Storage	15,400	12.70%
Delivered Liquid	Base Case Liquid	21,250	0.00%
	New NFPA Separation Distances	18,252	14.11%
	New Liquid Delivery	19,080	10.21%
	Gasoline Co-Location	**25,330**	-19.20% (Increase)
	Underground Direct-Bury	15,515	**26.99%**
	Rooftop Storage	19,840	6.63 %
On-Site Electrolysis	Base Case	14,756	0.00%
	New NFPA Separation Distances	**11,934**	19.12%
	Gasoline Co-Location	21,980	-48.96% (Increase)
	Underground Direct-Bury	13,340	9.60%
	Underground Vault	16,240	-10.06% (Increase)
	Rooftop Storage	11,466	22.30%

Progress: Approximated potential to site stations in dense urban areas

H2FIRST

- Cities in five states (CA, CT, MD, MA, NY) were selected
- Total of 40 gasoline stations in these cities were analyzed
  - Located using Google Maps
- The lot size (ft^2) of each station was obtained from county property tax records
- The lot size was compared to generic station designs
- The number of available stations that can be converted into hydrogen stations were identified

Illustrates potential effect of reduction in lot sizes

Siting results on delivered gas designs

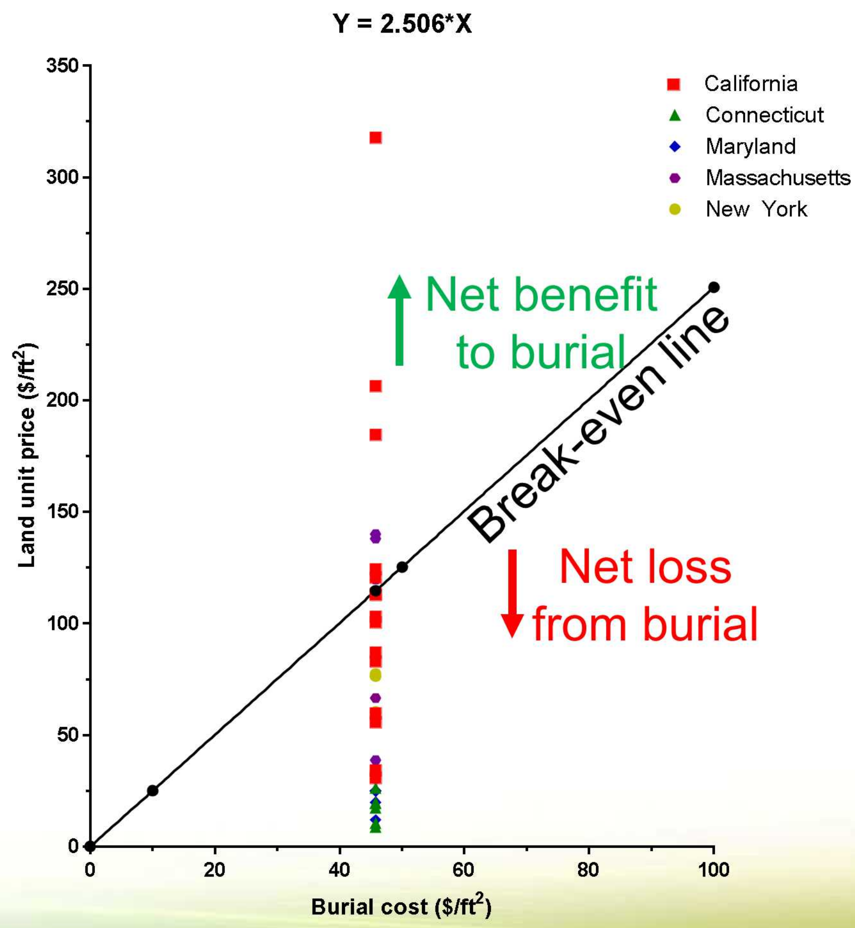
	Lot Area (ft^2)	Reduction from Base Case	Lot available (out of 40) [%]
Base Case Gas	17,640	--	12 [30%]
New NFPA Separation Distances	17,640	0.00%	12 [30%]
New Delivery Single Truck	14,391	18.42%	16 [40%]
New Delivery Double Truck	15,875	10.01%	16 [40%]
Gasoline Co-Location	21,980	-24.60% (increase)	8 [20%]
Underground Direct-Bury	16,060	8.96%	16 [40%]
Underground Vault	13,720	22.22%	18 [45%]
Rooftop Storage	15,400	12.70%	16 [40%]

Progress: Demonstrated economic impact of station design changes (with special consideration for underground)

- Same 40 gasoline stations analyzed
- The land unit price ($/ft²) calculated by the land price and lot size obtained from county property tax record
- Underground direct-bury cost estimated from underground propane tank installation cost: **$45.8/ft²**
- Slope of break-even line determined by ratio of burial area for each design and the difference of lot size between base case and underground burial designs
- Multiple possible burial costs considered to show sensitivity vs land unit price

Illustrates potential economic trade-off of design change relative to base case

Gaseous hydrogen underground direct-bury

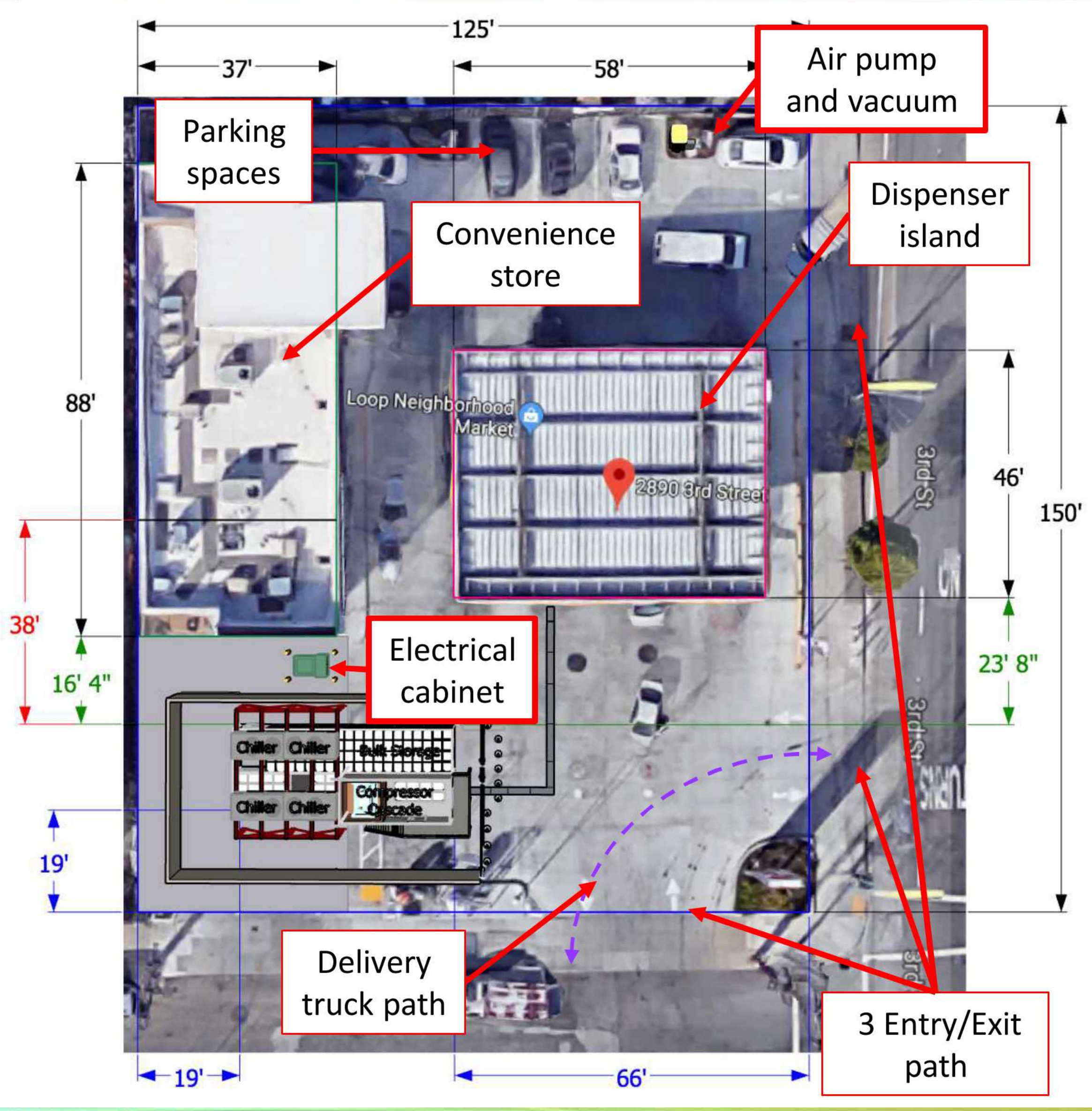


Accomplishment: Performed real station co-location case study to show impact of site-specific features

- San Francisco station on a corner
  - Delivery truck path is simplified
- One vehicle entry/exit blocked by hydrogen system
  - Still has 3 remaining
- Electrical cabinet was moved
- Air intakes on roof of convenience store would have to be moved
  - Must be 38 feet from hydrogen system

	SF Site Colocation	Generic Co-location
Lot Size	18,000 ft^2	21,000 ft^2
Convenience store size	3,256 ft^2	1,500 ft^2
Dispenser island	2,668 ft^2	1,600 ft^2

Real-world locations will differ from generic designs

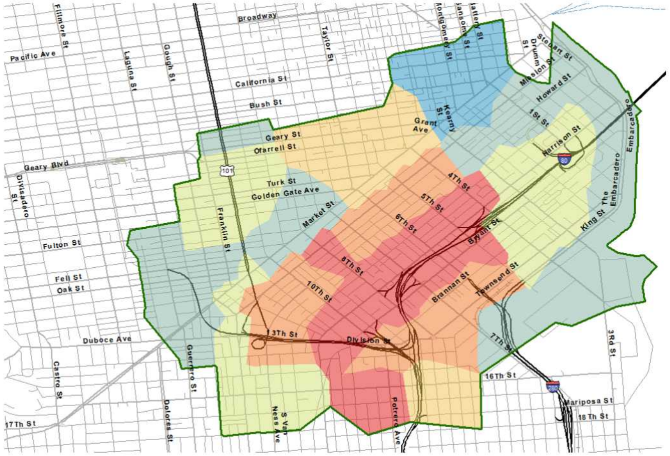


Remaining Barriers and Challenges

- Project challenge: Station design choices are based on code requirements for general hazards applicable to all stations
  - Choice of basis affects resulting requirements
  - Difference between alternative means and performance-based design
- Industry challenge: Current setback distances only take credit for fire-rated wall
  - Other active or passive prevention or mitigation measures considered only on a case-by-case basis
  - Project challenge: no way to incorporate these credits into generic station designs
- Project challenge: Siting and economics are specific to each particular location
  - Illustrative comparisons are useful for showing trends

Future Work

- Remainder of FY19
  - Finalize siting study, and economic comparisons
  - Make reduced footprint designs based on alternate means
  - Prepare final report
- Potential Future Work
  - Incorporation of standardized alternative means into safety codes and standards
  - Exploration of underground burial safety code requirements and justifications



Any proposed future work is subject to change based on funding levels

Response to Reviewer Comments

AMR 2018 Comment	Response
The project team should consider starting with a base case that focuses on what needs to be done to build a hydrogen station on a greenfield site and achieve the same footprint as a gasoline station.	This is the approach taken by the project; different design changes are compared to a base case, and all of the resulting lot sizes are compared to actual gasoline station sizes in the siting study.
The level of impact would change very significantly (in a positive direction) if the team took an actual gasoline or greenfield site and went through the same exercise.	Case study of San Francisco co-location station shows how generic station designs will differ from real-world designs, and how the same hydrogen system could fit into a real-world co-location station.
Instead of a national impact study, it is suggested that the team focus specifically on California and one state in the Northeast (the most challenging one) – this may help narrow efforts.	The siting study focused on cities in California, New York, Massachusetts, Connecticut, and Maryland; all of these states have large urban populations and have signed an MOU to promote hydrogen use.
The project team may want to consider eliminating rooftop storage as an option and focus all future efforts on underground storage.	Rooftop storage was retained as a cursory comparison for completeness, but the potential issues with this design are significant. Much more effort was put into different underground scenarios.

Collaborations

H2FIRST

- H2FIRST itself is a **SNL-NREL** co-led, collaborative project and members of both labs contributed heavily to this project.
- To be as relevant and useful as possible, the project integrates input and feedback from many stakeholders, such as:
  - H2USA's Hydrogen Fueling Station Working Group
  - California Fuel Cell Partnership
  - California Energy Commission
  - California Air Resources Board
  - UC Berkeley
  - Argonne National Lab
  - H2 Logic
  - Hydrogenics
  - ITM Power
  - Linde
  - Nuvera
  - PDC Machines
  - Proton OnSite
  - Siemens AG
  - FirstElement

Summary

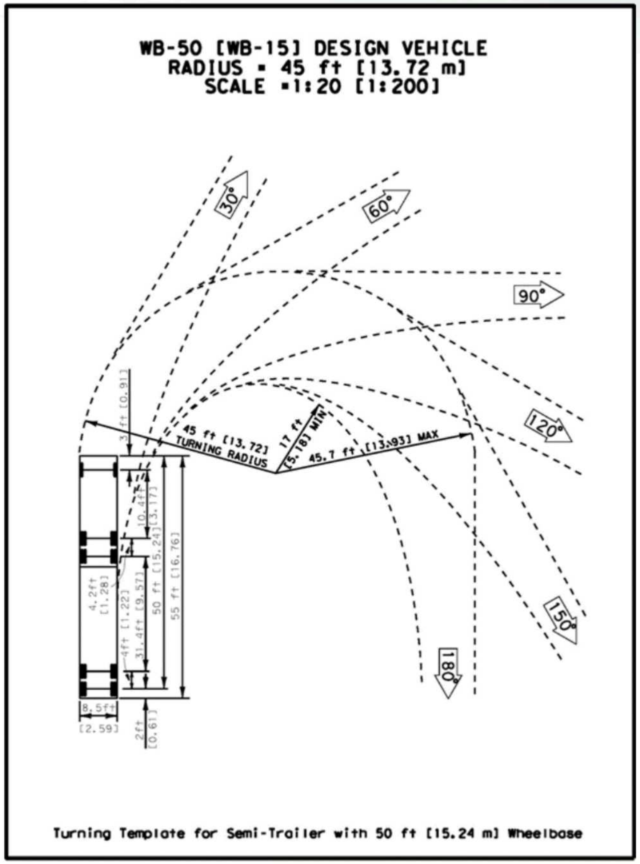
- **Relevance and Impact**
  - Reduction of refueling station footprint identified by FCTO and H2USA as high priority
- **Approach**
  - Comparison of different design changes to base cases quantifies impact
  - Changes include NFPA 2 code changes, gasoline co-location, alternate delivery truck, underground storage, and risk-informed designs
- **Accomplishments**
  - 600 kg/day stations completed for delivered gas, delivered liquid, and on-site electrolysis
  - Footprints quantified for base cases, alternate delivery, upcoming fire code changes, underground and elevated storage, and gasoline co-location
  - Real-world co-location case study on San Francisco gas station
- **Progress**
  - Siting study in US cities in California and Northeast shows impact of station lot size changes
  - Economic comparison shows trade-off trends for design changes over wide range of sensitivity
- **Future Work**
  - Finalizing siting study and economic comparison
  - Reduced footprint designs using alternate means
  - Final report preparation

TECHNICAL BACK-UP SLIDES

Non-hydrogen station components have large impact on footprint

Assumptions and considerations:

- Delivery truck path
  - Trucks must be capable of turning without reversing
  - Corner lot not considered (entry and exit only on single lot side)
- Convenience store
  - 50 x 30 ft
- Parking/Traffic Flow
  - Convenience store parking
  - Fueling positions
  - UT Parking Lot Design Manual
- Kept consistent between designs
- System was idealized for comparison
  - Other location-specific factors will also have large impact on footprint



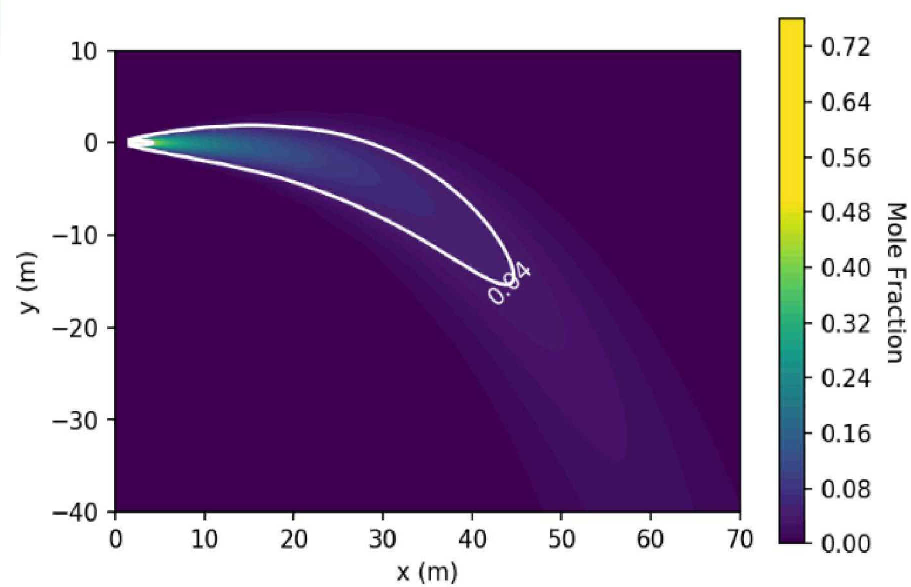
Texas DOT Road Design Manual

Stakeholder feedback solicited from:

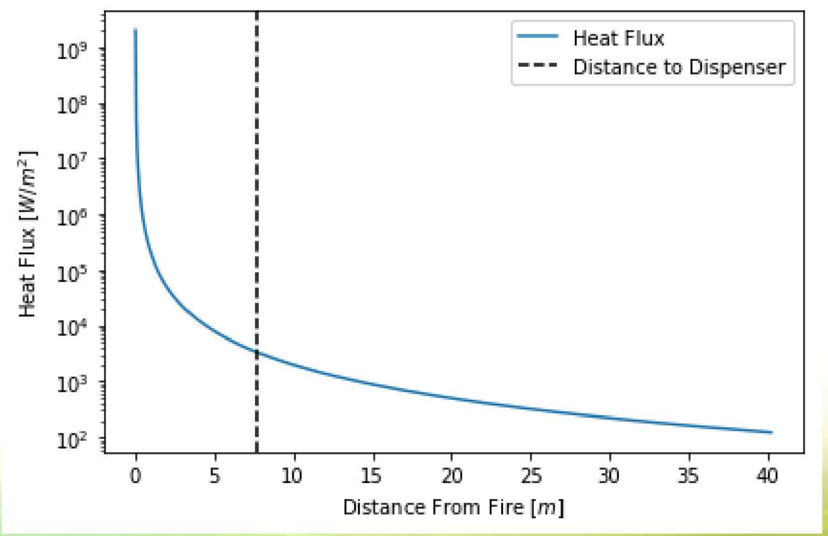
Name	Representation
Kyle McKeown	Linde
Amgad Elgowainy	Argonne National Laboratory
Michael Ciotti	Linde
Jonathan Zimmerman	Sandia National Laboratories
Patricia Gharagozloo	Sandia National Laboratories
Bikram Roy Chowdhury	Sandia National Laboratories
David Farese	Air Products
Jennifer Hamilton	Frontier Energy/CaFCP
Jay Keller	Zero Carbon Energy Solutions
Lucas White	Air Products and Chemicals, Inc
Gerald Hayes	Air Liquide
Lynne Kilpatrick	Sunnyvale Public Safety
James Petrecky	PDC Machines
Reid Larson	Chart Industries
Kevin Harris	Hexagon
Xuefang Li	Shandong University, China
Matt Bray	CARB
Sujin Wren	Hydrogenics Corporation
Sebastian Serrato	California Energy Commission
William Buttner	NREL
Cory Kreutzer	NREL
Lesley Stern	CARB
Edgar Wolff-Klammer	Underwriters Laboratories
Samuel Trompezinski	Air Liquide
Michael Kashuba	GoBiz

Alternative means

- Determine what performance criteria is applicable to each exposure.
  - NFPA 2 Annex I Table I.2(c) and (d) were used to determine the performance criteria and the hazardous material scenario
- Get numerical values that can be use to determine the separation distances for each exposure
  - Heat flux
  - Hydrogen flammable concentrations
  - Frequency of fatalities



Exposure	Heat flux	Notes
Personnel	1,577 W/m^2	Threshold to which personnel with appropriate clothing can be continuously exposed. Used as the **“no harm”** value.
Personnel	4,732 W/m^2	Threshold for exposure to employees for a maximum of 3 minutes.
Combustible materials	20,000 W/m^2	Minimum heat flux for the nonpiloted ignition of combustible materials, such as wood.
Non-combustible materials	25,237 W/m^2	Threshold heat flux imposed by the International Fire Code for noncombustible materials.

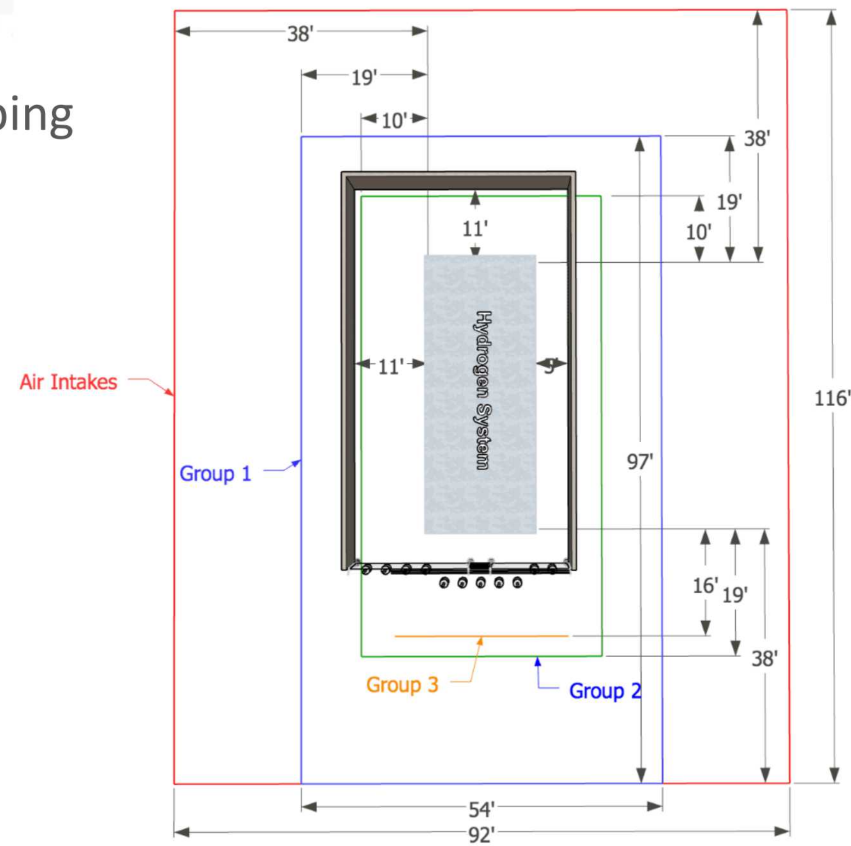


Accomplishment: Minimum footprint determined from outdoor bulk gas setback distances

H2FIRST

- Minimum Footprint
  - Hydrogen system only
- Based on pressure and ID of connecting piping

Grp		Description
1	a	Lot lines
	b	Air intakes (HVAC, compressors, other)
	c	Operable openings in buildings and structures
	d	Ignition sources such as open flames and welding
2	a	Exposed persons other than those servicing the system
	b	Parked cars
3	a	Buildings of noncombustible non-fire-rated construction
	b	Buildings of combustible construction
	c	Flammable gas storage systems above or below ground
	d	Hazardous materials storage systems above or below ground
	e	Heavy timber, coal, or other slow-burning combustible solids
	f	Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper, or combustible waste and vegetation other than that found in maintained landscaped areas
	g	Unopenable openings in building and structures
	h	Encroachment by overhead utilities (horizontal distance from the vertical plane below the nearest overhead electrical wire of building service)
	i	Piping containing other hazardous materials
	j	Flammable gas metering and regulating stations such as natural gas or propane



Different Exposures Have Very Different Setback Distances

Accomplishment: Minimum footprint for outdoor bulk liquid differs significantly from gas

- Based on total amount of bulk liquid hydrogen
  - Not pressure or diameter of piping
- Groups 1, 2, and 3 still exist, but setback distances are not grouped

Exposure	Distance
1 Lot lines *	15 m (50 ft)
2 Air intakes	23 m (75 ft)
3 Operable openings in buildings	23 m (75 ft)
4 Ignition sources	15 m (50 ft)
5 Places of public assembly	23 m (75 ft)
6 Parked cars	1.7 m (25 ft)
7(a)(1) Sprinklered non-combustible building*	1.5 m (5 ft)
7(a)(2)(i) Unsprinklered, without fire-rated wall*	15 m (50 ft)
7(a)(2)(ii) Unsprinklered, with fire-rated wall*	1.5 m (5 ft)
7(b)(1) Sprinklered combustible building*	15 m (50 ft)
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8 Flammable gas systems (other than H2)*	23 m (75 ft)
9 Between stationary LH2 containers	1.5 m (5 ft)
10 All classes of flammable and combustible liquids*	23 m (75 ft)
11 Hazardous material storage including LO2*	23 m (75 ft)
12 Heavy timber, coal*	23 m (75 ft)
13 Wall openings	15 m (50 ft)
14 Inlet to underground sewers	1.5 m (5 ft)
15a Utilities overhead: public transit electric wire	15 m (50 ft)
15b Utilities overhead: other overhead electric wire	7.5 m (25 ft)
15c Utilities overhead: hazardous material piping	4.6 m (15 ft)
16 Flammable gas metering and regulating stations	4.6 m (15 ft)

REVIEWER-ONLY SLIDES

Critical Assumptions and Issues

- We assume a single station capacity of 600 kg/day
  - This is significantly larger than previous H2FIRST reference station analyses, but may or may not be valid for particular local market conditions
- We assume that local AHJs will follow the NFPA 2 code
  - Anecdotal experience shows that different AHJs have specific concerns not listed in code or alternative interpretation
  - Anecdotal experience also shows that most designs need at least some deviation from code, whereas our generic designs follow code as completely as possible
- We assume that generic layouts can be applied to specific sites in siting study
  - Site-specific exposures (e.g., air intakes), local building and zoning requirements, and road access conditions will be considered as much as practical, but difficult to fully incorporate in large study
  - Single station case study illustrates some of these effects compared to generic design
- We assume that all stations will use a compressed gas cascade and chiller to dispense H_2 at H70-T40 conditions
  - Alternate designs/technologies may fuel in alternate ways, such as high pressure pumping of LH2 (briefly considered in previous reference station analysis)

Publications and Presentations

- Safety Codes and Standards Tech Team Meeting Webinar, 8/9/2018
- Workshop for Preliminary Results and Stakeholder Feedback, Livermore, CA, 9/6/2018
- DOE FCTO Weekly Staff Meeting, 2/4/2019