Increasing the Value Proposition: Hydrogen Safety

December 13, 2018
1:00 PM – 2:00 PM ET

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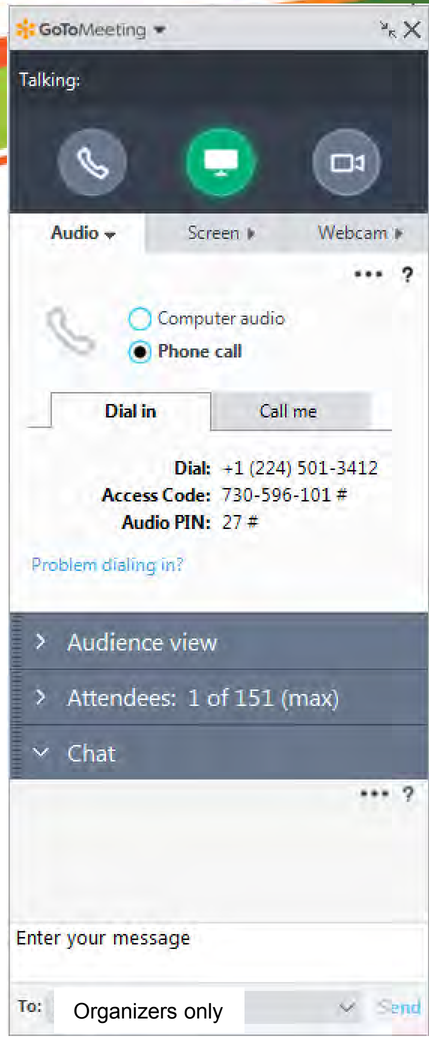

House Keeping

All participants are in “Listen-Only” mode. Select “Use Mic & Speakers” to avoid toll charges and use your computer’s VOIP capabilities. Or select “Use Telephone” and enter your PIN onto your phone key pad.

Submit your questions at any time by typing in the Chat Box, selecting “Organizer(s) Only”, and hitting Send.

This webinar is being recorded

You will find the presentations and a recording of this webinar at:

fchea.org/events/
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Northeast Electrochemical energy storage Cluster

FCHEA Fuel Cell & Hydrogen Energy Association

Connecticut Hydrogen-Fuel Cell Coalition

About NEESC

- Regional Industry Cluster
- New England States, NY, and NJ
- Hydrogen, Fuel Cell, and Battery Technologies
- Businesses, Government, Service Providers, Academia
- State Roadmaps, Regional Fleet Plans, White Papers
- NEESC is administered by CCAT & Regional Partners

WWW.NEESC.ORG

Northeast Electrochemical energy storage Cluster

FCHEA Fuel Cell & Hydrogen Energy Association

Connecticut Hydrogen-Fuel Cell Coalition

Today's Moderator

Karen Quackenbush
Senior Technical Specialist
Fuel Cell and Hydrogen Energy Association

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About the Fuel Cell and Hydrogen Energy Association (FCHEA)

- FCHEA represents the leading companies and organizations that are advancing innovative, clean, safe, and reliable energy technologies.

- FCHEA drives support and provides a consistent industry voice to regulators and policymakers. Our educational efforts promote the environmental and economic benefits of fuel cell and hydrogen energy technologies.

FCHEA
Fuel Cell & Hydrogen Energy Association

Our members

- 3M
- Air Liquide creative oxygen
- Air Products
- altergy Leading the Fuel Cell Revolution
- AngloAmerican
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- Audi
- BLACK & VEATCH Building a world of difference.
- Bloomenergy
- BMW
- California Fuel Cell Partnership Driving for the Future
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- GORE Creative Technologies Worldwide
- GTP
- HEXAGON
- HONDA The Power of Dreams
- HYUNDAI
- HYDROGENICS Advanced Hydrogen Solutions
- INL Idaho National Laboratory
- Intelligent Energy
- JM Johnson Matthey Fuel Cells the power within
- THE LINDE GROUP
- myFC YOUR POWER SOURCE
- nel
- NREL National Renewable Energy Laboratory
- Nebraska Public Power District Always there when you need us
- NISSAN GROUP OF NORTH AMERICA
- NUVERA
- LG
- OFCC Ohio Fuel Cell Coalition
- Pdc
- PLUG POWER
- Sandia National Laboratories
- SRNL Savannah River National Laboratory
- South Coast AQMD
- Shell
- TOYOTA
- United Hydrogen

FCHEA Regulatory Affairs

- FCHEA WGs make a significant contribution to the development of RCS that impact our industry
  - Examples include Model Code work of TWG, Micro FC Standards and regulations of PPWG, and harmonization of domestic and international industry standards
- FCHEA is focused on the areas of regulations, codes and standards with the greatest impact on commercialization
  - **Priorities are set annually by FCHEA's Board of Directors**
    - Our regulatory affairs matrix helps us keep track of our RCS priorities
  - RCS activities are managed through our technical working groups
    - Transportation Working Group
      - Hydrogen Codes Task Force
    - Solid Oxide Fuel Cell Working Group
    - Stationary Power Working Group
    - Portable Power Working Group
- Regular updates are available in monthly webinars and bi-monthly electronic newsletters.
  - www.hydrogenandfuelcellsafety.info

FCHEA
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Nick Barilo, P.E.,

Hydrogen Safety Panel Program Manager

HYDROGEN Safety Panel

AIChE The Global Home of Chemical Engineers

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The Safety Challenge

- Safety issues must be addressed for successful hydrogen technology acceptance and deployment
- Safety issues can be a ‘deal breaker’
- Hydrogen technology stakeholders may not be able to identify and effectively address all safety issues
- Stakeholders benefit from an independent and experienced hydrogen safety review (ISR) resource involved in early design and safety planning activities

Outline for the Webinar

- Introduction to the Hydrogen Safety Panel
- Hydrogen Safety Primer
- Codes and Standards
- Hydrogen Safety Resources
- Opportunities for Utilizing the Hydrogen Safety Panel
- AIChE Center for Hydrogen Safety

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Hydrogen Safety Resources

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

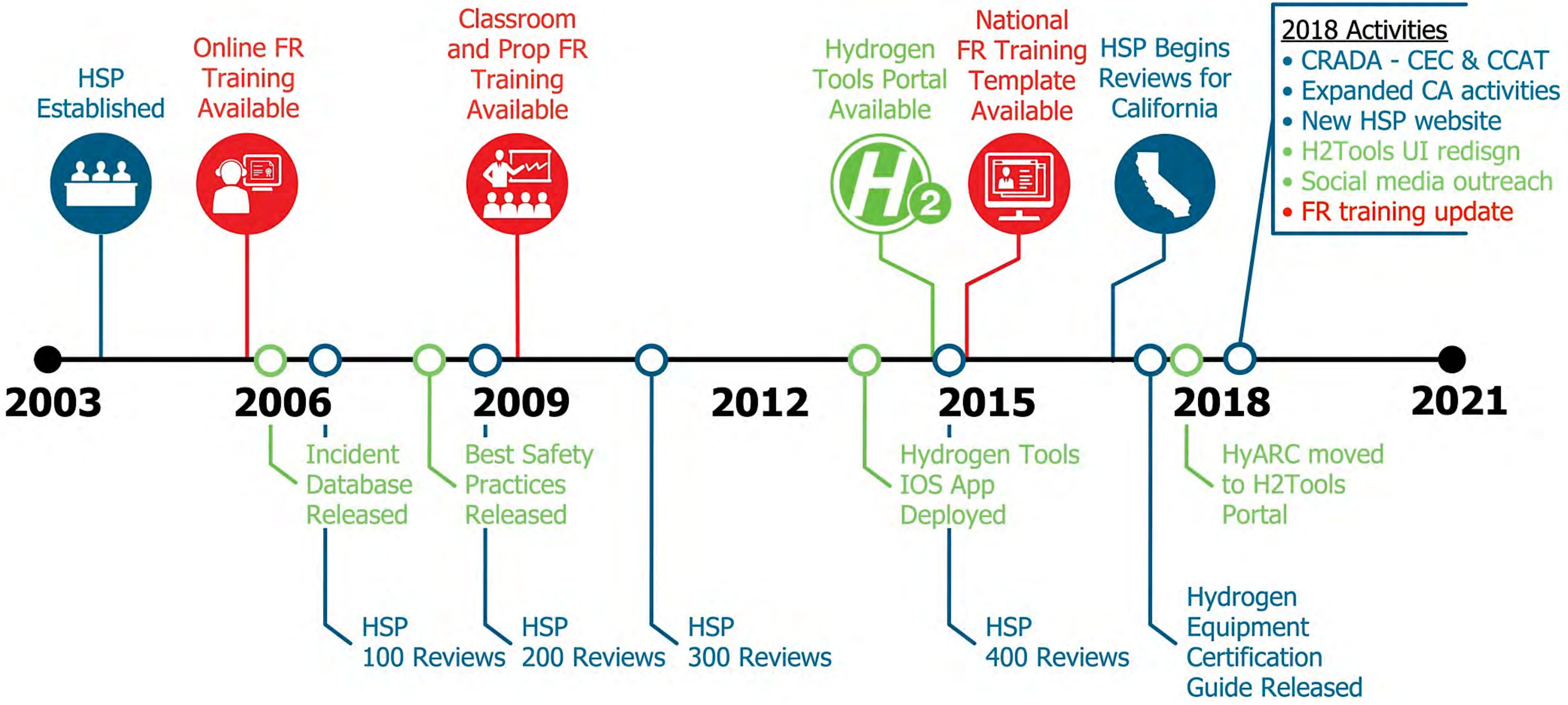
Hydrogen Tools *Web Portal* (*http://h2tools.org*)

- 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

Project Timeline



Introducing the Hydrogen Safety Panel (HSP)

Experienced, Independent, Trusted Expertise

The HSP promotes safe operation, handling, and use of hydrogen

- Formed in 2003
- 15 members with **400+ yrs** combined experience
- **495 hydrogen safety reviews completed** – hydrogen fueling, auxiliary power, backup power, CHP, portable power, and lab R&D
- White papers, reports, and guides
- Provides support on the application of hydrogen codes and standards
- **H_2 safety knowledge shared through the H_2 Tools Portal** (h2tools.org)

Some of the fire officials and hydrogen experts that comprise the Hydrogen Safety Panel (24th meeting, 2017, Cambridge, MA)

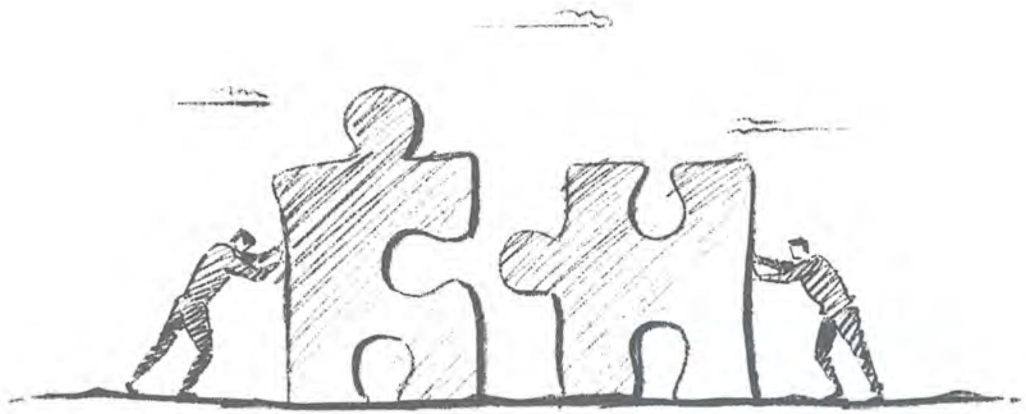
Since 2003

495	335	86	12
Reviews	Projects	Presentations	Guides

Impact of the HSP's Activities

Involving the HSP in hydrogen project and program activities will have these beneficial impacts:

- Serves as a non-regulatory, objective and neutral expert resource
- Responds with a balanced solution to questions, problems and issues
- Sees the "big picture"
  - Shares learnings
  - Identifies gaps
- Helps reduce costs by avoiding
  - Over-engineering and unnecessary features
  - Delayed approvals
  - Missed safety considerations/features
- Aids in avoiding repeating costly mistakes among disparate project proponents
- Helps project proponents avoid industry-impacting incidents
- Helps establish stakeholder and public confidence and receptivity



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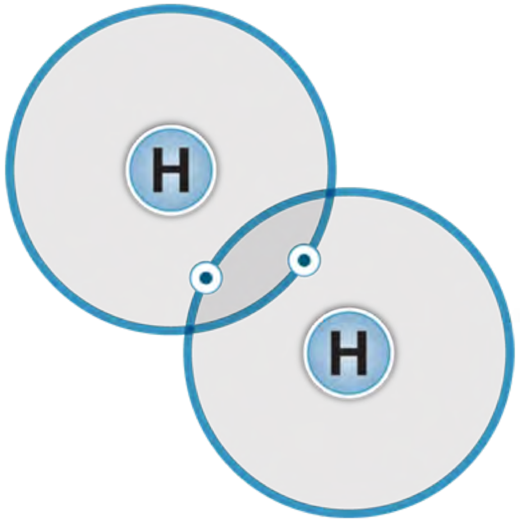
Hydrogen Properties and Behavior

- **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 gal gasoline
  - 33.3 kWh/kg H_2 vs 32.8 kWh/gal gasoline



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

Codes and Standards: IFGC Chapter 7, ASME B31.12, CGA G5.5

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 Conductivity0.157 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

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

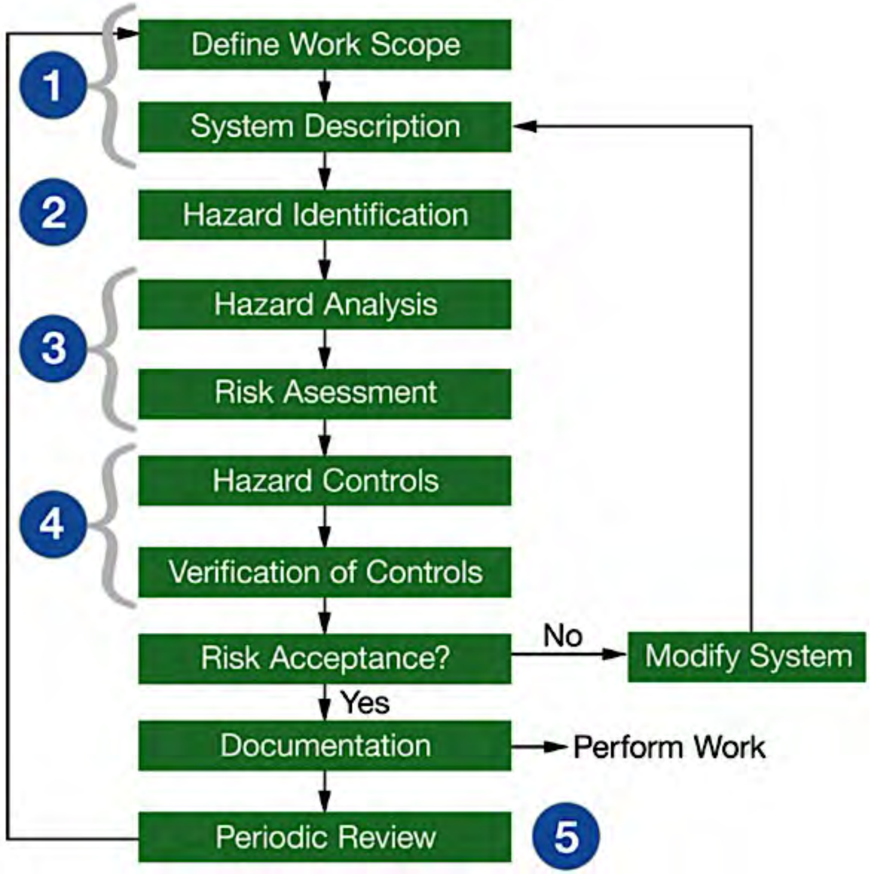
Fuel cell backup power connected to a data center

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 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.

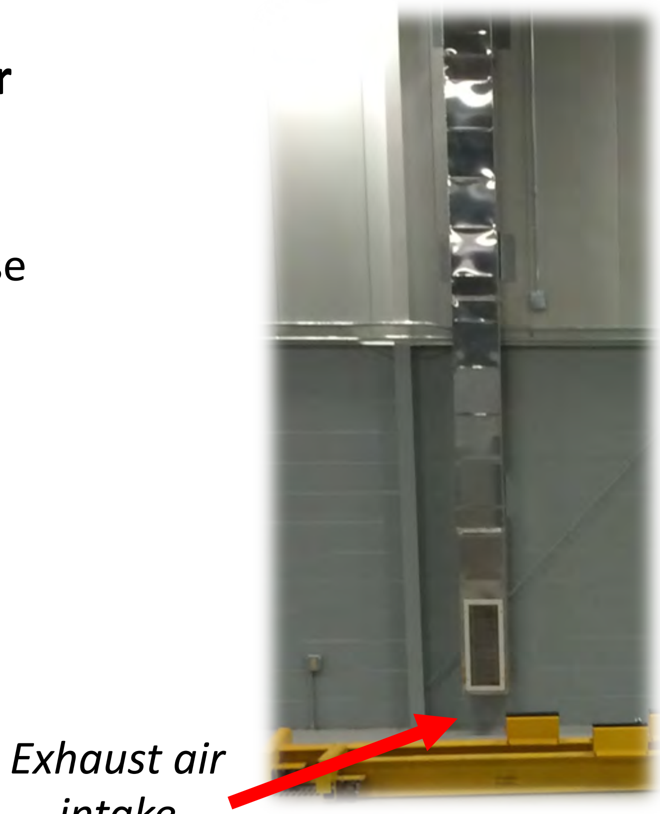
Compressor HEE with mechanical ventilation

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 air intake shall be within 12 inches of ceiling
  - Supply shall be within 12 inches of floor



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

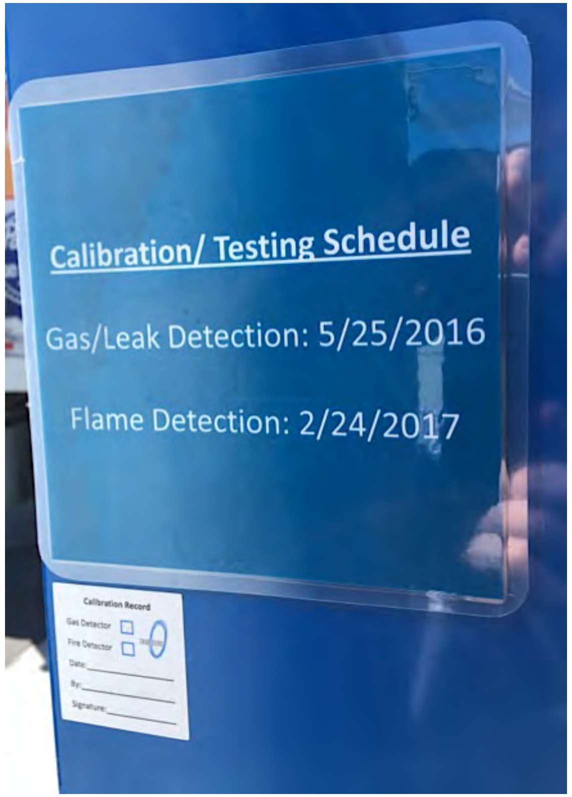
H_2 Leak Detection Goals

- 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



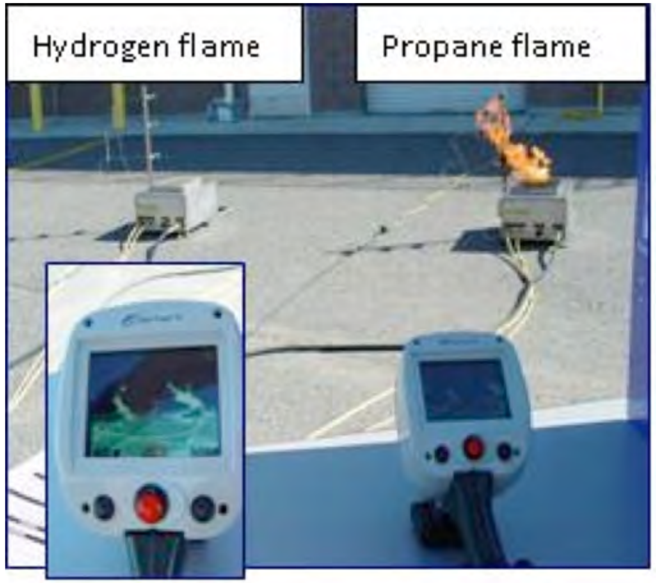
Code and Standards: IFC 5003.2.2, NFPA 2:2016 -7.1.22, 7.1.23, 103.1.18

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



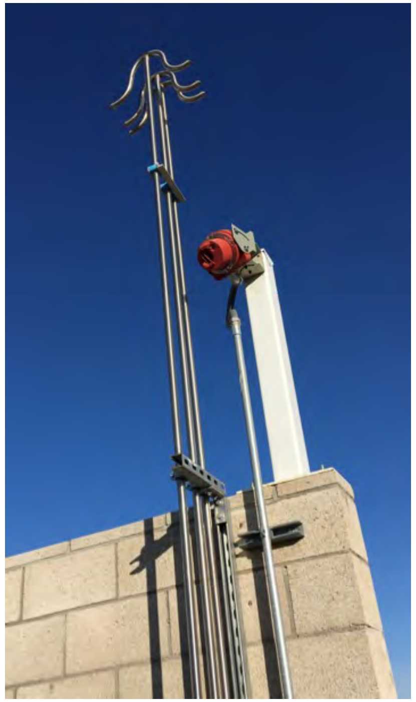
Hydrogen and propane flames in daylight

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

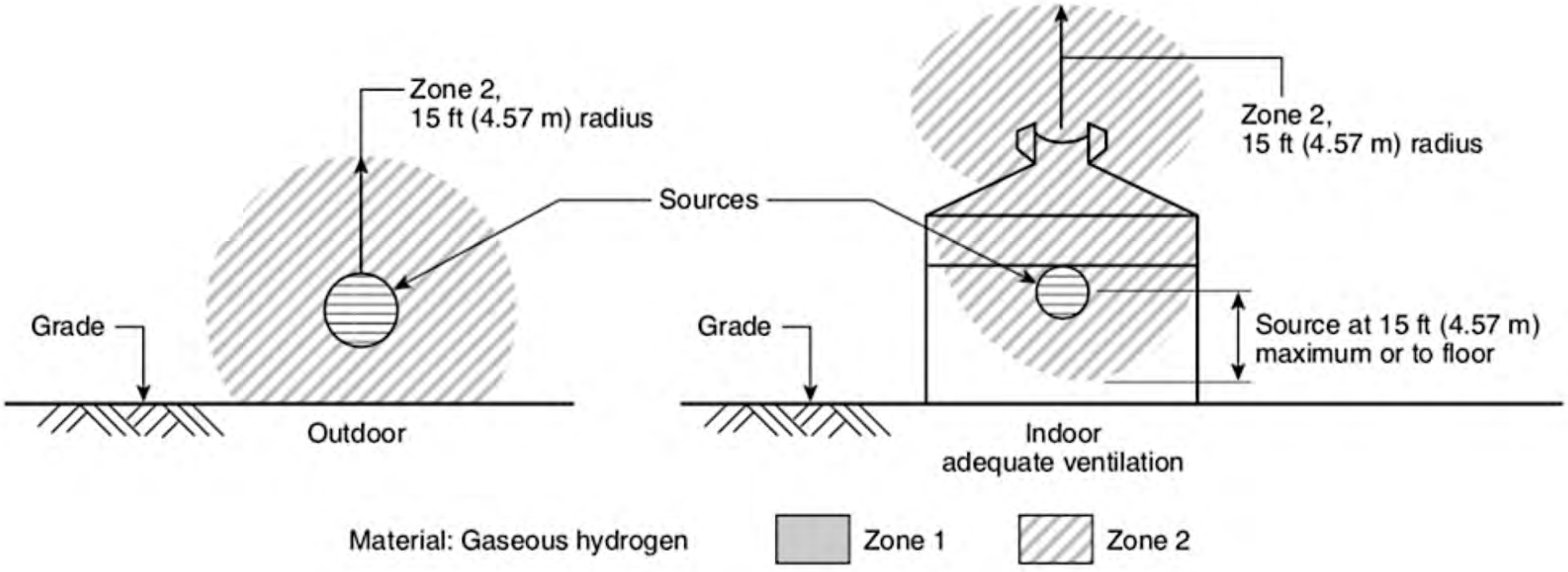
Code and Standards: NFPA 2-10.3.1./11.3.3

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)

Code and Standards: IFC 2309.2.3, NFPA 2-10.3.1.16

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

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, and excess flow valves 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

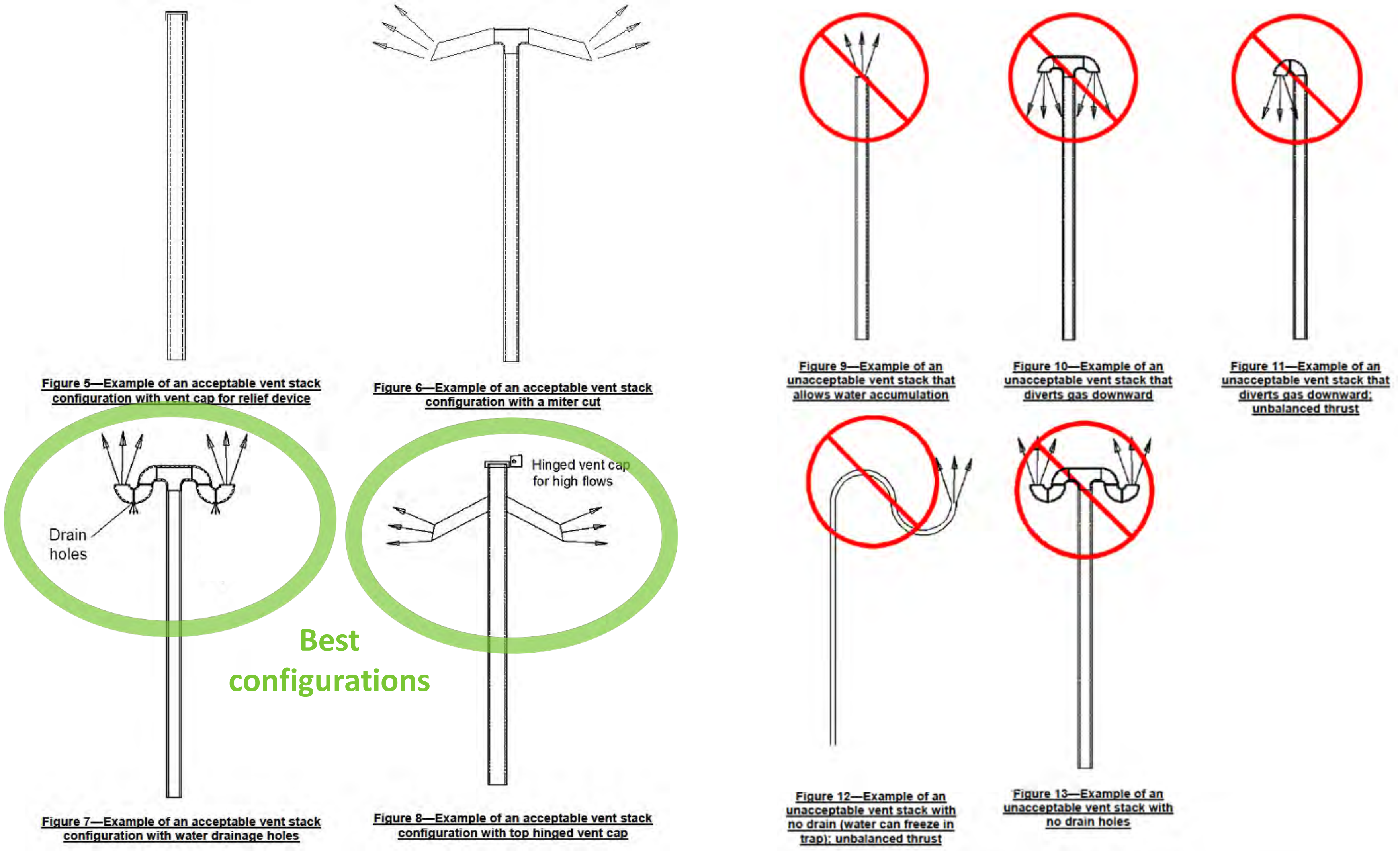


Figure 5—Example of an acceptable vent stack configuration with vent cap for relief device

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

Figure 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

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 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

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U.S. Codes and Standards for Hydrogen Facilities

National Hydrogen Specific Codes[78]

- NFPA 2 Hydrogen Technologies Code
- NFPA 30A Motor Fuel Dispensing Facilities and Repair Garages
- NFPA 55 Compressed Gases and Cryogenic Fluids Code

Component Design Standards

- ASME Boiler and Pressure Vessel[79]
- ASME B31.12–Hydrogen Piping and Pipelines
- ASME B31.1–Power Piping
- ASME B31.8–Gas Transmission and Distribution Piping Systems
- ASME B31.8S–Managing System Integrity of Gas Pipelines
- ASME B31.3–Process Piping
- CGA S-1.1-3: Pressure Relief Device Standards
- CGA-G-5.5: Hydrogen Vent Systems
- SAE J2600–Compressed Hydrogen Surface Vehicle Fueling Connection Devices
- UL 2075–Standard for Gas and Vapor Detectors and Sensors
- NFPA 77 and API RP 2003 offer guidance on grounding and static electricity

Model Codes

- International Fire Code
- International Building Code

Component Listing and Design Standards

Currently, few existing components are tested to listing standards implemented by a nationally recognized testing laboratory (NRTL). AHJs may allow the station manufacturer to provide technical information to prove that the compression, storage, and dispensing components used are fit for service. As the market develops, the list of listed components (and systems) is expected to grow.

Station Developer Standards (For informational use)

- SAE J2601–Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles[80]
- SAE J2799–Hydrogen Surface Vehicle to Station Communications Hardware and Software
- SAE J2719–Hydrogen Fuel Quality for Fuel Cell Vehicles
- HGV CSA Series Standards (currently being updated)

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

Station

Dispenser Component Standards
CSA HGV series
ISO 19880 family

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

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

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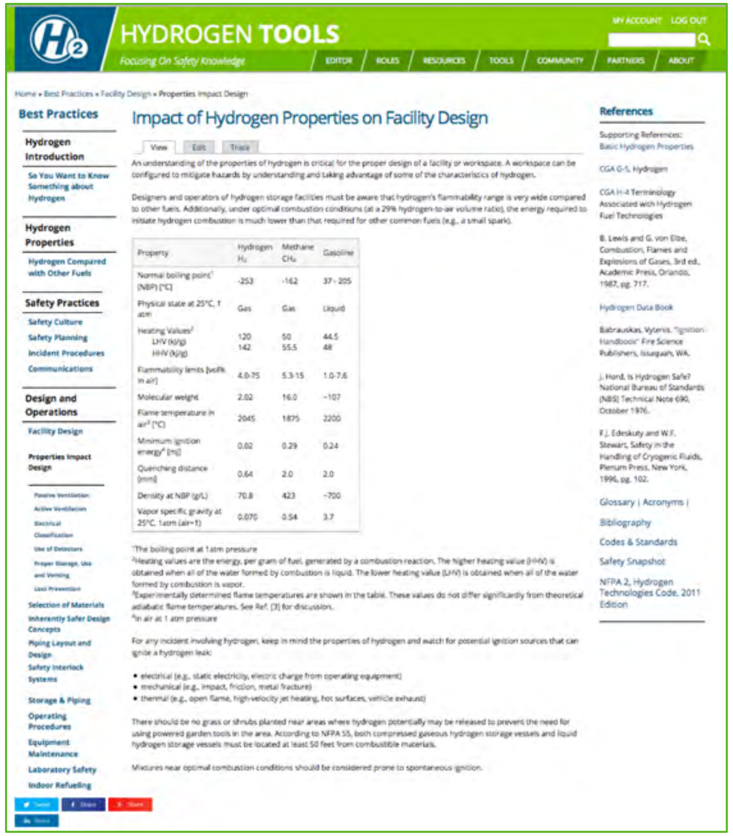
Hydrogen Tools Portal

A Transformative Step Towards Hydrogen Adoption

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



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, 1atm (air=1)	0.070	0.54	3.7

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

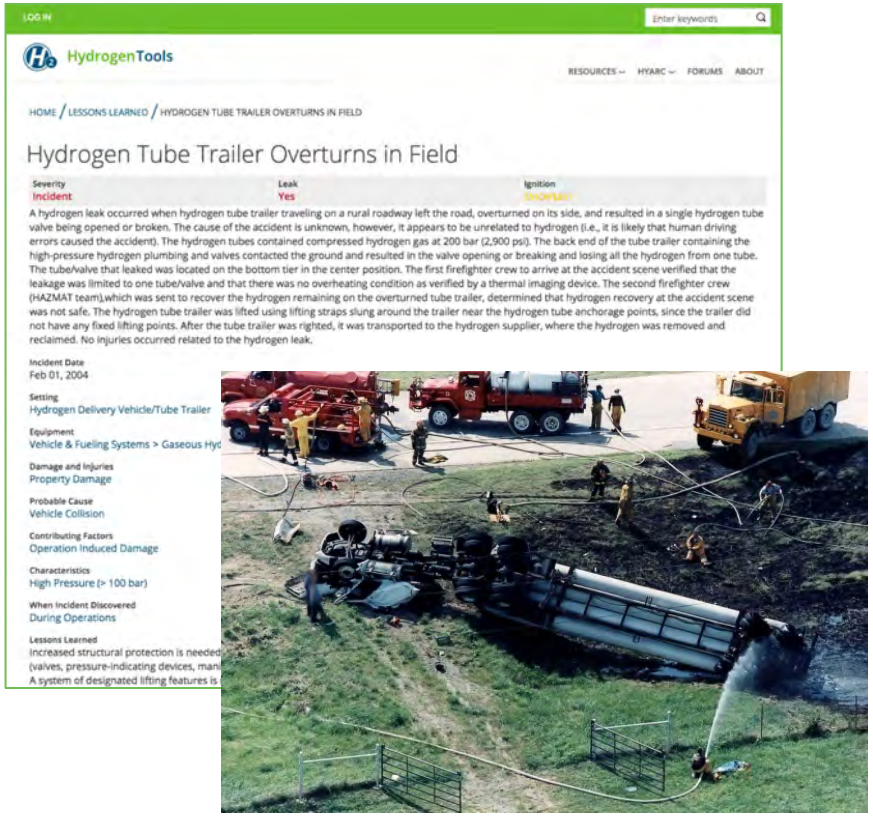
URL: http://h2tools.org/bestpractices

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



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Enter keywords

HydrogenTools

RESOURCES HYARC FORUMS ABOUT

HOME / LESSONS LEARNED / HYDROGEN TUBE TRAILER OVERTURNS IN FIELD

Hydrogen Tube Trailer Overturns in Field

Severity	Leak	Ignition
Incident	Yes	Uncertain

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 (HAZMAT team),which 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.

Incident Date
Feb 01, 2004

Setting
Hydrogen Delivery Vehicle/Tube Trailer

Equipment
Vehicle & Fueling Systems > Gaseous

Damage and Injuries
Property Damage

Probable Cause
Vehicle Collision

Contributing Factors
Operation Induced Damage

Characteristics
High Pressure (> 100 bar)

When Incident Discovered
During Operations

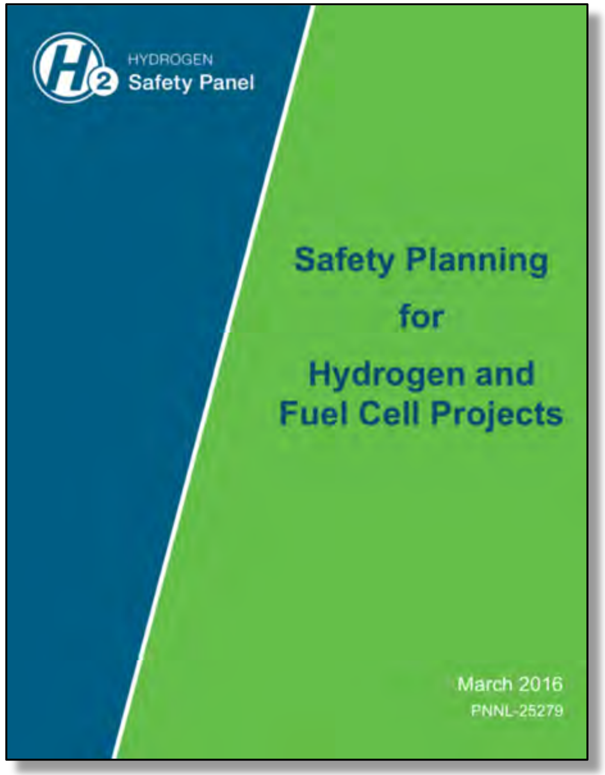
Lessons Learned
Increased structural protection is needed
(valves, pressure-indicating devices,
A system of designated lifting features is

Tube trailer rollover

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.


HYDROGEN Safety Panel

Safety Planning for Hydrogen and Fuel Cell Projects

March 2016
PNNL-25279

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

Addressing the Certification Challenge

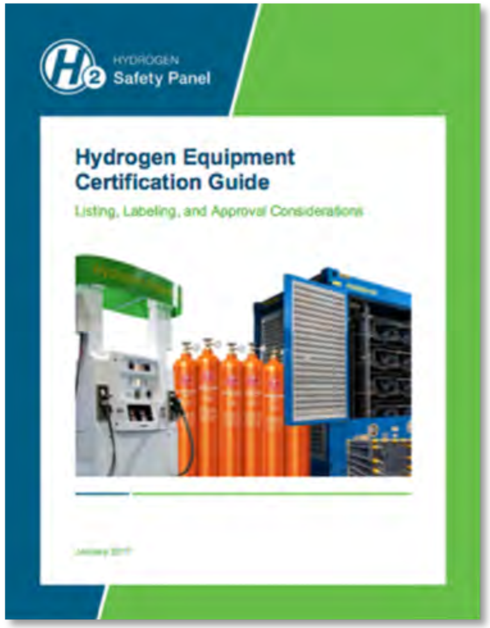
A ***Hydrogen Equipment Certification Guide*** has been released to assist code officials, designers, owners, evaluators, and others with the application of the listing and approval requirements pertinent to the design and/or installation of hydrogen equipment as regulated by the model codes.

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

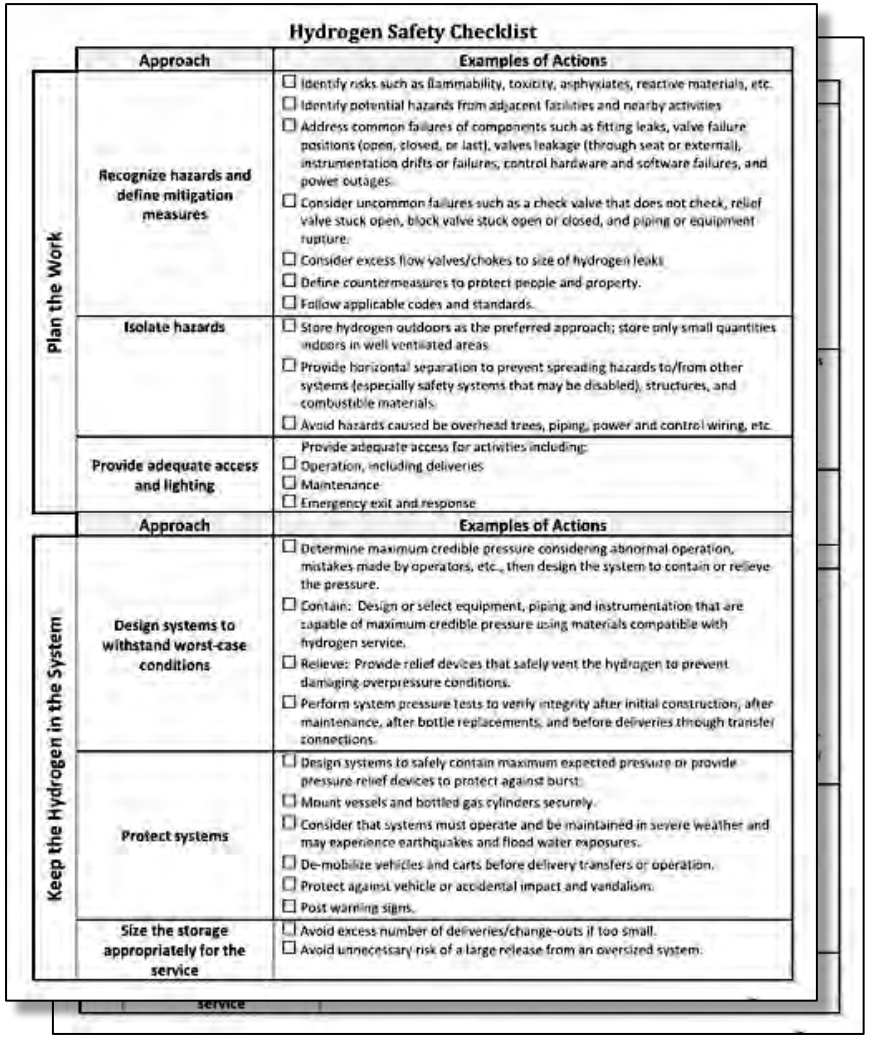


- Consistent application of requirements among providers, regardless of hydrogen experience, results in a level playing field as the technology emerges

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

Hydrogen Safety Considerations Checklist

- Intended users
  - Those developing designs for hydrogen systems
  - Those involved with the risk assessment of hydrogen systems.
- While 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



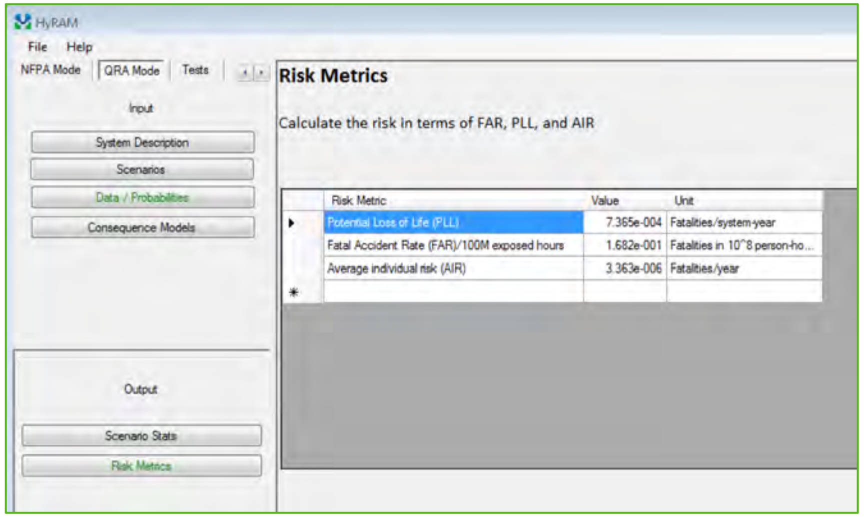
Hydrogen Safety Checklist

	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

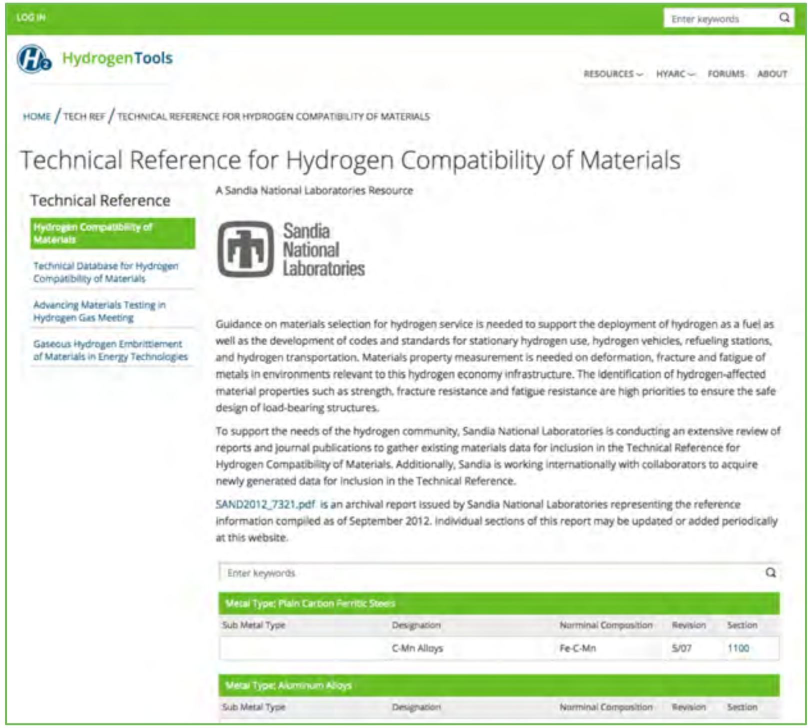
First-of-its-kind software tool for integrating H_2 consequence models w/ QRA models
Includes behavior models & data developed through FY12

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

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.

Outline for the Webinar

- Introduction to the Hydrogen Safety Panel
- Hydrogen Safety Primer
- Codes and Standards
- Hydrogen Safety Resources
- **Opportunities for Utilizing the Hydrogen Safety Panel**
- AIChE Center for Hydrogen Safety

CRADA Activities and Opportunities

CRADA with the Connecticut Center for Advanced Technologies

The objectives include:

- Raising awareness of the HSP among state/local officials and project developers
- Establishing working relationships with key state and local organizations to enable seamless incident response and development of safety lessons learned
- Identifying types of projects that would benefit from HSP involvement
- Identifying methods to facilitate outside organizations paying for HSP

Pacific Northwest NATIONAL LABORATORY

CCAT Connecticut Center for Advanced Technology, Inc.

Support for the Safe Implementation of Hydrogen Technologies

Activities that can Benefit from HSP Involvement

Early Concept Support

Pre-Project

- **Safety planning webinars**
- Pre-project outreach to stakeholders
- ***H_2 Safety training and orientation for code officials**
- Project team safety planning consultations

Early Design

- Safety plans reviews
- ***Review project/facility early designs**
- Participate in risk analyses development
- **Review risk analyses**
- *Address AHJ safety questions

Early Operation

- Evaluate safety features of completed facilities
- **Onsite safety evaluations**
- Provide first responder H_2 safety training

Program Support

- **Identify safety gaps**
- Develop industry guides
- ***Expert support for incident fact-finding and investigations**
- Bolster stakeholder and public confidence

Successful Project Implementation

* Support for AHJ and code officials can bridge the gap for inexperienced staff, facilitate faster approvals, support a greater confidence in project safety and provide more technically justified safety features or alternate means and methods

Outline for the Webinar

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Future Direction and Sustainability

Pacific Northwest NATIONAL LABORATORY

AIChE

The Global Home of Chemical Engineers

American Institute of Chemical Engineers (AIChE)

Streamlined access to HSP

HYDROGEN Safety Panel

AIChE* has partnered with PNNL to establish a Center for Hydrogen Safety (CHS). CHS will expand the HSP's access to new customers by:

- **Making the HSP more readily available to industry, state, and federal government agencies (national and international)**
- **Enabling less cumbersome/time-consuming contracting efforts**

PNNL will transfer its first responder hydrogen safety training resources to AIChE to enable broader access to online and in-person training resources (with continued subject matter support from PNNL and CaFCP)

** AIChE is the world's leading organization for chemical engineering professionals, with more than 60,000 members from more than 110 countries. AIChE has the breadth of resources and expertise to support industries or emerging areas, such as hydrogen and fuel cell technologies.*

Introducing the Center for Hydrogen Safety

CENTER FOR Hydrogen SAFETY

An AIChE Technical Community • A Global Resource On Hydrogen Safety

The Center for Hydrogen Safety (CHS) is a not-for-profit, non-bias, membership organization within AIChE that promotes the safe operation, handling, and use of hydrogen and hydrogen systems across all installations and applications. The CHS identifies and addresses concerns regarding the safe use of hydrogen:

- As a sustainable energy carrier
- In commercial and industrial applications
- In hydrogen and fuel cell technologies

URL for more info: www.aiche.org/chs

Concluding Thoughts and Next Steps

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

Next Steps

- Let us know if you have a project that could benefit from a review by the HSP
- Join the Center for Hydrogen Safety… Your membership will provide access to the HSP and key safety resources and help your organization show that safety is a priority

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

Connecticut Center for Advanced Technology, Inc.

Questions

Thanks for Your Attention!

<u>My Contact Information</u>:

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