HYDROGEN
Safety Panel

Introduction to Hydrogen and Fuel Cell Technologies and Safety Considerations

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PNNL-SA-137745

PNNL's Hydrogen Safety Program

Hydrogen Safety Panel (HSP)

- Identify Safety-Related Technical Data Gaps
- Review Safety Plans and Project Designs
- Perform Safety Evaluation Site Visits
- Provide Technical Oversight for Other Program Areas

Hydrogen Tools *Web Portal* (*http://h2tools.org*)

- Hydrogen Facts, Training, Forums, HyARC Tools
- Hydrogen Lessons Learned, Best Practices, Workspaces

Emergency Response Training Resources

- Online Awareness Training
- Operations-Level Classroom/Hands-On Training
- National Hydrogen and Fuel Cell Emergency Response Training Resource

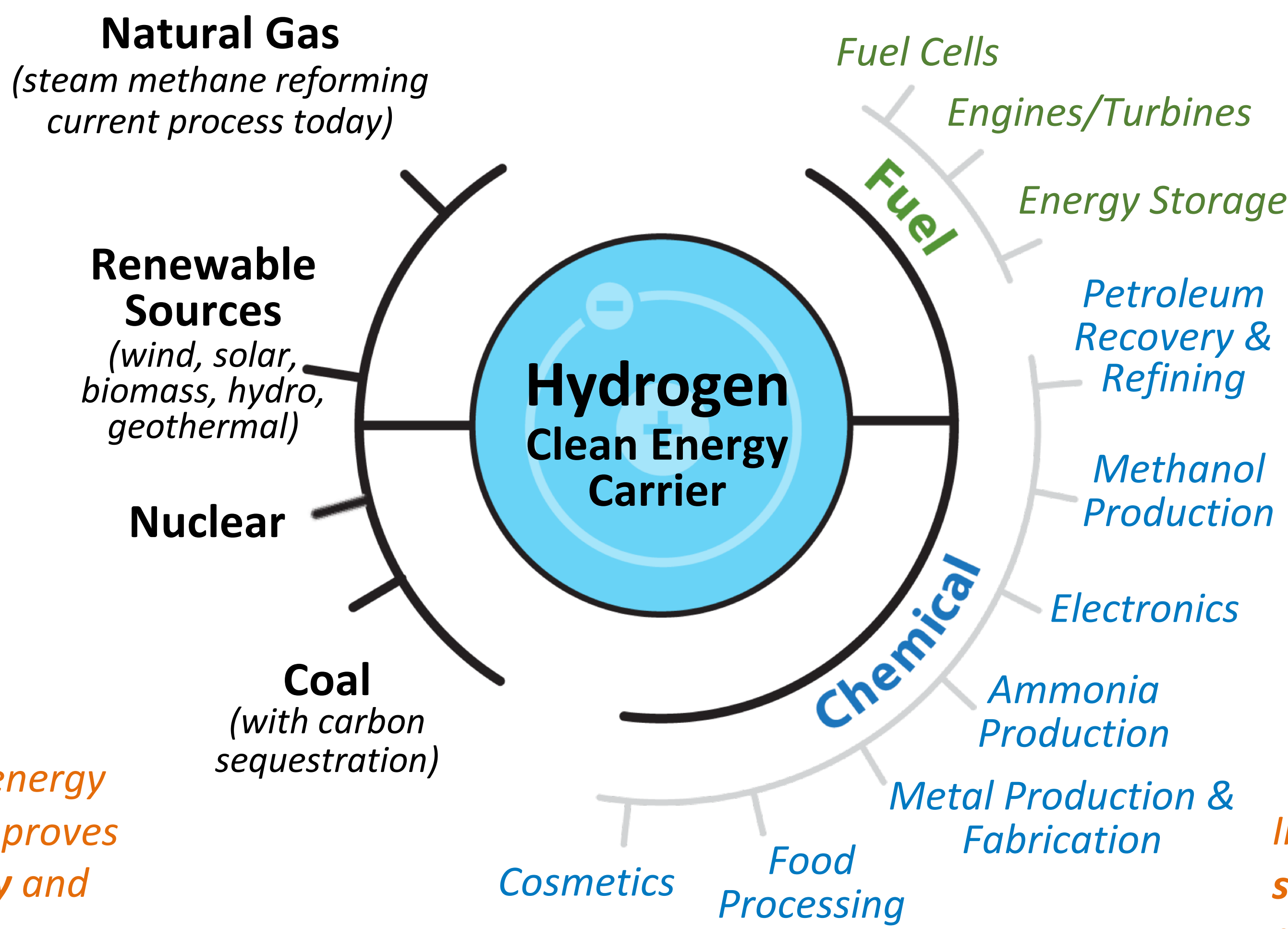
Why Hydrogen Fuel?

- Most abundant element in the universe
- Excellent energy carrier
- Ultra-low/Zero emissions
- Economically competitive
- Safe and secure
    - *More than 80 years of industrial use*
    - *Can be used as safely as gasoline*
    - *Domestically produced from a variety of sources*

Hydrogen fuel dispenser
(Photo :California Fuel Cell Partnership)

Hydrogen – A Clean, Flexible Energy Carrier

Diverse Sources | Diverse Applications



*H_2 services all energy sectors AND improves **Energy Security** and **Domestic Economy***

*Industry has used H_2 **safely** for **over eight decades**!*

Source: U.S. Department of Energy and NREL Hydrogen and Fuel Cells Program

Why Fuel Cells?

Efficient

	Efficiency
Internal combustion engine in a car	20% - 30%
Fuel cell in a car	60%

Uses domestic fuels

- Natural gas
- Renewable sources (wind, solar, biomass, etc.)
- Nuclear
- Coal

Convenient

Refuels in minutes

Quiet

No noise in operation

Clean

Zero tailpipe emissions

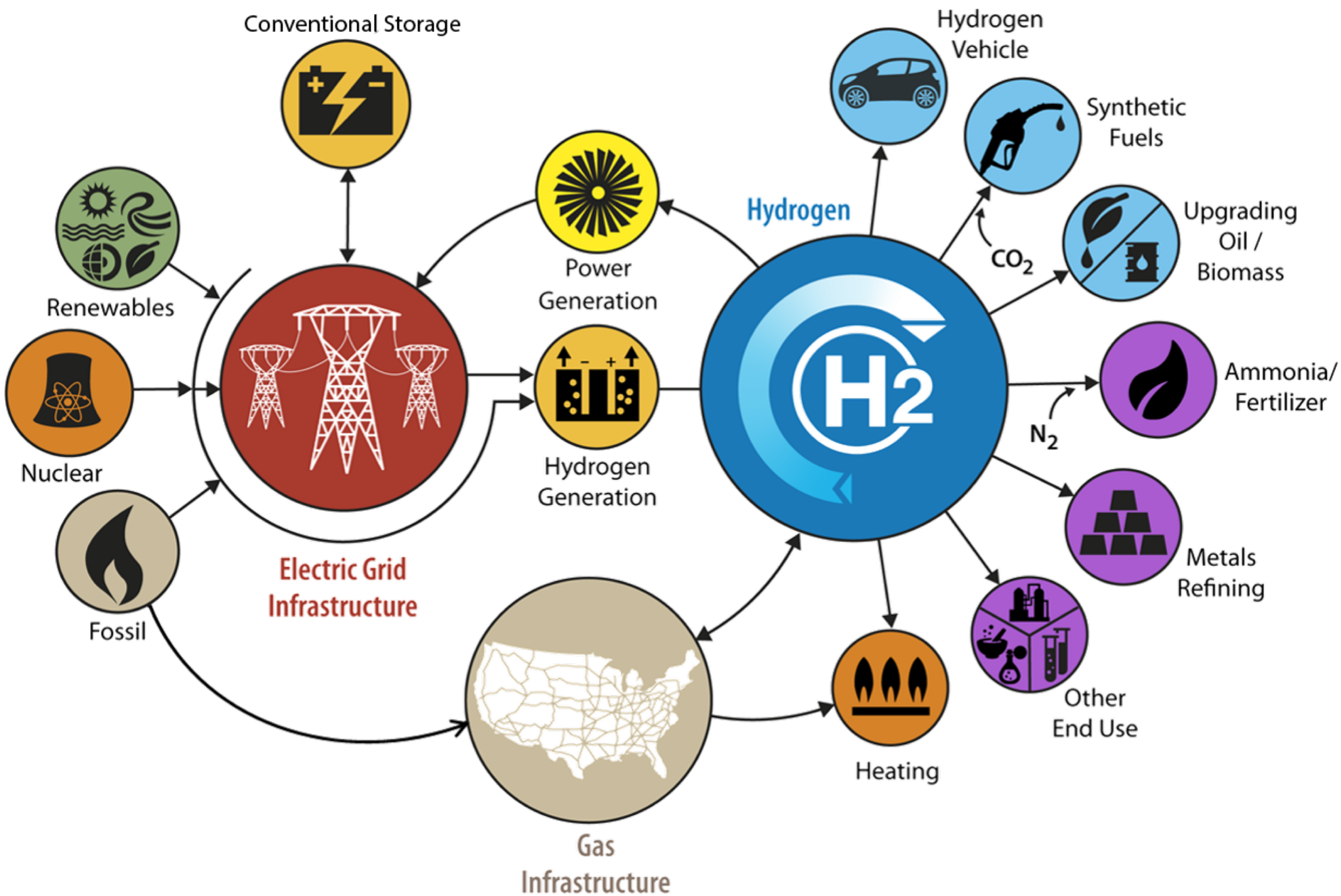
Versatile and easily scalable

Transportation

Stationary

Source: U.S. Department of Energy Hydrogen and Fuel Cells Program

H_2@scale: Enabling Affordable, Reliable, Clean, and Secure Energy Across Sectors

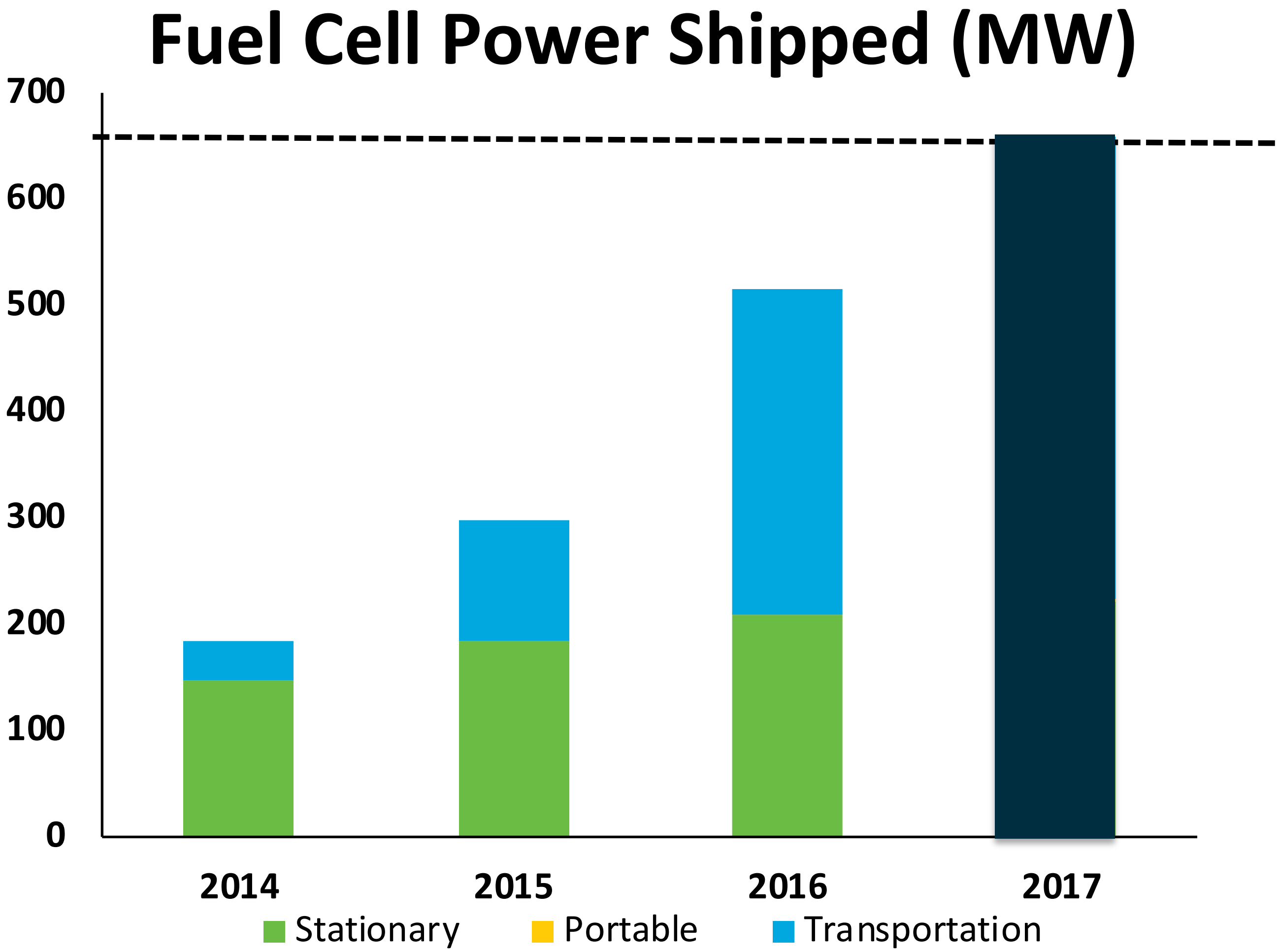


Source: DOE Fuel Cell Technologies Office

Exciting time for hydrogen & fuel cells

Source: DOE Fuel Cell Technologies Office

Upward trend with global fuel cell shipments



650 MW
fuel cell power
shipped worldwide

70,000
fuel cell units
shipped worldwide

Approximately
$2 Billion
fuel cell revenue

Source: DOE and E4Tech

Electrolyzers: Over 100MW/year estimated global sales

*Courtesy of NOW, E4tech and partners: A collaborative effort to assess electrolyzer market potential

Source: DOE Fuel Cell Technologies Office

2018 U.S. Snapshot

Honda Clarity

Over **5,000** | **sold or leased** in the United States

Hyundai Tucson Fuel Cell SUV

Commercial **fuel cell electric cars are here**

Toyota Mirai

- ✓ No petroleum, no pollution
- ✓ Refuels in minutes
- ✓ More than 360 mi driving range
- ✓ Over 60 mpgge

Source: DOE Fuel Cell Technologies Office, August 2018

Interest in material handling equipment applications

More than **20,000 forklifts**

Over **12 million refuelings**

Source: DOE Fuel Cell Technologies Office, June 2018

Long-Range, Heavy Duty Applications Emerging

Fuel cell delivery and parcel trucks starting deliveries in CA and NY

Over 30 buses in 4 states
19M passengers in CA buses

Industry demonstrates first heavy duty fuel cell truck in CA

Source: DOE Fuel Cell Technologies Office, June 2018

Hydrogen Stations in the U.S.

Source: DOE Fuel Cell Technologies Office

Stationary Power Applications Emerging

Fuel cells provided backup power during Hurricane Sandy in the U.S. Northeast

Fuel cells used to power new World Trade Center in NYC

Fuel cell power for maritime ports demonstrated in Honolulu, Hawaii

Over 240 MW of fuel cell stationary power installed across more than 40 US states

Source: DOE Fuel Cell Technologies Office, June 2018

Multiple H_2 and Fuel Cell Applications in the U.S.

U.S. Snapshot

Over
>240MW
Backup Power

More than
20,000
Forklifts

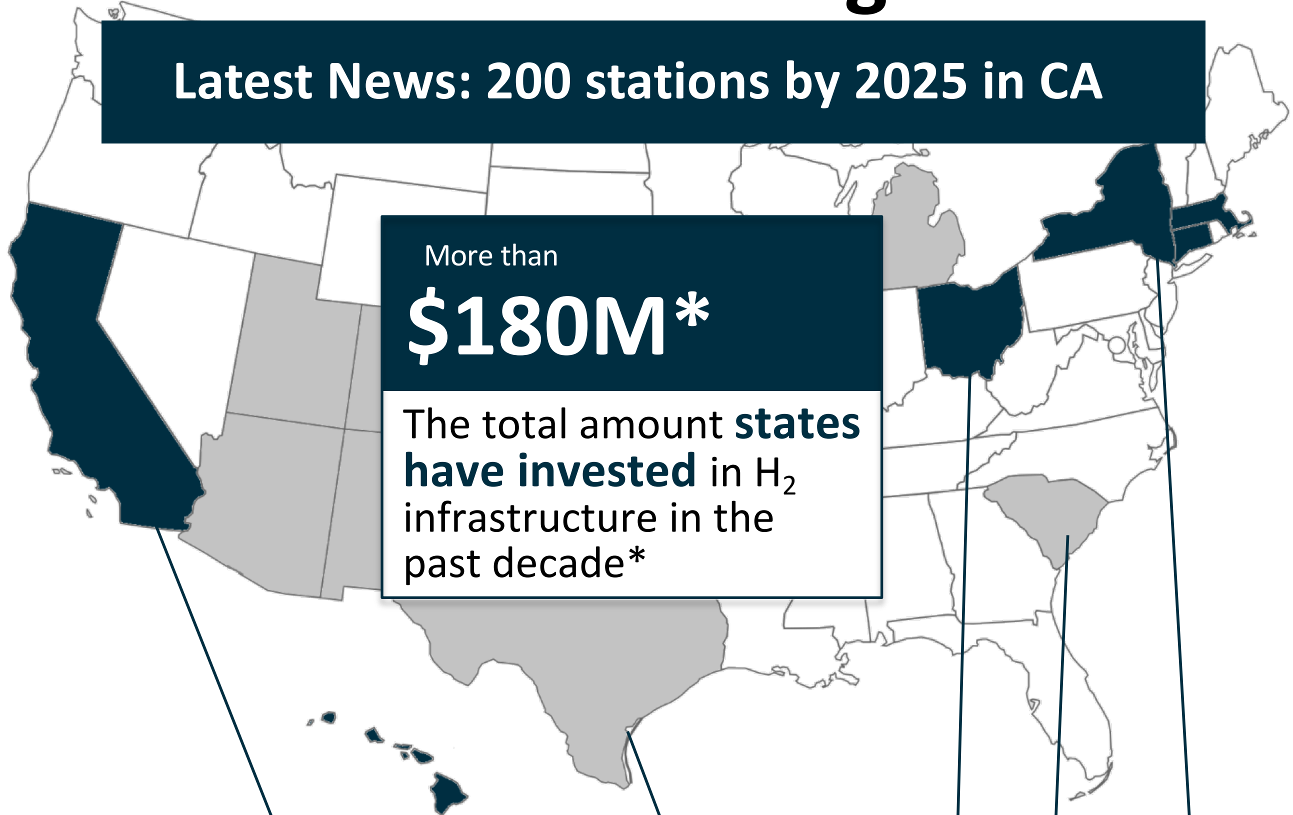
More than
30
Fuel Cell Buses

More than
35
H_2 Retail Stations

More than
5,000
Fuel Cell Cars

States with Growing Interest

Latest News: 200 stations by 2025 in CA



More than
$180M*
The total amount **states have invested** in H_2 infrastructure in the past decade*

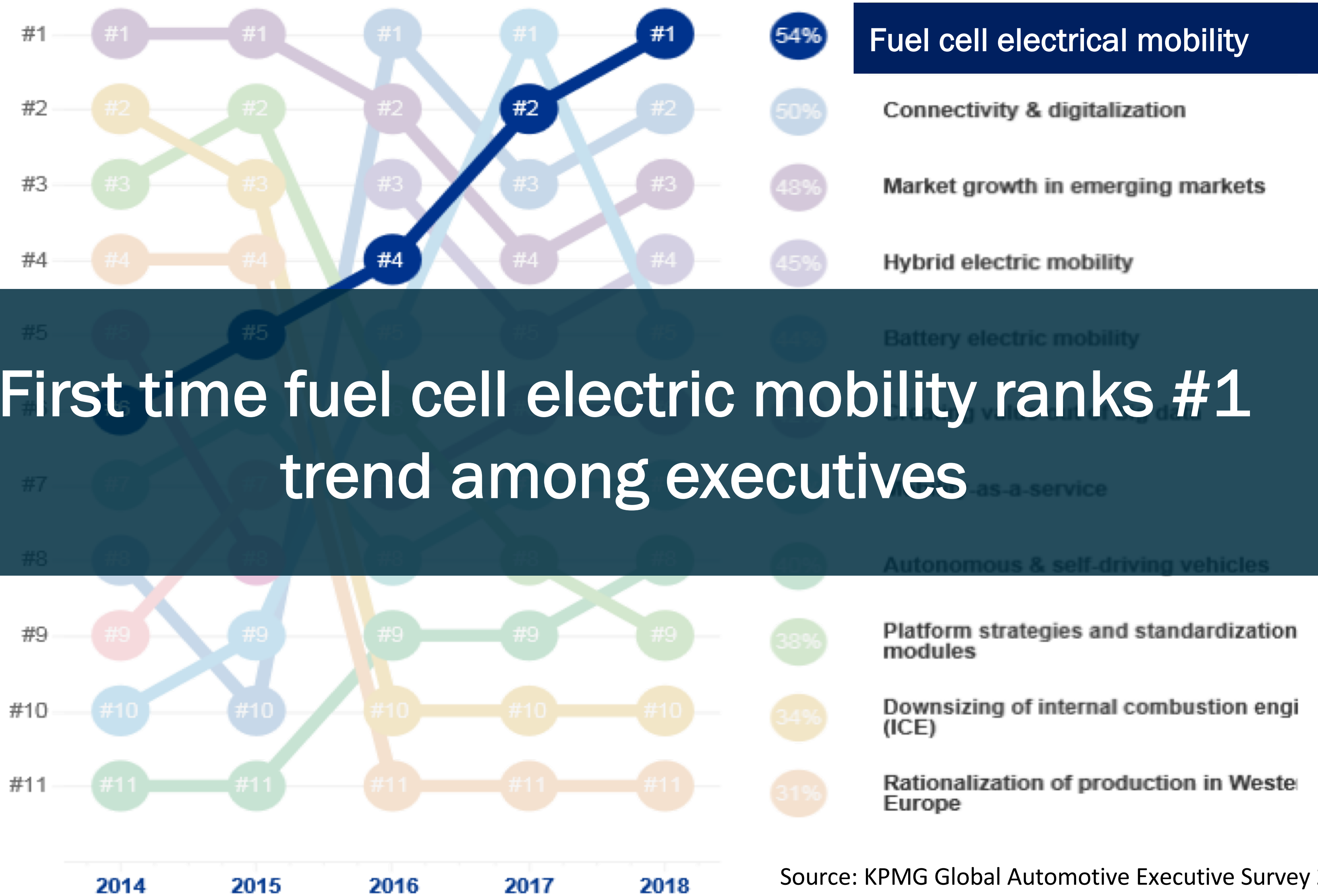
CA
- 200 stations planned
- Over 30 public stations open
- $150M invested
- $235M announced in 2018

HI, OH, SC, NY, CT, MA, CO, UT, TX, MI, and others with interest
- Over $27M invested
- 12-25 stations planned in the NE

*Excludes recent announcement from CA to invest $235M in electric vehicles

Source: DOE Fuel Cell Technologies Office, June 2018

Automotive Executives Survey Results



First time fuel cell electric mobility ranks #1 trend among executives

Source: KPMG Global Automotive Executive Survey 2018

Real World Applications Abroad – Examples

World's first 4-seater fuel cell plane takes off at German Airport

Photo Credit: Christoph Schmidt/dpa via AP and phys.org.

Fuel cell cab fleet launched in Paris, France

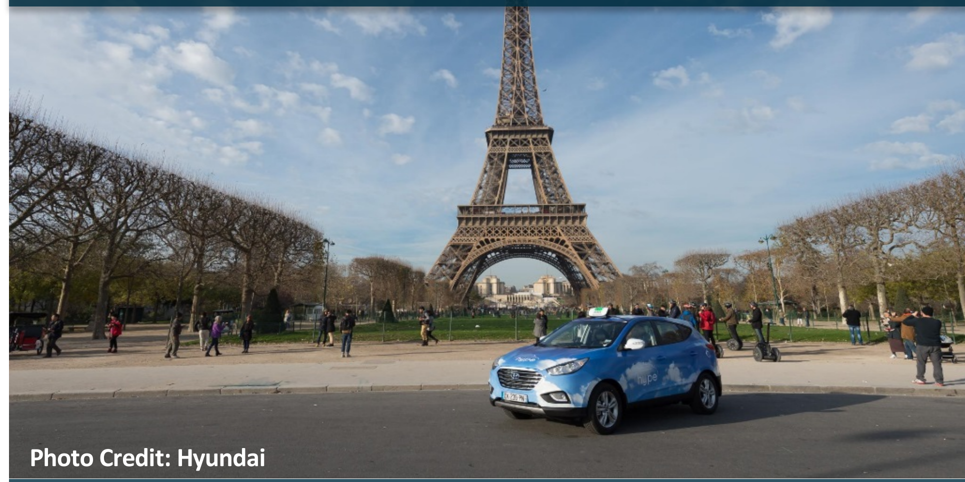


Photo Credit: Hyundai

A town in in Fukuoka, Japan running on hydrogen

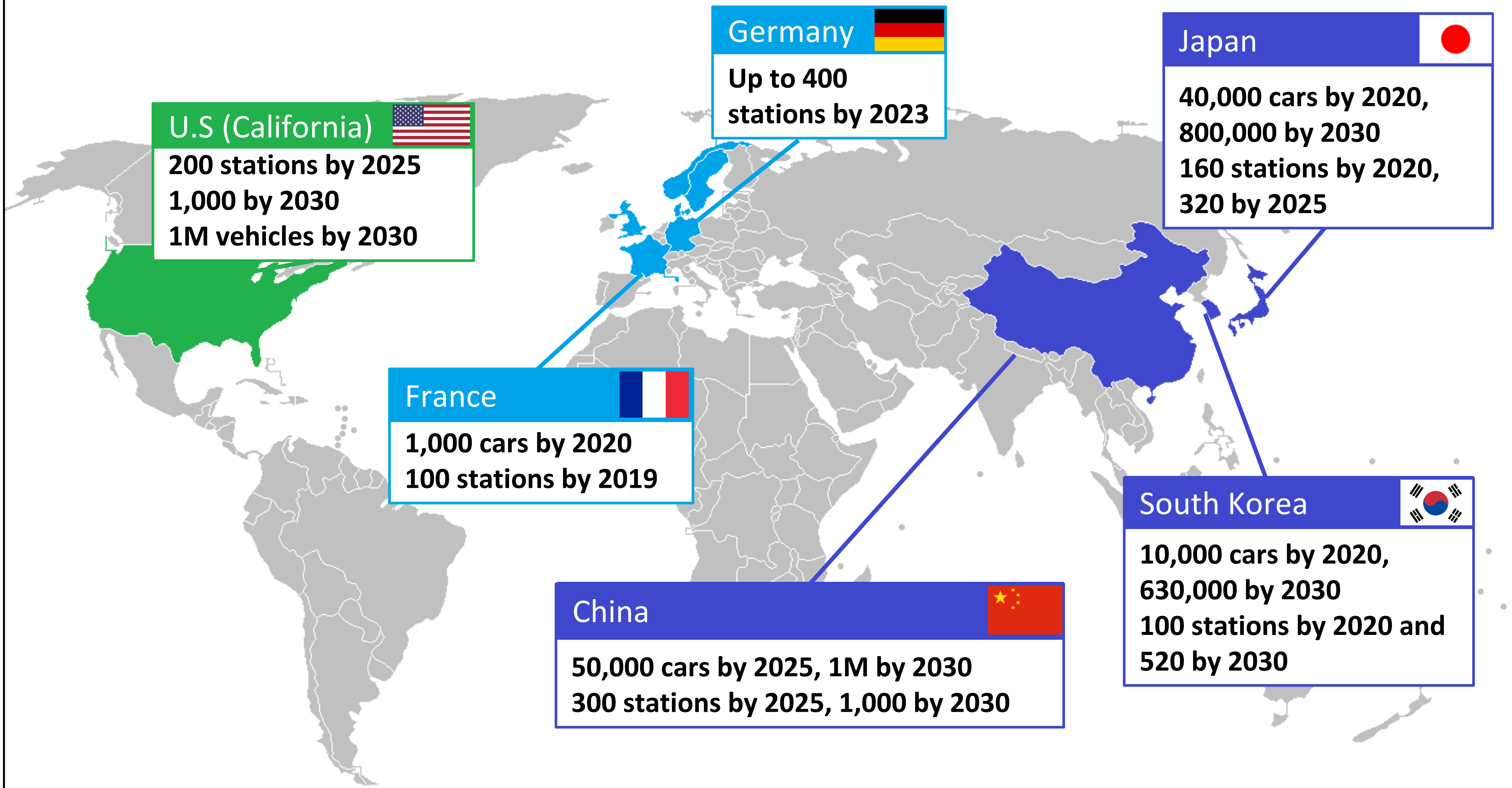
Photo Credit: Fukuoka Pref.

World's first hydrogen fuel cell train in Germany

Photo Credit: Hydrogenics and Alstom

Source: DOE Fuel Cell Technologies Office, June 2018

Increased International Activity – Examples

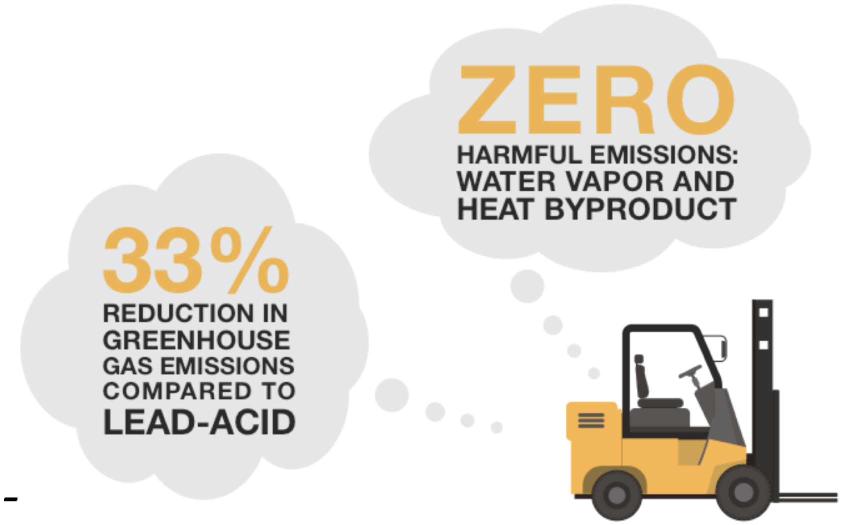


Source: DOE Fuel Cell Technologies Office, August 2018

Material Handling - FCV Success Story

> 20000 operating/ordered HFC fork trucks in 26 US states

- **Amazon** buying 23% of FC maker Plug Power and adding *PEM* fuel cell forklifts into distribution operations in CA, CT
- **USPS** using 80 FC in Capitol Heights, Maryland material handling fleet
- In planning or use by *Ace Hardware, Coca-Cola, FedEx, Home Depot, Newark Farmer's Market, Kroger, Lowe's, Proctor & Gamble, Sysco, Walmart, Wegmans, Honda, Volkswagen, BMW,* and more
- **Space saving** H_2 infrastructure takes much less space than a battery room, recouping valuable warehouse storage space

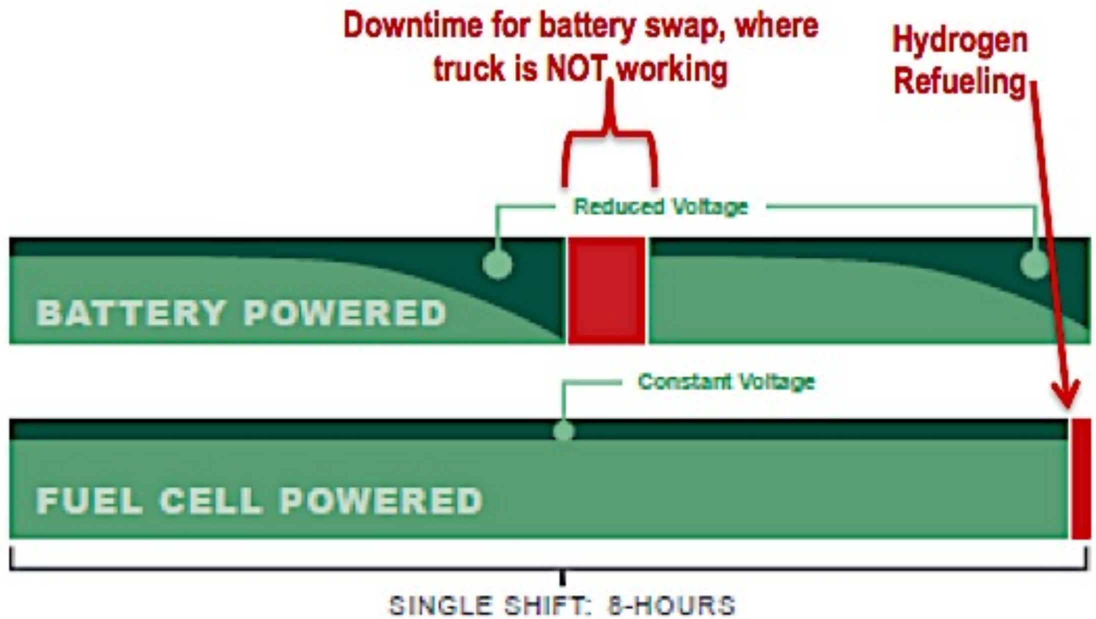


- The Business Case for Fuel Cells: Delivering Sustainable Value (http://www.fchea.org/s/2016-Business-Case-dwcy.pdf)
- Yale 2016 brochure - The Adoption of Hydrogen Fuel Cell-Powered Lift Trucks
- https://about.usps.com/postal-bulletin/2017/pb22465/html/cover_006.htm

FC Powered Industrial Trucks Can Do More Work

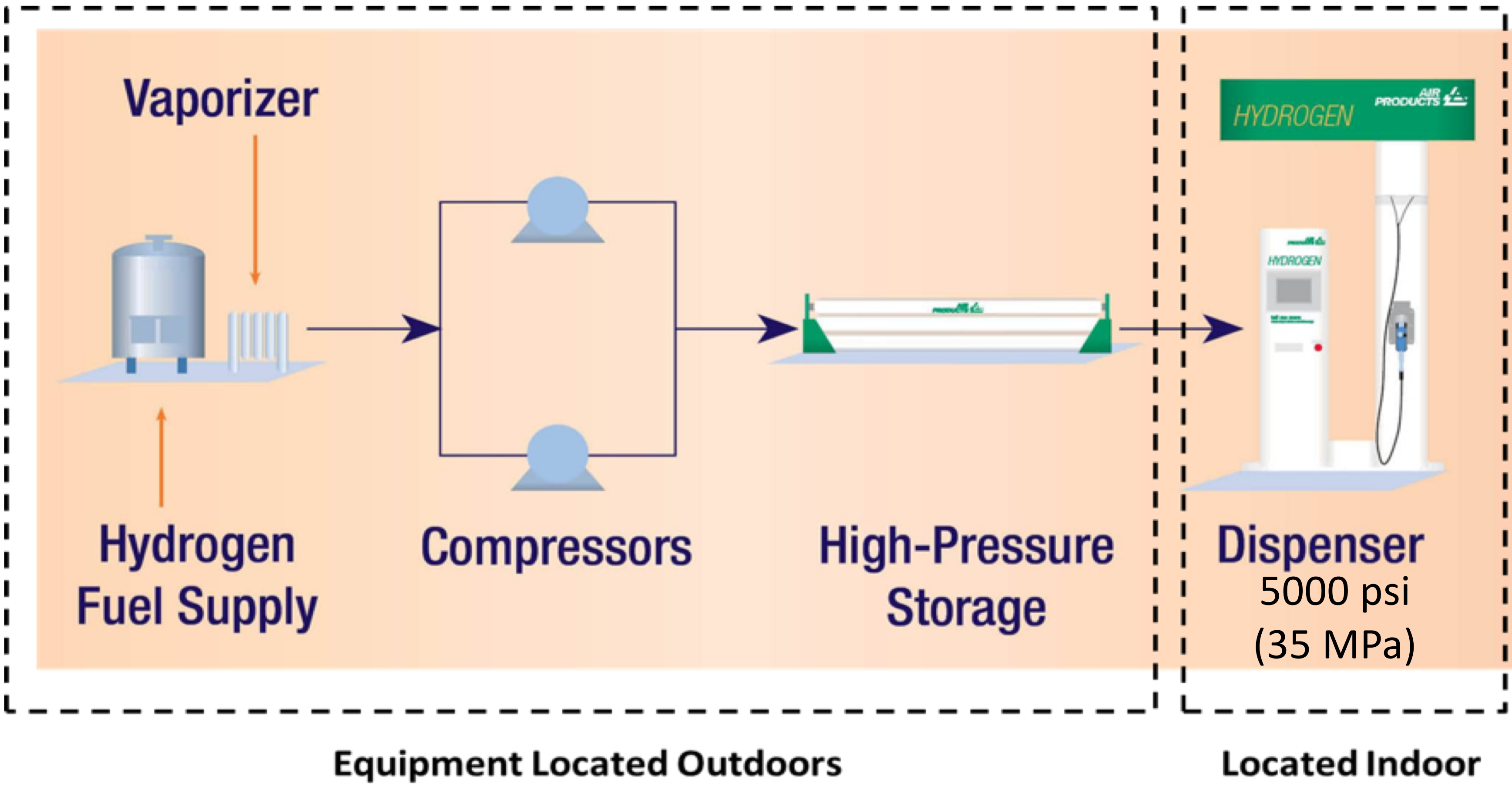
	Lead-acid battery	H_2 fuel cell pack
Recharge	~20 min swap to charge room	<5 min H_2 fueling by operator
Work	voltage decay => power loss	Constant FC voltage = max. power

FC retrofit truck at inside H_2 fueling station



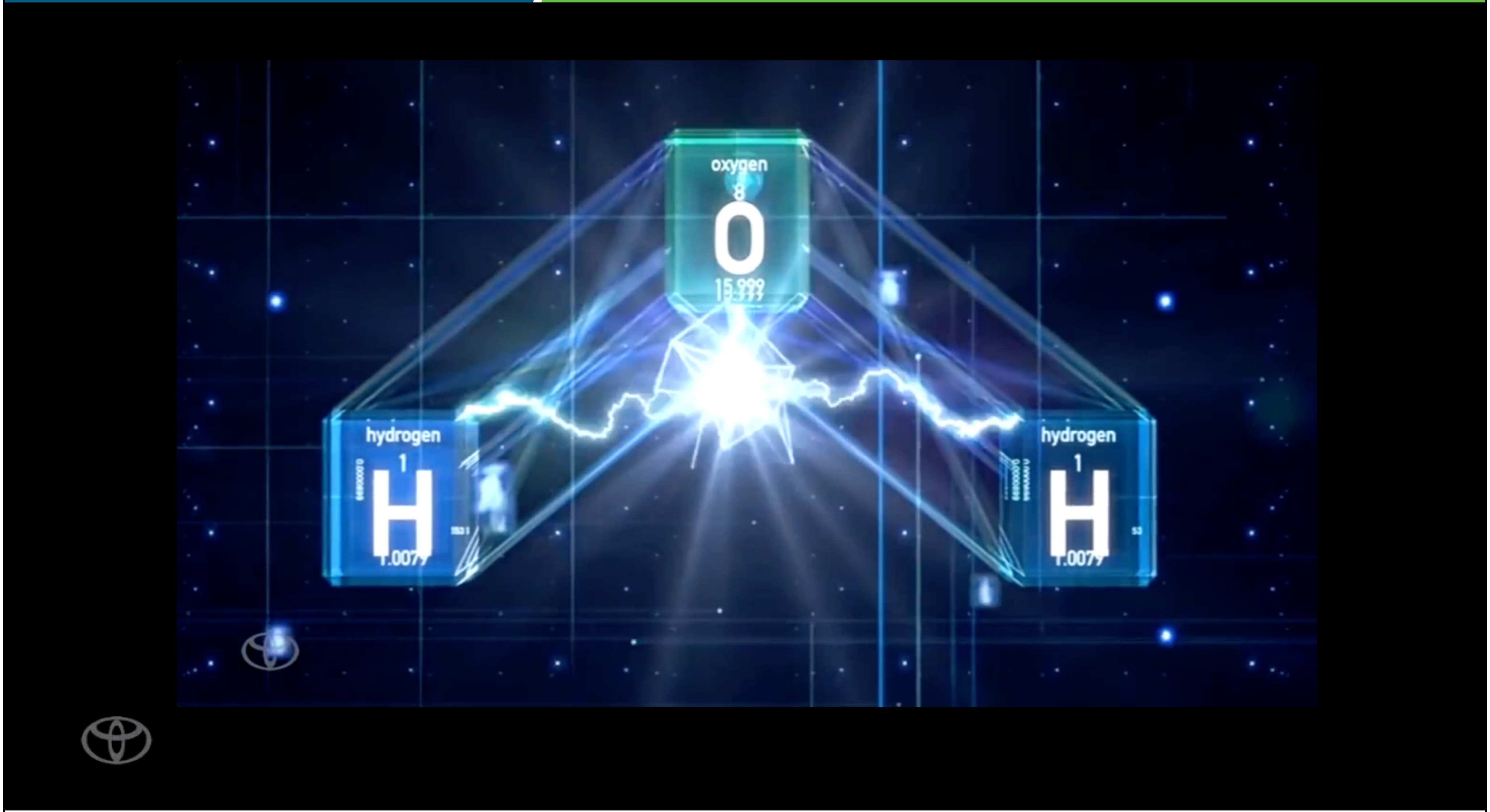
BMW regained > 156 hours of lost productivity over three-shift operation, saving > $65 million annually

Typical H_2 Fueling Installation for FC Fork Trucks



Hydrogen may be supplied as cryogenic liquid, as compressed bulk gas, or generated onsite via natural gas reformation or water electrolysis

Why Fuel Cell Vehicles (FCV)?



Video Source: Toyota

https://h2tools.org/sites/default/files/barilo/Intro_GameChanger.mp4

FCV Are Now Available

As of August 2018, there are over 5,000 FCVs in the US

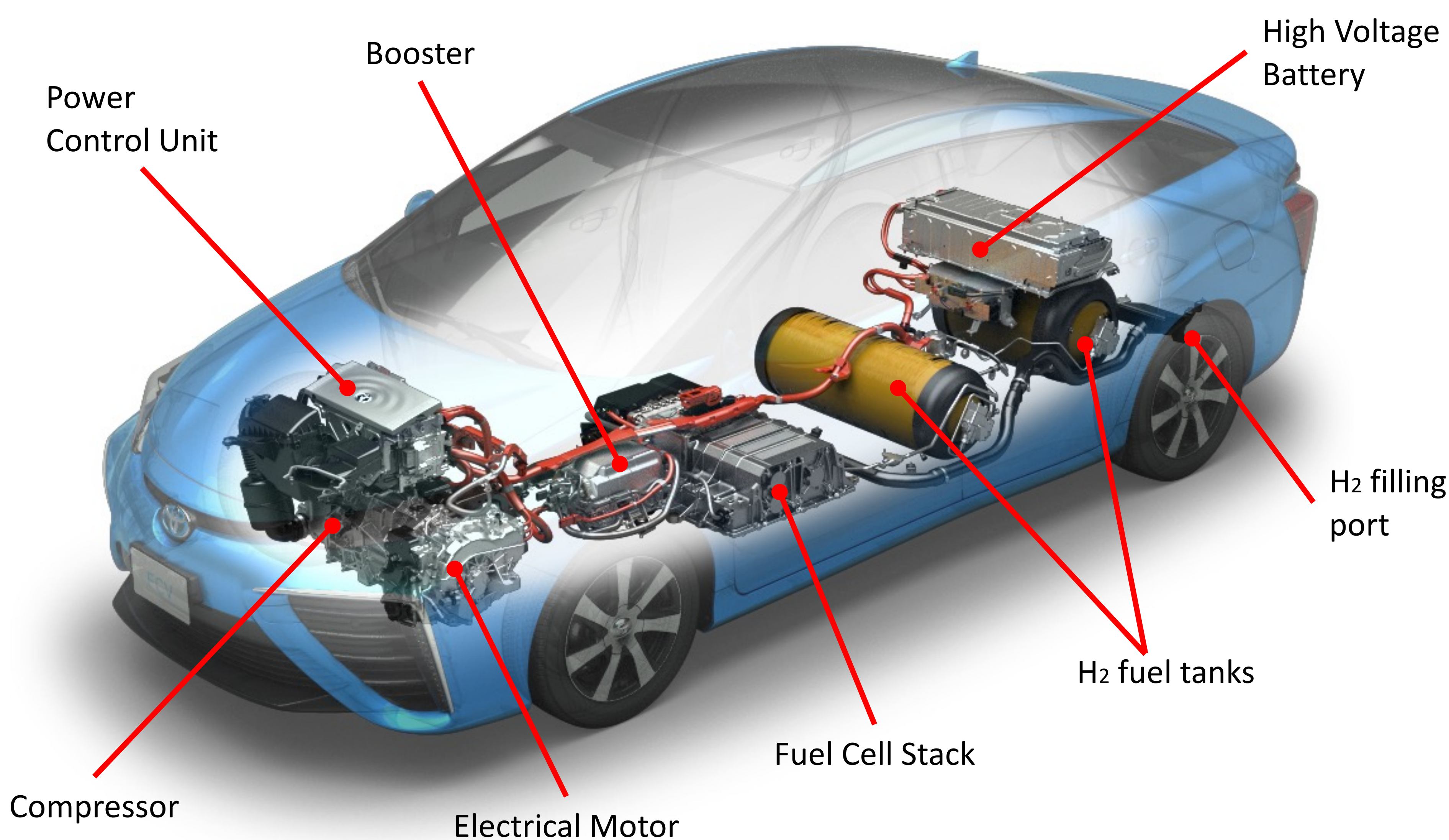
Honda Clarity Fuel Cell Electric Vehicle

Hyundai Tucson Fuel Cell Electric Vehicle

Toyota Mirai Fuel Cell Electric Vehicle

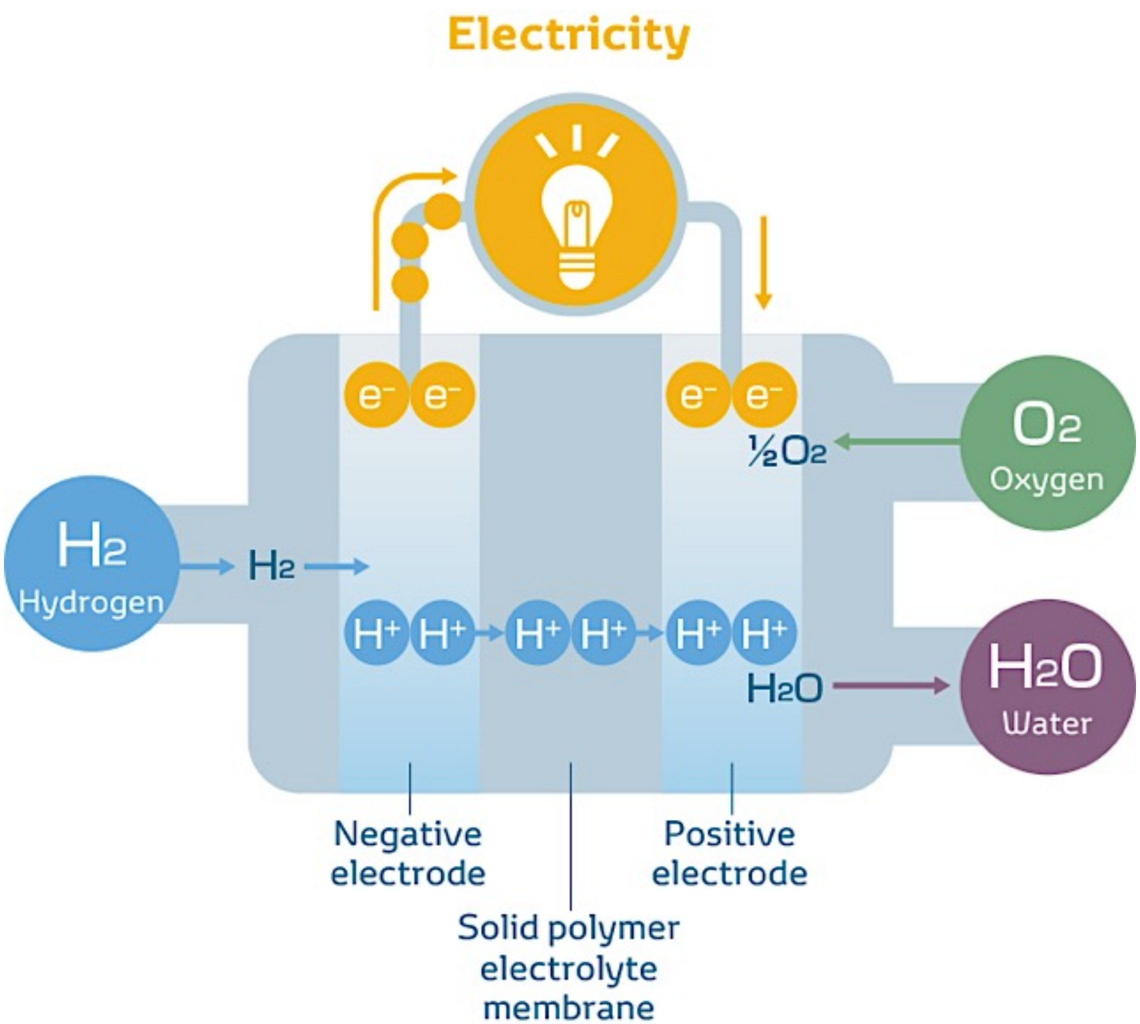
Chevrolet Colorado ZM2 – Military Vehicle (not publicly available)

FCV System Layout



Source: Toyota

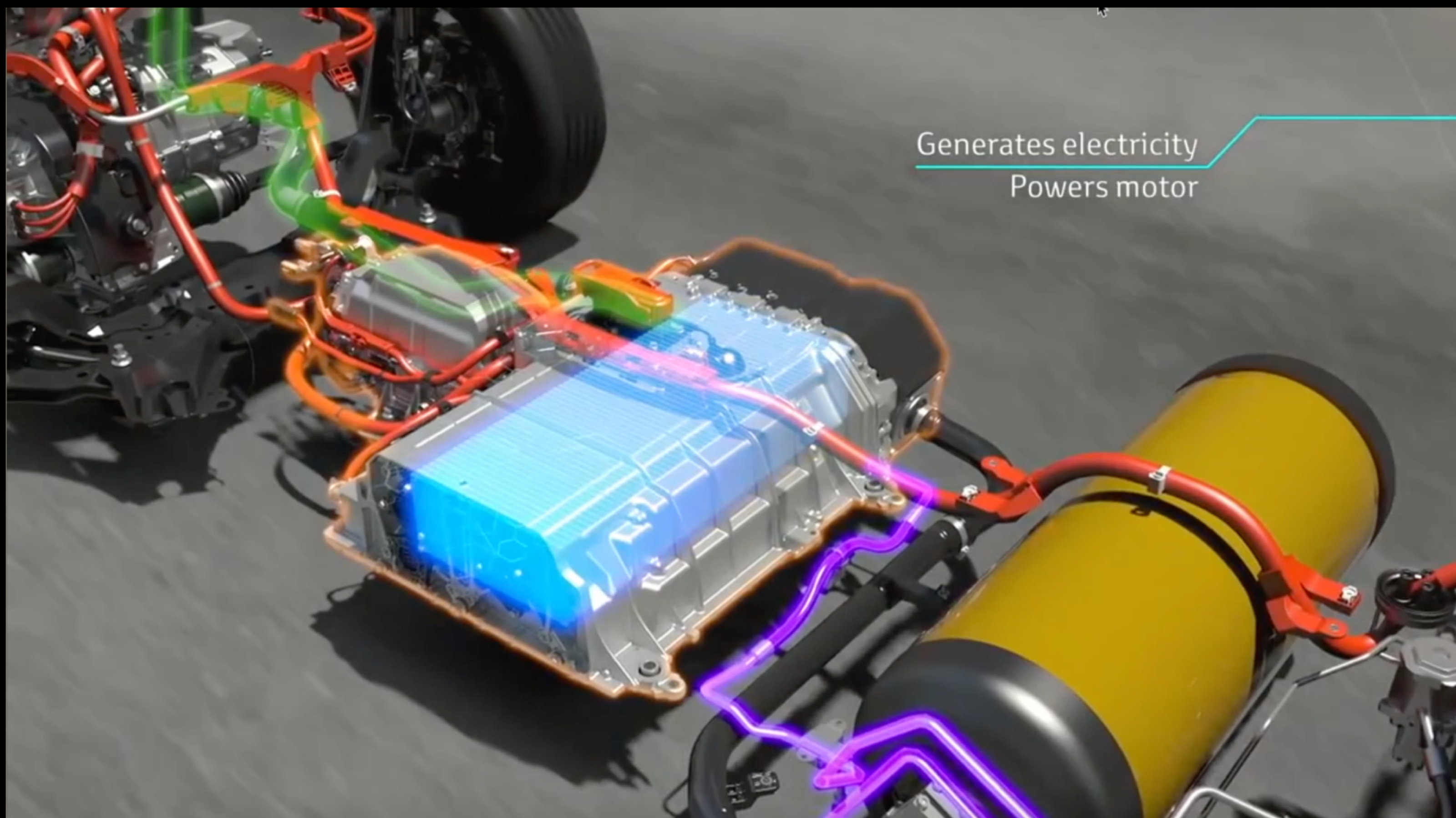
How a PEM* Hydrogen Fuel Cell Works:



*(*Proton exchange membrane)*

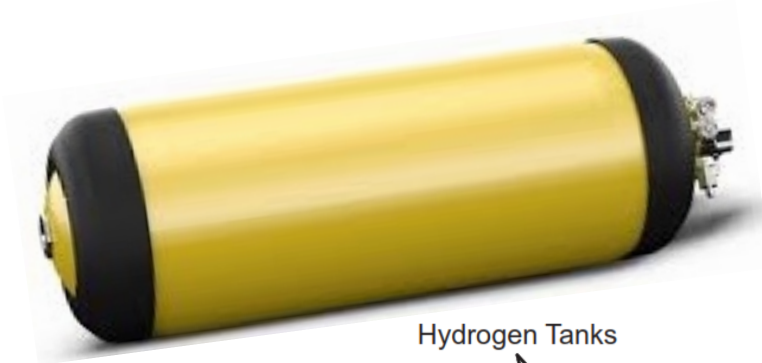
1. **Hydrogen** (**H_2**) to anode side (*negative electrode*)
2. H2 molecules react at anode, release ***electrons*** (**e-**)
3. Electrons travel external circuit toward cathode (*positive electrode*), as **electrical current,** to do **work**
4. Hydrogen ions (**H+,** *protons*) exchange through *solid polymer electrolyte membrane (PEM)* to cathode
5. Hydrogen ions react with airborne **oxygen** (**O_2**) and electrons at the cathode electrode to form **water**

How a Fuel Cell Works in a FCV

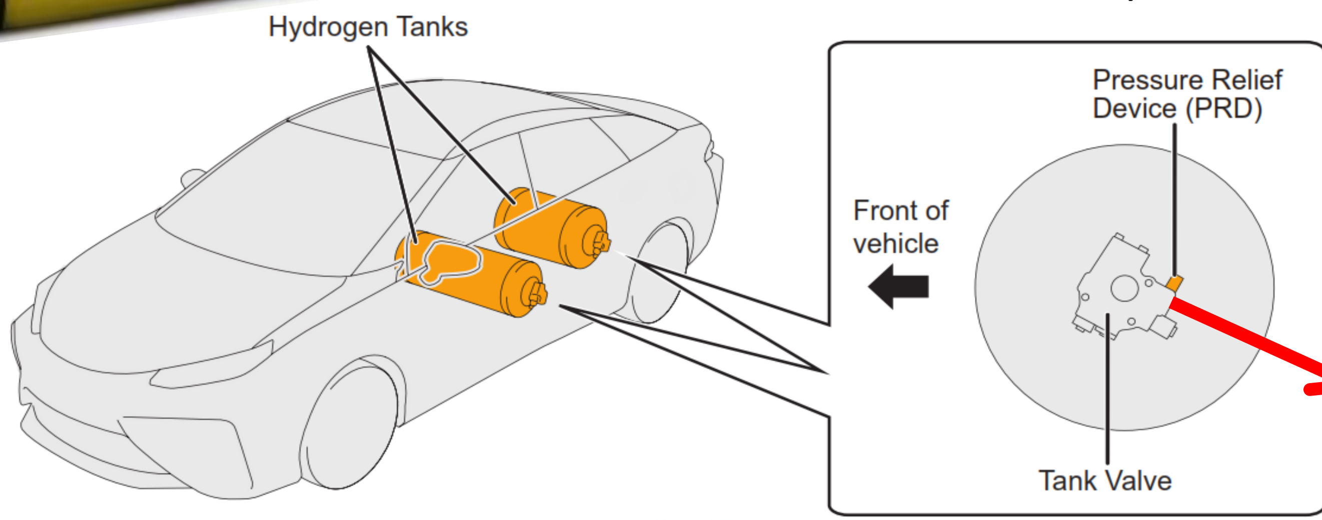


Source: Toyota
Video download URL:
https://h2tools.org/sites/default/files/barilo/Fuel_Cell_Animation.mp4

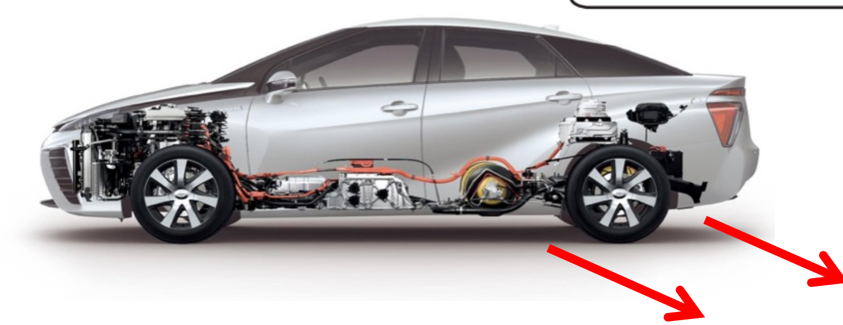
FCV Onboard Hydrogen Tanks



- 10000 psi (700 bar) composite tanks with TPRDs (Type III or Type IV tanks) 5-8 kg H_2
- Designed for 2x pressure, impact
- In-tank shutoff valve isolates gaseous H_2 when vehicle is off or impacted



TPRD opens at 110° C



Direction of H_2 discharge on TPRD activation

Source: Toyota
Example of Thermal Pressure Relief Device (TPRD) – Toyota

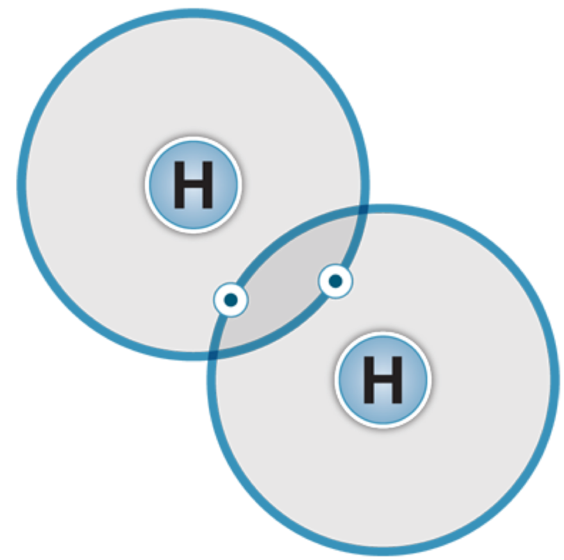
FCV H_2 Fueling Stations - Infrastructure

Photo courtesy: CaFCP

Source: DOE Fuel Cell Technologies Office

Hydrogen Properties and Behavior

- **Gas** at ambient conditions
  - Rises and disperses rapidly (14x lighter than air)
  - Flammable range 4-75% in air
- **Liquid** at -423°F (-253°C) – a *cryogen*
  - LH_2 stored at 50 psi in vacuum insulated tanks
  - No liquid phase in compressed gas H_2 storage
- **Volumetric ratio** liquid to gas is 1:848
  - Compare water to steam (1:1700)
- **Energy content comparison** : 1kg of H_2 ~ 1 gallon gasoline
  - 33.3 kWh/kg H_2 vs 32.8 kWh/gal gasoline



Molecular Hydrogen Model:
2 protons (H+) sharing 2 electrons (e-)

Properties of Hydrogen

Description

- Colorless, odorless, tasteless

General Properties

- Flammable
- Non-irritating, nontoxic, asphyxiant
- Non-corrosive
- Lightest gas, buoyant, can escape earth's gravity

Physical Properties

GH_2 density @ NTP	0.0838 kg/m^3 (1/15th air)
GH_2 specific gravity	0.0696 (Air = 1.0)
Viscosity	33.64 x 10^{-3} kg/m hr (1/2 air)
Diffusivity	1.697 m^2/hr (4x NG in air)
Thermal Conductivity	0.157 kcal/m hr K (7 x air)

Potential Hazards

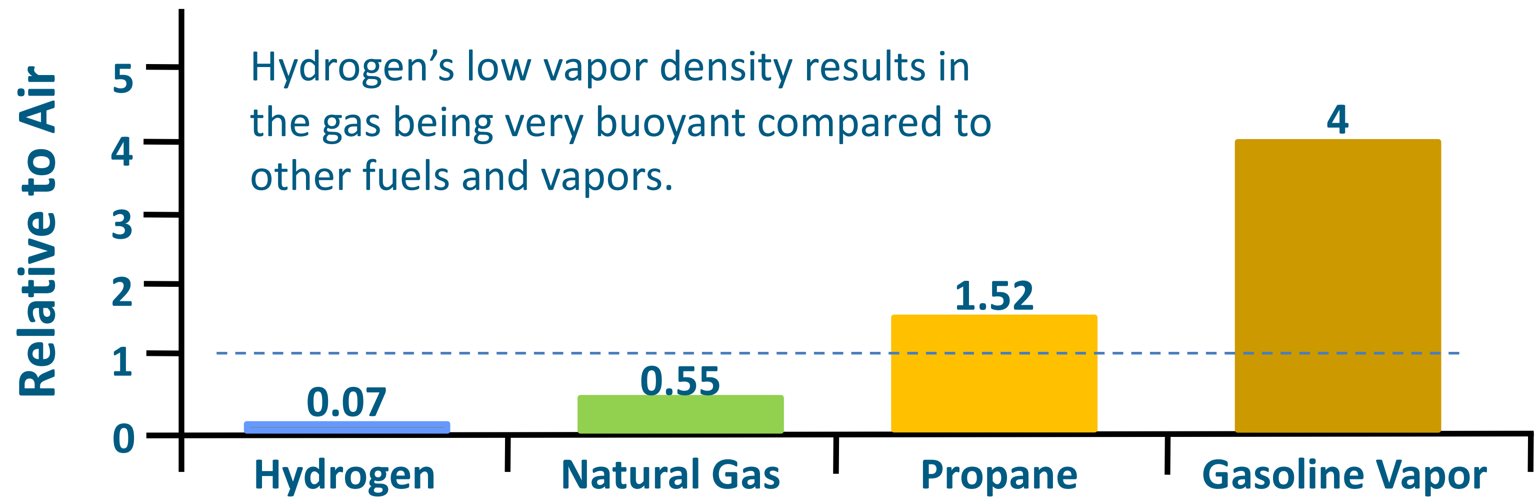
- Combustion
- Pressure hazards
- Low temperature
- Hydrogen embrittlement
- Exposure and health

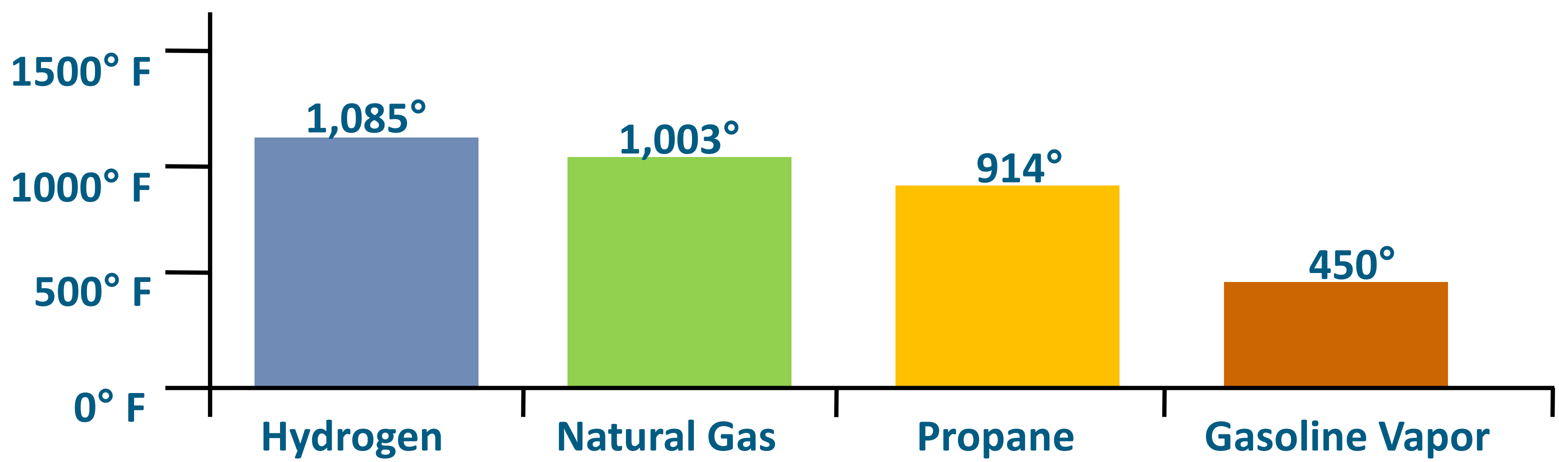
Hydrogen Properties: *A Comparison*

	Hydrogen Gas	Natural Gas	Gasoline
Color	No	No	Yes
Toxicity	None	Some	High
Odor	Odorless	Yes (mercaptan)	Yes (benzene)
Buoyancy *Relative to **Air***	14X Lighter	2X Lighter	3.75X Heavier
Energy by Weight	2.8X > Gasoline	~1.2X > Gasoline	43 MJ/kg
Energy by Volume	4X < Gasoline	1.5X < Gasoline	120 MJ/Gallon

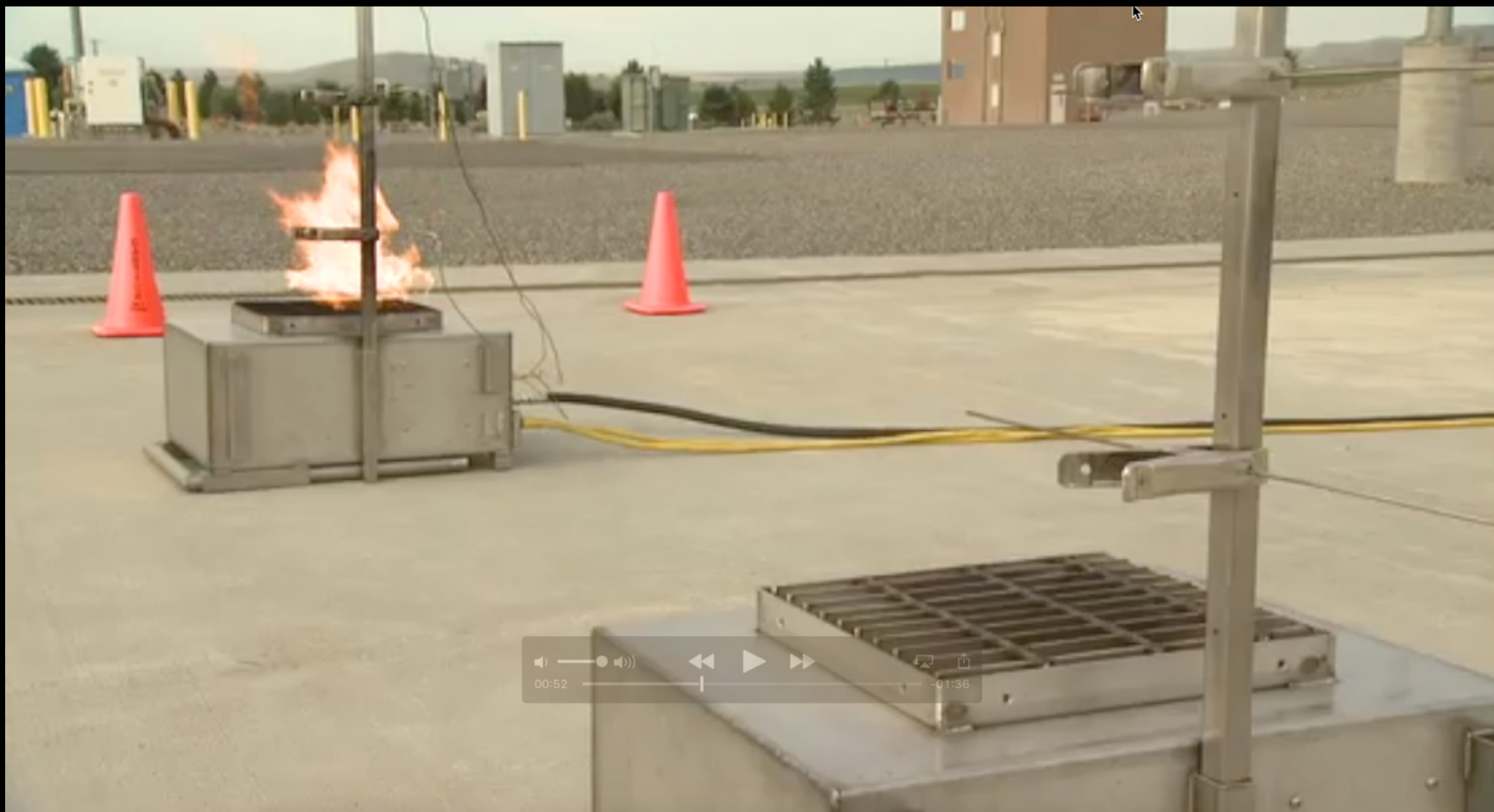
Source: California Fuel Cell Partnership

Vapor Density and Autoignition Temperature





Demonstration of Hydrogen Flames



Video download URL:
https://h2tools.org/sites/default/files/barilo/BurnDemo.mp4

How is H_2 Stored and Transported?

Well-established industrial supply system

Liquid (LH_2)

- Cryogenic: -423°F (-253°C)
- Double walled, vacuum insulated tanks with burst disks, vents, and pressure relief devices
- Low pressure - 50 psi

Gaseous (GH_2)

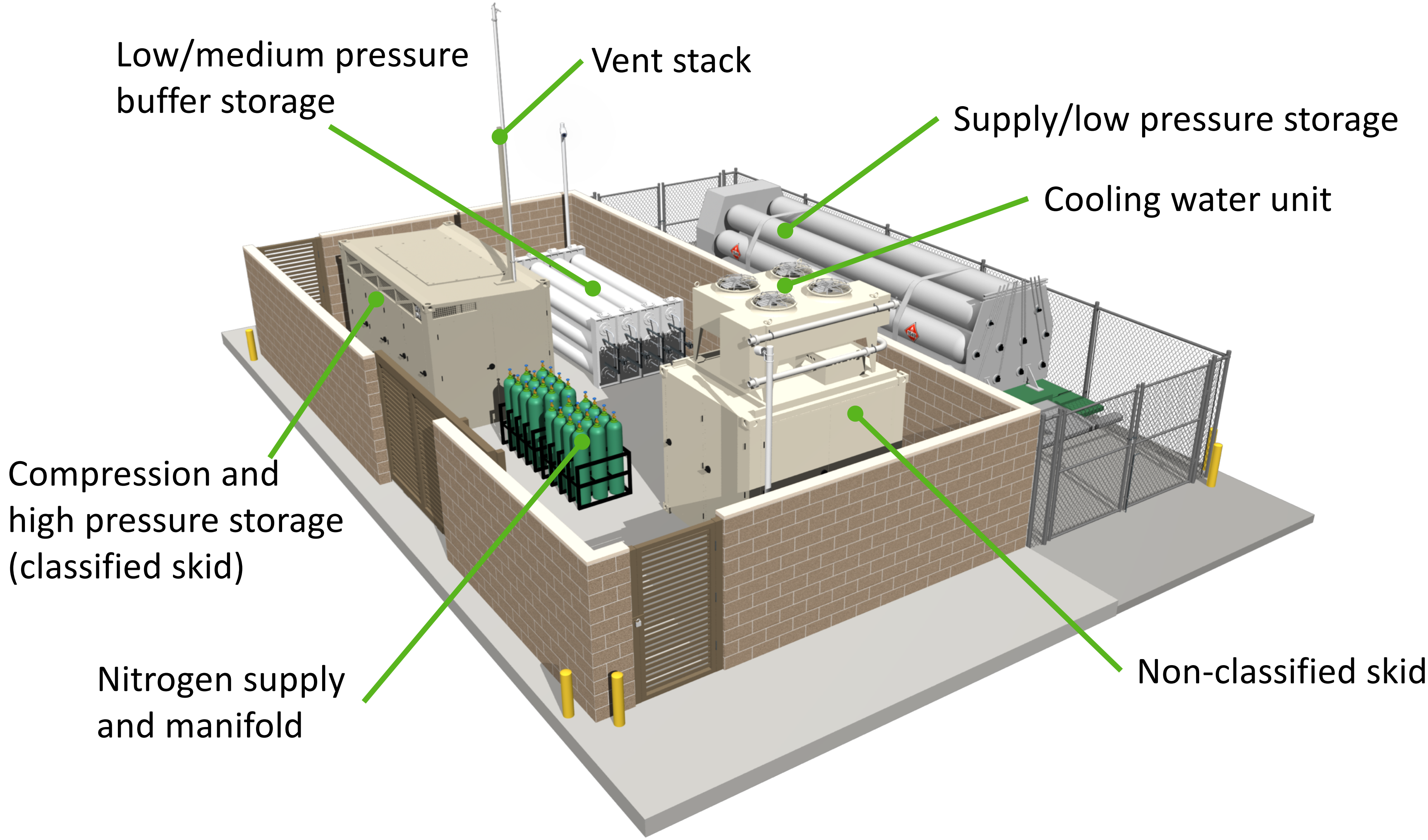
- Thick walled metallic (Type I) or composite reinforced tanks (Type II or III)
- 2400-8000 psi
  - *No liquid phase in compressed gas H_2 storage*
  - *Compression does not liquefy*

Typical Station Configurations

- Hydrogen can be produced at a central plant and delivered or made on site
- Delivered Hydrogen
  - Liquid – refill bulk storage tank
  - Gaseous- tube trailer swap or refill
  - Pipeline
- On-site production
  - Natural gas (Steam Methane Reformer- SMR)
  - Electrolysis of water
- Final product = gaseous hydrogen dispensing

Example FCV Gaseous H_2 Station Configuration

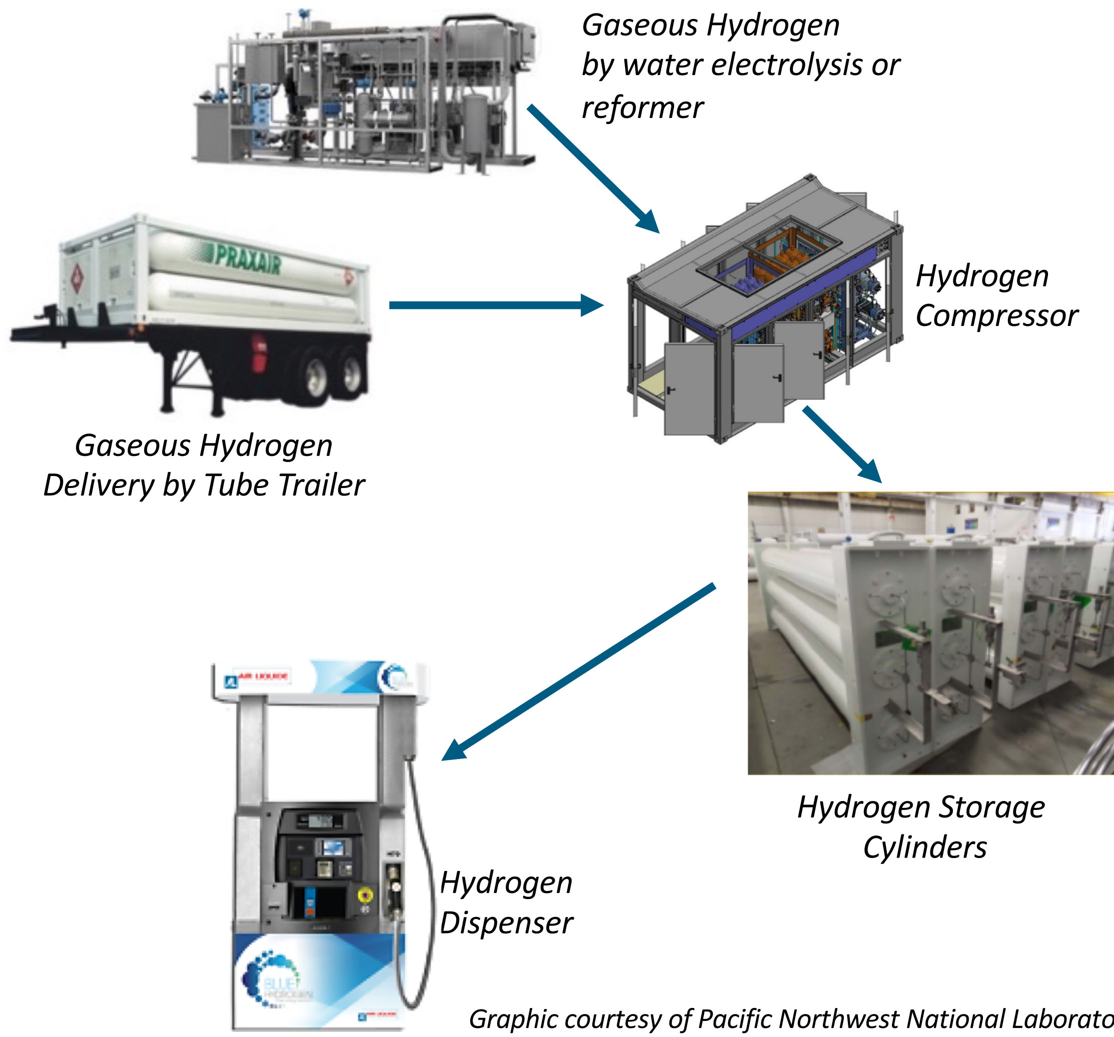
Gaseous Hydrogen Storage System Layout



Source: Air Liquide

FCV H_2 Fueling Stations - **Gaseous H_2 Storage**

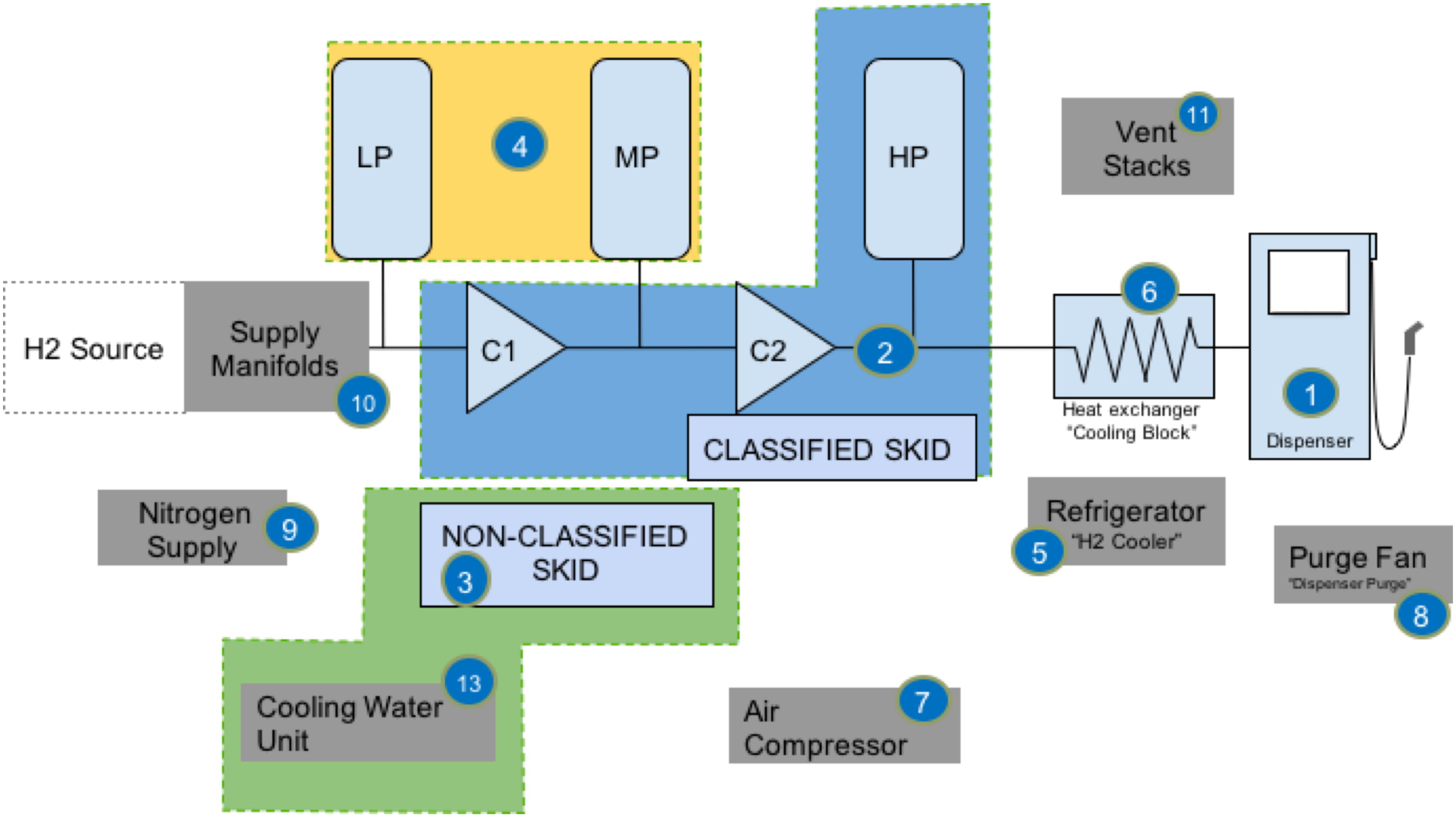
- Delivered to fueling station by trailer, or generated onsite
- Compressed and stored onsite in cylinders
- Piped to dispenser for fueling vehicles



Graphic courtesy of Pacific Northwest National Laboratory

H_2 Fueling Stations

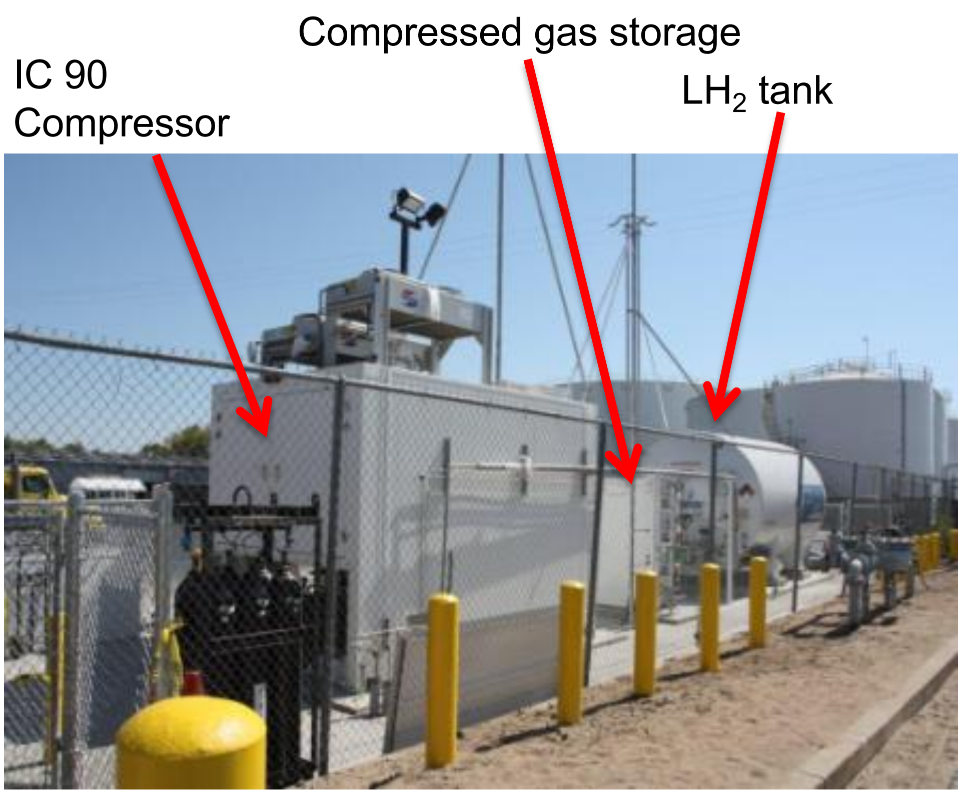
Gaseous H_2 Storage System Flow Diagram



Source: Air Liquide

Hydrogen Fueling Stations
Liquid Hydrogen Delivery

Liquid hydrogen can be delivered to the fueling station by tanker truck, as is shown for this hydrogen and gasoline station



Fueling dispenser & canopy

Photos: California Fuel Cell Partnership and Linde.

- New Class of Turnkey *Hydrogen Refueling Appliance*
- Enables Cost-Effective Commercial & Industrial Fleets
- Produces Hydrogen On-Site & On-Demand: Water & Electricity
- Modular, Drop-In Installation, Supports 10-20 FCEVs
- Networkable Solution for Clean Mobility Fleets

H2refuel
U.S. Department of Energy
$1MM H-Prize Winner

Source: Ivys Energy Solutions

General Station Safety Systems

- Design elements
  - Engineering safety margins and risk analysis (HAZOP, FMEA, etc.)
    - Hydrogen Risk Assessment Model (HyRAM) available on h2tools.org
  - Hydrogen compatible materials
    - Prevents hydrogen embrittlement
  - Siting to established regulations
    - IFC and NFPA 2
- Other systems
  - Emergency stops
  - Dispenser hose break-away devices
  - Impact sensors at dispenser
  - Leak detection with automatic shut-off
  - Redundant isolation of systems

The Safety Basics

Hydrogen safety, like all flammable gas, relies on these key safety considerations:

- Eliminate hazards or define mitigation measures
- Ensure system integrity
- Provide proper ventilation to prevent accumulation
- Manage discharges
- Detect and isolate leaks
- Train personnel

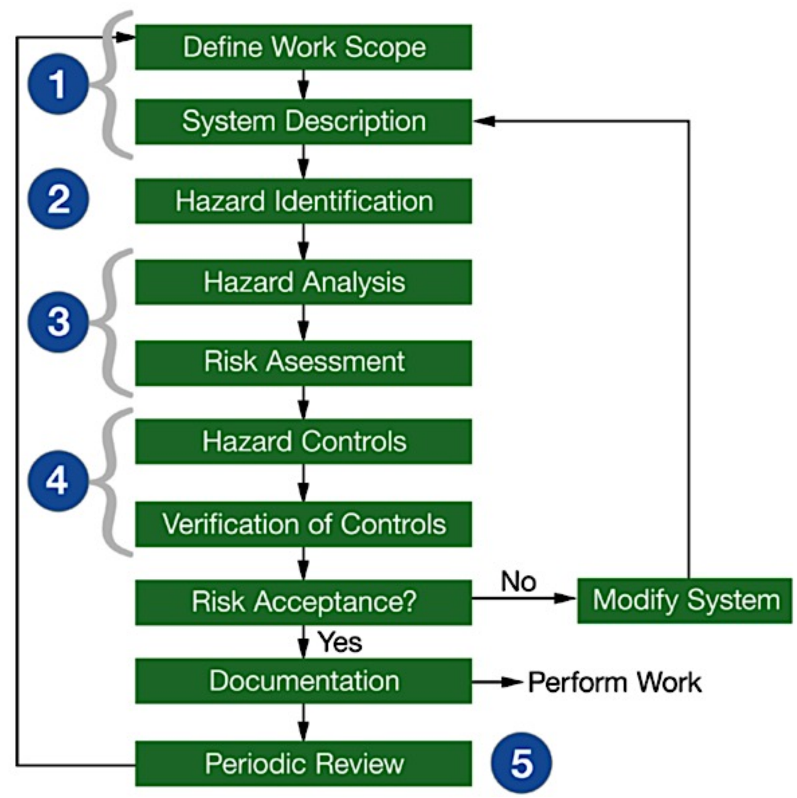
Fuel cell backup power connected to a data center

Analyzing the Hazards

A hazard analysis shall be conducted on every hydrogen project by qualified personnel with proven expertise in hydrogen systems, installations, and hazard analysis techniques.

Hazard Analysis and Risk Assessment Steps

1. Define the scope of work
2. Identify hazards
3. Evaluate the impact of the hazards on
   a) the environment and public
   b) the facility and institution
   c) the equipment and personnel
4. Assess the likelihood and severity of each hazard
5. Resolve hazards
6. Follow up actively with periodic review of work scope and hazards



See https://h2tools.org/bestpractices/safety_planning/hazard_and_risk, and https://h2tools.org/sites/default/files/h2_snapshot_v2i2.pdf

General Considerations

Best practices for compressed hydrogen containers supplying a manifold:

- locate outside
- use welded lines to connect to indoor equipment
- be provided with an exterior shutoff valve and flow restrictor or excess flow valve

Store hydrogen cylinders and storage tanks outside at safe distances from:

- structures
- ventilation intakes
- vehicle routes
- even while in use

Code and Standards: IFC, IBC, IFGC, NFPA 2, NFPA 70

Indoor Storage - Safety Considerations

Safety considerations for indoor storage or use of bulk gaseous hydrogen include:

- Buildings shall be constructed of noncombustible materials.
- Hydrogen sensors shall be installed at ceiling level near ventilation exhaust.
- Install automatic shutoff that activates if a leak or fire is detected in the facility that is being supplied with hydrogen.
- Avoid ignition sources in storage areas.
- Classified electrical equipment shall be be in close proximity to storage systems.
- Gaseous hydrogen system components shall be electrically bonded and grounded.

Code and Standards: IFC, IBC, IFGC, NFPA 2, NFPA 70

Passive Ventilation, Indoors and Outdoors

- **Passive ventilation with roof or eave vents can prevent H_2 buildup if a leak or discharge occurs**
  - Evaluate passive ventilation thoroughly to ensure that a hydrogen leak will dissipate safely both normal conditions and emergency situations.
  - Locate Inlet openings at floor level in room exterior walls.
  - Locate outlet openings at highest point in room exterior walls or the roof to avoid pockets of $H_{2.}$
- **Passive/natural ventilation easily applied outdoors**
  - Avoid pockets under weather awnings.
  - Ensure at least 75% open on sides.

Code and Standards: IFC 2311.7.1/5808.3.1, IFGC 703.1.1, NFPA 2-6.17

Active (Mechanical or Forced) Ventilation

- **When passive ventilation is insufficient, active ventilation can be used to prevent the accumulation of flammable mixtures.**
  - Use fan motors, actuators for vents and valves with applicable electrical classification, approval for H_2 use.
  - Ensure active ventilation is operational **at all times when H_2 is present or could be accidentally released.**
  - Automatically shutdown H_2 equipment and/or isolate H_2 source if active ventilation system fails.
  - Install H_2 sensors at the exhaust within the enclosure.

Compressor HEE with mechanical ventilation

Be aware that no practical indoor ventilation features can quickly disperse hydrogen from a massive release by a pressurized vessel, pipe rupture, or blowdown.

Code and Standards: IFC 2311.7.1/5808.3.1, IFGC 703.1.2, NFPA 2-6.17

Ventilation Reduces Chance of Flammable Mix

- **Reduce likelihood of flammable H_2-air mix in case of release or leak with <u>air dilution</u>**
  - Ventilation (passive or active) shall be not less than 1 scf/min/ft^2 (0.3048 Nm^3/min/m^2) of floor area over the area of storage or use
  - Minimum air rates dilute a potential H_2 leak to <25% of lower flammability limit (LFL) for all operations and credible accident scenarios. [25% LFL = 1% H_2 in air]
  - Exhaust shall be within 12 inches of ceiling
  - Supply shall be within 12 inches of floor

Exhaust air intake

Is there a problem here?

Code and Standards: IFC 2311.7.1/5808.3.1, IFGC 703.1.1, NFPA 2-6.17

Hydrogen Leak Detection

- Detection may be required by AHJ or code/standards
- Detection enhances safety of operation

Provide leak detection by:

- Hydrogen (or flammable gas) detectors in a room or enclosure, or
- Monitoring internal piping pressures and/or flow rates for changes that suggest a leak

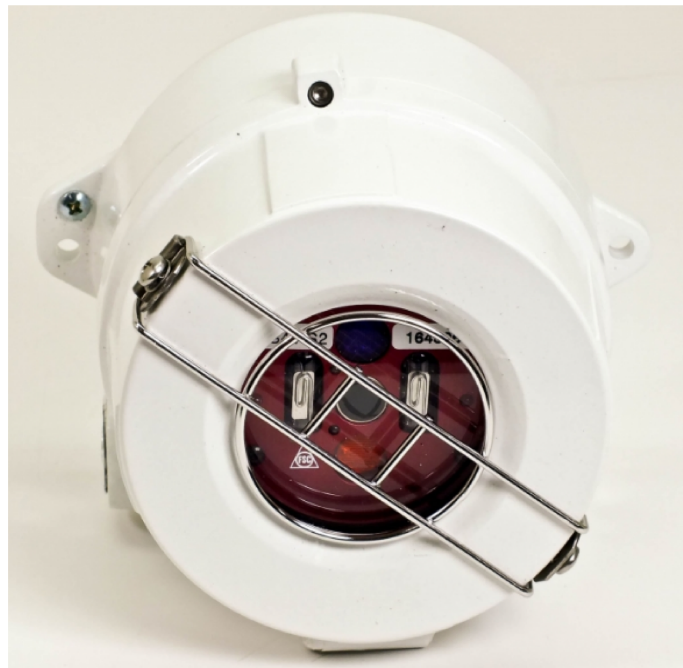
Other methods:

- H_2 detectors in close proximity to exterior piping
- Locate hydrogen piping within another pipe and monitor annulus for leaks

Code and Standards: IFC 5003.2.2, NFPA 2-7.1.22

H_2 Leak Detection Goals

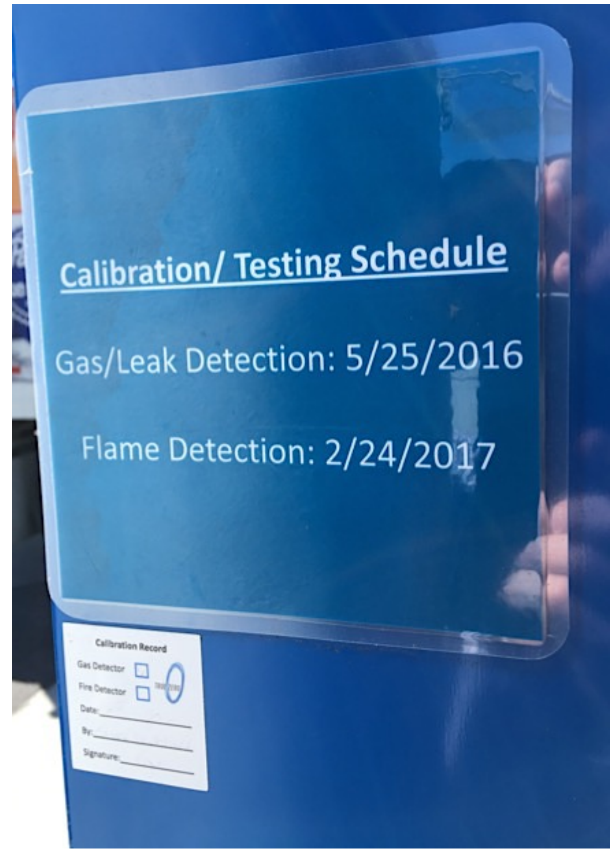
- Provide for automatic shut-off and isolation of hydrogen sources
- Shut down process equipment to a safe mode
- Control active ventilation
- Activate audible and visual alarms



Code and Standards: IFC 5003.2.2, NFPA 2-7.1.22

H_2 Leak Detection Performance

- Detection sensitivity of +/-0.25% by volume of H_2 in air
- Response time of <1 second at 1% H_2 in air
- Ensure any leaking hydrogen would pass by H_2 detector.
- Consider detector sensitivity to other gases, vapors
  - Explain such interference to personnel
- Recommend alarm at 1% H_2 / air [25% LFL]
- Require manual reset to restart automatic shutdown systems
- Perform routine maintenance / recalibration per manufacturer's instruction, typically every 3-6 months
  - Record events in facility records



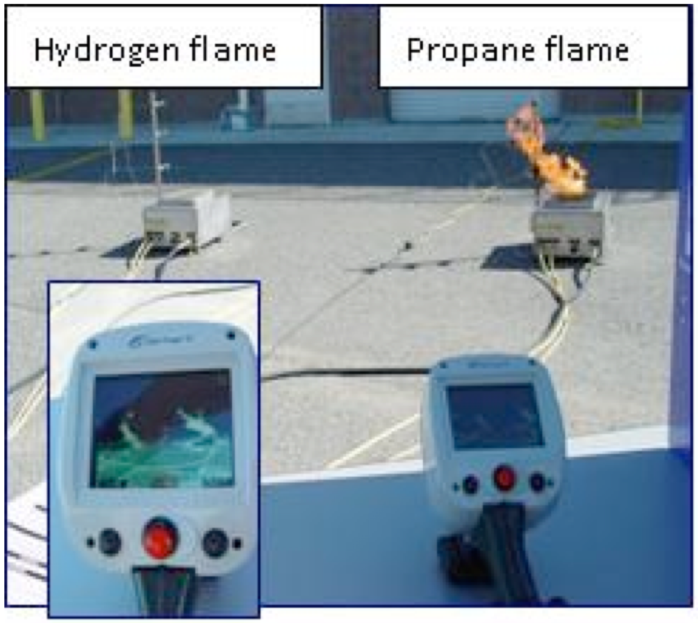
Code and Standards: IFC 5003.2.2, NFPA 2:2016 -7.1.22, 7.1.23, 103.1.18

Checking for H_2 Leaks Best Practices

Burning H_2 has pale blue flame, nearly invisible in daylight

H_2 flames emit low radiant heat - may not feel heat until very close to flame

- Use portable flame detector (e.g., thermal imaging camera) if possible
- Otherwise, listen for venting gas, watch for thermal waves that signal heat and flame
- Use a combustible probe (e.g., broom)
- Allow enough time to troubleshoot/debug monitoring system before placing it in service
- Where multiple gases are co-located, investigate and mitigate most hazardous



Hydrogen and propane flames in daylight

Photo courtesy of HAMMER

Flame Detection / Thermal Detectors

Hydrogen flames are almost invisible - **thermal and optical sensors should be used**

- To cover large area or volume, many thermal detectors are needed and should be located at or near the site of a potential fire
- Optical sensors for detecting H_2 flames operate in the ultraviolet or infrared spectral region
  - H_2 specific **Triple IR** detectors are the least likely to be susceptible to to false trips

Flame detectors are required in applications such as H_2 fueling station dispensers. Detector systems should:

- Provide rapid and reliable flame indication.
- Provide for H_2 source automatic shut-off / isolation
- Shut down the system to a safe mode
- Control active ventilation
- Activate audible and visual alarms

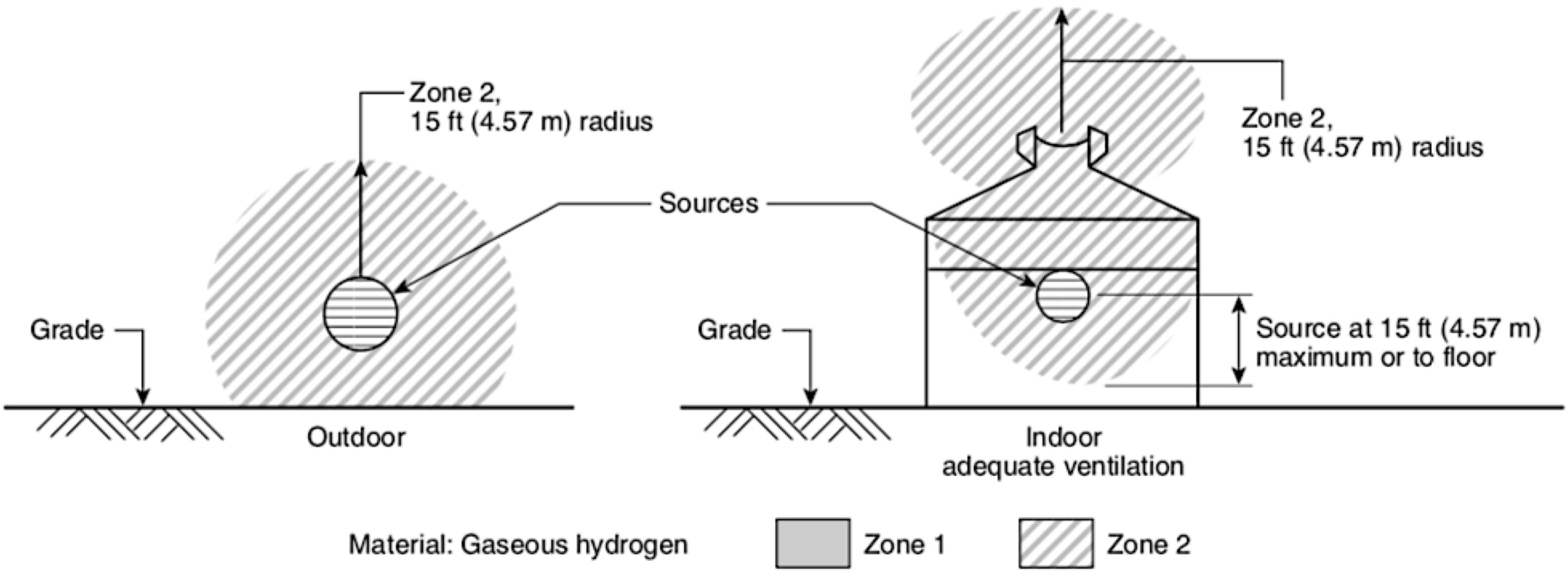
Code and Standards: NFPA 2-10.3.1./11.3.3

Electrical Equipment Considerations

- **Vent Fans** should be non-sparking (typical: aluminum or plastic)
- **Equipment** designed for use in H_2 service (Group B)
- H_2 systems should be electrically bonded and grounded
- Equipment not conforming to NEC (NFPA 70) requirements should be located outside the area classified as hazardous

Code and Standards: IFC 2309.2.3, NFPA 2-10.3.1.16

Electrical Equipment Classifications



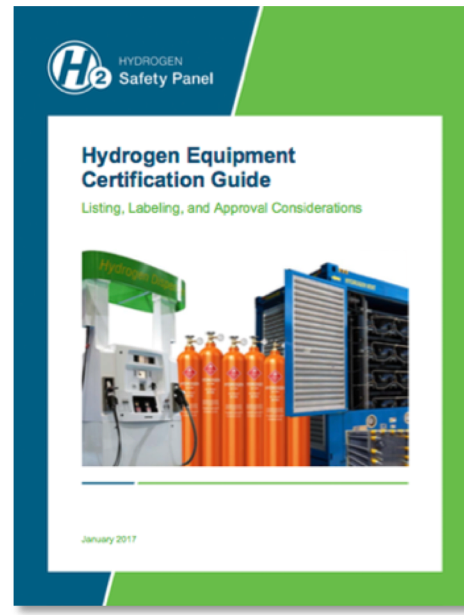
*All equipment must be rated for Group B applications (NFPA 70-500.6)

Addressing the Certification Challenge

A ***Hydrogen Equipment Certification Guide*** has been released to assist code officials, designers, owners, evaluators, and others with the application of the listing and approval requirements pertinent to the design and/or installation of hydrogen equipment as regulated by the model codes.

Gaps Addressed

- In the early market, the availability of systems or equipment that are listed, labeled, or certified is limited.
- When equipment is not listed or available, "approval" by the code official is required before installation occurs.



Benefits Provided

- Enables code users to better apply the requirements where the use of *listed, labeled, certified,* or *approved* equipment or methods is required, and to increase awareness and understanding of what the equipment is expected to do
- Increased consistency in the application of requirements with the expectation of an expedited permitting process
- Consistent application of requirements among providers, regardless of hydrogen experience, results in a level playing field as the technology emerges

Code and Standards: IFC 2309.2.2, NFPA 2-7.1.3
Download URL: https://h2tools.org/hsp/hecg

Emergency Shutdown System (ESS)

General ESS Considerations

- ESS should operate on:
  - Detection alarms
  - Fire alarms
  - Loss of ventilation
  - Activation of manual emergency shutdown devices (ESD)
- When activated, the ESS should:
  - De-energize unclassified electrical
  - Close all automatic shutoff control valves
- ESDs should be located:
  - On hydrogen equipment
  - Remote from the equipment (>25 feet)

Code and Standards: NFPA 2-7.1.23.13

ESS Shutdown Matrix

Example of a simple shutdown table

Equipment/Alarms	Instrument Air	Dispenser	Compressor Control Panel	Compressor	Compressor Diaphragm	H2 Storage	Hydrogen System Entry way	25 ft away from H2 System	Hydrogen Fill	Hydrogen Equipment Enclosure	Equipment Shutdown Scenario	Site Shutdown Scenario
E-Stop		●	●	●			●	●				●
Heat Detection		●		●		●				●		●
Flame Detection		●		●	●	●				●		●
Leak Detection		●		●	●	●						●
Hose Break		●							●		●	
Mechanical Ventilation										●	●	
High Pressure				●							●	
Low Pressure	●			●							●	
High Temperature		●		●							●	
Low Temperature		●		●							●	
Mechanical Relief Device	●	●		●		●			●		N/A	N/A

Equipment Shutdown - Stops fill and isolates valves to the dispenser and contacts system operator

Site Shutdown Scenario - Stops Fill, isolates storage system, shuts down compressor and contacts fire department and/or system operator

- Used to identify safety critical equipment and functions
- Enables designers and reviewers to ensure that critical actions are aligned with appropriate equipment
- Can aid in equipment approval

Gaseous H_2 Outdoor Storage

- Hydrogen cylinders and storage tanks should be stored outside at a safe distance from structures, ventilation intakes, and vehicle routes
- Separation distance requirements based on quantity of hydrogen
- A bulk hydrogen compressed gas system has a capacity of more than 5,000 scf and consists of:
  - storage containers
  - pressure regulators
  - pressure relief devices
  - compressors
  - manifolds and piping

Note that the storage system terminates at the source valve

Photo courtesy of Shell Hydrogen

Code and Standards: NFPA 2-7.3.2.3

Selection of Materials

- Materials used in H_2 piping, valves, tanks and seals must be carefully selected to account for deterioration when exposed to H_2 at maximum operating conditions
- Exposure of some metals to H_2 can lead to:
  - embrittlement
  - cracking and/or significant loss in tensile strength
  - ductility
  - fracture toughness

  These can result in premature failure in load-carrying components
- Additionally, hydrogen diffuses through many materials, particularly nonmetals, due to its small molecular size

Preferred

- austenitic stainless steels, aluminum alloys, copper, and copper alloys.

Avoid

- Nickel and most nickel alloys - subject to severe hydrogen embrittlement
- Gray, ductile, and malleable cast irons

See http://www.h2tools.org/tech-ref/technical-reference-for-hydrogen-compatibility-of-materials

Codes and Standards: IFGC 5003.2.2.1, IFGC 704.1.2.3, NFPA 2-10.3.1.3

Hydrogen Piping System Layout and Design

- Design in accordance with applicable codes and standards
- Minimize leaks - use of welded joints where possible
- To the extent possible, do not conceal H_2 piping - arrange for easy joint / fittings access (to check for leaks)
- Minimize chance of personal injury (i.e., contact with cold surfaces, head impact, tripping hazards, etc.)
- Minimize stresses (structural and thermal) in piping components and connected equipment
- Provide proper sizes and settings of pressure relief devices
- Include properly labeled shutoff valves at safe locations
- Label piping to indicate content, flow direction, and design and test pressures

Flow restrictors, such as orifice meters, in supply lines are effective means of limiting supply flow rate and controlling leakage rate.

Codes and Standards: IFGC 704.1.2.3, ASME B31.12, CGA G-5.5

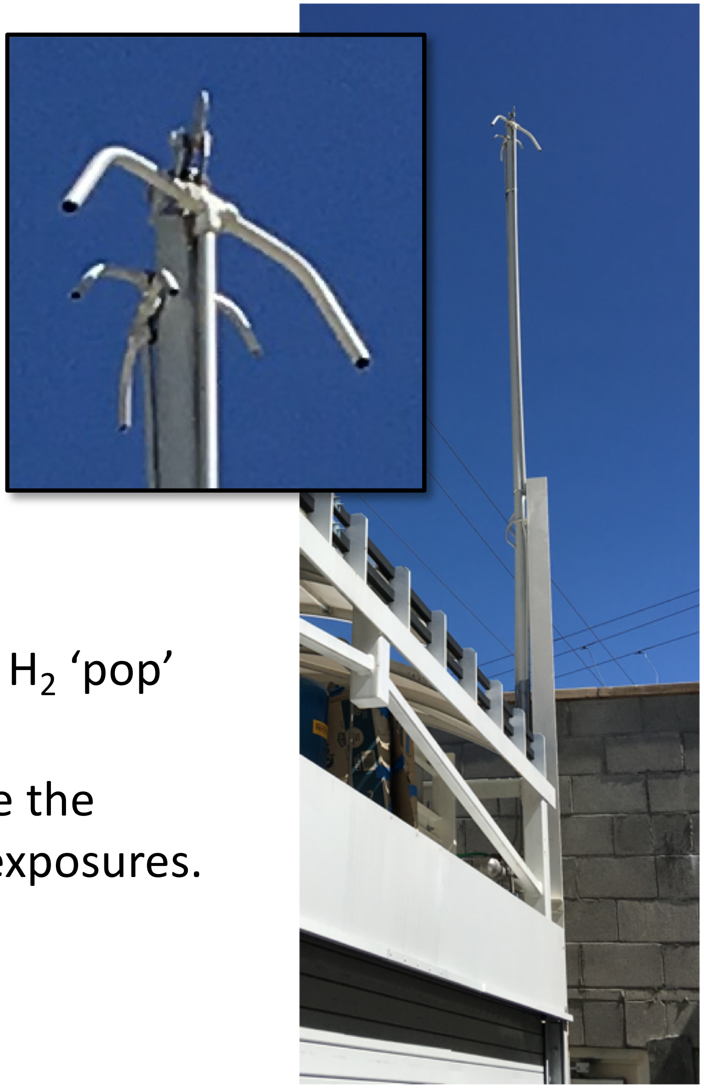
Hydrogen Vent Lines

H_2 vent lines (including pressure relief lines and cryogenic boil-off) should be vented to safe outside locations

Vents should be designed to:

- be unobstructed and protected from the weather
  - moisture or ice can accumulate and restrict flow
- carry the excess flow of the venting gas or liquid
- be leak tight and use welded or non-fusible joints
- avoid air intrusion or be designed to handle possible H_2 'pop' deflagration inside (~145 psig / 1000 kPa)
- safely release the unused hydrogen at a height above the facility roof, overhangs, personnel, equipment, and exposures.

See CGA G-5.5 for additional design criteria



Good and Bad Vent Stack Designs

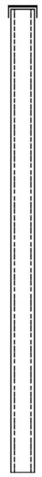


Figure 5—Example of an acceptable vent stack configuration with vent cap for relief device

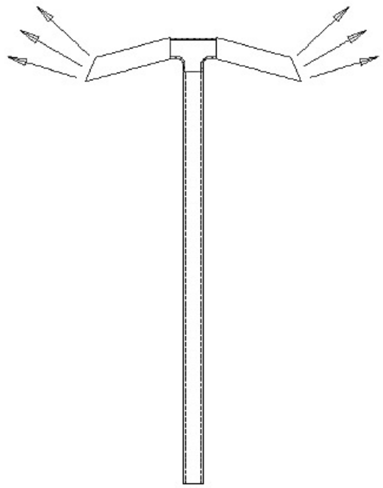


Figure 6—Example of an acceptable vent stack configuration with a miter cut

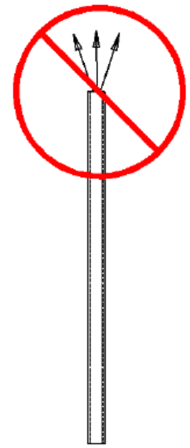


Figure 9—Example of an unacceptable vent stack that allows water accumulation

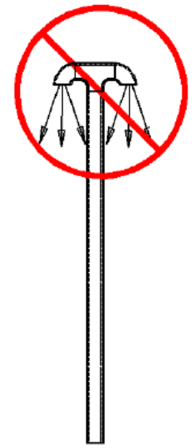


Figure 10—Example of an unacceptable vent stack that diverts gas downward

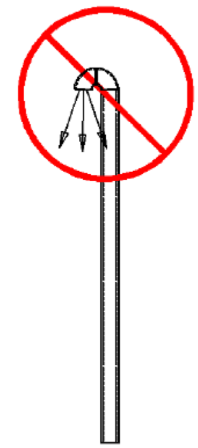


Figure 11—Example of an unacceptable vent stack that diverts gas downward; unbalanced thrust

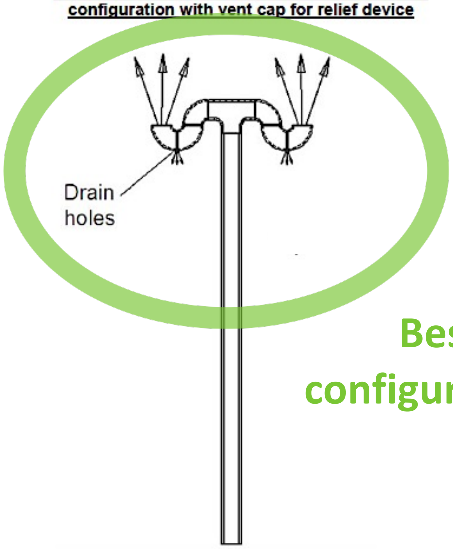


Figure 7—Example of an acceptable vent stack configuration with water drainage holes

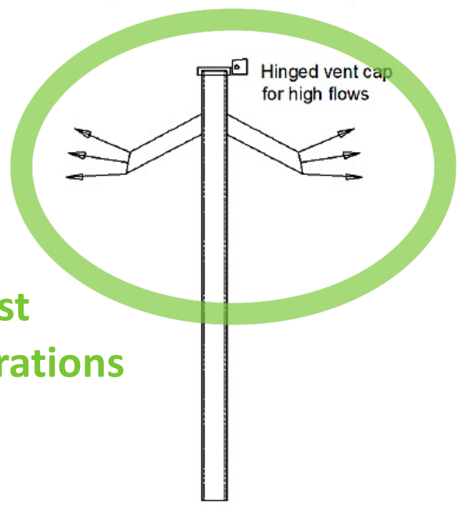


Figure 8—Example of an acceptable vent stack configuration with top hinged vent cap

Best configurations

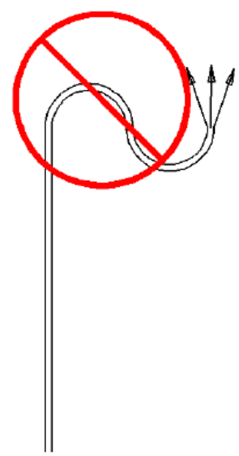


Figure 12—Example of an unacceptable vent stack with no drain (water can freeze in trap); unbalanced thrust

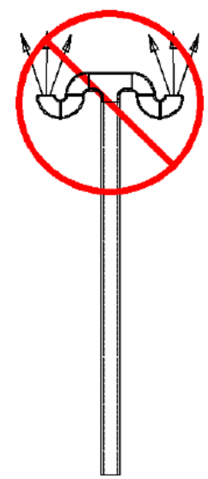


Figure 13—Example of an unacceptable vent stack with no drain holes

Source: CGA G-5.5

Codes and Standards Map for FCVs

Vehicle

Refueling Guidelines
SAE J2601

Interface Standards
HGV 4.3 – Temperature Comp.
SAE J2719
OIML and NIST Handbook 44

Fuel Cell Vehicle System
GTR (harmonized with ISO and SAE J2978)
FMVSS
SAE J2615 – System Performance
SAE J2572 – Fuel Consumption Measurement
SAE J2574 – General Vehicle Safety
SAE J2617 – Stack Performance
SAE J2574 – Design for Recycling PEM stacks

Station

Dispenser Component Standards
CSA HGV 4.1 - Dispenser
CSA HGV 4.2 - Hose
CSA HGV 4.4 - Breakaway
CSA HGV 4.5 - Priority and Sequencing
CSA HGV 4.6 - Manual Valves
CSA HGV 4.7 - Automated Valves

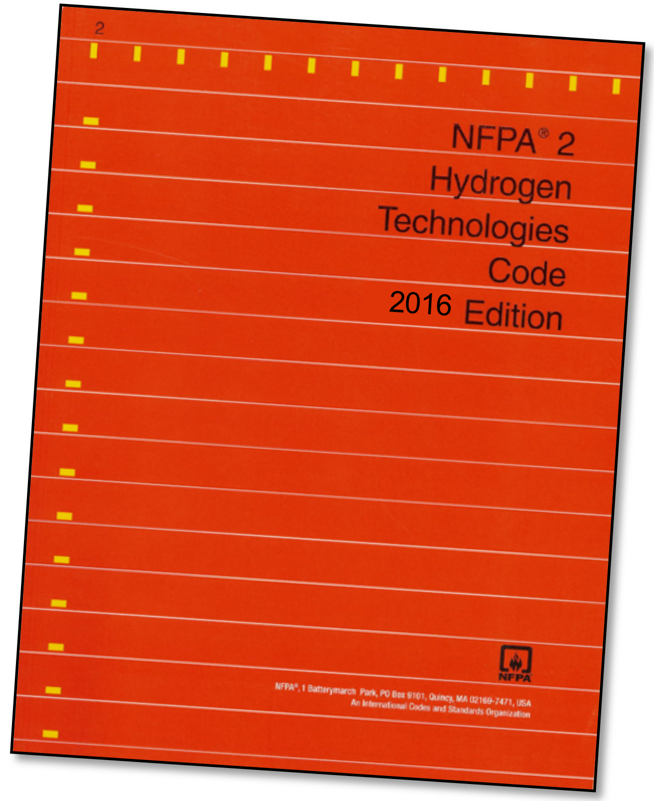
Compression & Storage
NFPA 2 and Local Codes
ASME BPVC - Storage
CSA HGV 4.8 – Compressors

Installation
NFPA 2 and Local Codes
NEC
ASME 31.12
CSA HGV 4.9 - Stations
ISO 19880-1

Source: Air Liquide

Critical Infrastructure H_2 Codes & Standards

International Fire Code (IFC)



NFPA 2 Hydrogen Technologies Code

Hydrogen Tools

A Transformative Step Towards Hydrogen Adoption

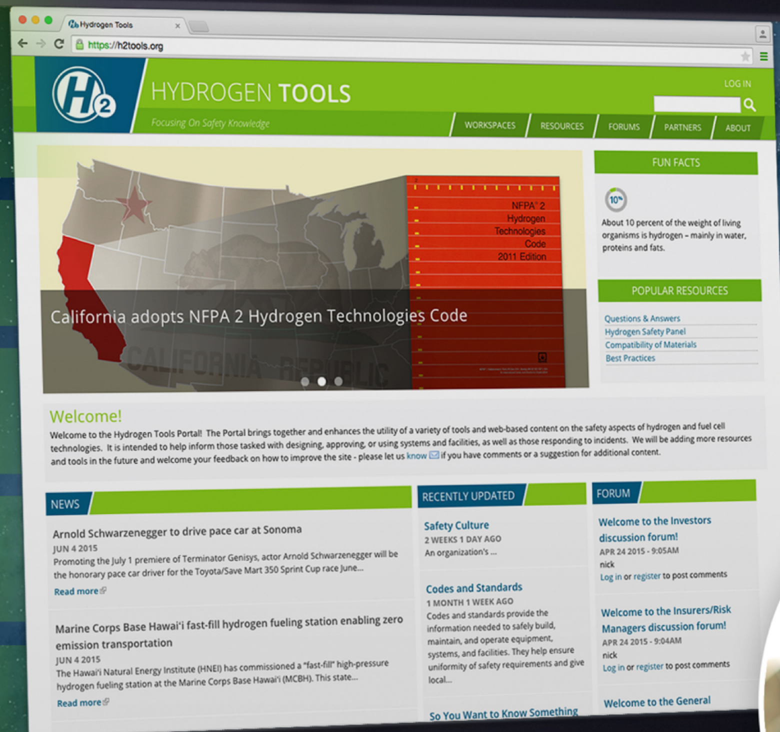
CENTRALIZED LOCATION organizes current H_2 resources in one robust location—including many proven tools, with plans for adding future content

FOCUSED CONTENT tailored to the specialized needs of H_2 user groups

RESPONSIVE DESIGN enables H_2 safety work across both desktop and mobile devices

TRUSTED COMMUNITIES fostered through social networking around H_2 subject matter expertise

EXPANDABLE FORMAT built with frequently requested future feature sets in mind

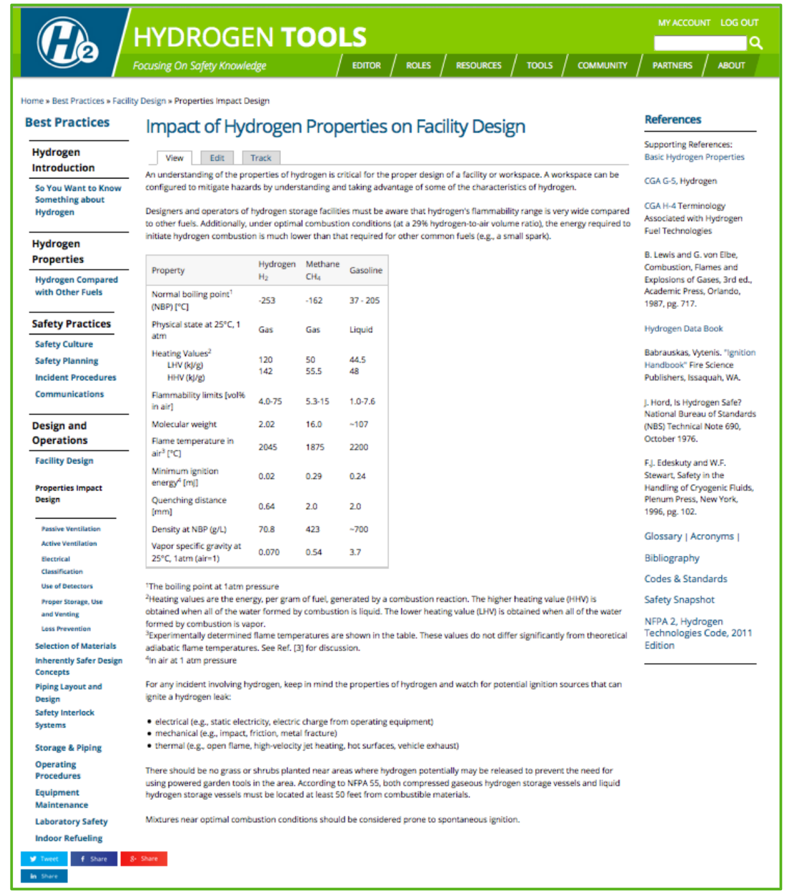


http://h2tools.org

› **Credible** and **reliable** safety information from a **trustworthy** source

H2tools.org/bestpractices
…Sharing Experience, Applying Best Practices

- Introduction to Hydrogen
  - So you want to know something about hydrogen?
- Hydrogen Properties
  - Hydrogen compared with other fuels
- Safety Practices
  - Safety culture
  - Safety planning
  - Incident procedures
  - Communications
- Design and Operations
  - Facility design considerations
  - Storage and piping
  - Operating procedures
  - Equipment maintenance
  - Laboratory safety
  - Indoor refueling of forklifts



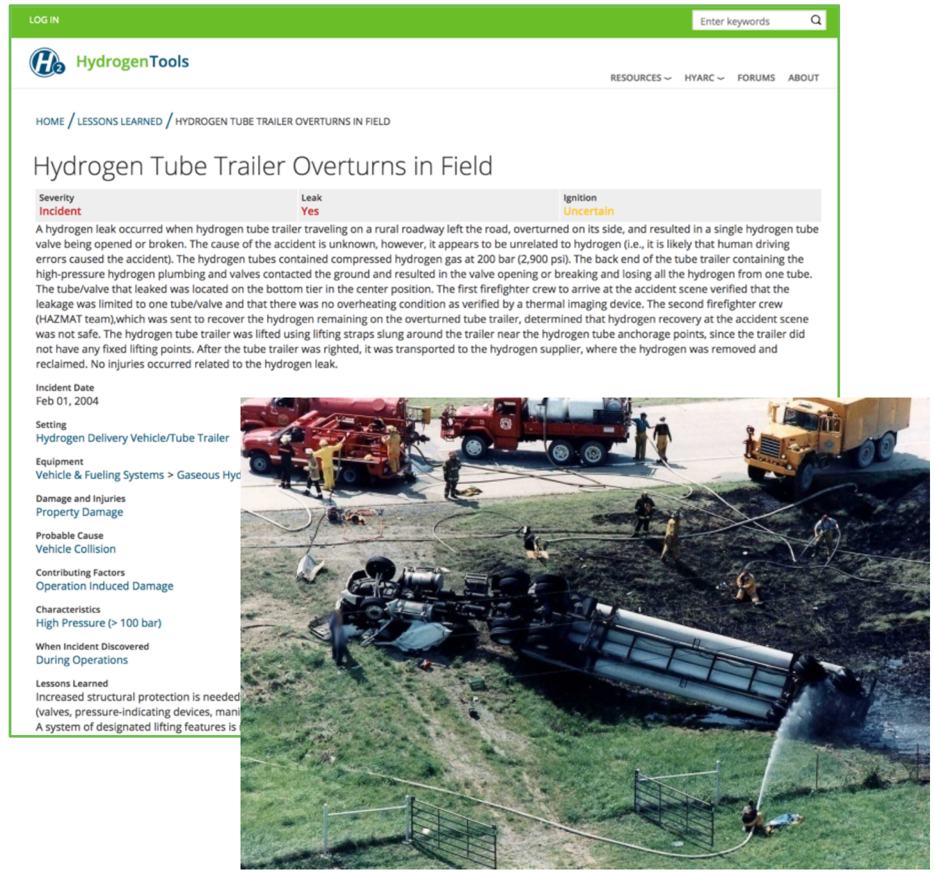
Safety events from "H2incidents.org" illustrate what can go wrong if best practices are not followed.

URL: http://h2tools.org/bestpractices

H2tools.org/lessons
…Capturing the Event, Focusing on Lessons Learned

Each safety event record contains:

- Description
- Severity (Was hydrogen released? Was there ignition?)
- Setting
- Equipment
- Characteristics (High pressure? Low temperature?)
- Damage and Injuries
- Probable Cause(s)
- Contributing Factors
- Lessons Learned/Suggestions for Avoidance/Mitigation Steps Taken



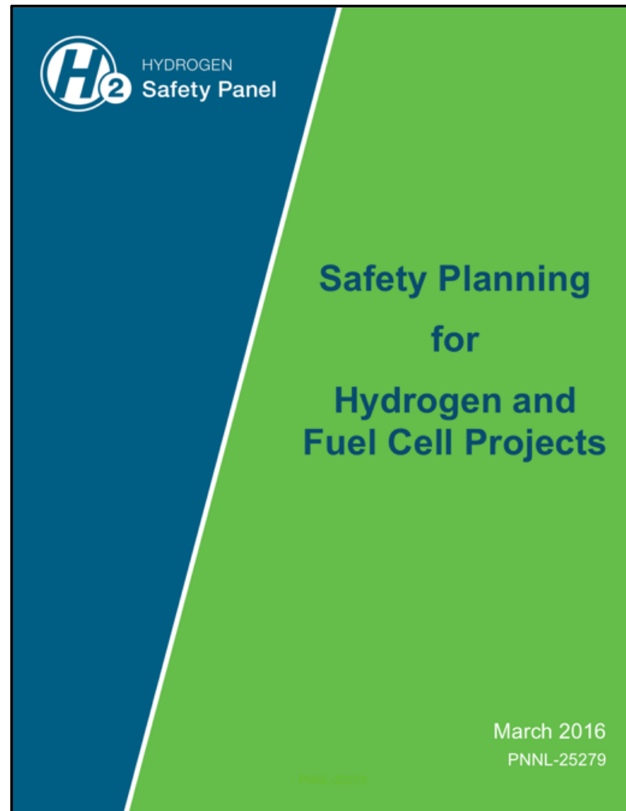
Tube trailer rollover

URL: http://h2tools.org/lessons

Guidance for Safety Planning of H_2 Projects

Safety planning should be an integral part of the design and operation of an H_2 system.

- Originally developed by the HSP for the U.S. Department of Energy in 2005
- The document provides information on safety practices for hydrogen and fuel cell projects
- The project safety planning process is meant to help identify risks and avoid potential hydrogen and related incidents.
- This document can aid in generating a good safety plan that will serve as a guide for the safe conduct of all work related to the development and operation of hydrogen and fuel cell equipment.



URL: https://h2tools.org/hsp/reviews

Hydrogen Safety Considerations Checklist

- Intended users
  - Those developing designs for hydrogen systems
  - Those involved with the risk assessment of hydrogen systems.
- While fairly inclusive, it is not possible to include all variables that need to be considered
- A hazard analysis process should include
  - Personnel who are familiar with applicable codes and standards
  - Team members with expertise in the technical aspects of the specific project

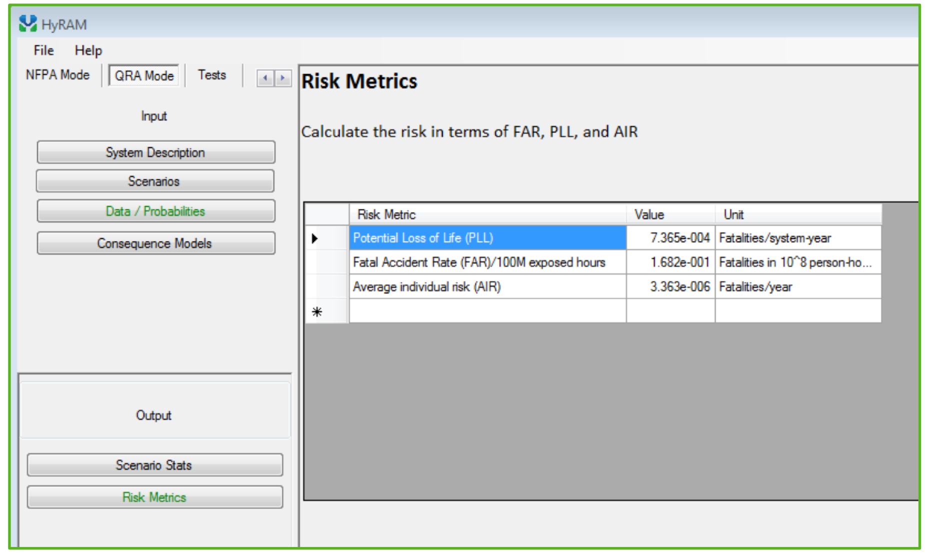
Hydrogen Safety Checklist

	Approach	Examples of Actions
Plan the Work	Recognize hazards and define mitigation measures	☐ Identify risks such as flammability, toxicity, asphyxiates, reactive materials, etc. ☐ Identify potential hazards from adjacent facilities and nearby activities ☐ Address common failures of components such as fitting leaks, valve failure positions (open, closed, or last), valves leakage (through seat or external), instrumentation drifts or failures, control hardware and software failures, and power outages. ☐ Consider uncommon failures such as a check valve that does not check, relief valve stuck open, block valve stuck open or closed, and piping or equipment rupture. ☐ Consider excess flow valves/chokes to size of hydrogen leaks ☐ Define countermeasures to protect people and property. ☐ Follow applicable codes and standards.
	Isolate hazards	☐ Store hydrogen outdoors as the preferred approach; store only small quantities indoors in well ventilated areas. ☐ Provide horizontal separation to prevent spreading hazards to/from other systems (especially safety systems that may be disabled), structures, and combustible materials. ☐ Avoid hazards caused be overhead trees, piping, power and control wiring, etc.
	Provide adequate access and lighting	Provide adequate access for activities including: ☐ Operation, including deliveries ☐ Maintenance ☐ Emergency exit and response
	Approach	**Examples of Actions**
Keep the Hydrogen in the System	Design systems to withstand worst-case conditions	☐ Determine maximum credible pressure considering abnormal operation, mistakes made by operators, etc., then design the system to contain or relieve the pressure. ☐ Contain: Design or select equipment, piping and instrumentation that are capable of maximum credible pressure using materials compatible with hydrogen service. ☐ Relieve: Provide relief devices that safely vent the hydrogen to prevent damaging overpressure conditions. ☐ Perform system pressure tests to verify integrity after initial construction, after maintenance, after bottle replacements, and before deliveries through transfer connections.
	Protect systems	☐ Design systems to safely contain maximum expected pressure or provide pressure relief devices to protect against burst. ☐ Mount vessels and bottled gas cylinders securely. ☐ Consider that systems must operate and be maintained in severe weather and may experience earthquakes and flood water exposures. ☐ De-mobilize vehicles and carts before delivery transfers or operation. ☐ Protect against vehicle or accidental impact and vandalism. ☐ Post warning signs.
	Size the storage appropriately for the service	☐ Avoid excess number of deliveries/change-outs if too small. ☐ Avoid unnecessary risk of a large release from an oversized system.

URL: https://h2tools.org/sites/default/files/HydrogenSafetyChecklist.pdf

Quantitative Risk Assessment

- Developed toolkit to enable integrated probabilistic and deterministic modeling
  - Relevant H_2 hazards (thermal, mechanical)
  - Probabilistic models (traditional QRA models) & H_2-specific component data
  - H_2 phenomena (gas release, heat flux, overpressure)
- Variable Users
  - High level, generic insights (e.g., for C&S developers, regulators)
  - Detailed, site-specific insights (e.g., for AHJs, station designers)
- Currently, two interfaces (views):
  - **"QRA mode"** and **"Physics mode"**
  - Planned "performance-based design" mode for targeted analyses



HYRAM
HYDROGEN RISK ASSESSMENT MODELS

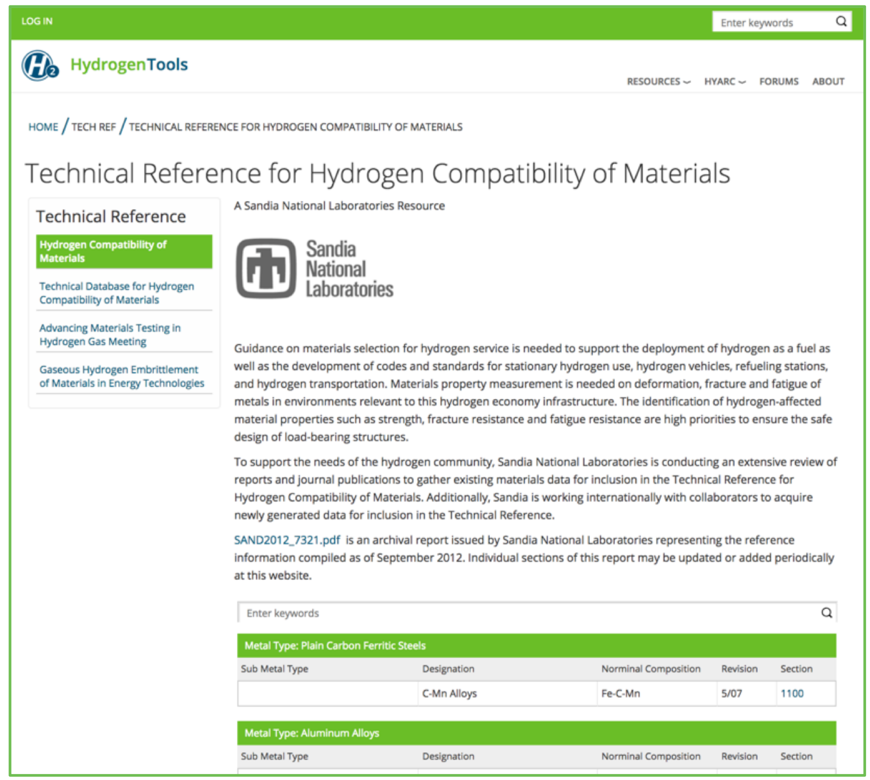
First-of-its-kind software tool for integrating H_2 consequence models w/ QRA models
Includes behavior models & data developed through FY12

URL: http://hyram.sandia.gov

Technical Reference for Hydrogen Compatibility of Materials

Consists of material specific chapters (as individual PDF files) summarizing mechanical-property data from journal publications and technical reports

- Plain Carbon Ferritic Steels
- Low-Alloy Ferritic Steels
- High-Alloy Ferritic Steels
- Austenitic Steels
- Aluminum Alloys
- Copper Alloys
- Nickel Alloys
- Nonmetals



URL: http://h2tools.org/tech-ref/technical-reference-for-hydrogen-compatibility-of-materials

H_2 Fueling Station Permitting Videos

Permitting Hydrogen Fueling Stations Part One

Permitting Hydrogen Fueling Stations Part Two: Planning and Building Considerations

Permitting Hydrogen Fueling Stations Part Three: Fire Department Regulations

Permitting Hydrogen Fueling Stations Part Four: Annual Inspections

- Gives AHJs, Project Developers, and other interested parties a quick orientation in permitting hydrogen fueling stations.
- Provides basic background information on hydrogen technologies followed by a description of the permitting process including an overview of key codes and standards.
- Contains interviews with code officials, emergency responders, and technical experts as well as footage of hydrogen stations.

Videos available at https://h2tools.org/videos

Working with First Responders

Preplanning

- Facility owners and first responders should work together to perform preplanning activities. This should include a tour of the hydrogen facilities with focused attention on safety features and emergency shutoffs.

Training

- Training of emergency response personnel should be a high priority to ensure that these personnel understand how to properly respond to a hydrogen incident.
- A variety of resources are available to assist with this training (and discussed in the next slide).

Equipment

- A hydrogen fire is often difficult to detect without a thermal imaging camera or flame detector. First responders have one available for their use.

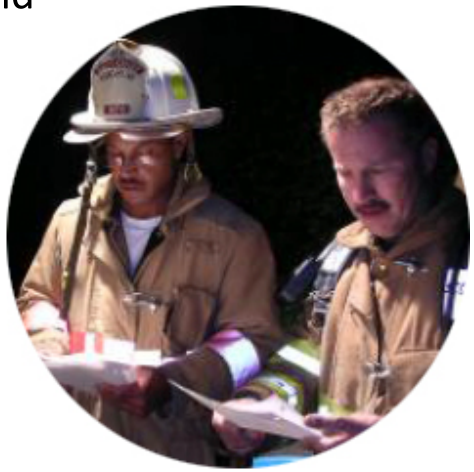
Volpentest HAMMER Federal Training Center

Code and Standards: IFC 5003.9.1

First Responder Hydrogen Safety Training

- **National Goal**
  - Support the successful implementation of hydrogen and fuel cell technologies by providing technically accurate hydrogen safety and emergency response information to first responders
- **Integrated Activities**
  - Online, awareness-level training (http://hydrogen.pnl.gov/FirstResponders/)
  - Classroom and hands-on operations-level training
  - National training resource (enabling trainers)

(http://h2tools.org/fr/nt)



A properly trained first responder community is critical to the successful introduction of hydrogen fuel cell applications and their transformation in how we use energy.

Introducing a New Hydrogen Safety Resource

AIChE Center for Hydrogen Safety

A timely partnership to enable broader impact and sustainability of significant safety resources

Pacific Northwest NATIONAL LABORATORY AIChE

A not-for-profit membership organization within AIChE

Promotes the safe operation, handling, and use of hydrogen across all applications by providing

- Diverse accredited education and outreach resources, including accredited first responders
- Hydrogen safety guidelines
- Global hydrogen safety conferences
- Greater accessibility to the PNNL Hydrogen Safety Panel for industry, state, and government agencies
- Leadership in addressing safety gaps
- Access to and utilization of the Hydrogen Tools Portal for dissemination of information

PNNL is partnering with AIChE to establish a

CENTER FOR Hydrogen SAFETY

HYDROGEN Safety Panel

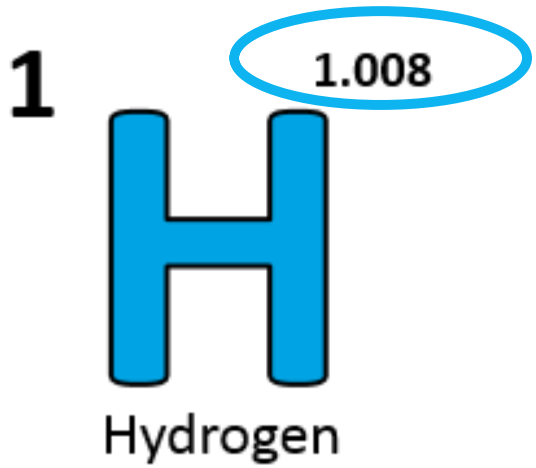
HYDROGEN Emergency Response Training Resources

Opportunities for Outreach and to Increase Awareness

Celebrate National Hydrogen & Fuel Cell Day

October 8 or 10/8

(Held on its very own atomic- weight-day)



Information and Training Resources to Increase Awareness

H2tools.org

INCREASE YOUR H_2IQ

Download for free at:
energy.gov/eere/fuelcells/downloads/increase-your-h2iq-training-resource

Learn more at: energy.gov/eere/fuelcells

Concluding Thoughts

- Hydrogen can be used safely – the industrial sector has over 80 years of operating experience
- There have been significant efforts over the past 15 years to develop codes, standards and guides to support the safe implementation of hydrogen and fuel cell technologies
- Online resources are available to help code officials and project proponents better understand and apply the necessary safe practices for the successful deployment of this technology
- Stakeholders and the public benefit from an independent and experienced hydrogen safety review resource such as the HSP is involved in early design and safety planning activities

Thanks to Our Sponsors and Partners

- U.S. Department of Energy Fuel Cell Technologies Office (Sunita Satyapal, Director; and Laura Hill, Safety, Codes, and Standards Manager)
- Connecticut Center for Advanced Technologies (Joel Rinebold and Paul Aresta)

U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

CCAT Connecticut Center for Advanced Technology, Inc.

Thanks for Your Attention!

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