SAND2018-9895PE

H2FIRST
Hydrogen Fueling Infrastructure Research and Station Technology

Reference Stations for Urban Sites Workshop

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Alice Muna, Ethan Sena

Sandia National Laboratories
September 6, 2018

SAND2018-XXXX

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Acknowledgements

- We are grateful for support from the United States Department of Energy, Energy Efficiency & Renewable Energy, Fuel Cell Technologies Office for all of the H2FIRST projects managed by Neha Rustagi, Jason Marcinkoski, and Laura Hill

- We appreciate contributions to the project from Joe Pratt (formerly Sandia, now Golden Gate Zero Emission Marine) and Chris LaFleur

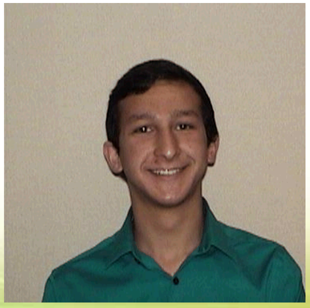
INTRODUCTIONS

Presented by Ethan Hecht

Project Team

- Ethan Hecht
  - Sandia National Labs H_2FIRST lead
  - Principal investigator for safety codes and standards behavior work
- Brian Ehrhart
  - Reference Station for Urban Sites project lead
  - Expertise with risk analysis, thermochemical hydrogen production
- Gaby Bran-Anleu
  - Computational fluid dynamics expertise
  - 2 years experience with hydrogen for FCEVs
- Alice Muna
  - Principal investigator for safety codes and standards risk work
  - 5 years experience with hydrogen for FCEVs
- Ethan Sena
  - Student intern from University of New Mexico

- Carl Rivkin
  - NFPA 2 Hydrogen storage task group lead



Workshop Participants

- Name
- Who you are representing
- Experience with FCEVs
- What you hope to get out of the workshop

PROJECT OVERVIEW

Presented by Ethan Hecht

Background

- H_2FIRST (https://www.energy.gov/eere/fuelcells/h2first)
  - Started in 2014 with a vision of: research and development of advanced technologies to lower cost and enhance reliability of hydrogen fueling stations.
  - Collaborative tasks led by Sandia National Laboratories and the National Renewable Energy Laboratory
- Reference station tasks
  - Grew out of a benchmarking report by Aaron Harris et al. (SAND2014-3416) who noted only about 20% of gasoline stations can readily accept hydrogen refueling infrastructure
  - 2015 Report (NREL/TP-5400-64107) provides publically accessible component needs, layouts, economic analyses and more for gaseous and liquid stations from 100-300 kg/day
  - 2017 report (SAND2017-2832) details modular vs assemble-on-site designs, layouts, and economic analyses, and compares on-site production against delivered gas
  - Provide public documentation of station equipment, designs and costs enabling station design discussions by various stakeholders including
    - Station developers/operators
    - Local authorities having jurisdiction
    - Code developers
    - Businesses/entrepreneurs and R&D organizations
    - Local municipalities and the general public
    - Funding and financing organizations
  - Identify R&D needs

R&D to reduce the cost and speed the deployment of hydrogen stations

Goals

Project:

- Research challenges *and develop solutions* to enable *near-term (<5 yrs)* hydrogen fueling station rollout in urban areas
  - Understand the current requirements
  - Assess the hazards/risks associated with current fueling stations designed according to current code and compare to hazards/risks of non-compliant/future code compliant stations
  - Determine the impact of delivery and the potential for new delivery methods
  - Analyze the benefits/drawbacks of building vertically (rooftop/underground)
- Establish high-priority R&D needs such as
  - Revisions to the fire code
  - Technology improvements

Workshop:

- Educate stakeholders so that project results can accelerate fueling station deployment in urban areas
- Determine if we are missing challenges, issues, or potential solutions for fueling stations in urban areas

Feedback Instructions

- Ask questions and provide real-time feedback during presentations
- Facilitated discussion after the presentations
- Fill out a questionnaire and leave it for us to review
- Direct questions after reviewing your notes to:

Brian Ehrhart

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(505) 284-4906

Outline

- Methodology
- Base Case Gas
- Base Case Electrolysis
- Base Case Liquid
- New NFPA
- New Delivery
- Gasoline Co-Location
- Underground Storage
- Rooftop Storage
- Alternative means and measures
  - Gas
  - Liquid
  - Electrolysis
- Summary
- HyRAM demos/lab tour/facilitated Discussion round-robin
- Fueling station tour option

METHODOLOGY

Presented by Brian Ehrhart and Carl Rivkin

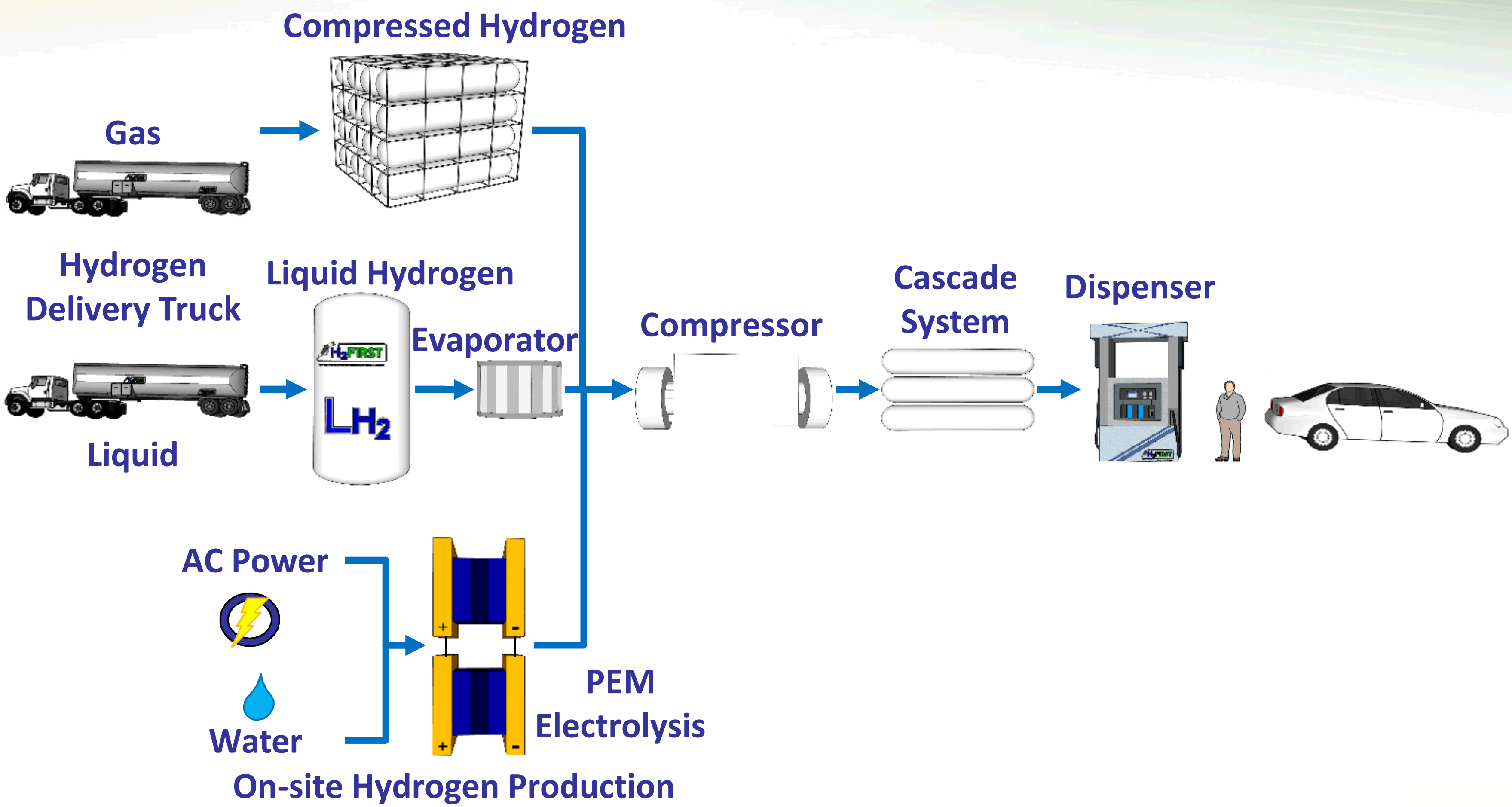
Project Structure

- Task 1: Definition of Requirements
- Task 2: Station Layout
  - Base Cases
  - Alternate Delivery
  - Changes to NFPA 2
  - Equivalent Risk
- Task 3: Underground Hydrogen Components
- Task 4: Rooftop Hydrogen Components
- Workshop ← Today!
- Task 5: Impact Assessment
  - Economic Assessment
  - Additional Site Availability
- Task 6: Outreach
  - Final Report

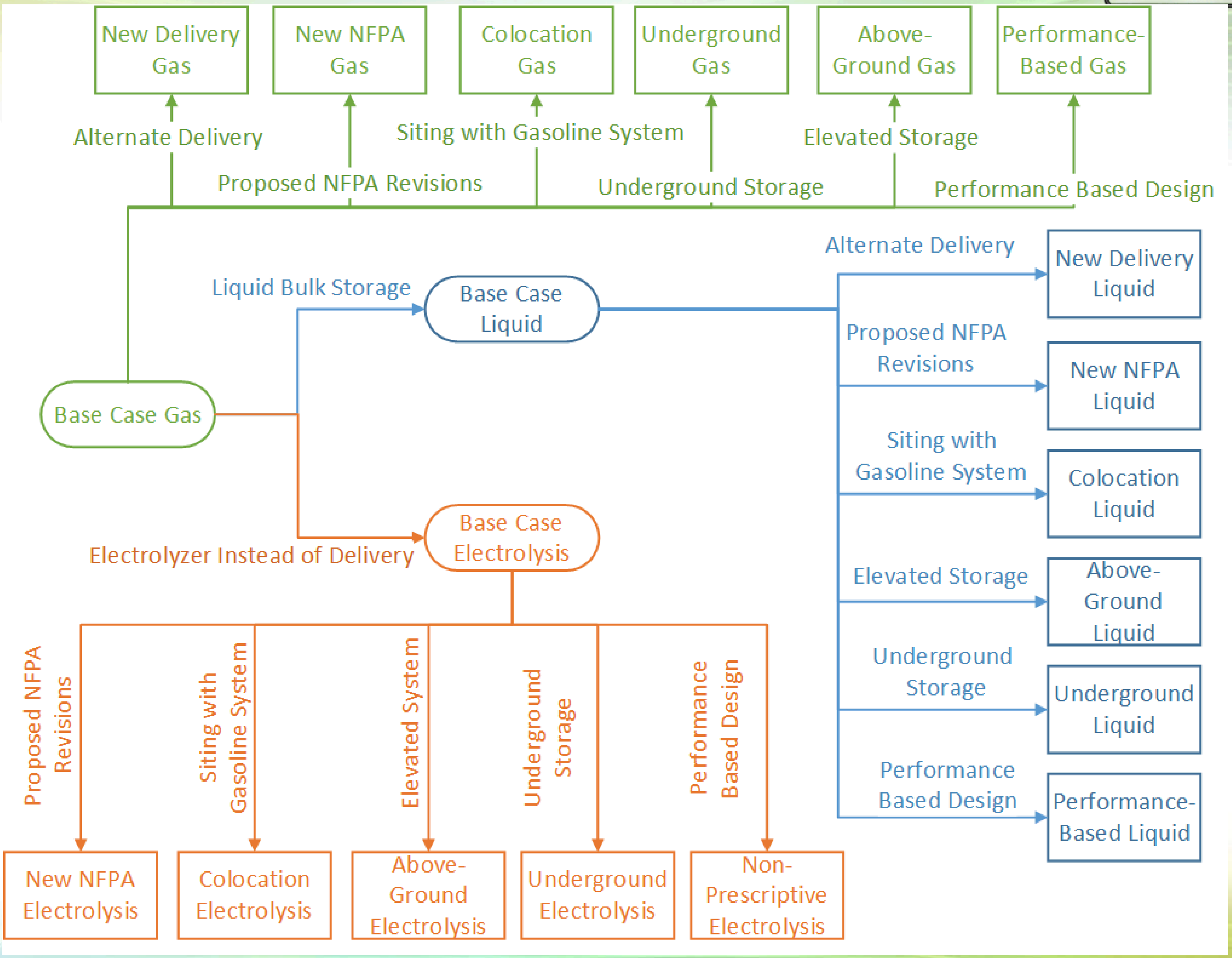
Design Parameters

- H2USA Hydrogen Fueling Station Working group identified station footprint reduction for urban areas as the *#1 priority* for the FY17 H2FIRST projects
  - Focus is on quantifying and reducing station footprint
- Analyzing larger station sizes
  - Previous:
    - 100-300 kg/day dispensed H2
    - 1-2 dispenser hoses
  - Current:
    - 600 kg/day dispensed H_2
    - 4 dispenser hoses
- Level of detail increased for station design elements that affect code requirements
  - Flow pressure drop and velocity design rules used to size tubing
  - Setback distances required by NFPA 2 based on both tube pressure and size
- Generic, “representative” stations
  - Rectangular lots
  - Assume things like utilities and hazards in nearby lots do not come into play

Similar Component Needs for Three Hydrogen Sources



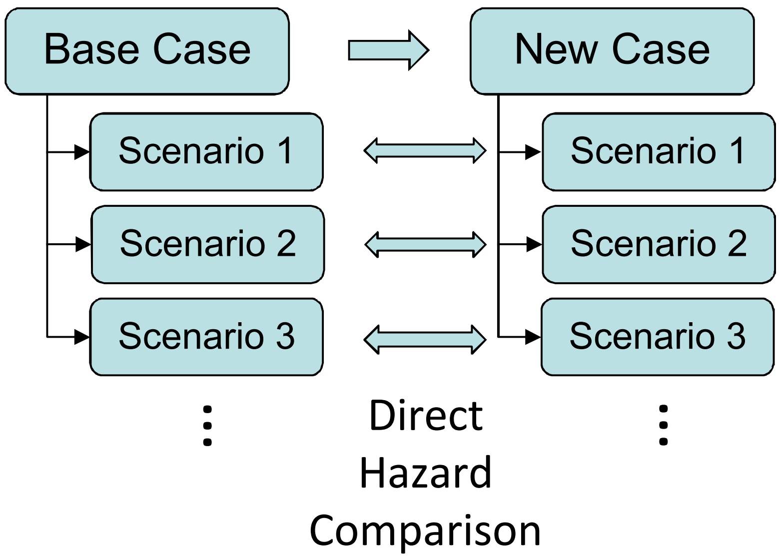
Scenario Structure



Hazard Comparisons to Base Cases

- Most designs follow **NFPA 2 2016** setback distances as written
- Some designs do not, so have two options
  - Performance-Based Designs
    - NFPA 2 Chapter 5
    - Completely independent of all other code requirements
  - Alternative Means
    - Only a few specific requirements (e.g., setback distances) can not be met
    - Analysis required to show that equivalent safety is possible
- How to show equivalent level of safety?
  - Comparisons to setback-distance compliant station designs
  - Analysis with Chapter 5 framework

Quantification of absolute safety is difficult; comparisons show trends



The NFPA 2 Compliance Process

- **Straight prescriptive compliance:** permit applicant meets all prescriptive requirements of the code without any variances
- **Safety equivalency provision in section 1.5 invoked**: permit applicant meets all prescriptive requirements with a small number of safety equivalences approved by the AHJ (this is a fairly common process)
- **Performance based compliance:** permit applicant uses performance based option in Chapter 5 at which point the prescriptive requirements are not applied (this option is used where the applicant can not meet many prescriptive requirements and is rarely used because of the complexity of the compliance demonstration and lengthy review process)

BASE CASE GAS

Presented by Brian Ehrhart

Goals of Base Case Gas Design

- Update/provide reference station for increased H2 capacity
- Explore NFPA 2 requirements as written
  - To identify potential issues
- Provide comparison point to other gaseous station designs
- Provide point of similarity for all other designs in terms of compressor, cascade, dispenser, cooling

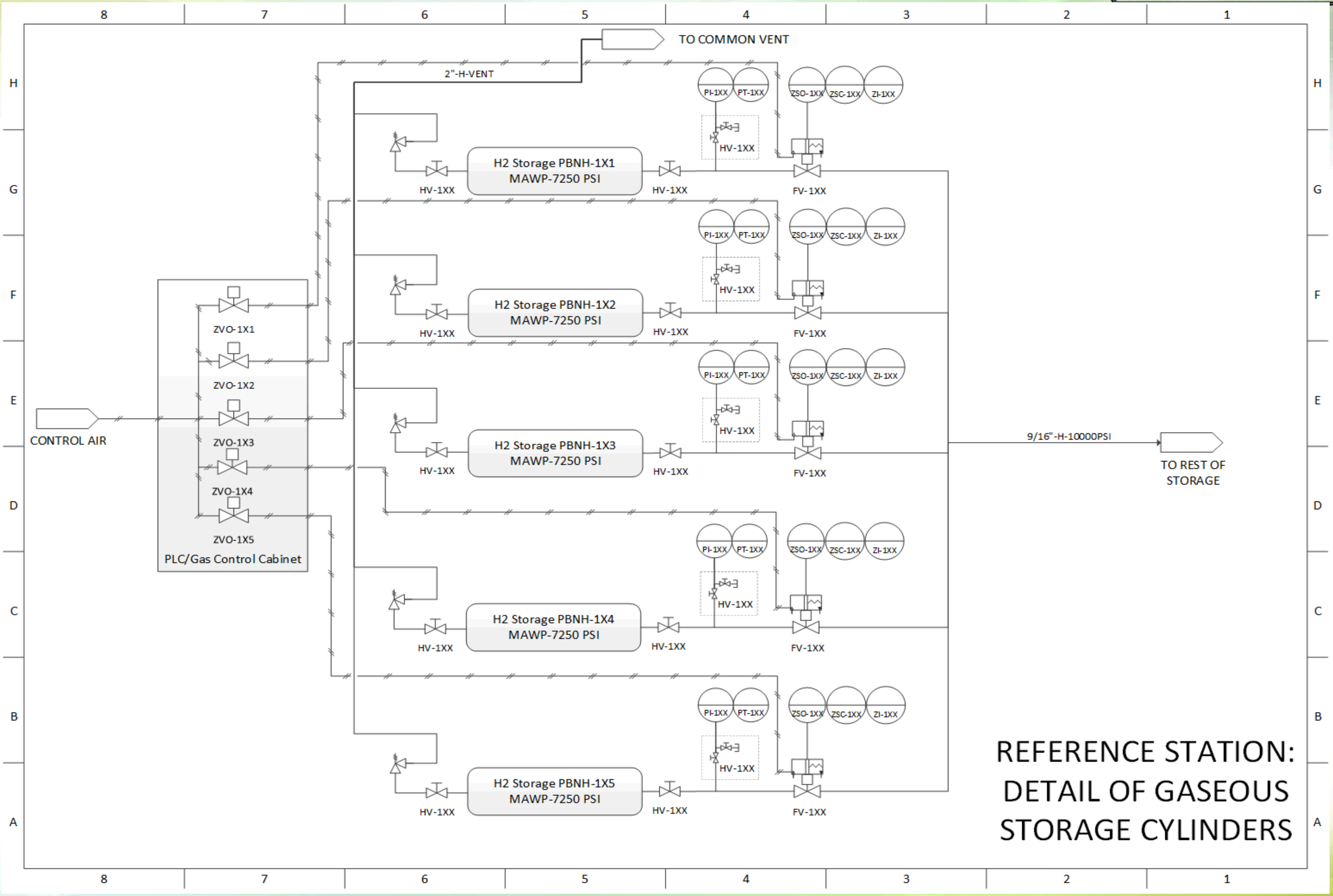
Base Case Gas Design Choices

- Capacity of 600 kg/day of dispensed hydrogen
- 2 dispensers, each with 2 hoses
  - 4 dispenser hoses in total

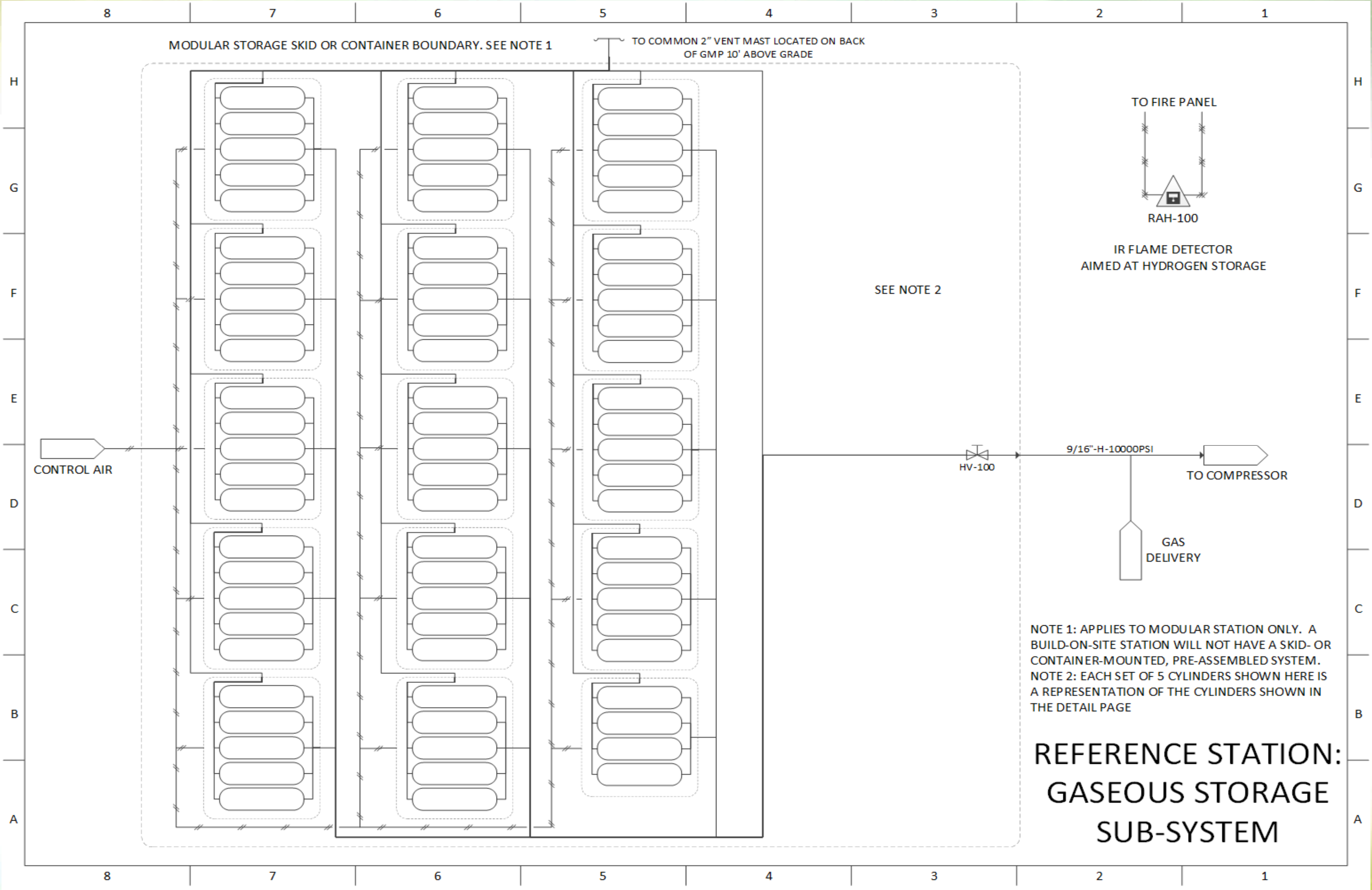
Base Case Gas Bulk Storage Design

- Capacity of 800 kg of GH2
  - Overdesign of 1/3 over daily capacity of 600 kg/day
- Operates between pressures:
  - Low: 6.9 MPa (1,000 psi)
  - High: 50 MPa (7,250 psi)
- 74 cylinders required for bulk storage
  - Cylinder hydraulic volume of 347 L (0.347 m^3)
- Connecting tubing sized for low system pressure of 6.9 MPa (1,000 psi) at a velocity of <20 m/s
  - Designed to also withstand high pressure of 50 MPa
  - Minimum pipe inner diameter of 9.1 mm (0.357 in.)
  - Outer diameter of 14.3 mm (0.5625 in.)
  - Max operating pressure of 68.9 MPa (10,000 psi)

Base Case Gas Bulk Storage Pressure Vessel P&ID



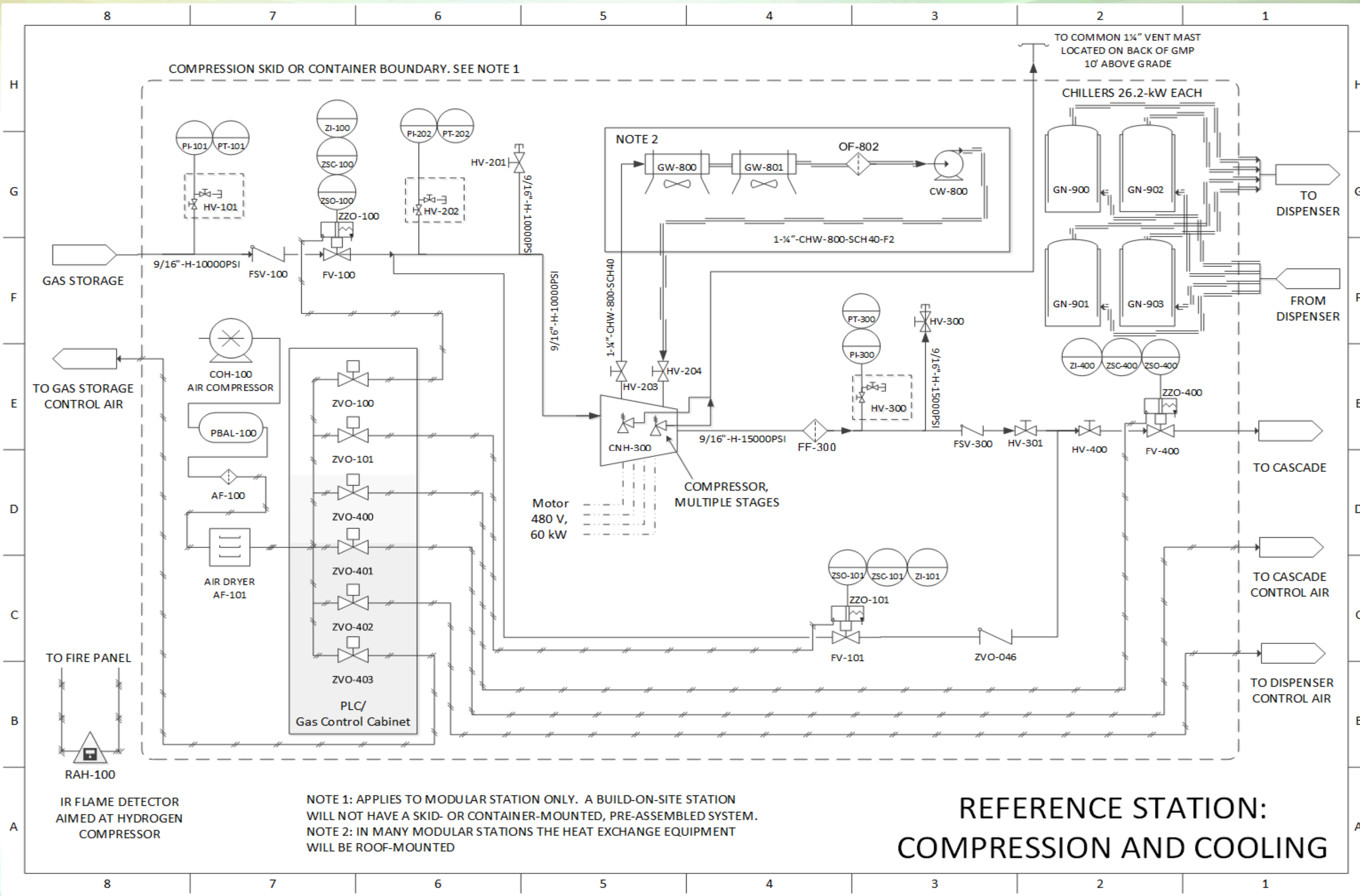
Base Case Gas Full Bulk Storage P&ID



Base Case Gas Compressor Design

- Operating rate of 25 kg/hr
  - Default value obtained by the Hydrogen Refueling Station Analysis Model (HRSAM) v2.0
- Minimum inlet (suction) pressure of 6.89 MPa (1,000 psi)
- Outlet pressure of 94.4 MPa (13,688 psi)
- Power of 60 kW needed, 480V
  - HRSAM values of 75% isentropic efficiency, 91% motor efficiency, and 110% motor over-design
- Physical footprint assumed to be 8 m^3

Base Case Gas Compressor P&ID



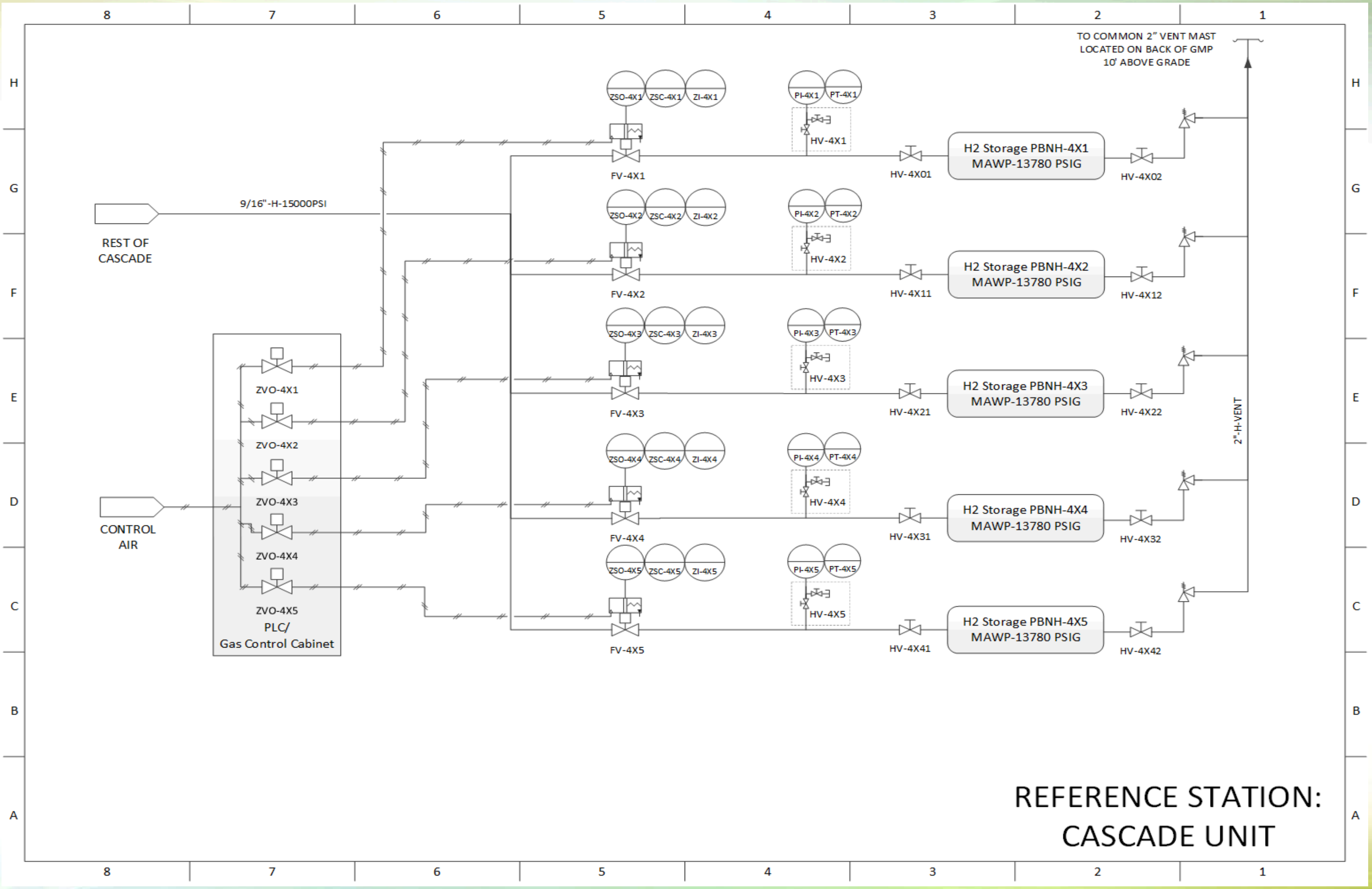
Base Case Gas Cascade Design

- Bank of high pressure gaseous H2 storage cylinders for cascade filling of vehicles
  - Default lower pressure vessel pressures:
    - Low 33.0 MPa (4,791 psi)
    - Medium 61.3 MPa (8.897 psi)
    - High 80.2 MPa (11,634 psi)
  - Default high pressure value is 94.4 MPa (13,688 psi)
  - Each cascade unit has 1 high, 1 medium, and 3 low pressure vessels
- Example pressure vessel diameter of 0.52 m (1.69 ft), length of 2.78 m (9.13 ft), wall thickness of 8 cm (3.15 in.)
  - 10 cascade units of 1:1:3 pressure vessels needed
  - **Total of 50 pressure vessels**

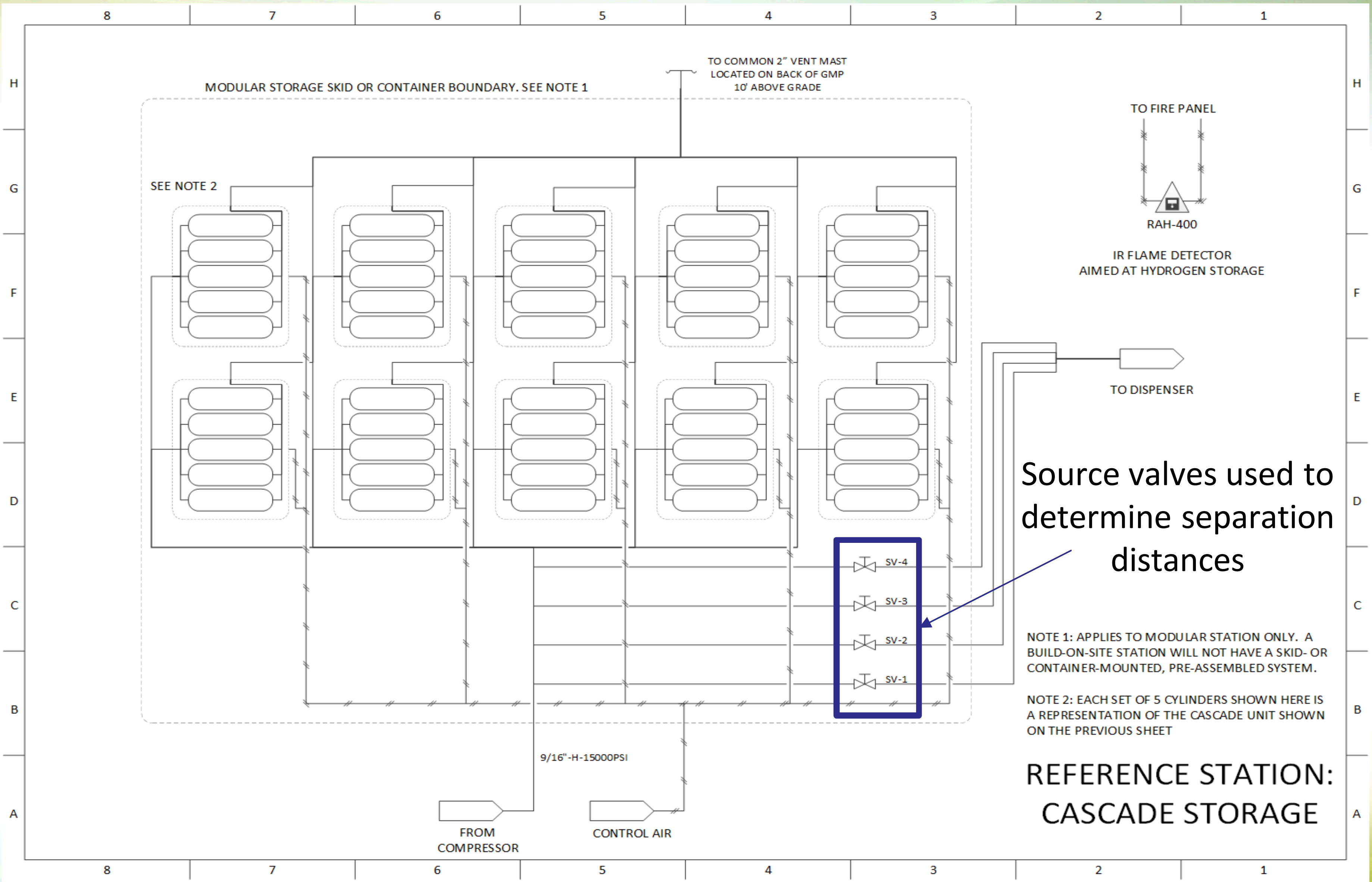
Base Case Gas Cascade Design Continued

- Mass flowrate of H2 has a maximum of 40 kg/hr
  - Will support 8 vehicles back-to-back with 4 filling positions and a max of 5 kg/fill -> 160 kg/fill
- Connection tubing also assumed to have velocity <20m/s
- At lowest cascade pressure of 31.0 MPa (4,500 psi) and minimum ID of 5.78 mm (0.23 in.), the connection tubing size is:
  - Inner diameter of 5.78 mm (0.23 in.)
  - Outer diameter of 14.3 mm (0.5625 in.)
  - Max operating pressure of 103.4 MPa (15,000 psi)

Base Case Gas Cascade Pressure Vessel Detail P&ID



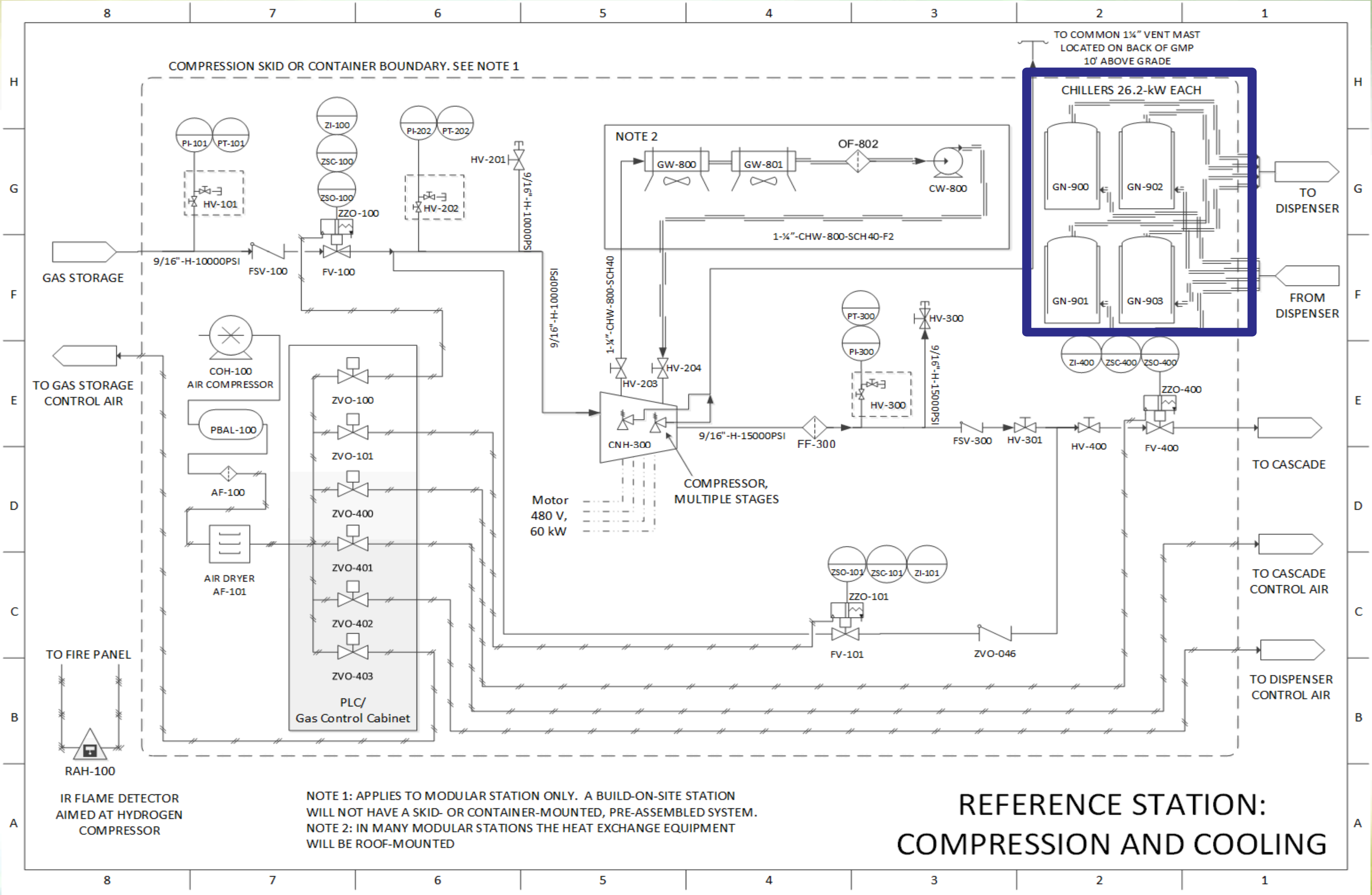
Base Case Gas Full Cascade P&ID



Base Case Gas Chiller Design

- Each dispenser hose has an associated chiller
- HRSAM calculates 25.2 kW (7.2 tons) of refrigeration needed
  - Also an aluminum cooling block of 1,330 kg (0.49 m^3) for each dispenser
  - The cooling blocks absorb the temperature fluctuation of a fill

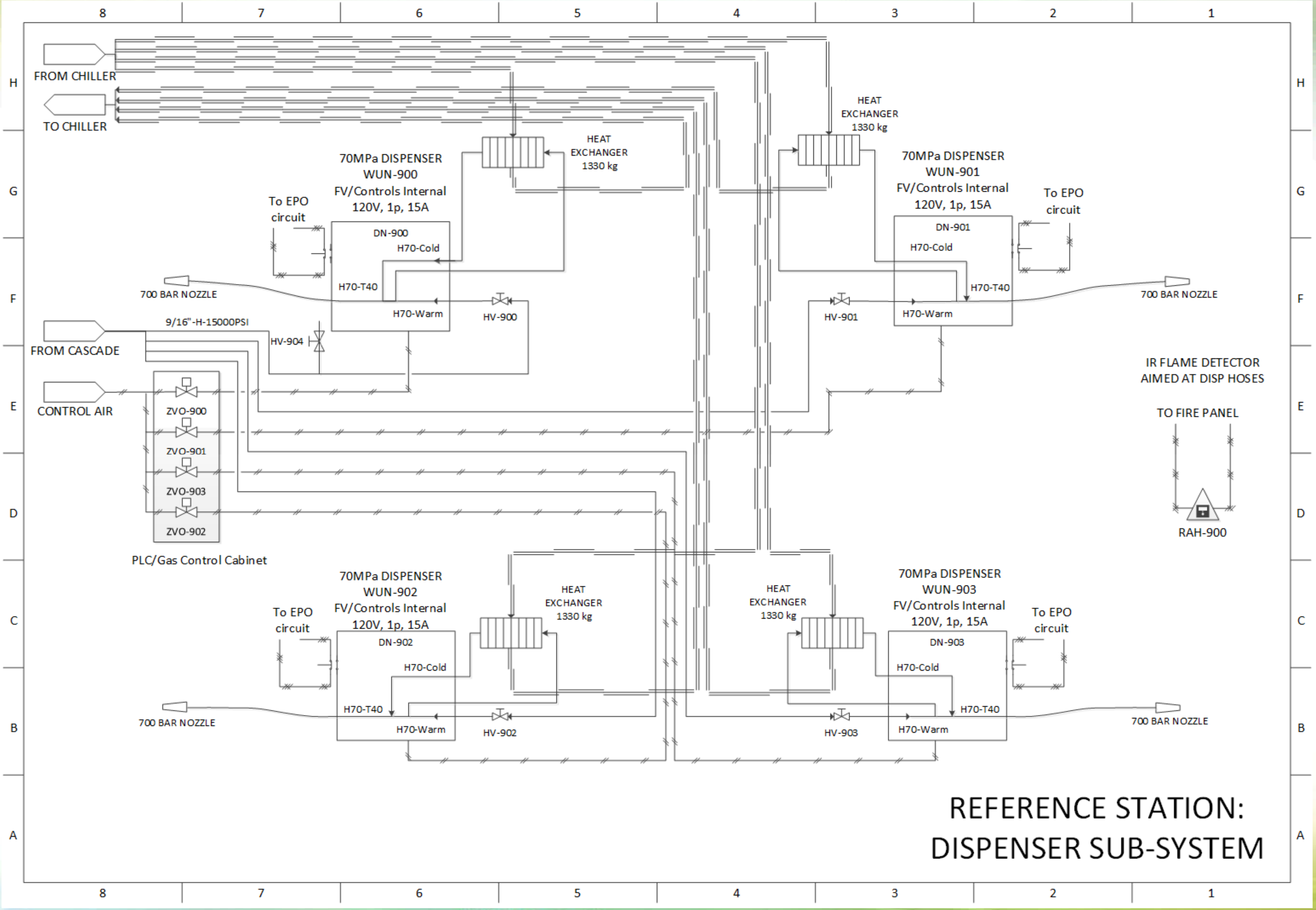
Base Case Gas Compressor P&ID- Highlighting Chillers



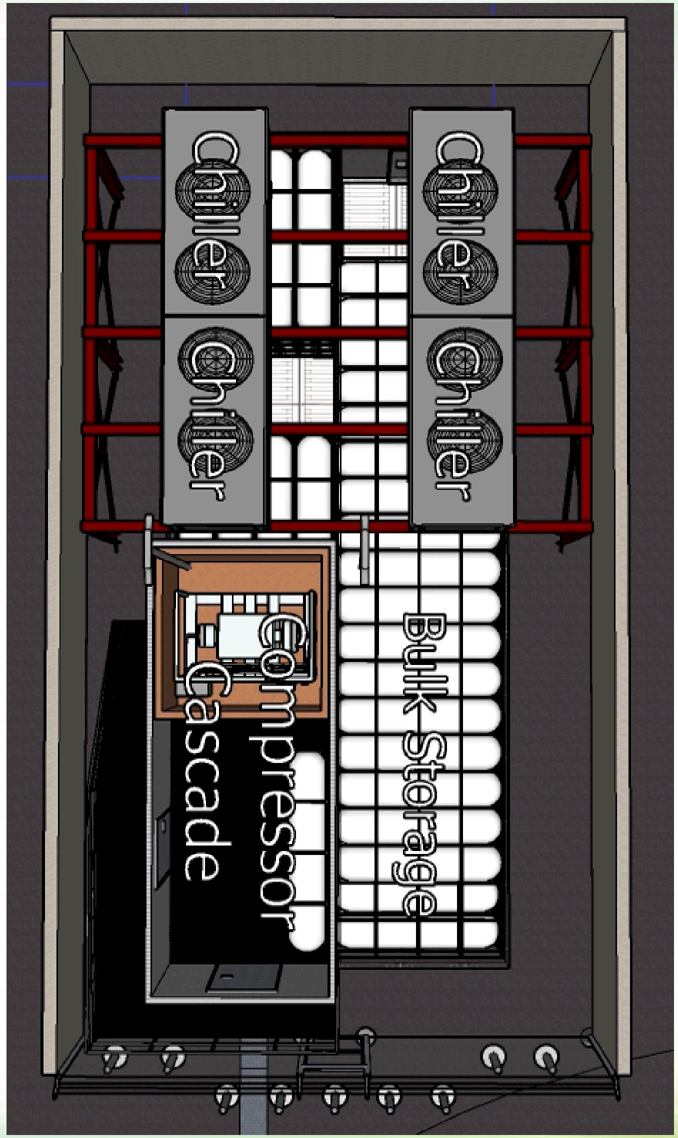
Base Case Gas Dispenser Design

- 4 Dispenser hoses
  - Each capable of dispensing H2 at 70 MPa (10,152.6 psi)
- Two dispenser towers on a dispenser “island”
- Each fueling position is equipped with an emergency shutdown (ESD) valve

Base Case Gas Dispenser P&ID



Base Case Gas Equipment Layout



Base Case Gas NFPA 2 2016 Setback Distances

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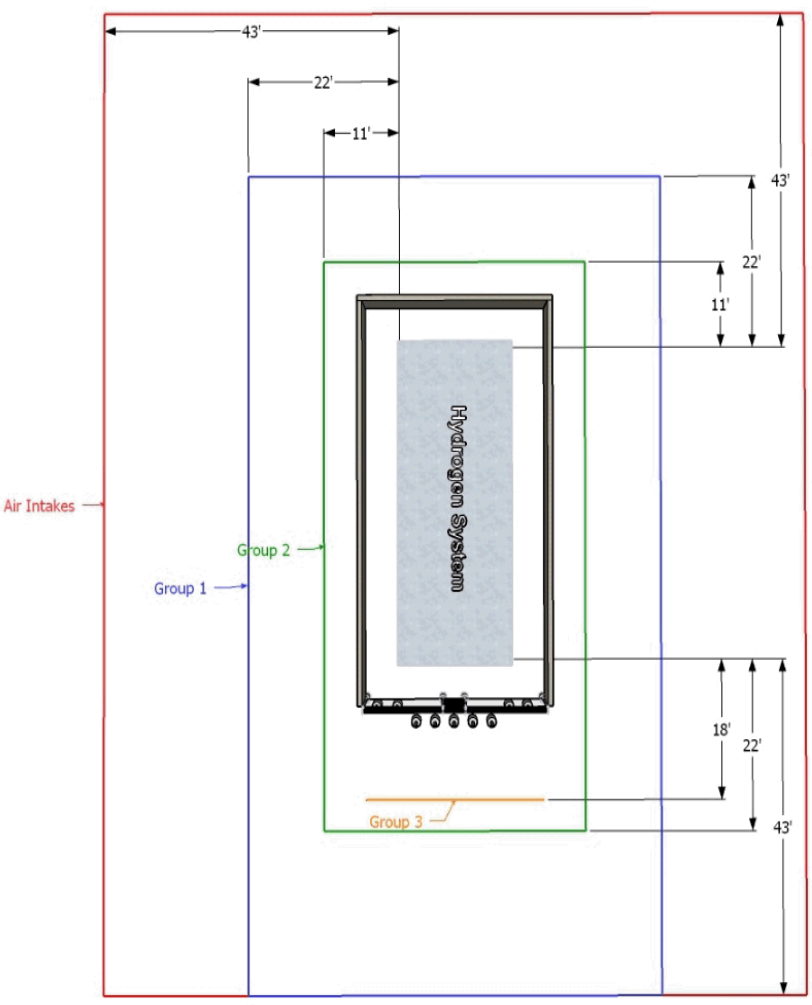
- Setback distances calculated for both bulk storage and cascade
  - Both systems contain >5,000 scf (141.6 Nm^3) of GH2 and meet bulk storage definition
  - Used maximum pressure and maximum inner tubing diameter for each section

	Source	Max Pressure	Max ID	Group 1	Group 2	Group 3
Bulk Storage	7.3.2.3.1.1(a)	50.0 MPa (7,250 psi)	N/A	9 m (29 ft)	4 m (13 ft)	4 m (12 ft)
	7.3.2.3.1.1(b)		9.07 mm (0.357")	10 m (33 ft)	5 m (16 ft)	4 m (14 ft)
Cascade	7.3.2.3.1.1(a)	94.4 MPa (13,688 psi)	N/A	10 m (34 ft)	5 m (16 ft)	4 m (14 ft)
	7.3.2.3.1.1(c)		6.4 mm (0.25")	9 m (30 ft)	4 m (14 ft)	4 m (13 ft)
Single System	7.3.2.3.1.1(a)	94.4 MPa (13,688 psi)	N/A	10 m (34 ft)	5 m (16 ft)	4 m (14 ft)
	7.3.2.3.1.1(c)		9.07 mm (0.357")	13 m (43 ft)	7 m (22 ft)	5 m (18 ft)

Max pressure from cascade system and max ID from bulk storage for worst case scenario

Used for analysis

Base Case Gas Minimum Footprint



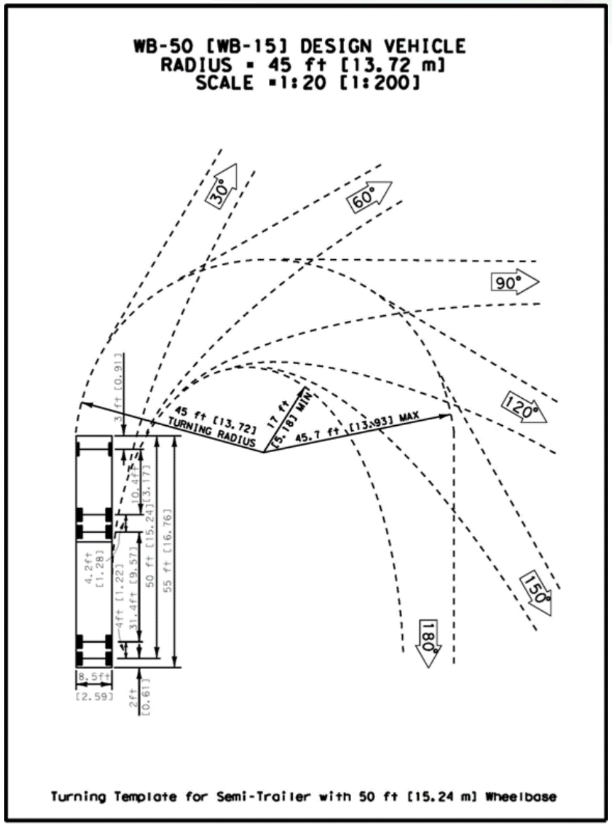
- System includes:
  - Bulk storage
  - Compressor
  - Cascade
- Not shown:
  - Dispensers
  - Chillers
  - Control air

Blue Lines:	Group 1 Exposures
Red Lines:	Air Intakes
Green Lines:	Group 2 Exposures
Orange Line:	Group 3 Exposures

Note: Fire-rated walls reduce all exposures for Group 1 (except air intakes) and Group 2 by half and eliminate Group 3 setback distances

Base Case Gas Delivery Truck Assumptions

- H2 is delivered via a truck
  - Entry/exit path from the property line to the fill point
  - 50 ft wheel base truck



Texas Department of Transportation (DOT), *Road Design Manual*. 2014.

Base Case Gas Convenience Store Assumptions

- Assumed a 1,500 ft^2 generic convenience store
  - Association for Convenience and Fuel Refueling (NACS) states that this is a Limited Selection Convenience Store
  - Convenience store size will likely have an impact on lot size
- Assumed to have six vehicle parking spaces

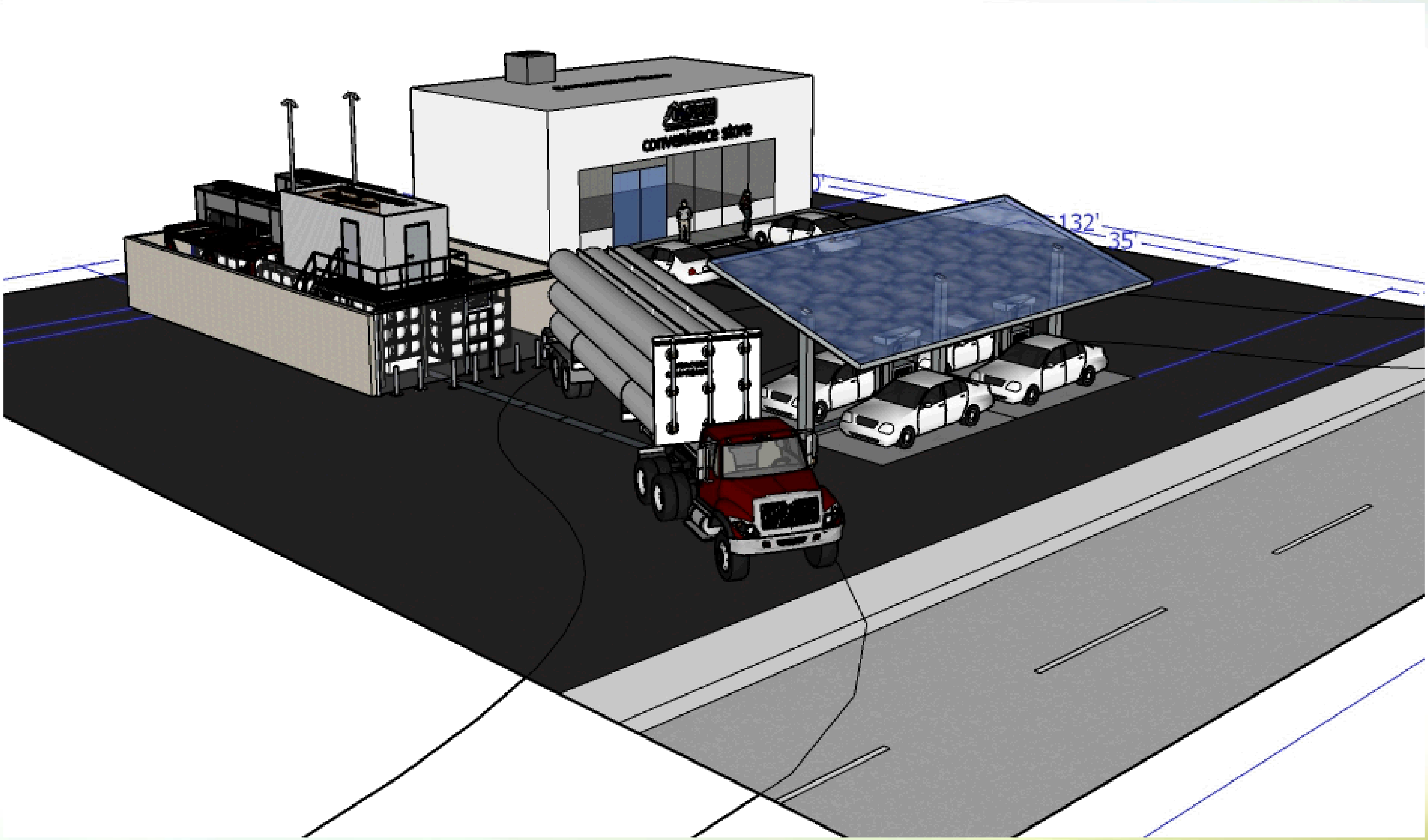
NACS. *What is a Convenience Store?* [cited 2018 Jan 22]; Available from: http://www.convenience.org/Research/Pages/What-is-a-Convenience-Store.aspx.

Base Case Gas Traffic Design Assumptions

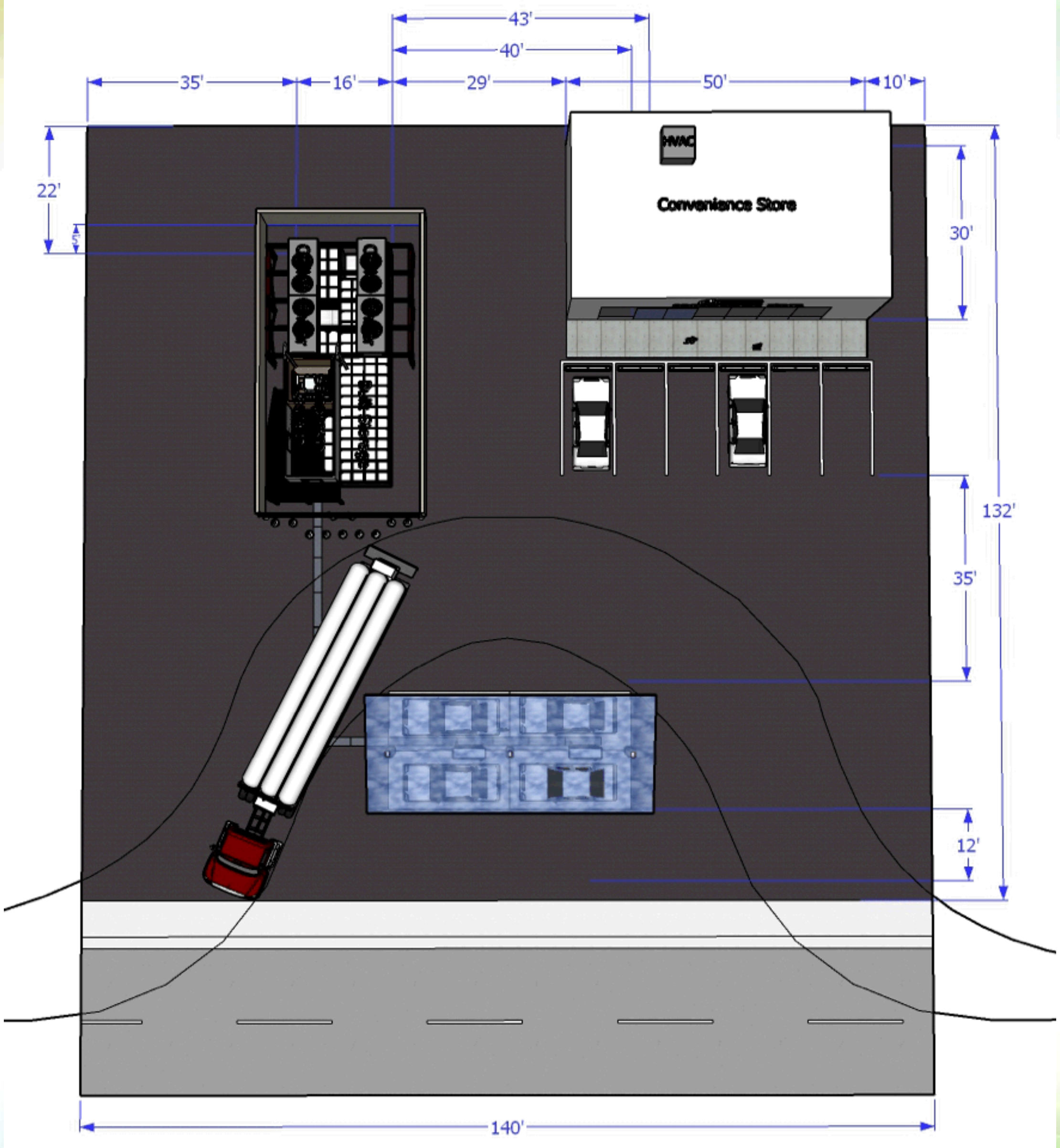
- Each filling location is sized as a parallel parking spot
  - 10 x 20 ft
  - 22 ft behind parking area in front of convenience store
  - 12 ft from lot line
- Sufficient space behind convenience store parking spaces
  - 22 ft – One-way driveway with parking on both sides
- Sufficient space on lot-line side of dispenser
  - 12 ft – One-way driveway

University of Houston, *Campus Design Guidelines and Standards*, in *Section 9 Parking Lot Design Standards* 2012.

Base Case Gas Full Layout



Base Case Gas Full Layout



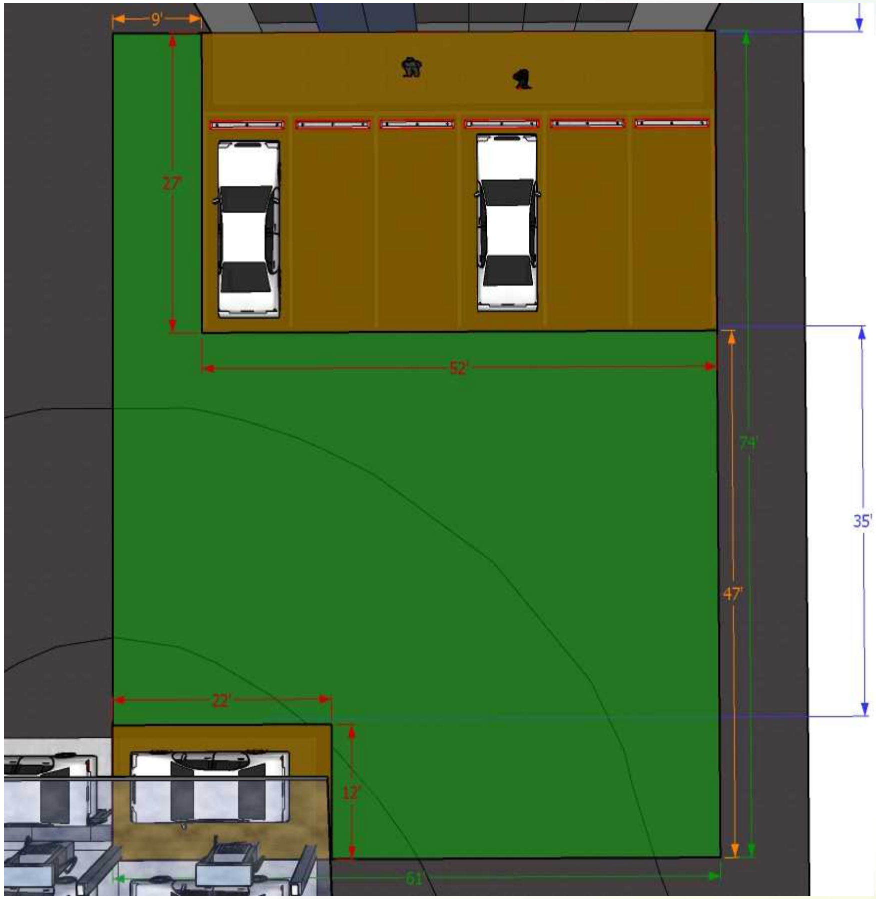
- Lot Size: 132 x 140 ft
- Total Area: 18,480 ft^2

Base Case Gas NFPA 2 Chapter 5 Hazard Scenarios

Required Scenario	Outdoor Fueling Station Scenario	Performance Criteria Approach
Fire	Hydrogen fire resulting from a leak at the hydrogen dispenser	Jet fire risk calculation
Explosion Scenario 1: Pressure Vessel Burst	Compressed gas storage	List of mitigations for burst
Explosion Scenario 2: Deflagration	A hydrogen deflagration within the enclosure housing the compressor.	Potential for deflagration conditions and peak overpressure
Explosion Scenario 3: Detonation	Localized H2/air mixture in the vent pipe	Vent pipe design specifications
Hazardous Material Scenario 1: Unauthorized Release	Release of hydrogen from storage vessel	Jet/plume for localized hypoxia
Hazardous Material Scenario 2: Exposure Fire	Unrelated vehicle fire at the lot line	Flame radiation from vehicle fire
Hazardous Material Scenario 3: External Event	Seismic event where largest pipe bursts	Risk metric calculation
Hazardous Material Scenario 4: Protection System Out of Service	A hydrogen discharge where the interlock fails	Layered safety features present in the system
Building Use Scenario 1: Emergency Exit Blocked	Hydrogen system outdoors	Not applicable
Building Use Scenario 2: Fire Suppression Out of Service	Hydrogen system outdoors	Not applicable

Base Case Gas Fire Scenario

- Only assumed a single fire source, simultaneous events not considered
- Dispenser assumed to develop a leak, ignite immediately and result in a jet fire
  - Only effects of jet fire considered, explosive conditions explored in other scenarios
- HyRAM QRA tool used to analyze results of jet fire risk
- Average Individual Risk (AIR) for jet fire scenario is:
  3.14×10^{-6} fatalities per year



Base Case Gas Explosion 1 – Pressure Vessel Burst

- Three ways for a H2 pressure vessel to burst
  - Fatigue
    - GH2 containers designed to withstand pressure cycling within the service life of cylinder so fatigue cycle failure probability is small
  - Impact Damage
    - GH2 pressure vessels are stationary and protected from accidental damage so impact damage failure is small
  - Fire
    - Mitigation includes pressure relief devices and pressure vessel design leak before burst

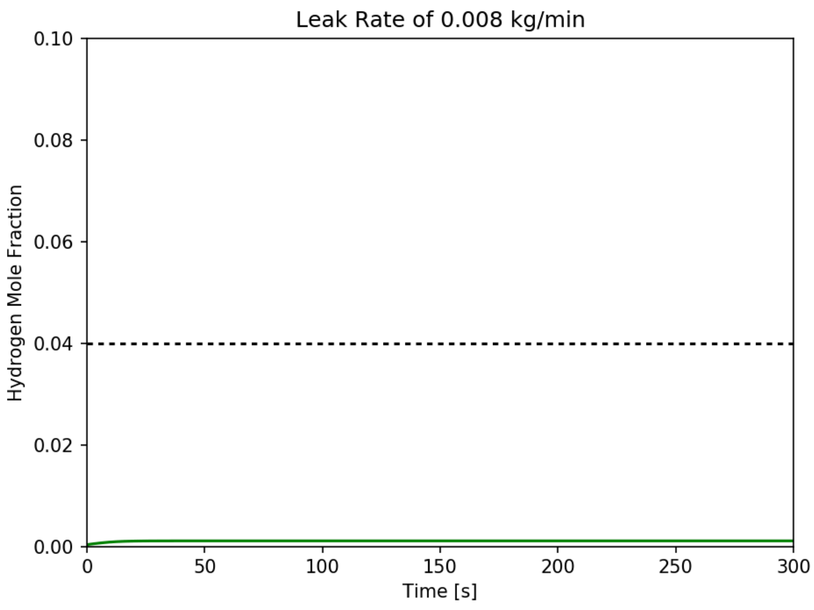
Base Case Gas Explosion 2 – Deflagration

- Analyzed a compressor leak in the modular equipment enclosure
  - Enclosure size: 2.9335 m long by 2.352 m wide by 2.385 m tall
  - Houses electrical equipment and compressor, estimated 25% of volume
- Compressor leak at pressure of 94.4 MPa (13,688 psi) and ID 6.35 mm (0.25 in.)
  - Most likely leak size is 0.01% of pipe area, more conservative is 1% of pipe area
- Ventilation system has flow rate of 0.3048 $Nm^3/min/m^2$ (1 $scf/min/ft^2$)
  - Exhaust vent size 0.054 m^2 (0.581 ft^2)

Base Case Gas Explosion 2 – Deflagration

- Lowesmith model used to determine the steady state H2 concentration
- For leak size of 0.01% pipe area, results showed that steady-state H2 concentration is 0.11% H2
  - Less than 4% lower flammability limit for H2

H2 Concentration from 0.01% of Pipe Size Leak

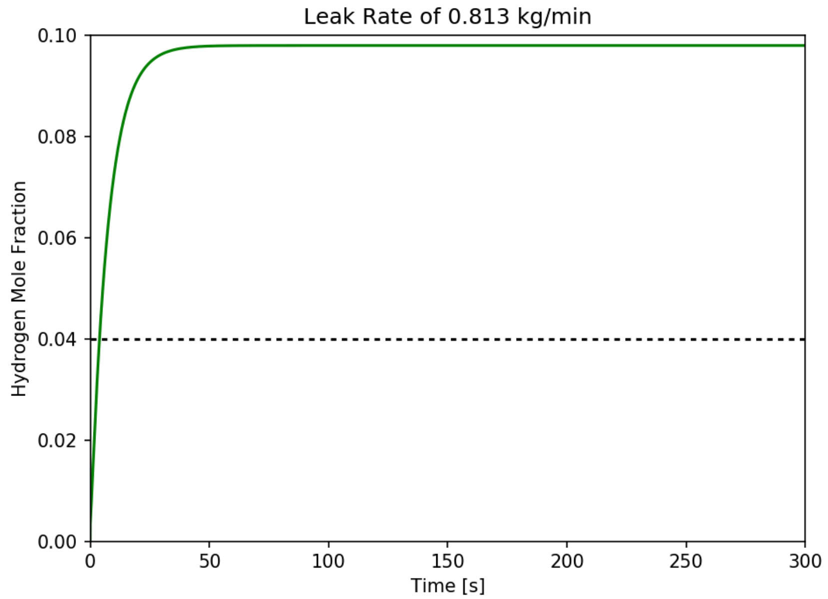


Base Case Gas Explosion 2 – Deflagration

H2FIRST

- For leak size of 1.0% pipe area, results showed that steady-state H2 concentration is 9.8% H2
  - Higher than 4% lower flammability limit for H2

H2 Concentration from 1.0% of Pipe Size Leak



Final Steady-State Overpressure

Leak Rate	Overpressure
0.01% of Pipe Size	0 Pa
1% of Pipe Size	3.89×10^5 Pa (56.5 psi)

← Used for analysis

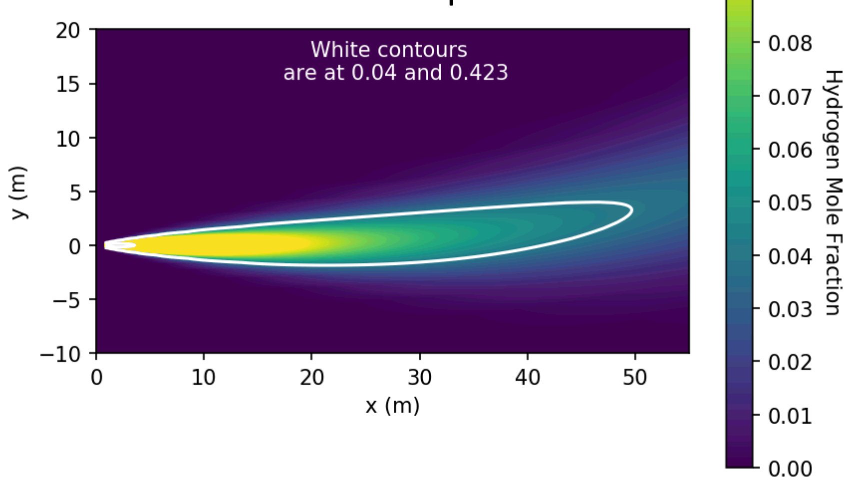
Base Case Gas Explosion 3 – Detonation

- Vent stack from the compressor is the most conservative credible scenario
- NFPA 2 requires vent stacks designed and built according to CGA 5.5
  - Requires a length to diameter ratio of <100:1 to prevent detonation
- L/D ratio has a 13% safety factor above code requirements, so no credible detonation scenario exists for the design

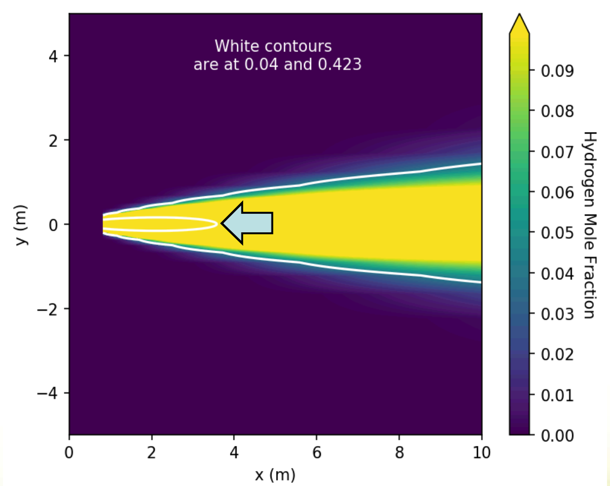
Base Case Gas Hazardous Material 1 – Unauthorized Release

- Scenario analyzed is the release of H from the cascade gaseous storage sub-system
- Release point was 0.25 in. ID pipe at outlet of cascade system
  - Max pressure of 94.4 MPa (13,688 psi)
- 2-D gas jet model used to characterize H2 concentration from release point and determine when oxygen level was below performance criterion

H2 Concentration Results of Plume Jet
H2 Release from 100% Pipe Sheer



H2 Release Results Focused on Release Point

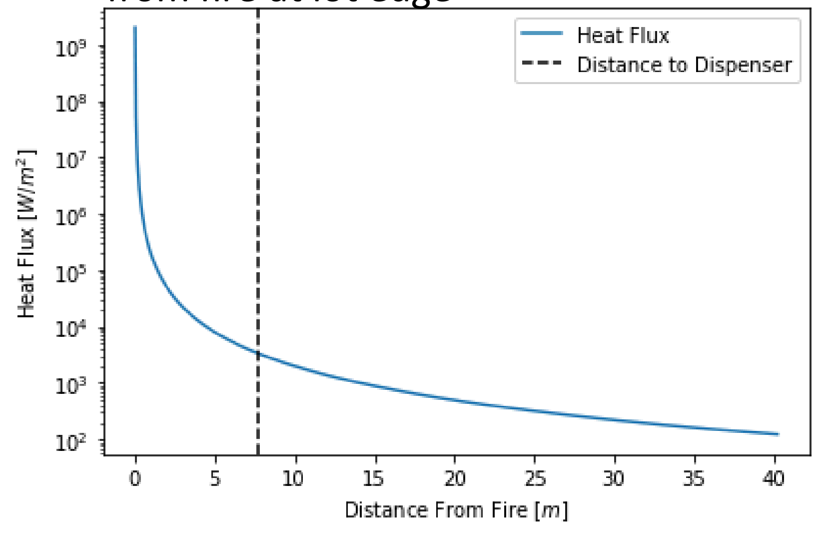


Performance criterion O2 level within 4 m of release point

Base Case Gas Hazardous Material 2 – Exposure Fire

- Most likely exposure fire is a vehicle fire, most likely due to an crash on the public street
- Scenario analyzed impact of vehicle fire on H2 dispenser system
- Heat flux was calculated from the heat release rate from a single passenger vehicle (5 MW)

Heat flux values for various distances from fire at lot edge



Heat flux of 3.3 kW/m^2 will be used for comparison to other scenarios

Base Case Gas Hazardous Material 3 – External Event

- Scenario is that a seismic event occurs that results in sheering the largest pipe resulting in 100% release
  - Pipe has OD of 14.3 mm (0.5625 in.) and inner diameter of 9.11 mm (0.359 in.) with pressure of 50 MPa (7,250 psi)
  - Number of vehicles set to zero
- HyRAM used to calculate baseline risk value for compliant station

External Event QRA Facility and Potential Individual Risk Locations

- Average Individual Risk (AIR) for external event scenario is:

  2.177 x 10^{-2} fatalities per year*

*conditional based on the occurrence of an earthquake

Base Case Gas Hazardous Material 4 – Discharge with Protection System Out of Service

- Scenario is an unintentional release with each protection system independently rendered ineffective
  - Interlock is the only protection system available for this type of evaluation
- Interlocks shut down the flow of H2 at several air-operated, fail-safe shut-off valves
  - Reliability of digital logic controllers was examined in this analysis
  - Probability that a controller with redundant processors will recover from a single processor failure ranges from 98.37% to 99.59%
- Ventilation is the only other safety system credited in another scenario
  - Both ventilation and system detection would need to fail simultaneously, which is exceedingly rare and outside the scope of this hazard scenario

Base Case Gas – Non-Applicable Scenarios

- Some scenarios are not applicable for an outdoor fueling station

Non-Applicable Scenarios	Justification for Exclusion
Building Use Design Scenario 1 involves an event in which the maximum occupant load is in the assembly building and an emergency event occurs blocking the principal exit/entrance to the building. [NFPA 2:5.4.5.1]	No assembly occupancies exist on or nearby the refueling station and there were no building structure exits or entrances to block.
Building Use Design Scenario 2 involves a fire in an area of a building undergoing construction or demolition while the remainder of the building is occupied. The normal fire suppression system in the area undergoing construction or demolition has been taken out of service. [NFPA 2: 5.4.5.2]	No partially-occupied buildings with out-of-service suppression system were present to analyze.

Base Case Gas Hazard Scenario Summary

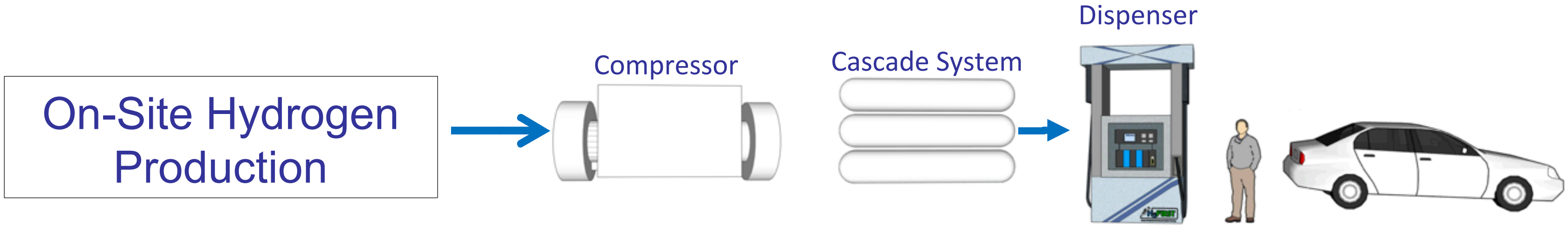
Outdoor Fueling Station Scenario	Baseline Result
Fire: Hydrogen fire resulting from a leak at the hydrogen dispenser	AIR = 3.140 × 10^{-6} fatalities/year
Explosion Scenario 1: Gaseous H_2 pressure vessel rupture	Mitigations listed for stationary pressure vessels
Explosion Scenario 2: H_2 deflagration within the enclosure housing the compressor	3.89 × 10^5 Pa overpressure for 1% of pipe size leak
Explosion Scenario 3: Venting of hydrogen forms localized H_2/air mixture in the vent pipe that detonates	Vent pipe length to diameter ratio to prevent detonation is present with a 13% additional safety factor
Hazardous Material Scenario 1: Release of hydrogen from storage tank	The hypoxia criterion of 12% O_2 is met within 4 m of the release point
Hazardous Material Scenario 2: An unrelated vehicle fire at the lot edge	Heat flux on dispenser: 3.3 kW/m^2 for single passenger vehicle
Hazardous Material Scenario 3: Seismic event where a pipe bursts (100% leak size on largest pipe)	AIR Fire = 2.177 × 10^{-2} fatalities per year, conditional upon the occurrence of an earthquake
Hazardous Material Scenario 4: A hydrogen discharge where the interlock fails	No additional risk scenarios are credible because the interlocks are not credited in the above hazard scenarios
Building Use Scenario 1: Maximum occupancy load present in building during fire with main entrance/exit blocked	Not applicable
Building Use Scenario 2: Fire during maintenance with fire suppression system out of service.	Not applicable

BASE CASE ELECTROLYSIS

Presented by Gaby Bran-Anleu

Base Case Electrolyzer Design

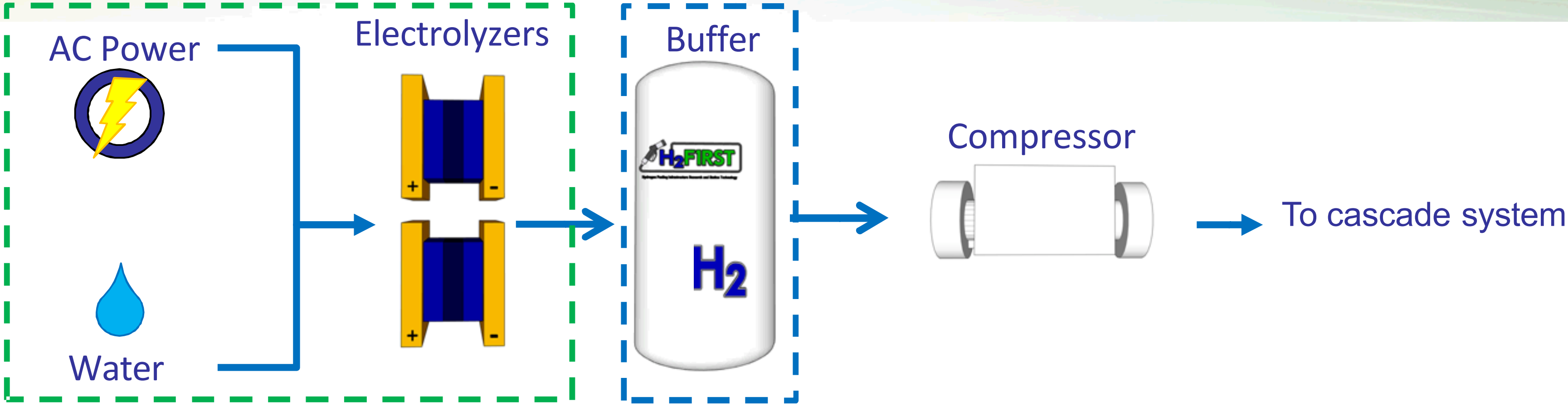
- This station considers a 600 kg/day dispensed H_2 with 4 dispenser hoses
- Components are similar to the Base Case Gas



- Design calculations use HRSAM [1]
  - Compressor
    - 25 kg/hr flow rate (constant 600 kg/day)
    - Outlet pressure of 94.4 MPa (13,688 psi)
    - Power of 92 kW (as compared to 60 kW for the Base Case Gas)
  - Chillers
    - 25.2 kW (7.2 tons) of refrigeration needed for each chiller
  - Dispensing
    - 4 fueling positions, 70 MPa, -40 °C
  - Cascade
    - 10 cascade units, each containing 5 (1:1:3) pressure vessels
    - Outlet flow rate 60 kg/hr to each dispenser
    - Low pressure 31.0 MPa (4,500 psi) yields minimum ID of 5.78 mm (0.23")
      - A pipe ID of 7.92 mm (0.312 inches) and OD of 14.29 mm (9/16 inches)

[1] https://hdsam.es.anl.gov/index.php?content=hrsam

Electrolyzers and Buffer Sizing

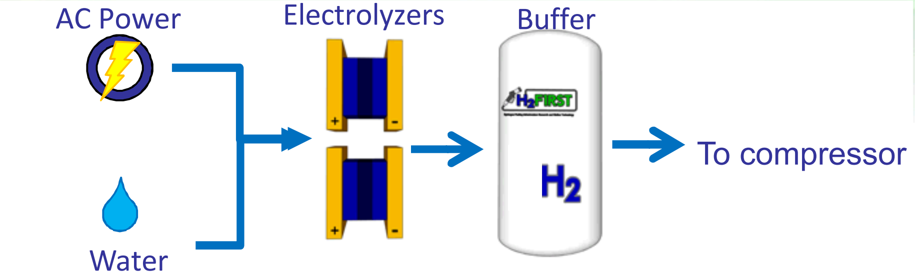


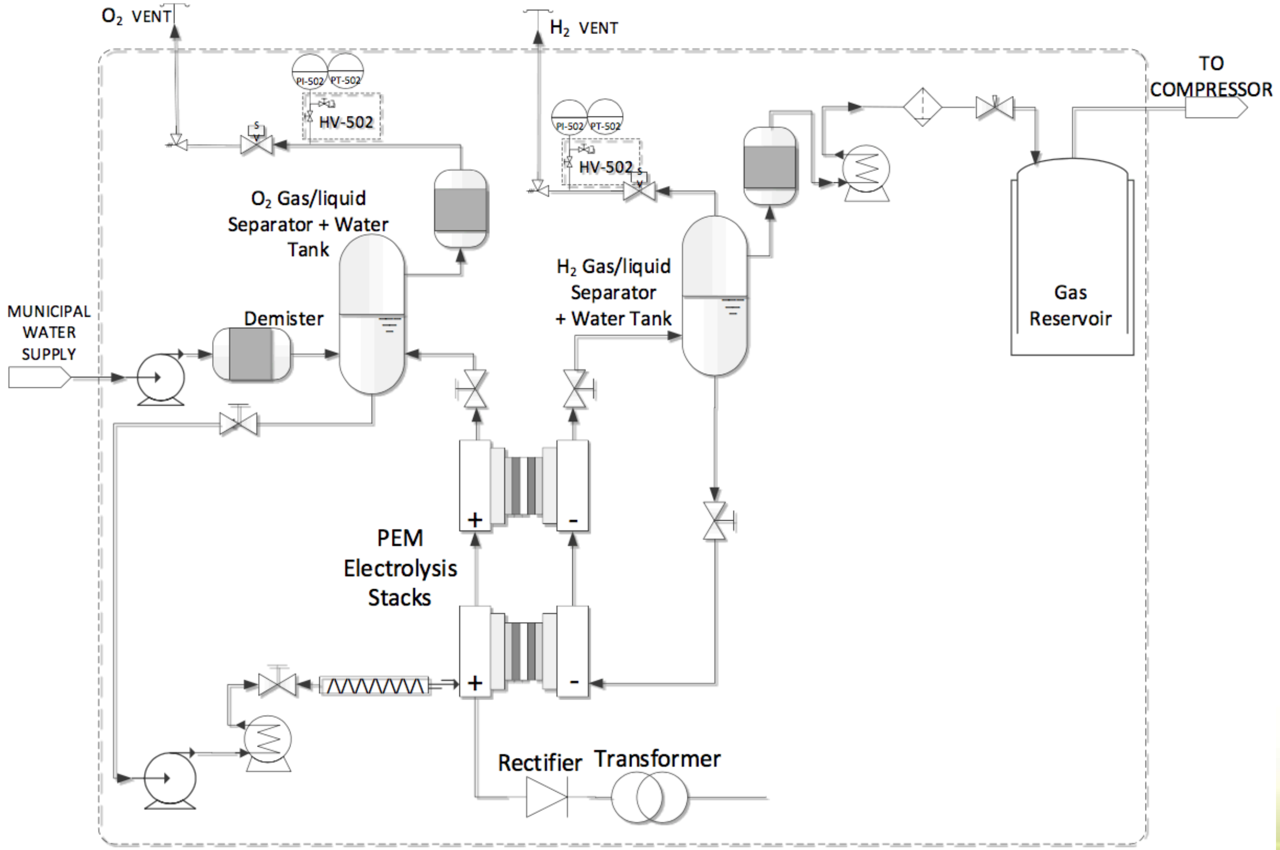
- On-site production of hydrogen is the only H_2 source on the station
  - No delivery truck necessary

- PEM electrolyzers to supply the total station capacity of 600 kg/day
  - H_2 production up to 36 kg/hr
  - Nominal input power ~2MW
  - Tap water consumption <16 liters/kg-H^2
  - Approximate footprint 40 ft + 20ft container

- GH_2 low pressure storage (buffer)
  - Total capacity of 25 kg at 50 bar
  - The tank is replenished by the electrolyzer

P&ID – Electrolyzer and Buffer

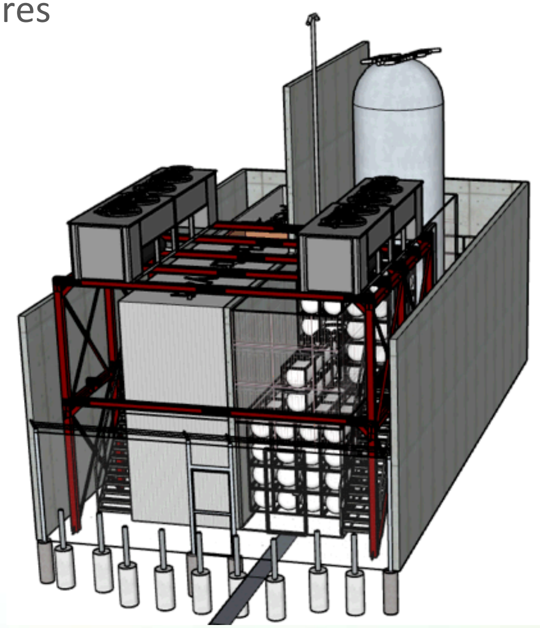


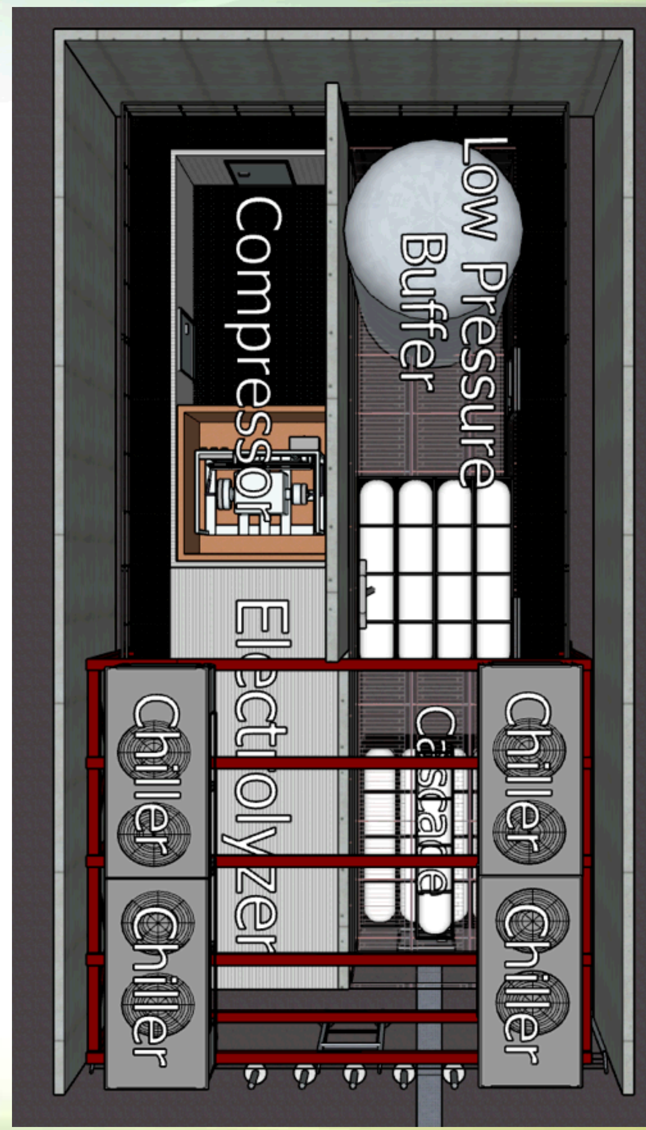


General NFPA 2 Requirements for Gas Hydrogen System

H_2FIRST

- The compressor and the electrolyzers should be fully enclosed in order to prevent environmental hazards from damaging that equipment
- The low and high pressure storage systems should be separated from the compressor and electrolyzers by a one-hour fire rated barrier wall
- A two-hour fire wall was added to reduce the minimum required distances from the bulk hydrogen system to exposures





Setback Distances for Base Case Electrolyzer

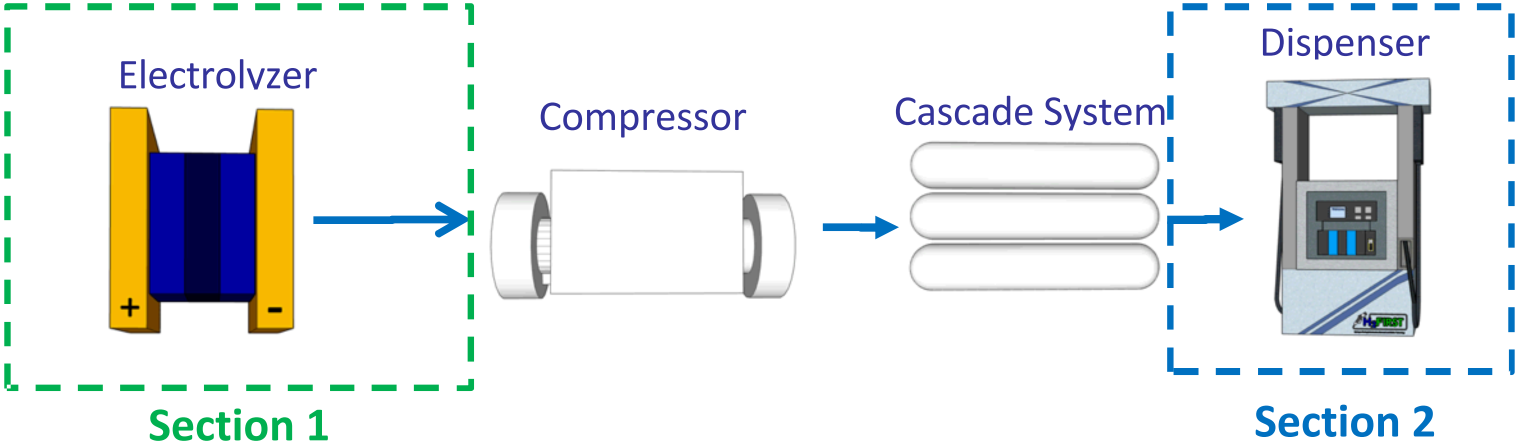
- Setback distances required by NFPA 2 based on both pressure and pipe size

Table 7.3.2.3.1.1(b) Minimum Distance (D) from Outdoor [GH_2] Systems to Exposures by Maximum Pipe Size with Pressures >15 to ≤3000 psig

Pressure		>15 to ≤250 psig >103.4 to ≤1724 kPa						>250 to ≤3000 psig >17.24 to ≤20,684 kPa					
		Exposures*†						Exposures*†					
Internal Pipe Diameter (ID)		Group 1		Group 2		Group 3		Group 1		Group 2		Group 3	
		D = 0.231d		D = 0.12584d – 0.47126		D = 0.096d		D = 0.738d		D = 0.43616d – 0.91791		D = 0.307d	
ID (in.)	d (mm)	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft
0.2	5.1	1	4	0	1	0	2	4	12	1	4	2	5

- The storage pressures and largest pipe diameters must be determined for each storage array in the system
- The largest separation distance for each storage array defines the value of the separation distance for the overall system

Sections of the Hydrogen System at Different Pressures



	Section 1	Section 2
P_{max}	5 MPa (725.19 psi)	94.4 MPa (13,688 psi)
P_{min}	2.0 MPa (290 psi)	33.0 MPa (4,791 psi)
Mass Flow Rate	25 kg/hr. (277 Nm^3/hr)	60 kg/hr. (667 Nm^3/hr)
Pipe ID	17.3 mm (0.68 in)	7.92 mm (0.312 in)
Pipe wall thickness	0.889 mm (0.035 in)	3.18 mm (0.125 in)
Max. Operating Pressure	10.3 MPa (1,500 psi)	137.9 MPa (20,000 psi)

Setback Distances for Sections of Hydrogen System

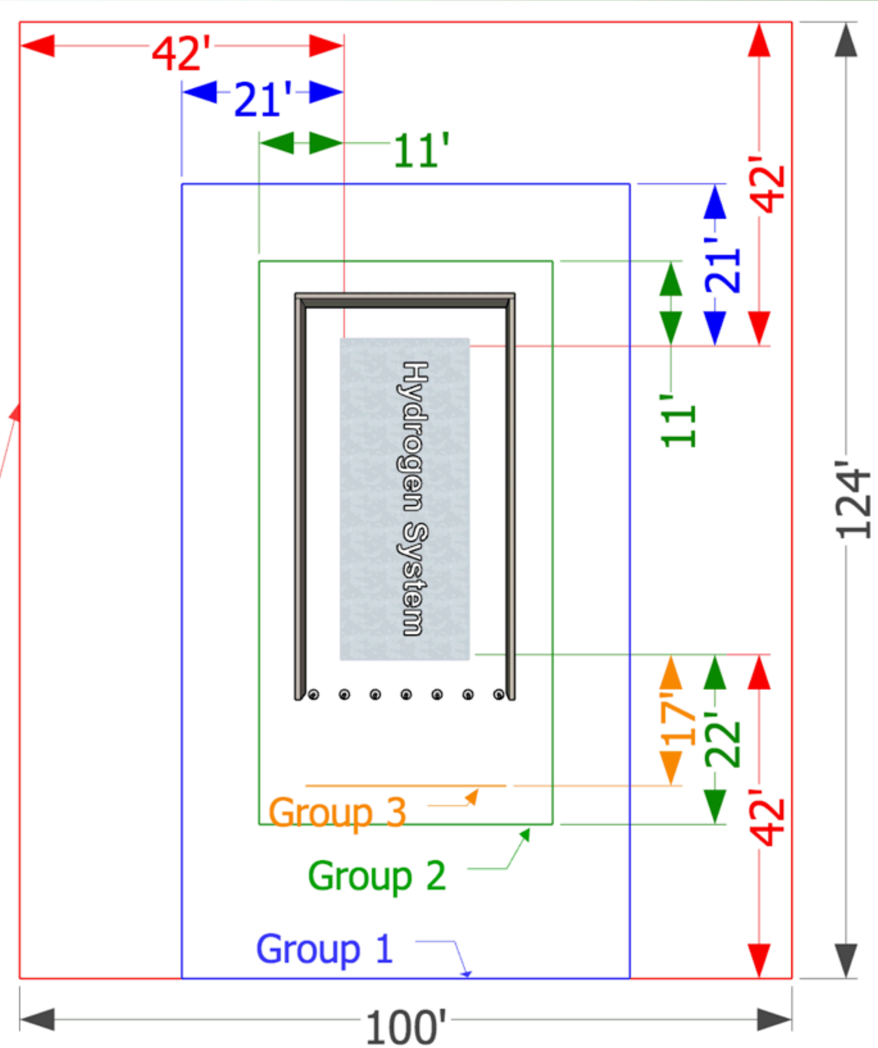
- The largest separation distance for each storage array defines the value of the separation distance for the overall system

	Fire Resistant Wall	Group1	Group 2	Group 3
Section 1	NO	**12.7 m (42 ft.)**	**6.6 m (22 ft.)**	**5.3 m (17 ft.)**
	YES	**6.4 m (21 ft.)**	**3.3 m (11 ft.)**	**0.0 m (0 ft.)**
Section 2	NO	11.5 m (38 ft.)	5.7 m (19 ft.)	4.8 m (16 ft.)
	YES	5.7 m (19 ft.)	2.8 m (9 ft.)	0.0 m (0 ft.)

Setback Distances Around Hydrogen System

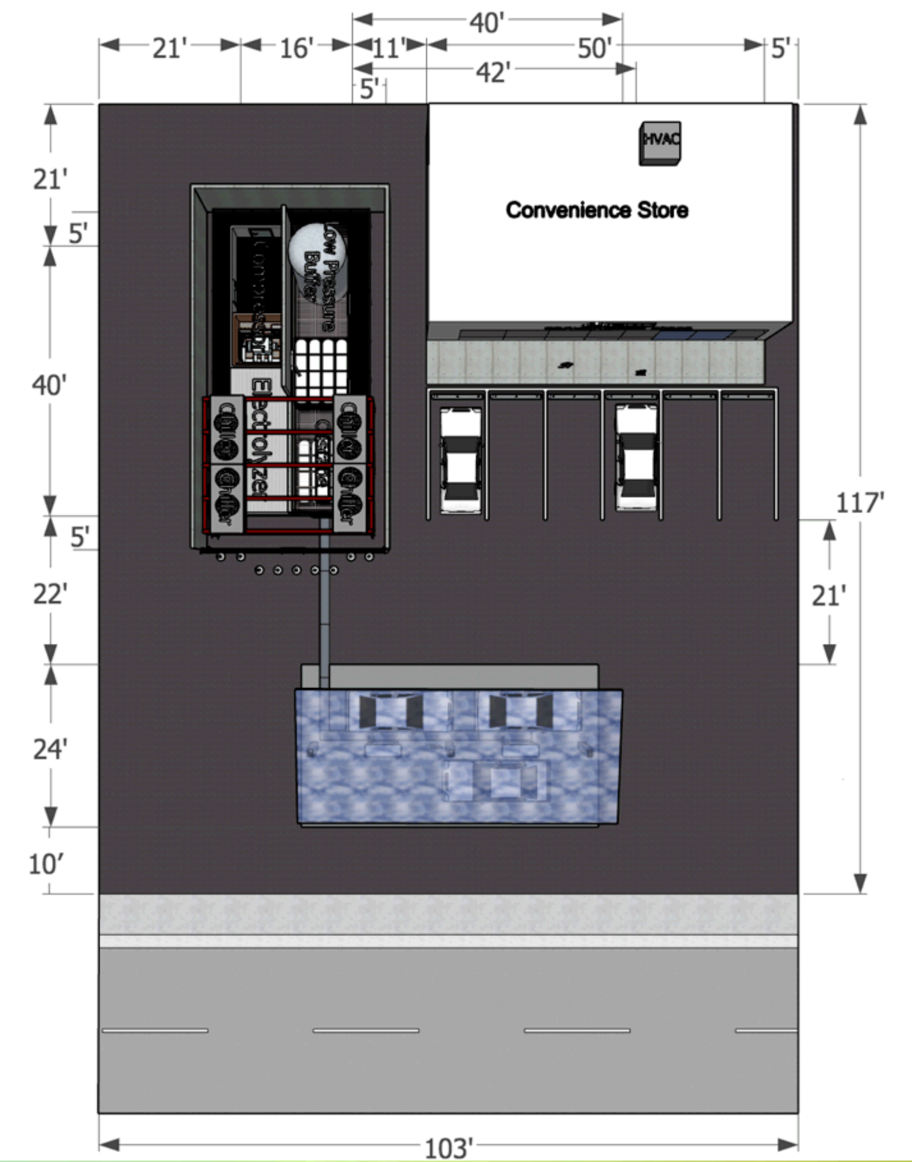
H2FIRST

- Minimum Footprint
  - Hydrogen system only - 12,400 ft^2
- Exposures applicable to station
  - Group 1
    - Air Intakes
    - Lot Lines
    - Operable openings in buildings
  - Group 2
    - Exposed persons other than those servicing the system
    - Parked cars
  - Group 3
    - Buildings of noncombustible non-fire-rated construction



Full Layout for Base Case Electrolyzer

- Full Layout
  - Convenience store
  - Parking
  - Traffic flow
- Total area
  - 12,051 ft^2
  - Hydrogen system only - 12,400 ft^2



Risk and Consequence Analysis on Hazard Scenarios

Hazard Scenario Analysis for Base Case Electrolyzer

H2FIRST

Required Scenario	Outdoor Fueling Station Scenario	Performance Criteria Approach
Fire – Hydrogen fire resulting from a leak at the hydrogen dispenser	Hydrogen fire resulting from a leak at the hydrogen dispenser	Jet fire risk calculation
Explosion Scenario 1 – Gaseous H_2 pressure vessel rupture	Compressed gas storage	List of mitigations for burst
Explosion Scenario 2 –H_2 deflagration within the enclosure housing the compressor (worst case)	A hydrogen deflagration within the enclosure housing the compressor.	Potential for deflagration conditions and peak overpressure
Explosion Scenario 3 – Venting of hydrogen forms localized H_2/air mixture in the vent pipe that detonates	Localized H2/air mixture in the vent pipe	Vent pipe design specifications
Hazardous Material Scenario 1 – Release of hydrogen from storage tank	Release of hydrogen from storage vessel	Jet/plume for localized hypoxia
Hazardous Material Scenario 2 – An unrelated vehicle fire at the lot edge	Unrelated vehicle fire at the lot line	Flame radiation from vehicle fire
Hazardous Material Scenario 3 – Seismic event where a pipe bursts (100% leak size on largest pipe)	Seismic event where largest pipe bursts	Risk metric calculation
Hazardous Material Scenario 4 – A hydrogen discharge where the interlock fails	A hydrogen discharge where the interlock fails	Layered safety features present in the system
Building Use Scenario 1 – Maximum occupancy load present in building during fire with main entrance/exit blocked	Hydrogen system outdoors	Not applicable
Building Use Scenario 2 – Fire during maintenance with fire suppression system out of service.	Hydrogen system outdoors	Not applicable

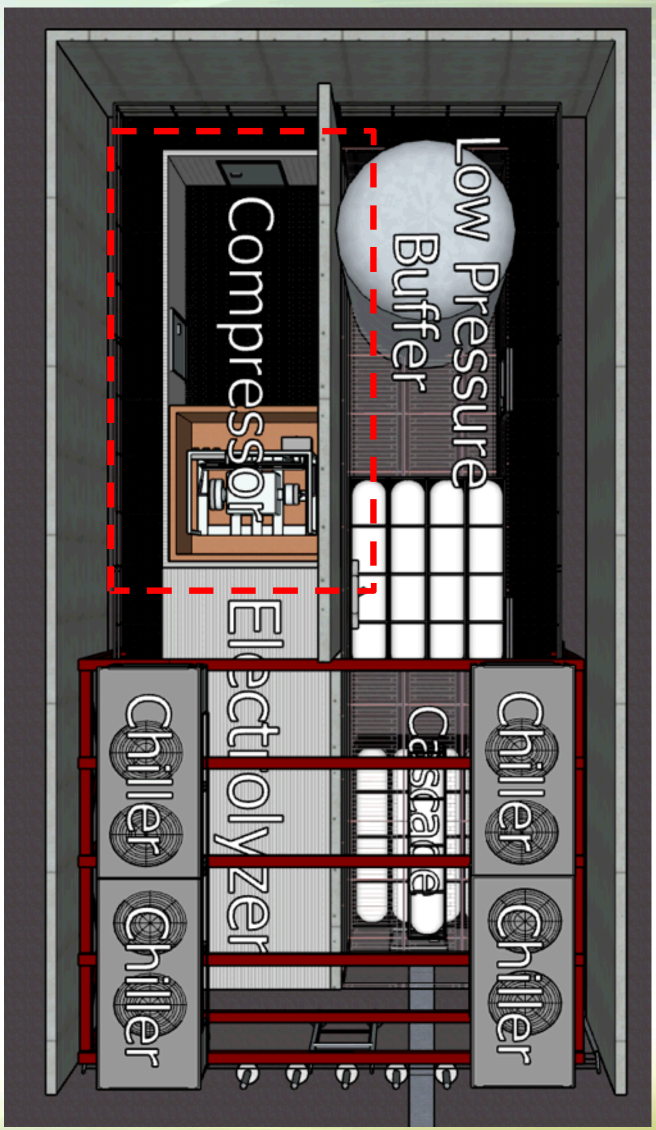
Fire - Hydrogen fire resulting from a leak at the hydrogen dispenser

- One single fire source
  - Simultaneous events not considered
- Dispenser assumed to develop a leak, ignite immediately and result in a jet fire
  - Only effects of jet fire considered, explosive conditions explored in other scenarios
- HyRAM QRA tool used to analyze results of jet fire risk
- Average Individual Risk (AIR) for jet fire scenario is:

4.637×10^{-06} fatalities per year

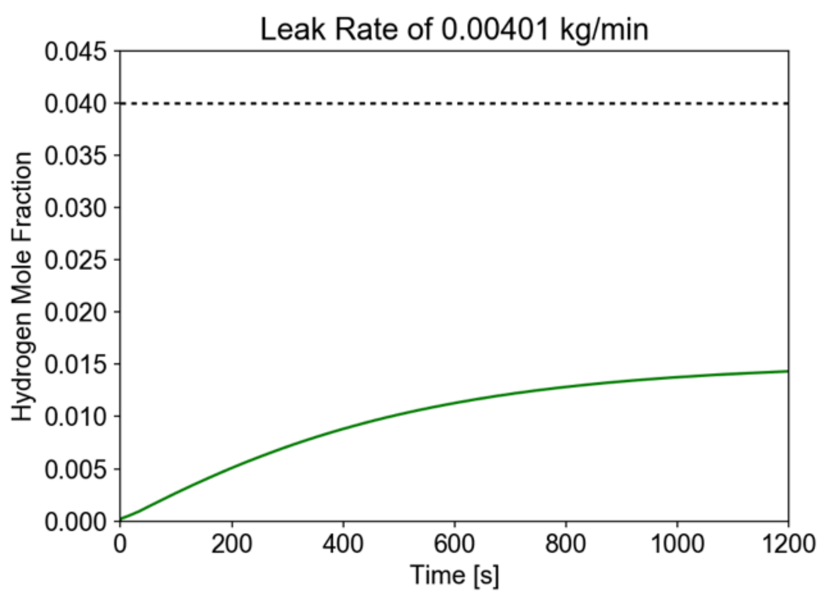
Explosion Scenario 2 –H2 deflagration within the enclosure housing the compressor

- The Lowesmith model was used to determine the steady state hydrogen concentration that will accumulate from the constant leak rate
- Ventilation rate of 4.38 m^3/min
  - Calculated using NFPA 2 guidelines
- The leak was assumed to be either at the inlet or the outlet of the compressor
  - There are two competing parameters that affect the amount of hydrogen being released: high pressure with a small pipe diameter (or vise versa).
- Three different leak sizes were analyzed
  - 0.01% of pipe area
  - 1% of pipe area
  - X % of Pipe size to achieve a 4% of hydrogen in the room (flammable limit)

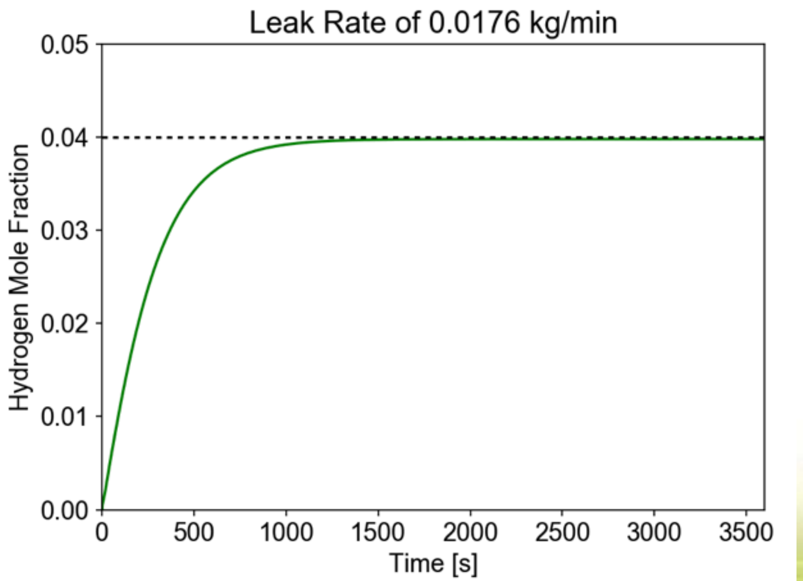


Explosion Scenario 2 –H2 deflagration within the enclosure housing the compressor

- Hydrogen concentration resulting for most probable compressor leak size (0.01% of pipe area) for the high pressure section
- Hydrogen concentration maintained below 1.5 %



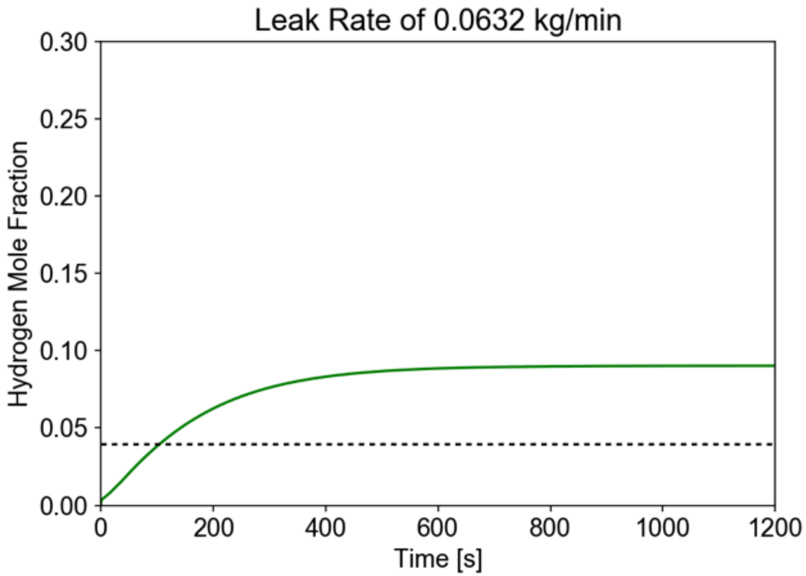
- Compressor leak rate required to achieve a steady state hydrogen concentration of 4% for
  - A leak size of 0.0439% of pipe size is needed for the high pressure section
  - A leak size of 0.278% of pipe size is needed for the low pressure section



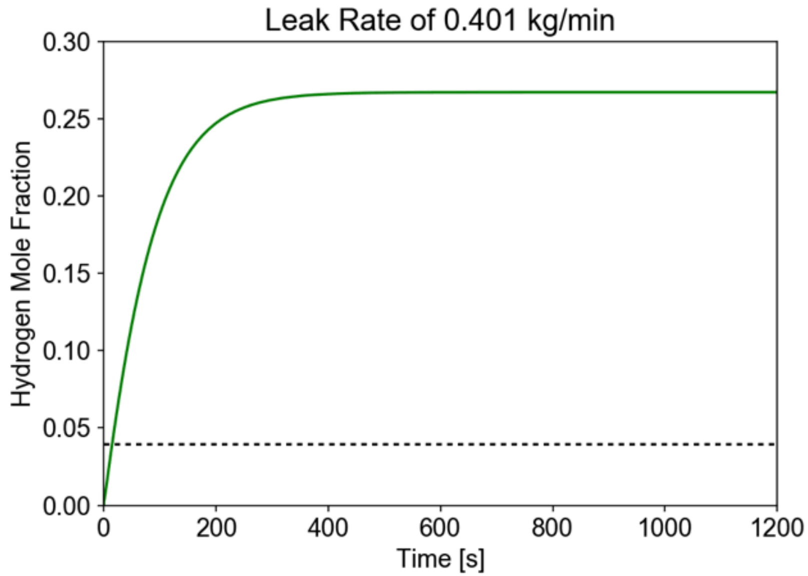
Explosion Scenario 2 –H2 deflagration within the enclosure housing the compressor

- Hydrogen concentration resulting for most probable compressor leak size (1% of pipe area)

Low Pressure Section



High Pressure Section



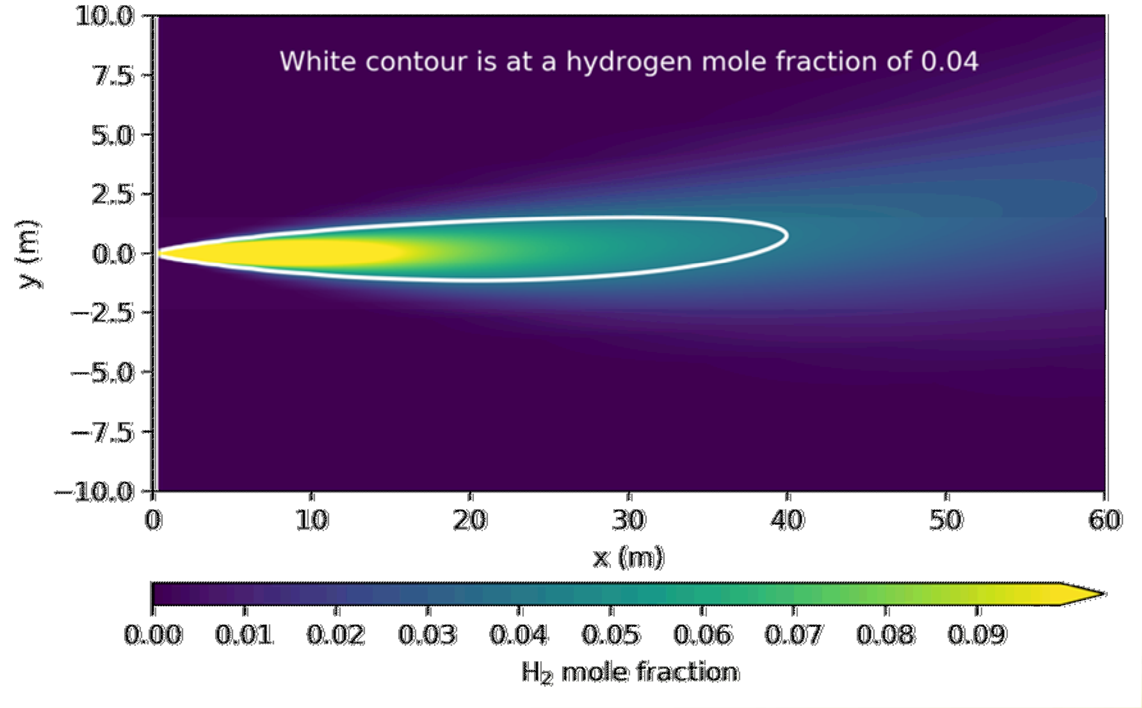
Leak Rate	Overpressure	
	Low Pressure	High Pressure
1% of Pipe Size	0.350 MPa	1.62 MPa

Hazardous Material Scenario 1 - Release of hydrogen from storage tank

- A significant release of hydrogen would reduce the oxygen concentration at the proximity of the leak
- The hydrogen release was assumed to happen at the low pressure bulk storage
  - ID pipe of 17.3 mm (0.68 in) connected to the low pressure buffer tank
- The release is assumed to happen when the low pressure buffer tank is at full capacity
  - Maximum pressure of 5 MPa (725.19 psi)

Hazardous Material Scenario 1 - Release of hydrogen from storage tank

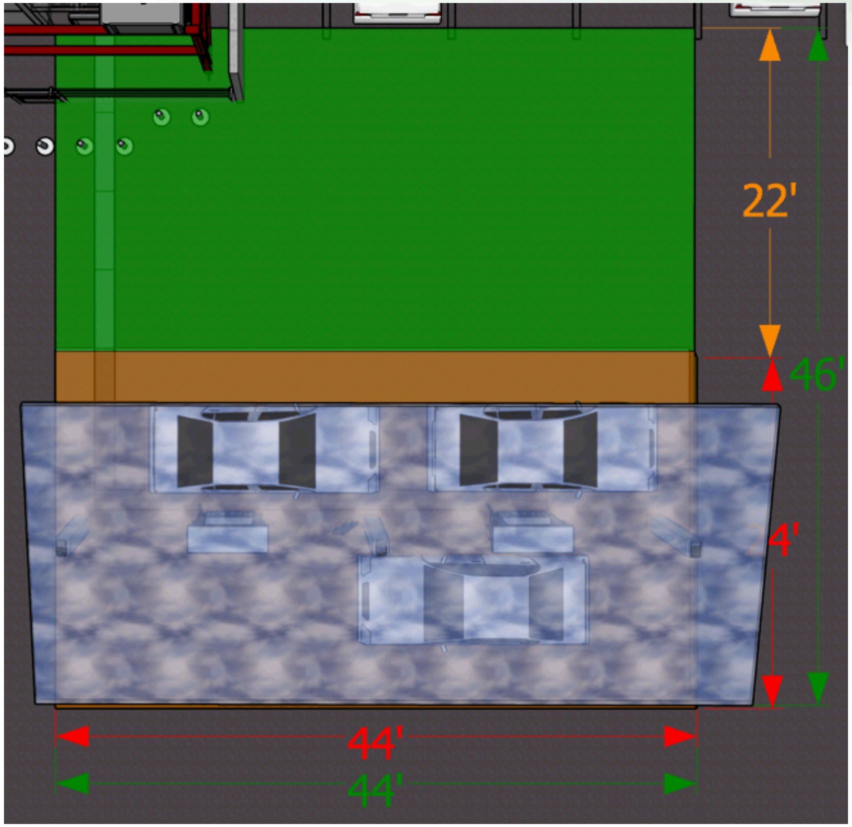
- The outer contour shows the flammable extent for the plume (4% hydrogen)
  - Flammable mass extends 42 meters from release point



Hazardous Material Scenario 3 – External Event

- A 100% leak on the largest pipe
  - Pipe connecting the electrolyzer, low pressure buffer, and the compressor
    - OD 19.05 mm (3/4")
    - Wall Thickness: 0.889 mm (0.035 in)
    - Maximum pressure at this pipe is 5 MPa
    - 10 m long pipe
- HyRAM QRA tool used to analyze results of jet fire risk
- Average Individual Risk (AIR) for jet fire scenario is:

1.549×10^{-2} fatalities per year*



*conditional based on the occurrence of an earthquake

Hazard Scenario Analysis for Base Case Electrolyzer

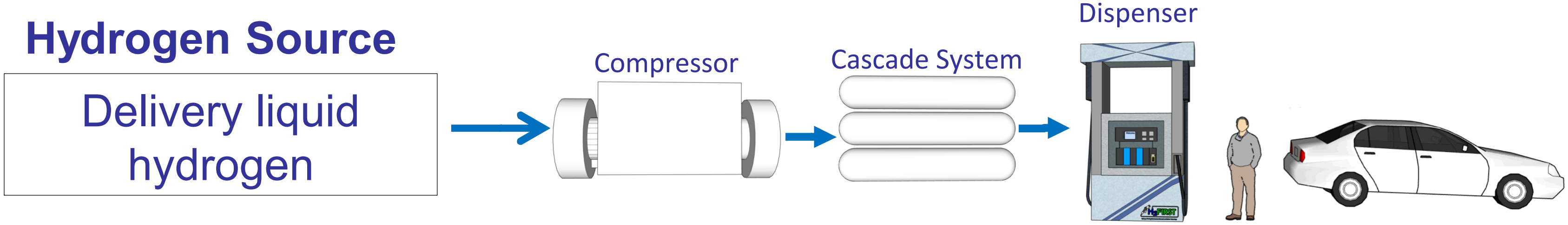
Outdoor Fueling Station Scenario	Baseline Result
Fire- Hydrogen fire resulting from a leak at the hydrogen dispenser	AIR =4.637 $\times$ 10^{-6} fatalities/year
Explosion Scenario 1 - Gaseous H_2 pressure vessel rupture	Mitigations listed for stationary pressure vessels
Explosion Scenario 2 – H_2 deflagration within the enclosure housing the compressor (worst case)	1.62 MPa overpressure for 1% of pipe size leak
Explosion Scenario 3 - Venting of hydrogen forms localized H_2/air mixture in the vent pipe that detonates	Vent pipe length to diameter ratio to prevent detonation is present with a 13% additional safety factor (same as Base Case Gas)
Hazardous Material Scenario 1 - Release of hydrogen from storage tank	The flammable hydrogen concentration extended 40 m from release point
Hazardous Material Scenario 2 - An unrelated vehicle fire at the lot edge	Heat flux on dispenser: 3.3 kW/m^2 for single passenger vehicle
Hazardous Material Scenario 3 - Seismic event where a pipe bursts (100% leak size on largest pipe)	AIR Fire = 7.736 $\times$ 10^{-5} fatalities per year, conditional upon the occurrence of an earthquake
Hazardous Material Scenario 4 - A hydrogen discharge where the interlock fails	No additional risk scenarios (same as Base Case Gas)
Building Use Scenario 1 – Maximum occupancy load present in building during fire with main entrance/exit blocked	Not applicable (same as Base Case Gas)
Building Use Scenario 2 – Fire during maintenance with fire suppression system out of service.	Not applicable (same as Base Case Gas)

BASE CASE LIQUID

Presented by Gaby Bran-Anleu

Base Case Liquid Design

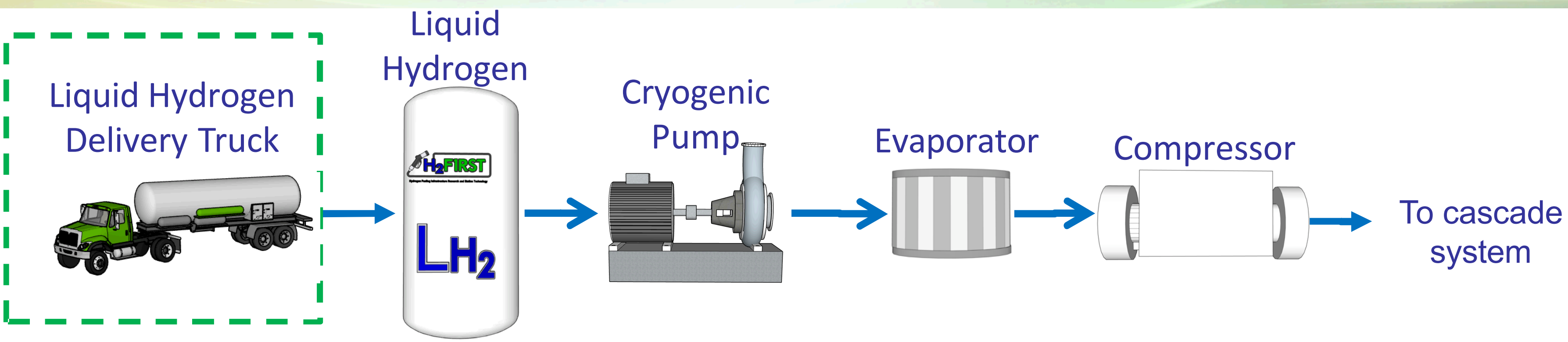
- This station considers a 600 kg/day dispensed H2 with 4 dispenser hoses
- Components are similar to the Base Case Gas



- Design calculations use HRSAM [1]
  - Compressor
    - 25 kg/hr flow rate (constant 600 kg/day)
    - Outlet pressure of 94.4 MPa (13,688 psi)
    - Power of 102 kW (as compared to 60 kW for the Base Case Gas)
  - Chillers
    - 25.2 kW (7.2 tons) of refrigeration needed for each chiller
  - Dispensing
    - 4 fueling positions, 70 MPa, -40° C
  - Cascade
    - 10 cascade units, each containing 5 (1:1:3) pressure vessels
    - Outlet flow rate 40 kg/hr to each dispenser
    - Low pressure 31.0 MPa (4,500 psi) yields minimum ID of 5.78 mm (0.23")
      - Example tubing 14.3 mm (0.5625"), ID of 6.4 mm (0.25")

[1] https://hdsam.es.anl.gov/index.php?content=hrsam

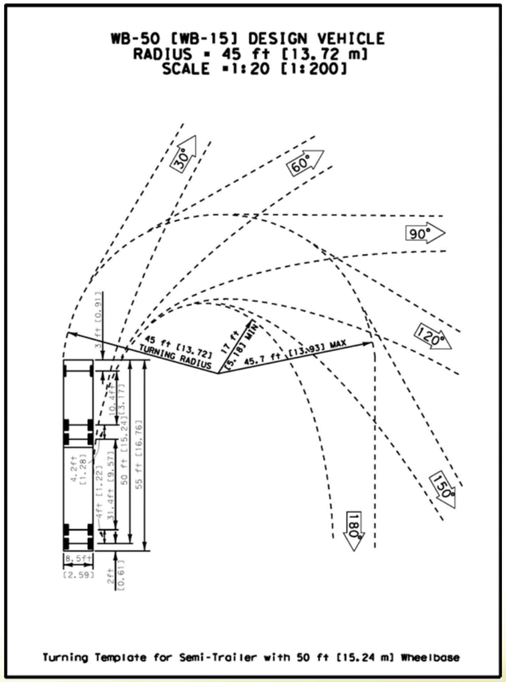
Liquid hydrogen delivery truck



- This design assumes that hydrogen is delivered via a truck
  - The truck has a straight entry/exit path from the property line to the hydrogen system fill point
  - The general dimensions of a 50 ft wheel base truck were used

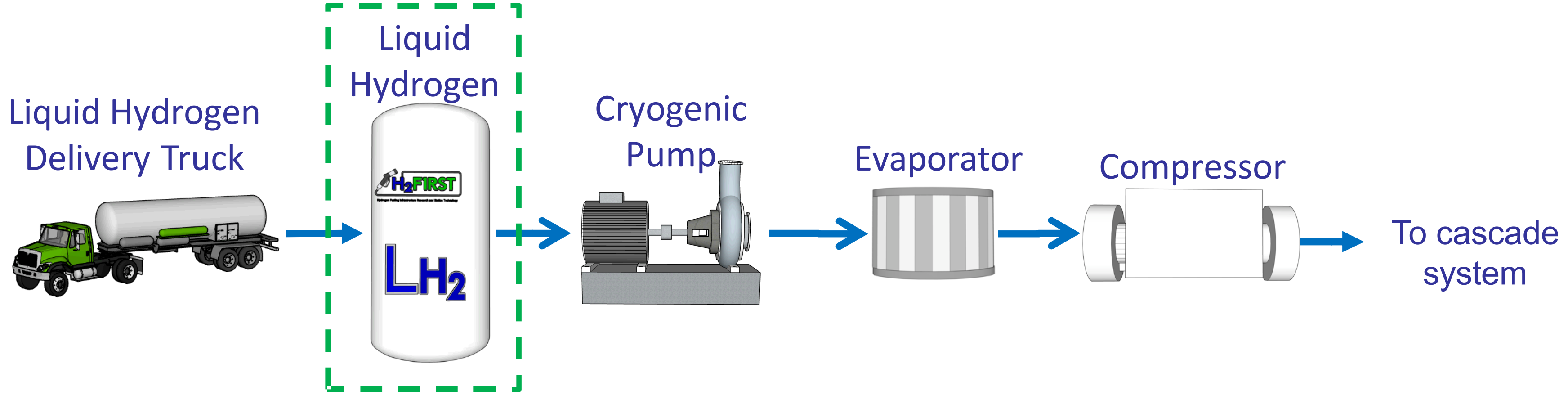
Hydrogen Capacity	3,000 kg
Truck-Trailer Length	19.8 m (65 ft)

  - The turning radius was determined using the DOT Road Design Manual

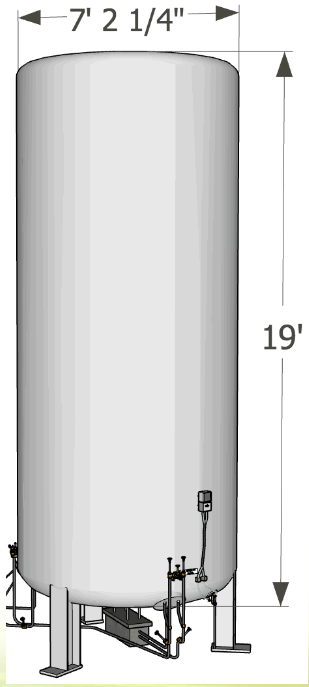


Texas Department of Transportation (DOT), *Road Design Manual*. 2014.

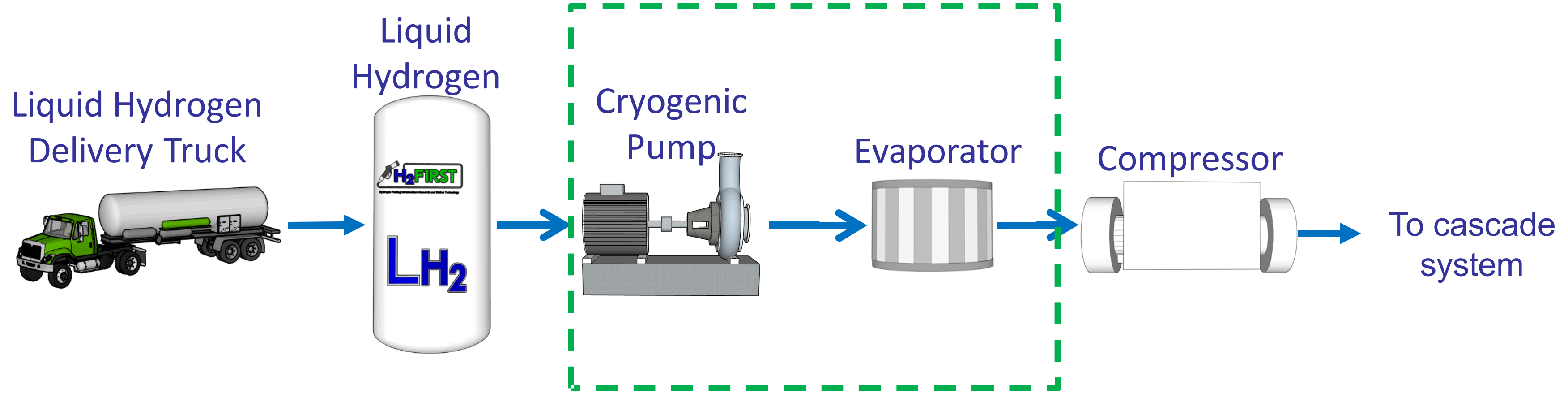
Liquid Hydrogen Bulk Storage



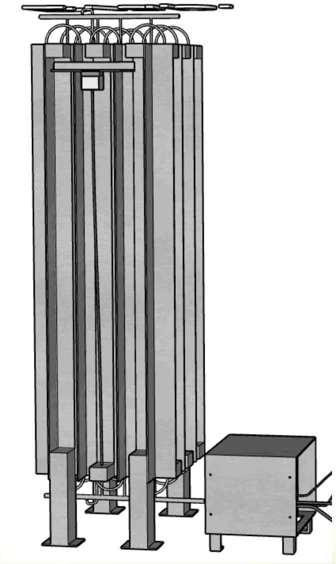
- Tank Capacity
  - Sized for 33% over daily design capacity
  - 800 kg, 11,299 L (2,985 gal)
- Tank dimensions
  - Diameter of 7.2 feet (2.18 m)
  - Height of 19 feet (5.8 m)
- Piping
  - OD of 25.40 mm (1 inch)
  - ID of 14.27 mm (0.562 inch
  - Pressure rating of 137.9 MPa (43,000 psi)



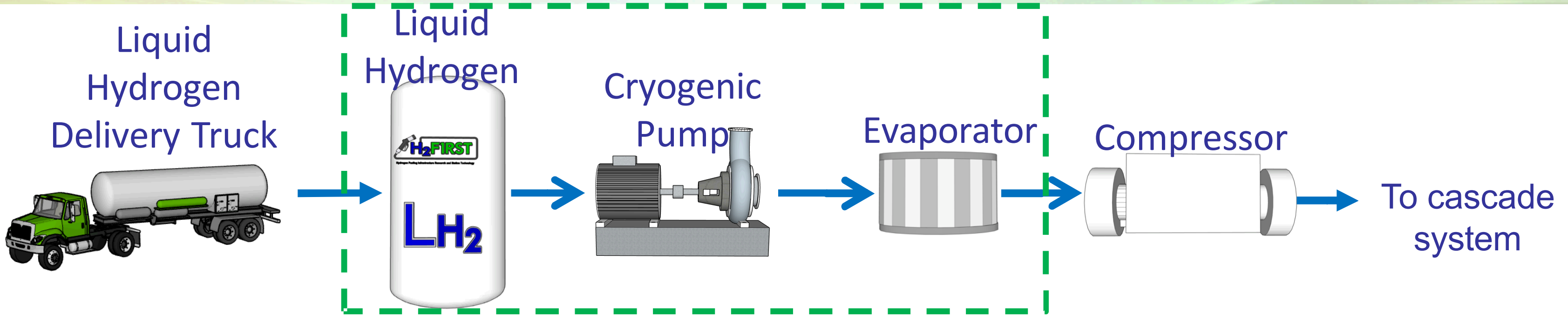
Cryogenic Pump and Evaporator

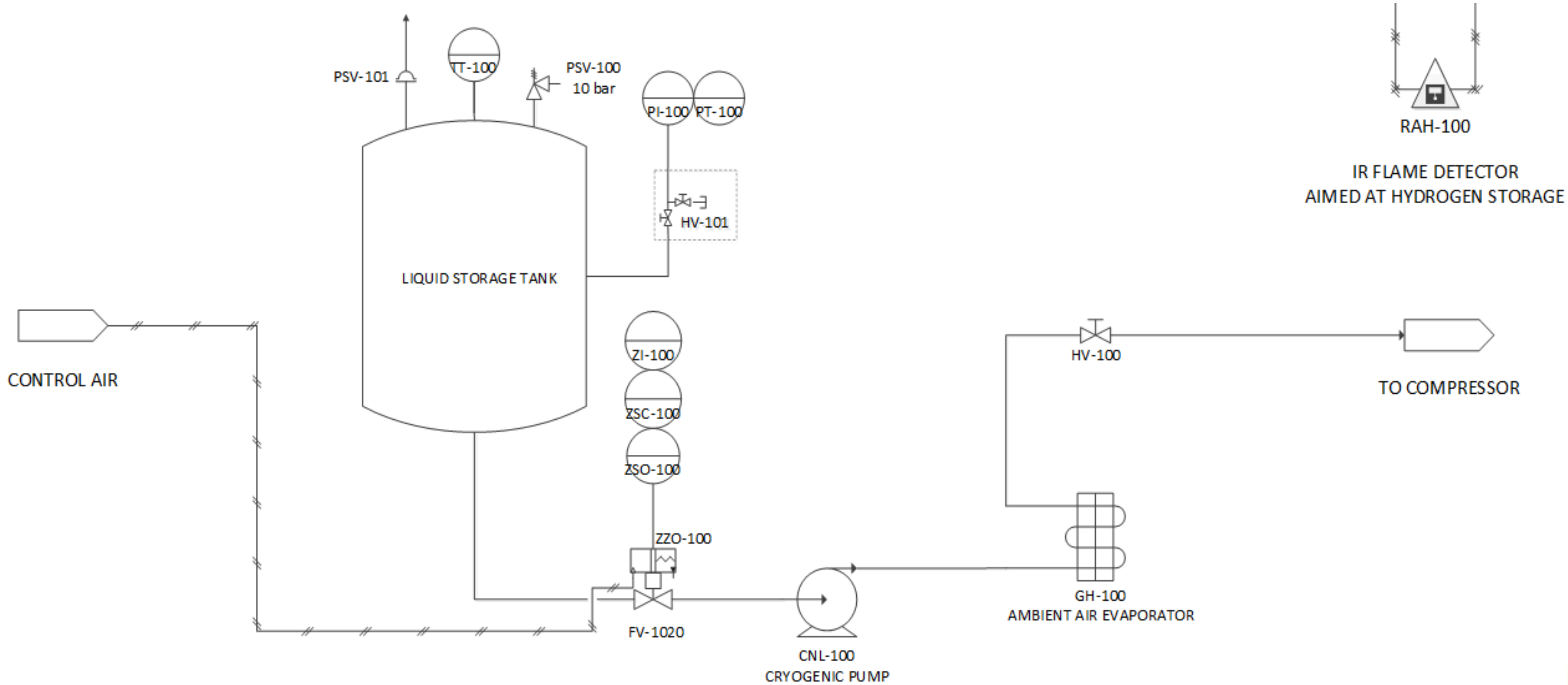


- Cryogenic Pump and evaporator need to be able to supply 25 kg/hr to the compressor



P&ID from Liquid Hydrogen Storage Tank to Compressor

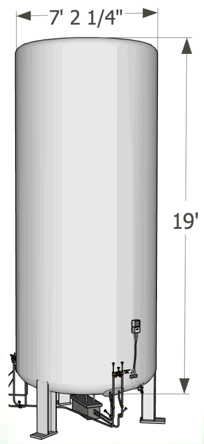


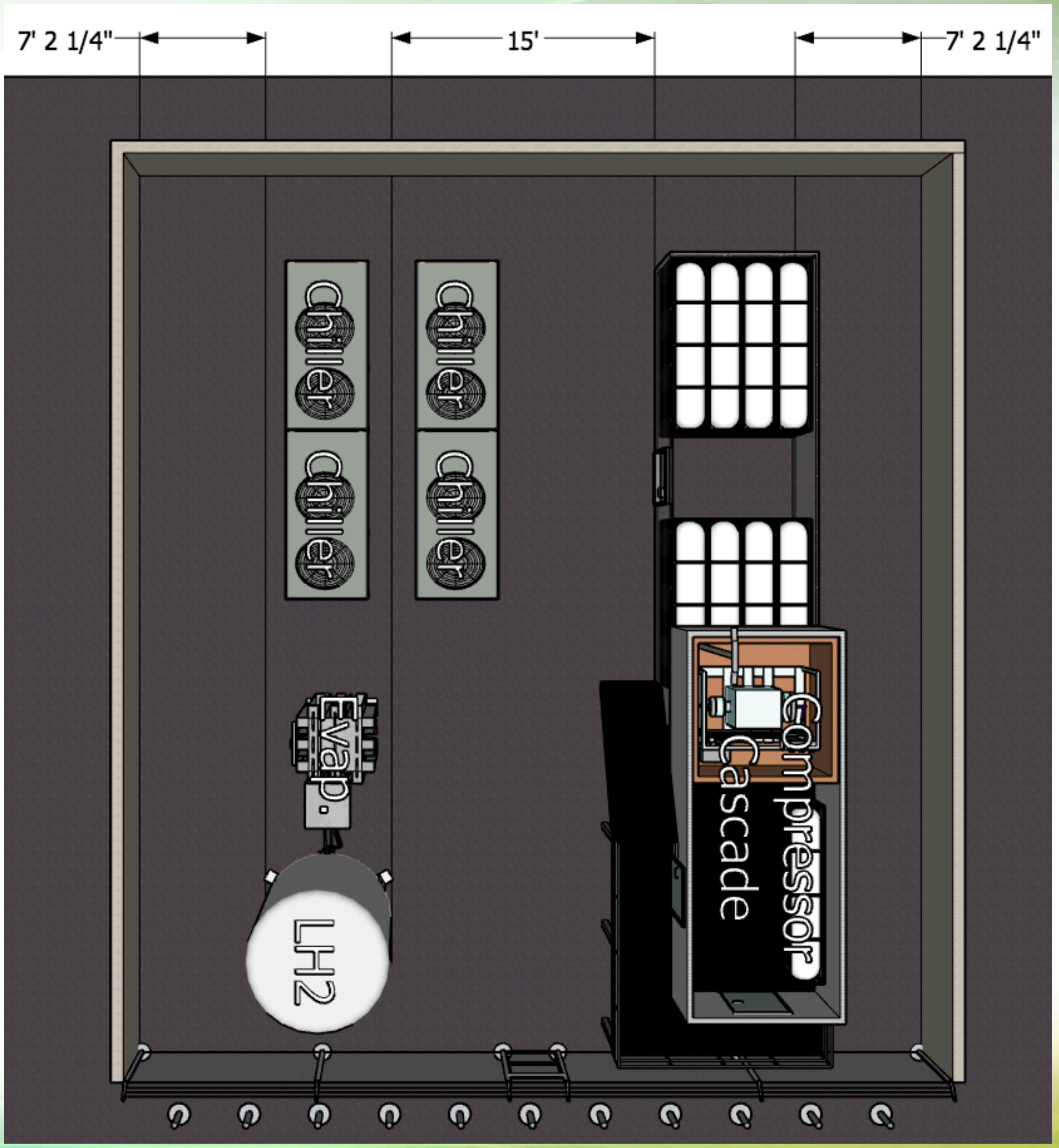


- The P&IDs for the rest of the components are the same as for the Base Case Gas P&IDs

General NFPA 2 Requirements for Hybrid Hydrogen System

- The hybrid hydrogen system includes both liquid and compressed gas storage
  - Compressor
  - Evaporator
  - Cryogenic pump
- Liquid and gaseous portions of the combined system must be separated by at least 4.6 m (15 ft)
- Vertical tanks shall be located at a distance not less than 1 tank diameter from the enclosing walls





Setback Distances for Liquid Hydrogen Bulk Systems

- Each type exposure has a different requirement
- Setback distances required by NFPA 2 (Chapter 10) are based only on total amount of bulk liquified hydrogen
  - The density of liquid hydrogen (70.8 g/L) is used to calculate a total combined hydrogen volume in the system

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

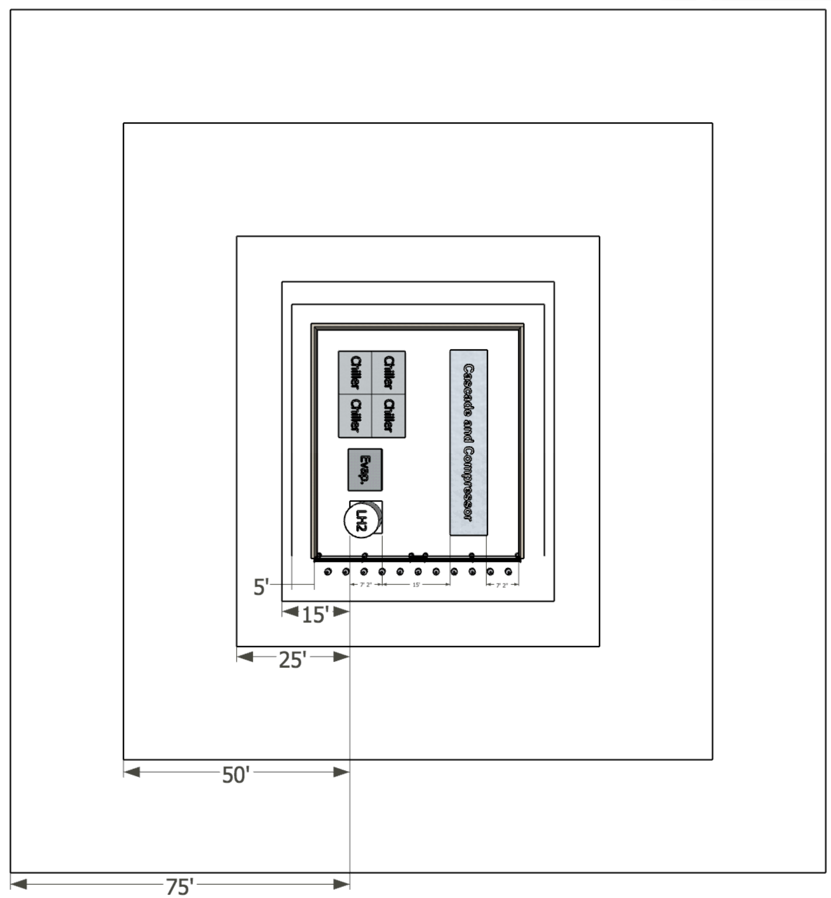
	Total Bulk Liquefied Hydrogen [LH_2] Storage					
	39.7 gal to 3500 gal	150 L to 13,250 L	3501 gal to 15,000 gal	13,251 L to 56,781 L	15,001 gal to 75,000 gal	56,782 L to 283,906 L
Type of Exposure	**ft**	**m**	**ft**	**m**	**ft**	**m**
Group 1						
1. Lot lines	25	7.6	50	15	75	23
2. Air intakes [heating, ventilating, or air conditioning equipment (HVAC, compressors, other]	75	23	75	23	75	23
3. Wall openings						
Operable openings in buildings and structures	75	23	75	23	75	23
4. Ignition sources such as open flames and welding	50	15	50	15	50	15
Group 2						
5. Places of public assembly	75	23	75	23	75	23
6. Parked cars (distance shall be measured from the container fill connection)	25	7.6	25	7.6	25	7.6
Group 3						
7. Building or structure						
(a) Buildings constructed of noncombustible or						
↓						
(c) Piping containing other hazardous materials	15	4.6	15	4.6	15	4.6
16. Flammable gas metering and regulating stations above grade	15	4.6	15	4.6	15	4.6

Setback Distances for Hybrid Hydrogen System

- The total volume in the hybrid hydrogen system is 20,056 L (5,298 gal)

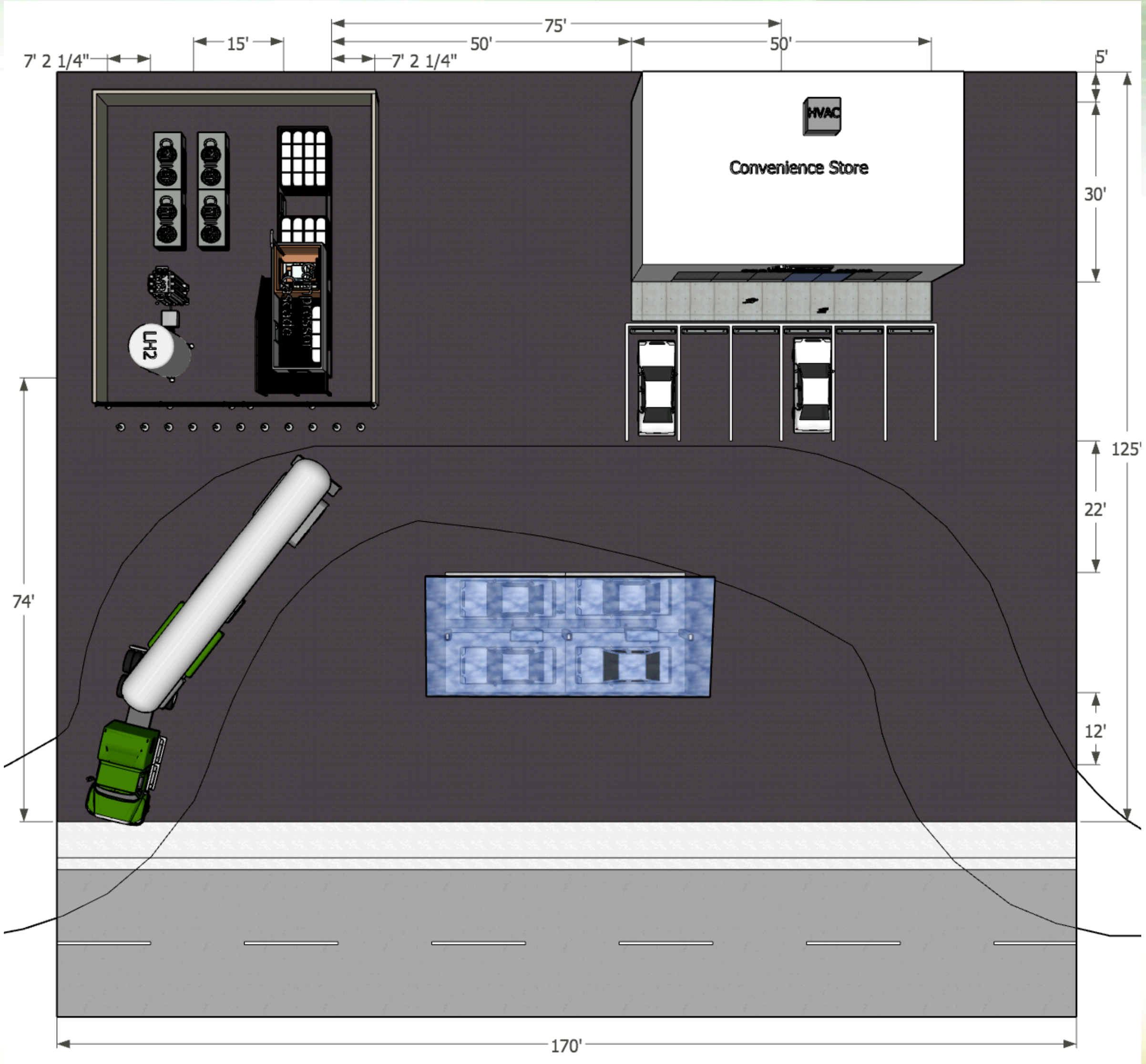
Base Case Liquid Required Setback Distances

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)



Minimum/Full Layouts for Base Case Liquid

- Full Layout
  - Convenience store
  - Parking
  - Traffic flow
  - Delivery
- Total Footprint
  - 21,250 ft^2



Non-hydrogen station components have large effect on final station layout

Base Case Liquid Hazard Scenarios

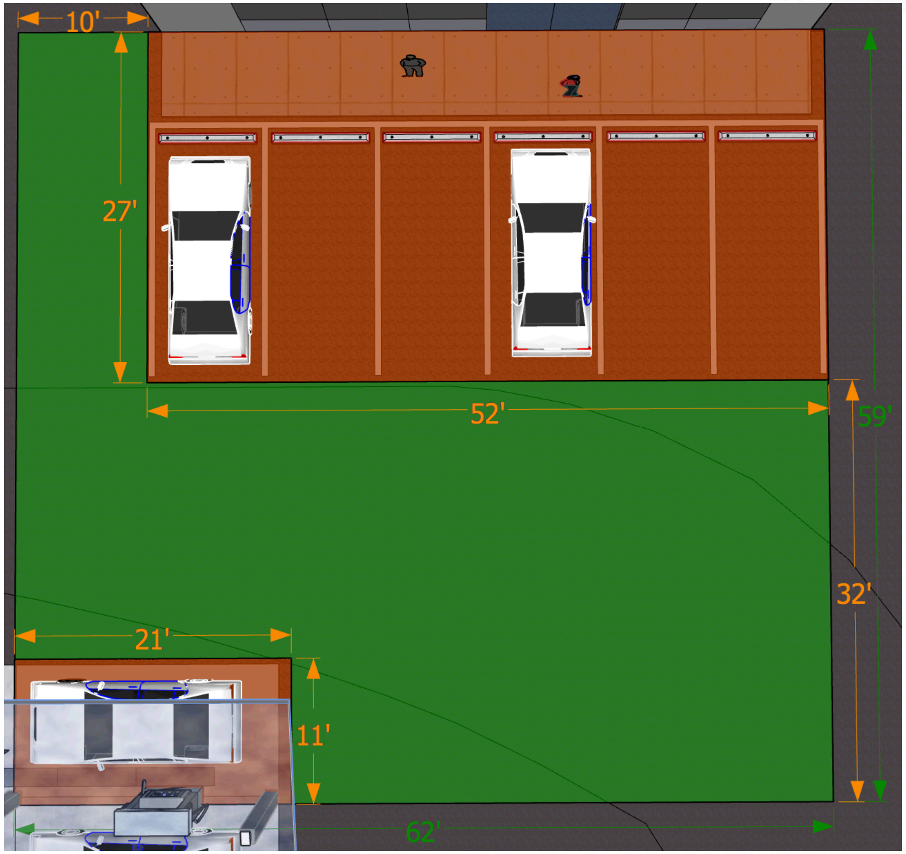
Hazard Scenario Analysis for Base Case Delivered Liquid

Required Scenario	Outdoor Fueling Station Scenario	Performance Criteria Approach
Fire	Hydrogen fire resulting from a leak at the hydrogen dispenser	Jet fire risk calculation
Explosion Scenario 1 - Pressure Vessel Burst	Compressed gas storage	List of mitigations of burst
Explosion Scenario 2 - Deflagration	A hydrogen deflagration within the enclosure housing the compressor.	Potential for deflagration conditions and peak overpressure
Explosion Scenario 3 - Detonation	Localized H2/air mixture in the vent pipe	Vent pipe design specifications
Hazardous Material Scenario 1 - Unauthorized Release	Release of hydrogen from storage tank	Jet/plume for localized hypoxia and temperature hazard
Hazardous Material Scenario 2 - Exposure Fire	Unrelated vehicle fire at the lot line	Flame radiation from vehicle fire
Hazardous Material Scenario 3 - External Event	Seismic event where largest pipe bursts	Risk metric calculation
Hazardous Material Scenario 4 - Protection System Out of Service	A hydrogen discharge where the interlock fails	Layered safety features present in the system
Building Use Scenario 1 - Emergency Exit Blocked	Hydrogen system outdoors	Not applicable
Building Use Scenario 2 - Fire Suppression Out of Service	Hydrogen system outdoors	Not applicable

Fire - Hydrogen fire resulting from a leak at the hydrogen dispenser

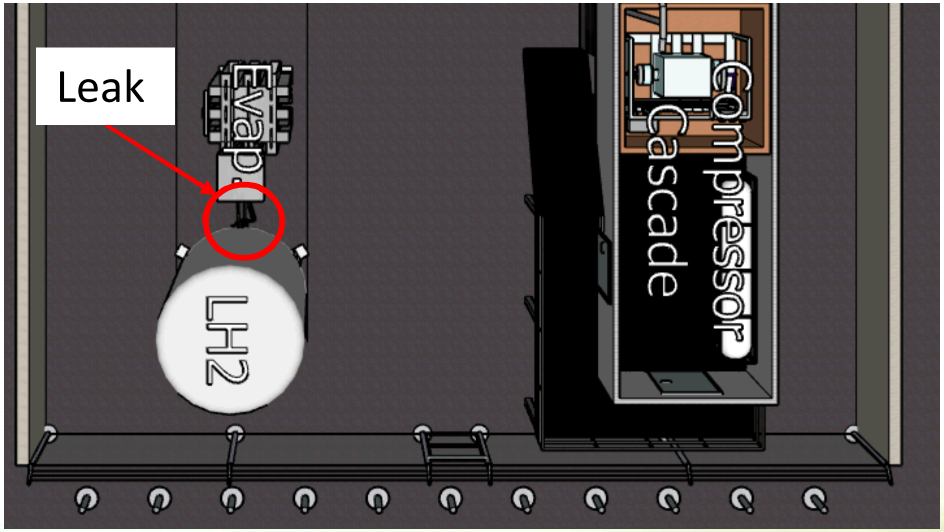
- One single fire source
  - Simultaneous events not considered
- Dispenser assumed to develop a leak, ignite immediately and result in a jet fire
  - Only effects of jet fire considered, explosive conditions explored in other scenarios
- HyRAM QRA tool used to analyze results of jet fire risk
- Average Individual Risk (AIR) for jet fire scenario is:

4.118 × 10^{-6} fatalities per year



Hazardous Material Scenario 1 - Release of hydrogen from storage tank

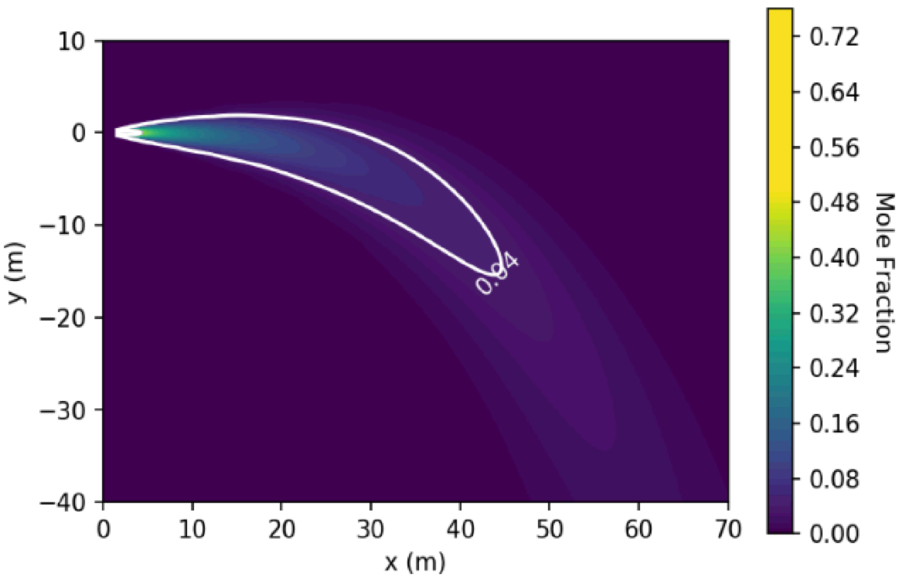
- A significant release of hydrogen would reduce the oxygen concentration at the proximity of the leak
- Temperature is also a hazard for a release of liquid hydrogen.
- A cold plume model was used to model the hydrogen concentration from the release point
- The hydrogen release was assumed to happen at the liquid storage tank
  - 25.4 mm (1 inch) OD pipe
  - At a pressure of 6 bar
  - An ID 14.27 mm (0.562 inch) leak of saturated liquid hydrogen is assumed



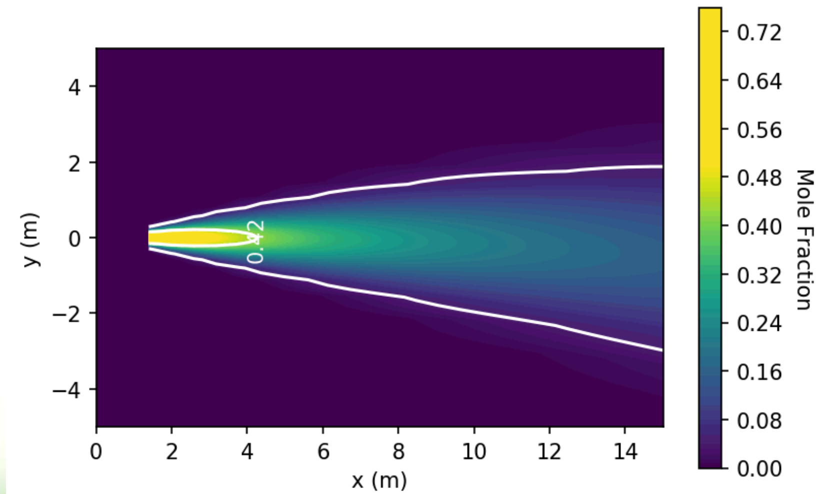
Hazardous Material Scenario 1 - Release of hydrogen from storage tank

H2FIRST

- The outer contour shows the flammable extent for the plume (4% hydrogen)
  - Flammable mass extends 45 meters from release point

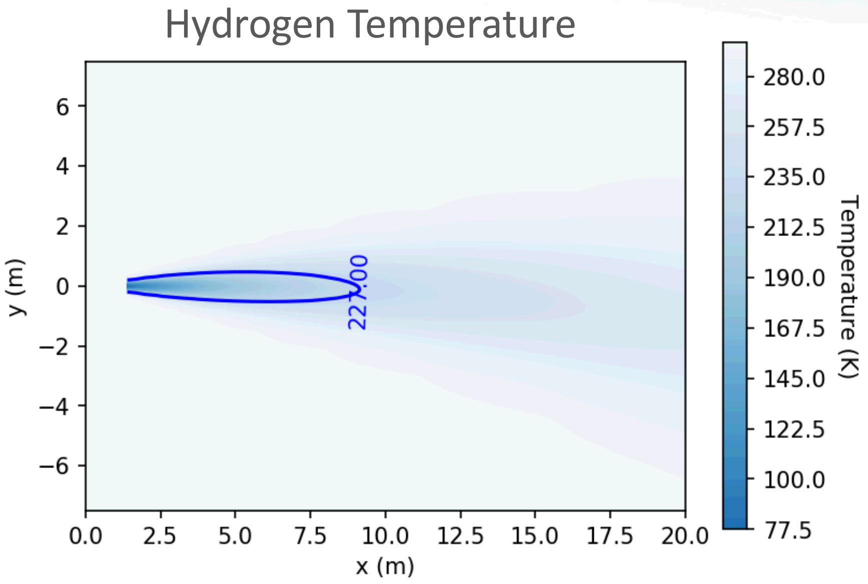


- The hydrogen concentration value for hypoxia was calculated as 42.3% H2
- The contour corresponding to this value was within 5 meters of the release point



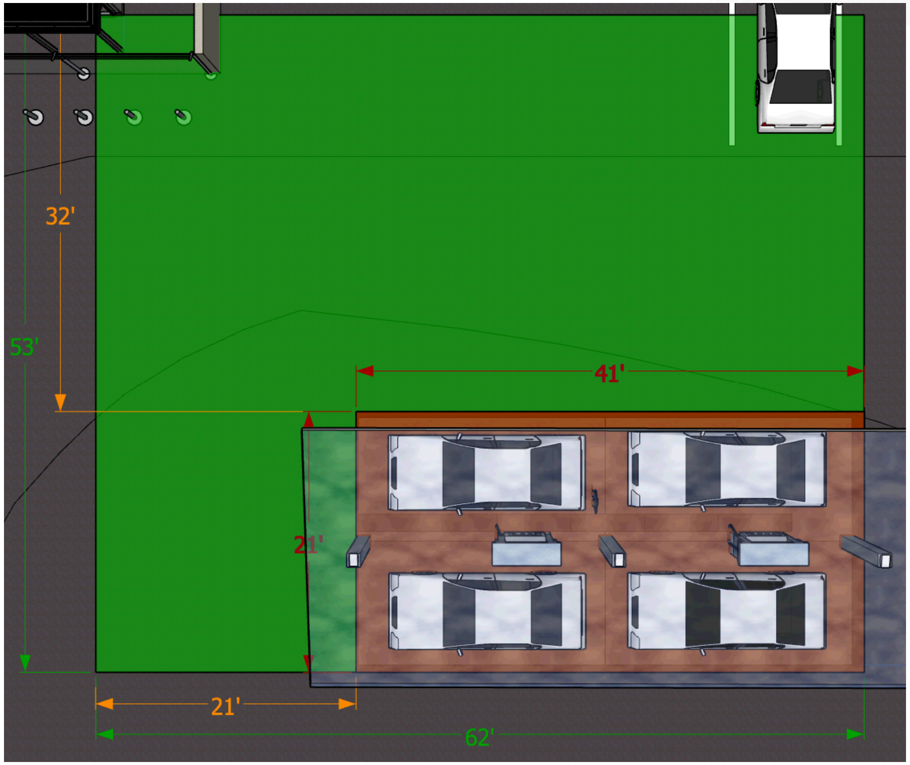
Hazardous Material Scenario 1 - Release of hydrogen from storage tank

- The temperature limit for harm due to low temperature gas is 227 K
  - The temperature contour extends approximately 10 meters from the leak point



Hazardous Material Scenario 3 – External Event

- A 100% leak on the largest pipe from the cascade storage system
  - Inner diameter of 5.78 mm (0.23 in.)
  - Outer diameter of 14.3 mm (0.5625 in.)
  - Max operating pressure of 103.4 MPa (15,000 psi)
- HyRAM QRA tool used to analyze results of jet fire risk
- Average Individual Risk (AIR) for jet fire scenario is:
  1.549 $\times$ 10^{-2} fatalities per year*



*conditional based on the occurrence of an earthquake

Summary od Base Case Liquid Hazard Scenarios

Outdoor Fueling Station Scenario	Baseline Result
Fire - Hydrogen fire resulting from a leak at the hydrogen dispenser.	AIR = 4.118×10^{-6} fatalities/year
Explosion Scenario 1 - Gaseous H_2 pressure vessel rupture	Mitigations listed for stationary pressure vessels (same as Base Case Gas)
Explosion Scenario 2 - H_2 deflagration within the enclosure housing the compressor	3.89×10^5 Pa overpressure for 1% of pipe size leak (same as Base Case Gas)
Explosion Scenario 3 - Venting of hydrogen forms localized H_2/air mixture in the vent pipe that detonates.	Vent pipe length to diameter ratio to prevent detonation is present (same as Base Case Gas)
Hazardous Material Scenario 1 - Release of hydrogen from storage tank	The hypoxia and temperature criteria are met within 5 m and 10 m of the release point, respectively.
Hazardous Material Scenario 2 - An unrelated vehicle fire at the lot edge.	Heat flux on dispenser: 4.4 kW/m^2 for single passenger vehicle (same as Base Case Gas)
Hazardous Material Scenario 3 - Seismic event where a pipe bursts (100% leak size on largest pipe).	AIR Fire = 1.559×10^{-2} fatalities/year, conditional upon the occurrence of an earthquake
Hazardous Material Scenario 4 - A hydrogen discharge where the interlock fails.	No additional risk scenarios (same as Base Case Gas)
Building Use Scenario 1 - Maximum occupancy load present in building during fire with main entrance/exit blocked	Not applicable (same as Base Case Gas)
Building Use Scenario 2 - Fire during maintenance with fire suppression system out of service.	Not applicable (same as Base Case Gas)

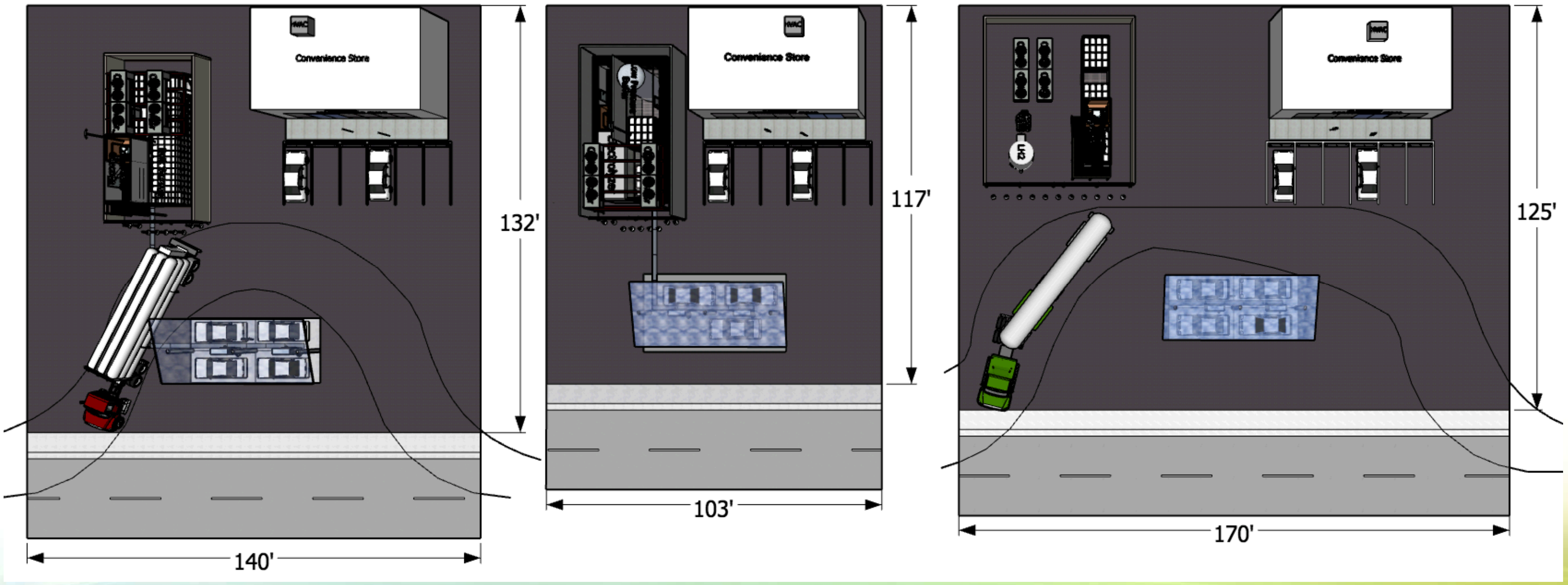
Summary of Design Choices

- 600 kg/day dispensed hydrogen
- Delivery of GH2/LH2
  - 800 kg H2 pre-compressor storage on-site
- Compressor
  - 25 kg/hr
- Cascade
  - 50 units of 1:1:3 high:medium:low
  - Sized for modified demand profile with 1 hour peak demand
- 4 dispenser hoses
  - 2 dispensers, 2 hoses per dispenser
  - H70-T40
  - With chiller/cooling block
- Delivery truck path and traffic flow included
- 30 ft x 50 ft convenience store
  - With ~6 parking spaces

Summary of Footprints

- The Base Case Gas total area is larger than the Base Case Electrolyzer mainly due to the delivery truck path
- The Base Case Liquid total area is the largest due to the setback distances and the delivery truck path

	Total Lot Area
Base Case Gas	18,480 ft^2
Base Case	12,051 ft^2
Base Case Liquid	21,250 ft^2



Summary of Results for the Fire and Explosion Scenarios

Outdoor Fueling Station Scenario	Base Case Gas	Base Case Electrolyzer	Base Case Liquid
Fire- Hydrogen fire resulting from a leak at the hydrogen dispenser	AIR = 3.140×10^{-6} fatalities/year	AIR = 4.637×10^{-6} fatalities/year	AIR = 4.118×10^{-6} fatalities/year
Explosion Scenario 1 - Gaseous H_2 pressure vessel rupture	Mitigations listed for stationary pressure vessels		
Explosion Scenario 2 – H_2 deflagration within the enclosure housing the compressor (worst case)	3.89×10^5 Pa overpressure for 1% of pipe size leak	16.2×10^5 Pa overpressure for 1% of pipe size leak	Same as Base Case Gas
Explosion Scenario 3 - Venting of hydrogen forms localized H_2/air mixture in the vent pipe that detonates	Vent pipe length to diameter ratio to prevent detonation is present with a 13% additional safety factor		

Summary of Results for the Hazardous Material Scenarios

Outdoor Fueling Station Scenario	Base Case Gas	Base Case Electrolyzer	Base Case Liquid
Hazardous Material Scenario 1 - Release of hydrogen from storage tank	The hypoxia criterion of 12% O_2 is met within 4 m of the release point	The flammable H_2 concentration extended 40 m from release point	The hypoxia and temperature criteria are met within 5 m and 10 m of the release point, respectively.
Hazardous Material Scenario 2 - An unrelated vehicle fire at the lot edge	Heat flux on dispenser: 3.3 kW/m^2 for single passenger vehicle		
Hazardous Material Scenario 3 - Seismic event where a pipe bursts (100% leak size on largest pipe) - conditional	AIR Fire = 2.177×10^{-2} fatalities per year,	AIR Fire = 7.736×10^{-5} fatalities per year	AIR Fire = 1.559×10^{-2} fatalities/year
Hazardous Material Scenario 4 - A hydrogen discharge where the interlock fails	No additional risk scenarios are credible because the interlocks are not credited in the above hazard scenarios		

Summary of Results for the Building Use Scenarios

H2FIRST

Outdoor Fueling Station Scenario	Base Case Gas	Base Case Electrolyzer	Base Case Liquid
Building Use Scenario 1 – Maximum occupancy load present in building during fire with main entrance/exit blocked		Not applicable	
Building Use Scenario 2 – Fire during maintenance with fire suppression system out of service.		Not applicable	

NEW NFPA REQUIREMENTS

Presented by Carl Rivkin and Gaby Bran-Anleu

NATIONAL RENEWABLE ENERGY LABORATORY

NFPA 2 and 55 Code Changes 2019 Revision Cycle

Carl Rivkin, P.E.
NREL
21 May 2018

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

NFPA 2/55 Revision Process

- NFPA 2 extracts material on hydrogen storage from NFPA 55 including safety separation distances
- Documents are being revised concurrently and NFPA 2 will extract new requirements from NFPA 55 on hydrogen storage
- There are several important changes including a complete revision of the safety separation distances for bulk gaseous storage systems and clarification on the application of these distances

NFPA 55 Compressed Gases and Cryogenic Fluids

Table 10.4.2.2.1(a) Minimum Distance (D) from Outdoor Bulk Hydrogen Compressed Gas Systems to Exposures — Typical Maximum Pipe Size

Pressure	> 15 to ≤ 250 psig		> 250 to ≤ 3000 psig		> 3000 to≤ 7500 psig		> 7500 to≤ 15000 psig	
Internal Pipe Diameter (ID)	>103.4 to≤ 1724 kPa		>1724 to ≤ 20,684 kPa		>20,684 to≤ 51,711 kPa		>51,711 to≤ 103,421 kPa	
dmm	d = 52.5mm		d = 18.97mm		d = 7.31mm		d = 7.16mm	
Group 1 Exposures	m	ft	m	ft	m	ft	m	ft
(a) Lot lines	~~12~~5	~~40~~16	~~14~~6	~~46~~20	~~9~~4	~~29~~13	~~105~~	~~34~~16
(b) Air intakes (HVAC, compressors, other)								
(c) Operable openings in buildings and structures								
(d) Ignition sources such as open flames and welding								
Group 2 Exposures	m	ft	m	ft	m	ft	m	ft
(a) Exposed persons other than those servicing the system	~~6~~5	~~20~~16	~~7~~6	~~24~~20	~~4~~3	~~13~~10	~~5~~4	~~16~~13
(b) Parked cars								
Group 3 Exposures	m	ft	m	ft	m	ft	m	ft
(a) Buildings of noncombustible non-fire-rated construction	~~5~~4	~~17~~13	~~6~~5	~~19~~16	43	~~12~~10	~~4~~4	~~14~~13

Major changes in distances- most restrictive distance reduced from 34 feet to 16 feet with 1.5 safety factor

NFPA 55 Compressed Gases and Cryogenic Fluids

- Proposed change to 2020 edition of NFPA 55 (to be extracted into NFPA 2)
-
- 11.3.2.4* Active Means or Design Means. Active control systems or design functions beyond base code requirements that mitigate the risk of system leaks and failures shall be permitted to be used as a means to reduce separation distances where approved by the AHJ under the authority as granted by Section 1.5.
-
- A.11.3.2.4 Safety measures to reduce setbacks could include the following (seep NFPA for complete text)
-

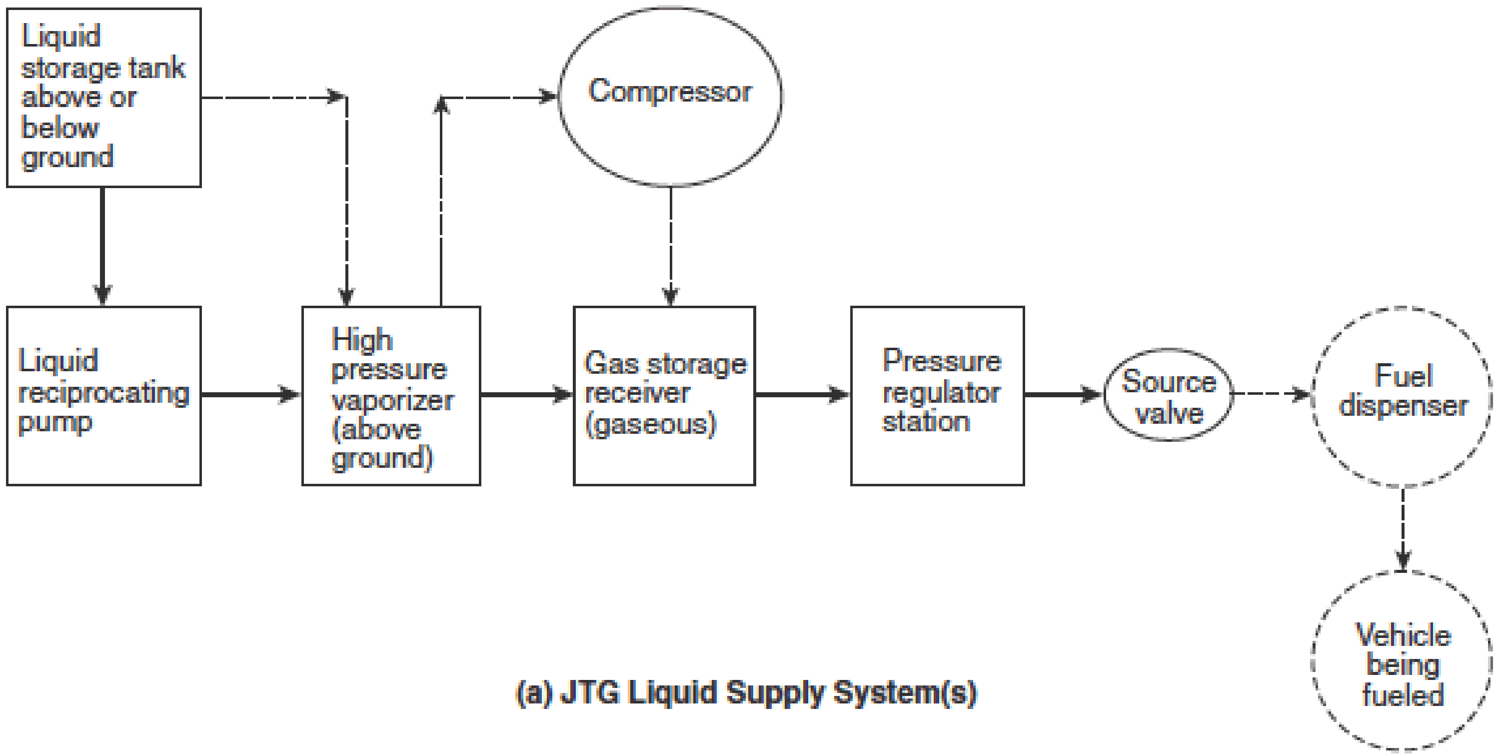
This changes will all reduction in bulk liquid hydrogen safety distances using active measures

NFPA 55 Compressed Gases and Cryogenic Fluids

- Public Comment 58 text
- NFPA 55; 10.4.2.1.1 and 11.3.2.1.1 “For the purpose of determining the minimum distances for siting bulk hydrogen storage systems, the bulk hydrogen storage system shall terminate at the valves or Pressure Relief Device (s) immediately upstream of the hydrogen storage system vent stack.
-
- 10.4.2.1.1.1 and 11.3.2.1.1.1 The location of the vent stack shall meet the requirements of CGA G-5.5

This text clarifies where the hydrogen storage system ends for the purpose of determining safety setback distances

NFPA 55 Compressed Gases and Cryogenic Fluids



(a) JTG Liquid Supply System(s)

Text submitted to clarify guidance on hybrid storage systems so that distances for gaseous systems can be applied to the gaseous portion of the system

NFPA 2 Hydrogen Technologies Code

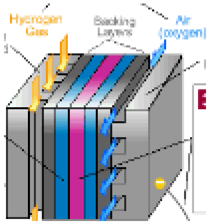
- Standard Permit Checklist Group produced draft permitting document for hydrogen fueling stations
- Material will be placed in Annex to Chapter 10 of NFPA 2 on hydrogen fueling pointing to the NFPA web site –
- https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=2

Code official will find information on permitting hydrogen fueling station in the Annex of NFPA 2 where they will be likely to use the material

Thank You and Questions

- **Carl Rivkin, CSP, P.E.** - *Safety Research Team Lead*
  carl.rivkin@nrel.gov

This work is supported by the DOE EERE Fuel Cell Technology Office!



NATIONAL RENEWABLE ENERGY LABORATORY

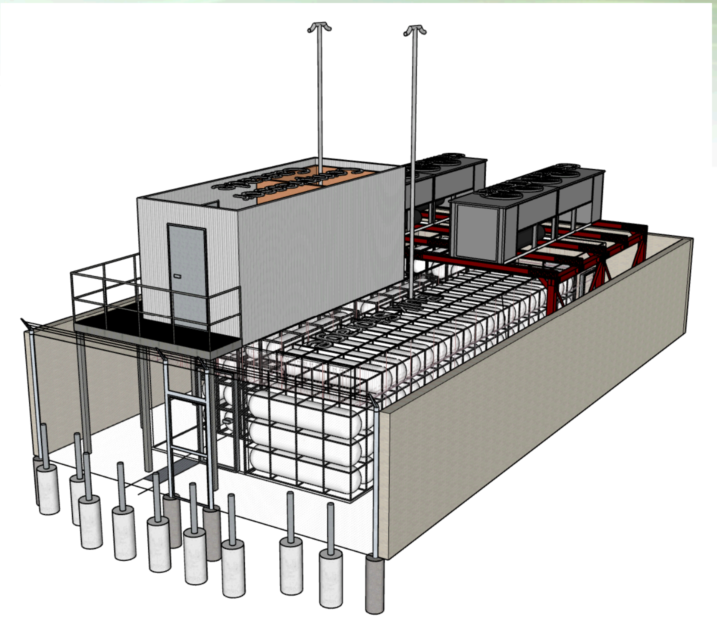
Possible Updates to NFPA 2 Code Citations for Gaseous Stations

NFPA 2 Citation	Code Summary	Current Proposal for NFPA 2 2020
6.17.1	Specifies a flow rate of 0.3048 $Nm^3/min/m^2$ (1 $scf/min/ft^2$) of floor area	Units only changed to 0.0051$m^3/sec/m^2$ (1 $scf/min/ft^2$)
Table 7.3.2.3.1.1(a)(b)(c)	Lists the exposure types for each exposure group as well as setback distances for four different pressure ranges, with typical pipe sizes for each pressure	Setback distances changed, see Table 2 below.
7.3.2.3.1.1(1)(d)	Indicates that the system pressure is determined by the maximum operating pressure of the storage array with content greater than 5000 scf	No text changed but section number changed to 7.3.2.3.1.1(A)(5)
10.3.1.13.12	Vehicles shall not be considered a source of ignition	This requirement has been removed in the 2020 Ed.

NEW NFPA GAS

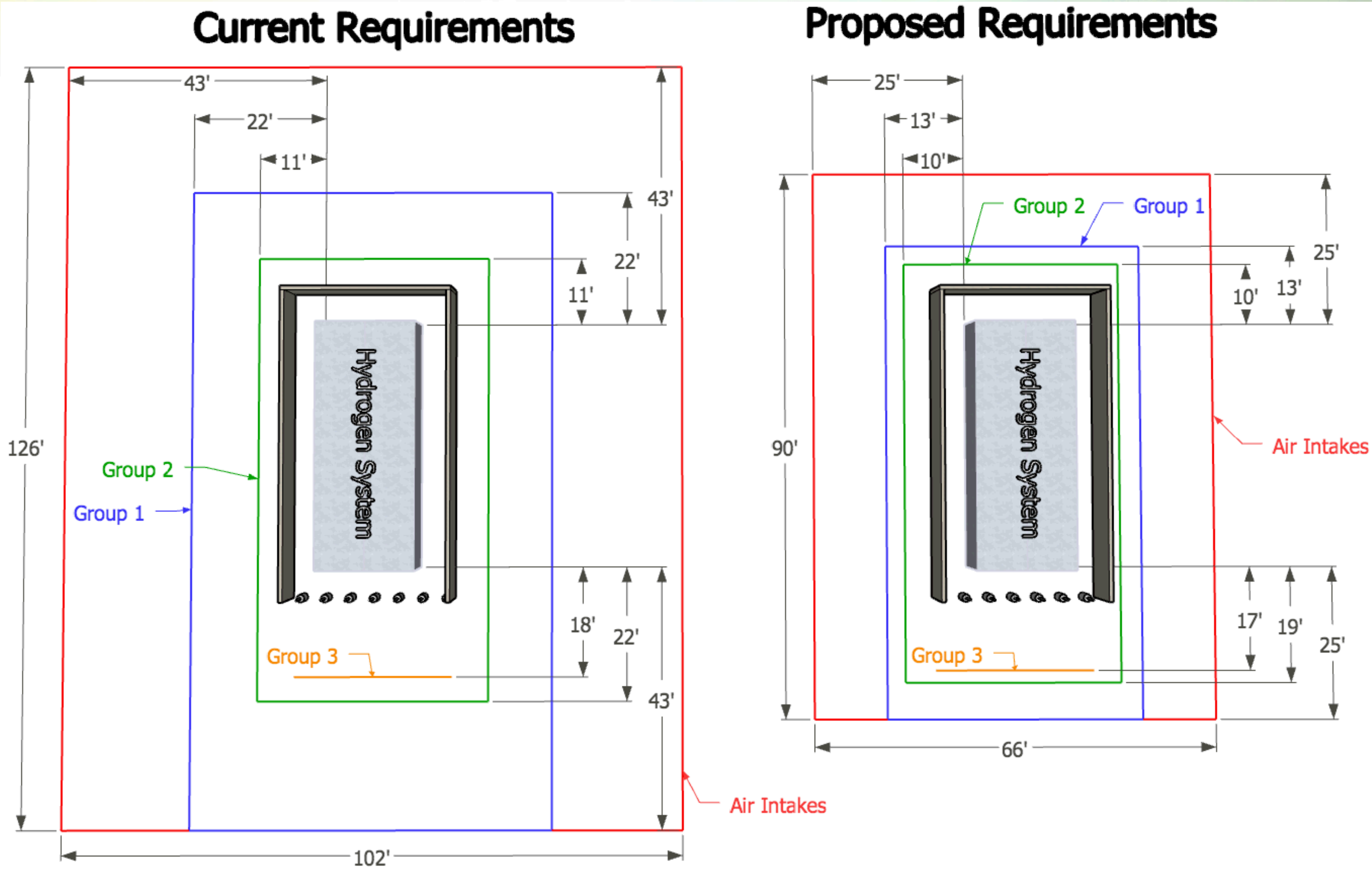
New NFPA 2 Delivered Gas

- The same components from the Base Case Gas design were used
- Calculated setback distances for proposed bulk gaseous storage based on:
  - Maximum Pressure of 9.4. MPa (13,688 psi)
  - ID of 9.07 mm (0.357")



	Current	Proposed
Group 1	13 m (43 ft)	8 m (25 ft)
Group 2	7 m (22 ft)	6 m (19 ft)
Group 3	5 m (18 ft)	5 m (17 ft)

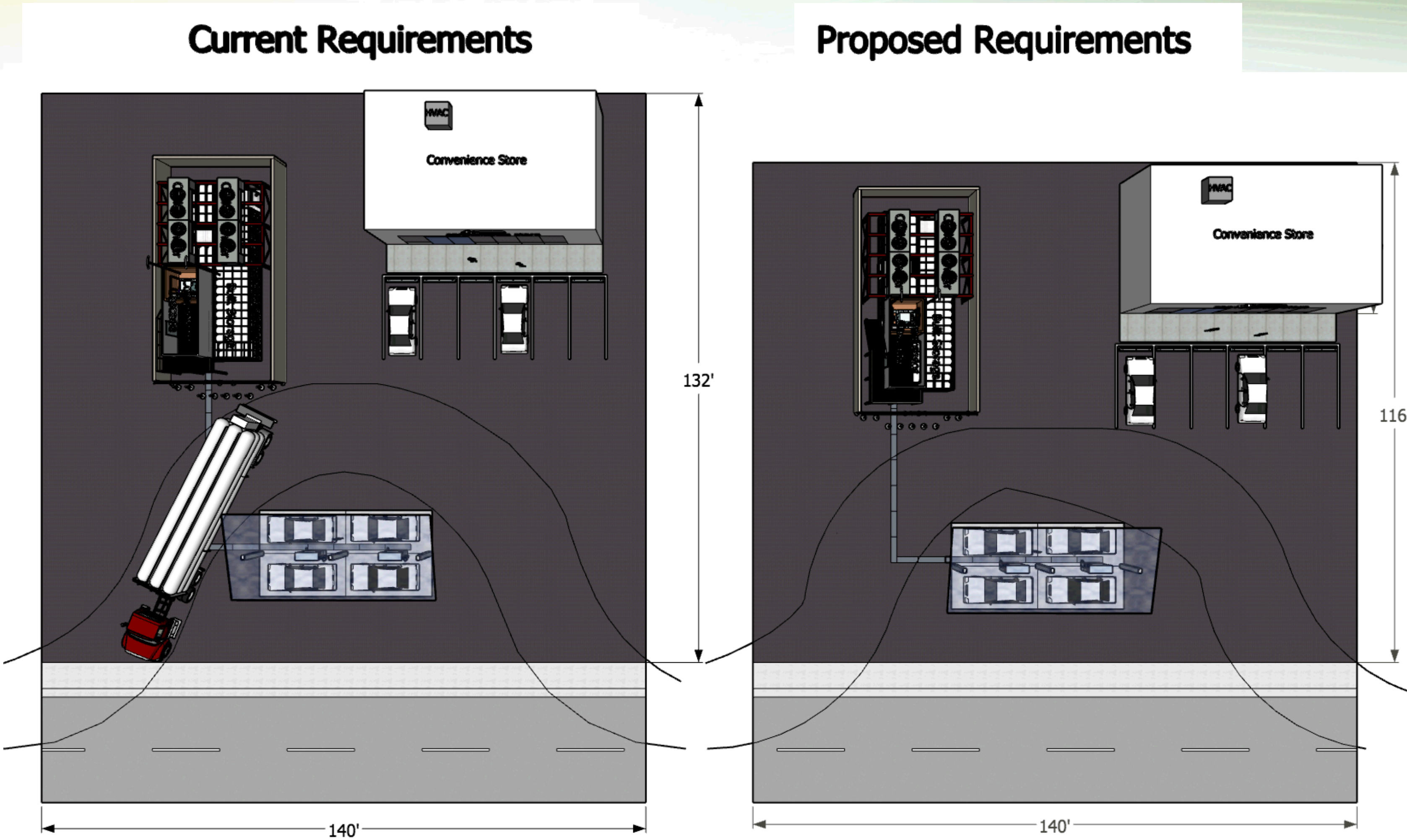
Comparison of Current and Proposed Minimum Layout for Base Case Gas



- Minimum Footprint
  - 12,852 ft^2

- Minimum Footprint
  - 5,940 ft^2

Comparison of Current and Proposed Full Layout for Base Case Gas



Non-hydrogen station components have large effect on final station layout

New NFPA 2 Base Case Gas Foot Print Reduction

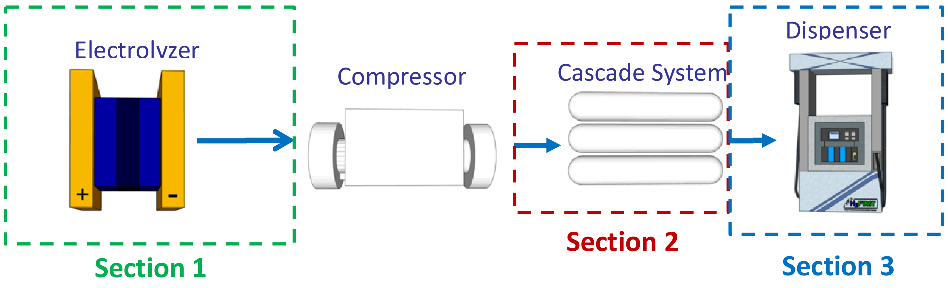
- Non-hydrogen station components have large effect on final station layout

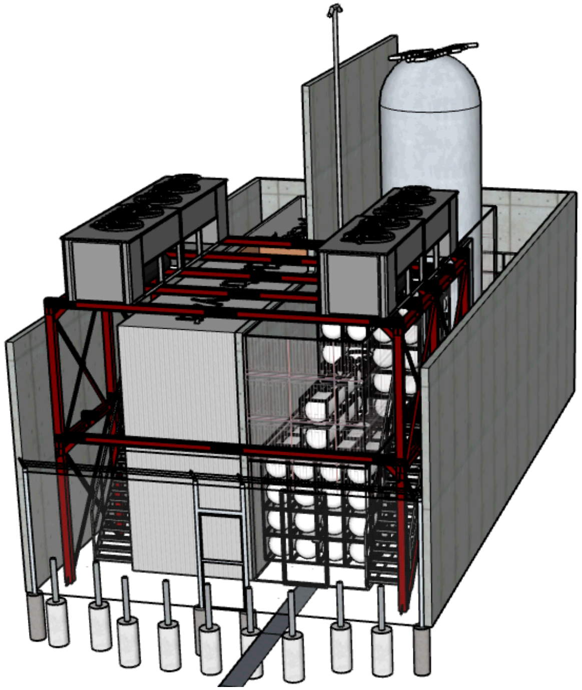
	Current Requirements	Proposed Requirements
Total Lot Area	18,480 ft^2	16,240 ft^2
% Reduction from Base Case	0	**12.1%**

NEW NFPA ELECTROLYZER

New NFPA 2 Delivered Gas Electrolyzer

- The same components from the Base Case Electrolyzer design were used
- Calculated setback distances for each section of the hydrogen system using proposed changes



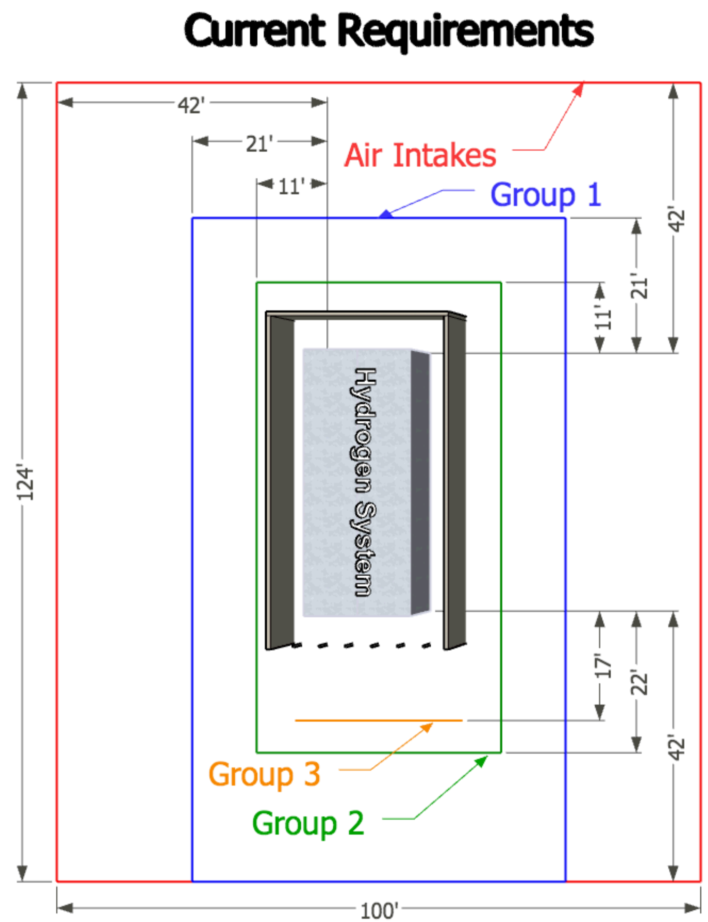


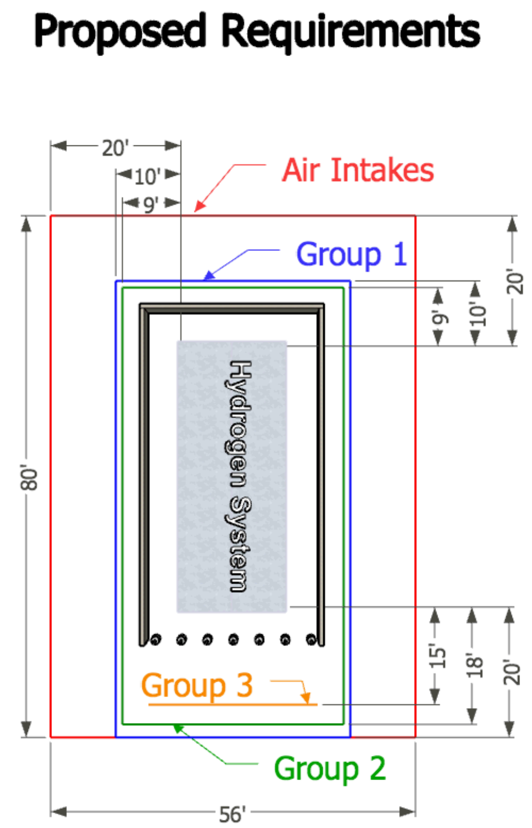
Calculated Setback Distances for New NFPA 2 Electrolyzer

- The largest separation distance for each storage array defines the value of the separation distance for the overall system
- Section 3 determines the setback distances for Group 1 exposures (current setbacks are determined only by section 1)

Group	Section	Wall	Current	Proposed
1	1	NO	**12.7 m (42 ft.)**	5.5 m (18 ft)
		YES	**6.4 m (21 ft.)**	2.7 m (9 ft)
	2	NO	7.5 m (24 ft.)	2.1 m (7 ft.)
		YES	3.7 m (12 ft.)	1.0 m (3 ft.)
	3	NO	11.5 m (38 ft.)	**6.1 m (20 ft.)**
		YES	5.7 m (19 ft.)	**3.1 m (10 ft.)**
2	1	NO	**6.6 m (22 ft.)**	**5.4 m (18 ft)**
		YES	**3.3 m (11 ft.)**	**2.7 m (9 ft)**
	2	NO	3.1 m (10 ft.)	2.1 m (7 ft.)
		YES	1.6 m (5 ft.)	1.1 m (4 ft.)
	3	NO	5.7 m (19 ft.)	4.7 m (15 ft.)
		YES	2.8 m (9 ft.)	2.4 m (8 ft.)
3	1	NO	**5.3 m (17 ft.)**	**4.6 m (15 ft.)**
		YES	**0.0 m (0 ft.)**	**0.0 m (0 ft.)**
	2	NO	3.1 m (10 ft.)	2.8 m (9 ft.)
		YES	0.0 m (0 ft.)	0.0 m (0 ft.)
	3	NO	4.8 m (16 ft.)	4.5 m (15 ft.)
		YES	0.0 m (0 ft.)	0.0 m (0 ft.)

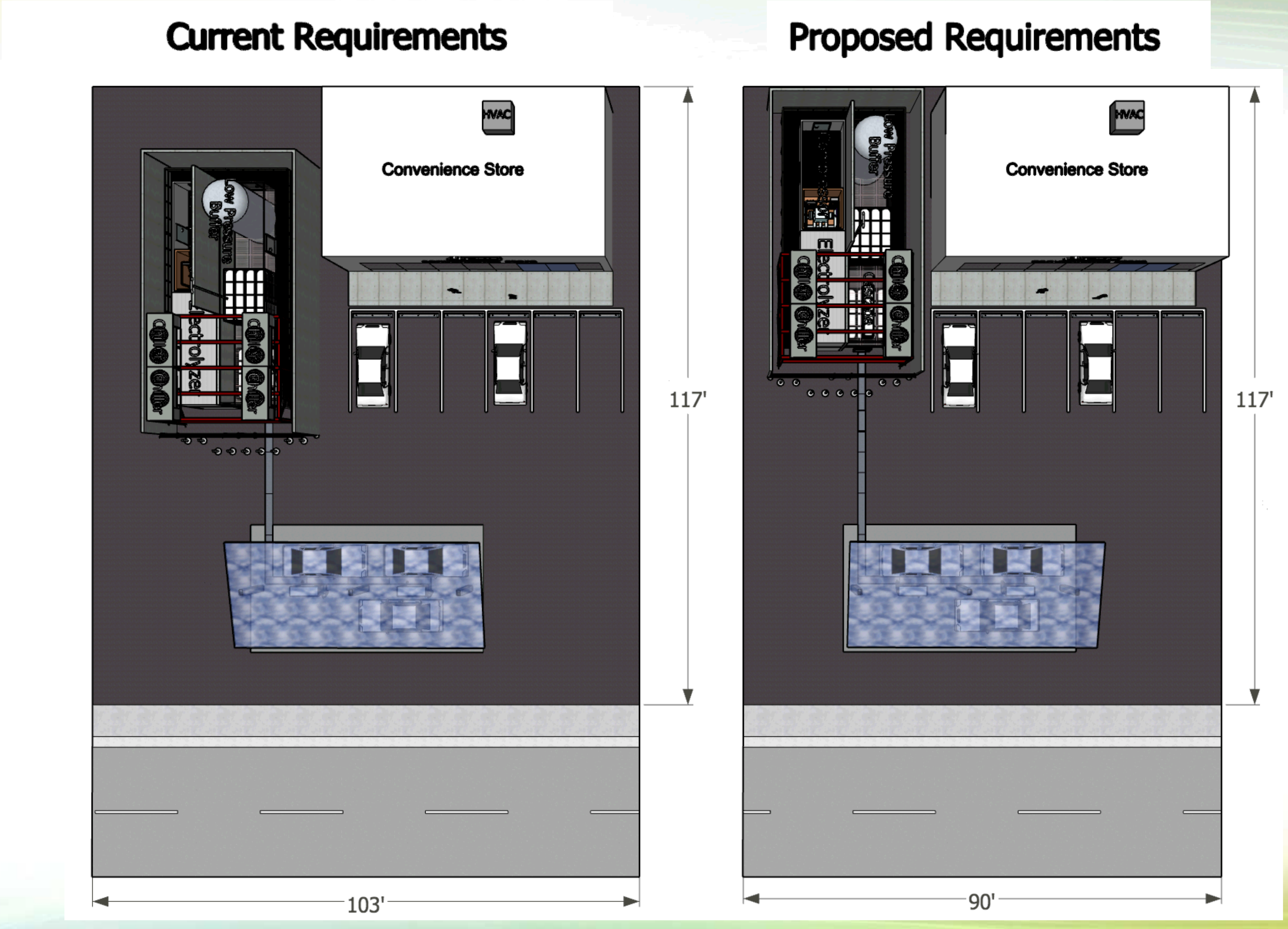
Comparison of Current and Proposed Minimum Layout for Base Case Electrolyzer





- Minimum Footprint
  - 12,400 ft^2
- Minimum Footprint
  - 4,480 ft^2

Comparison of Current and Proposed Full Layout for Base Case Electrolyzer



New NFPA 2 Base Case Electrolyzer Foot Print Reduction

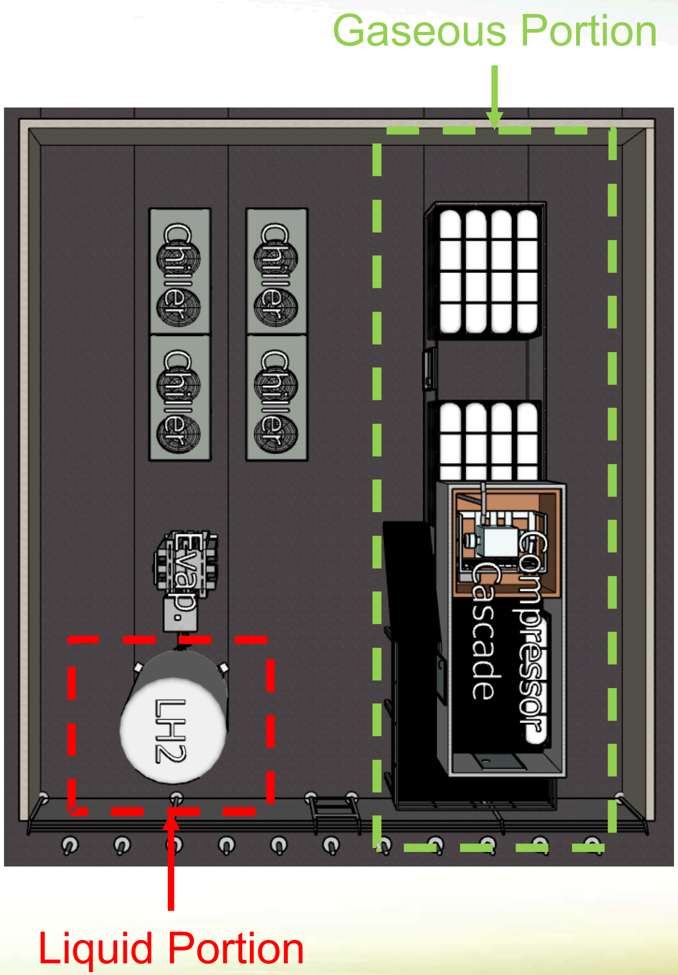
- Non-hydrogen station components have large effect on final station layout

	Current Requirements	Proposed Requirements
Total Lot Area	12,051 ft^2	10,530 ft^2
% Reduction from Base Case	0	**12.6%**

BAS CASE LIQUID

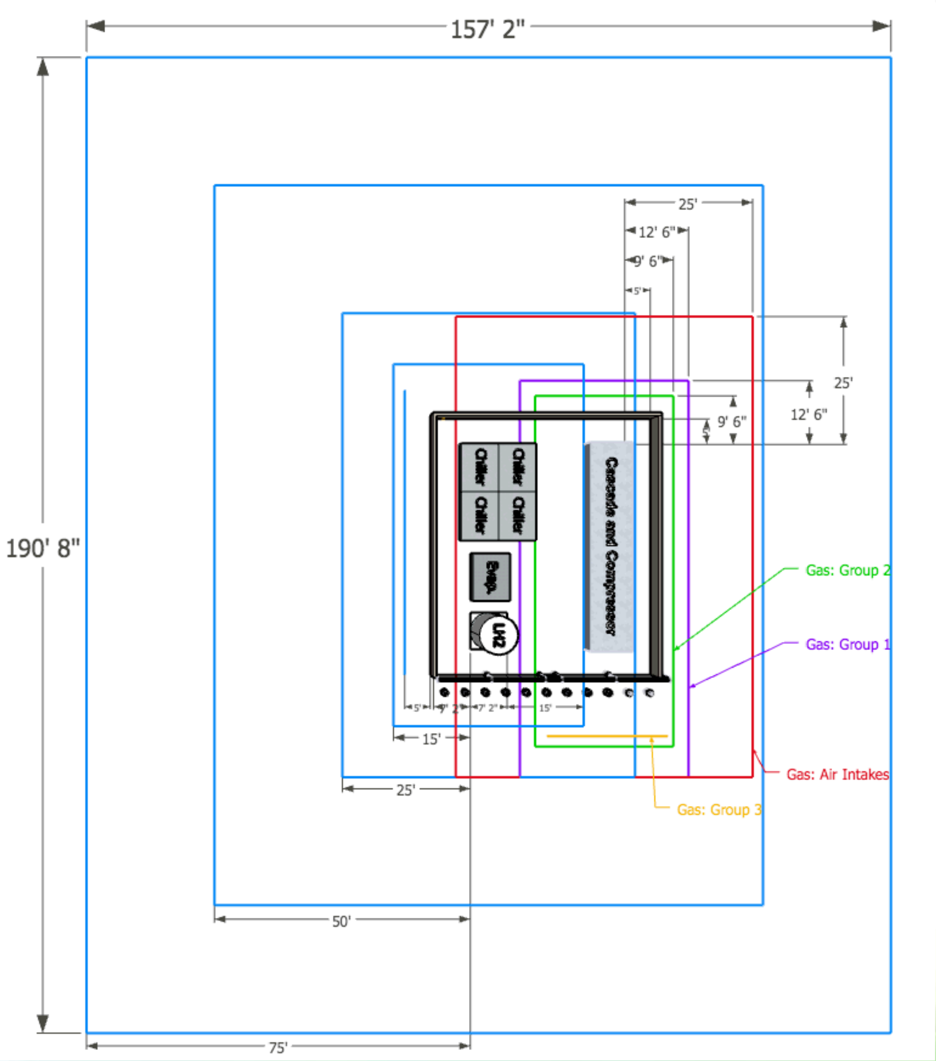
New NFPA 2 Delivered Liquid

- The same components from the Base Case Liquid design were used
- The setback distances values for the liquid hydrogen did not change (as they did for the compressed gas)
- The mayor change is on the definition of the hybrid storage system
- With new definition:
  - Distances for gaseous systems (NFPA 2 Chapter 7) should be applied to the gaseous portion
  - Distances for liquid systems (NFPA 2 Chapter 8) should be applied to the liquid portion

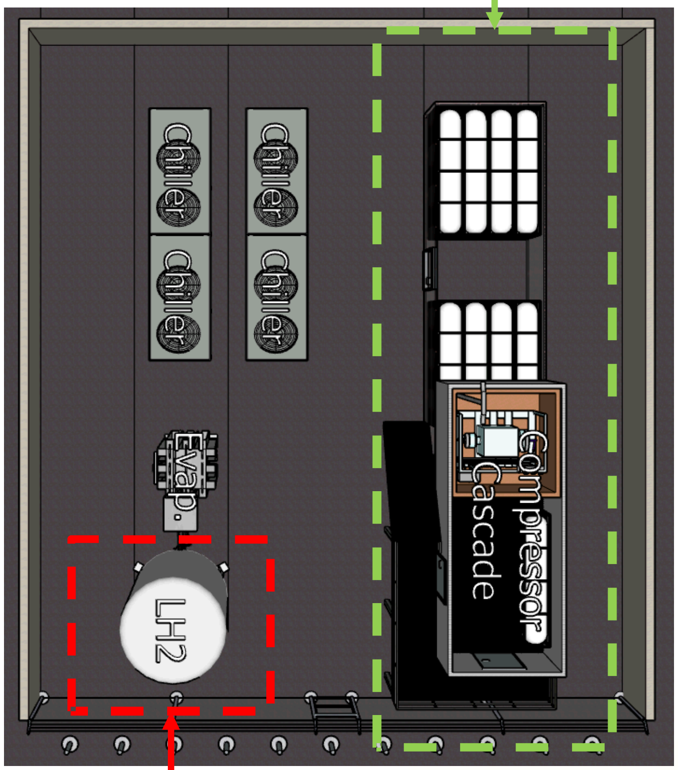


Minimum Layout for Base Case Liquid with Proposed Changes

Proposed Requirements

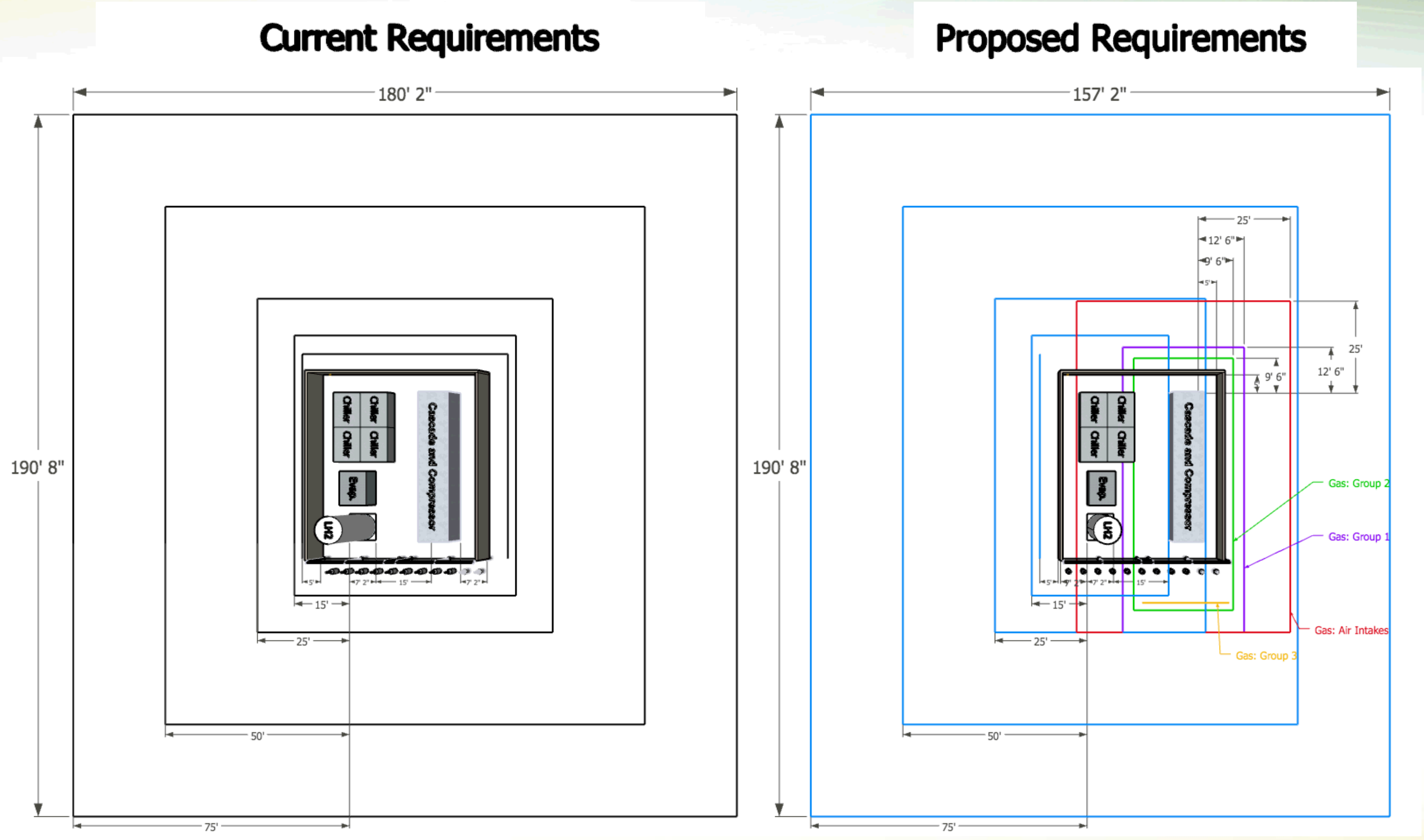


Gaseous Portion



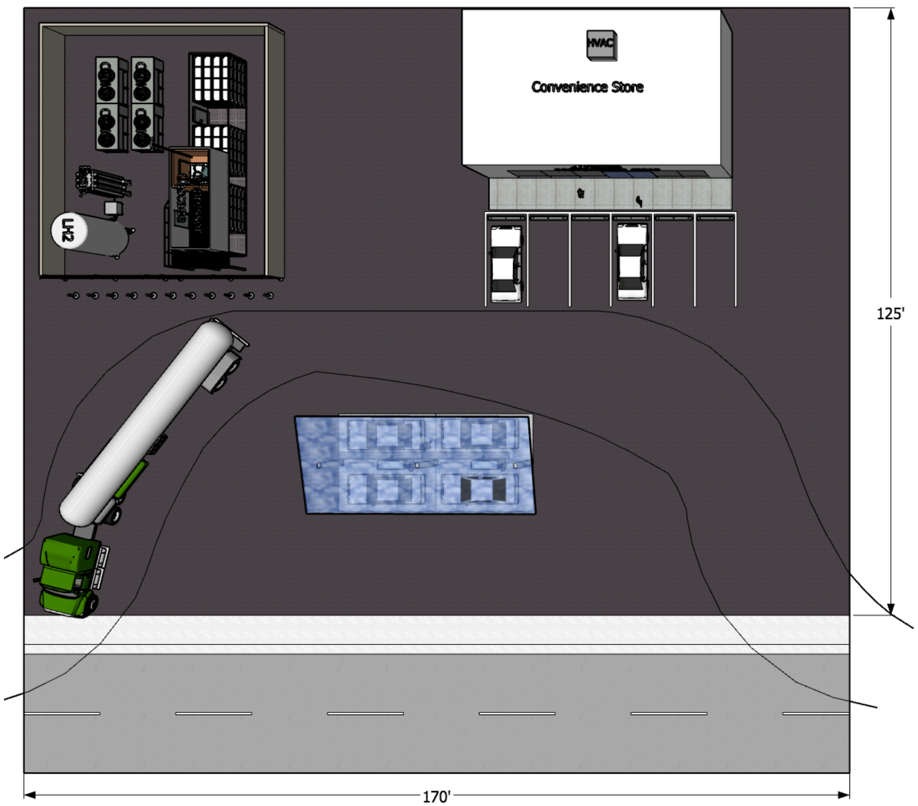
Liquid Portion

Comparison of Current and Proposed Minimum Layout for Base Case Liquid

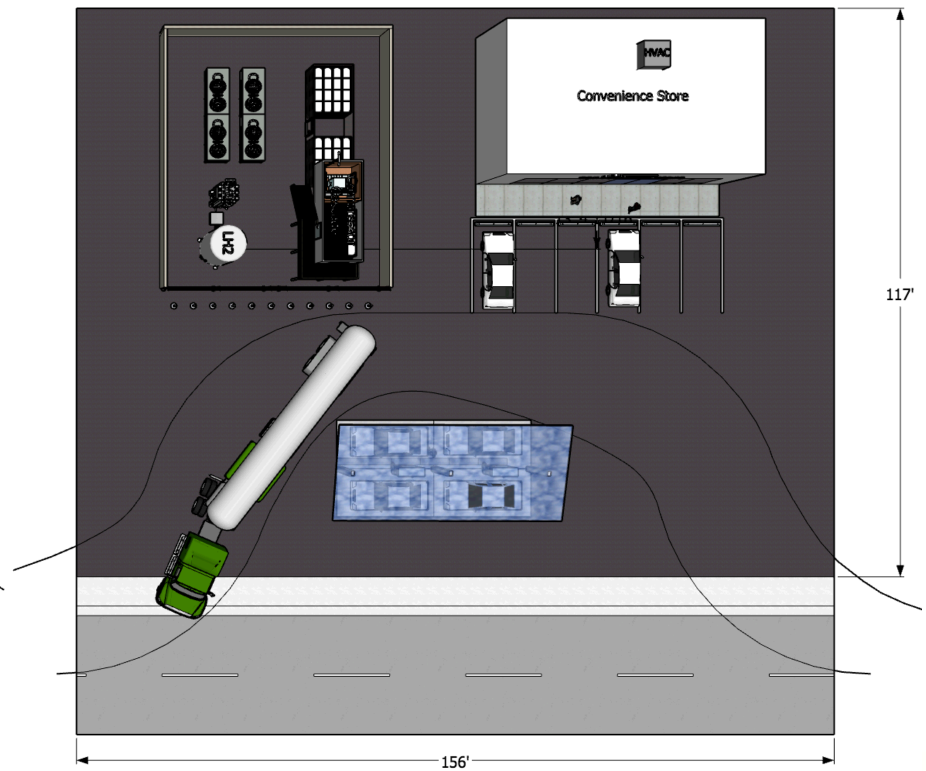


Comparison of Current and Proposed Full Layout for Base Case Liquid

Current Requirements



Proposed Requirements



New NFPA 2 Base Case Liquid Foot Print Reduction

- Non-hydrogen station components have large effect on final station layout

	Current Requirements	Proposed Requirements
Total Lot Area	21,250 ft^2	18,252 ft^2
% Reduction from Base Case	0	**14.1%**

New NFPA 2 Summary

- The proposed changes to NFPA 2 help reduce the total lot area of the three Base Cases
- Non-hydrogen station components have large effect on final station layout

	Gas		Electrolyzer		Liquid	
Requirements	Current	Proposed	Current	Proposed	Current	Proposed
Total Lot Area (ft^2)	18,480	16,240	12,051	10,530	21,250	18,252
% Reduction from Base Case	0	**12.1%**	0	**12.6%**	0	**14.1%**

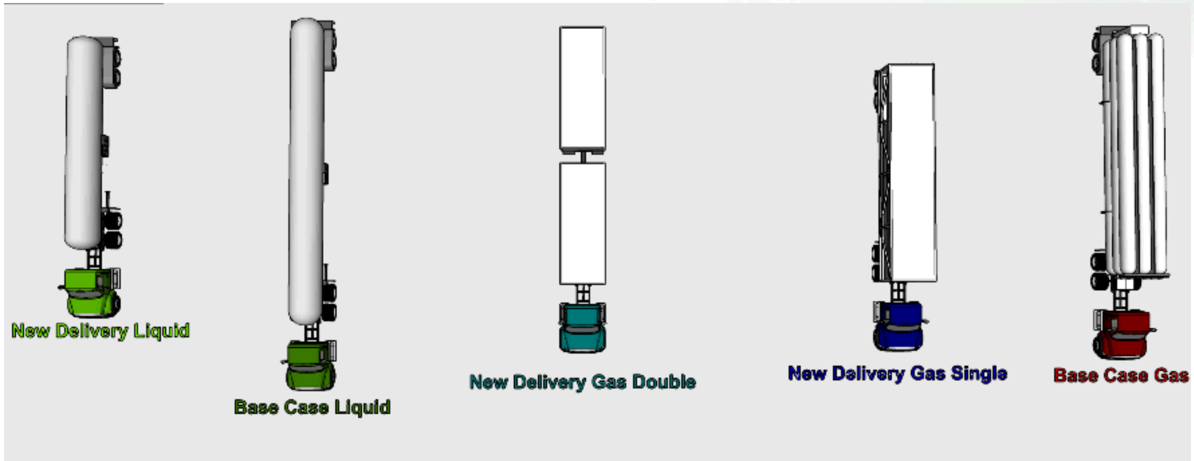
ALTERNATE DELIVERY – GAS AND LIQUID

Presented by Brian Ehrhart

Goals of Alternate Delivery

- Quantify example of smaller delivery trucks
- Meets all setback distances, so hazard analysis not done

New Delivery Truck Sizes



- Delivery truck specifications can have a large impact on station utilization and layout
  - Low delivery capacity or pressure mean station utilization is limited
  - Truck dimensions and turning radius can have a significant impact on station layout
- Delivery truck specifics will depend on local market conditions and supplier availability

New Delivery Truck Sizes

- Delivered Gas
  - Base assumptions under-utilize station
  - “New” option can fully utilize station
  - Shorter delivery truck will lead to smaller footprint
- Delivered Liquid
  - Both Base Case and “New” can fully supply multiple stations
  - Shorter delivery truck will lead to smaller footprint

	Delivered Gas			Delivered Liquid	
	Base Case	New Delivery Single	New Delivery Double	Base Case	New Delivery
Hydrogen Pressure	25 MPa (3626 psi)	50 MPa (7,252 psi)	25 MPa (3626 psi)	--	
Hydrogen Capacity	300 kg	1,200 kg	300 kg	3,000 kg	1,800 kg
Truck-Trailer Length	15.2 m (50 ft)	12.2 m (40 ft)	20.4 m (67 ft)	18.9 m (62 ft)	12.2 m (40 ft)

Delivery very localized, but can still have major impact on station design

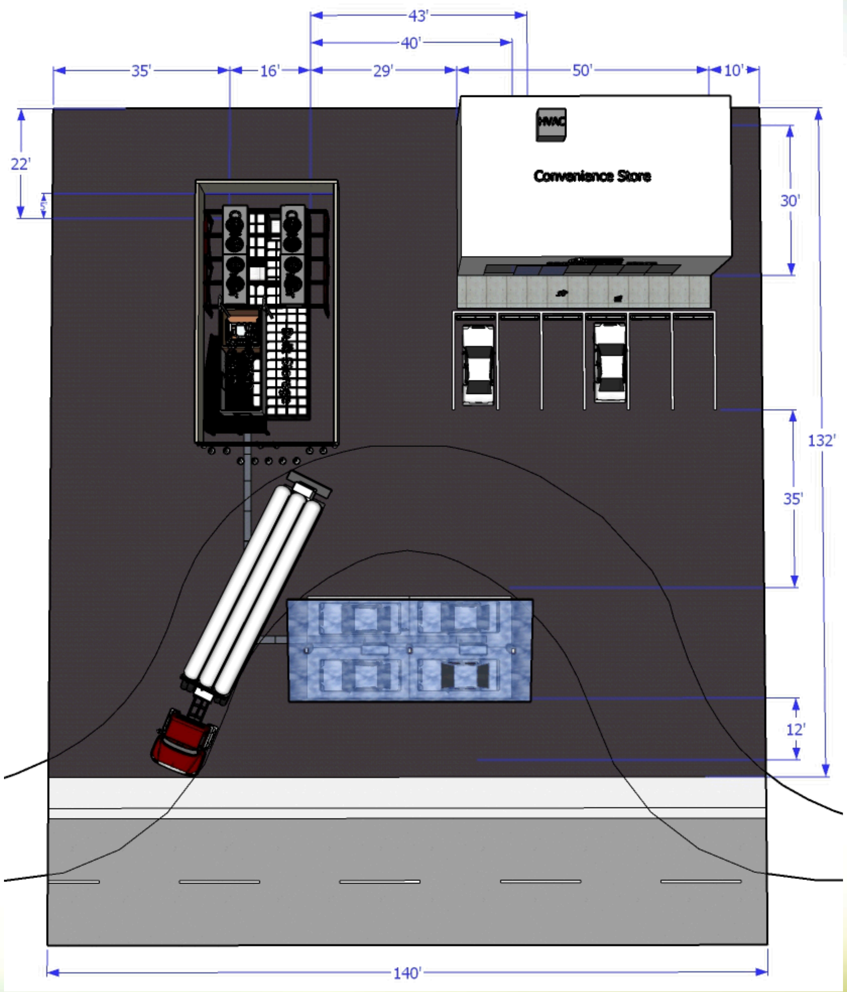
New Delivery Gas Design Choices

- The fueling station design consists of the following major components:
  - 800 kg gaseous hydrogen (GH2) storage at 50 MPa and ambient temperature
  - One compressor with a flowrate of 25 kg/hr
  - A bank of high pressure gaseous hydrogen storage cylinders for cascade filling of vehicles
  - Underground, joint-less stainless-steel piping from storage bank to dispenser island
  - 2 dispensers, each with 2 hoses: 4 dispenser hoses in total
  - Station rated at a 600 kg/day capacity
- Storage and dispensing system are the **same as the base case gas**
- Only **variances** for this analysis are: **varied truck trailer size and path**

Base Case Gas

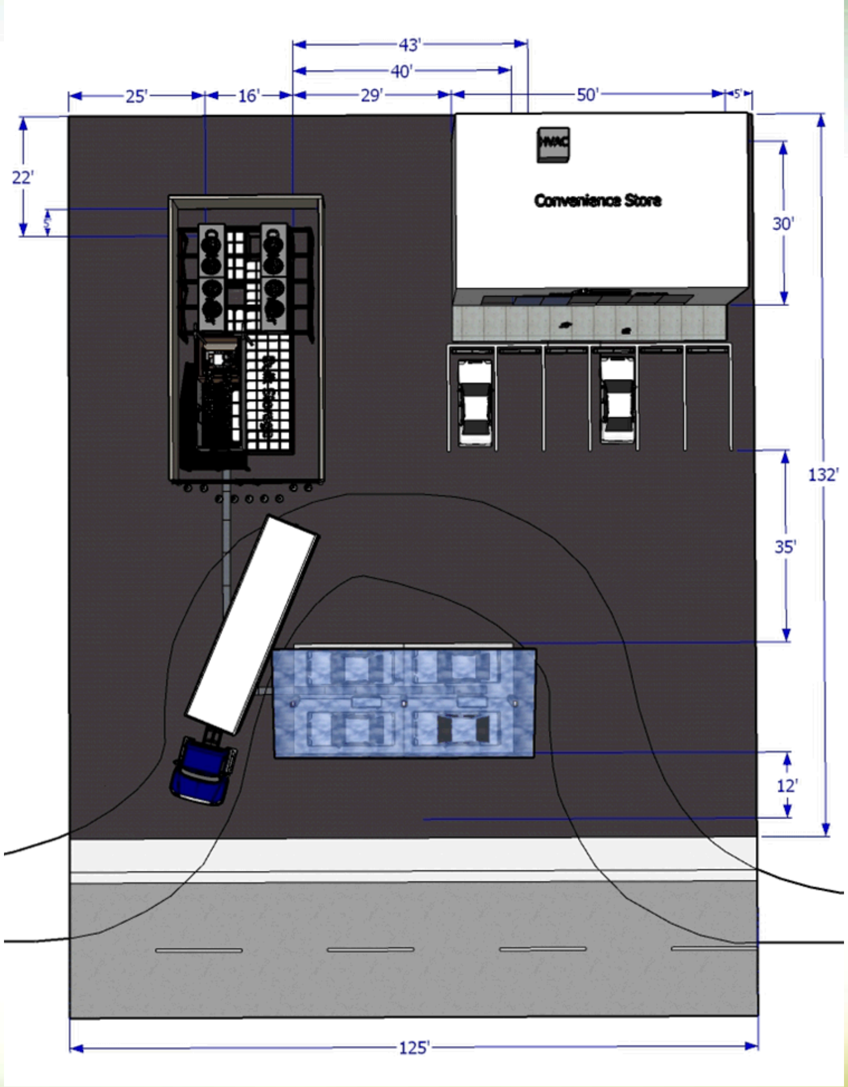
H_2FIRST

- Lot Size: 140 x 132 ft
- Total Area: 18,480 ft^2
- Truck Trailer
  - Pressure: 25 MPa (3,626 psi)
  - Capacity: 300 kg
  - Length: 50 ft (15.2 m)



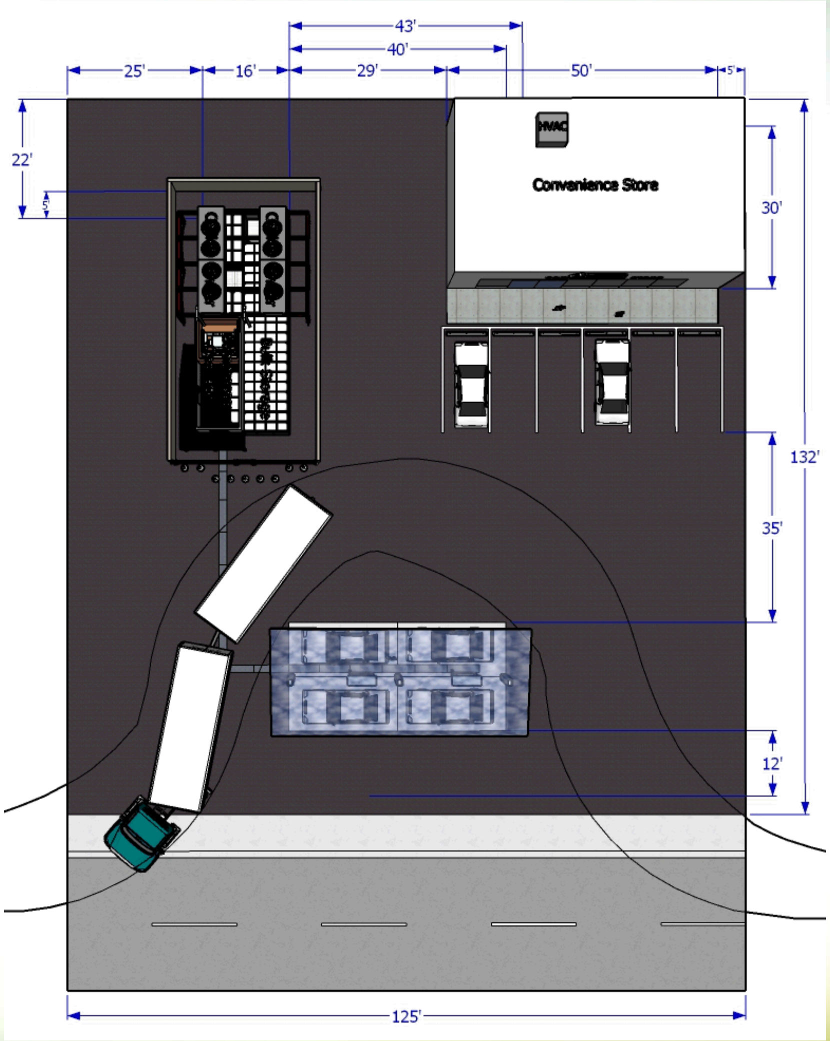
New Delivery Gas – Full Layout Single Truck

- Lot Size: 125 x 132 ft
- Total Area: 16,500 ft^2
- Truck Trailer
  - Pressure: 50 MPa (7,252 psi)
  - Capacity: 1,200 kg
  - Length: 40 ft (12.2 m)



New Delivery Gas – Full Layout Double Truck

- Lot Size: 125 x 132 ft
- Total Area: 16,500 ft^2
- Truck Trailer
  - Pressure: 25 MPa (3,626 psi)
  - Capacity: 300 kg
  - Length: 67 ft (20.4 m)

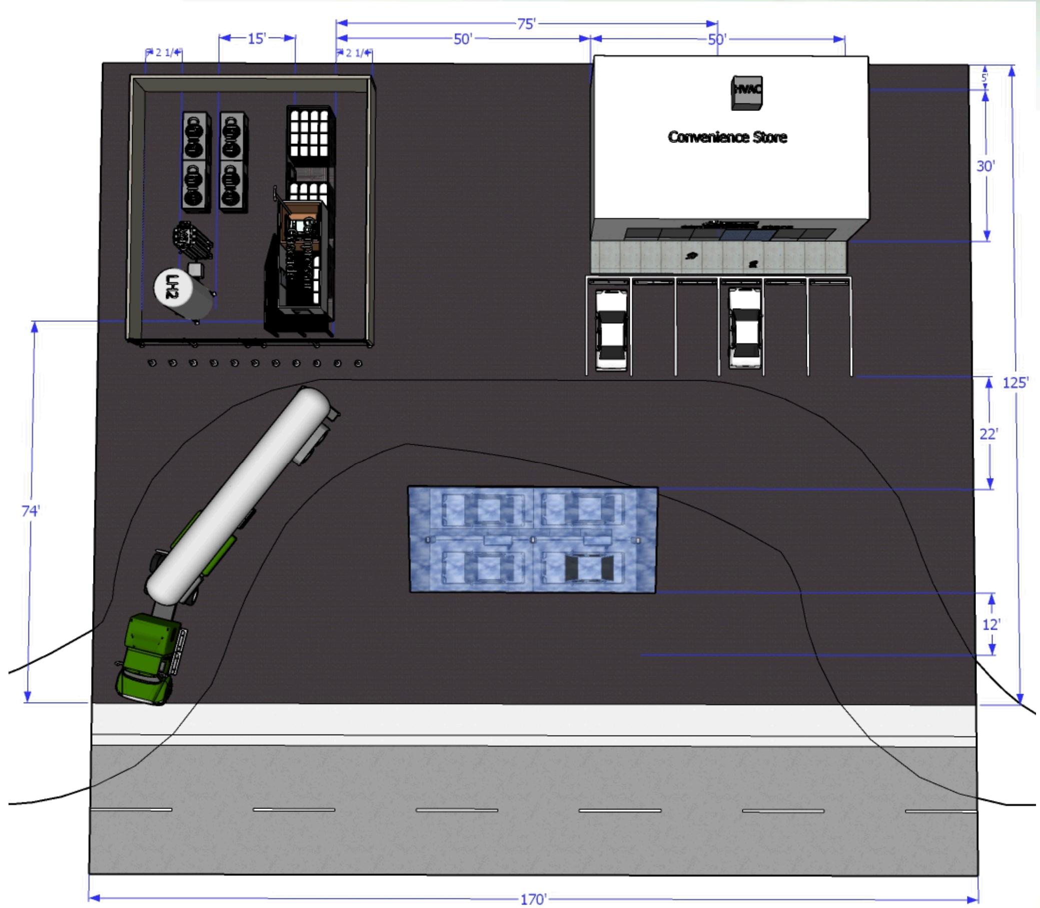


New Delivery Liquid Truck Sizes

- The fueling station design consists of the following major components:
  - 800 kg liquid hydrogen (LH2) storage at 0.6 MPa
  - One compressor with a flowrate of 25 kg/hr
  - A bank of high pressure gaseous hydrogen storage cylinders for cascade filling of vehicles
  - Underground, joint-less stainless-steel piping from storage bank to dispenser island
  - 4 dispenser hoses (fueling positions)
  - Station rated at a 600 kg/day capacity
- Storage and dispensing system are the **same as the base case liquid**
- Only **variances** for this analysis are: **varied truck trailer size and path**

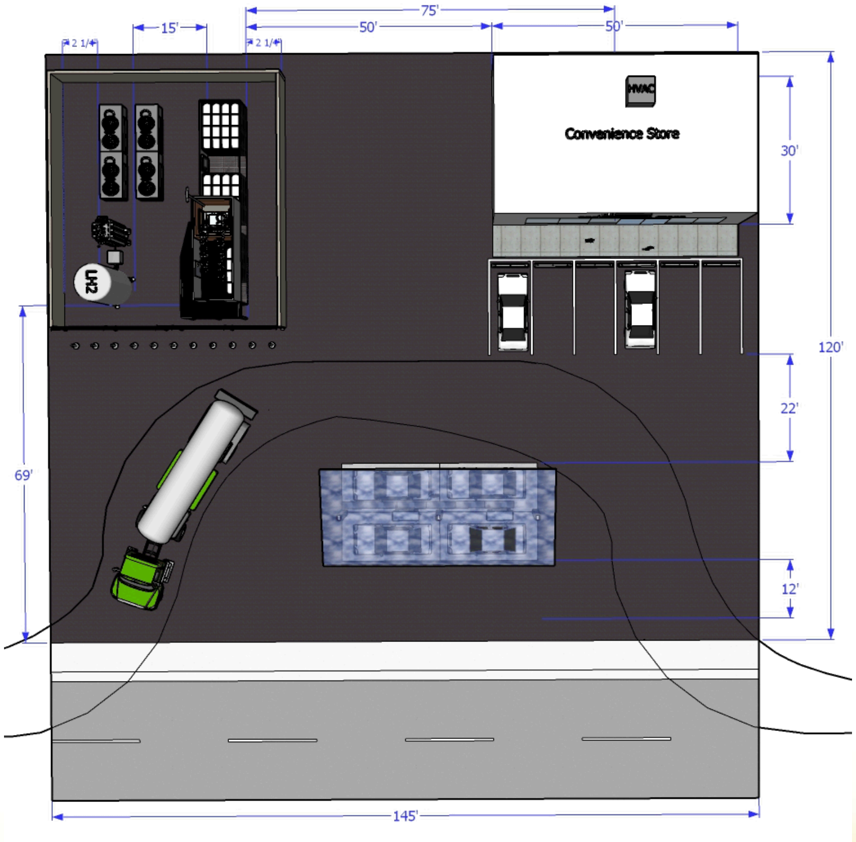
Base Case Liquid

- Lot Size: 170 x 125 ft
- Total Area: 21,250 ft^2
- Truck Trailer
  - Capacity: 3,000 kg
  - Length: 62 ft (18.9 m)



New Delivery Liquid – Full Layout

- Lot Size: 145 x 120 ft
- Total Area: 17,400 ft^2
- Truck trailer
  - Capacity: 1,800 kg
  - Length: 40 ft (12.2 m)



New Delivery Summary

	Delivered Gas			Delivered Liquid	
	Base Case	New Delivery Single	New Delivery Double	Base Case	New Delivery
Total Lot Area	18,480 ft^2	16,500 ft^2	16,500 ft^2	21,250 ft^2	17,400 ft^2
% Reduction from Base Case	0	10.7%	10.7%	0	18.1%

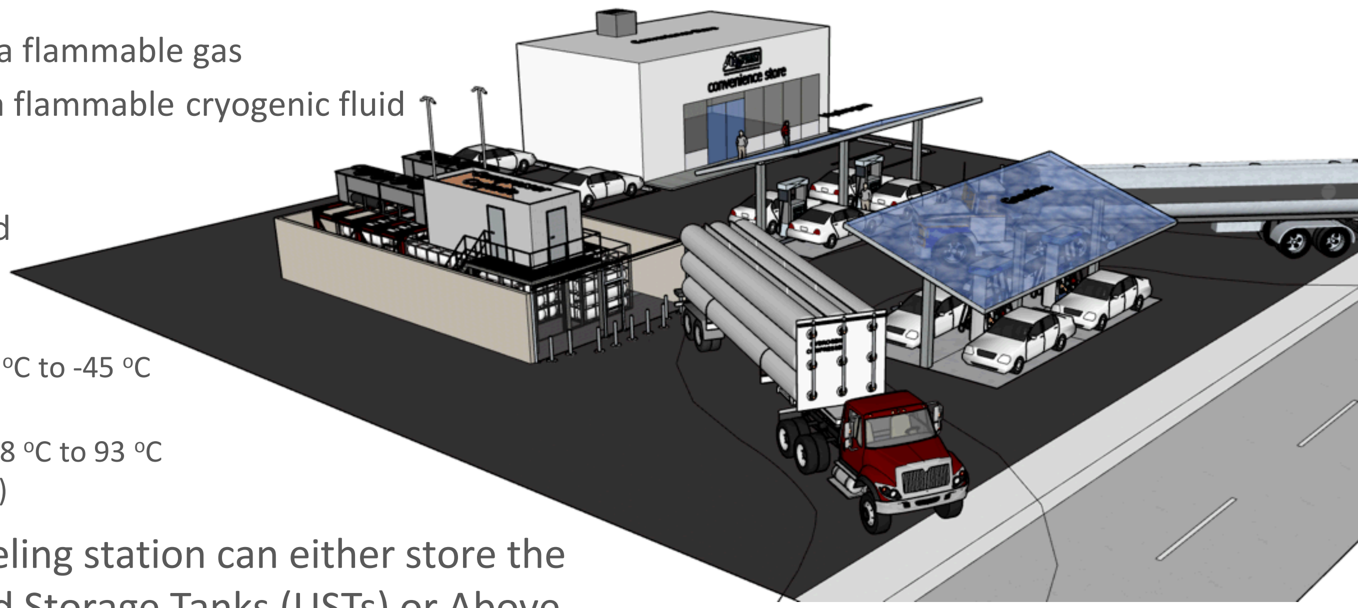
GASOLINE CO-LOCATION

Presented by Gaby Bran-Anleu

Co-Location Station - Gasoline and Hydrogen Fueling Station

H2FIRST

- A code compliant co-location station needs to satisfy the following regulations:
  - NFPA 2 and NFPA 55
    - GH2 is classified as a flammable gas
    - LH2 is classified as a flammable cryogenic fluid
  - NFPA 30 and 30A
    - Gasoline is classified as a Class IB flammable liquid
      - flash point of -40 °C to -45 °C (-40 °F to -50 °F)
      - boiling range of 38 °C to 93 °C (100 °F to 200 °F)



- Public retail gasoline fueling station can either store the gasoline in Underground Storage Tanks (USTs) or Above Storage Tanks (ASTs)
  - For this study, USTs were used since these are the most common

Setback distances for Gasoline system

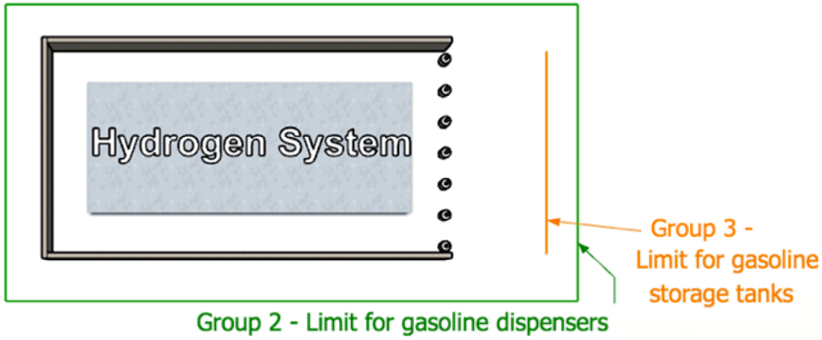
- Underground storage tanks need to be at least 3 ft from property lines
- Filling, emptying, and vapor recovery connections should be at least 5 ft from building opening or air intakes

Type of Exposure	Minimum Distance	Code
Lot lines	0.9 m (3 ft)	NFPA 30 23.4.2
Air intakes or building openings	1.5 m (5ft)	NFPA 30 23.13.6
Wall of basement or pit	0.3 m (1 ft)	NFPA 30 23.4.2
Powered ventilation air intake devices	4.5 m (15 ft)	NFPA 30 27.8.2.2

Gasoline System as Exposure Type for Gaseous Hydrogen System

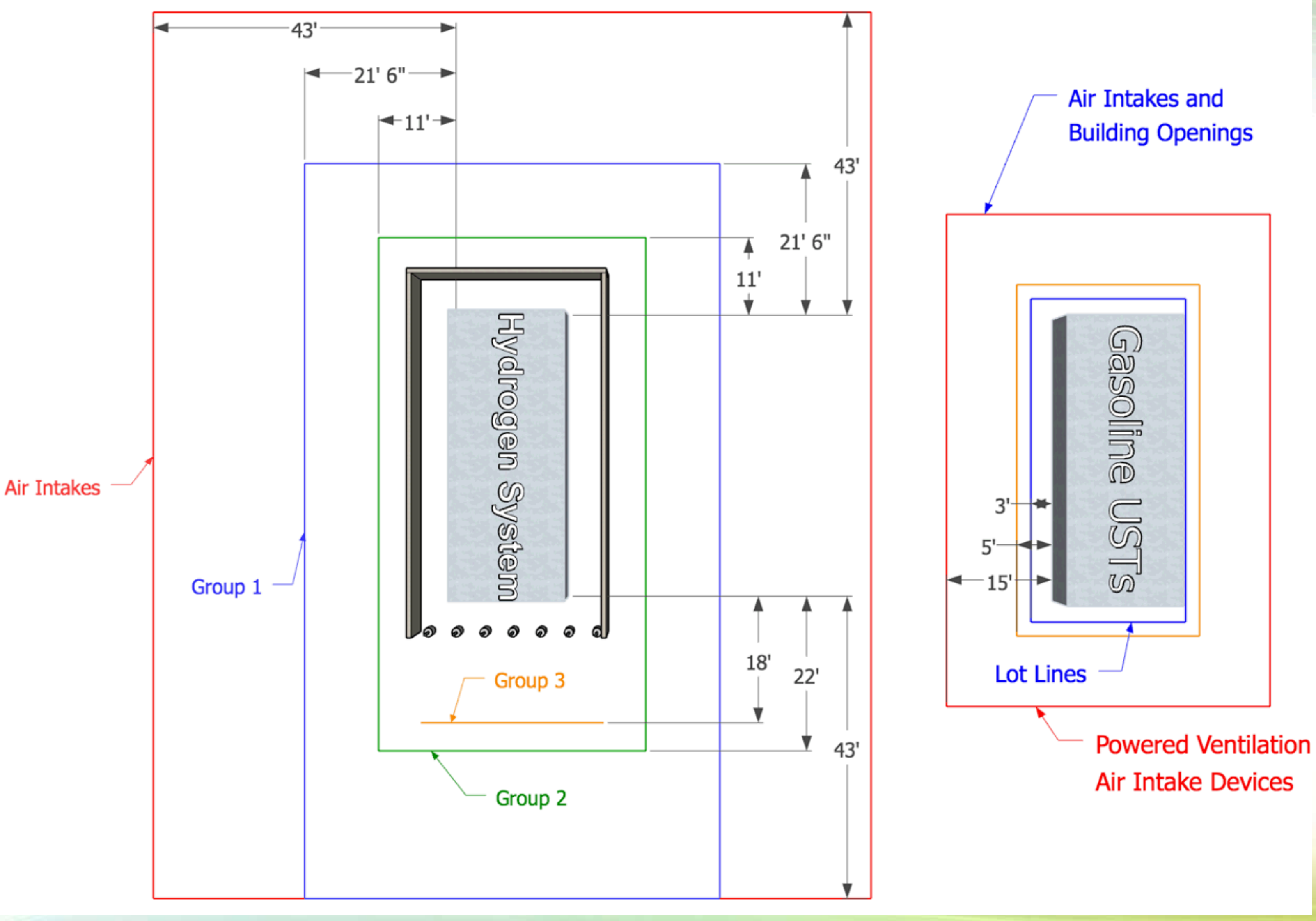
- NFPA 2 Table 7.3.2.3.1.1(a) was used to determine the minimum distances between the Gasoline components (exposure) and the gaseous hydrogen system
  - It needs to be determined what type of exposure each components is
- The gasoline dispensing island will have exposed persons and parked cars
  - Group 2 exposure
- Gasoline is a hazardous material (either above or below ground)
  - Group 3(d) exposure
- The piping containing gasoline
  - Group 3(i) exposure

Gasoline Component	Type of Exposure
Dispenser	Group 2
USTs vent or fill openings	Group 3 (d)
Piping	Group 3 (i)



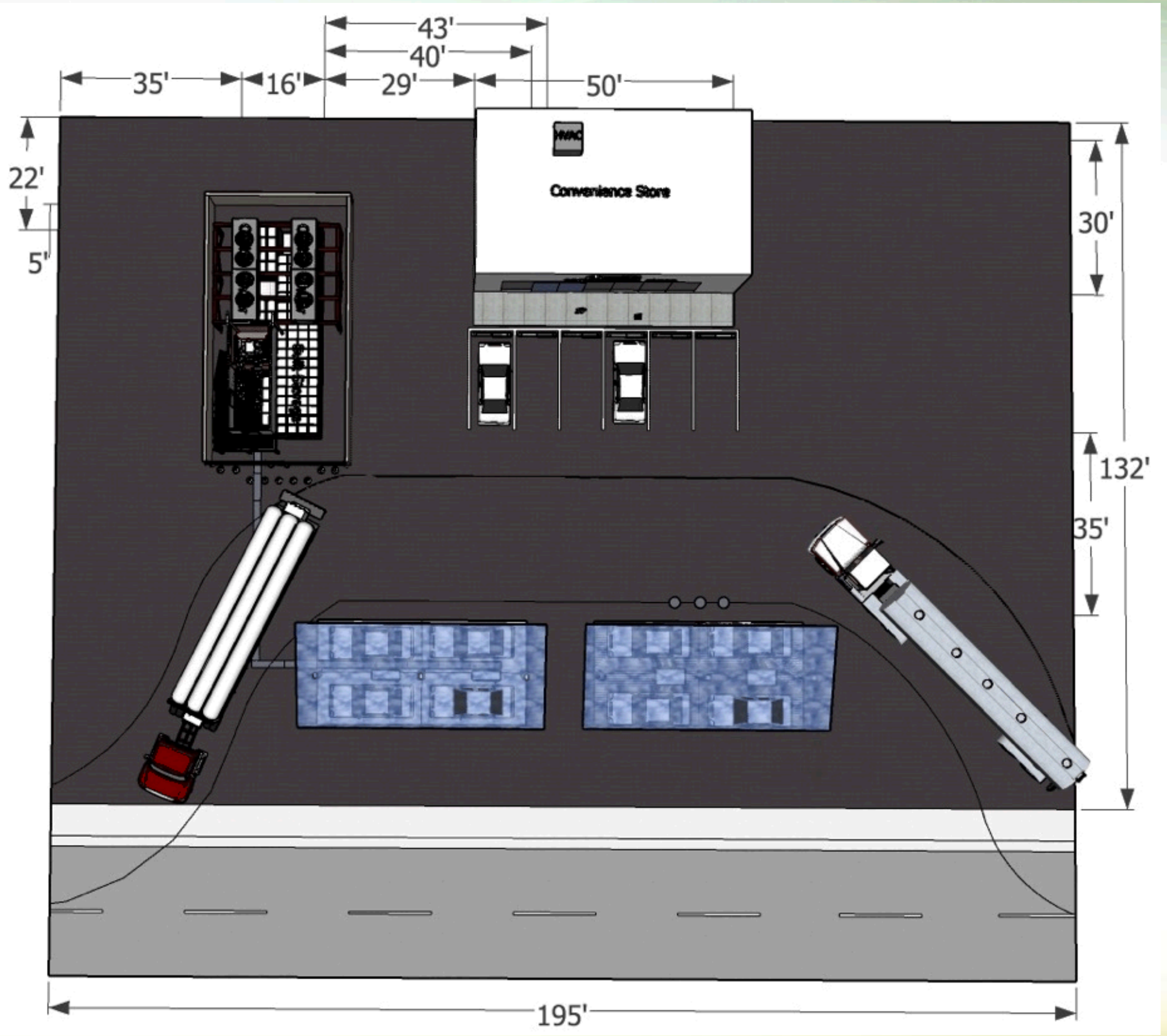
Group 2 and 3 exposures distances can be used to determine layout for co-location station.

Minimum Setback Distances for the Hydrogen and Gasoline Systems



Full Layout for Co-location Delivered Gas

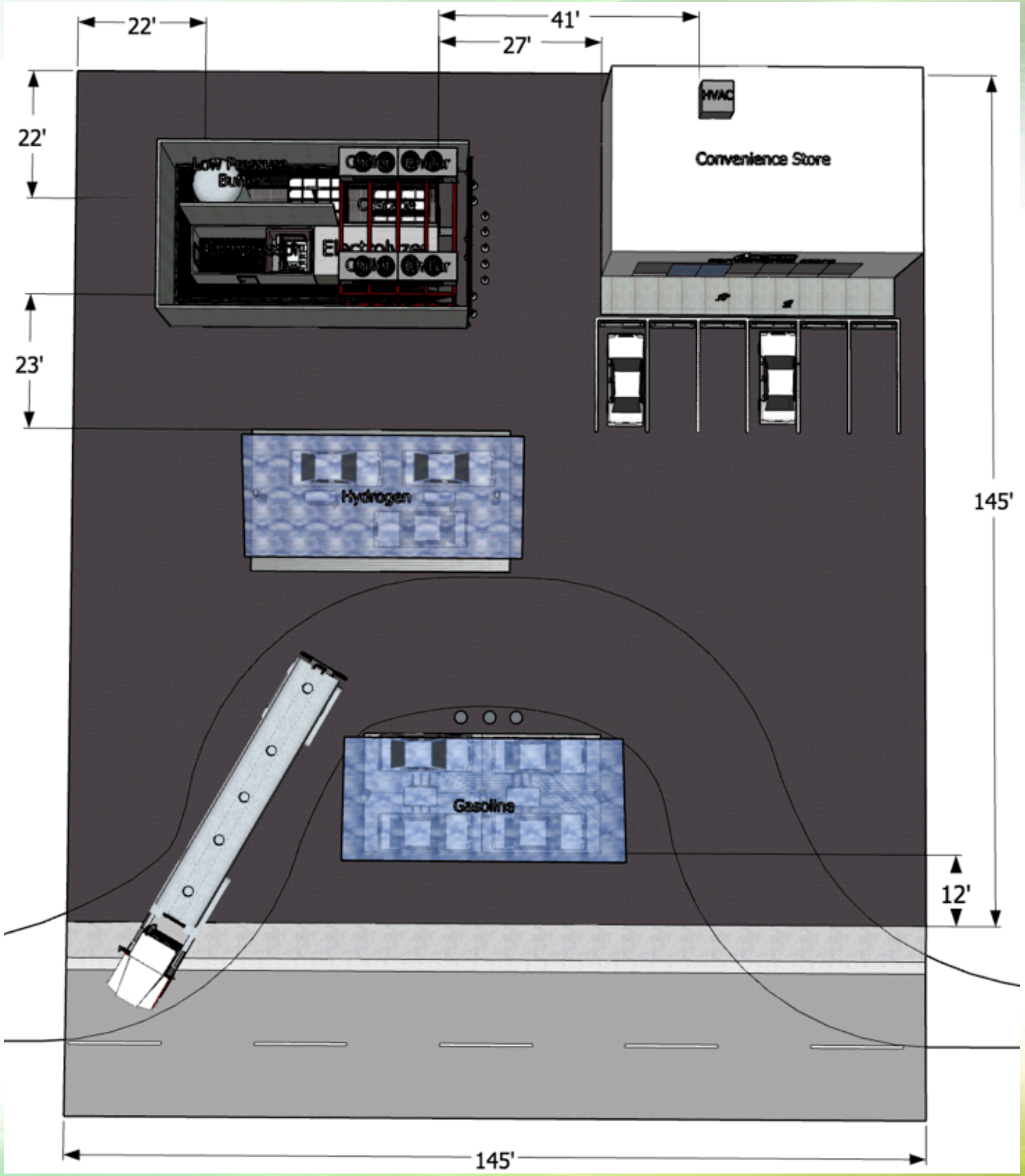
- Full Layout
  - Convenience store
  - Parking
  - Traffic flow
  - Delivery
- Total Lot Area
  - 25,740 ft^2



Non-hydrogen station components have large effect on final station layout

Full Layout for Co-location Electrolyzer

- Full Layout
  - Convenience store
  - Parking
  - Traffic flow
- This station has to account for the gasoline delivery truck (Base Case Electrolyzer didn't need to)
- Total Lot Area
  - 21,145 ft^2



Gasoline System as Exposure Type for Liquid Hydrogen System

- NFPA 2 Table Table 8.3.2.3.1.6(A) was used to determine the minimum distances between the Gasoline components (exposure) and the liquid hydrogen system
  - It needs to be determined what type of exposure each components is
- The gasoline dispensing island will have exposed persons and parked cars
  - Group 2(6) exposure
- Gasoline is a hazardous material (either above or below ground)
  - Group 3(11) exposure
- The piping containing gasoline
  - Group 3(15c) exposure

Gasoline Component	Type of Exposure
Dispenser	Group 2(6)
USTs vent or fill openings	Group 3(10)
Piping	Group 3(15c)

Minimum setback distances for Co-location Liquid Hydrogen

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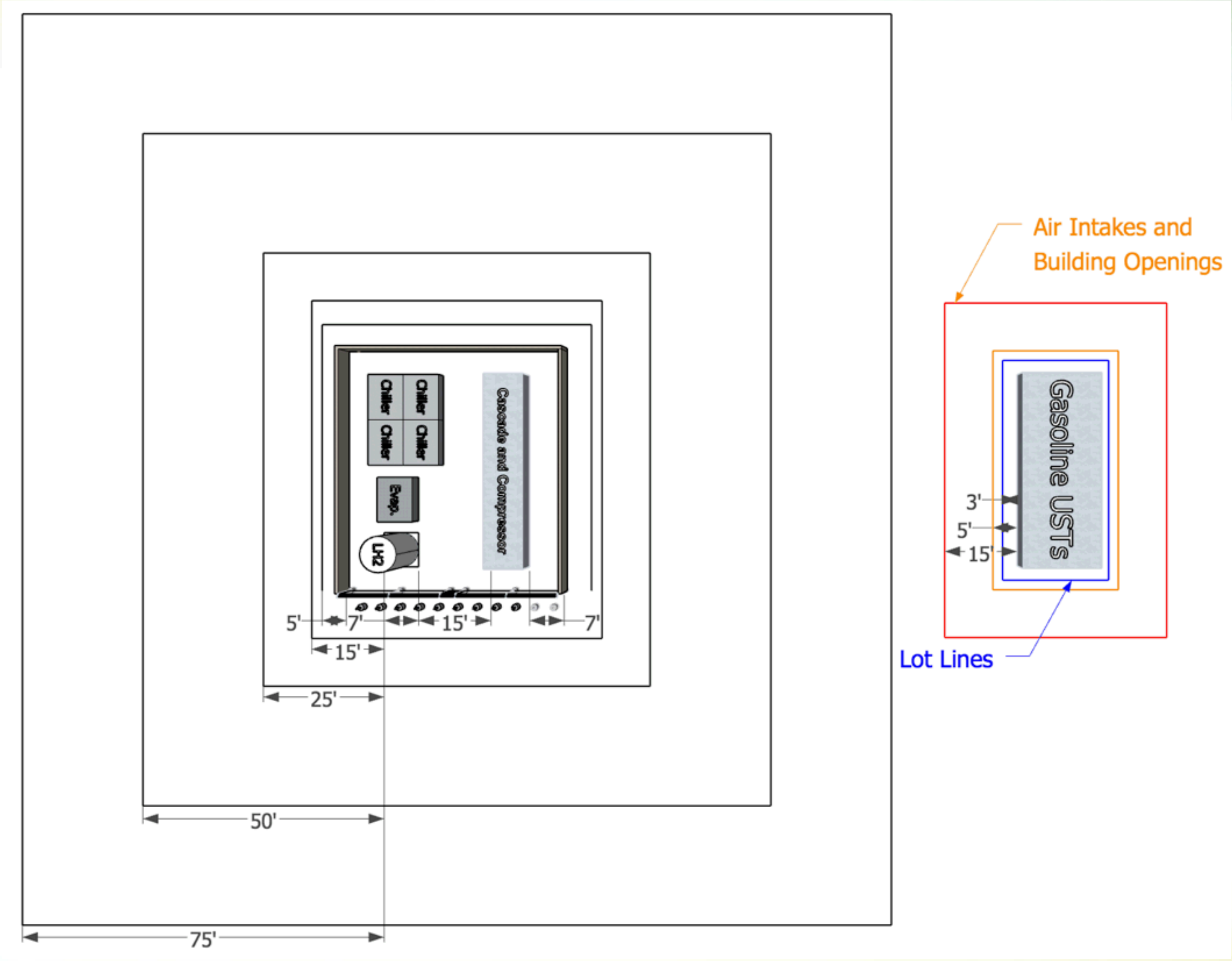
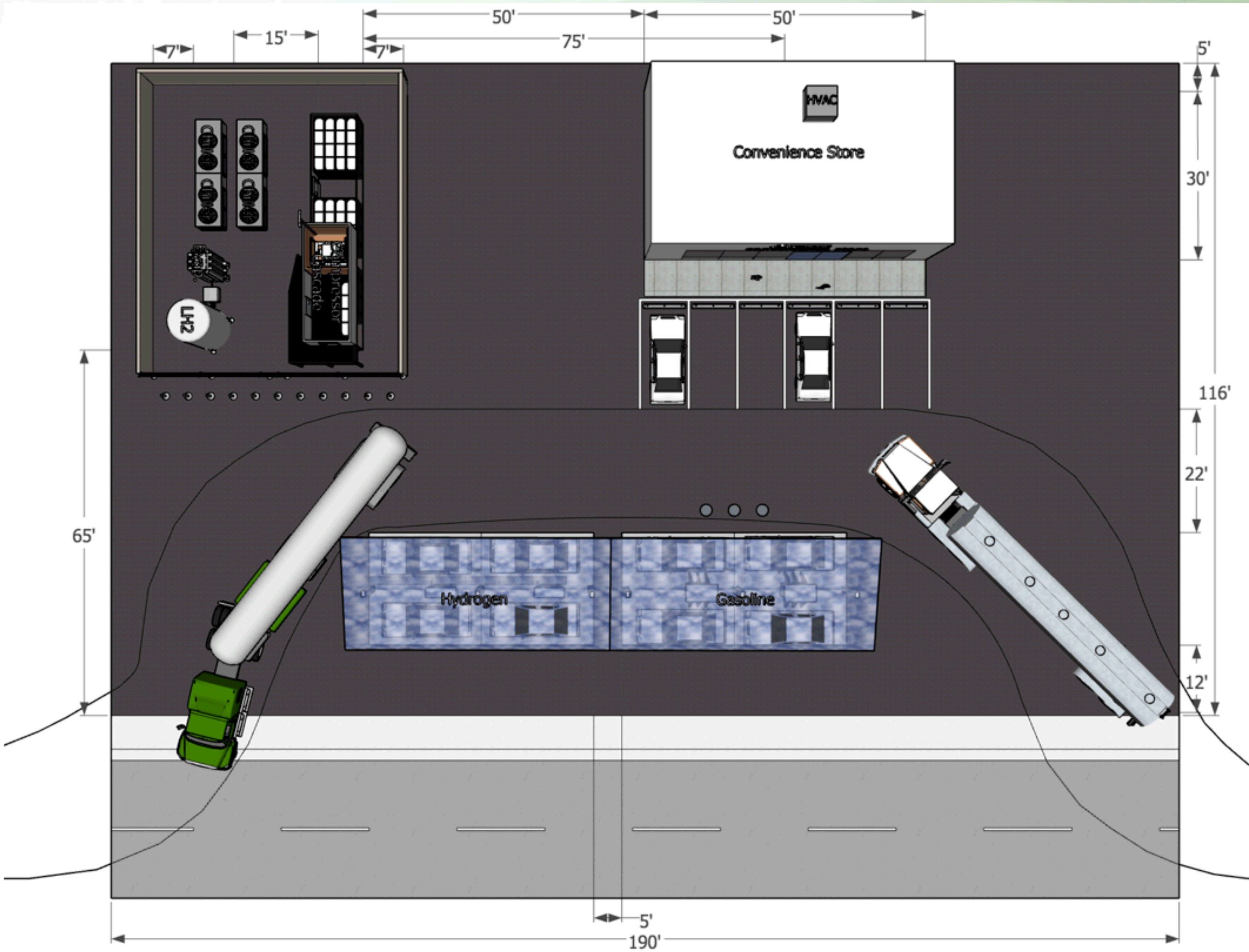


Full Layout for Co-location Liquid Hydrogen

- Full Layout
  - Convenience store
  - Parking
  - Traffic flow
  - Delivery
- Total Lot Area
  - 22,040 ft^2



Co-Location Stations Summary

- The greatest increase in total lot area is for the co-location electrolyzer station
  - Addition of gasoline delivery truck path
- The co-location liquid station is only increased by 3%
  - Liquid hydrogen setback distances are already large

	Gas		Electrolyzer		Liquid	
Requirements	Base	Co-Location	Base	Co-Location	Base	Co-Location
Total Lot Area (ft^2)	18,480	25,740	12,051	21,145	21,250	22,040
% Increase from Base Case	0	**39.2%**	0	**75.5%**	0	**3.7%**

UNDERGROUND HYDROGEN STORAGE

Presented by Brian Ehrhart

Goals of Underground Storage

- Quantify examples of storing hydrogen storage underground
- Identify specific code requirements and potential issues
- Meets all setback distances, so hazard analysis not done

Underground Gas Design Choices

- Bulk storage gas assumptions same as base case gas:
  - Capacity of 800 kg/day of GH2
  - Operating pressures between 6.0 MPa (1,000 psi) and 50 MPa (7,250 psi)
  - Assumptions are the same, but design will be different
- Two ways for an underground system:
  - Direct burial
  - Vault
- Compressor, cascade & dispenser designs same as base case gas
- Convenience storage size, number of parking spaces and delivery truck size same for base case gas

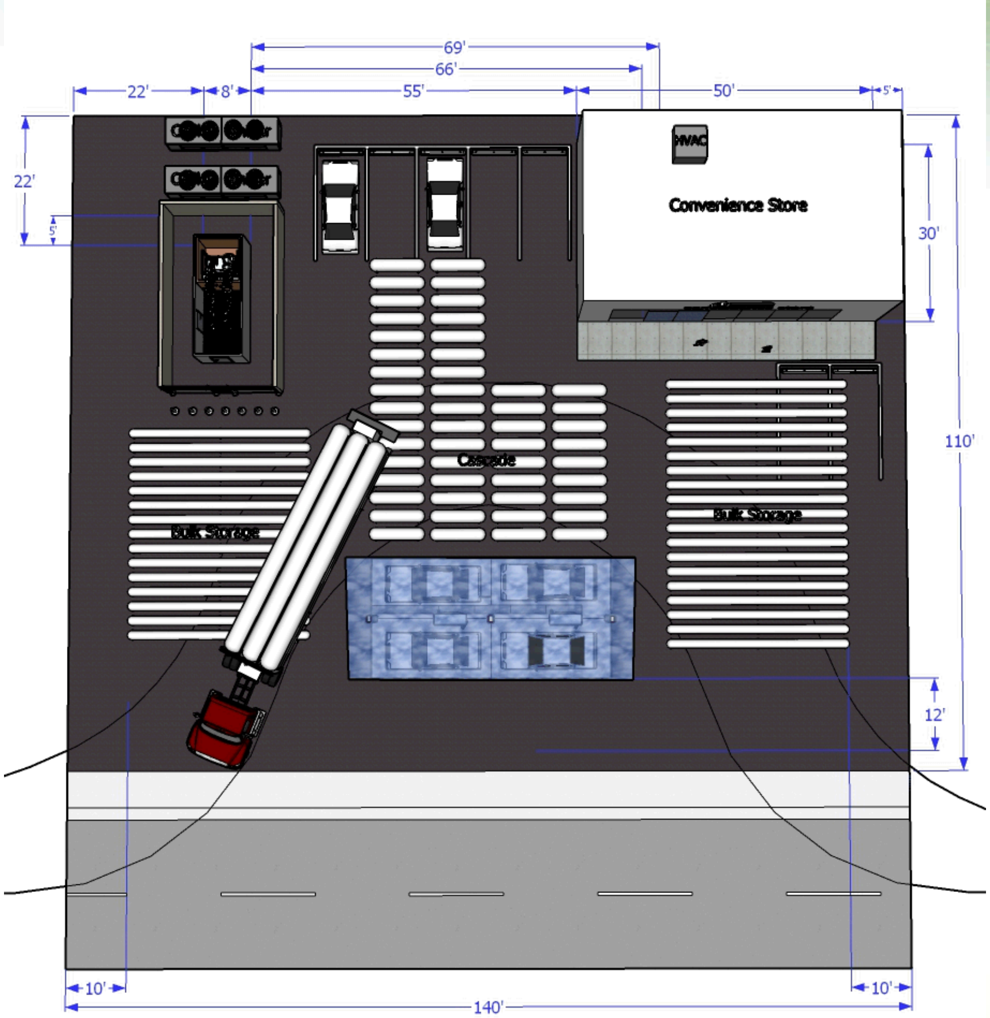
Underground Gas Direct Bury Requirements

- Direct burial system- direct contact with earth or fill for system piping and tanks
- Requirements found in NFPA 2 Section 7.3.2.4
  - Not located under buildings
  - Storage containers spaced 1 ft (0.3 m) from each other
  - Set on a foundation (no stacking of cylinders)
  - All valves, controls, safety devices and instrumentation above ground
  - 1 ft (0.3 m) of earth on top of container and 101 mm (4 in.) of concrete
- Cylinders selected: 100 MPa (14,504 psi) and a hydraulic volume of 756 L (0.756 m^3)
  - 34 cylinders needed for layout

Underground Direct Bury Gas – Full Layout

- Lot Size: 140 x 110 ft
- Total Area: 15,400 ft[2]

- 34 Bulk Storage Cylinders
- 50 Cascade Cylinders
- Valves, instrumentation, etc. located in ISO container



Note: Storage cylinders are located underground

Underground Gas Vault Requirements

- Vault system- keeps the earth/fill away from direct contact with the system behind walls
- Requirements found in NFPA 2 Section 7.3.2.1.3 and IFC 5303.16
  - Top of vault designed to relieve safely or contain explosion
  - Top of vault designed to withstand vehicular traffic
  - Internal clearance for maintenance of 30 in. and any point of vault < 20 ft from access way
  - Ventilation of 1 cfm of flow area with minimum flow rate of 150 cfm
  - Relief vents terminate at least 12 ft above ground
  - Requirement that valves, controls, safety devices and instrumentation above ground **only for direct bury**

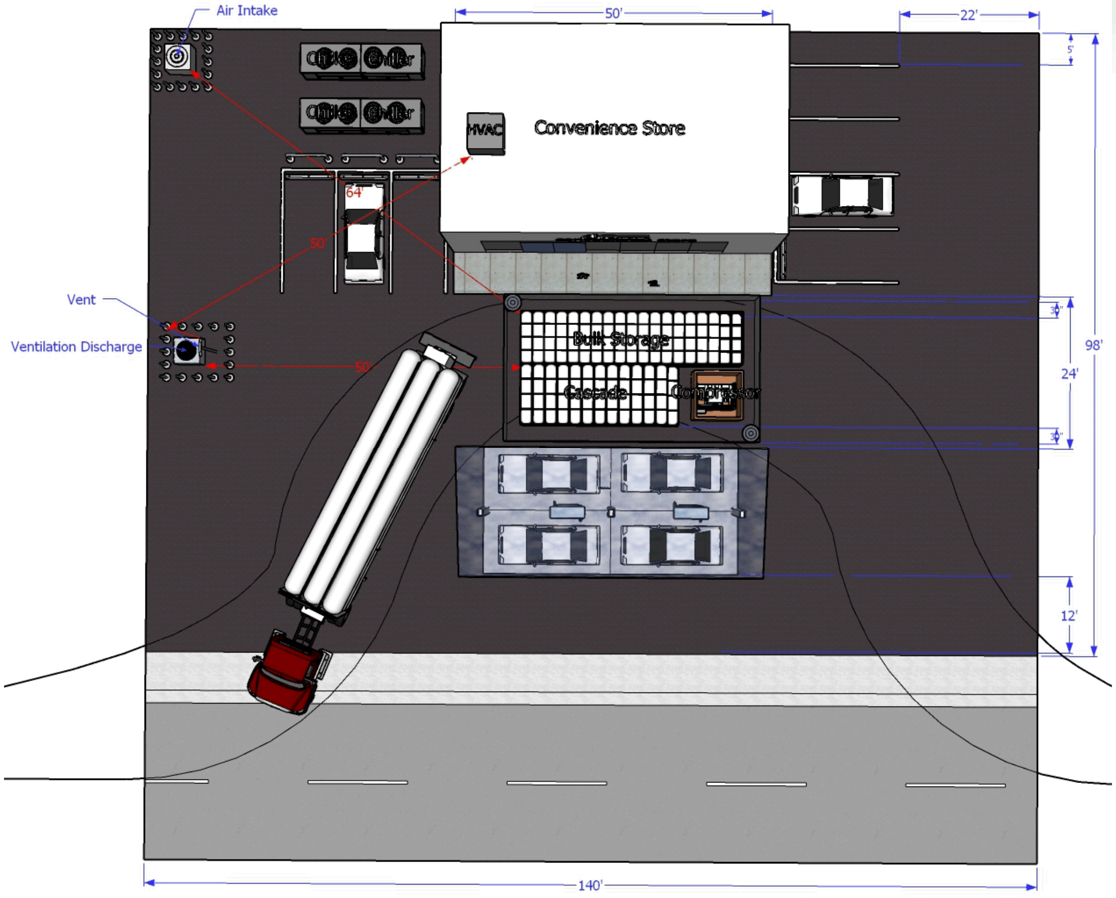
Underground Gas Vault Design

- Underground vault designed to contain bulk storage, cascade cylinders, the compressor and all associated valves, controls, safety devices and instrumentation
  - Equipment housed in a 16 x 40 ft space
  - 74 bulk storage cylinders, 50 cascade cylinders
  - Chillers located aboveground
- Setback distances not applied since everything but vent stack and dispenser
  - Vent stack does not have a separation distance requirement
  - Dispensing equipment 3.0 m from property line
- Ventilation discharge 50 ft away from air-handling systems, air-conditioning equipment, and air compressors

Underground Vault Gas – Full Layout

- Lot Size: 140 x 98 ft
- Total Area: 13,720 ft^2

- 34 Bulk Storage Cylinders
- 50 Cascade Cylinders
- Vault size: 22 ft 4 inches x 39 ft



Note: Vault system is located underground

Underground Liquid Design Choices

- Base case liquid assumptions:
  - Capacity of 800 kg of LH2
  - Volume is 11,299 L (2,985 gal)
  - Tank has a net capacity of 11,470L (3,030 gal), diameter of 7.2 ft (2.18 m) and a length of 19 ft (5.8 m)
- Compressor, cascade & dispenser designs same as base case gas
- Convenience storage size, number of parking spaces and delivery truck size same for base case gas
- **Only analyzed direct bury for LH2**

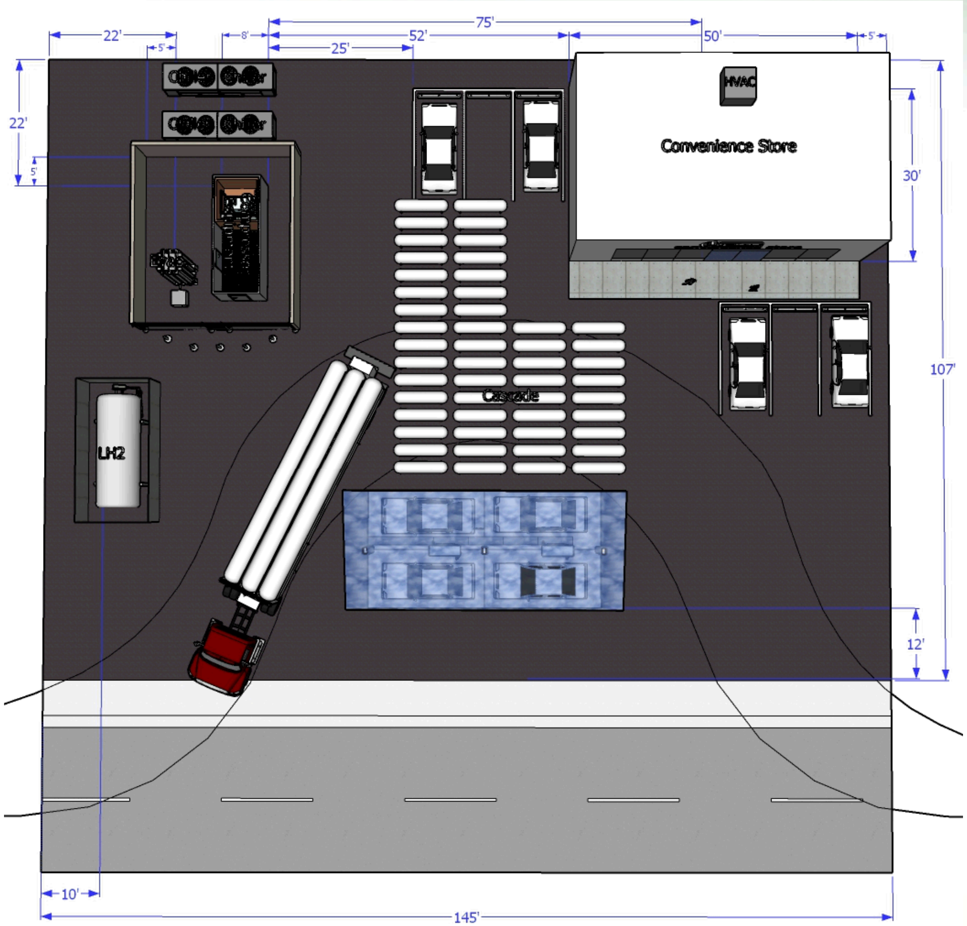
Underground Direct Bury Liquid Requirements

- Requirements found in NFPA 2 Section 8.3.2.3.1.7
  - Not located under buildings
  - Spaced 10 ft (3.1 m) away from basement, pit, cellar or lot line
  - Storage containers spaced 1 ft (0.3 m) from each other
  - Set on a foundation (no stacking of cylinders)
  - 1 ft (0.3 m) of earth on top of container and 101 mm (4 in.) of concrete
  - All piping vacuum jacketed
- NFPA 2 Section 7.3.2.4.4.2 requires that valves, controls, safety devices, and instrumentation located aboveground
  - Will apply to cascade system
  - Not a similar requirement for LH2

Underground Direct Bury Liquid – Full Layout

- Lot Size: 145 x 107 ft
- Total Area: 15,515 ft^2

- 1 Bulk Storage Tank
- 50 Cascade Cylinders
- Valves, instrumentation, etc. located in ISO container



Note: Storage cylinders are located underground

Underground Summary

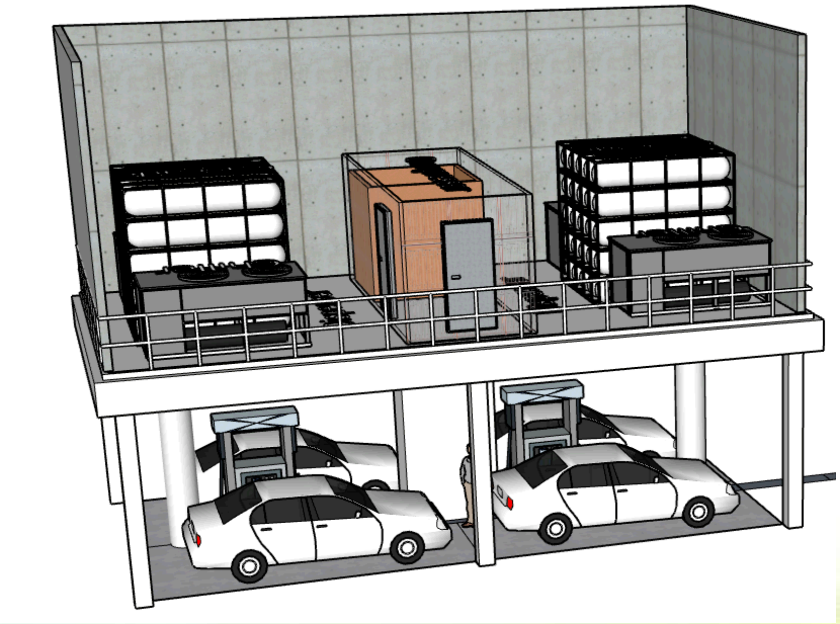
	Base Case Gas	Direct Bury Gas	Vault Gas	Base Case Liquid	Direct Bury Liquid
Total Lot Area	18,480 ft^2	15,400 ft^2	13,720 ft^2	21,250 ft^2	15,515 ft^2
% Reduction from Base Case	0	16.7%	25.8%	0	27.0%

UNDERGROUND STORAGE

Presented by Gaby Bran-Anleu

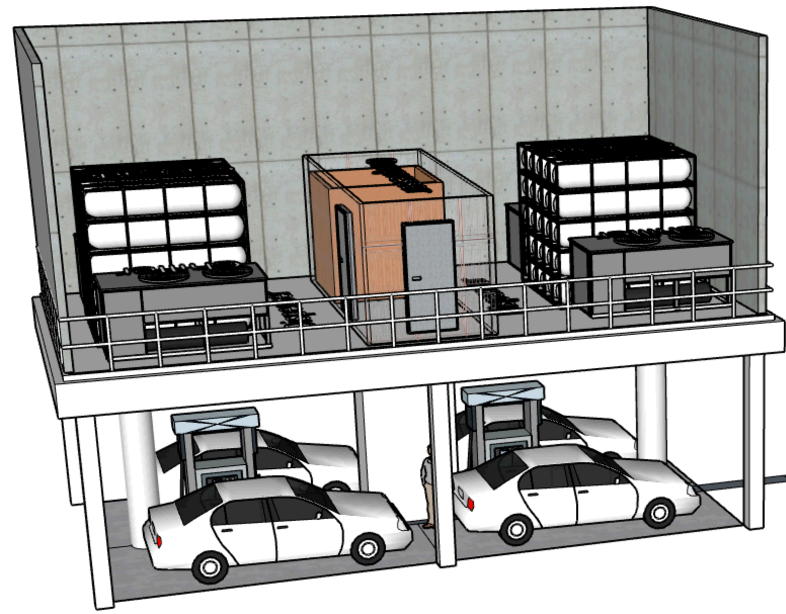
Fueling Station with Hydrogen Systems Installed on Rooftop

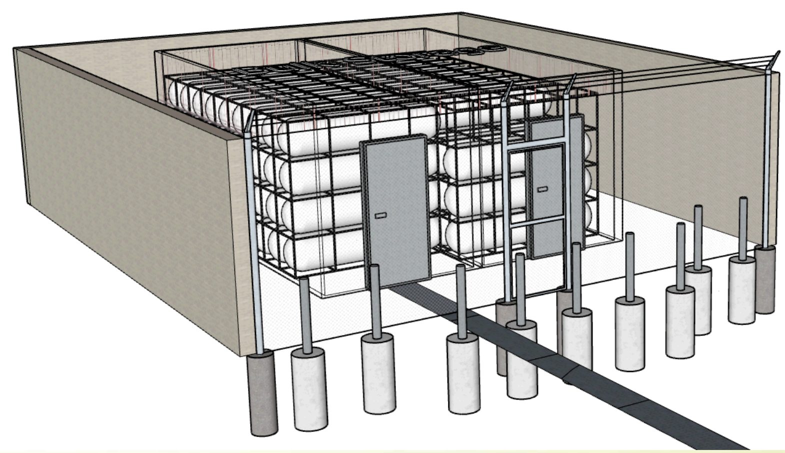
- A canopy was used to shelter dispensing operations
  - Hydrogen systems is located on the roof of the canopy
- Canopies shall be in accordance with the following:
  - The canopy shall meet or exceed Type I construction requirements of the adopted building code
  - Operations located under canopies shall be limited to refueling only
  - The canopy shall be constructed in a manner that prevents the accumulation of hydrogen gas



Delivered Gas Hydrogen Systems Installed on Canopy

- Components located on the canopy
  - Compressor
  - Cascade system
  - Chillers
- The bulk storage system was not located on the canopy
  - Delivery truck access
- Fire rated wall surrounds both the low pressure bulk storage, and the rest of the system located on the canopy

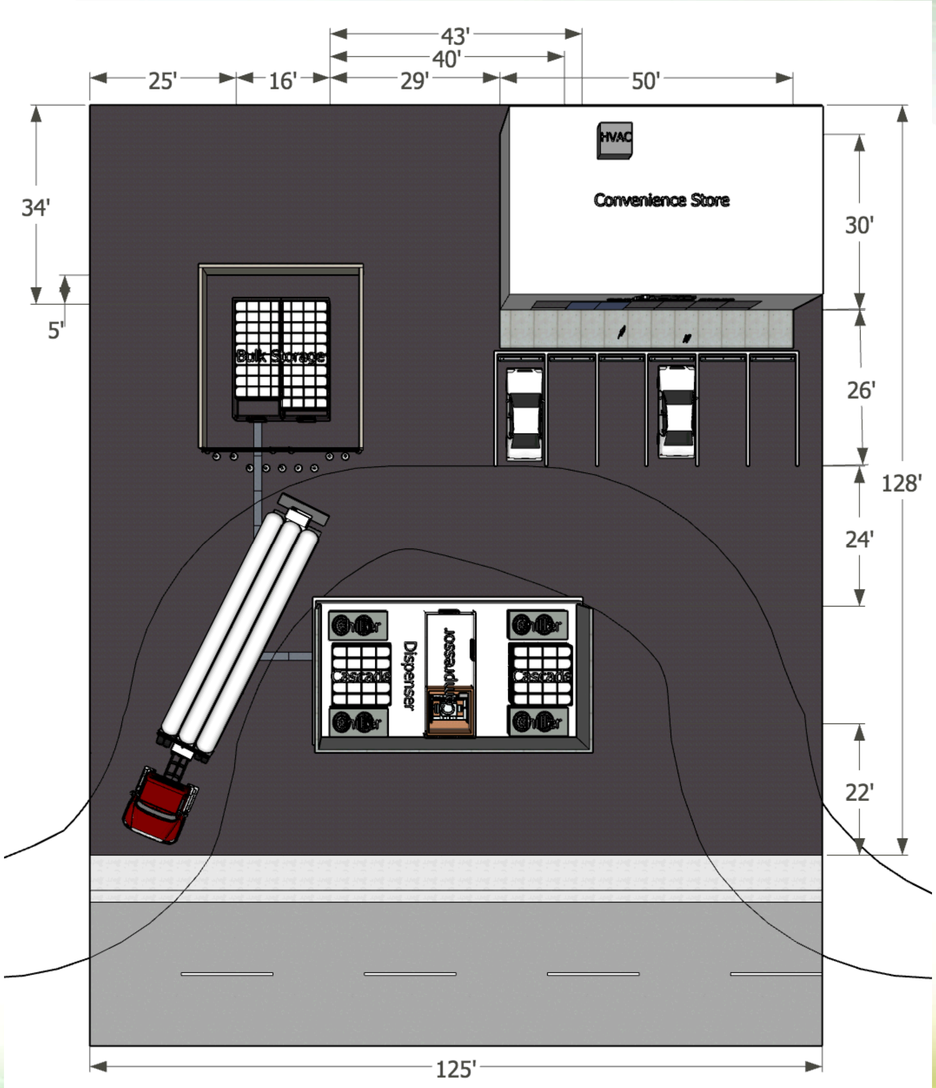




Delivered Gas Hydrogen Systems Installed on Canopy

H2FIRST

- Lot Size: 128 x 125 ft
- Total Area: 16,000 ft^2



Gas Hydrogen System Weight on Canopy

- Compressor
  - Weight 17.5 ton (35,000 lbs)
- Cascade
  - 10 cascade units, each containing 5 (1:1:3) pressure vessels
  - ~ weight of each tank is 400 kg (881.849 lbs)
    - Total weight 20,000 kg (44,092 lbs = 22 tons)
- Chillers
  - 7.2 tons of refrigeration needed for each chiller
  - Aluminum cooling block of 1,330 kg needed for each
- Bulk Storage
  - ~ weight of each tank is 250 kg (551 lbs)
    - Total weight 1,250 kg (2,755 lbs)

Drawbacks for Rooftop Hydrogen Systems Installation

- Weight and loading of hydrogen storage on commercial buildings and canopies
- Seismic loading
  - Issues with a large mass at the top of a structure in an earthquake.
- Engulfing fire of the hydrogen storage if the building were set ablaze
  - Depends on the type of hydrogen storage
- Aesthetics
  - Generally the cities do not want to see storage, even if it's on the roof
- Maintenance Access

ALTERNATE MEANS – DELIVERED GASEOUS HYDROGEN

Presented by Brian Ehrhart

Goals of Alternate Means Gas Design

- Explore alternate method of system design
- Explore NFPA 2 requirements as written, identify potential issues
- Compare hazard analysis to base case

Alternate Means Gas Design Choices

- The fueling station design consists of the following major components:
  - 800 kg gaseous hydrogen (GH2) storage at 50 MPa and ambient temperature
  - One compressor with a flowrate of 25 kg/hr
  - A bank of high pressure gaseous hydrogen storage cylinders for cascade filling of vehicles
  - Underground, joint-less stainless-steel piping from storage bank to dispenser island
  - 2 dispensers, each with 2 hoses: 4 dispenser hoses in total
  - Station rated at a 600 kg/day capacity
- Compressor, cascade and dispenser design same as the base case gas

Alternate Means Requirements

- Indoor storage of bulk H2 requirements found in NFPA 2 Section 7.3.2.2
  - >425 Nm3 (15,000 scf) of H2, detached building required
- Detached buildings requirements found in NFPA 2 Section 7.3.2.2.2
  - Building made of non- or limited-combustible materials
  - Ventilation requirements
  - Explosion control
  - Class I, Div 2
  - Heating must be indirect or meet additional requirements
- Assumption is that detached building meets all prescriptive requirements

NFPA 2 2016 Bulk Gaseous Indoor Setback Distances

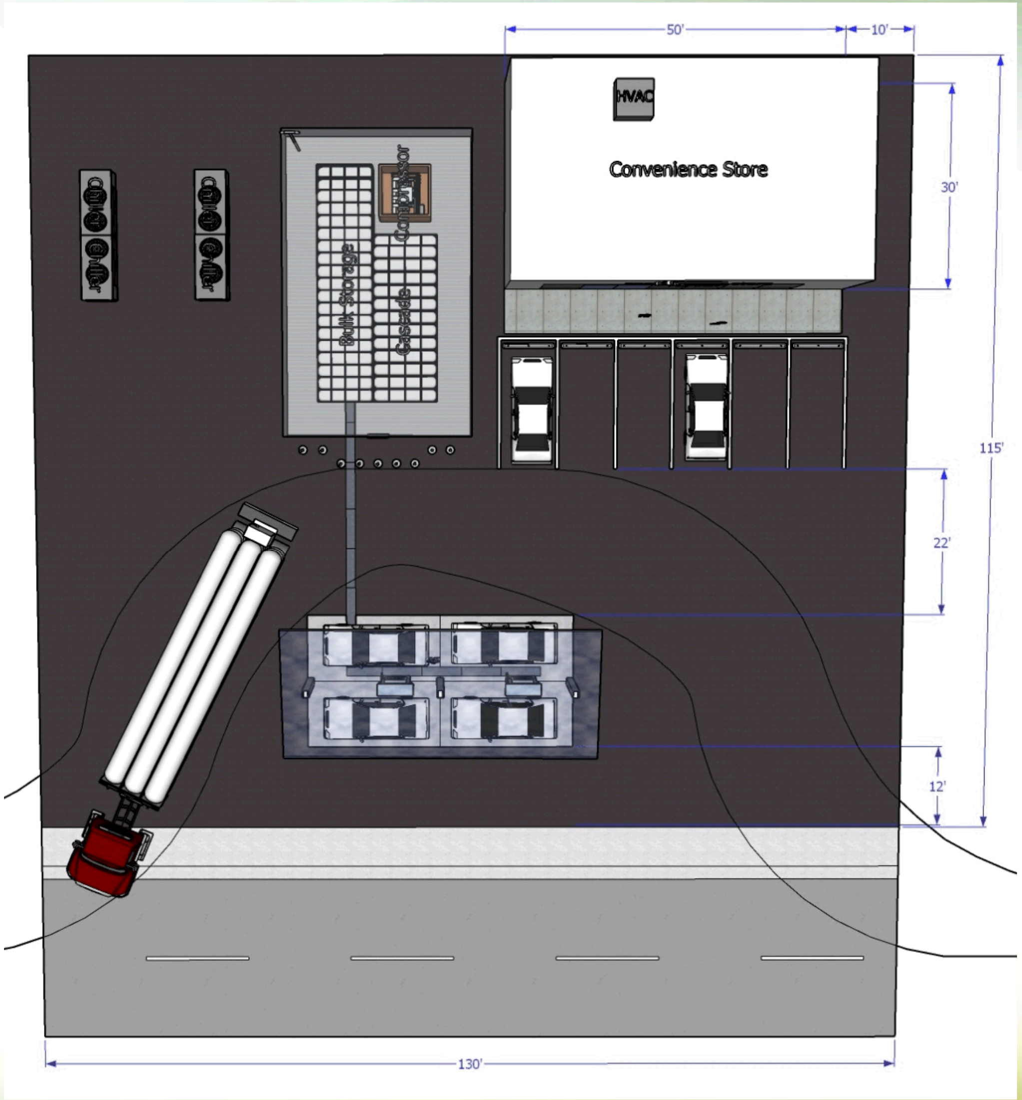
- NFPA 2 Section 7.3.2.3.1.3(A) requires that delivery equipment connections subject to same as bulk; however 7.3.2.3 applies only to outdoor locations
- Since H2 system is indoors, it is subject to 7.3.2.2 where there are no separation distance requirements listed for indoor storage

Alternate Means Gas Minimum Footprint

- Equipment layout is identical to the base case gas: 16 ft x 40 ft
- Assumed that there is 5 ft between the system and the walls of the building
- Building size is 27 ft x 51 ft

Alternate Means Gas Full Layout

- Lot Size: 115 ft x 130 ft
- Total Area: 14,950 ft^2
- Comparison to Base Case:
  - 132 ft x 140 ft
  - 18,480 ft2
  - 19.1% Reduction
- Additional reduction possible with smaller delivery truck



Alternate Means Gas Chapter 5 Hazard Scenarios

H2FIRST

Required Scenario
Fire
Explosion Scenario 1: Pressure Vessel Burst
Explosion Scenario 2: Deflagration
Explosion Scenario 3: Detonation
Hazardous Material Scenario 1: Unauthorized Release
Hazardous Material Scenario 2: Exposure Fire
Hazardous Material Scenario 3: External Event
Hazardous Material Scenario 4: Protection System Out of Service
Building Use Scenario 1: Emergency Exit Blocked
Building Use Scenario 2: Fire Suppression Out of Service

Alternate Means Gas Fire Scenario

- Fire Scenarios Analyzed
  - Fire from a H2 system
    - Fire in modular skids not as much risk to the public
  - Fire from a large transport pipe
    - Considered in separate hazard scenario
  - Fire caused by an external source
    - Scenario looked at jet fire from dispenser
- Jet Fire from Dispenser
  - Distance from the assumed leak point is the same for the two occupants near the dispensers
  - Design same as alternate means for different pipe sizes which was found to be of equivalent risk

Alternate Means Gas Explosion 1 – Pressure Vessel Burst

- Pressure vessel burst inside the building will impact the walls and ceiling before it impacts the public
- Assumed to be of lesser risk than the base case gas due to the indoor location of the pressure vessels

Alternate Means Gas Explosion 2 – Deflagration

- Source is a constant leak from the compressor outlet (highest pressure in the system)
  - Having the leak go into a larger volume would lead to less hazard (longer accumulation)
  - However, flammable mass for same concentration will be larger

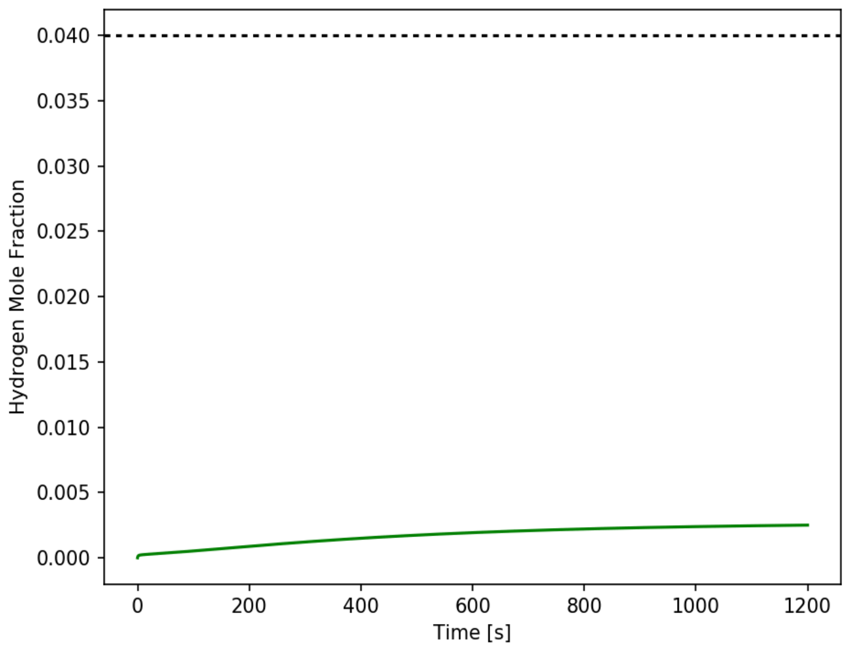
Alternate Means Gas Explosion 2 – Deflagration

- Analyzed a compressor leak in the modular equipment enclosure
  - Enclosure size: 7.92 m long by 15.24 m wide by 3.6 m tall
  - Houses electrical equipment and compressor, estimated 25% of volume
- Compressor leak at pressure of 94.4 MPa (13,688 psi) and ID 6.35 mm (0.25")
  - Most likely leak size is 0.01% of pipe area, more conservative is 1% of pipe area
- Ventilation system has flow rate of 36.8 m^3/min (1,299.2 scf/min)
  - Exhaust vent size 1.42 m^2 (15.28 ft^2)

Alternate Means Gas Explosion 2 – Deflagration

- Lowesmith model used to determine the steady state H2 concentration
- For leak size of 0.01% pipe area, results showed that steady-state H2 concentration is 0.25% H2
  - Less than 4% lower flammability limit for H2

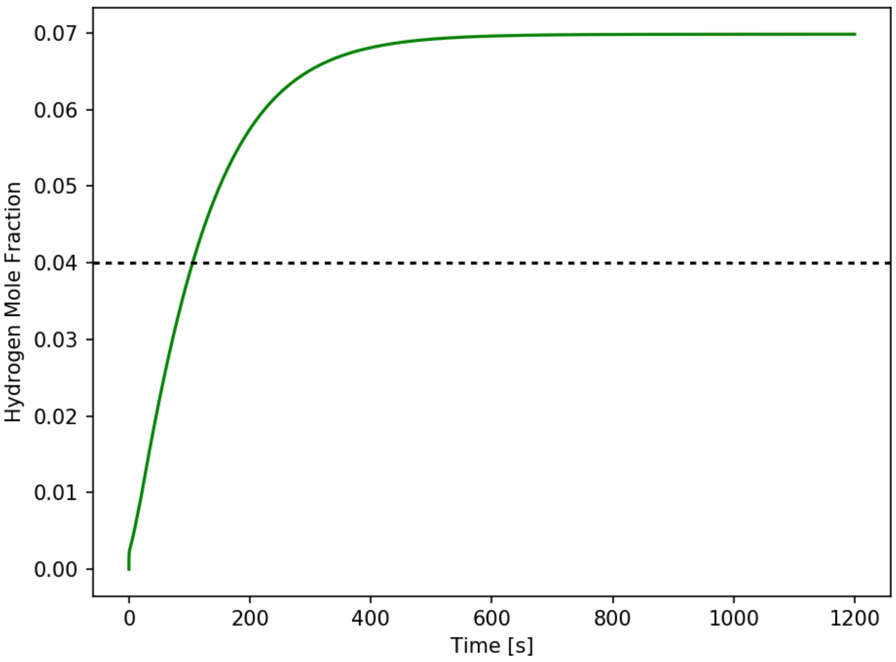
H2 Concentration from 0.01% of Pipe Size Leak



Alternate Means Gas Explosion 2 – Deflagration

- For leak size of 1.0% pipe area, results showed that steady-state H2 concentration is 6.9% H2
  - Higher than 4% lower flammability limit for H2

H2 Concentration from 1.0% of Pipe Size Leak



Final Steady-State Overpressure

Leak Rate	Overpressure
0.01% of Pipe Size	0 Pa
1% of Pipe Size	2.5×10^5 Pa (36.9 psi)

Base case gas overpressure 3.89×10^5 Pa

Scenario deemed to have lesser risk than the base case

Alternate Means Gas Explosion 3 – Detonation

- Base case gas considered a vent stack issue
- Assumed that other detonation hazards could not exist given the outdoor station
- Explosion Scenario 2- Deflagration addressed the case of H2 accumulation in the indoor location
- No additional hazard assumed to exist

Alternate Means Gas Hazardous Material 1 – Unauthorized Release

- Base case gas design analyzed a full-scale leak from the cascade system
  - Leak would be indoors and wouldn't affect the public directly
  - This case examined in Explosion Scenario 2- Deflagration
- Dispenser release
  - This case examined in Fire Scenario
- No other release scenario seems to present a hazard to public safety
  - Scenario is assumed to be of lesser risk than the base case

Alternate Means Gas Hazardous Material 2 – Exposure Fire

- Base case gas design analyzed a vehicle fire in the street, most likely exposure fire
  - Analysis is the same for alternate means
- In alternate means the H2 system is indoors
  - But base case gas is also behind fire-rated walls
- Hazard scenario is equivalent hazard to base case

Alternate Means Gas Hazardous Material 3 – External Event

- Base case gas design analyzed a shearing of the largest pipe in the H2 system- 100% leak resulting in a jet fire
- Seismic event would likely damage building
- Hazard scenario is equivalent hazard to base case

Alternate Means Gas Hazardous Material 4 – Discharge with Protection System Out of Service

- Base case gas design analyzed low probability of digital logic controllers failing
  - Analysis concluded that H2 most likely to dissipate since system is outdoors
- Current design more reliant on digital controllers for detection and shutoff
- Previous hazard scenario quantified the hazard consequence of accumulation of H2 in the indoor space without protection systems
- Hazard scenario is equivalent hazard to base case

Alternate Means Gas – Non-Applicable Scenarios

- Two building use scenarios not applicable since building is not open to the public

Non-Applicable Scenarios
Building Use Design Scenario 1 involves an event in which the maximum occupant load is in the assembly building and an emergency event occurs blocking the principal exit/entrance to the building. [NFPA 2:5.4.5.1]
Building Use Design Scenario 2 involves a fire in an area of a building undergoing construction or demolition while the remainder of the building is occupied. The normal fire suppression system in the area undergoing construction or demolition has been taken out of service. [NFPA 2: 5.4.5.2]

Alternate Means Gas Hazard Scenario Summary

Indoor Gas Scenario	Indoor Gas Result
Fire: Hydrogen fire resulting from a leak at the hydrogen dispenser	Equivalent to Base Case Gas/PBD-PipeSize
Explosion Scenario 1: Gaseous H_2 pressure vessel rupture	Lesser risk than Base Case Gas
Explosion Scenario 2: H_2 deflagration within the enclosure housing the compressor	2.5×10^5 Pa overpressure for 1% of pipe size leak, lesser risk than Base Case Gas
Explosion Scenario 3: Venting of hydrogen forms localized H_2/air mixture in the vent pipe that detonates	Equivalent risk to Base Case Gas
Hazardous Material Scenario 1: Release of hydrogen from storage tank	Lesser risk than Base Case Gas
Hazardous Material Scenario 2: An unrelated vehicle fire at the lot edge	Equivalent risk to Base Case Gas
Hazardous Material Scenario 3: Seismic event where a pipe bursts (100% leak size on largest pipe)	Equivalent risk to Base Case Gas
Hazardous Material Scenario 4: A hydrogen discharge where the interlock fails	Equivalent risk to Base Case Gas
Building Use Scenario 1: Maximum occupancy load present in building during fire with main entrance/exit blocked	Not applicable
Building Use Scenario 2: Fire during maintenance with fire suppression system out of service.	Not applicable

ALTERNATE MEANS – DELIVERED LIQUID HYDROGEN

Presented by Brian Ehrhart

Goals of Alternate Means Liquid Design

H2FIRST

- Explore alternate method of system design
- Explore NFPA 2 requirements as written, identify potential issues
- Compare hazard analysis to base case

Alternate Means Liquid Design Choices

- Design of hydrogen system is similar to Base Case Liquid
  - Bulk Storage - 800 kg LH2 pre-compressor
  - Compressor/Cascade for vaporized GH2
  - 4 dispenser hoses, 600 kg/day H2 dispensed
- Will consider setback distances based on upcoming NFPA 55/2 requirements
  - Gas and liquid setbacks are separate
- Will consider small LH2 delivery truck
  - Otherwise this change won't have much of an affect
- Will vary layout to affect footprint

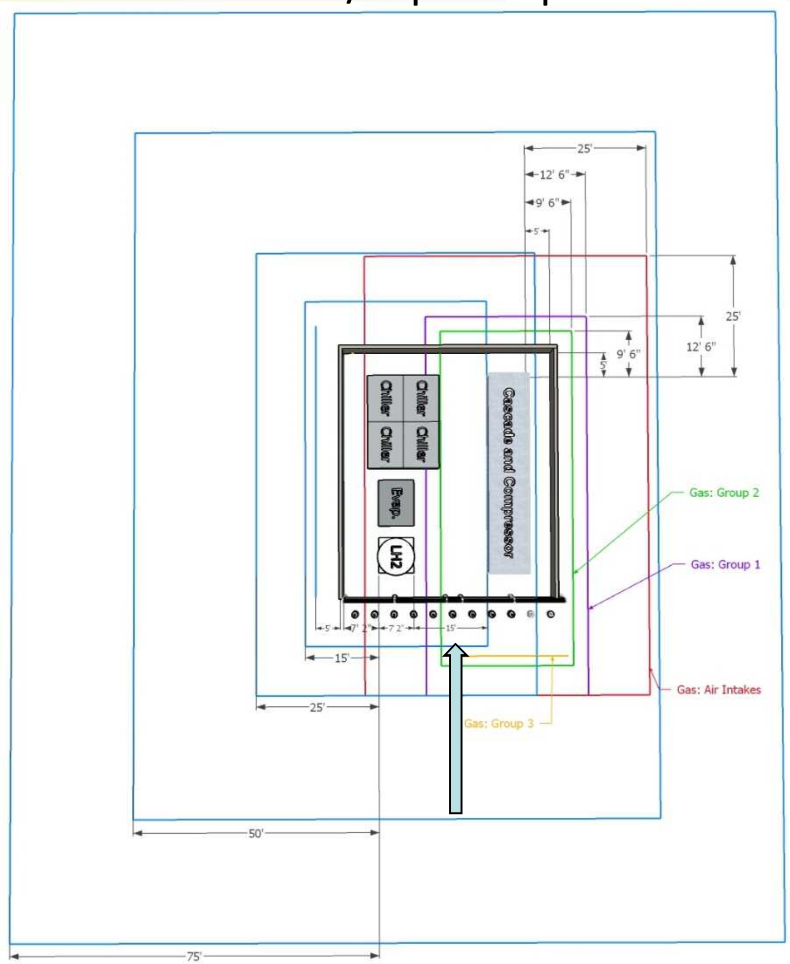
NFPA 2 2016 Bulk Liquid Setback Distances

- NFPA 2 7.3.2.3.1.3(B):
  - Liquid and gaseous portions of combined systems be separated by at least 4.6 m (15 ft)
- NFPA 2 8.3.2.3.1.6(A):

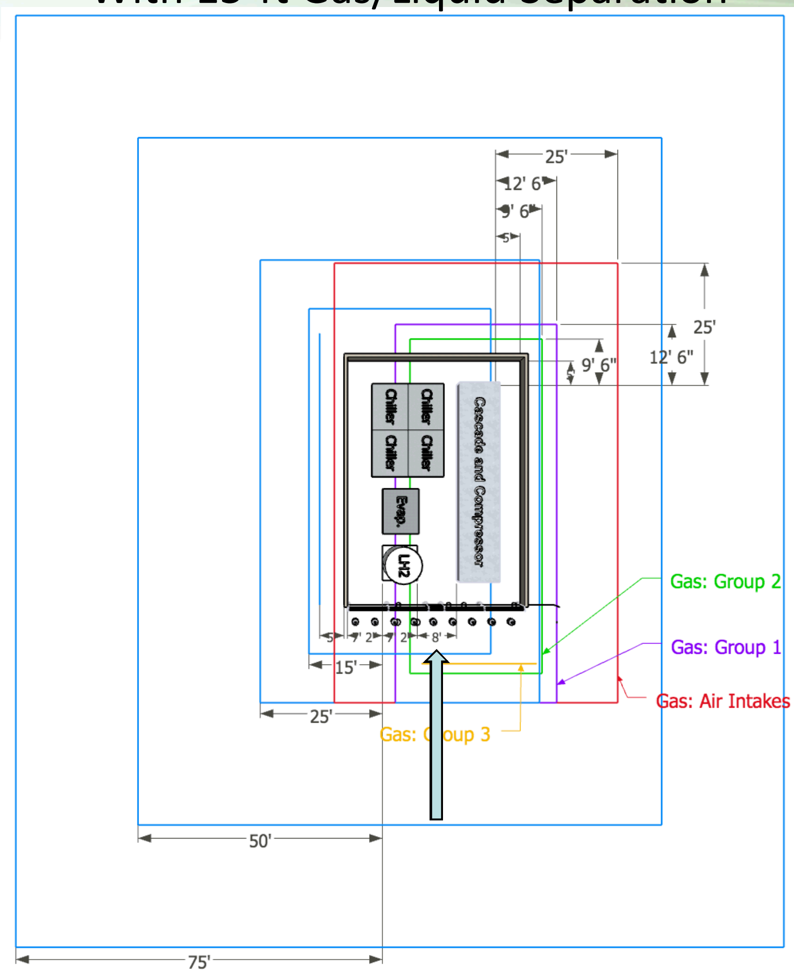
Group	Exposure	Reducible	Distance
1	1 Lot lines	*	15 m (50 ft)
1	2 Air intakes		23 m (75 ft)
1	3 Operable openings in buildings		23 m (75 ft)
1	4 Ignition sources		15 m (50 ft)
2	5 Places of public assembly		23 m (75 ft)
2	6 Parked cars		1.7 m (25 ft)
3	7(a)(1) Sprinklered non-combustible building	*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

Alternate Means Liquid Minimum Footprint

With 15-ft Gas/Liquid Separation



With 15-ft Gas/Liquid Separation



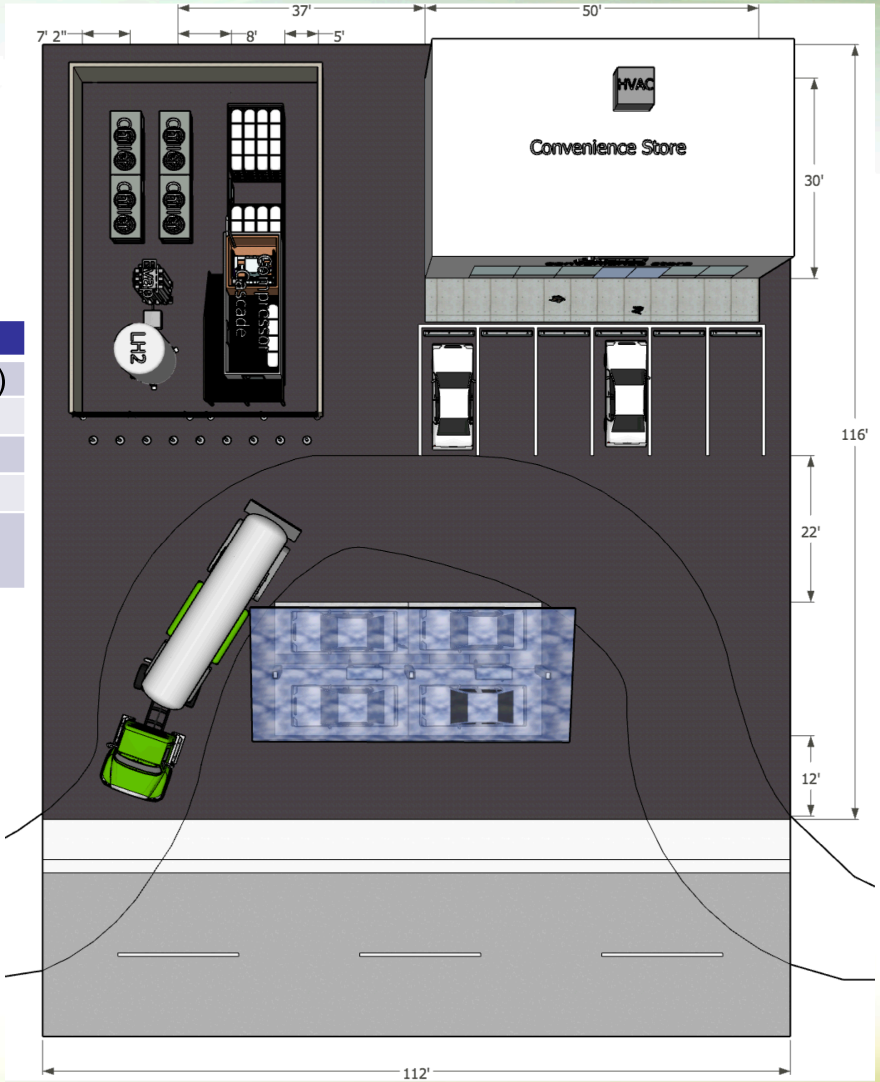
Why 8 feet?

Vertical cylindrical tank is 7.2 feet in diameter, walls are required to be this far away from it; 8.0 > 7.2 feet

Alternate Means Liquid Full Layout

- Footprint: 116 feet x 112 feet
  - Lot size: 12,992 ft^2
- Meets most setback distances, not others

Exposure	Required	Current
1 Lot lines	*15 m (50 ft)	*3.87 m (12.2 ft)
2 Air intakes	23 m (75 ft)	18.9 m (62 ft)
3 Operable openings in buildings	23 m (75 ft)	18.9 m (62 ft)
6 Parked cars	7.6 m (25 ft)	11.3 m (37 ft)
7(a)(2)(i) Unsprinklered, without fire-rated wall	*15 m (50 ft)	*11.3 m (37 ft)



* Reducible to 0 m (0 ft)

Alternate Means Liquid Chapter 5 Hazard Scenarios

Required Scenario	Outdoor Fueling Station Scenario	Performance Criteria Approach
Fire	Hydrogen fire resulting from a leak at the hydrogen dispenser	Jet fire risk calculation
Explosion Scenario 1: Pressure Vessel Burst	Compressed gas storage	List of mitigations for burst
Explosion Scenario 2: Deflagration	A hydrogen deflagration within the enclosure housing the compressor.	Potential for deflagration conditions and peak overpressure
Explosion Scenario 3: Detonation	Localized H2/air mixture in the vent pipe	Vent pipe design specifications
Hazardous Material Scenario 1: Unauthorized Release	Release of hydrogen from storage vessel	Jet/plume for localized hypoxia
Hazardous Material Scenario 2: Exposure Fire	Unrelated vehicle fire at the lot line	Flame radiation from vehicle fire
Hazardous Material Scenario 3: External Event	Seismic event where largest pipe bursts	Risk metric calculation
Hazardous Material Scenario 4: Protection System Out of Service	A hydrogen discharge where the interlock fails	Layered safety features present in the system
Building Use Scenario 1: Emergency Exit Blocked	Hydrogen system outdoors	Not applicable
Building Use Scenario 2: Fire Suppression Out of Service	Hydrogen system outdoors	Not applicable

Alternate Means Liquid Fire Scenario

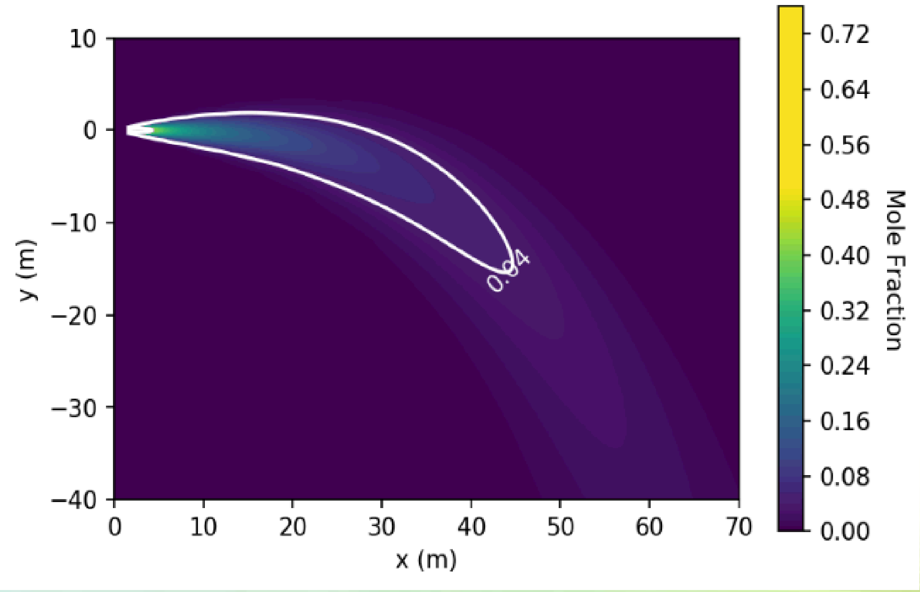
- One single fire source
  - Simultaneous events not considered
- Dispenser assumed to develop a leak, ignite immediately and result in a jet fire
  - Only effects of jet fire considered, explosive conditions explored in other scenarios
- HyRAM QRA tool used to analyze results of jet fire risk
- Average Individual Risk (AIR) for jet fire scenario is:

4.005×10^{-6} fatalities per year

- **Lesser risk than Base Case Liquid**

Alternate Means Liquid Hazardous Material 1 – Unauthorized Release

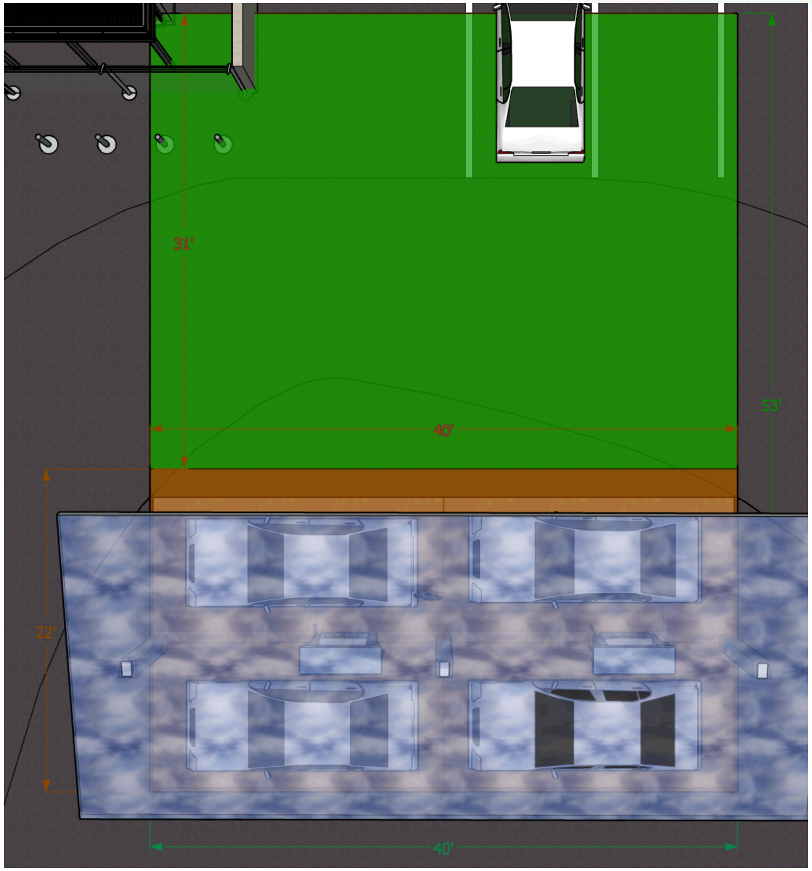
- Base Case Liquid design analyzed a full-scale leak from liquid hydrogen storage tank
  - Analysis is the same for alternate means
- The flammable mass extended 45 meters from the point of release
- The hydrogen concentration value for hypoxia was calculated as 42.3% H2, and it extends 5 meters of the release point
- Hazard scenario is equivalent hazard to base case



Alternate Means Liquid Hazardous Material 3 – External Event

- A 100% leak on the largest pipe from the cascade storage system
  - Inner diameter of 5.78 mm (0.23 in.)
  - Outer diameter of 14.3 mm (0.5625 in.)
  - Max operating pressure of 103.4 MPa (15,000 psi)
- HyRAM QRA tool used to analyze results of jet fire risk
- Average Individual Risk (AIR) for jet fire scenario is:

2.178 × 10^{-2} fatalities per year*



*conditional based on the occurrence of an earthquake

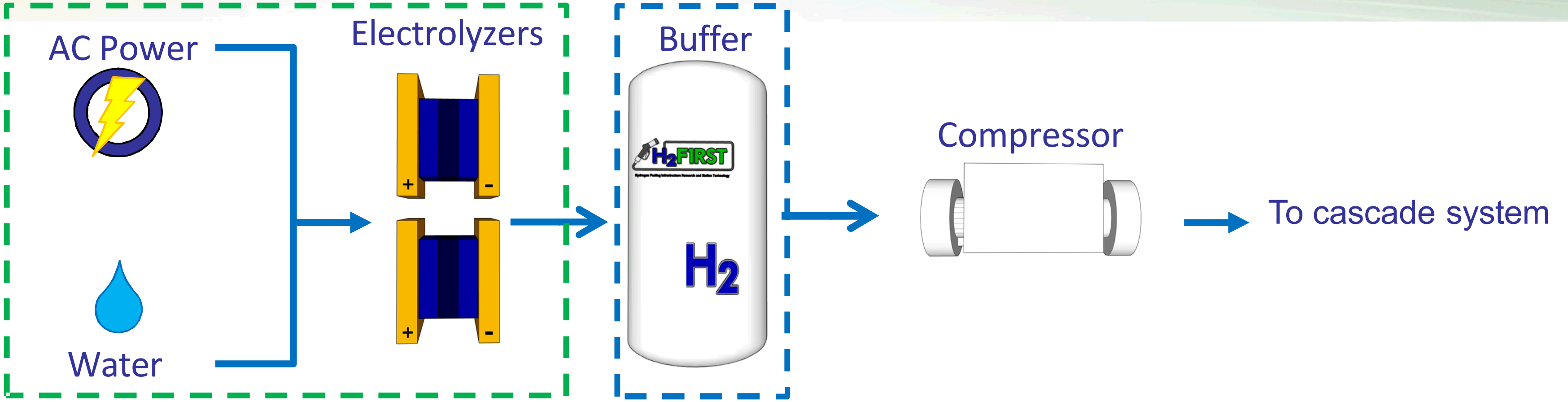
Alternate Means Liquid Hazard Scenario Summary

Outdoor Fueling Station Scenario	Baseline Result	Alternate Means
Fire - Hydrogen fire resulting from a leak at the hydrogen dispenser.	AIR = 4.118×10^{-6} fatalities/year	AIR = 4.005×10^{-6} fatalities/year
Explosion Scenario 1 - Gaseous H_2 pressure vessel rupture	Mitigations listed for stationary pressure vessels (same as Base Case Gas)	Mitigations listed for stationary pressure vessels (same as Base Case Gas)
Explosion Scenario 2 - H_2 deflagration within the enclosure housing the compressor	3.89×10^5 Pa overpressure for 1% of pipe size leak (same as Base Case Gas)	3.89×10^5 Pa overpressure for 1% of pipe size leak (same as Base Case Liquid)
Explosion Scenario 3 - Venting of hydrogen forms localized H_2/air mixture in the vent pipe that detonates.	Vent pipe length to diameter ratio to prevent detonation is present (same as Base Case Gas)	Vent pipe length to diameter ratio to prevent detonation is present (same as Base Case Liquid)
Hazardous Material Scenario 1 - Release of hydrogen from storage tank	The hypoxia and temperature criteria are met within 5 m and 10 m of the release point, respectively.	The hypoxia and temperature criteria are met within 5 m and 10 m of the release point, respectively (same as Base Case Liquid)
Hazardous Material Scenario 2 - An unrelated vehicle fire at the lot edge.	Heat flux on dispenser: 4.4 kW/m^2 for single passenger vehicle (same as Base Case Gas)	Heat flux on dispenser: 4.4 kW/m^2 for single passenger vehicle (same as Base Case Liquid)
Hazardous Material Scenario 3 - Seismic event where a pipe bursts (100% leak size on largest pipe).	AIR Fire = 1.559×10^{-2} fatalities/year, conditional upon the occurrence of an earthquake	AIR Fire = 2.178×10^{-2} fatalities/year, conditional upon the occurrence of an earthquake (Comparable to setback distance for only the hydrogen system)
Hazardous Material Scenario 4 - A hydrogen discharge where the interlock fails.	No additional risk scenarios (same as Base Case Gas)	No additional risk scenarios (same as Base Case Gas)
Building Use Scenario 1 - Maximum occupancy load present in building during fire with main entrance/exit blocked	Not applicable (same as Base Case Gas)	Not applicable (same as Base Case Gas)
Building Use Scenario 2 - Fire during maintenance with fire suppression system out of service.	Not applicable (same as Base Case Gas)	Not applicable (same as Base Case Gas)

NON-PRESCRIPTIVE ELECTROLYSIS

Presented by Gaby Bran-Anleu

Alternate Means Electrolyzer Design



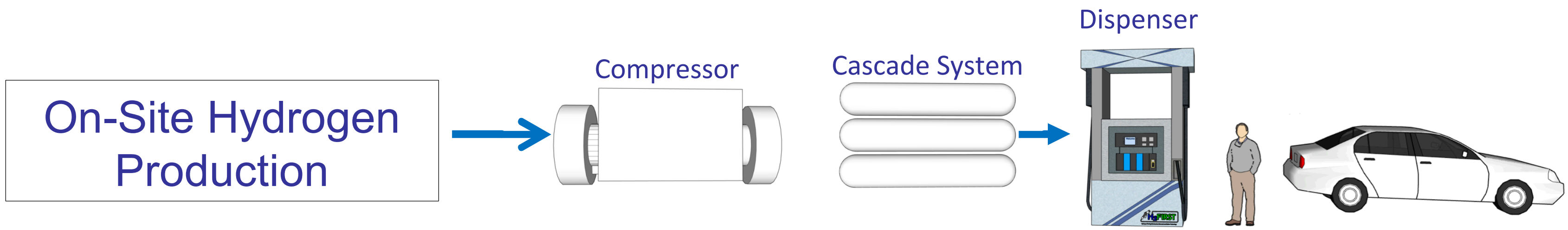
- On-site production of hydrogen is the only H_2 source on the station
  - No delivery truck necessary

- PEM electrolyzers to supply the total station capacity of 600 kg/day
  - H_2 production up to 36 kg/hr
  - Nominal input power ~2MW
  - Tap water consumption <16 liters/kg-H^2
  - Approximate footprint 40 ft + 20ft container

- GH_2 low pressure storage (buffer)
  - Total capacity of 25 kg at 50 bar
  - The tank is replenished by the electrolyzer

Alternate Means Electrolyzer Design

- This station considers a 600 kg/day dispensed H2 with 4 dispenser hoses
- Components are similar to the Base Case Gas



- Design calculations use HRSAM [1]
  - Compressor
    - 25 kg/hr flow rate (constant 600 kg/day)
    - Outlet pressure of 94.4 MPa (13,688 psi)
    - Power of 92 kW (as compared to 60 kW for the Base Case Gas)
  - Chillers
    - 25.2 kW (7.2 tons) of refrigeration needed for each chiller
  - Dispensing
    - 4 fueling positions, 70 MPa, -40 °C
  - Cascade
    - 10 cascade units, each containing 5 (1:1:3) pressure vessels
    - Outlet flow rate 60 kg/hr to each dispenser

[1] https://hdsam.es.anl.gov/index.php?content=hrsam

Differences Between Alternate Means Electrolyzer Design and Base Case Electrolyzer

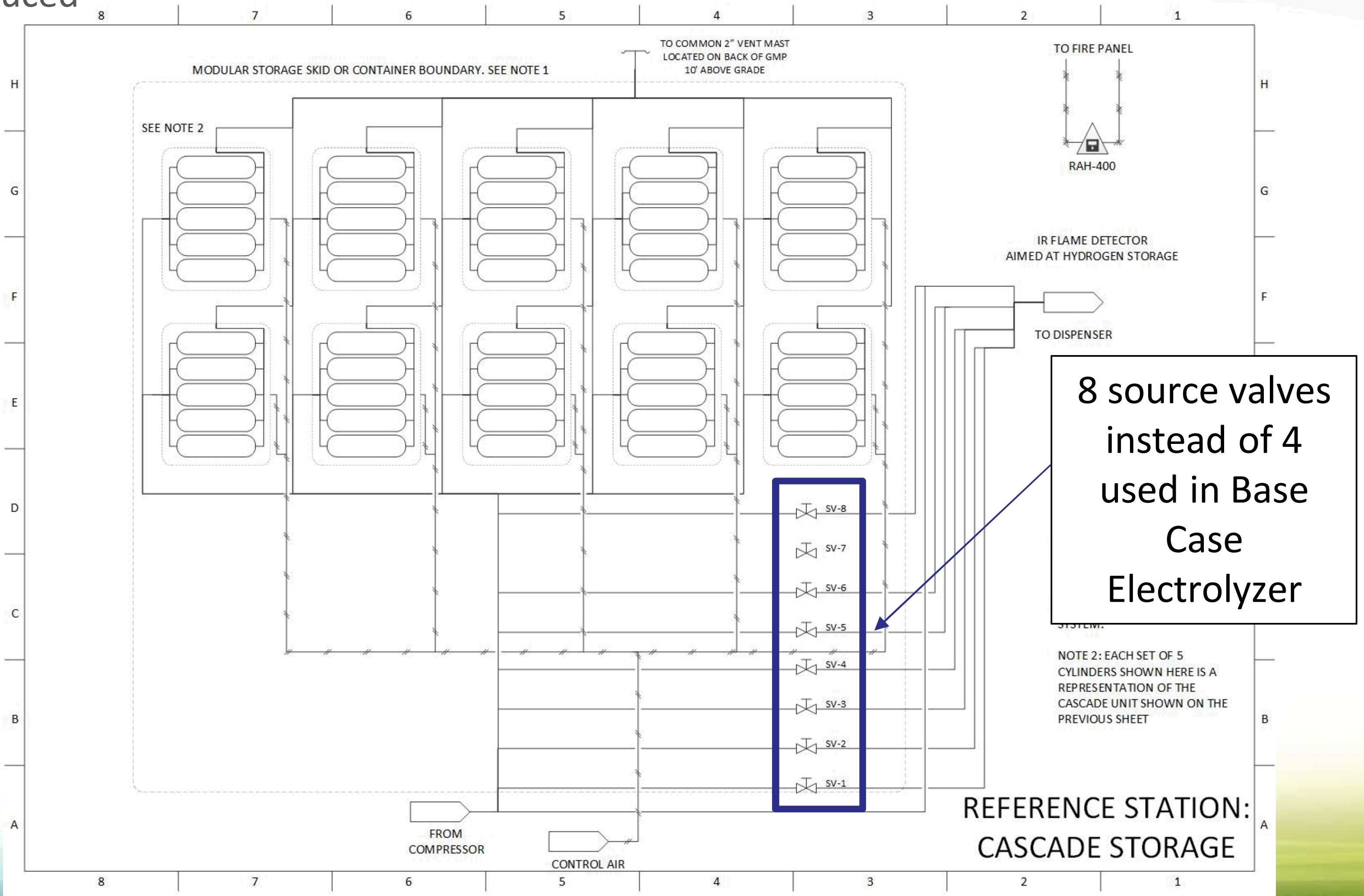
- A smaller pipe size was used between cascade system and source valve
  - By reducing the pipe size before the source valves, the setback distances are also reduced

	Alternate Means	Base Case
P_{max}	94.4 MPa (13,688 psi)	94.4 MPa (13,688 psi)
P_{min}	33.0 MPa (4,791 psi)	33.0 MPa (4,791 psi)
Mass Flow Rate	30 kg/hr (277 Nm3/hr)	60 kg/hr. (667 Nm^3/hr)
Pipe ID	5.15 mm (0.203 in)	7.92 mm (0.312 in)
Pipe wall thickness	2.18 mm (0.086 in)	3.18 mm (0.125 in)

- The largest setback distances for each section was not chosen and applied to the overall hydrogen system
  - Instead, the setback distances were applied to each section
    - Cascade system
    - Electrolyzer and bulk storage

Alternate Means Electrolyzer Full Cascade P&ID

- By reducing the pipe size before the source valves, the setback distances are also reduced



Setback Distances for Sections of Hydrogen System for Alternate Means Design

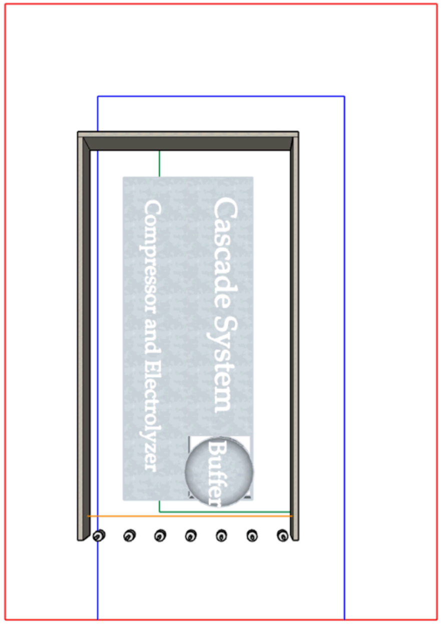
- The largest separation distance for each storage array defines the value of the separation distance for the overall system

	Fire Resistant Wall	Group1	Group 2	Group 3
Section 1	NO	12.7 m (42 ft.)	6.6 m (22 ft.)	5.3 m (17 ft.)
	YES	6.4 m (21 ft.)	3.3 m (11 ft.)	0.0 m (0 ft.)
Section 2	NO	7.5 m (24 ft.)	3.1 m (10 ft.)	3.1 m (10 ft.)
	YES	3.7 m (12 ft.)	1.6 m (5 ft.)	0.0 m (0 ft.)
Base Case Electrolyzer Section 2	NO	11.5 m (38 ft.)	5.7 m (19 ft.)	4.8 m (16 ft.)
	YES	5.7 m (19 ft.)	2.8 m (9 ft.)	0.0 m (0 ft.)

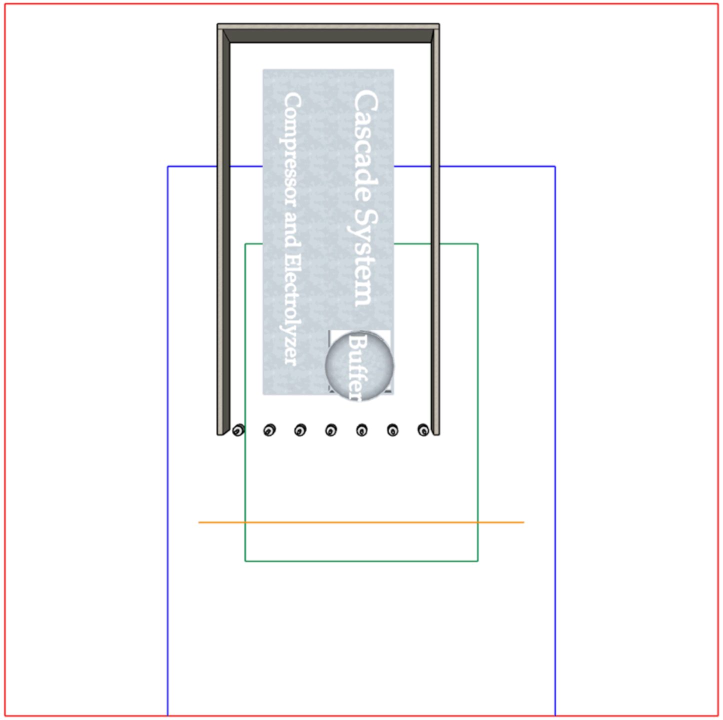
Base Case overall setback distances

Setback Distances Around each Storage Array Hydrogen System

- Cascade System

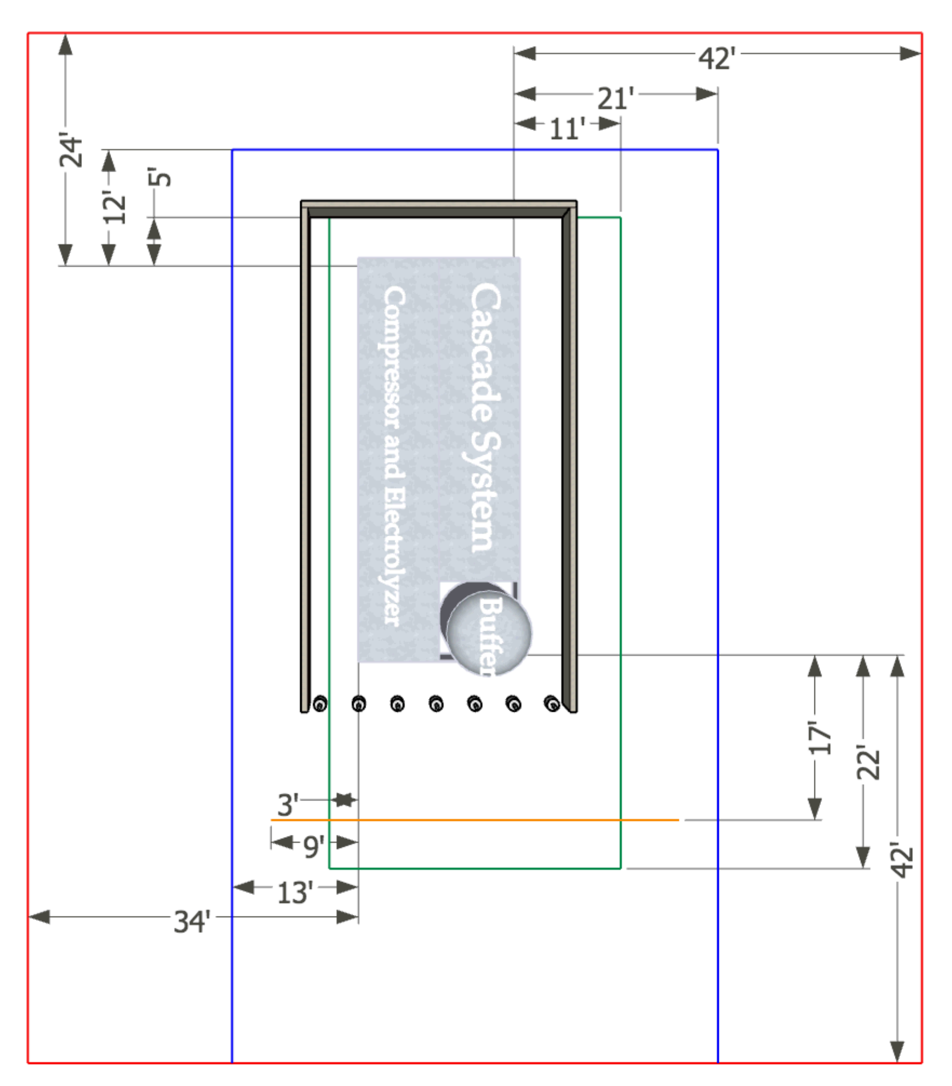


- Bulk Storage



Setback Distances Around each Storage Array Hydrogen System

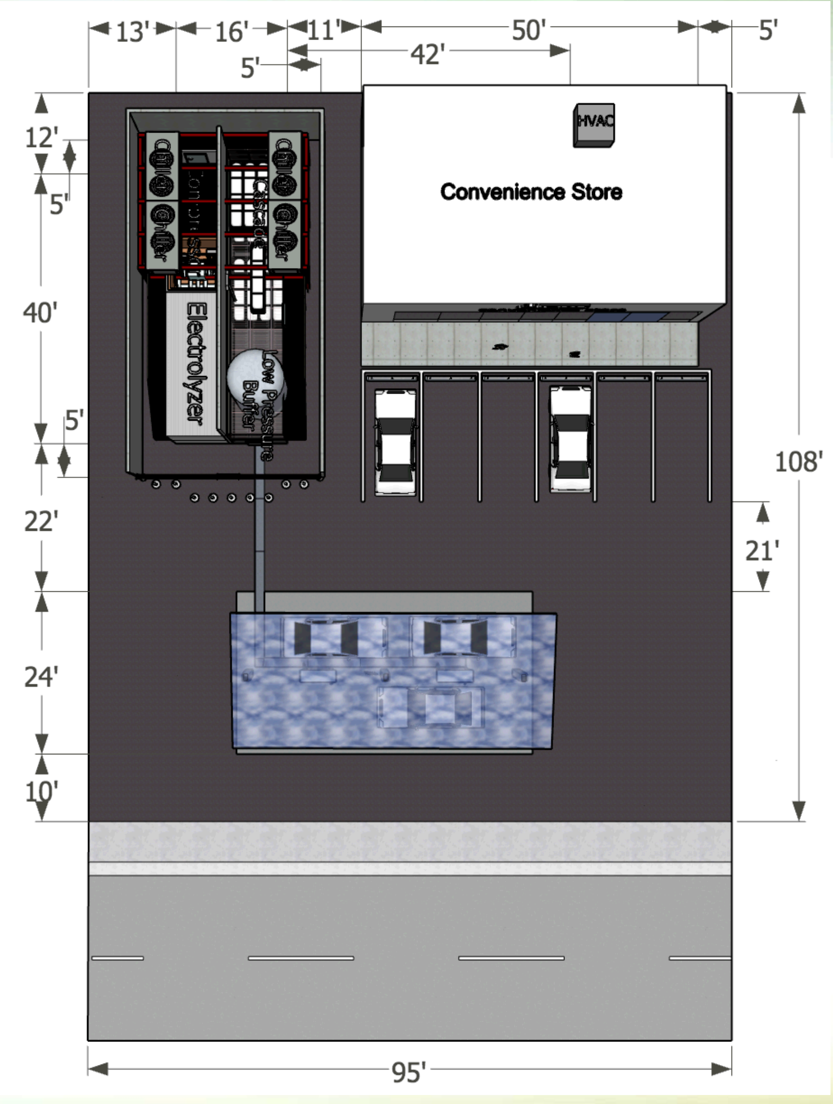
- Minimum Footprint
  - Hydrogen system only



Full Layout for Alternate Means Design

H2FIRST

- Full Layout
  - Convenience store
  - Parking
  - Traffic flow
- Total area
  - 10,260 ft^2



Risk and Consequence Analysis on Hazard Scenarios

Hazard Scenario Analysis for Alternate Means Design

Required Scenario	Outdoor Fueling Station Scenario	Performance Criteria Approach
Fire – Hydrogen fire resulting from a leak at the hydrogen dispenser	Hydrogen fire resulting from a leak at the hydrogen dispenser	Jet fire risk calculation
Explosion Scenario 1 – Gaseous H_2 pressure vessel rupture	Compressed gas storage	List of mitigations for burst
Explosion Scenario 2 –H_2 deflagration within the enclosure housing the compressor (worst case)	A hydrogen deflagration within the enclosure housing the compressor.	Potential for deflagration conditions and peak overpressure
Explosion Scenario 3 – Venting of hydrogen forms localized H_2/air mixture in the vent pipe that detonates	Localized H2/air mixture in the vent pipe	Vent pipe design specifications
Hazardous Material Scenario 1 – Release of hydrogen from storage tank	Release of hydrogen from storage vessel	Jet/plume for localized hypoxia
Hazardous Material Scenario 2 – An unrelated vehicle fire at the lot edge	Unrelated vehicle fire at the lot line	Flame radiation from vehicle fire
Hazardous Material Scenario 3 – Seismic event where a pipe bursts (100% leak size on largest pipe)	Seismic event where largest pipe bursts	Risk metric calculation
Hazardous Material Scenario 4 – A hydrogen discharge where the interlock fails	A hydrogen discharge where the interlock fails	Layered safety features present in the system
Building Use Scenario 1 – Maximum occupancy load present in building during fire with main entrance/exit blocked	Hydrogen system outdoors	Not applicable
Building Use Scenario 2 – Fire during maintenance with fire suppression system out of service.	Hydrogen system outdoors	Not applicable

Fire - Hydrogen fire resulting from a leak at the hydrogen dispenser

H2FIRST

- One single fire source
  - Simultaneous events not considered
- Dispenser assumed to develop a leak, ignite immediately and result in a jet fire
  - Only effects of jet fire considered, explosive conditions explored in other scenarios
- HyRAM QRA tool used to analyze results of jet fire risk
- Average Individual Risk (AIR) for jet fire scenario is:

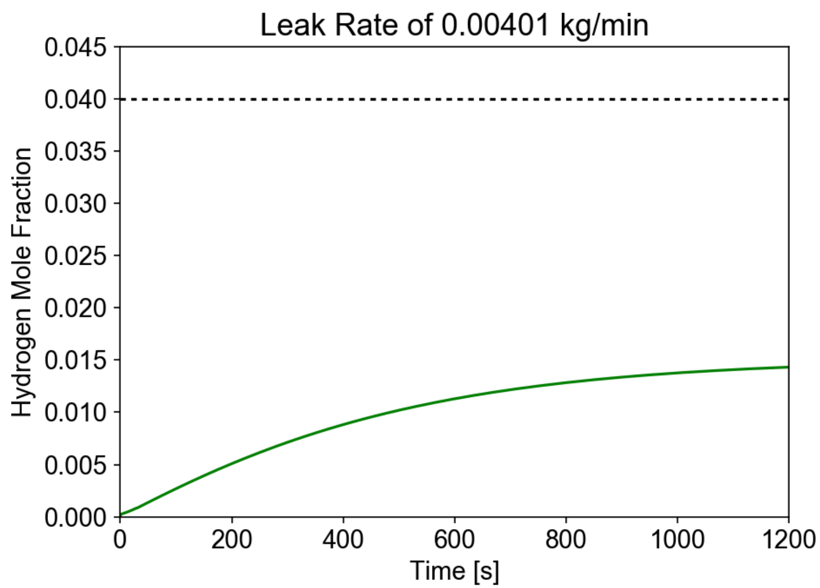
3.334 x 10^{-06} fatalities per year

	Base Case Electrolyzer	Alternate Means Design
AIR	4.637 × 10^{-6} fatalities/year	3.334 × 10^{-6} fatalities/year

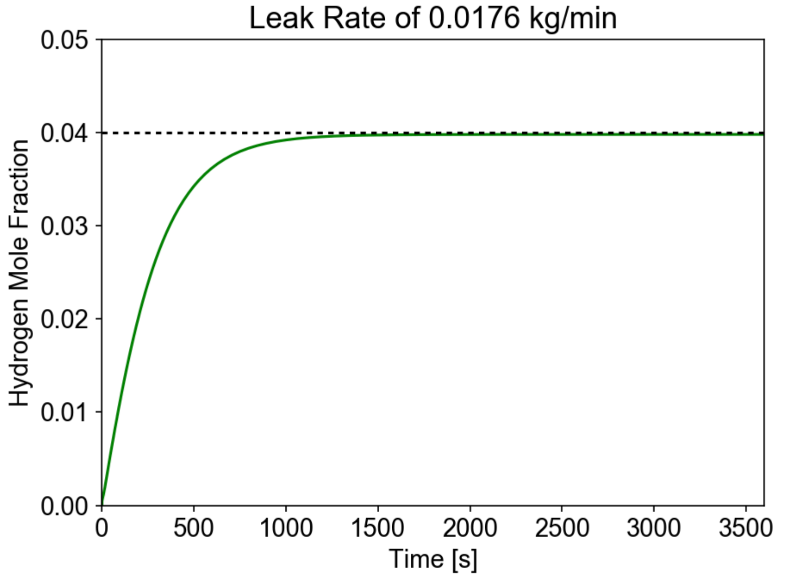
The average Individual Risk is smaller for the the alternative design.

Explosion Scenario 2 –H2 deflagration within the enclosure housing the compressor

- Hydrogen concentration resulting for most probable compressor leak size (0.01% of pipe area) for the high pressure section
- Hydrogen concentration maintained below 1.5 %



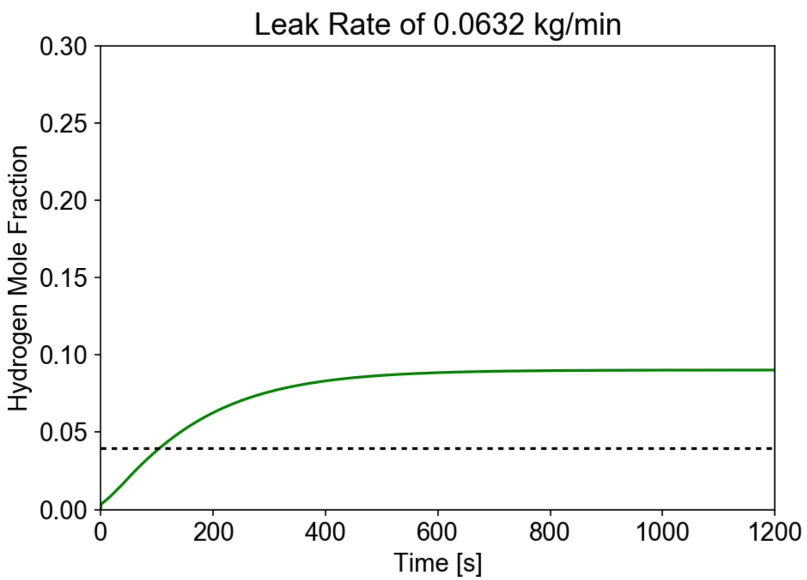
- Compressor leak rate required to achieve a steady state hydrogen concentration of 4% for
  - A leak size of 0.0439% of pipe size is needed for the high pressure section
  - A leak size of 0.278% of pipe size is needed for the low pressure section



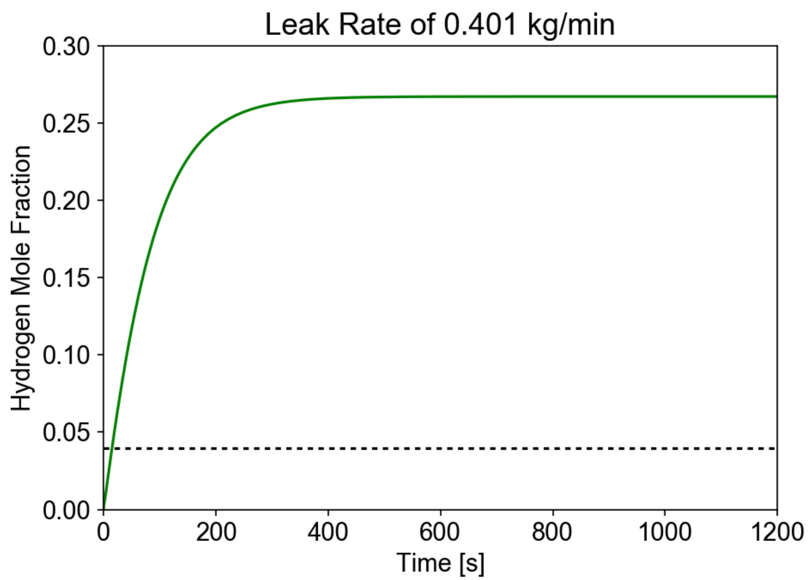
Explosion Scenario 2 –H2 deflagration within the enclosure housing the compressor

- Hydrogen concentration resulting for most probable compressor leak size (1% of pipe area)

Low Pressure Section



High Pressure Section



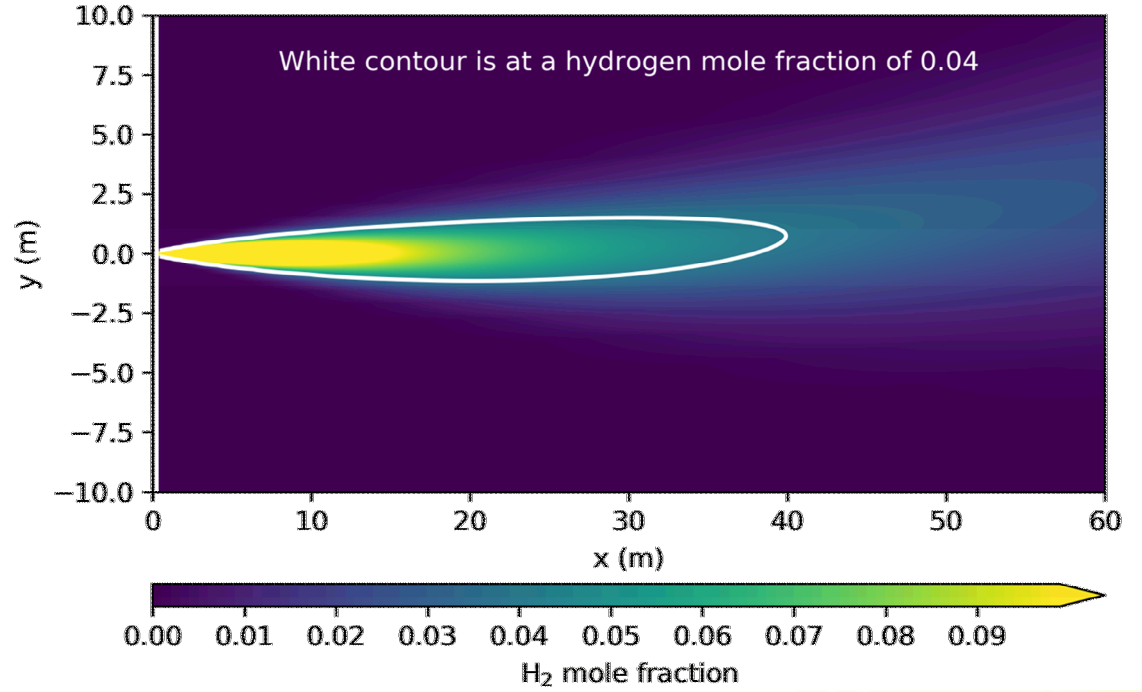
Leak Rate	Overpressure	
	Low Pressure	High Pressure
1% of Pipe Size	0.350 MPa	1.62 MPa

Hazardous Material Scenario 1 - Release of hydrogen from storage tank

- A significant release of hydrogen would reduce the oxygen concentration at the proximity of the leak
- The hydrogen release was assumed to happen at the low pressure bulk storage
  - ID pipe of 17.3 mm (0.68 in) connected to the low pressure buffer tank
- The release is assumed to happen when the low pressure buffer tank is at full capacity
  - Maximum pressure of 5 MPa (725.19 psi)

Hazardous Material Scenario 1 - Release of hydrogen from storage tank

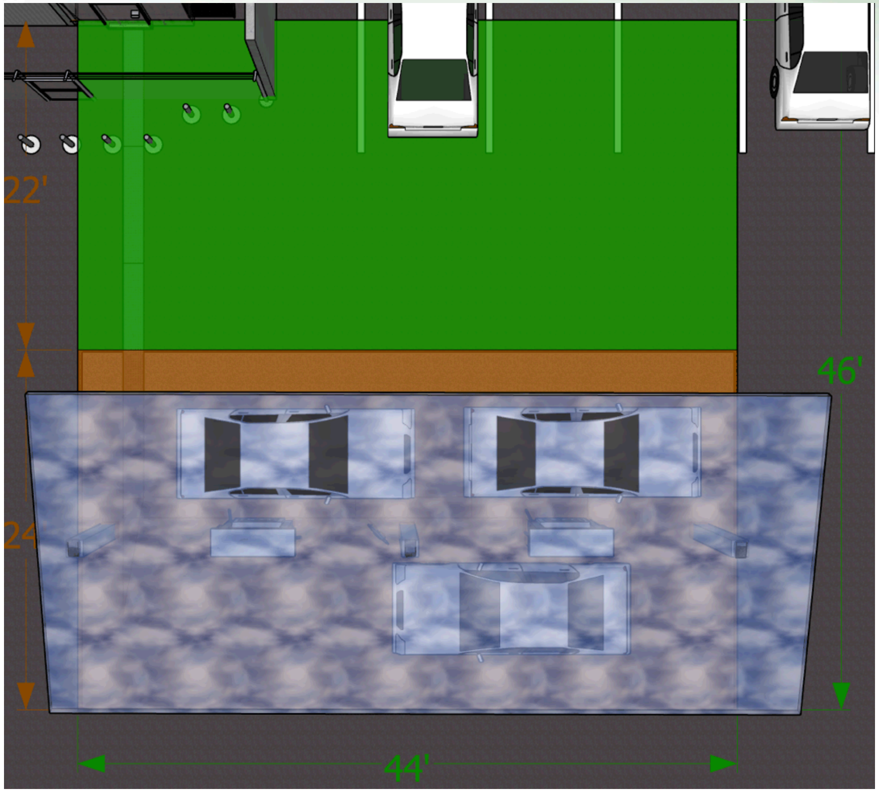
- The outer contour shows the flammable extent for the plume (4% hydrogen)
  - Flammable mass extends 42 meters from release point



Hazardous Material Scenario 3 – External Event

- A 100% leak on the largest pipe
  - Pipe connecting the electrolyzer, low pressure buffer, and the compressor
    - OD 19.05 mm (3/4”)
    - Wall Thickness: 0.889 mm (0.035 in)
    - Maximum pressure at this pipe is 5 MPa
    - 10 m long pipe
- HyRAM QRA tool used to analyze results of jet fire risk
- Average Individual Risk (AIR) for jet fire scenario is:

1.549 $\times$ 10^{-2} fatalities per year*



*conditional based on the occurrence of an earthquake

Hazard Scenario Analysis for Base Case Electrolyzer

Outdoor Fueling Station Scenario	Baseline	Alternative Means
Fire- Hydrogen fire resulting from a leak at the hydrogen dispenser	4.637×10^{-6} fatalities/year	3.334×10^{-6} fatalities/year
Explosion Scenario 1 - Gaseous H_2 pressure vessel rupture	Mitigations listed for stationary pressure vessels	Mitigations listed for stationary pressure vessels
Explosion Scenario 2 – H_2 deflagration within the enclosure housing the compressor (worst case)	1.62 MPa overpressure for 1% of pipe size leak	Same as Base Case
Explosion Scenario 3 - Venting of hydrogen forms localized H_2/air mixture in the vent pipe that detonates	Vent pipe length to diameter ratio to prevent detonation is present with a 13% additional safety factor (same as Base Case Gas)	Same as Base Case
Hazardous Material Scenario 1 - Release of hydrogen from storage tank	Same as Base Case	Same as Base Case
Hazardous Material Scenario 2 - An unrelated vehicle fire at the lot edge	Heat flux on dispenser: 3.3 kW/m^2 for single passenger vehicle	Heat flux on dispenser: 3.3 kW/m^2 for single passenger vehicle
Hazardous Material Scenario 3 - Seismic event where a pipe bursts (100% leak size on largest pipe)	AIR Fire = 7.736×10^{-5} fatalities per year, conditional upon the occurrence of an earthquake	Same as Base Case
Hazardous Material Scenario 4 - A hydrogen discharge where the interlock fails	No additional risk scenarios (same as Base Case Gas)	Same as Base Case
Building Use Scenario 1 – Maximum occupancy load present in building during fire with main entrance/exit blocked	Not applicable (same as Base Case Gas)	Same as Base Case
Building Use Scenario 2 – Fire during maintenance with fire suppression system out of service.	Not applicable (same as Base Case Gas)	Same as Base Case

SUMMARY, FUTURE WORK, FINAL FEEDBACK

Presented by Brian Ehrhart

Summary of Design Choices

- 600 kg/day dispensed hydrogen
- Delivery of GH2/LH2
  - 800 kg H2 pre-compressor storage on-site
- Compressor
  - 25 kg/hr
- Cascade
  - 50 units of 1:1:3 high:medium:low
  - Sized for modified demand profile with 1 hour peak demand
- 4 dispenser hoses
  - 2 dispensers, 2 hoses per dispenser
  - H70-T40
  - With chiller/cooling block
- Delivery truck path and traffic flow included
- 30 ft x 50 ft convenience store
  - With ~6 parking spaces

Summary of Footprints: Gas

	Total Lot Area (ft^2)	Reduction from Base Case
Base Case Gas	18,480	--
New NFPA Separation Distances	16,240	12.1%
New Delivery Single Truck	16,500	10.7%
New Delivery Double Truck	16,500	10.7%
Gasoline Co-Location	25,740	39.2% (Increase)
Underground Direct-Bury	15,400	16.7%
Underground Vault	13,720	25.8%
Rooftop Storage	16,000	13.4 %
Non-Prescriptive Gas	14,950	19.1%

Summary of Footprints: Liquid

	Total Lot Area (ft^2)	Reduction from Base Case
Base Case Liquid	21,250	--
New NFPA Separation Distances	18,252	14.1%
New Liquid Delivery	17,400	18.1%
Gasoline Co-Location	22,040	3.7% (Increase)
Underground Direct-Bury	15,515	27.0%
Rooftop Storage	19,840	6.63 %
Non-Prescriptive Liquid	12,992	38.9%

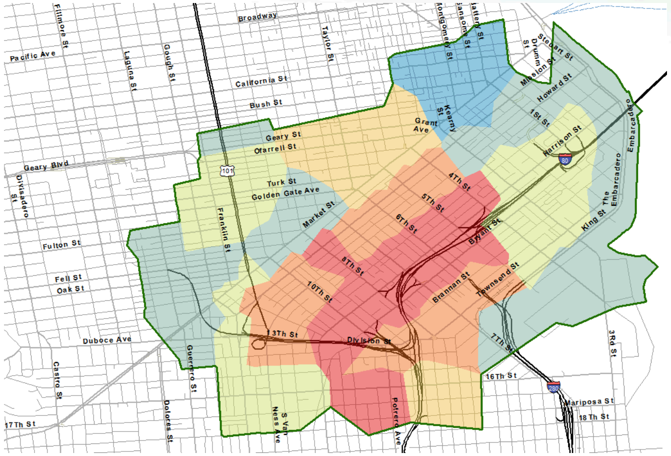
Summary of Footprints: Electrolysis

H2FIRST

	Total Lot Area (ft^2)	Reduction from Base Case
Base Case	12,051	--
New NFPA Separation Distances	9,180	23.8%
Gasoline Co-Location	21,145	75.5% (Increase)
Rooftop	11,020	8.5%

Future Work

- Edit station layouts based on feedback from workshop
  - Also outline future needs
- Economic evaluation
  - Economic impact of different footprint reductions
- National siting study for reduced footprint
  - Can quantify effect of varying footprint size



Preferred location of stations in San Francisco

Summary

- **Relevance**:
  - Create compact hydrogen reference station designs appropriate for urban locations, enabled by hazard/harm mitigations, near-term technology improvements, and/or risk-informed (performance-based) layout designs
- **Approach**:
  - Direct comparison of hazards/risks for base cases vs. alternative layouts with reduced footprints
- **Accomplishments and Progress:**
  - Completed base case designs and hazard analysis for delivered gas, delivered liquid, on-site electrolysis, and performance-based designs
  - Completed designs for underground, roof-top storage, and alternate delivery
  - Identified and submitted code changes, alternate delivery assumptions, gasoline co-location
- **Future Work**:
  - Incorporate feedback from workshop
  - Economic evaluation
  - Siting study for reduced footprint