



HYDROGEN
Safety Panel

Hydrogen and Fuel Cells are Coming... Are You Ready?

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PNNL Hydrogen Safety Program

Hydrogen Safety Panel

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



Safety Knowledge Tools and Dissemination

- Hydrogen Lessons Learned
- Hydrogen Best Practices
- Hydrogen Tools (iPad/iPhone mobile application)
- Hydrogen Tools Portal (<http://h2tools.org>)



Hydrogen Safety First Responder Training

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



Outline for Today's Presentation

- Fuel Cell Basics and Applications
- Properties of Hydrogen
- Primary Codes and Standards
- Fundamental Safety Considerations
- Hydrogen Safety Resources
- First Responder Training Resources
- Concluding Thoughts

Fuel Cell Basics and Applications

Why Hydrogen?

- Excellent energy carrier
- Nonpolluting
- Economically competitive
- As safe as gasoline
- Used safely for over 50 years
- Produced from a variety of sources



Photo courtesy of the California Fuel Cell Partnership

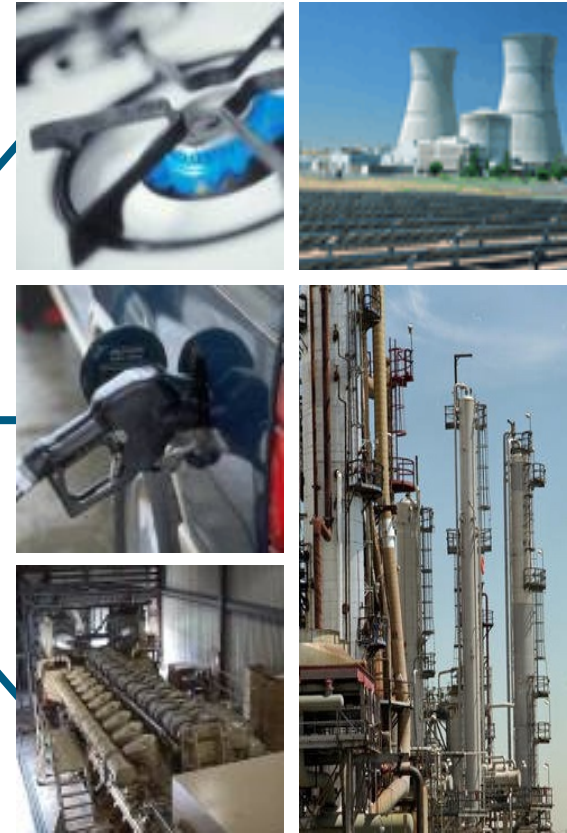
Where Do We Get Hydrogen?

Renewable Sources

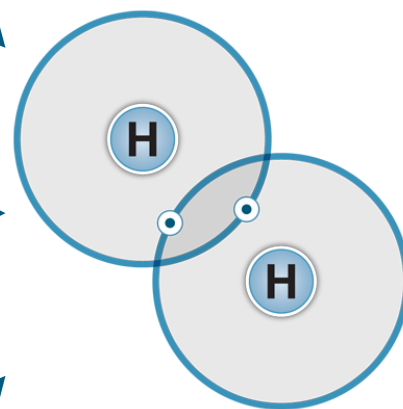


*Solar, wind, geothermal,
hydro, biomass, algae*

Traditional Sources



*Natural gas, gasoline,
nuclear, coal*



Hydrogen Uses

The use of hydrogen is not new; private industry has used it safely for many decades. Nine million tons of hydrogen are safely produced and used in the United States every year. 56 billion kg/yr are produced globally. For example, H₂ is used for:

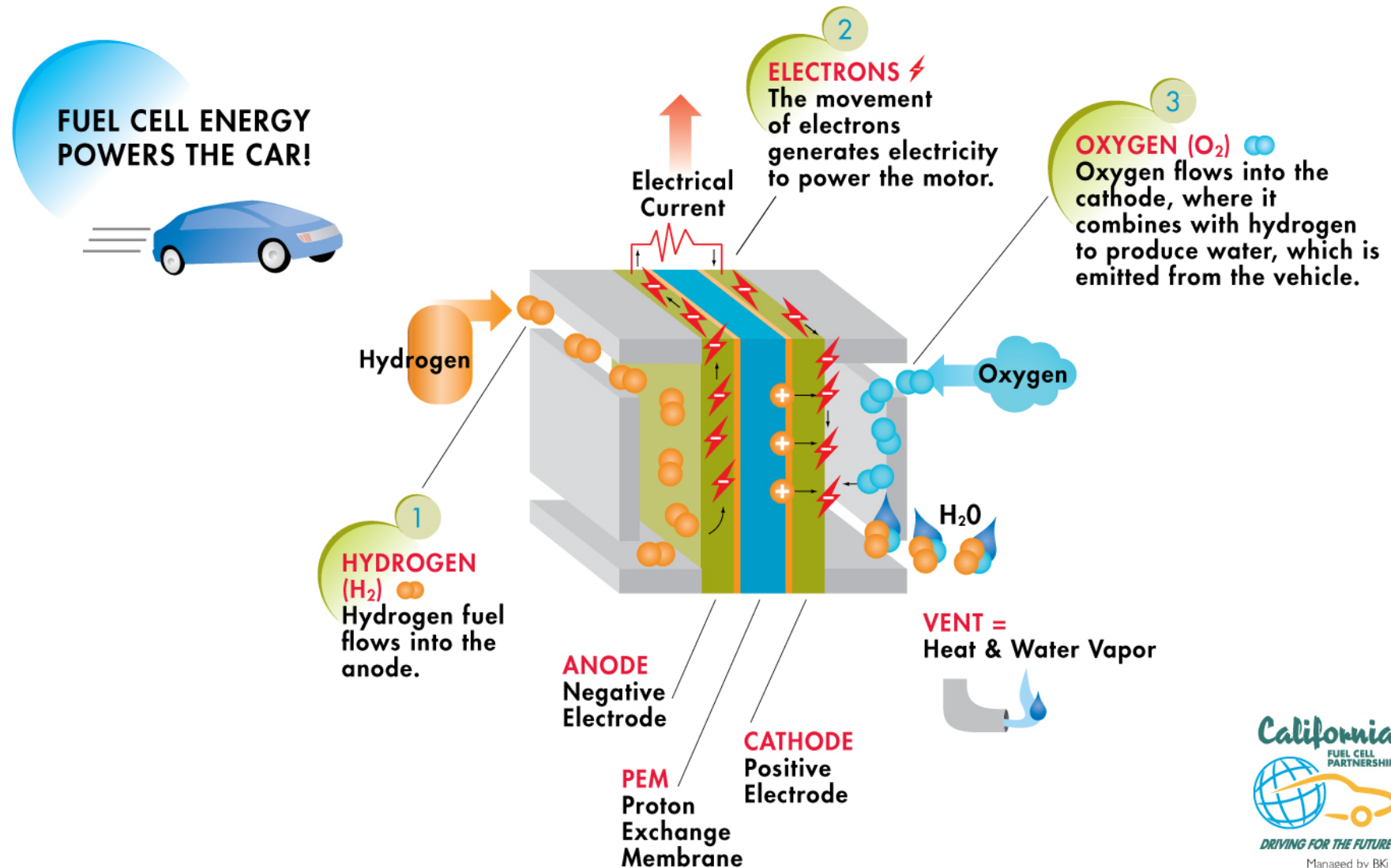
- Petroleum refining
- Glass purification
- Aerospace applications
- Fertilizers
- Annealing and heat treating metals
- Pharmaceutical products



The Air Products and Chemicals hydrogen production facilities in Port Arthur, Texas, is funded by the Energy Department through the 2009 Recovery Act. | Photo credit Air Products and Chemicals hydrogen production facilities.

- Petrochemical manufacturing
- Semiconductor industry
- Hydrogenation of unsaturated fatty acids in vegetable oil
- Welding
- Coolant in power generators

How a Fuel Cell Works



Fuel Cell Applications

Fuel cells have a broad range of applications:

- Transportation
 - Light and medium duty
 - Heavy duty and transit
 - Auxiliary power for refrigeration trailers and trucks
 - Forklifts
 - Maritime
- Stationary power
 - Backup power for cell tower sites
 - Combined heat and power
 - Data centers, etc.
- Portable power



Photo: Nuvera



Toyota's stationary power supply in Torrance, CA

Fuel Cells

Where are We Today?

Fuel Cells for Stationary Power, Auxiliary Power, and Specialty Vehicles

The largest markets for fuel cells today are in stationary power, portable power, auxiliary power units, and forklifts

*More than 35,000 fuel cells shipped in 2013
(~a consistent 30% annual growth since 2010)*

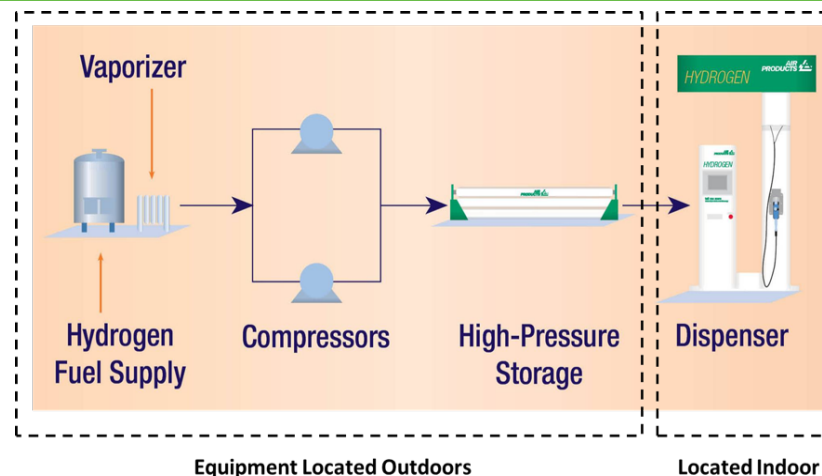
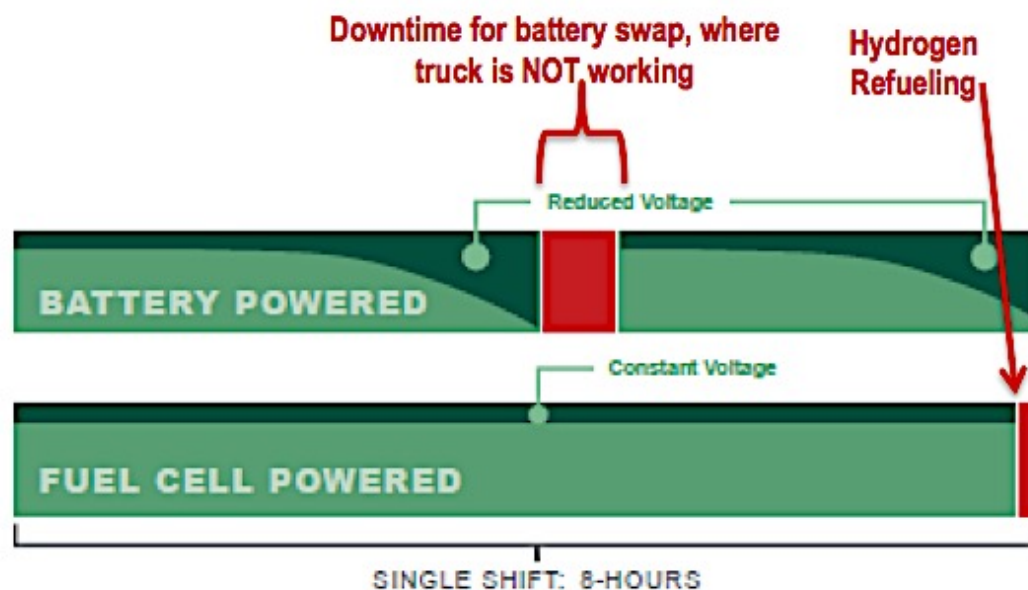
Fuel cells can be a cost-competitive option for critical-load facilities, backup power, and forklifts



Industrial Trucks



Forklift Equipped with Fuel Cells

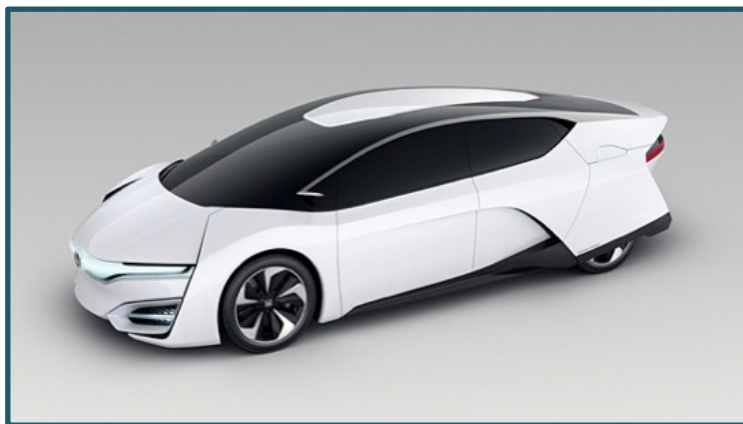


Typical Hydrogen Fueling Infrastructure (Courtesy of Air Products and Chemicals, Inc.)

- Forklifts are equipped with fuel cells as a replacement for traditional battery packs.
- A typical project consists of a refueling system (tank, compressor, piping, etc.) providing hydrogen to a dispenser located inside a warehouse.

Fuel Cell Cars are Here!

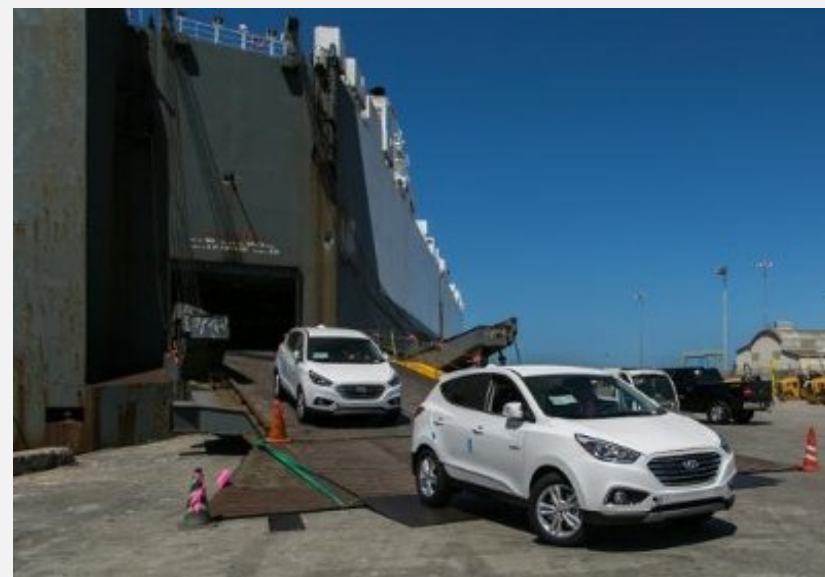
FCEVs on display at North American auto shows.



Honda Fuel Cell Electric Vehicle



Toyota Mirai Fuel Cell Electric Vehicle



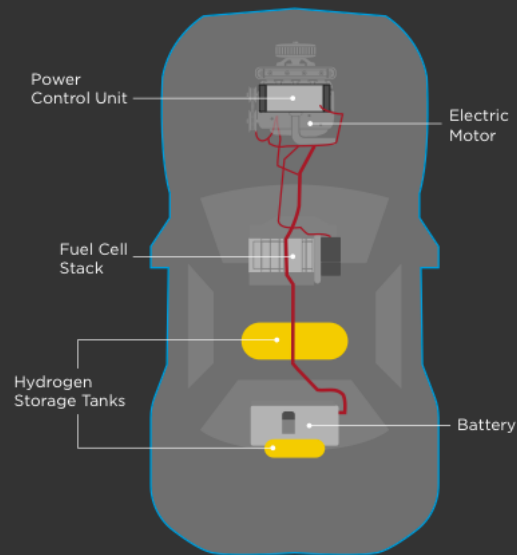
**Hyundai's first mass-produced
Tucson Fuel Cell SUVs arrived in
Southern California
May 20, 2014**

Lease includes **free H₂ and
maintenance.**

The Fuel Cell Electric Vehicle (FCEV)

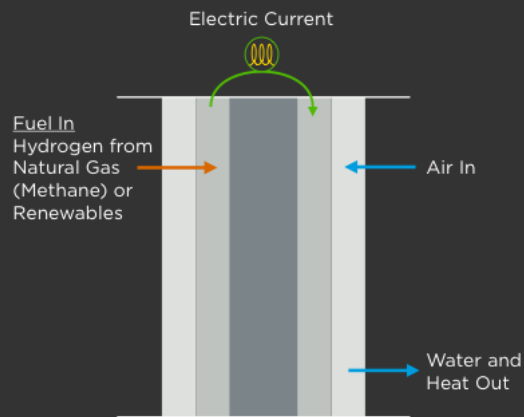
FCEVs are available now in southern California and coming soon to a neighborhood near you.

Hydrogen FCEV System

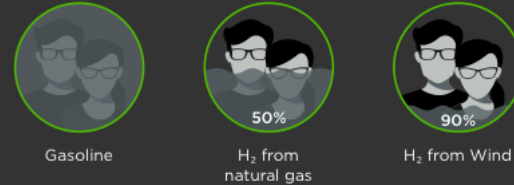


FCEVs generate electricity via the chemical reaction of combining hydrogen and oxygen into water.

Hydrogen Fuel Cell



Reduces Greenhouse Gas Emissions



Refuels Rapidly

taking only a few minutes and using familiar technology



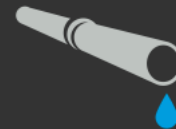
Can travel 300 Miles

between refills



Emits Only Water

from the tailpipe

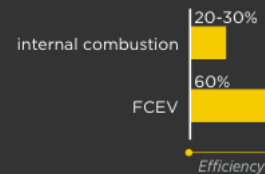


Uses Domestic Fuel



- natural gas
- water (electrolysis)
- biomass
- waste products

Operates Efficiently



Runs Quietly

even at highway speeds, since there are no mechanical gears or combustion

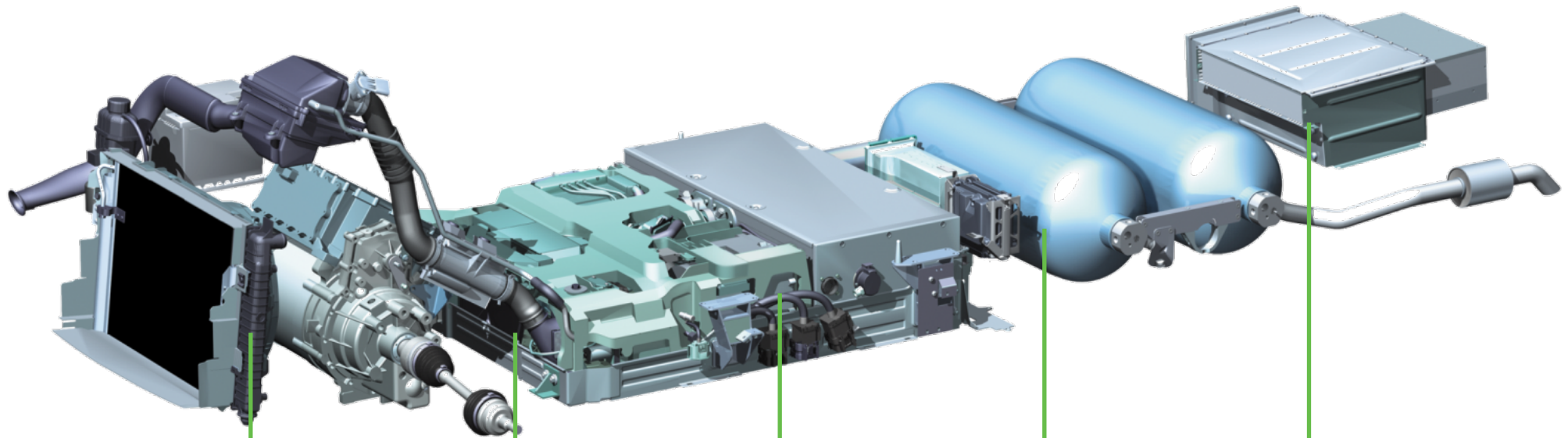


Scales Up Easily

as fuel cells can be added to the stack to increase power



FCEV System Layout



Cooling System

Typically, slightly larger radiators than conventional

Electric Motor

Electrical component; drives vehicle by electricity

Power Electronics

Electrical component; distributes electricity

Fuel Cell

Electrical component; generates electricity from hydrogen

Hydrogen Tanks

Compressed, gaseous fuel; vehicle fueled with hydrogen

High Voltage Battery

Electrical component; captures regen braking, supports acceleration

Source: California Fuel Cell Partnership

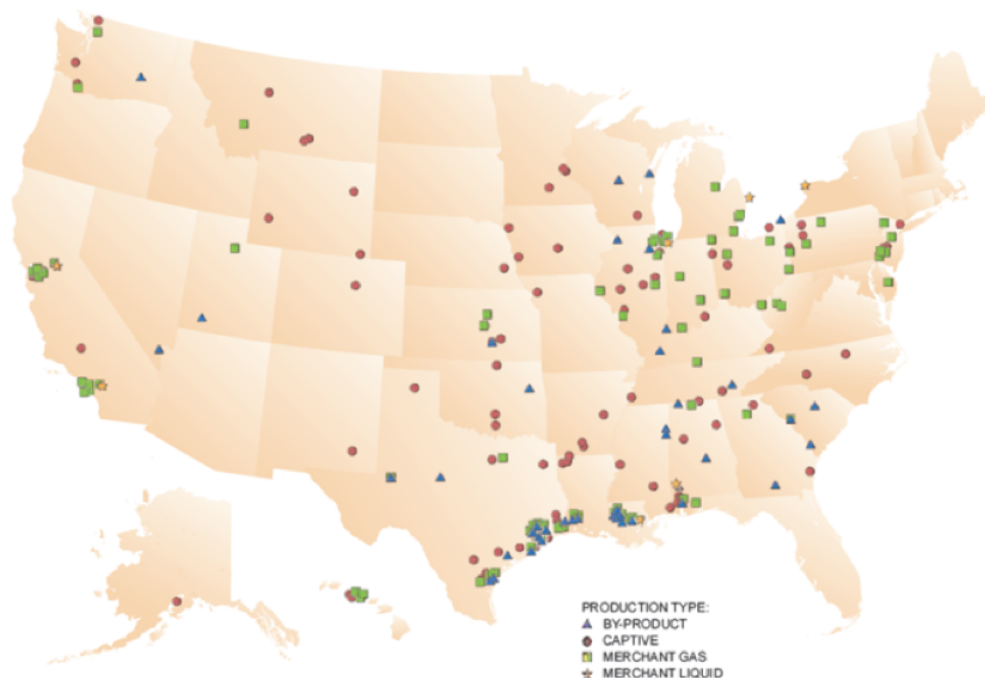
Hydrogen Fueling Stations



H₂ Infrastructure Development and Status

Nationwide

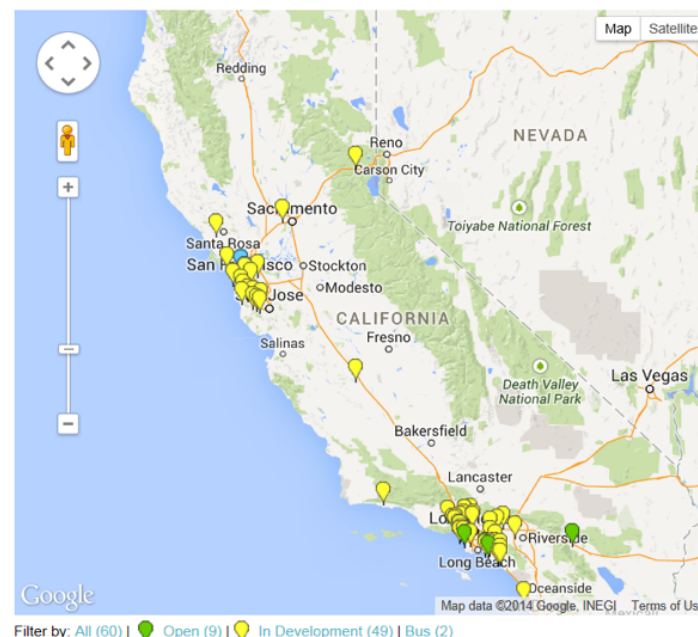
- **1500 mi.** of H₂ pipeline
- **>9M** metric tons produced per year
- **~50 stations** (~10 public)



Centralized H₂ Production Facilities (source: NREL)

States

- **CA- 100 stations, ~\$100M** planned through 2023
- **8 State MOU- 3.3M ZEVs** by 2025
- **Northeast states, Hawaii**



H₂ stations in CA (source: CAFCP)

Typical Station Configurations



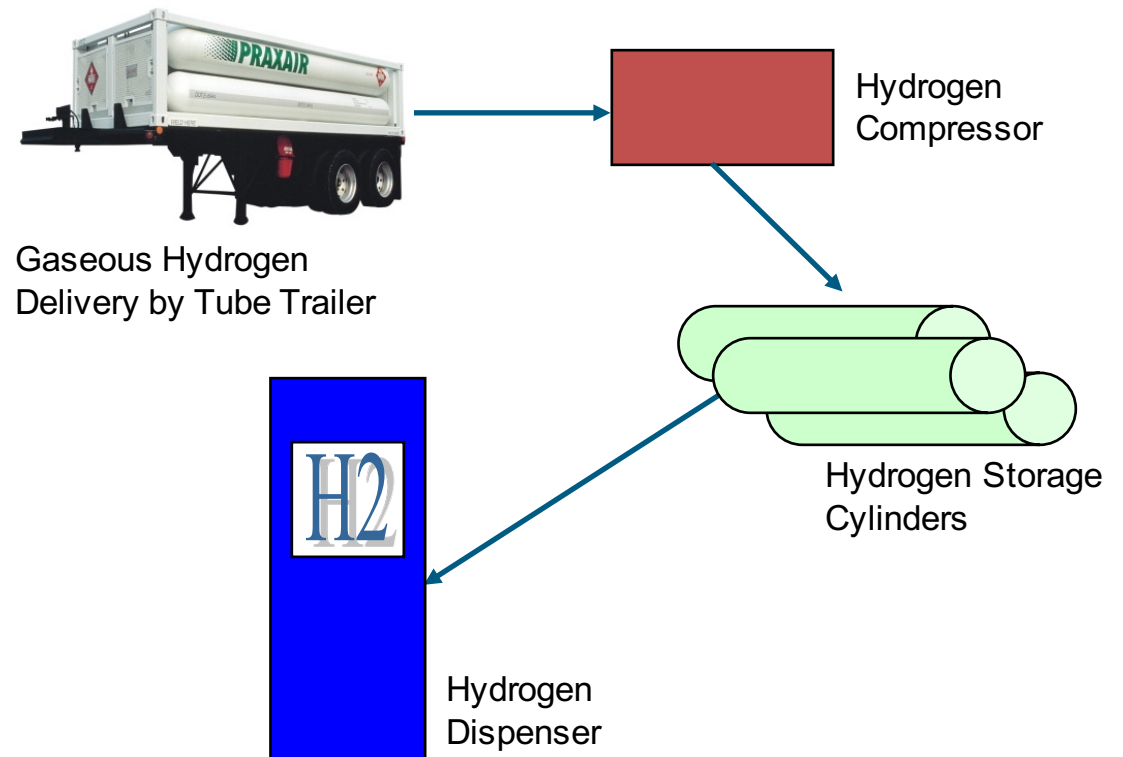
- Hydrogen can be delivered or made on site
- Liquid delivered → gaseous H_2
- Gaseous delivered or piped → booster compressed gaseous H_2
- Natural gas → gaseous H_2
- Water + electricity → gaseous H_2

Hydrogen Fueling Stations

Gaseous Hydrogen Storage

Gaseous hydrogen is:

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

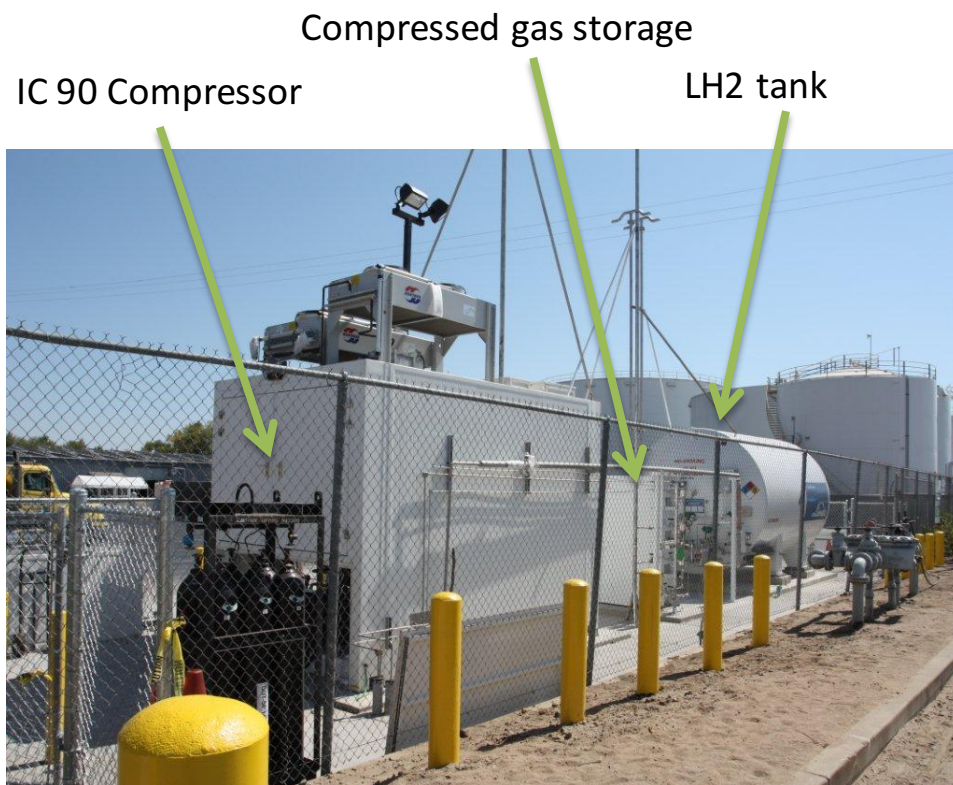


Graphic: Pacific Northwest National Laboratory

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.

Hydrogen Fueling Stations

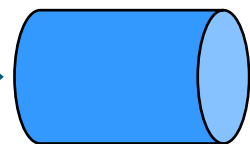
Liquid Hydrogen Storage

Liquid hydrogen is:

- Delivered to fueling station by tanker truck
- Stored underground as a liquid
- Vaporized in above-ground vessel
- Compressed and stored onsite in cylinders
- Piped to dispenser for fueling vehicles



Liquid Hydrogen Delivery
by Tanker Truck



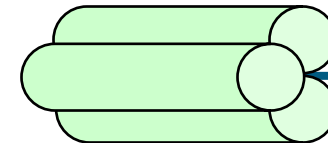
Liquid Hydrogen
Storage Tank
(underground)



Vaporizer



Hydrogen
Compressor



Hydrogen
Storage
Cylinders

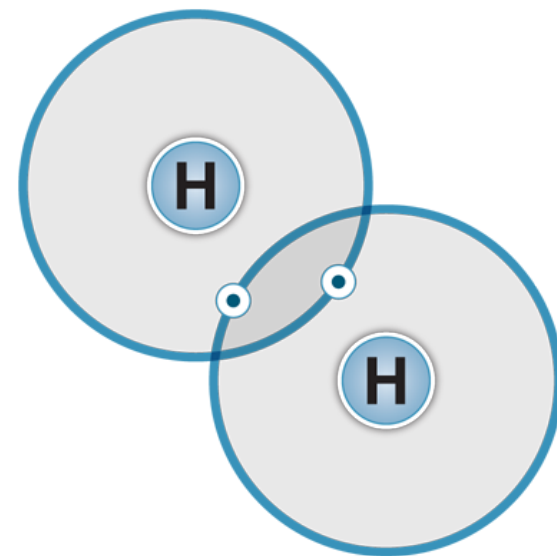


Hydrogen
Dispenser

Properties of Hydrogen

Hydrogen Properties and Behavior

- A gas at ambient conditions
- Hydrogen is a cryogen: exists as a liquid at -423°F (-253°C).
 - Compressing the gas does not liquefy it
 - No liquid phase in a compressed gaseous hydrogen storage tanks
- LH2 storage at relatively low pressure (50 psi)
- Double walled, vacuum insulated tanks with burst disks, vents, and PRDs
- Volumetric ratio of liquid to gas is 1:848
 - Compare water to steam (1:1700)
- Energy content of 1kg of H_2 is approximately equal to 1 gal of gasoline (in BTUs)



Molecular Hydrogen

Gaseous Hydrogen

Gaseous hydrogen:

- has a flammable range of 4-75% in air
- will typically rise and disperse rapidly (14x lighter than air)
- diffuses through materials not normally considered porous
- requires only a small amount of energy for ignition (0.02 mJ)
- burns with a pale blue, almost invisible flame
- can embrittle some metals

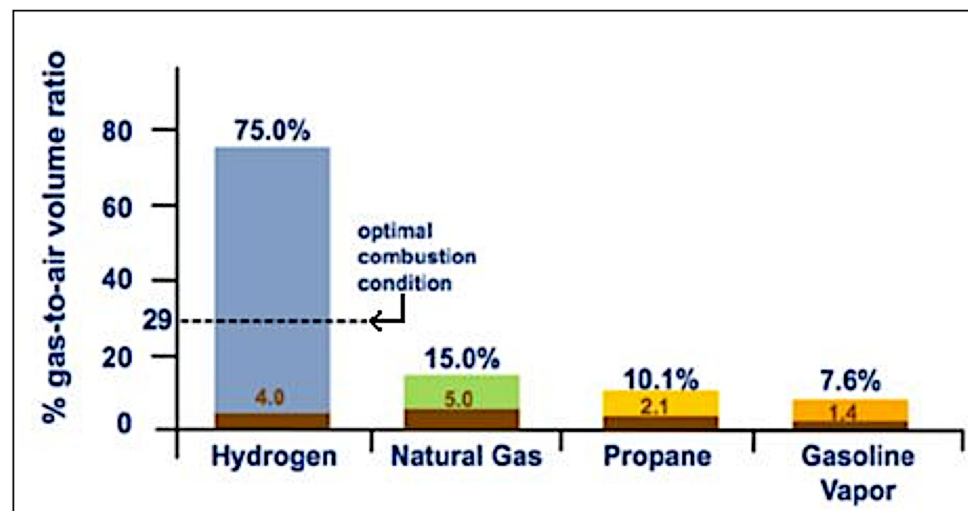


Figure 3. Flammability Range

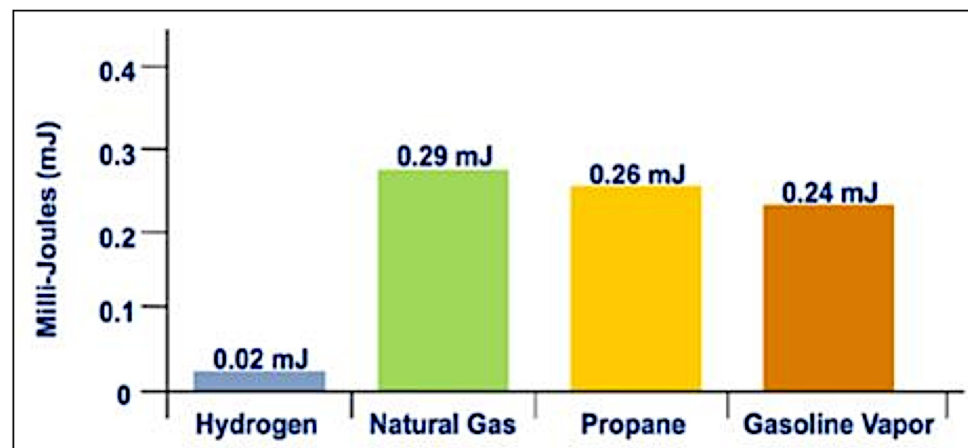


Figure 4. Minimum Ignition Energy

Hydrogen Properties: A Comparison

	Hydrogen	Natural Gas	Gasoline
Color	No	No	Yes
Toxicity	None	Some	High
Odor	Odorless	Mercaptan	Yes
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

Comparing Hydrogen and Propane Flames

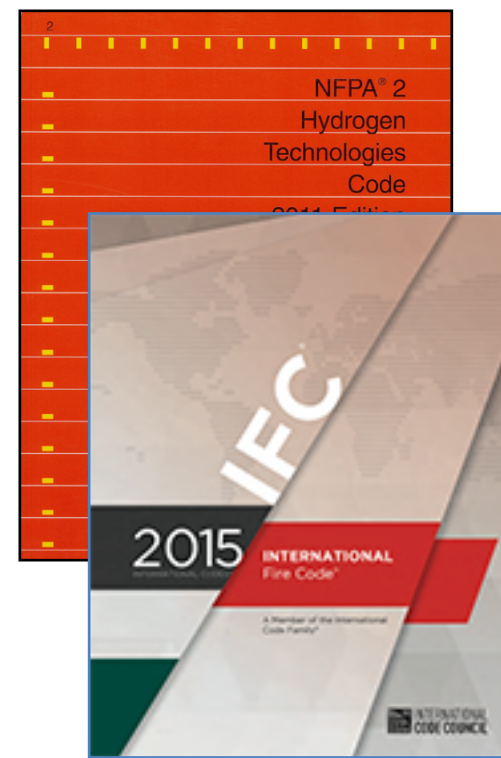


Primary Codes and Standards

Design Consideration: Codes & Standards

There are many organizations working on codes, standards and guides. <https://h2tools.org/fuelcellstandards-view> is currently tracking the world-wide development of over 300 hydrogen and fuel cell standards and related documents. Let's focus on the critical infrastructure documents.

- International Fire Code (IFC) - addresses hydrogen applications
- International Building Code (IBC) - general construction requirements
- International Fuel Gas Code (IFGC)
- NFPA 1 Fire Code
- NFPA 2 Hydrogen Technologies Code
- NFPA 55 Compressed Gases and Cryogenic Fluids Code
- NFPA 70 National Electrical Code
- ASME B31.12 Hydrogen Pipelines and Piping Code - hydrogen piping design



Important ICC 2015 Code References

- **IFC Section 2309** – Hydrogen Motor Fuel-Dispensing and Generation Facilities
- **IFC Chapter 50** – Hazardous Materials - General Provisions
- **IFC Chapter 53** – Compressed Gases
- **IFC Chapter 58** – Flammable Gases and Flammable Cryogenic Fluids
- **International Fuel Gas Code (IFGC) Chapter 7** – Gaseous Hydrogen Systems



Significant changes in the 2015 IFC

“Compressed hydrogen (CH₂) for use as a vehicular fuel shall also comply with Chapters 23 and 58 of this code, the International Fuel Gas Code and NFPA 2.” (IFC 5301.1)

“Hydrogen motor fuel-dispensing stations and repair garages and their associated above-ground hydrogen storage systems shall also be designed, constructed and maintained in accordance with Chapter 23 and NFPA 2.” (IFC 5801.1)

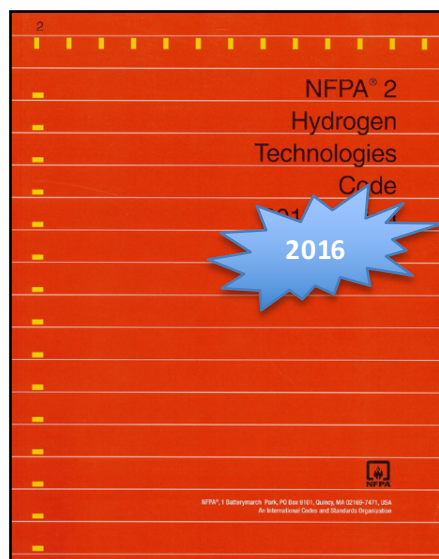
The Need for a National Hydrogen Code

With the increased interest in hydrogen being used as a fuel source, the National Fire Protection Association was petitioned to develop an all-encompassing document that establishes the necessary requirements for hydrogen technologies.

- Origin and development of the NFPA 2, Hydrogen Technologies Code
 - Technical committee formed in 2006
 - Focus is to address all aspects of hydrogen storage, use, and handling
 - Draws from existing NFPA codes and standards (extracts from NFPA 52, 55 and 853) (*NFPA 52 hydrogen requirements removed and transferred to NFPA 2*)
 - Identifies and fills technical gaps for a complete functional set of requirements
 - Developed for code users and enforcers
 - Structured so that it works seamlessly with building and fire codes

In the course of this presentation, any comment as to the “meaning” of any part of any NFPA code or standard is only the opinion of the presenter and is NOT to be relied upon as either accurate or official. Only the NFPA may issue a formal interpretation of its codes and standards.

Contents of NFPA 2, 2016 Edition



Fundamental Chapters

Use Specific Chapters

Document Title, *Hydrogen Technologies Code*

Chapter 1, *Administration*

Chapter 2, *Referenced Publications*

Chapter 3, *Definitions*

Chapter 4, *General Fire Safety Requirements*

Chapter 5, *Performance-Based Option*

Chapter 6, *General Hydrogen Requirements*

Chapter 7, *Gaseous Hydrogen*

Chapter 8, *Liquefied Hydrogen*

Chapter 9, *Explosion Protection*

Chapter 10, *GH2 Vehicle Fueling Facilities*

Chapter 11, *LH2 Fueling Facilities*

Chapter 12, *Hydrogen Fuel Cell Power Systems*

Chapter 13, *Hydrogen Generation Systems*

Chapter 14, *Combustion Applications*

Chapter 15, *Special Atmosphere Applications*

Chapter 16, *Laboratory Operations*

Chapter 17, *Parking Garages*

Chapter 18, *Road Tunnels*

Chapter 19, *Repair Garages*

Annex A

Annexes B-M

} Reserved

Fundamental Safety Considerations

The Basics...

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

- ▶ Recognize hazards and define mitigation measures
- ▶ Ensure system integrity
- ▶ Provide proper ventilation to prevent accumulation (manage discharges)
- ▶ Ensure that leaks are detected and isolated
- ▶ Train personnel

General Considerations

Hydrogen cylinders and storage tanks should be stored outside at a safe distance from structures, ventilation intakes, and vehicle routes. This applies even while in use. Best practices call for compressed hydrogen bottles supplying a manifold to be located outside, with welded lines to connect to indoor equipment. Safety considerations for indoor storage or use of bulk gaseous hydrogen include:

- ▶ Buildings should be constructed of noncombustible materials.
- ▶ Mechanical ventilation systems should have inlets low to the ground and exhausts at the highest point of the room in the exterior wall or roof. Consideration should be given to providing venting for both normal conditions and emergency situations.
- ▶ Hydrogen sensors should be installed at the exhaust within the enclosure.
- ▶ Automatic shutoff that activates if a leak or fire is detected in the facility that is being supplied with hydrogen.
- ▶ Ignition sources in storage areas should be avoided.
- ▶ Classified electrical equipment should be used in close proximity to storage systems.
- ▶ Gaseous hydrogen system components should be electrically bonded and grounded.

Electrical Equipment

Specific considerations:

- Fans for active ventilation systems should be provided with a rotating element of nonferrous or spark-resistant construction.
- Equipment or devices should be designed for use in hydrogen service.
- The gaseous hydrogen system should be electrically bonded and grounded.
- Equipment not conforming to NEC requirements must be located outside the area classified as hazardous.

Electrical Equipment Requirements for Bulk Systems

Location	Classification*	Distance
Area containing gaseous hydrogen storage, compression or ancillary equipment	Class 1, Division 2	Up to 15 ft from storage/equipment
Area containing liquefied hydrogen storage	Class 1, Division 2	Up to 25 ft from the storage equipment, excluding the piping system, downstream of the source valve
	Class 1, Division 1	Within 3 ft from points where connections are regularly made and disconnected
Interior of dispensing equipment	Class 1, Division 2	Up to the support mechanism (anchoring the dispenser) or connection to the ground level
Exterior of outdoor dispensing equipment	Class 1, Division 2	Up to 5 ft from dispenser
Exterior of indoor dispensing equipment	Class 1, Division 2	Up to 15 ft from the point of transfer from floor to ceiling
Outdoor discharge from relief vents	Class 1, Division 1	Up to 5 ft from the source
	Class 1, Division 2	5-15 ft from the source
Discharge from relief vents within 15 degrees of the line of discharge	Class 1, Division 1	Within 15 ft from source

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

Outdoor Separation Distances

- Hydrogen cylinders and storage tanks should be stored outside at a safe distance from structures, ventilation intakes, and vehicle routes.
- A **bulk hydrogen compressed gas system** is an assembly of equipment that consists of, but is not limited to, storage containers, pressure regulators, pressure relief devices, compressors, manifolds, and piping, with a storage capacity of more than 5,000 scf (141.6 Nm³) of compressed hydrogen gas and that terminates at the source valve.



Photo: h2tools.org

Outdoor Separation Distances for Bulk Hydrogen Systems

Pressure (psig)	> 15 to ≤ 250	> 250 to ≤ 3000	> 3000 to ≤ 7500	> 7500 to ≤ 15000
Pipe Internal Diameter (in.)	2.07	0.75	0.29	0.28
Exposure Group 1 a) Lot lines b) Air intakes (HVAC, compressors, Other) c) Operable openings in buildings and Structures d) Ignition sources such as open flames and welding	40 ft	46 ft	29 ft	34 ft
Exposure Group 2 a) Exposed persons other than those servicing the system b) parked cars	20 ft	24 ft	13 ft	16 ft
Exposure Group 3 a) Buildings of non-combustible non-fire-rated construction b) Buildings of combustible construction c) Flammable gas storage systems above or below ground d) Hazardous materials storage systems above or below ground e) Heavy timber, coal, or other slow-burning combustible solids f) Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper, or combustible waste and vegetation other than that found in maintained landscaped areas g) Unopenable openings in building and structures h) Utilities overhead including electric power, building services or hazardous materials piping systems	17 ft	19 ft	12 ft	14 ft

Source: NFPA 55, 2013 Edition

Selection of Materials

- Materials of construction, including materials used in piping, valves and seals, must be carefully selected to account for their deterioration when exposed to hydrogen at the intended operating conditions.
- The mechanical properties of metals, including steels, aluminum and aluminum alloys, titanium and titanium alloys, and nickel and nickel alloys are detrimentally affected by hydrogen.
- **Exposure of metals to hydrogen can lead to embrittlement, cracking and/or significant losses in tensile strength, ductility, and fracture toughness. This can result in premature failure in load-carrying components.**
- Additionally, hydrogen diffuses through many materials, particularly nonmetals, due to its small molecular size.

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

Preferred

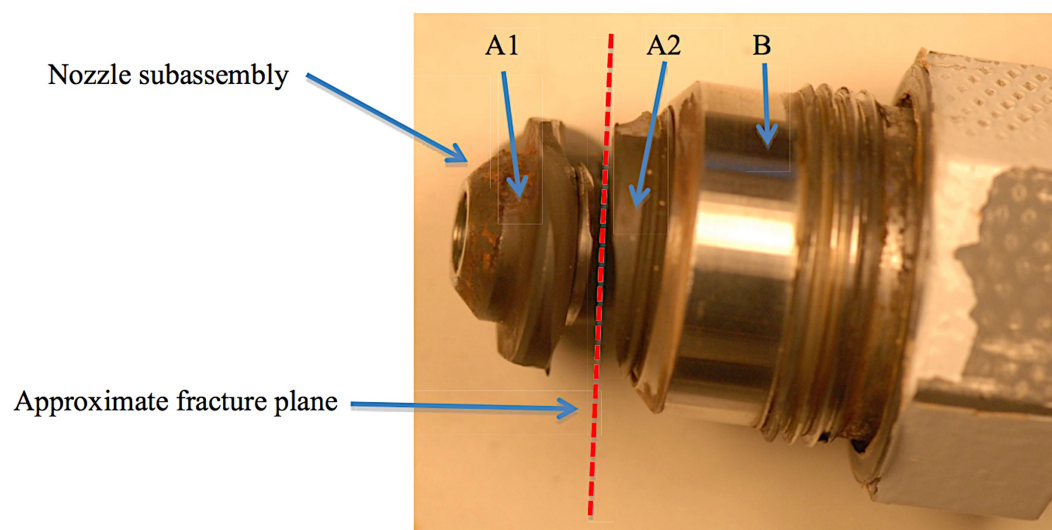
- Generally acceptable materials include austenitic stainless steels, aluminum alloys, copper, and copper alloys.

Avoid

- Nickel and most nickel alloys should not be used since they are subject to severe hydrogen embrittlement.
- Gray, ductile, and malleable cast irons should generally not be used for hydrogen service.

A Lesson Learned on Material Selection

A pressure relief device (PRD) valve failed on a high-pressure storage tube at a hydrogen fueling station, causing the release of approximately 300 kilograms of hydrogen gas. The gas ignited at the exit of the vent pipe and burned for 2-1/2 hours until technicians were permitted by the local fire department to enter the station and stop the flow of gas.



- The root cause of the incident was a failed pressure relief valve...
- An extensive metallurgical analysis of the failed valve concluded that **improper material selection and deviations from valve production processes led to the valve failure.**

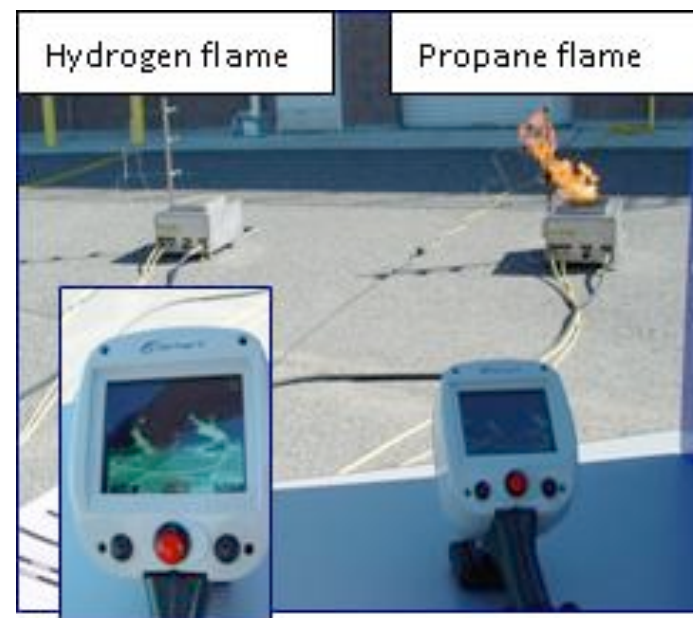
The good news... There were no injuries and very little property damage. The corrugated roof on an adjacent canopy over a fueling dispenser was slightly singed by the escaping hydrogen flame, causing less than \$300 in damage.

Source: <http://www.h2tools.org/lessons>

Checking for Leaks

Hydrogen burns with a pale blue flame that is nearly invisible in daylight. Hydrogen flames also emit low radiant heat, so a person may not feel heat until they are very close to the flame. Best practices include the following:

- A portable flame detector (e.g., thermal imaging camera) should be used if possible.
- Otherwise, listen for venting hydrogen and watch for thermal waves that signal the presence of a flame.
- Use a combustible probe (e.g., broom)
- Always allow enough time for troubleshooting/debugging a monitoring system before it's used.
- Where multiple gases are co-located, always respond in a manner to investigate/ mitigate the most hazardous gas.



Hydrogen and Propane Flames in Daylight
(Photo courtesy of HAMMER)

A Lesson Learned on Hydrogen Leaks

Hydrogen Explosion and Iron Dust Flash Fires in Powdered Metals Plant

- Operators in a powdered metals production facility heard a hissing noise near one of the plant furnaces and determined that it was a gas leak in the trench below the furnaces. The trench carried hydrogen, nitrogen, and cooling water runoff pipes as well as a vent pipe for the furnaces.
- ***Maintenance personnel presumed that the leak was nonflammable nitrogen because there had recently been a nitrogen piping leak elsewhere in the plant.*** Using the plant's overhead crane, they removed some of the heavy trench covers. They determined that the leak was in an area that the crane could not reach, so they brought in a forklift with a chain to remove the trench covers in that area.
- Eyewitnesses stated that as the first trench cover was wrenched from its position by the forklift, friction created sparks followed immediately by a powerful explosion. Several days after the explosion, Chemical Safety Board (CSB) investigators observed a large hole (~3x7 inches) in a corroded section of hydrogen vent piping inside the trench.
- As the hydrogen-air mixture in the partially open trench exploded, the resulting overpressure dispersed large quantities of iron dust from the rafters and other surfaces in the plant, and some of this dust subsequently ignited. Eyewitnesses reported that embers were raining down and igniting iron dust flash fires in the area. Visibility was so poor due to dust and smoke that even with a flashlight, it was impossible to see more than 3 or 4 feet. Three plant employees eventually died from burn injuries despite wearing supposedly flash-fire-resistant garments. Two others suffered smoke-inhalation injuries. Due to the extensive nature of the injuries, and the abundance of both hydrogen and combustible dust present at the time of the incident, it is difficult to specifically determine which fuel, if not both, caused the fatal injuries to the victims.

source: <http://www.h2tools.org/lessons>

Hydrogen Safety Resources



Hydrogen Safety Panel

The Hydrogen Safety Panel is a team of highly experienced individuals created to address concerns about hydrogen as a safe and sustainable energy carrier.

Principal Objective: Promote the safe operation, handling, and use of hydrogen and hydrogen systems across all installations and applications by:

- identifying and addressing safety-related technical data gaps
- making design, construction, and operations personnel aware of relevant issues and best practices that affect safe operation and handling of hydrogen and related systems
- convincing design, construction, and operations personnel to give sufficient priority to safety in their daily, ongoing work.

Hydrogen Safety Panel Activities

The Hydrogen Safety Panel contributes to its objective by:

- ▶ participating in safety reviews
- ▶ providing safety planning guidance
- ▶ reviewing project designs and safety plans
- ▶ sharing safety knowledge and best practices
- ▶ presenting and recognizing safety as a priority
- ▶ participating in incident investigations.



Hydrogen Safety Panel members at the California Fuel Cell Partnership in West Sacramento, CA, for the 21st meeting

Hydrogen Safety Panel Accomplishments

- Reviewed over 270 projects covering vehicle fueling stations, auxiliary power, backup power, combined heat and power, industrial truck fueling, portable power and R&D activities.
- White papers with recommendations recently include:
 - Secondary Protection for 70MPa Fueling
 - Safety of Hydrogen Systems Installed in Outdoor Enclosures
- Supported development/updating of safety knowledge tools: Lessons Learned and Best Safety Practices on the Hydrogen Tools Portal (h2tools.org).
- Conducted 21 Hydrogen Safety Panel meetings since 2003. Panel meetings currently engage a broad cross-section of the hydrogen and fuel cell community.

Current Hydrogen Safety Panel Members

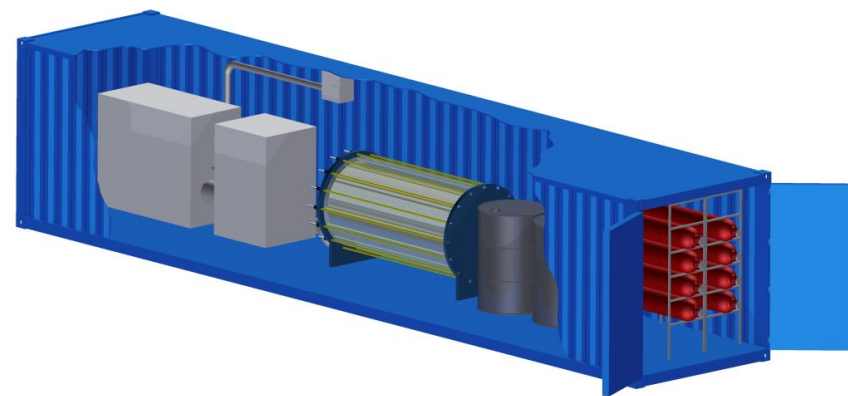
Name	Affiliation
Nick Barilo, Manager	Pacific Northwest National Laboratory
Richard Kallman, Chair	City of Santa Fe Springs, CA
David Farese	Air Products and Chemicals
Larry Fluor	Fluor, Inc.
Bill Fort	Consultant
Donald Frikken	Becht Engineering
Aaron Harris	Air Liquide
Chris LaFleur	Sandia National Laboratories
Miguel Maes	NASA-JSC White Sands Test Facility
Steve Mathison	Honda Motor Company
Larry Moulthrop	Proton OnSite
Glenn Scheffler	GWS Solutions of Tolland
Steven Weiner	Excelsior Design, Inc.
Robert Zalosh	Firexplo

New Requirements for NFPA 2-2016



NFPA 2, 2016 Edition has prescriptive requirements for Hydrogen Equipment Enclosures¹, including:

- Ventilation
- Isolation (gas and fire barrier)
- Electrical requirements
- Bonding/grounding
- Explosion control
- Detection



¹ A prefabricated area confined by at least three walls and a roof, not routinely occupied or used in a laboratory, with a total area less than 450 ft² designed to protect hydrogen.

The Certification Challenge

The scarcity of listed hydrogen equipment places an extraordinary burden on code officials to ensure (approve) that products include the appropriate inherent or automatic safety measures.

Certification presents significant challenges.

- Few systems or equipment that are listed, labeled or certified
- Significant costs since the technology and products are still rapidly changing and each new iteration would require recertification

Development of a Certification Guide

The Hydrogen Safety Panel is developing a guide to assist code officials, designers, owners, evaluators and others with the application of requirements pertinent to the design and/or installation of hydrogen equipment as regulated by the model codes. The scope of the Guideline will be limited to those requirements where the terms *approved*, *certified*, *listed* and/or *labeled* are used.



Supporting State Efforts

The Panel is a unique resource and can be a valuable asset for supporting the safe commercial rollout of fuel cell vehicles, stationary applications and the supporting infrastructure.

Can provide support to:

- ▶ Other federal agencies
- ▶ State agencies, code officials and permitting authorities
- ▶ Private industry and commercial installers

Types of Activities:

- ▶ Design and document reviews
- ▶ Participation in or review of risk assessments
- ▶ Site reviews



Safety is paramount - its the first question we get asked in California when we go into local communities. If anything, we need to figure out how to expand the Safety Panel's reach. The reviews from the Panel have already shown benefit to the state - its a crucial, trusted 3rd party resource. – 2015 DOE AMR Reviewer Comment

Hydrogen Tools

A Transformative Step Towards Hydrogen Adoption

CENTRALIZED LOCATION

organizes current H₂ resources in one robust location—including many proven tools, with plans for adding future content

FOCUSED CONTENT

tailored to the specialized needs of H₂ user groups

RESPONSIVE DESIGN

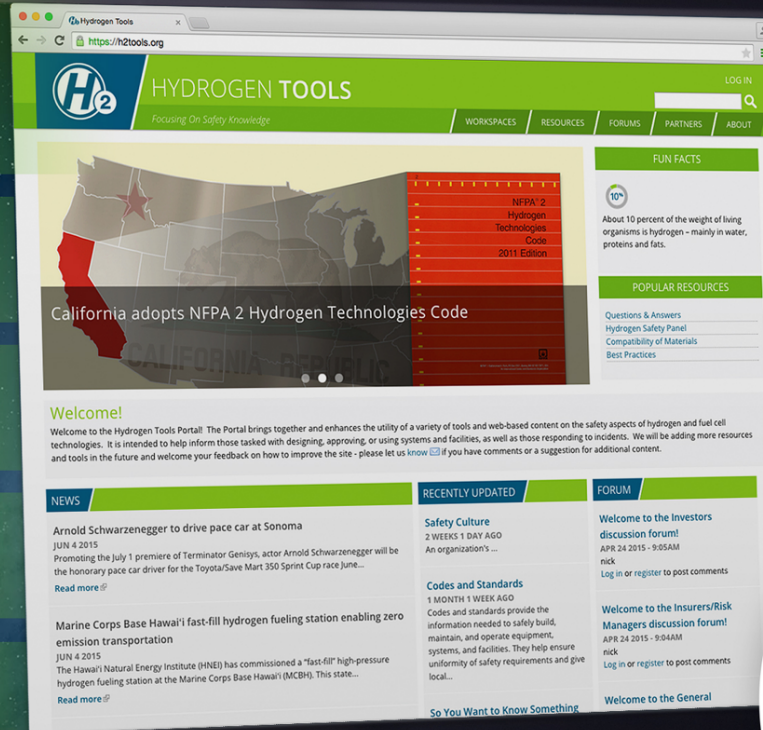
enables H₂ safety work across both desktop and mobile devices

TRUSTED COMMUNITIES

fostered through social networking around H₂ subject matter expertise

EXPANDABLE FORMAT

built with frequently requested future feature sets in mind



+ Mobile Friendly

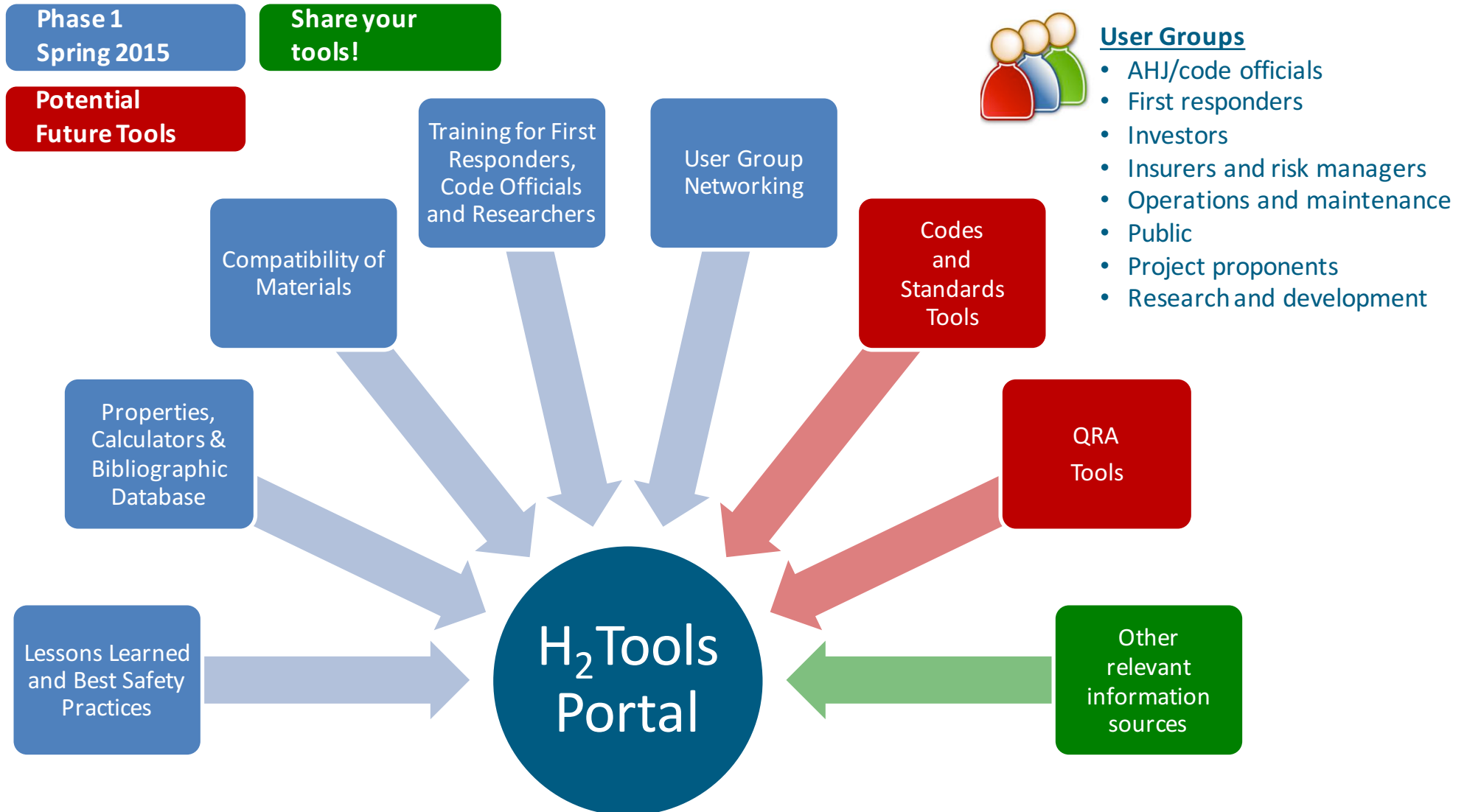


<http://h2tools.org>



› Credible and reliable safety information from a trustworthy source

Opportunities for Information/Knowledge Dissemination



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

<http://h2tools.org/bestpractices>

HYDROGEN TOOLS
Focusing On Safety Knowledge

Home » Best Practices » Facility Design » Properties Impact Design

Best Practices

Hydrogen Introduction
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

Properties Impact Design
Positive Ventilation
Active Ventilation
Electrical Classification
Use of Detectors
Proper Storage, Use and Venting
Loss Prevention
Selection of Materials
Inherently Safer Design Concepts
Piping Layout and Design
Safety Interlock Systems
Storage & Piping
Operating Procedures
Equipment Maintenance
Laboratory Safety
Indoor Refueling

Impact of Hydrogen Properties on Facility Design

View Edit Track

An understanding of the properties of hydrogen is critical for the proper design of a facility or workspace. A workspace can be configured to mitigate hazards by understanding and taking advantage of some of the characteristics of hydrogen.

Designers and operators of hydrogen storage facilities must be aware that hydrogen's flammability range is very wide compared to other fuels. Additionally, under optimal combustion conditions (at a 29% hydrogen-to-air volume ratio), the energy required to initiate hydrogen combustion is much lower than that required for other common fuels (e.g., a small spark).

Property	Hydrogen H ₂	Methane CH ₄	Gasoline
Normal boiling point ¹ (NBP) [°C]	-253	-162	37 - 205
Physical state at 25°C, 1 atm	Gas	Gas	Liquid
Heating Values ² LHV (kJ/g) HHV (kJ/g)	120 142	50 55.5	44.5 48
Flammability limits (vol% in air)	4.0-75	5.3-15	1.0-7.6
Molecular weight	2.02	16.0	~107
Flame temperature in air ³ [°C]	2045	1875	2200
Minimum ignition energy ⁴ [mJ]	0.02	0.29	0.24
Quenching distance (mm)	0.64	2.0	2.0
Density at NBP (g/L)	70.8	423	~700
Vapor specific gravity at 25°C, 1 atm (air=1)	0.070	0.54	3.7

¹The boiling point at 1 atm pressure
²Heating values are the energy, per gram of fuel, generated by a combustion reaction. The higher heating value (HHV) is obtained when all of the water formed by combustion is liquid. The lower heating value (LHV) is obtained when all of the water formed by combustion is vapor.
³Experimentally determined flame temperatures are shown in the table. These values do not differ significantly from theoretical adiabatic flame temperatures. See Ref. [3] for discussion.
⁴In air at 1 atm pressure

For any incident involving hydrogen, keep in mind the properties of hydrogen and watch for potential ignition sources that can ignite a hydrogen leak:

- electrical (e.g., static electricity, electric charge from operating equipment)
- mechanical (e.g., impact, friction, metal fracture)
- thermal (e.g., open flame, high-velocity jet heating, hot surfaces, vehicle exhaust)

There should be no grass or shrubs planted near areas where hydrogen potentially may be released to prevent the need for using powered garden tools in the area. According to NFPA 55, both compressed gaseous hydrogen storage vessels and liquid hydrogen storage vessels must be located at least 50 feet from combustible materials.

Mixtures near optimal combustion conditions should be considered prone to spontaneous ignition.

References

Supporting References:
Basic Hydrogen Properties
CGA G-5, Hydrogen
CGA H-4 Terminology Associated with Hydrogen Fuel Technologies
B. Lewis and G. von Elbe, Combustion, Flames and Explosions of Gases, 3rd ed., Academic Press, Orlando, 1987, pg. 717.
Hydrogen Data Book
Babrauskas, Vytenis, "Ignition Handbook" Fire Science Publishers, Issaquah, WA.
J. Hord, "Is Hydrogen Safe?" National Bureau of Standards (NBS) Technical Note 690, October 1976.
F.J. Edeskuty and W.F. Stewart, Safety in the Handling of Cryogenic Fluids, Plenum Press, New York, 1996, pg. 102.
Glossary | Acronyms | Bibliography
Codes & Standards
Safety Snapshot
NFPA 2, Hydrogen Technologies Code, 2011 Edition

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

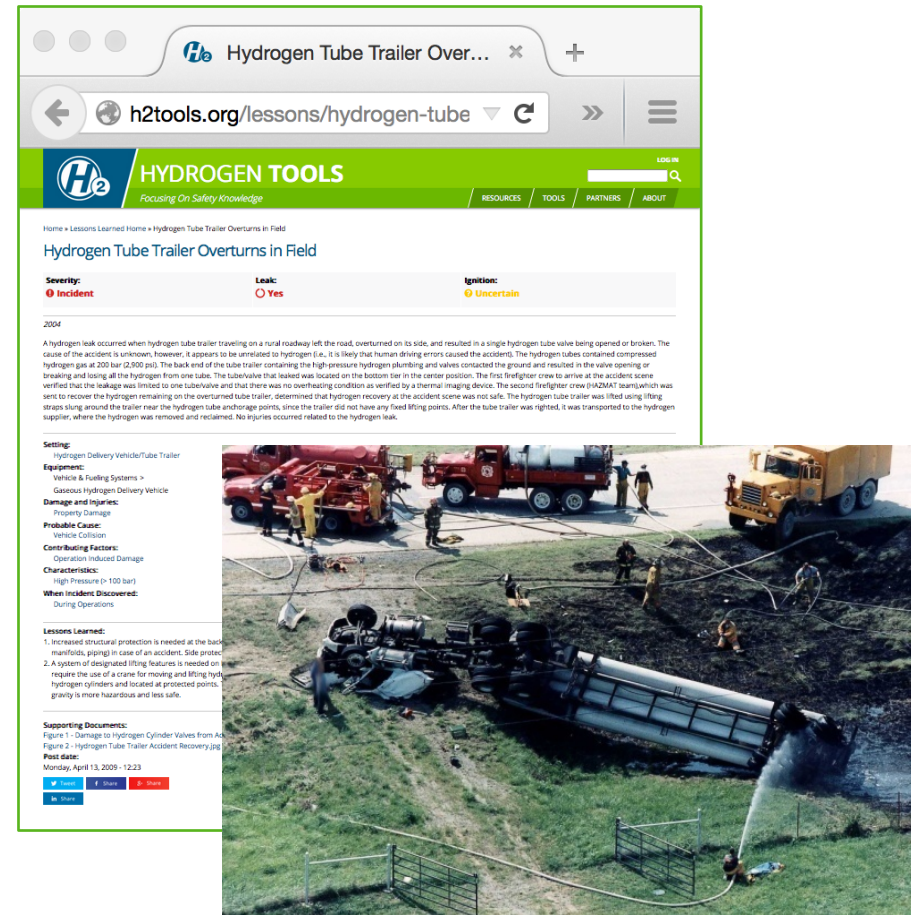
H2tools.org/lessons

...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

<http://h2tools.org/lessons>

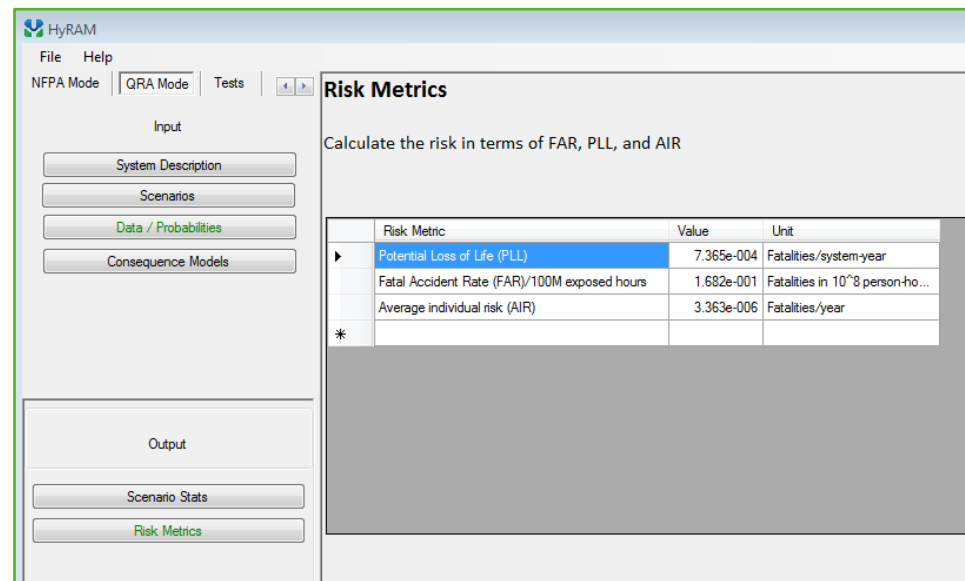


The screenshot displays the H2tools.org website interface. The browser address bar shows the URL h2tools.org/lessons/hydrogen-tube. The page title is "Hydrogen Tube Trailer Overturns in Field". The severity is marked as "Incident", the leak status is "Yes", and the ignition status is "Uncertain". The incident occurred in 2004. The description states: "A hydrogen leak occurred when hydrogen tube trailer traveling on a rural roadway left the road, overturned on its side, and resulted in a single hydrogen tube valve being opened or broken. The cause of the accident is unknown, however, it appears to be unrelated to hydrogen (i.e., it is likely that human driving errors caused the accident). The hydrogen tubes contained compressed hydrogen gas at 200 bar (2,900 psi). The back end of the tube trailer containing the high-pressure hydrogen plumbing and valves contacted the ground and resulted in the valve opening or breaking and losing all the hydrogen from one tube. The tube valve that leaked was located on the bottom tier in the center position. The first firefighter crew to arrive at the accident scene verified that the leakage was limited to one tube valve and that there was no overheating condition as verified by a thermal imaging device. The second firefighter crew (H2AZAR) team/vehicle was sent to recover the hydrogen remaining on the overturned tube trailer, determined that hydrogen recovery at the accident scene was not safe. The hydrogen tube trailer was lifted using lifting straps slung around the trailer near the hydrogen tube anchorage points, since the trailer did not have any fixed lifting points. After the tube trailer was righted, it was transported to the hydrogen supplier, where the hydrogen was removed and reclaimed. No injuries occurred related to the hydrogen leak." The page also includes sections for "Setting", "Equipment", "Damage and Injuries", "Probable Cause", "Contributing Factors", "Characteristics", "When Incident Discovered", "Lessons Learned", and "Supporting Documents". A large photograph shows a hydrogen tube trailer overturned on its side in a field, with emergency responders and equipment nearby.

Tube Trailer Rollover

Quantitative Risk Assessment

- Developed toolkit to enable integrated probabilistic and deterministic modeling
 - Relevant H2 hazards (thermal, mechanical)
 - Probabilistic models (traditional QRA models) & H2-specific component data
 - H₂ 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



First-of-its-kind software tool for integrating H2 consequence models w/ QRA models
Includes behavior models & data developed through FY12

Introduction to Hydrogen for Code Officials

Provides an overview of hydrogen and fuel cell technologies, discusses how these technologies are used in real-world applications and discusses the codes and standards required for permitting them.

- Hydrogen and fuel cell basics
- Hydrogen and fuel cell applications
- Hydrogen fueling stations
- Fuel cell facilities

Developed by the National Renewable Energy Laboratory

Introduction to Hydrogen for Code Officials

U.S. Department of Energy
Hydrogen Program
www.hydrogen.energy.gov

COURSE MATERIALS LIBRARY EXIT

☐ Hydrogen & Fuel Cell Basics ☐ Hydrogen & Fuel Cell Applications ☐ Hydrogen Fueling Stations ☐ Fuel Cell Facilities

While a hydrogen fueling station is still on the drawing board, developers conduct a safety analysis to analyze, quantify, and mitigate potential risks.

Safety planning tools include:

- Failure modes and effects analysis (FMEA)
- What-if analysis
- Hazard and operability analysis (HAZOP)
- Checklist analysis
- Fault tree analysis
- Event tree analysis
- Probabilistic risk assessment (PRA)

A hydrogen fueling station in Oakland, California.
Graphic courtesy of California Fuel Cell Partnership

To view references for related hydrogen codes and standards and learn more about hydrogen safety, visit the following links:

- [Operation Approvals for Fire Safety and Emergency Planning](#)
- [Safety Planning Guidance for Hydrogen Projects document \(PDF 157 KB\)](#)

Download Adobe Reader.

Back Slide 2 of 27 Next

<http://h2tools.org/content/training-materials>

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

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

The screenshot shows the 'HYDROGEN TOOLS' website with a green header. The main content area is titled 'Technical Reference for Hydrogen Compatibility of Materials' and is identified as a 'Sandia National Laboratories Resource'. It includes a brief introduction about the need for materials selection guidance for hydrogen service. Below this, there are two tables: 'Plain Carbon Ferritic Steels' and 'Low-Alloy Ferritic Steels'. The first table lists 'C-Mn Alloys' with a nominal composition of 'Fe-C-Mn', revision '5/07', and section '1100'. The second table lists 'Quenched & Tempered Steels' for both 'Cr-Mo Alloys' (Fe-Cr-Mo, revision 12/05, section 1211) and 'Ni-Cr-Mo Alloys' (Fe-Ni-Cr-Mo, revision 12/05, section 1212).

Sub Metal Type	Designation	Nominal composition	Revision	Section
	C-Mn Alloys	Fe-C-Mn	5/07	1100

Sub Metal Type	Designation	Nominal composition	Revision	Section
Quenched & Tempered Steels	Cr-Mo Alloys	Fe-Cr-Mo	12/05	1211
Quenched & Tempered Steels	Ni-Cr-Mo Alloys	Fe-Ni-Cr-Mo	12/05	1212

H2USA Public-Private Partnership to address H2 Infrastructure Challenges



<http://h2usa.org>

The mission of H2USA is to promote the commercial introduction and widespread adoption of FCEVs across America through creation of a public-private collaboration to overcome the hurdle of establishing hydrogen infrastructure.



GlobalAutomakers



Fuel Cell &
Hydrogen Energy
Association

AGA
American Gas Association



HONDA
The Power of Dreams



Mercedes-Benz



TOYOTA



HNEI

HYDROGENICS
Advanced Hydrogen Solutions



KOBELCO
Kobelco Compressors(America), Inc.



NACS



NUVERA
Making hydrogen make sense.



*Representative sample of member logos

Key Early Market Challenges Addressed by H2USA



- **Station Cost Reduction**
 - Fueling resources & delivery
 - State and local regulations
- **Station Locations**
 - Identify and prioritize markets
 - Regulatory barriers (zoning)
 - Station rollout timing
- **Investment and Finance**
 - Private sector financing
 - Government support
- **Market Support and Acceleration**
 - Product launch and timeline
 - Codes and standards (non-vehicle related)
 - Public education

First Responder Training Resources

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 (see the resource lists at the end of this presentation).

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.



Photo: Volpentest HAMMER Federal Training Center

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

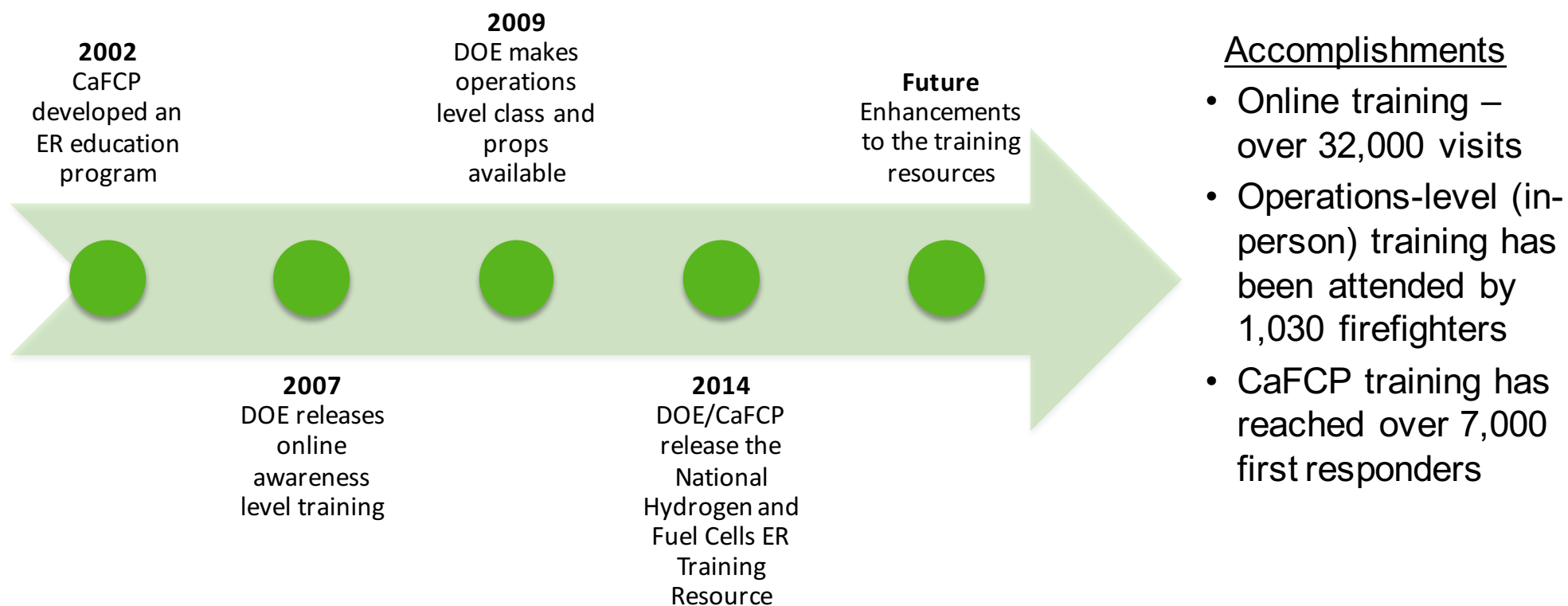
► Integrated Activities

- 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.

Training Resources Timeline and Accomplishments



Online Awareness-level Training

Address <http://www.ehammertraining.us/energy/hydrogen/controller.cfm>

Introduction to Hydrogen Safety for First Responders

U.S. Department of Energy
Hydrogen Program
www.hydrogen.energy.gov

COURSE MATERIALS LIBRARY EXIT ▶

☒ Hydrogen Basics ☒ Transport & Storage ☒ Hydrogen Vehicles ☒ Hydrogen Dispensing ☒ Stationary Facilities ☒ Codes & Standards ☒ Emergency Response ☒ Summary

INCREASE YOUR
H₂IQ
www.hydrogen.energy.gov

The Course Materials cover the following topics:

- Hydrogen Basics
- Transport & Storage
- Hydrogen Vehicles
- Hydrogen Dispensing
- Stationary Facilities
- Codes & Standards
- Emergency Response

Online course content

You can view the topic modules in sequence or select them in random order using the top navigation bar.

A short quiz follows at the end of the course. User responses will be collected but will not be attributed to you as an individual.

Begin the Course ▶

<http://hydrogen.pnl.gov/FirstResponders/>

- 100 from hydrogen and emergency response community conduct broad review (Summer 2006)
- On-line training launched January 27, 2007
- 200-300 unique visits monthly; >30,000 total.

Classroom and Hands-on Training

► Classroom Content

- Hydrogen and Fuel Cell Basics
- Hydrogen Vehicles
- Stationary Facilities
- Emergency Response
- Incident Scenarios



Multiple instructors for classroom training

► Demonstrations/Hands-on Exercise with FCEV Prop

- Demonstration of Hydrogen Flame Characteristics
- Student Participation in Rescue Evolutions



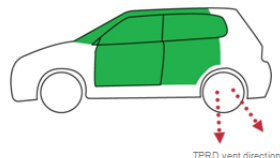
A "rescue" at Sunnyvale (CA) Department of Public Safety

National First Responder Training Resource



Hydrogen Vehicle Safety Systems

- When a leak is detected by hydrogen sensors, solenoid valves close, shutting off the flow of hydrogen, and the vehicle safely shuts down
- When collision sensors activate:
 - Tank solenoid valves close so that hydrogen remains locked in the tank.
 - In FCVs, high-voltage relays open so that the high-voltage battery/capacitors are isolated from the system
- Tank solenoid valves also close when the vehicle is turned off or the power is disrupted
- Tanks have thermally activated pressure relief devices (TPRDs)



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National Hydrogen and Fuel Cells EMERGENCY RESPONSE TRAINING

A properly trained first responder can help ensure that hydrogen and fuel cell applications are safe. This training resource as a comprehensive classroom instructor to conduct the slides.

This nationally-focused delivery of a variety of for different presentation comprehensive classroom

- L1 (Overview)** - that has little knowledge is limited to background technologies and additional slides
- L2 (Short Course)** - has an intermediate not necessarily classroom sessions minimized and
- L3 (Full Course)** - materials contain groups would do for purposes intended

Feedback from presenters and Cells Emergency Response updated training content resource. Feedback sheet

Revision Date: September 30, 2014

A TEMPLATE for TRAINING

NATIONAL HYDROGEN AND FUEL CELLS EMERGENCY RESPONSE TRAINING

Slide #1: What and Why
Slide #2: National Hydrogen and Fuel Cells Emergency Response Training

Example Uses of Training Slides

L1 Overview	L2 Short Course	L3 Full Course

1. Introduction and Background Slide #3

Slide #4: Fuel Cells Overview and Benefits	✓	✓	✓
Slide #5/6/7: Fuel Cells – Where are We Today?			✓
Slide #8: Diverse Fuel Cell Transportation Applications			✓

2. Hydrogen and Fuel Cell Basics Slide #9

2.1 Hydrogen – Where does it come from and how do we use it now?

Slide #10: Why Hydrogen?	✓	✓	✓
Slide #11: Where Do We Get Hydrogen?	✓		✓
Slide #12: Hydrogen Uses	✓	✓	✓
Slide #13: Hydrogen Distribution			✓
Slide #14: Transporting Hydrogen Today			✓

2.2 Properties of hydrogen and its safe use

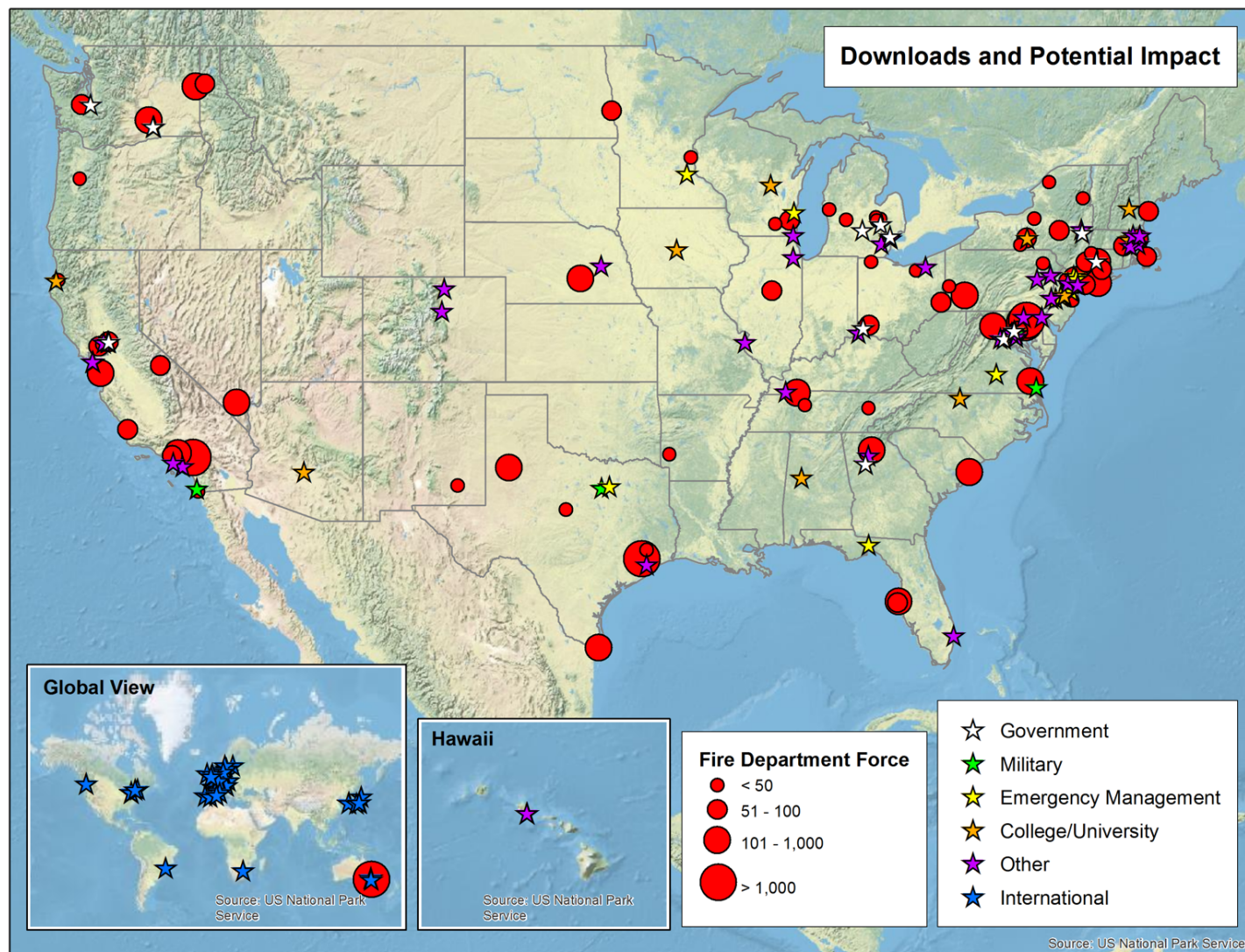
Slide #15: Hydrogen Properties and Behaviors	✓		✓
Slide #16: Hydrogen Properties: A Comparison	✓	✓	✓
Slide #17: Relative Vapor Density			✓
Slide #18: Auto-Ignition Temperature			✓
Slide #19: Comparison of Flammability	✓	✓	✓
Slide #20: Flammability Range			✓
Slide #21: Explosive Range			✓
Slide #22: Comparison of Fuel Odorants and Toxicity			✓
Slide #23/24/25: Designing Safe Systems – Gaseous Hydrogen			✓
Slide #26: Designing Safe Systems – Liquid Hydrogen			✓

Revision Date: September 30, 2014

2

Can be downloaded at <http://h2tools.org/fr/nt>

National Training Resource Downloads



Since October 2014

- 278 downloads
- in 6 Continents
- and 35 of 50 states
- translated into Japanese in support of Japan fuel cell activities

Concluding thoughts

- ▶ Safe practices in the production, storage, distribution and use of hydrogen are essential for deployment of hydrogen and fuel cell technologies. ***A significant incident involving a hydrogen project could negatively impact the public's perception of hydrogen systems as viable, safe, and clean alternatives to conventional energy systems.***
- ▶ Hydrogen CAN be used safely. However, because hydrogen's use as a fuel is still a relatively new endeavor, the proper methods of handling, storage, transport and use are often not well understood across the various communities either participating in or impacted by its demonstration and deployment. Those working with hydrogen and fuel cell technologies should utilize the online resources discussed in this presentation to become familiar with the technology.
- ▶ The IFC, IFCG and NFPA 2 provide fundamental requirements for the use 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.

Thank You for Your Attention!

The author wishes to thank the U.S. Department of Energy's Fuel Cell Technologies Office (Sunita Satyapal, Director and Charles James, Safety, Codes and Standards Lead), Dave Conover from the Pacific Northwest National Laboratory and the California Fuel Cell Partnership for their support of this work.

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