SAND2020-0754PE

H2FIRST

Hydrogen Fueling Infrastructure Research and Station Technology

Hydrogen Refueling Reference Station Lot Size Analysis for Urban Sites

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Sandia National Laboratories

Briefing to FCTO

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SAND2020-XXXX

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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

Background: Hydrogen Vehicle Fueling Infrastructure

- Past and current hydrogen refueling stations in California have capacities of 350 kg/day (or less)
  - Higher capacity stations needed to meet increasing demand
- Past stations with liquid hydrogen (LH2) storage range from 30,000 to >100,000 ft^2
  - Urban locations require much smaller footprints

- **DOE FCTO Target: Reduce footprint of liquid stations by 40% by 2022, relative to 2016 baseline**

BM1
BDE25

- Project 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

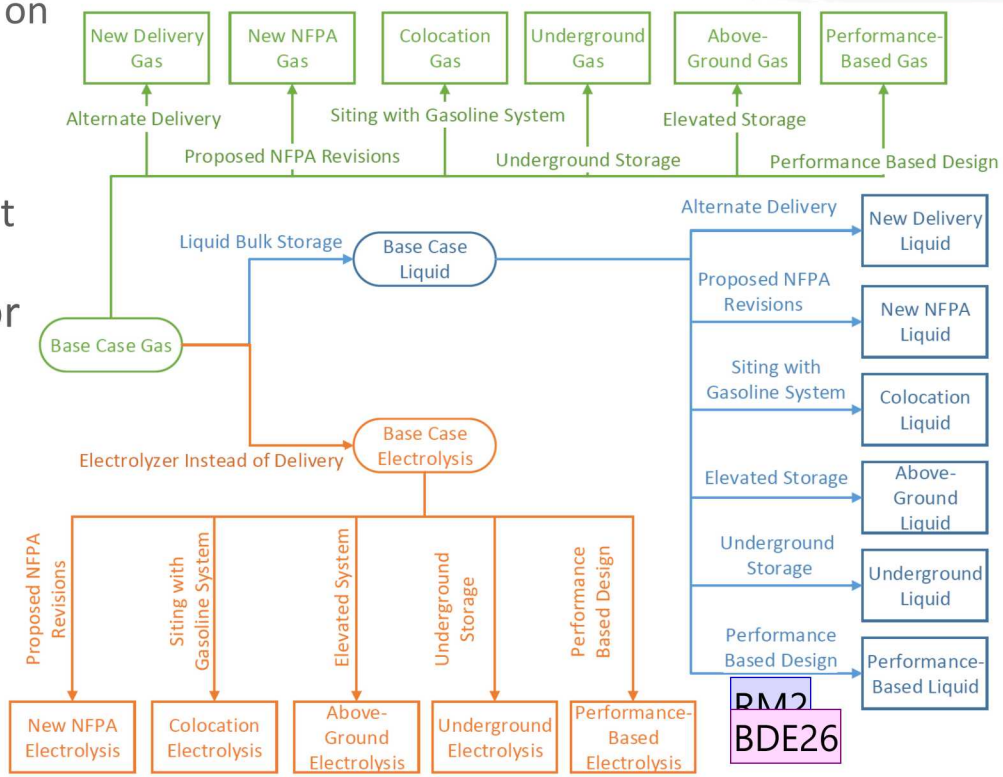
Slide 3

RM1 Added a space between FCTO Target and Objective and added Project in front of objective to clearly separate target and project objective.
Richards, Mark, 1/7/2020

BDE25 Makes sense, agree
Brian Ehrhart, 1/16/2020

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

- Focus on **reducing station footprint**
  - Previous reference station analyses focused on system layout, physical footprint, and cost
- Simplified, generic, rectangular stations
  - All requirements and setback distances met
- Make **comparisons** to base case designs for
  1. Delivered gas,
  2. Delivered liquid, and
  3. On-site production via electrolysis
- Assess the impact of:
  - New code requirements
  - New delivery methods
  - Gasoline refueling station co-location
  - Underground storage
  - Roof-top storage
  - Performance-based designs

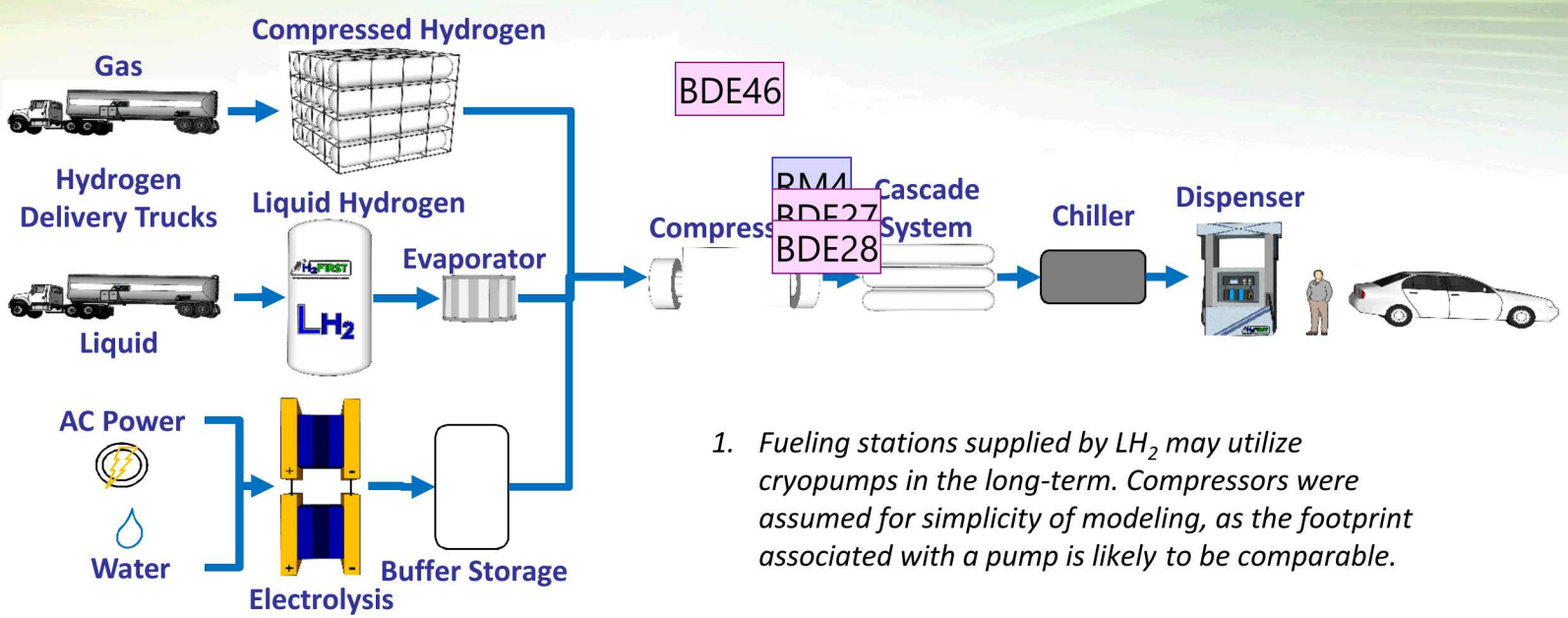


Slide 4

RM2 Can Non-Prescriptive Electrolysis be changed to Performance-Based Electrolysis? Consistency with other diagram elements.
Richards, Mark, 1/7/2020

BDE26 Changed in updated image
Brian Ehrhart, 1/16/2020

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 BDE29
  - 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

Slide 5

RM3 Is 25 kg/day compressor peak/rated or average flow? Probably can't run compressor non-stop (cascade will fill at some point).
Richards, Mark, 1/7/2020

BDE29 Rated flow. For the design point of 600 kg/day dispensed, and given the fueling demand profile in HRSAM, the compressor would run non-stop 24 hours/day. However, if (and when) the station dispensed less than this amount, the compressor would need to be shut off like you suggest.
Brian Ehrhart, 1/16/2020

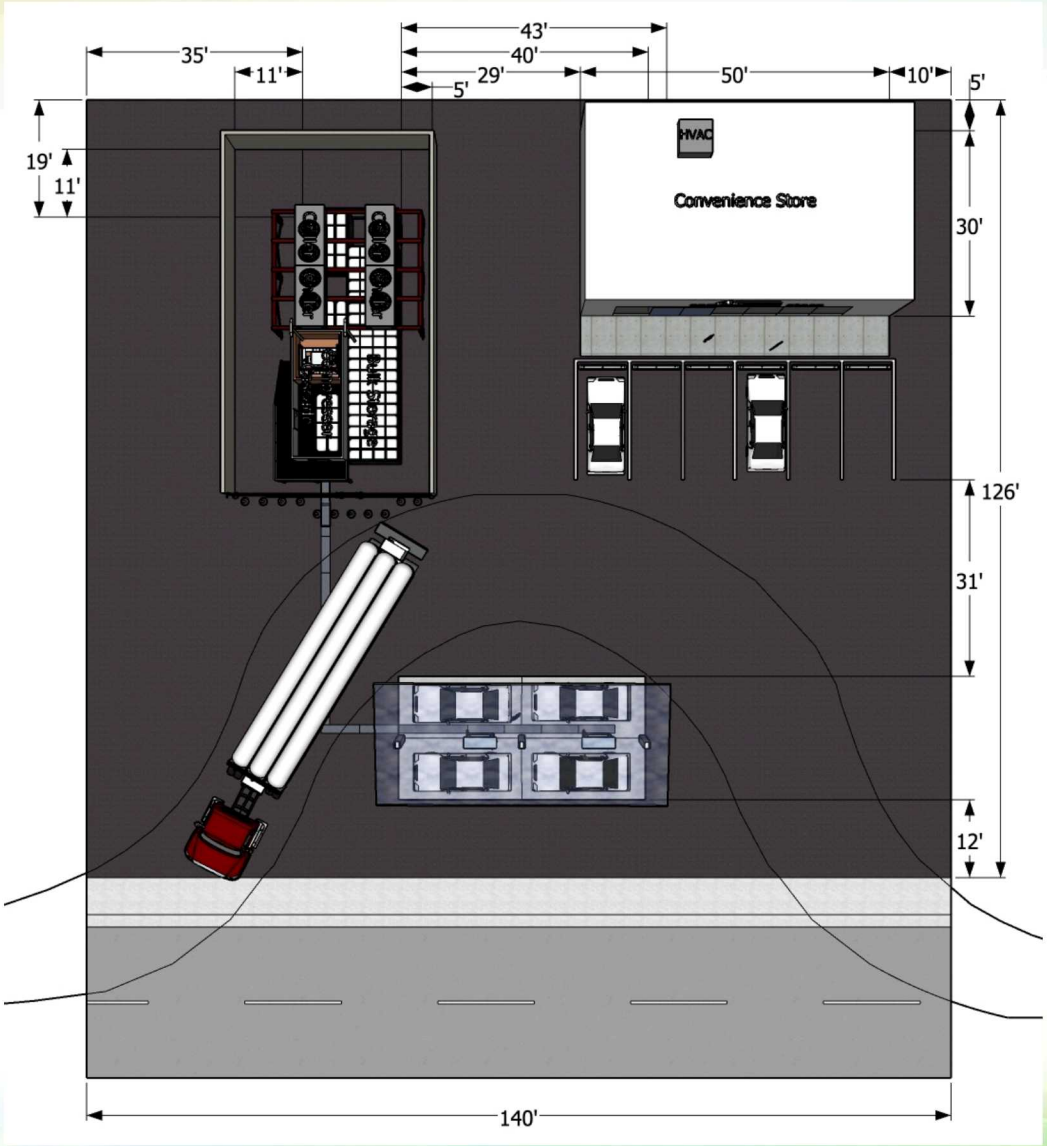
RM4 What happened to the compressor cartoon? Looks like there is an white box obscuring the middle. Also, there's a footnote "1" there that should be removed if possible (or obscured).
Richards, Mark, 1/7/2020

BDE27 I believe the compressor cartoon has been like that for a while; I don't think the white box is meant to obsure it, I think it originally meant to be a generic equipment housing?
Brian Ehrhart, 1/16/2020

BDE28 The footnote 1 was something Neha asked me to add a while back; it refers to the note (1.) right next to it
Brian Ehrhart, 1/16/2020

BDE46 Based on HDTT presentaiton feedback, added buffer storage for electrolyzer and chiller before dispenser
Brian Ehrhart, 1/16/2020

Base Case Gas: Delivery truck path (rather than setback distances) extends lot in two dimensions

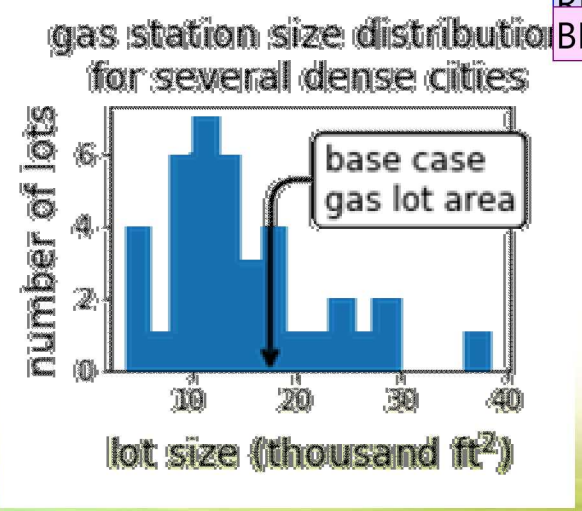


- Lot Size: 126 x 140 ft
- Total Area: 17,640 ft^2

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

BM6 BDE30

BM7 BDE31



Slide 6

RM6 Consider change to: "...median of a small sample of existing..." to eliminate the double parens/bracket combo.
Richards, Mark, 1/7/2020

BDE30 Done
Brian Ehrhart, 1/16/2020

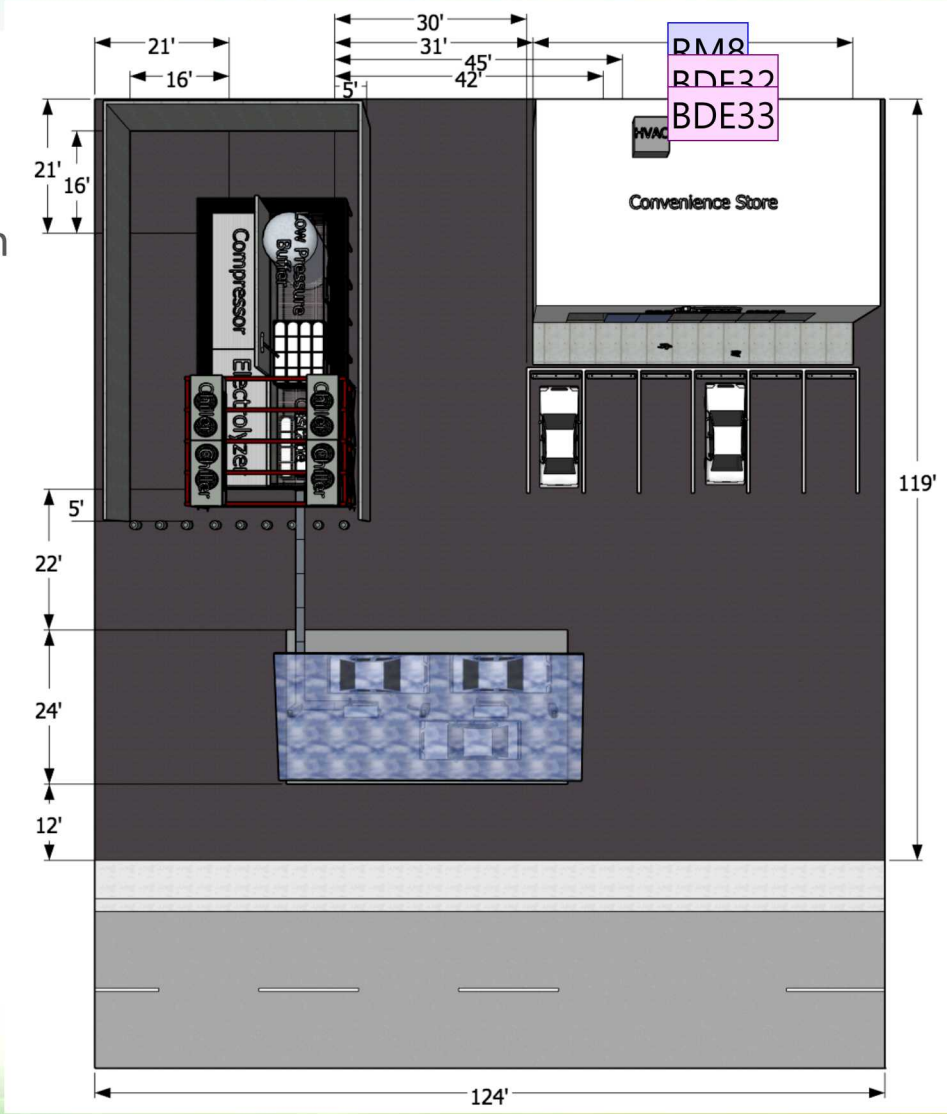
RM7 Just curious: does this distribution only include stations with c-stores? I imagine removing the c-store shrinks the space requirement appreciably.

After getting further on, it appears that this may be the 40 lots that appear in slide 14. Don't know if it matters to make this clear at some point.
Richards, Mark, 1/7/2020

BDE31 Many stations do have c-stores, but we did not break out the stations by those that did/did not have them. C-store size can also vary widely.
Brian Ehrhart, 1/16/2020

Base Case Electrolysis: Small footprint without delivery

- PEM electrolyzer (nominal 2 MW)
  - Sized for 24 hour/day use
  - Buffer storage used to smooth flow from electrolyzer to compressor
- No delivery truck
  - Reduces footprint
  - Could reduce resiliency
    - No direct way to delivery emergency hydrogen if electrolyzer is down
    - Unless small truck or on corner lot
- Lot Size: 124 x 119 ft
- Total Area: 14,756 ft^2



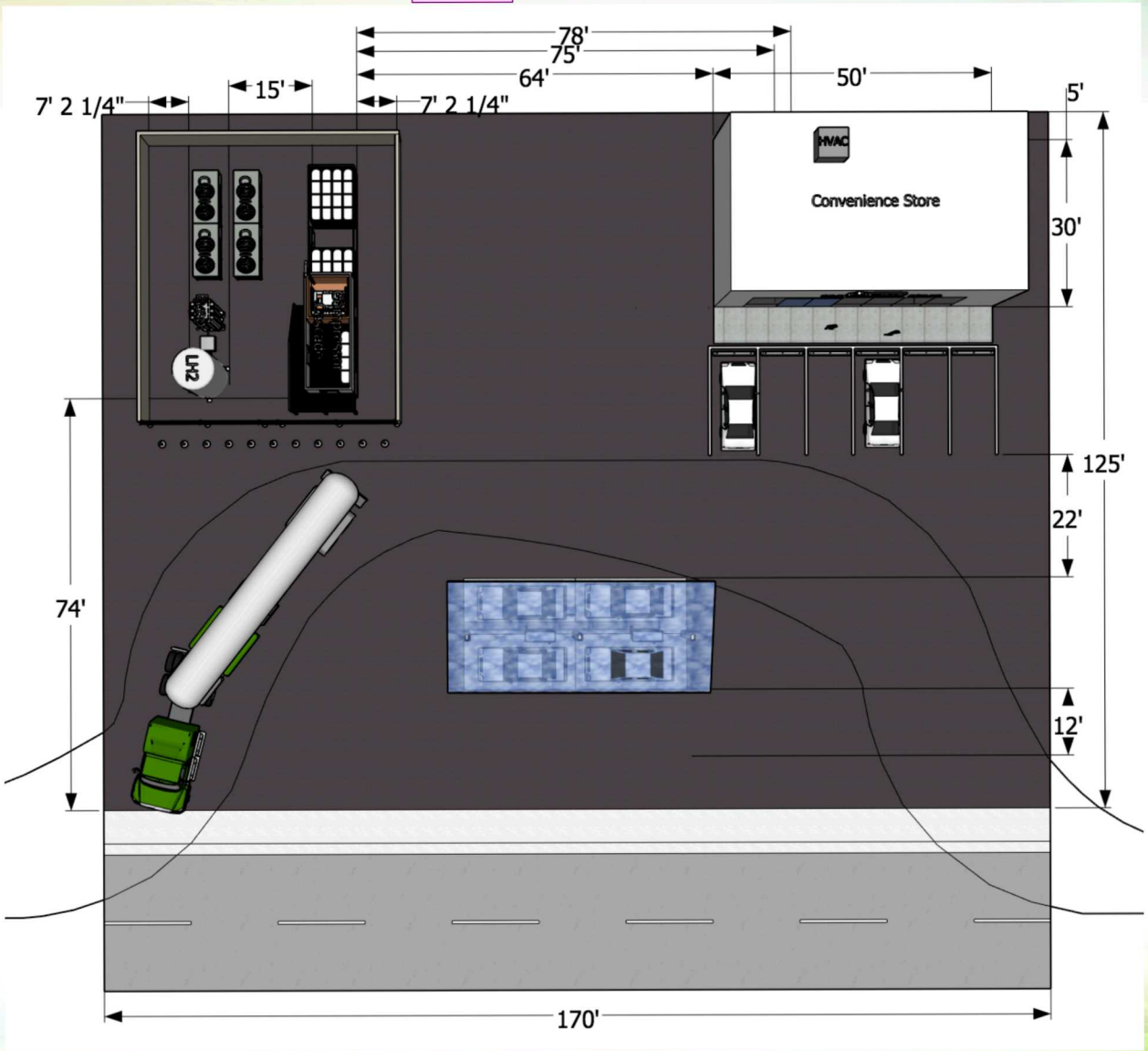
Slide 7

RM8 What happened to the HVAC unit on the c-store roof? Looks like the setback is still there (42').
Richards, Mark, 1/7/2020

BDE32 Oops! This was an older version of the image. The setback as shown still applied to the door of the c-store (hard to see, but there on the front of the store) we added the HVAC on the roof later to make it easier to see from the top-view.
Brian Ehrhart, 1/16/2020

BDE33 However, in checking this one, this is not the most recent version of the image that is in the final report; we had decided that having the door/HVAC (air intakes) so far over to the side of the c-store was unrealistic, and so moved them over slightly. I have updated the image here with the actual final image (from the report) and gone through the rest of the images (and tables) in the presentation to make sure they are updated as well. Sorry about that! This doesn't change any conclusions, but does tweak a few of the numbers.
Brian Ehrhart, 1/16/2020

Base Case Liquid: Large footprint due to delivery truck and non-reducible 75 ft intakes setback



- Bulk liquid storage
  - 800 kg, 11,299 L (2,985 gal)
- NFPA 2-2016 Section 8.3.2.3.1.6(A):
  - 75 ft setback to air intakes for all sizes of bulk liquid systems
  - Not reducible by insulation or fire-rated walls
- Lot size: 170 x 125 ft
- Total Area: 21,250 ft^2

Slide 8

RM9 Could be helpful here to quote or summarize the code clause(s) containing the 75' requirement (off to the right of the diagram).
Richards, Mark, 1/7/2020

BDE34 Done
Brian Ehrhart, 1/16/2020

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

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

RM10 BDE35 n 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 55/2***
- Setbacks are different for most exposure RM11 BDE36
- Only a few able to be reduced in current code RM1 BDE

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

Slide 9

RM10 What is the implication of only being in Appx I?
Richards, Mark, 1/7/2020

BDE35 The appendicies are in the code for information only, not as "enforcable" language. Often they describe background information or justification for why the requirements are what they are. Any requirement is ultimately up to the local AHJ to decide what it means, but having this requirement as ambiguous in the code is confusing.
Brian Ehrhart, 1/16/2020

RM11 Probably need to explain "able to be reduced" a little more: through a mechanism existing in the code, through further research/analysis leading to future code changes, etc.
Richards, Mark, 1/7/2020

BDE36 Added clarification; based on current code requirements
Brian Ehrhart, 1/16/2020

RM12 Legibility changes: reduced font size under Liquid heading, widened the table, changed the table serif font to sans serif, removed numbering, put some space between text and left table borders.
Richards, Mark, 1/7/2020

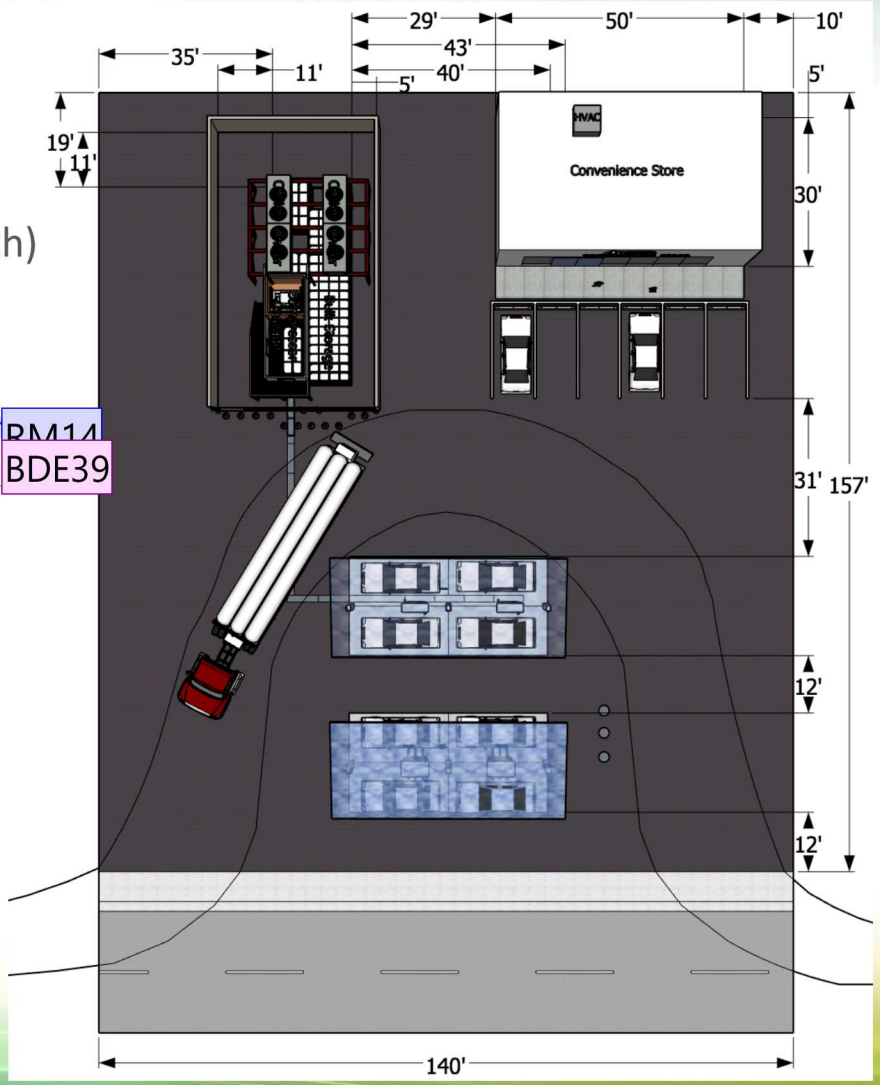
BDE37 Thank you!
Brian Ehrhart, 1/16/2020

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

- **Effects of 2020 Edition of NFPA 2**
  - Code changes result in significant reduction in minimum footprint
  - But other factors (traffic and delivery truck path) reduce impact on full layout
- **Alternate Delivery to Station**
  - 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 increases footprint relative to hydrogen-only design

Different design changes have different impacts on station footprints

Gasoline Co-Location



Slide 10

RM13 Could be more clear, I believe this is saying that the addition of gasoline dispensers and delivery points increased the footprint relative to a gaseous hydrogen station without gasoline.
Richards, Mark, 1/7/2020

BDE38 Is this for the NFPA 2 2020 edition design? If so, this is not correct. If this is for the Gasoline Co-Location design, this is correct. Clarified language.
Brian Ehrhart, 1/16/2020

RM14 Maybe another word than delivery (which in this bullet means delivery to HFCVs, right?), fueling?. Delivery is mostly used in the sense of getting hydrogen to the station.
Richards, Mark, 1/7/2020

BDE39 No, you are right: delivery is meant to get hydrogen to the station. I would use "dispensing" for getting hydrogen from station to FCEV. Clarified title bullet.
Brian Ehrhart, 1/16/2020

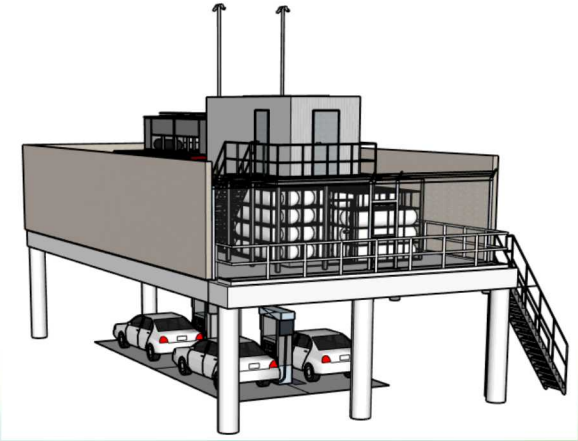
Created elevated and underground storage station designs that reduce footprint

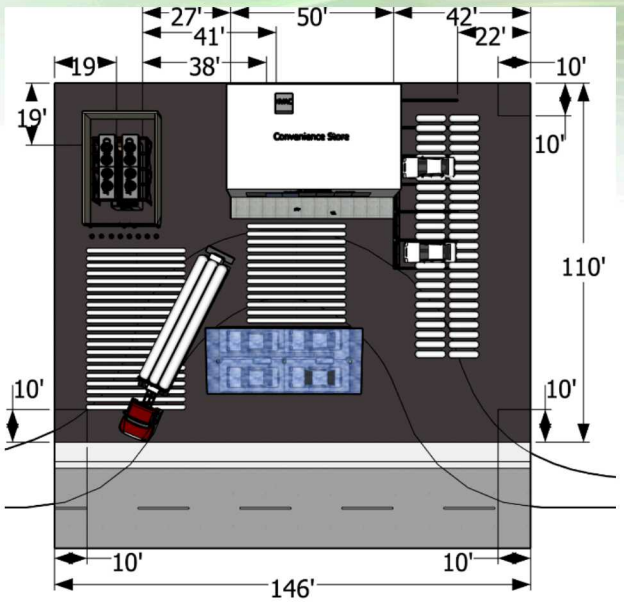
Underground Storage

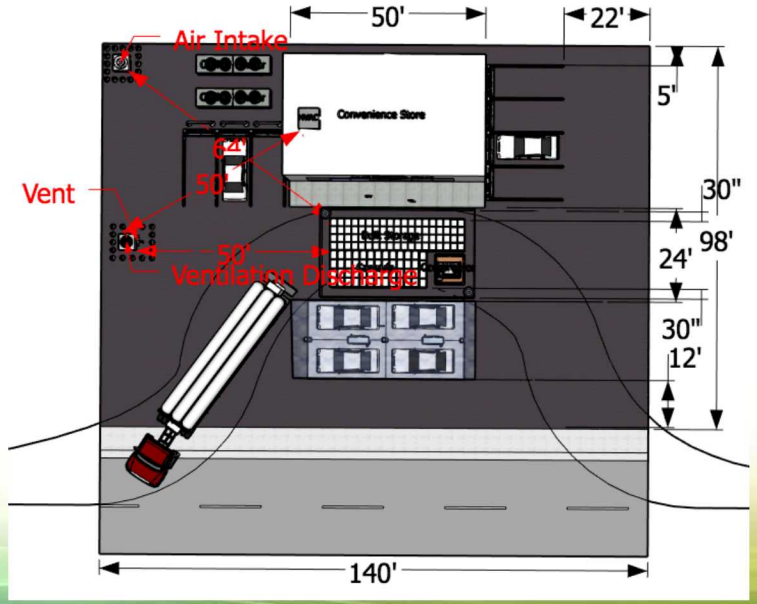
- Direct burial
- Vault
- Only buried components eliminate setbacks

Elevated Storage

- Setback distances still apply to line-of-sight
- Very large weight of equipment
- Seismic loading and aesthetics are issues







Summary of lot sizes for all cases with truck path

	Design	Total Lot Area (ft^2)	Reduction from Base Case
Delivered Gas	Base Case Gas	17,640	--
	New NFPA Separation Distances	17,640	0.0%
	New Delivery Single Truck	14,391	18.4%
	New Delivery Double Truck	15,875	10.0%
	Gasoline Co-Location	21,980	-24.6% (Increase)
	Underground Direct-Bury	16,060	9.0%
	Underground Vault	13,720	**22.2%**
	Rooftop Storage	15,400	12.7%
Delivered Liquid	Base Case Liquid	21,250	0.0%
	New NFPA Separation Distances	18,252	14.1%
	New Liquid Delivery	19,080	10.2%
	Gasoline Co-Location	**25,330**	-19.2% (Increase)
	Underground Direct-Bury	15,515	**27.0%**
	Rooftop Storage	20,060	5.6%
On-Site Electrolysis*	Base Case	14,756	0.0%
	New NFPA Separation Distances	**11,934**	19.1%
	Gasoline Co-Location	15,113	-2.42% (Increase)
	Underground Direct-Bury	13,340	9.6%
	Underground Vault	16,240	-10.1% (Increase)
	Rooftop Storage	11,466	22.3%

BM16
BDE40

Smallest GH2

Largest overall

Smallest LH2

Smallest practical station

* No truck path

Slide 12

RM16 Consider displaying none, or maybe one, decimal place in the Reduction column.
Richards, Mark, 1/7/2020

BDE40 Done
Brian Ehrhart, 1/16/2020

Approximated potential to site stations in dense urban areas

- 7 cities in 5 states
  - San Francisco, C BM17 BDE42
  - Los Angeles, CA
  - San Diego, CA
  - Hartford, CT
  - Baltimore, MD
  - Boston, MA
  - New York City (Manhattan), NY
- Total of 227 gasoline stations analyzed
- Lot size of each station BM18 BDE41 ned from county property tax records
- Lot size was compared to generic station designs
- Number of existing gasoline stations that can be converted into hydrogen stations was identified

Illustrates potential effect of reduction in lot sizes

Siting results on delivered gas designs

Design	Lot Area (ft^2)	Reduction from Base Case	Lots available (out of 227) [%]
Base Case Gas	17,640	--	77 [34%]
New NFPA Separation Distances	17,640	0.0% BDE43	77 [34%]
New Delivery Single Truck	14,391	18.4%	107 [47%]
New Delivery Double Truck	15,875	10.0%	88 [39%]
Gasoline Colocation	21,980	-24.6% (increase)	52 [23%]
Underground Direct-Bury	16,060	9.0%	88 [39%]
Underground Vault	13,720	22.2%	112 [49%]
Rooftop Storage	15,400	12.7%	97 [43%]

Slide 13

RM17 Any value to listing the seven cities rather than the five states?
Richards, Mark, 1/7/2020

BDE42 Yes, added
Brian Ehrhart, 1/16/2020

RM18 Consider changing "available" to "existing"
Richards, Mark, 1/7/2020

BDE41 Good point. It's not as if we checked if they were vacant or "for sale" or anything. Changed.
Brian Ehrhart, 1/16/2020

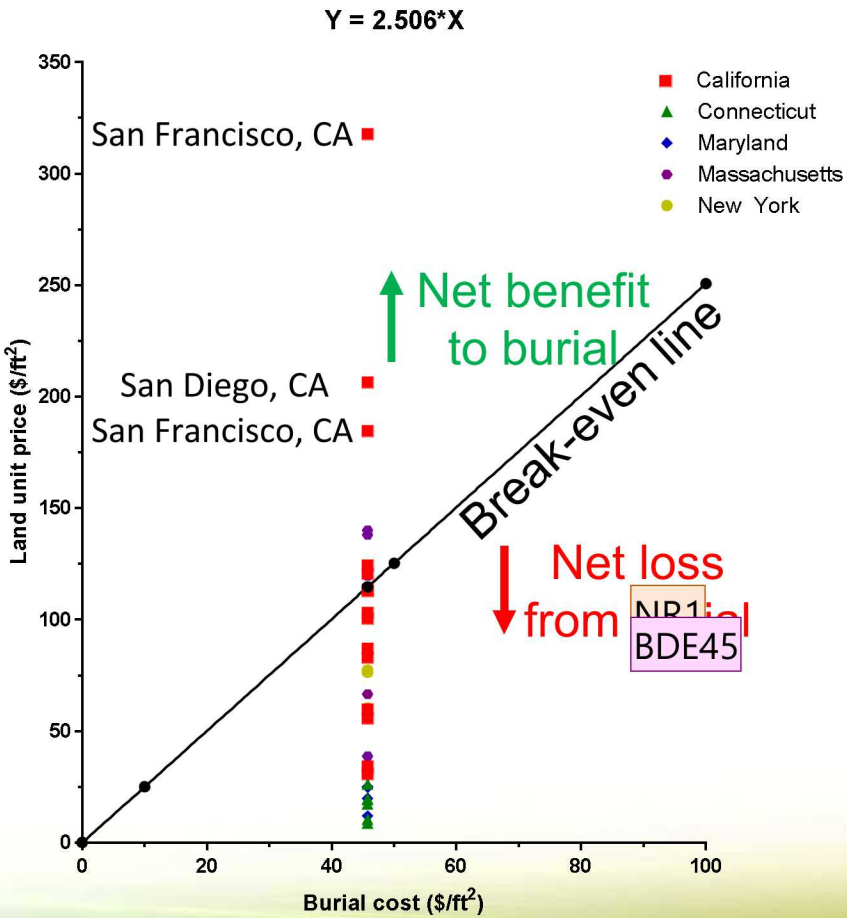
BDE43 Also changed to one decipal point as per comment on last slide
Brian Ehrhart, 1/16/2020

Demonstrated simplified economic impact of station design changes for underground

- Sub-set of 40 gasoline stations analyzed
- Land unit price ($/ft^2) calculated from county property tax records
- Underground direct-bury cost estimated from underground propane tank installation cost: $45.8/ft^2
- Break-even line determined by ratio of burial area 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



Slide 14

NR1 can you list the cities for the three highest CA data points?
Neha Rustagi, 1/13/2020

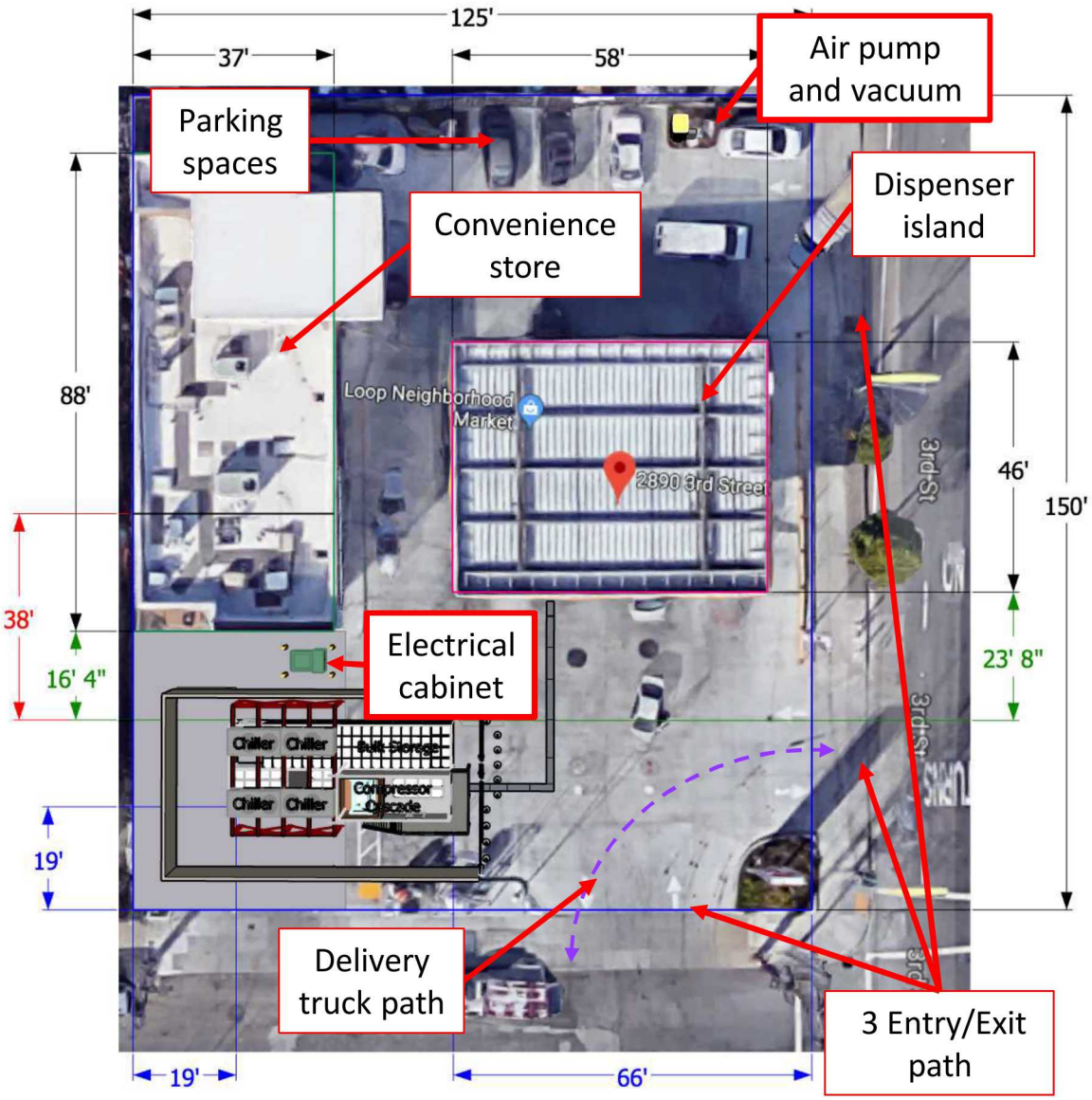
BDE45 Added
Brian Ehrhart, 1/16/2020

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



Summary

- **Relevance and Impact**
  - Practical engineering decisions to minimize refueling station footprint and maximize acceptance
- **Approach**
  - Detailed review of requirements (NFPA 2)
  - Development of base cases (delivered GH_2, delivered LH_2, on-site electrolysis generation) with a comparison of different design changes to base cases to quantify impact
  - Changes include NFPA 2 code changes, gasoline co-location, alternate delivery truck, underground storage
- **Accomplishments**
  - 600 kg/day station designs for delivered gas, delivered liquid, and on-site electrolysis
    - Including base cases, alternate delivery, upcoming fire code changes, underground storage, elevated storage, and gasoline co-location (32 total stations)
  - Identified issues with interpretation (and descriptions) in NFPA 2:
    - Calculation of GH_2 setback distances
    - GH_2/LH_2 hybrid systems – resulted in update to NFPA 2 (2020)
    - Source valve (and underground) system setback applicability
  - Real-world co-location case study on San Francisco gas station (smaller lot than generic station due to traffic flow)
  - Siting study in US cities (CA and Northeast) shows impact of station lot size changes (up to 67% of current gasoline lots can accommodate hydrogen-only fueling station)
  - Simple economic comparison shows trade-off trends for design changes (large variations in land cost can influence station design choices)

BM20
BDE44

Slide 16

RM20 Where did 67% come from? The table on slide 13 has a max of 49%.
Richards, Mark, 1/7/2020

BDE44 Good point. The table on slide 13 is a sub-set of our results for illustration; it is only looking at the delivered gas results that include a truck path. The 67% number happens to come from delivered gas design without a truck path, so not on that table. I have added more back-up slides with these many additional tables
Brian Ehrhart, 1/16/2020

TECHNICAL BACK-UP SLIDES

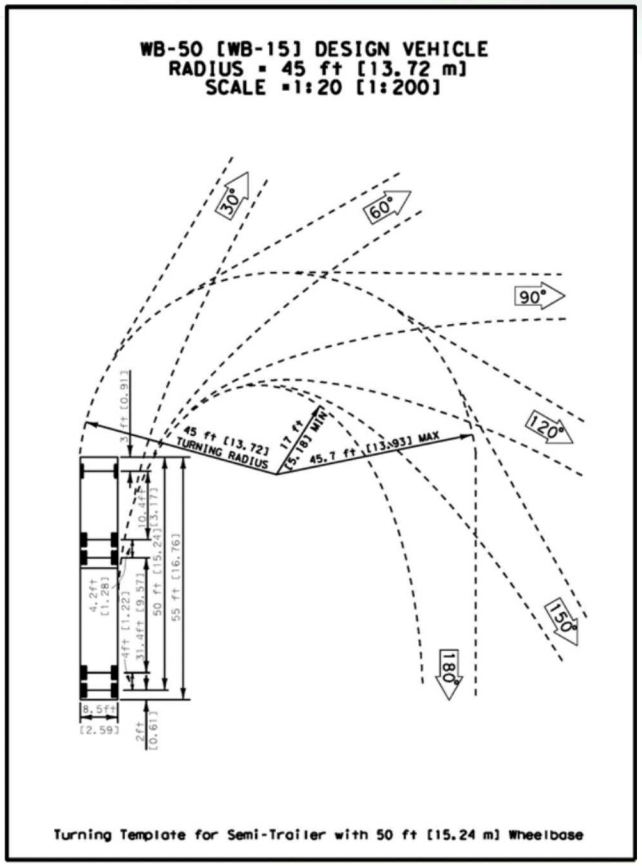
Collaborations

- 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

Non-hydrogen station components have large impact on footprint

Assumptions and considerations:

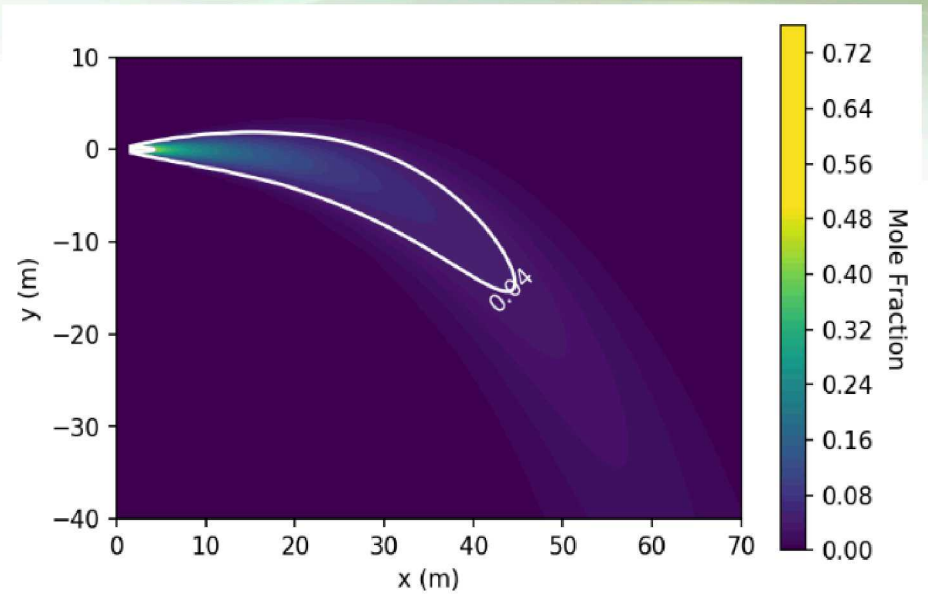
- Delivery truck path
  - Trucks must be capable of turning without reversing
  - Corner lot not considered (entry and exit only on single lot side)
- Convenience store
  - 50 x 30 ft
- Parking/Traffic Flow
  - Convenience store parking
  - Fueling positions
  - UT Parking Lot Design Manual
- Kept consistent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

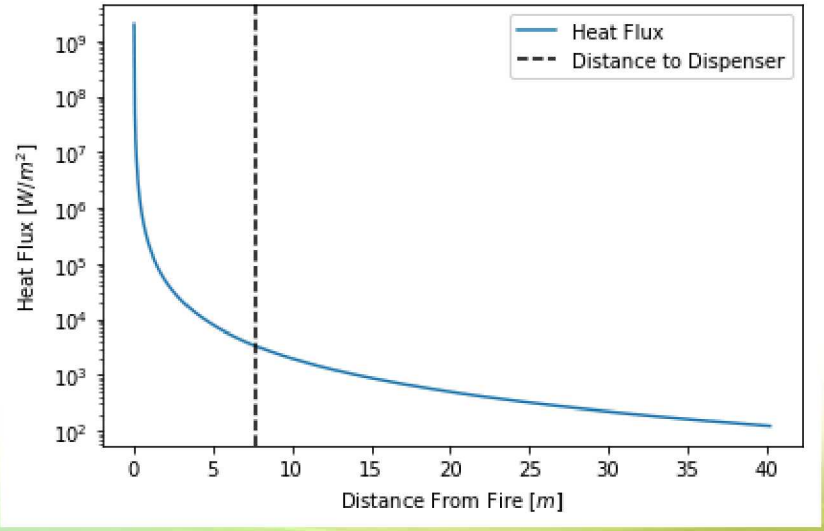


Texas DOT Road Design Manual

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



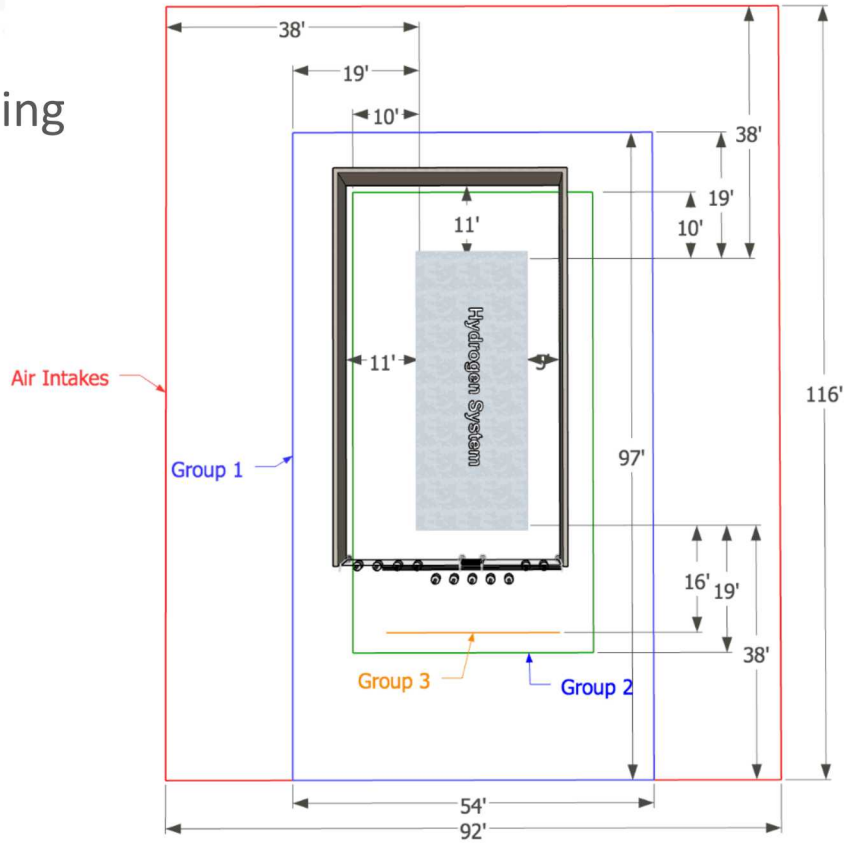


Exposure	Heat flux	Notes
Personnel	1,577 W/m^2	Threshold to which personnel with appropriate clothing can be continuously exposed. Used as the **"no harm"** value.
Personnel	4,732 W/m^2	Threshold for exposure to employees for a maximum of 3 minutes.
Combustible materials	20,000 W/m^2	Minimum heat flux 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

- 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)
7(b)(2) Unsprinklered combustible building*	23 m (75 ft)
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)

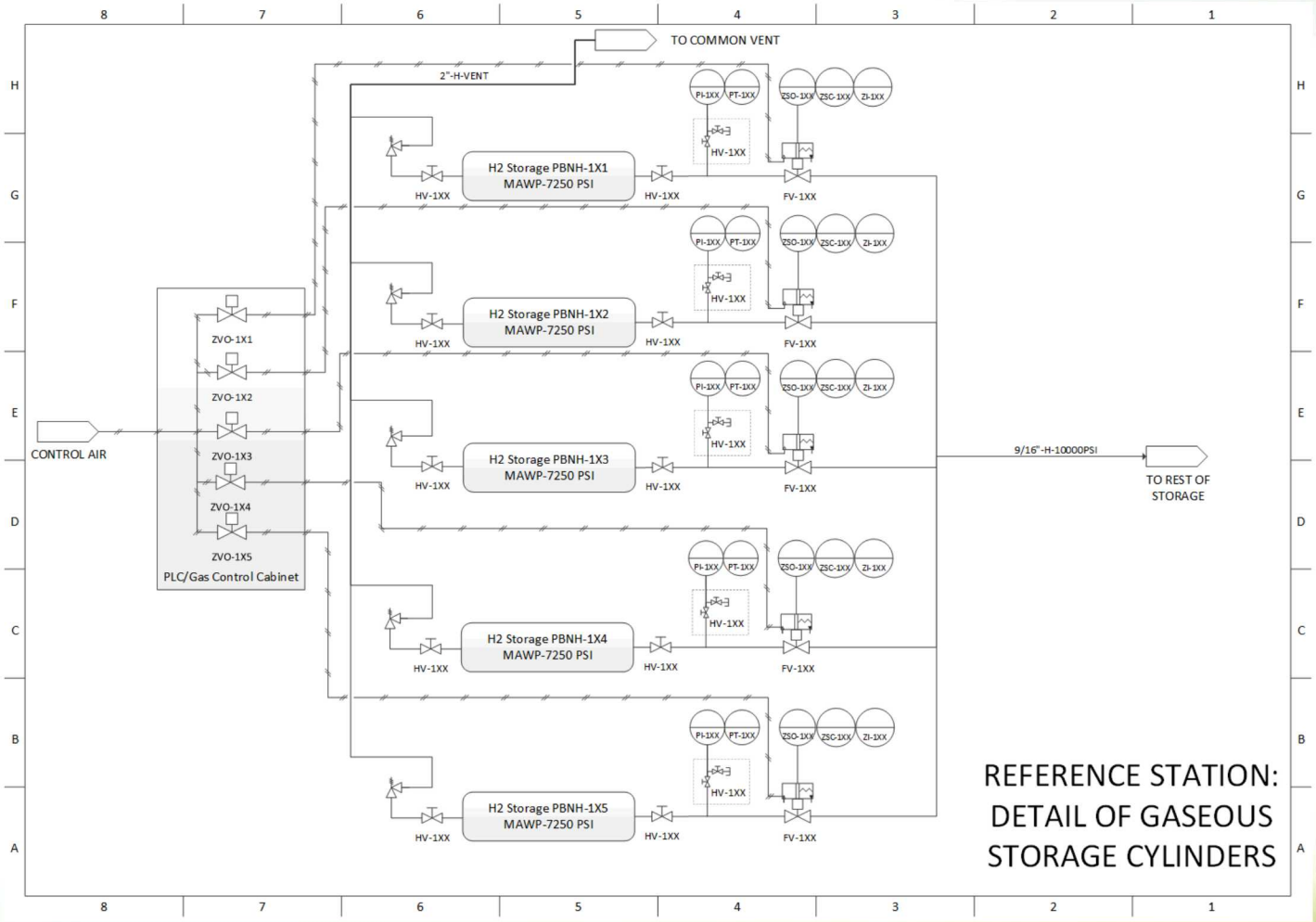
Remaining Barriers and Challenges

- 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

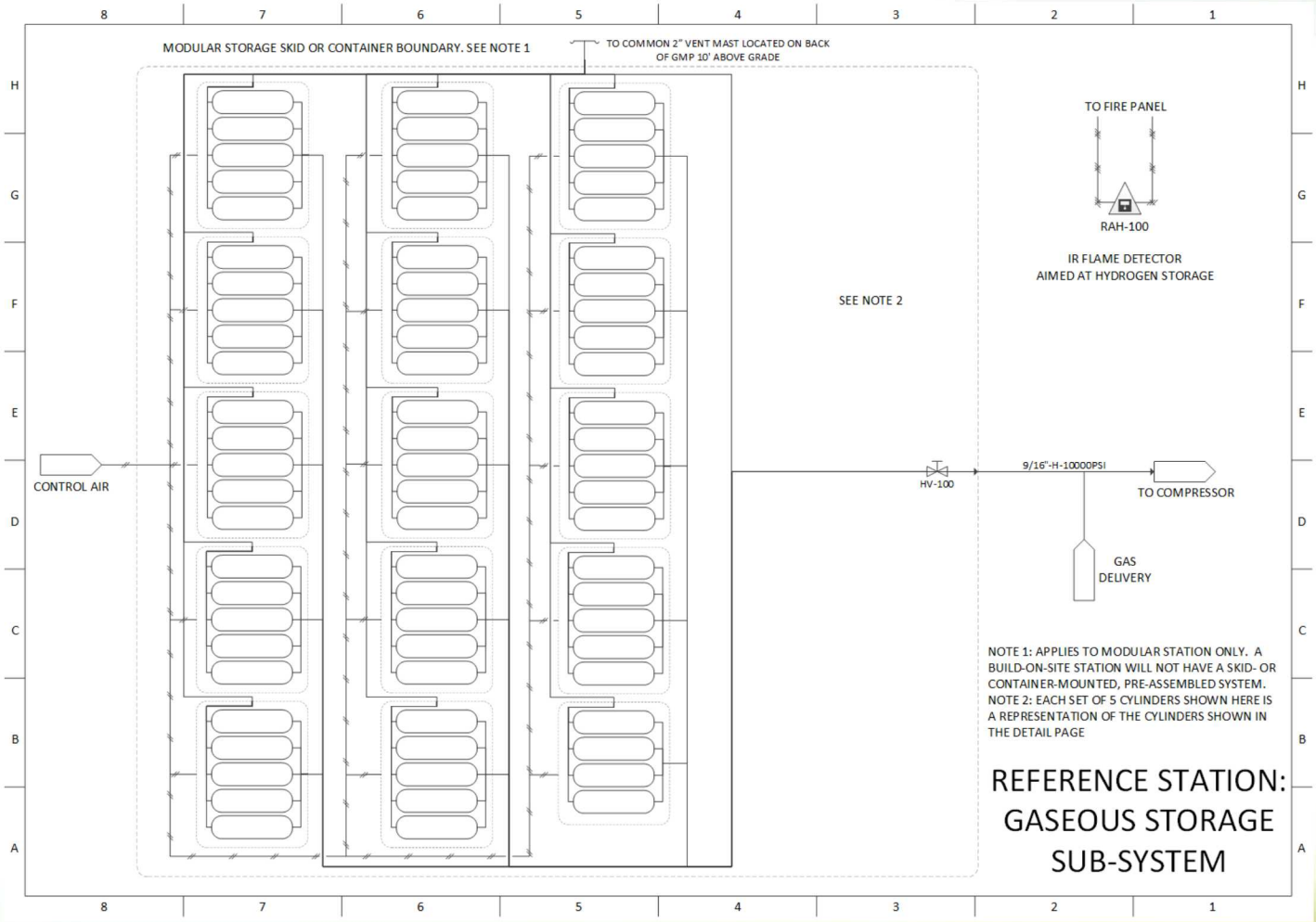
- Industry challenge: Current setback distances only take credit for fire-rated wall
  - Other active or passive prevention or mitigation measures considered only on a case-by-case basis
  - Project challenge: no way to incorporate these credits into generic station designs

- Project challenge: Siting and economics are specific to each particular location
  - Illustrative comparisons are useful for showing trends

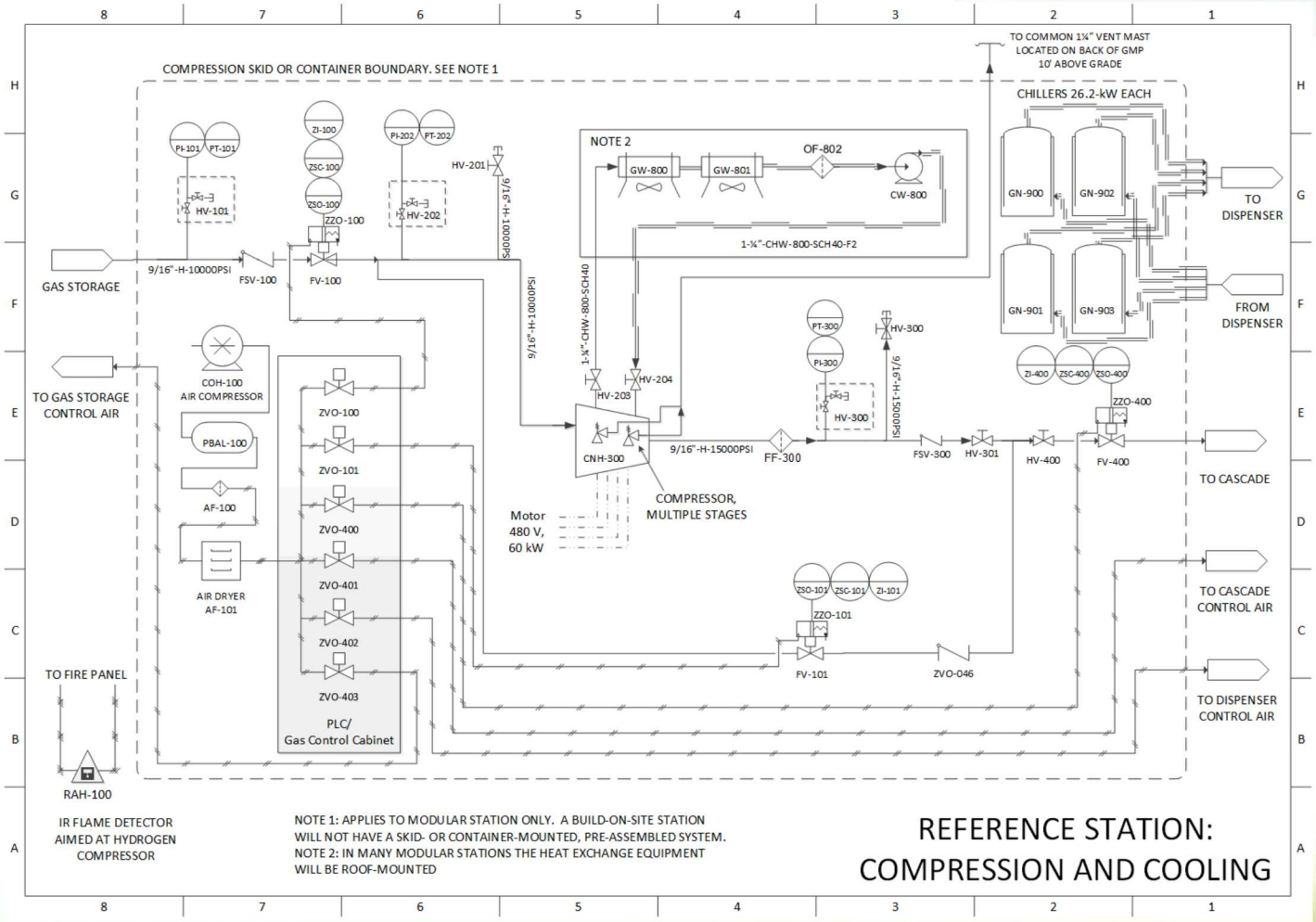
Base Case Gas Bulk Gas Storage Pressure Vessel Detail Piping and Instrumentation Diagram



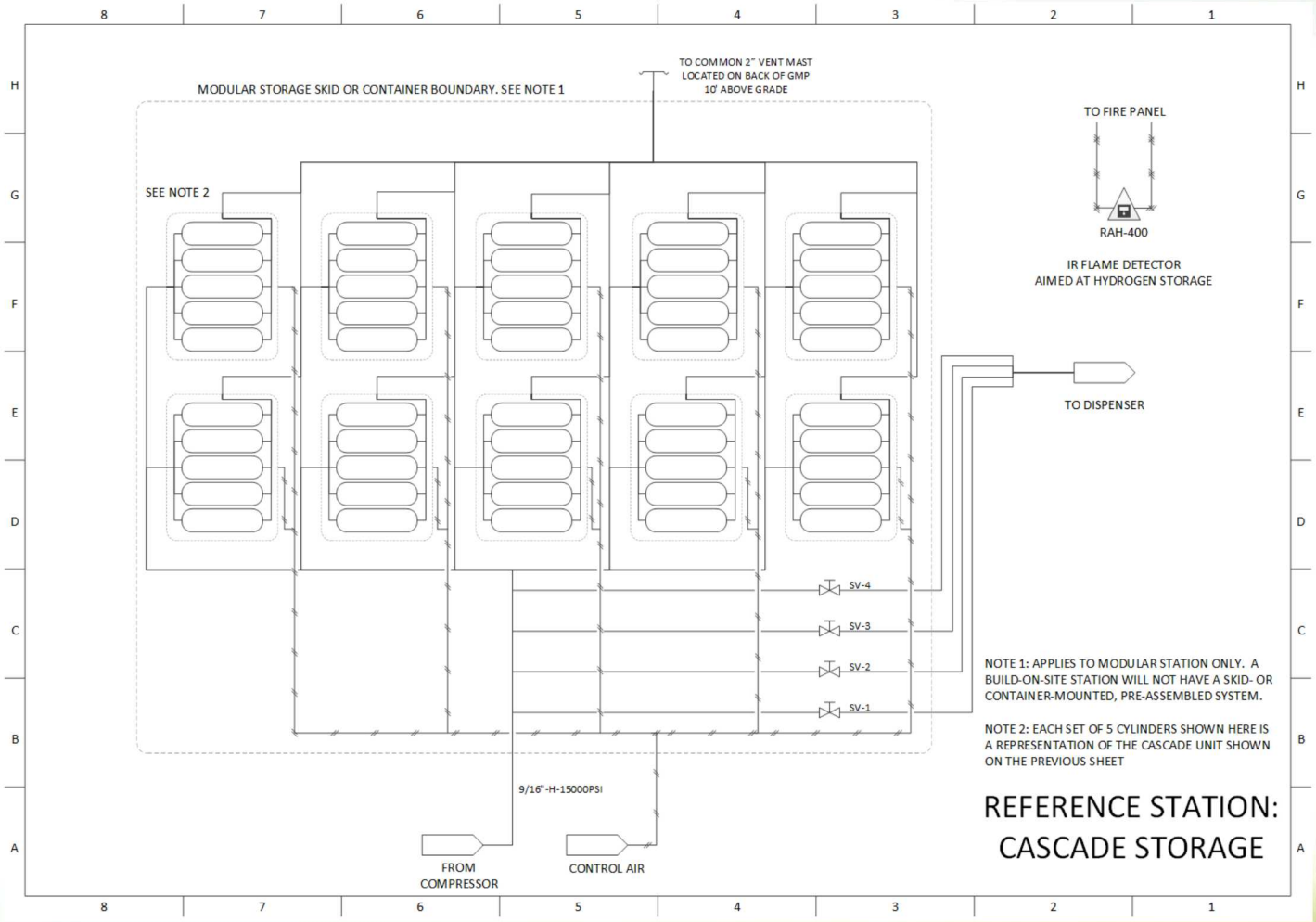
Base Case Gas Full Bulk Gas Storage Piping and Instrumentation Diagram



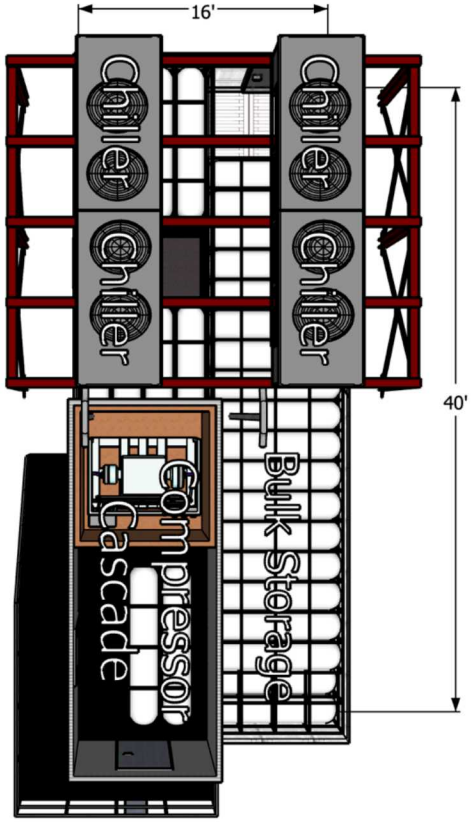
Base Case Gas Compression and Other Equipment Piping and Instrumentation Diagram

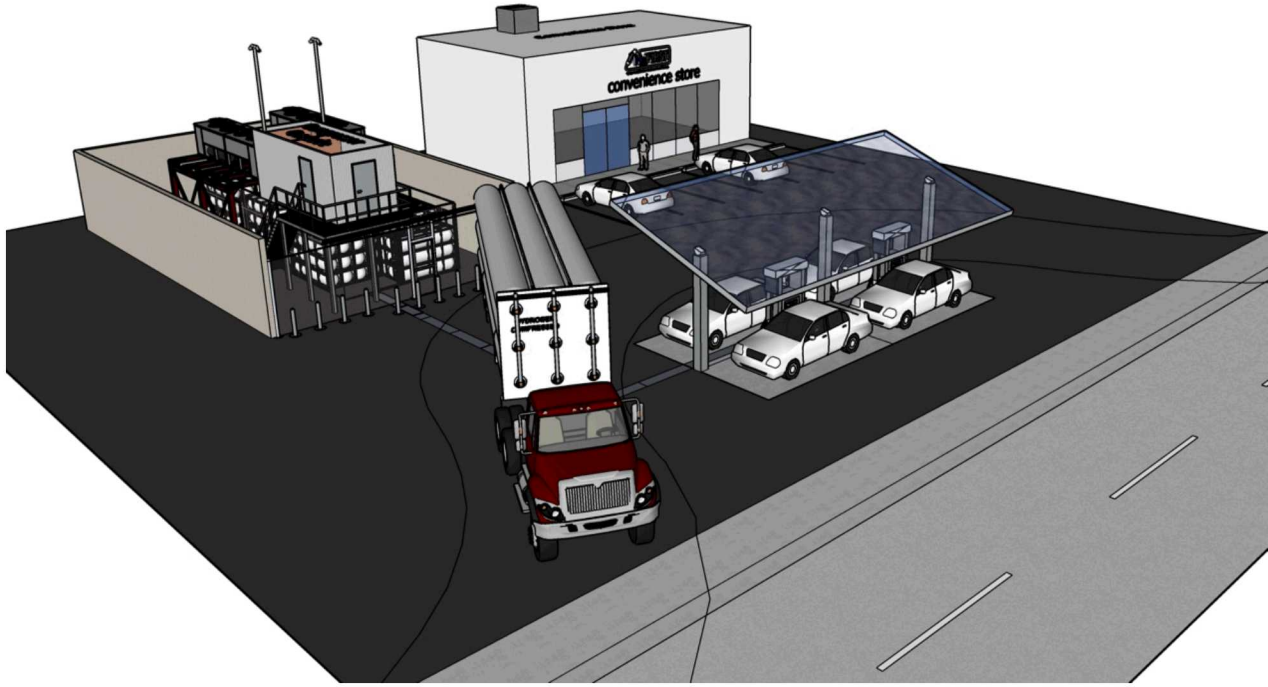


Base Case Gas Full Cascade Piping and Instrumentation Diagram

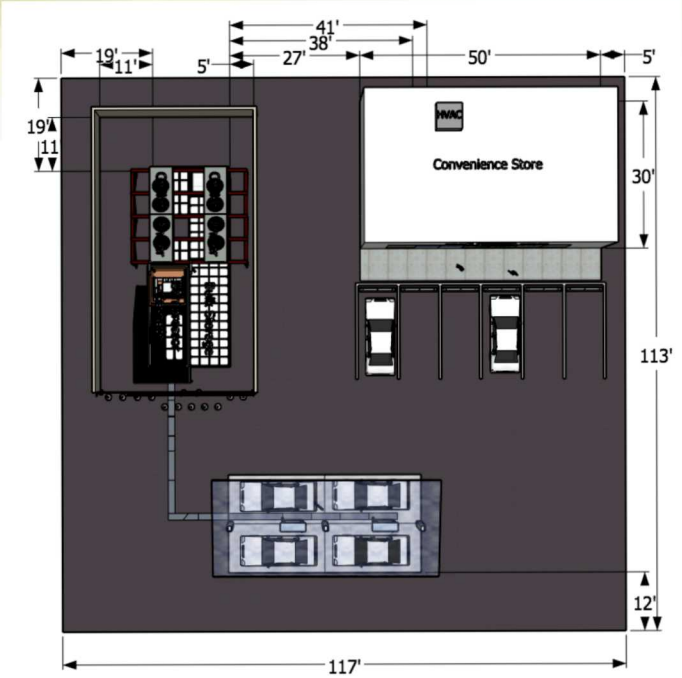


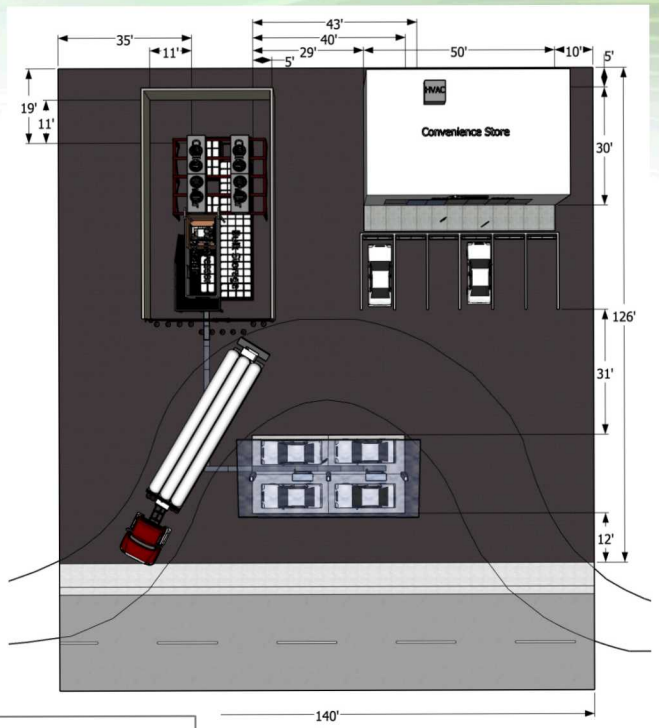
Base Case Gas Equipment Layout

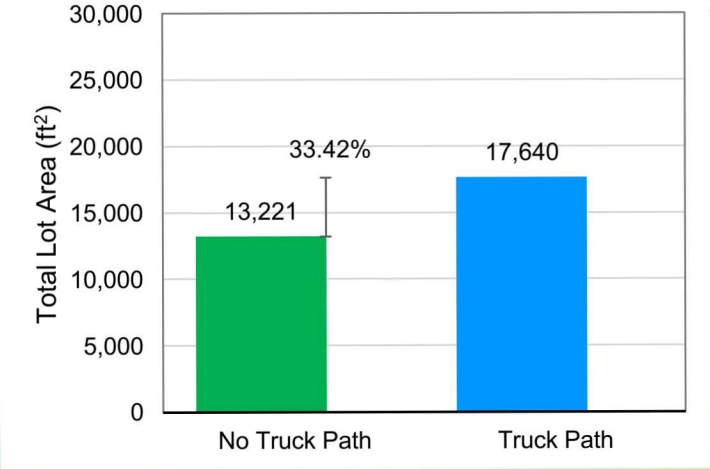




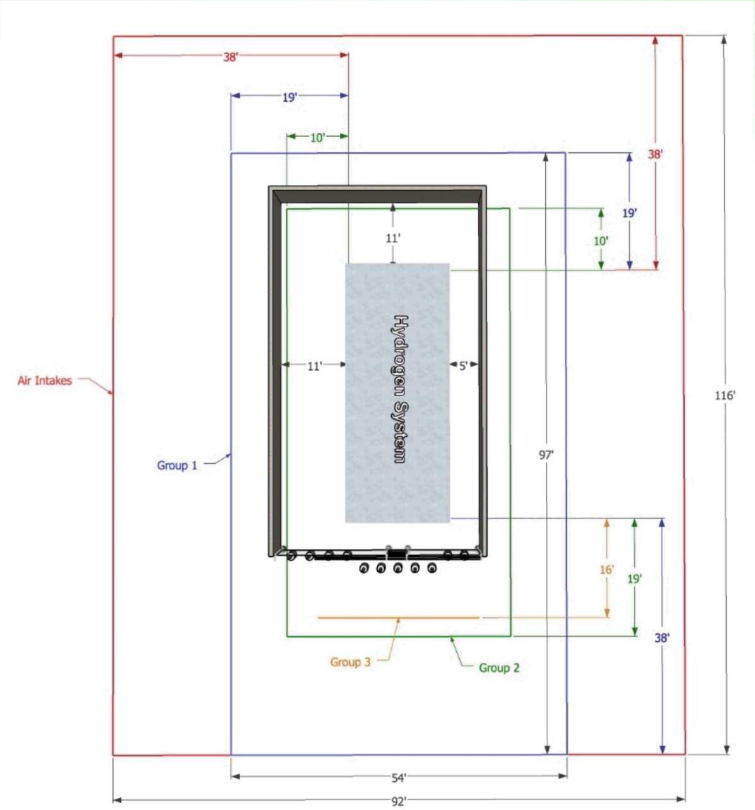
Base Case Gas: Truck vs No Truck





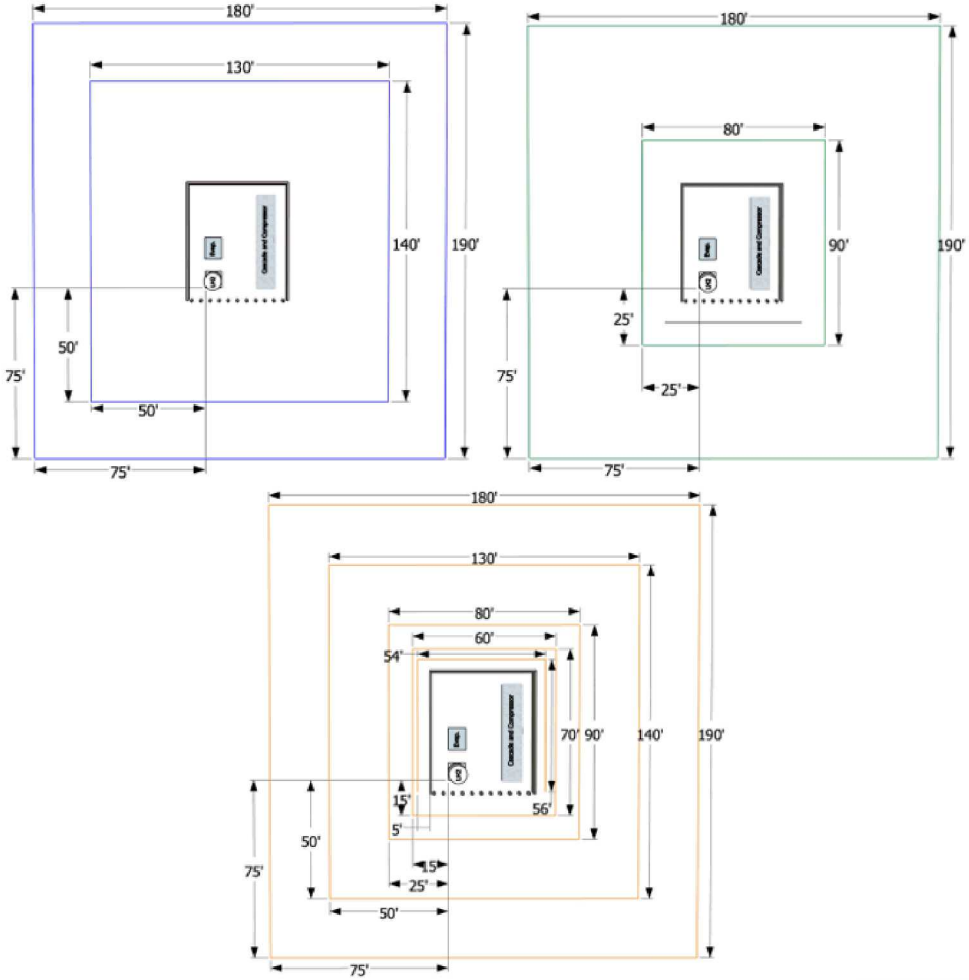


Base Case Gas Setback Distances



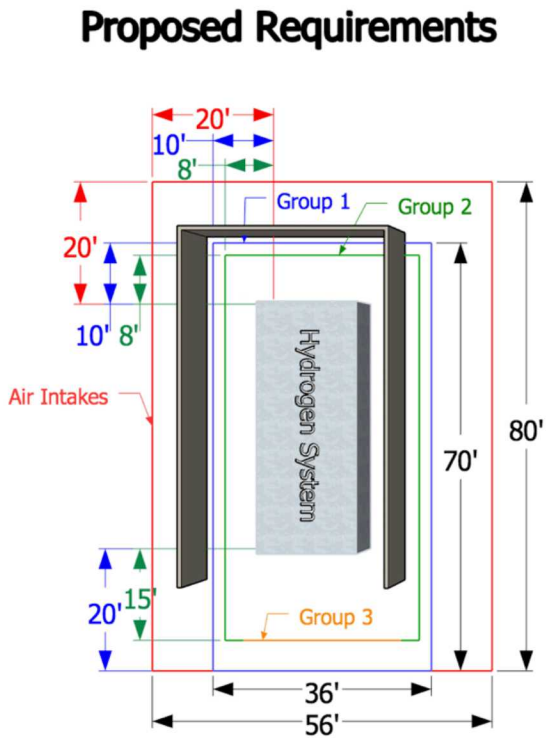
Sub-system	Description	Source	Maximum Pressure	Maximum ID	Group 1	Group 2	Group 3
1	Bulk storage to compressor	7.3.2.3.1.1(b)	50.0 MPa (7,250 psi)	9.07 mm (0.357 inch)	10 m (33 ft)	5 m (16 ft)	4 m (14 ft)
2	Compressor to cascade	7.3.2.3.1.1(c)	94.4 MPa (13,688 psi)	5.15 mm (0.203 in)	8 m (24 ft)	3 m (10 ft)	3 m (10 ft)
3	Cascade to dispenser	7.3.2.3.1.1(c)	94.4 MPa (13,688 psi)	7.925 mm (0.312 in)	11 m (38 ft)	6 m (19 ft)	5 m (16 ft)

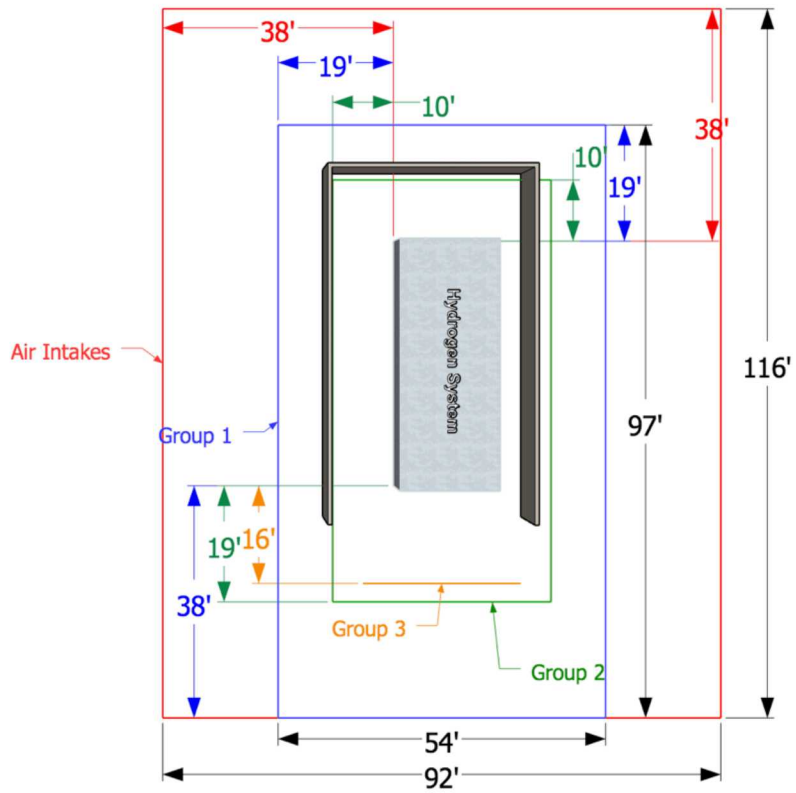
Base Case Liquid Setback Distances



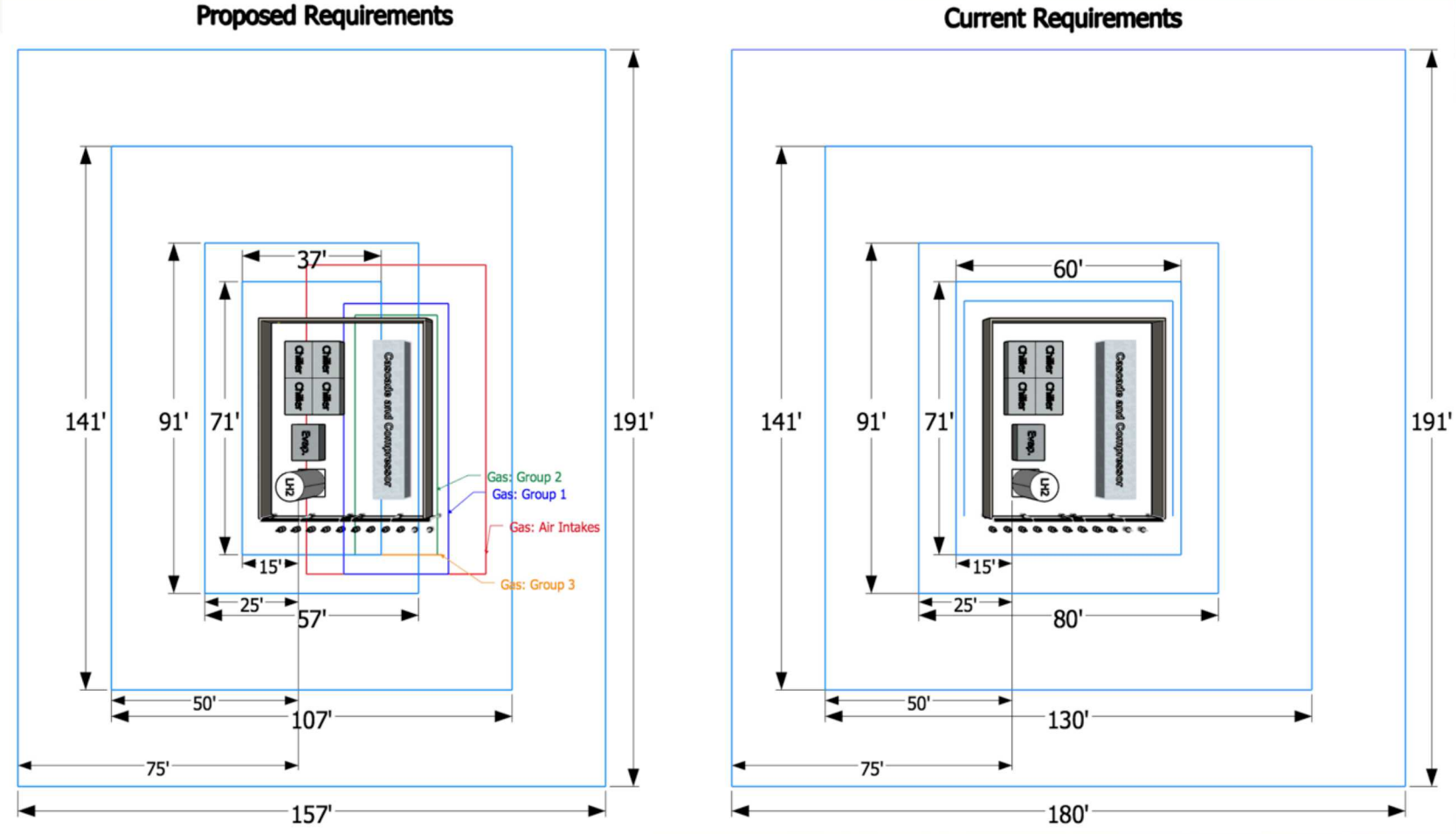
Group	Exposure	Reducible	Distance
1	1 Lot lines	*	15 m (50 ft)
	2 Air intakes		23 m (75 ft)
	3 Operable openings in buildings		23 m (75 ft)
	4 Ignition sources		15 m (50 ft)
2	5 Places of public assembly		23 m (75 ft)
	6 Parked cars		1.7 m (25 ft)
3	7(a)(1) Sprinklered non-combustible building	*	1.5 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)
	7(b)(2) Unsprinklered combustible building	*	23 m (75 ft)
	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)

New NFPA 2 2020 Setback Distances for Gas

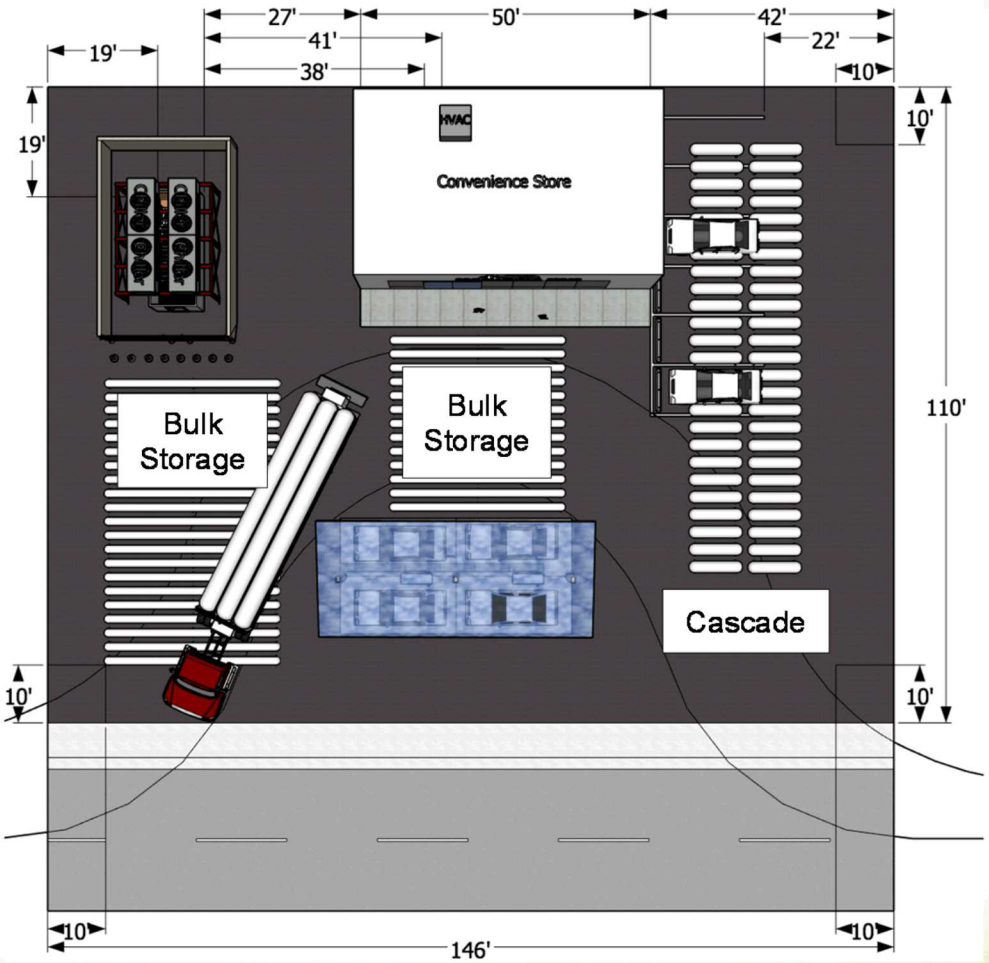




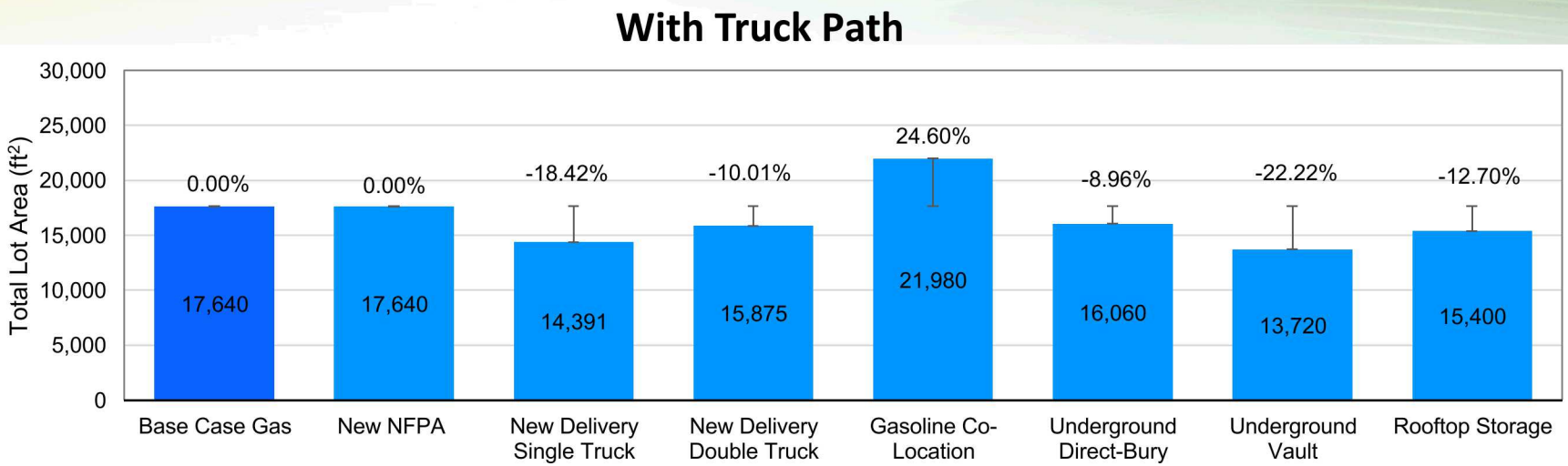
New NFPA 2 2020 Setback Distances for Liquid

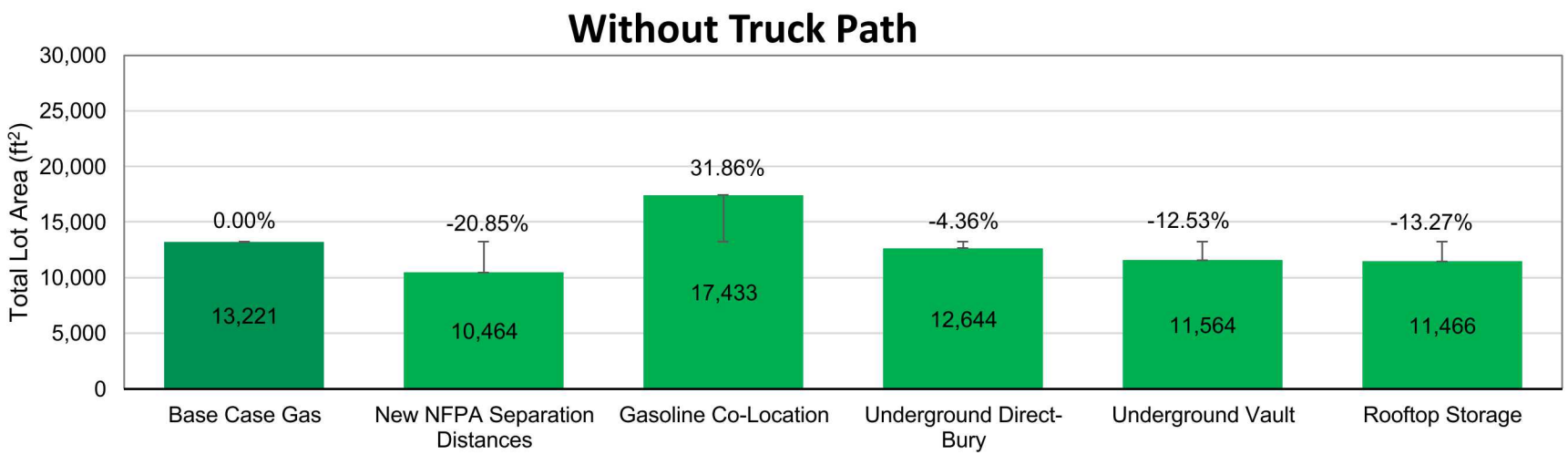


Underground Direct-Bury Gas

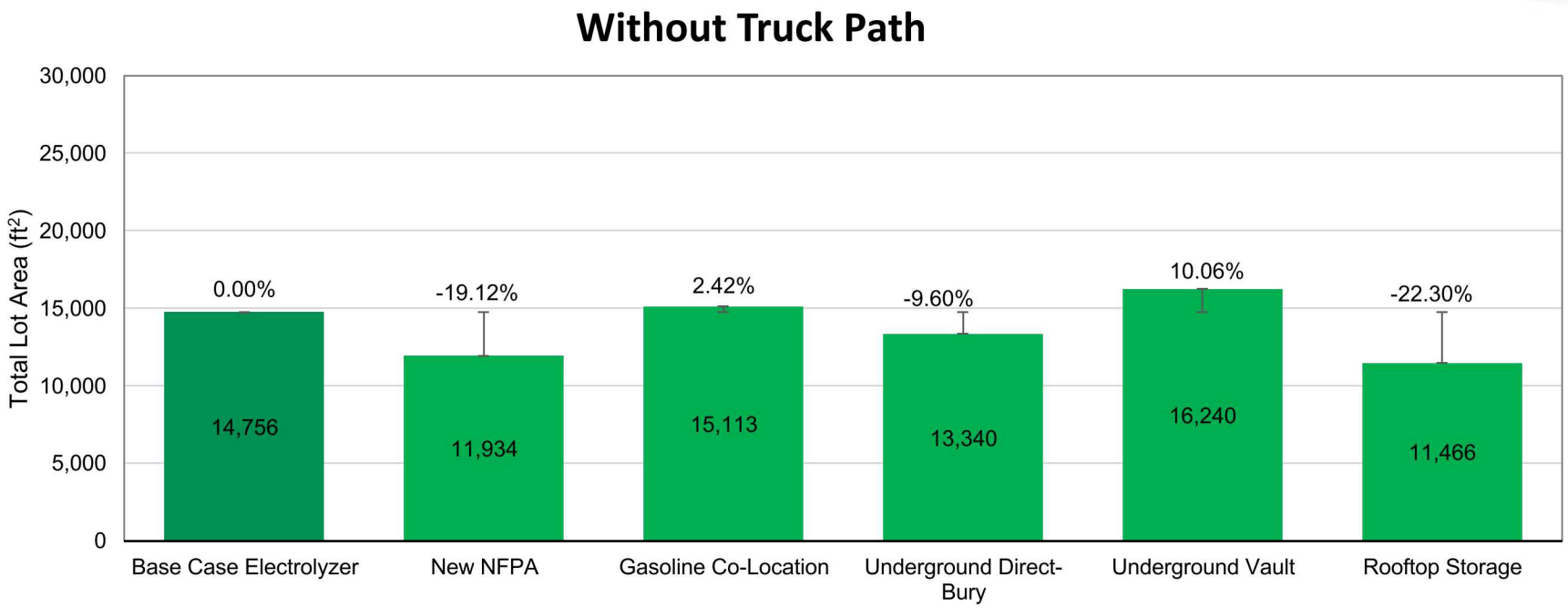


Summary of Lot Sizes – Delivered Gas



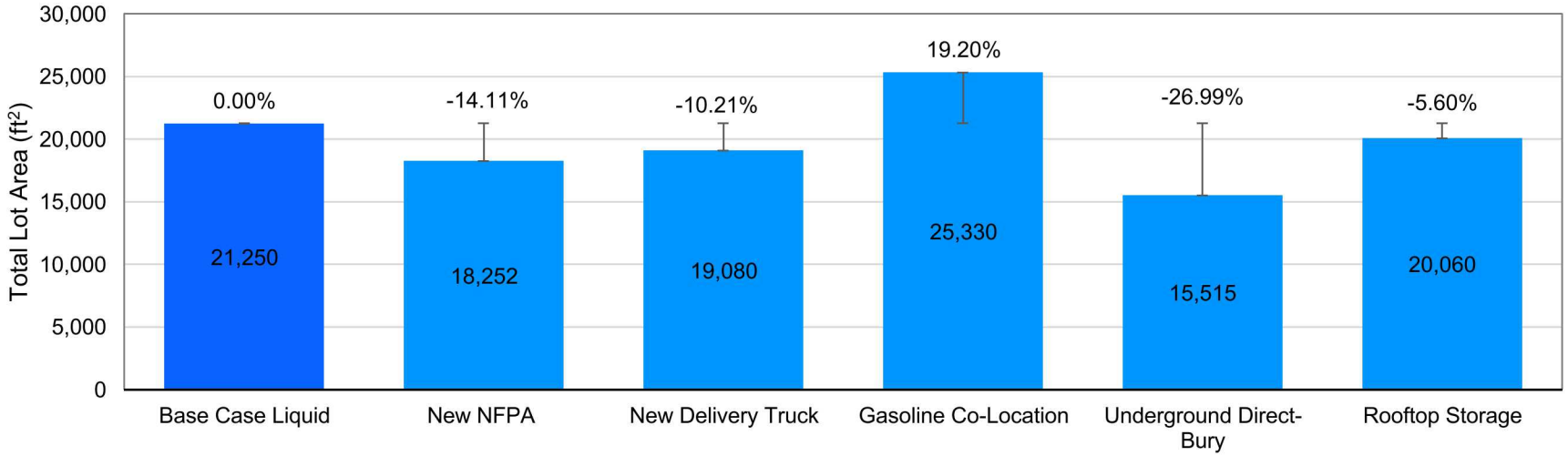


Summary of Lot Sizes – On-Site Electrolysis

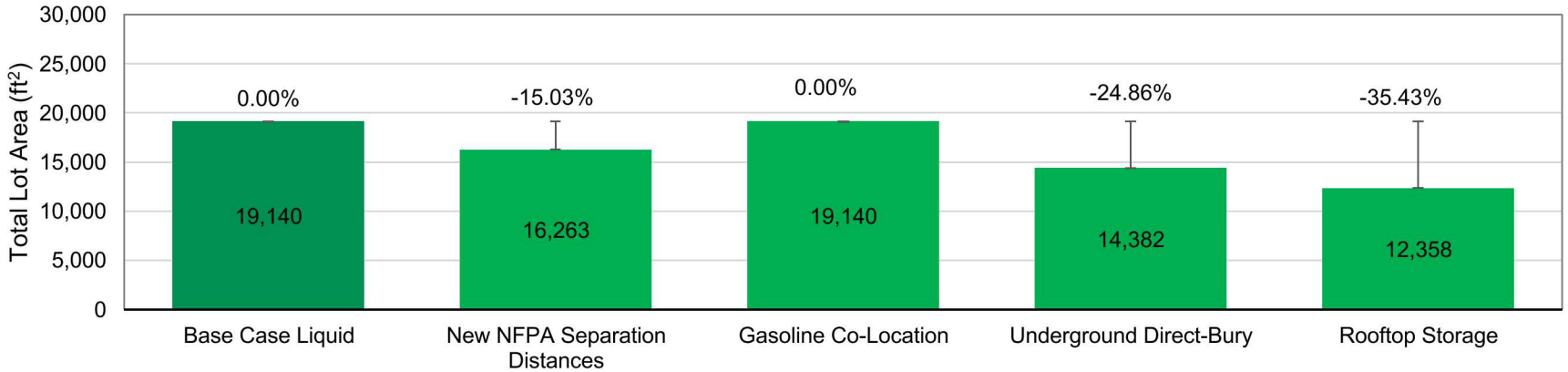


Summary of Lot Sizes – Delivered Liquid

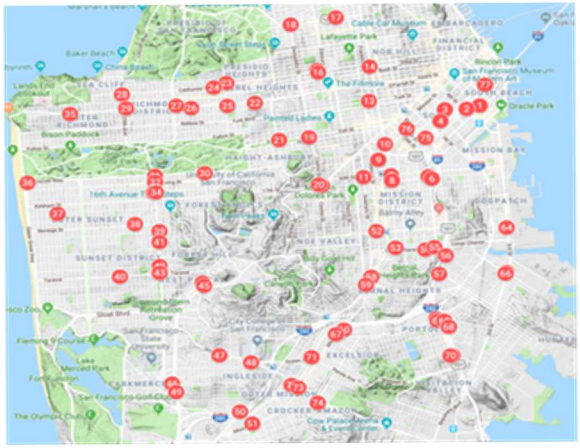
With Truck Path



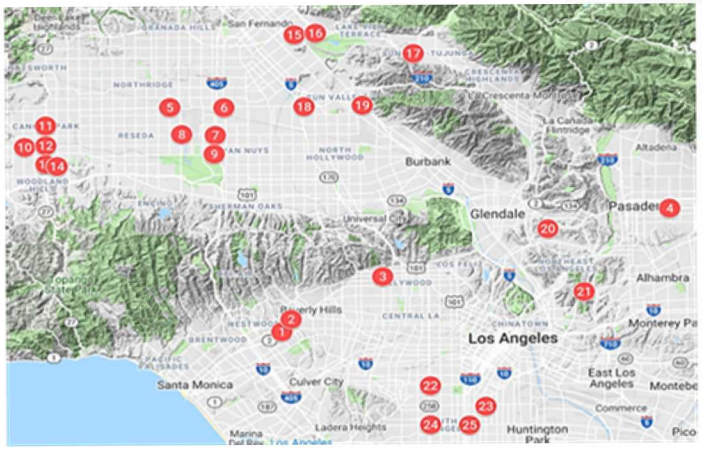
Without Truck Path



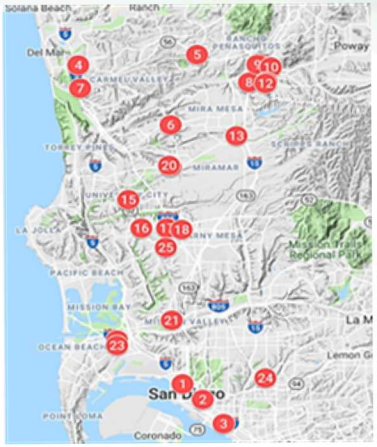
Gasoline Station Locations



San Francisco, CA



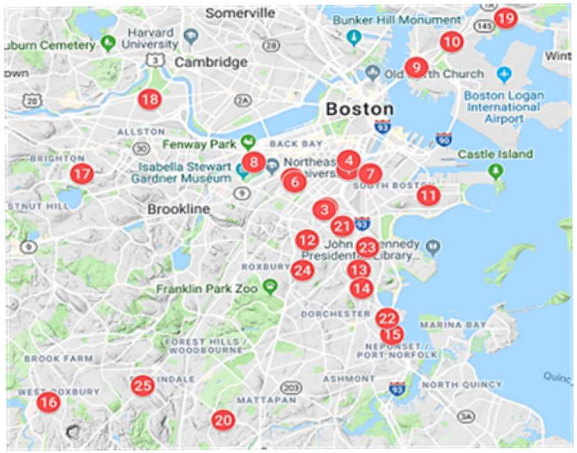
Los Angeles, CA



San Diego, CA

Hartford, CT

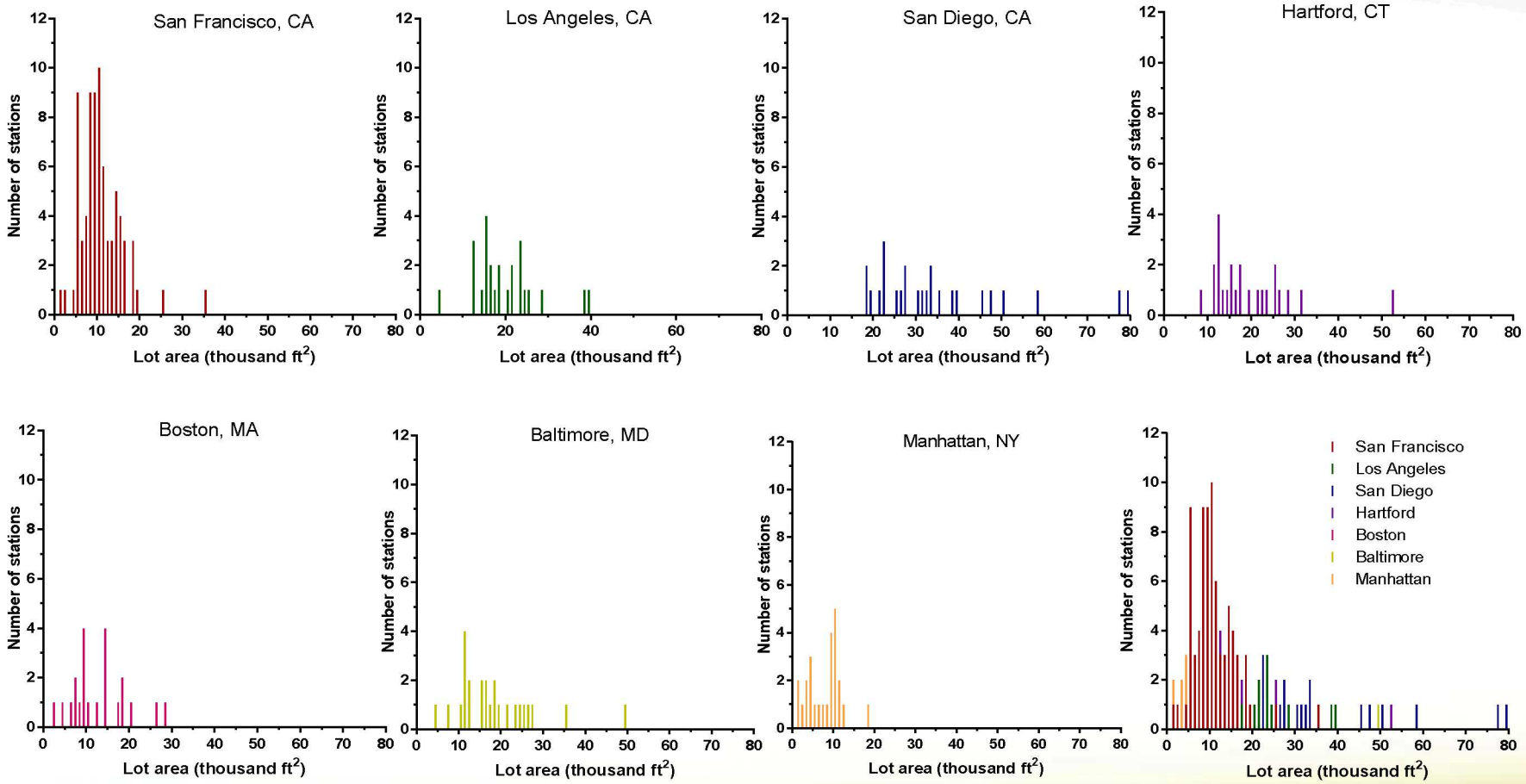
Baltimore, MD



Boston, MA

Manhattan, NY

Existing Gasoline Station Lot Size Histograms



Siting Study Results – Delivered Gas

H2FIRST

With Truck Path

Design	Lot Area (ft^2)	Reduction from Base Case	Lots available (out of 227) [%]
Base Case Gas	17,640	--	77 [34%]
New NFPA Separation Distances	17,640	0.00%	77 [34%]
New Delivery Single Truck	14,391	18.42%	107 [47%]
New Delivery Double Truck	15,875	10.01%	88 [39%]
Gasoline Colocation	21,980	-24.60% (increase)	52 [23%]
Underground Direct-Bury	16,060	8.96%	88 [39%]
Underground Vault	13,720	22.22%	112 [49%]
Rooftop Storage	15,400	12.70%	97 [43%]

Without Truck Path

Design	Lot Area (ft^2)	Reduction from Base Case	Lots available (out of 227) [%]
Base Case Gas	13,211	--	113 [50%]
New NFPA Separation Distances	10,464	20.85%	152 [67%]
Gasoline Colocation	17,433	-31.86% (increase)	78 [34%]
Underground Direct-Bury	12,644	4.36%	121 [53%]
Underground Vault	11,546	12.53%	133 [59%]
Rooftop Storage	11,466	13.27%	135 [59%]

Siting Study Results – On-Site Electrolysis

Without Truck Path

Design	Lot Area (ft^2)	Reduction from Base Case	Lots available (out of 227) [%]
Base Case	14,756	--	102 [45%]
New NFPA Separation Distances	11,934	19.12%	131 [58%]
Gasoline Colocation with truck path	21,980	-48.96% (increase)	52 [23%]
Gasoline Colocation without truck path	15,113	-2.42% (increase)	99 [44%]
Underground Direct-Bury	13,340	9.60%	113 [50%]
Underground Vault	16,240	-10.06% (increase)	87 [38%]
Rooftop Storage	11,466	22.30%	135 [59%]

Siting Study Results – Delivered Liquid

H2FIRST

With Truck Path

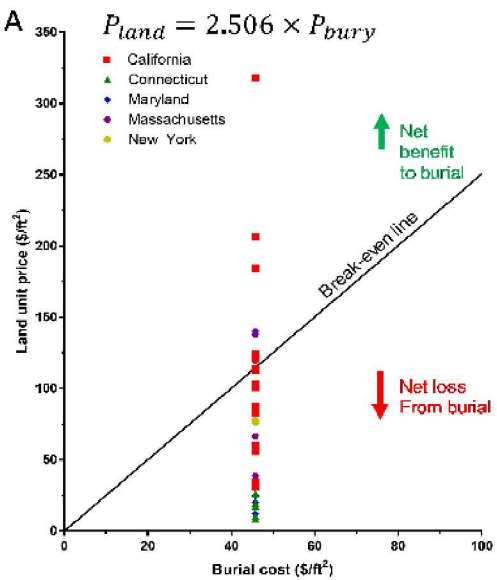
Design	Lot Area (ft^2)	Reduction from Base Case	Lots available (out of 227) [%]
Base Case Liquid	21,250	--	56 [25%]
New NFPA Separation Distances	18,252	14.11%	73 [32%]
New Liquid Delivery	19,080	10.21%	62 [27%]
Gasoline Colocation	25,330	-19.20% (increase)	38[17%]
Underground Direct-Bury	15,515	26.99%	95 [42%]
Rooftop Storage	20,060	5.60%	59 [26%]

Without Truck Path

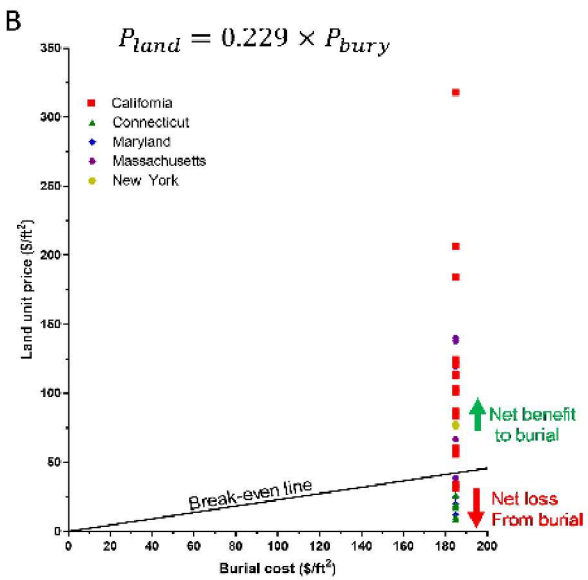
Design	Lot Area (ft^2)	Reduction from Base Case	Lots available (out of 227) [%]
Base Case Liquid	19,140	--	62 [27%]
New NFPA Separation Distances	16,263	15.031%	87 [38%]
Gasoline Colocation	19,140	0.0%	62 [27%]
Underground Direct-Bury	14,382	24.86%	107 [47%]
Rooftop Storage	12,358	35.45%	124 [55%]

Economic Comparison Results – Underground Storage

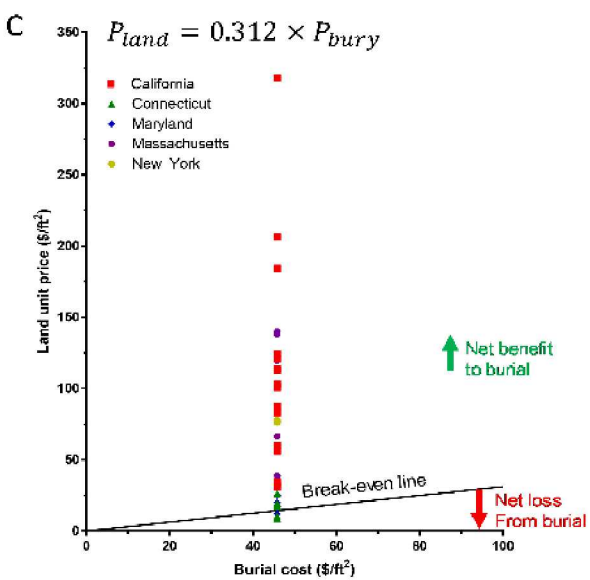
Gas Direct-Bury



Gas Vault



Liquid Direct-Bury



Economic Comparison Results – H2 Delivery Price

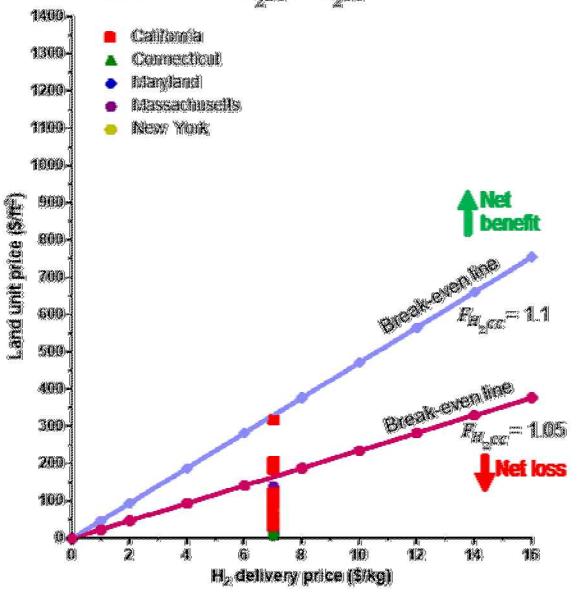
Gas New Delivery

A

$P_{land} = 47.18 \times P_{H_2BC}$, $F_{H_2CC} = 1.1$

$P_{land} = 23.59 \times P_{H_2BC}$, $F_{H_2CC} = 1.05$

$P_{land} = 0 \times P_{H_2BC}$, $F_{H_2CC} = 1.0$



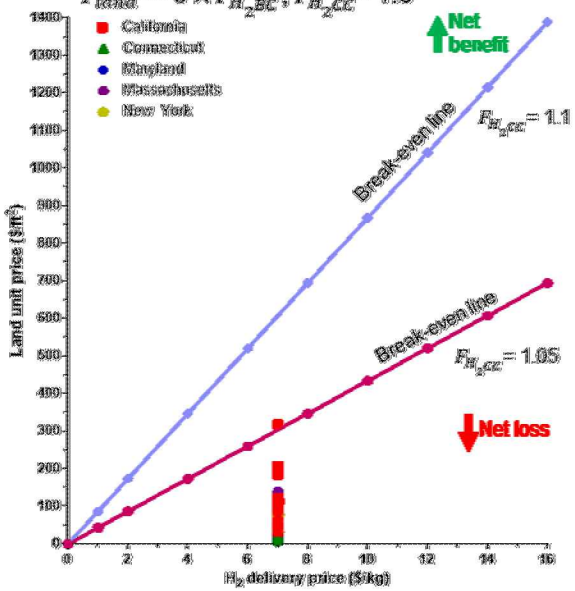
Gas New Delivery (Double-Trailer)

B

$P_{land} = 86.86 \times P_{H_2BC}$, $F_{H_2CC} = 1.1$

$P_{land} = 43.43 \times P_{H_2BC}$, $F_{H_2CC} = 1.05$

$P_{land} = 0 \times P_{H_2BC}$, $F_{H_2CC} = 1.0$



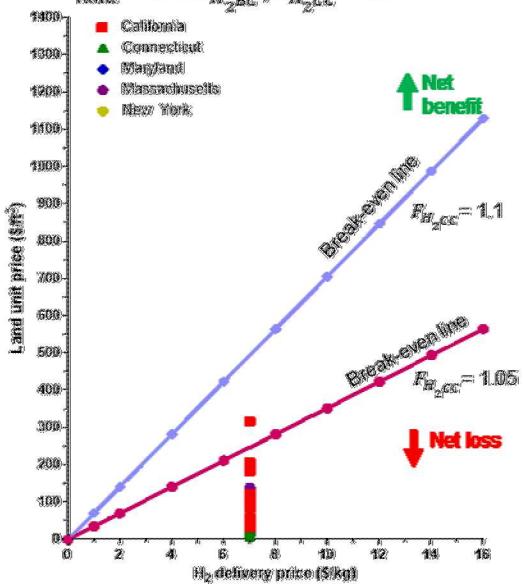
Liquid New Delivery

C

$P_{land} = 70.65 \times P_{H_2BC}$, $F_{H_2CC} = 1.1$

$P_{land} = 35.32 \times P_{H_2BC}$, $F_{H_2CC} = 1.05$

$P_{land} = 0 \times P_{H_2BC}$, $F_{H_2CC} = 1.0$



Economic Comparison Results – Case Study for Delivered Gas with Track Path

Design	Total Lot Area (ft^2)	Station 1 $A_{1,g}$=16,496 ft^2	Station 2 $A_{2,g}$=18,750 ft^2	Station 3 $A_{3,g}$=35,401 ft^2
Base Case Gas	17,640	No	1,387,500	2,619,674
New NFPA Separation Distances	17,640	No	1,387,500	2,619,674
New Delivery Single Truck	14,391	1,220,704	1,387,500	2,619,674
New Delivery Double Truck	15,875	1,220,704	1,387,500	2,619,674
Gasoline Colocation	21,980	No	No	2,619,674
Underground Direct-Bury	16,060	1,220,704	1,387,500	2,619,674
Underground Vault	13,720	1,220,704	1,387,500	2,619,674
Rooftop Storage	15,400	1,220,704	1,387,500	2,619,674