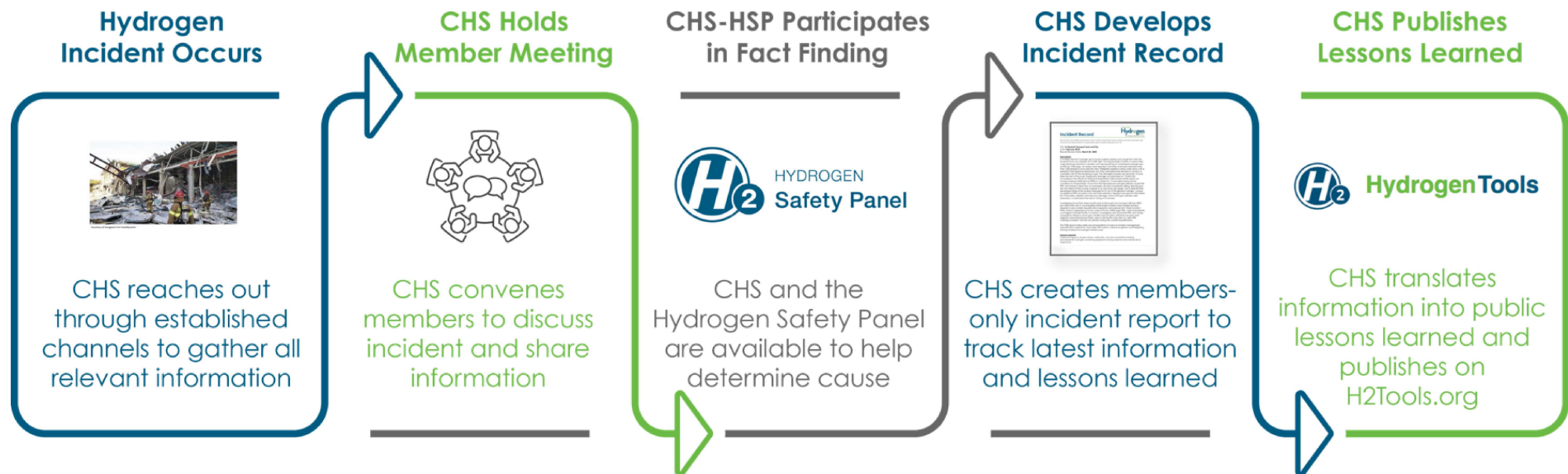


# Hydrogen Incidents and Lessons Learned

Nick Barilo  
Executive Director, Center for Hydrogen Safety  
April 17, 2024



# CHS Hydrogen Incident Response Activities



## Other resources CHS may use for responding to an incident:

- Education Materials – new courses, revised course content, etc.
- Technical Bulletins – members only and public safety bulletins developed and disseminated
- Working Groups – to address important safety issues and develop learnings for community and industry
- Conferences & Workshops – share incident information and learnings
- Incident Management Guide

# Lessons Learned



*Those who cannot remember the past are condemned to repeat it.*

- George Santayana

A few benefits of lessons-learned activities:

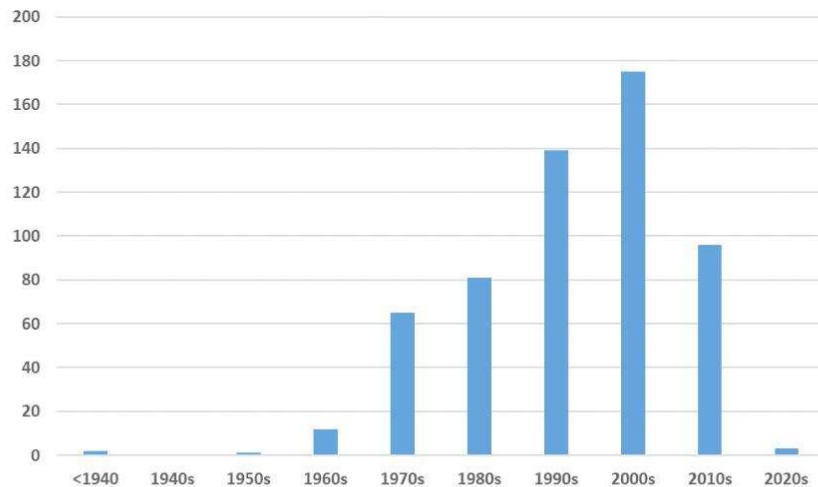
- ▶ It helps an organization understand the root causes of incidents and prevent future occurrences
- ▶ It can help protect finances and reputation
- ▶ It enables the industry to consider and evaluate where similar vulnerabilities exist
- ▶ Informs standards development organizations
- ▶ It is important to support a strong safety culture



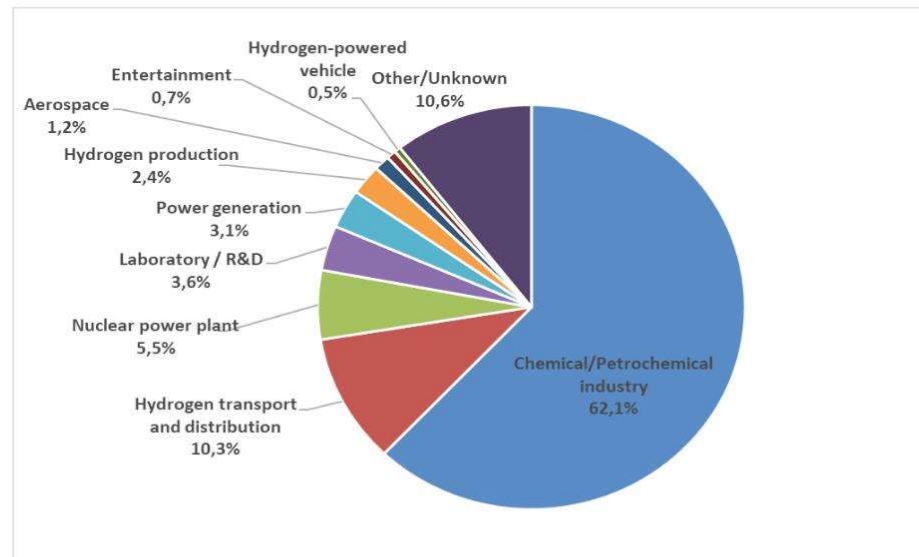
## Results from the statistics analysis (1)

The analysis reported here is based on the 706 incidents, which were in the database as of May 2021. A total of 576 of these events were considered to be statistically relevant and formed the basis for the statistical analysis to inform lessons learned and recommendations.

**Years**

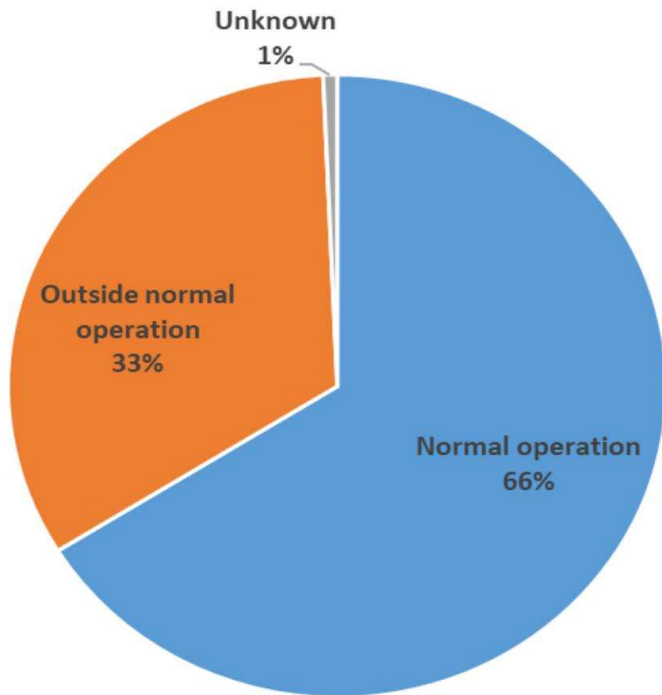


**Industrial sectors**

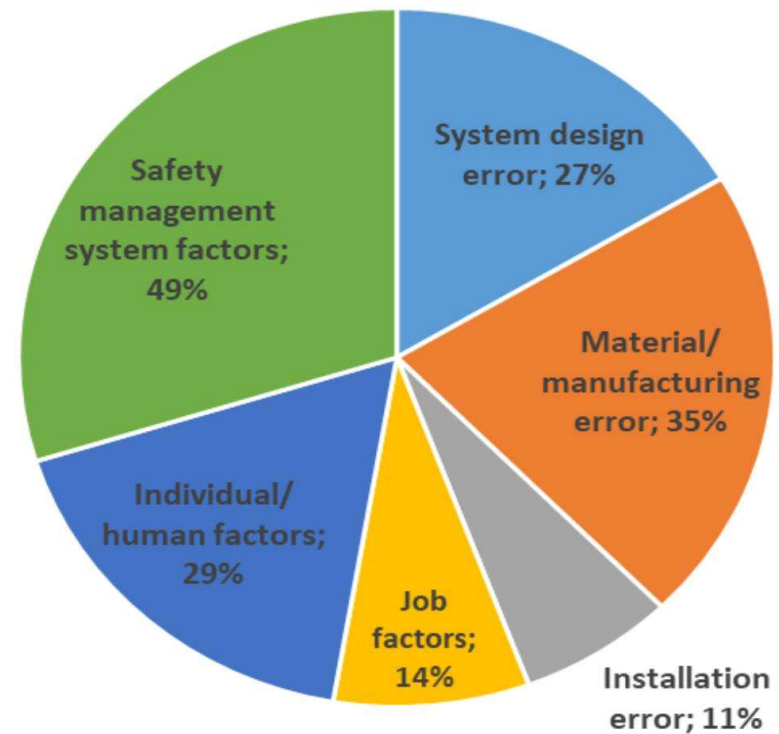


## Results from the statistics analysis (3)

Operational mode



Causes (multiple entries per incident possible)



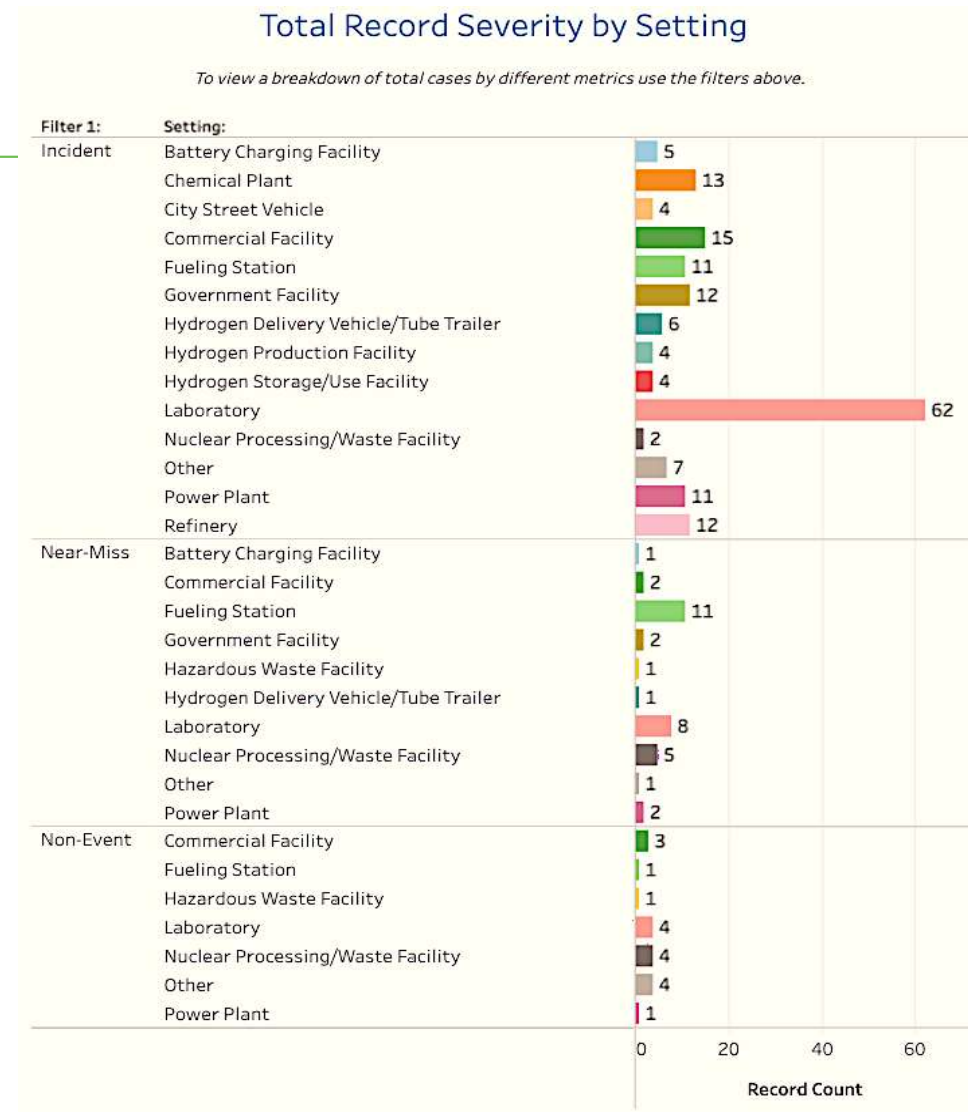
# H2Tools Lessons Learned

221 Records spanning 50+ years

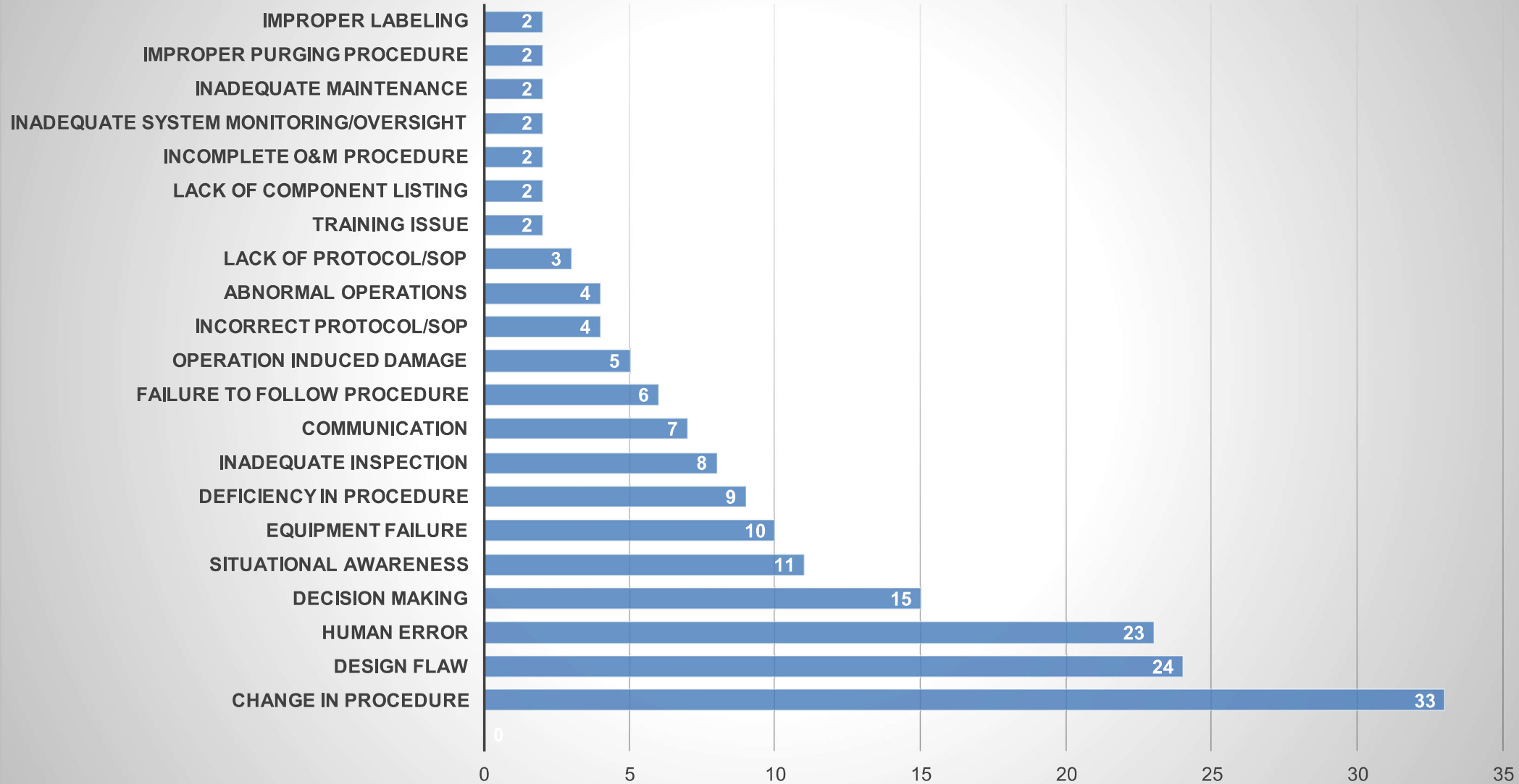
A database-driven website to facilitate the sharing of lessons learned and other relevant information gained from actual experiences using and working with hydrogen.

The database also serves as a voluntary reporting tool for capturing records of events involving either hydrogen or hydrogen-related technologies.

*It does not reflect all incidents that have occurred, only those reported*



## H2Tools Lessons Learned Contributing Factors for 176 Events



# Stationary Facility Incidents



# Tank Explosion at Research Facility



## Event Summary

- ▶ An outdoor hydrogen tank exploded at a research and development complex during test of a water electrolyzer

## Cause

- ▶ Ignition of a hydrogen-oxygen gas mixture within the tank resulting in vessel overpressure
  - Electrolyzer cell membrane degradation may have permitted excessive oxygen gas crossover rate through the electrolyzer cell membranes into the product hydrogen gas

## Lessons Learned

- ▶ Understand interrelation of electrolyzer membrane gas permeability, membrane degradation, and dynamic operating range when establishing process safety controls
- ▶ Consider automatic gas storage isolation and stopping gas generation when safety limits are exceeded



## Event Impact

- Two fatalities
- Six injuries
- \$30 million damage

# Fueling Station Tank Leak, Fire and Explosion



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## Event Summary

- ▶ A leak from one tank within a high-pressure hydrogen storage unit serving a hydrogen vehicle fueling station resulted in a jet fire and an open-air deflagration

## Cause

- ▶ An assembly error of a specific sealing end plug for the high-pressure hydrogen tank
  - The inner bolts of the plug had not been adequately torqued, allowing seal failures to progress into an explosion and subsequent jet fire

## Lessons Learned

- ▶ Implement rigorous assembly, double-witness verification, and documentation/marketing procedures for hydrogen-containing equipment



## Event Impact

- No injuries
- Station damage
- Airbag activated in nearby vehicle

# Hydrogen Plant Truck Fueling Deflagration and Fire

## Event Summary

- ▶ A gaseous hydrogen leak, fire, and deflagration occurred at a hydrogen production and trailer loading station during a filling operation

## Cause

- ▶ Unauthorized repair and failure to follow procedures during a minor leak resulted in more severe consequences

## Lessons Learned

- ▶ Repairs must be performed by authorized, trained maintenance personnel following valid procedures
- ▶ When two persons are utilized for transfer operations, ensure that equipment configuration is verified before performing critical actions
- ▶ Hydrogen deflagration overpressures may cause secondary system leaks and degrade integrity



## Event Impact

- No injuries
- Equipment damage
- Four tankers damaged

# Bus Fueling Station Fire



## Event Summary

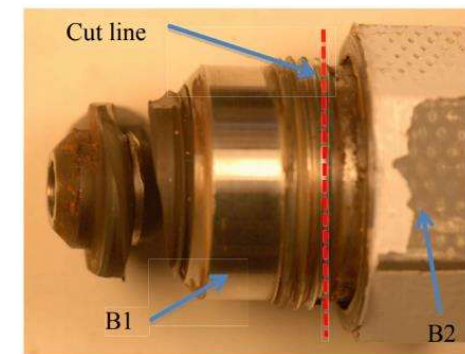
- ▶ A pressure relief valve failed, causing the release of approximately 300 kg (660 lbs.) of hydrogen over approximately 2.5 hours

## Cause

- ▶ An incompatible pressure relief device was installed

## Corrective Actions

- ▶ Before reopening the station, physical changes were made using the correct pressure relief device (PRD) and higher vent stacks
- ▶ New and modified procedures were instituted to improve the timely communication of station status during emergency events
- ▶ Additional training of personnel focused on improving the response time and effective communication between employees, first responders, and the hydrogen equipment supplier



Approximate location of cut line to separate nozzle subassembly from inlet base

## Event Impact

- No injuries
- Very minor equipment damage
- Extensive evacuation of residents and businesses

# H<sub>2</sub> Explosion at a Powdered Metals Plant



- ▶ Operators 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 incorrectly presumed that the leak was nonflammable nitrogen because there had recently been a nitrogen piping leak elsewhere in the plant**
  - A forklift with a chain was used to remove a trench covers to access the piping
- ▶ 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
- ▶ The investigation revealed a large hole (~3x7 inches) in a corroded section of hydrogen vent piping inside the trench



Top: hole in hydrogen pipe  
Bottom: cover plates dislodged by explosion

Source: Chemical Safety Board and <http://www.h2tools.org/lessons>

# Transportation Incidents

# H<sub>2</sub> Liquid Trailer (14k gallons) is Broadsided



The car and hydrogen trailer after the fire was extinguished

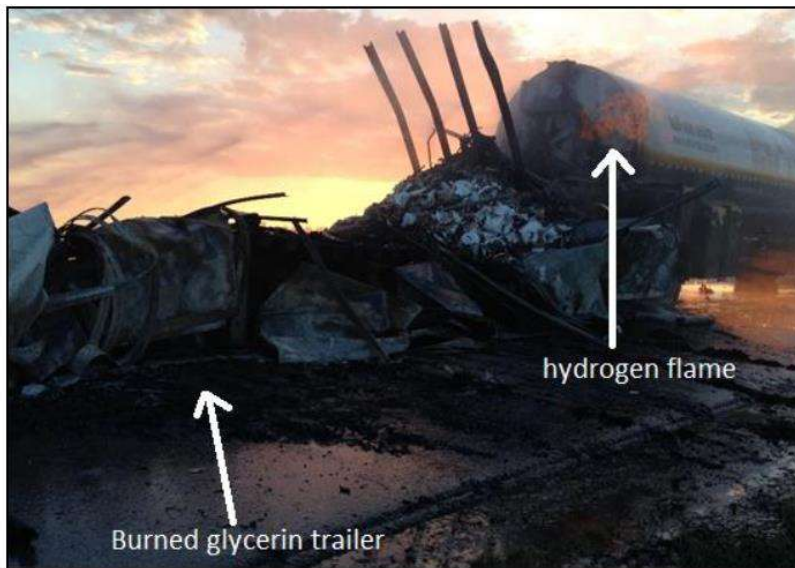
The vehicle recovery team led a safe and successful transfer of all liquid hydrogen from the damaged trailer to another one

- Driver in opposite lane swerved and went across median, slamming into LH<sub>2</sub> trailer
- The gasoline in the car caught fire
- The shell of the hydrogen trailer withstood the impact with no loss of containment

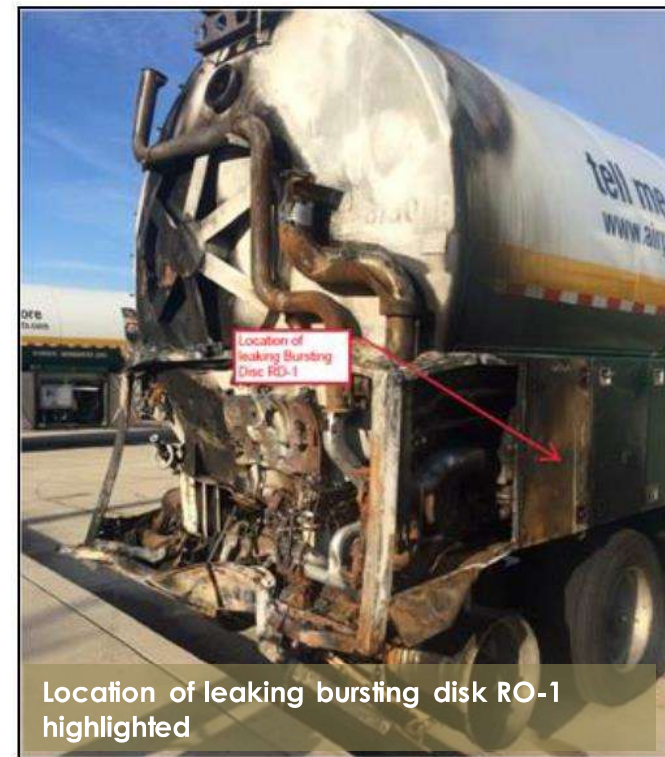


Successful liquid transfer following the accident in Louisiana

# H<sub>2</sub> Liquid Trailer Rear Ended at High Speed



Stationary LH<sub>2</sub> trailer hit by glycerin tanker at high speed. Diesel fire ensued.



The valve used to pull vacuum between the inner and outer shells was damaged. This resulted in a loss of insulation. This and heat from fire increased the temperature of the LH<sub>2</sub> and built pressure, which vented through safety valves as designed.

Total vent time: 30 hours (for 3,000 gallons)



# Modular Transport Leak and Fire

## Event Summary

- ▶ Multiple elements of a hydrogen gas module suddenly leaked and caught fire while the transport truck was stopped at a traffic light
- ▶ No injuries, but approximately 1,500-2,000 people from surrounding businesses and residential areas were involved in an evacuation

## Cause

- ▶ Incorrectly rated and incompatible PRDs installed during maintenance activity
- ▶ PRD vent tubing compression fittings to some of the gas cylinders had not been sufficiently secured

## Lessons Learned

- ▶ Implement rigorous double-witness verification, and documentation/marking procedures for hydrogen-containing equipment during assembly and maintenance inspections



# Traffic Accident Involving H<sub>2</sub> Storage Trailer



- ▶ A traffic accident with a passenger vehicle led to loss of control and leaving the roadway at the intersection
  - F350 Dual Rear Wheel tow vehicle
  - Light Duty tri-axle trailer carrying two vessels “tube bundles”
- ▶ Impacted traffic light pole and ditch on the side of the roadway
- ▶ Full loss of hydrogen containment (240 kg)
- ▶ Damage
  - Three minor injuries
  - The trailer and pickup truck were both a total loss from the impact and fire
  - Damage to light pole and overhead wires



# Traffic Accident Involving H<sub>2</sub> Storage Trailer



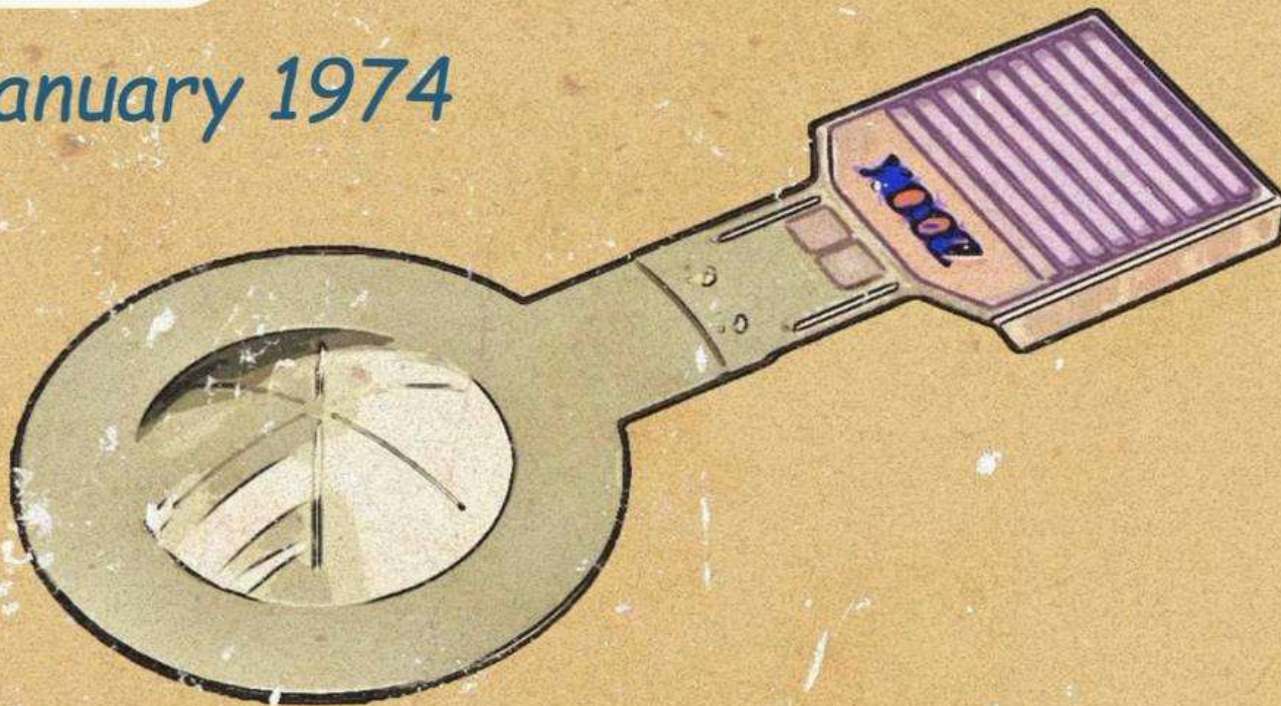
- ▶ The method of anchoring the tube bundles to the trailer allowed for movement
  - Movement of bundle combined with gooseneck deformation allowed contact
- ▶ Vent piping appears to be insufficiently supported for PRD reaction forces
  - This led to the non-vertical venting of hydrogen
- ▶ Trailer and tube bundle frame appear to have been insufficient to protect piping in this accident
  - Line shear plus open valves may have played a role in the initial hydrogen release
  - PRDs may have played a role in the initial hydrogen release
  - Vent piping may have been inadequately restrained to withstand impact
- ▶ Ball valves might have failed to provide containment
  - The impact may have opened valves
  - Impact broke the stem of at least one valve
  - Packing/Seals damaged in fire likely led to further leakage
  - Packing/Seals damaged in fire may have allowed valves to open

# Liquid Hydrogen Lessons Learned



Lesson Learned

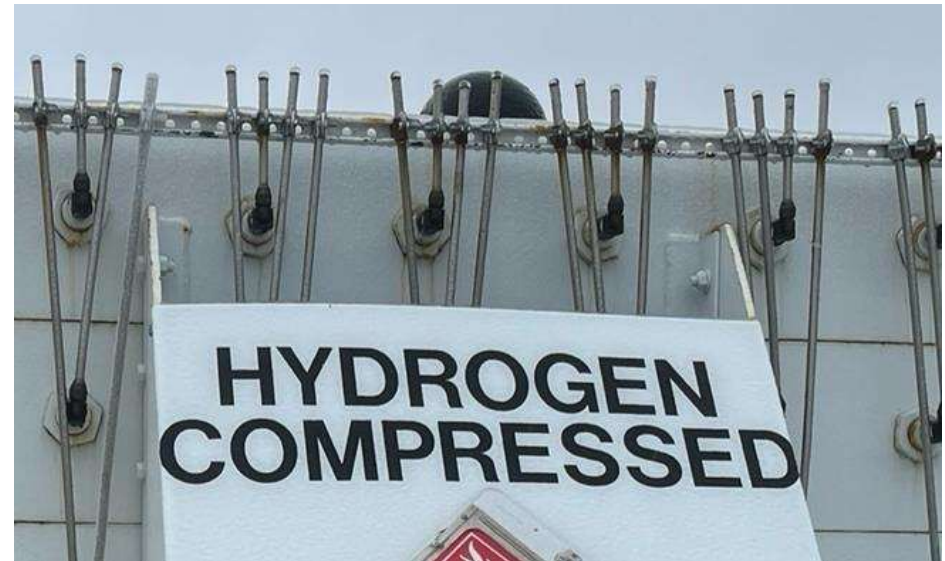
*January 1974*



# Trailer Vent System Weather Protection



- ▶ The tube trailer was located at a customer location
- ▶ Water entered the vent stack
  - Vertical discharge but no caps
  - Weather-related
- ▶ Water froze during inclement weather
  - Abnormal for area
- ▶ Ice plug pushed against and damaged a rupture disc
  - Rupture disc activated and led to loss of containment
  - The vent system remained in place, minimizing the consequences
  - No ignition, well-sited
  - Must replace remaining devices since they may have been damaged
- ▶ Lessons learned
  - Provide weather protection to vent outlets
  - Blockages can also damage relief devices



# CNG Incident – February 2024

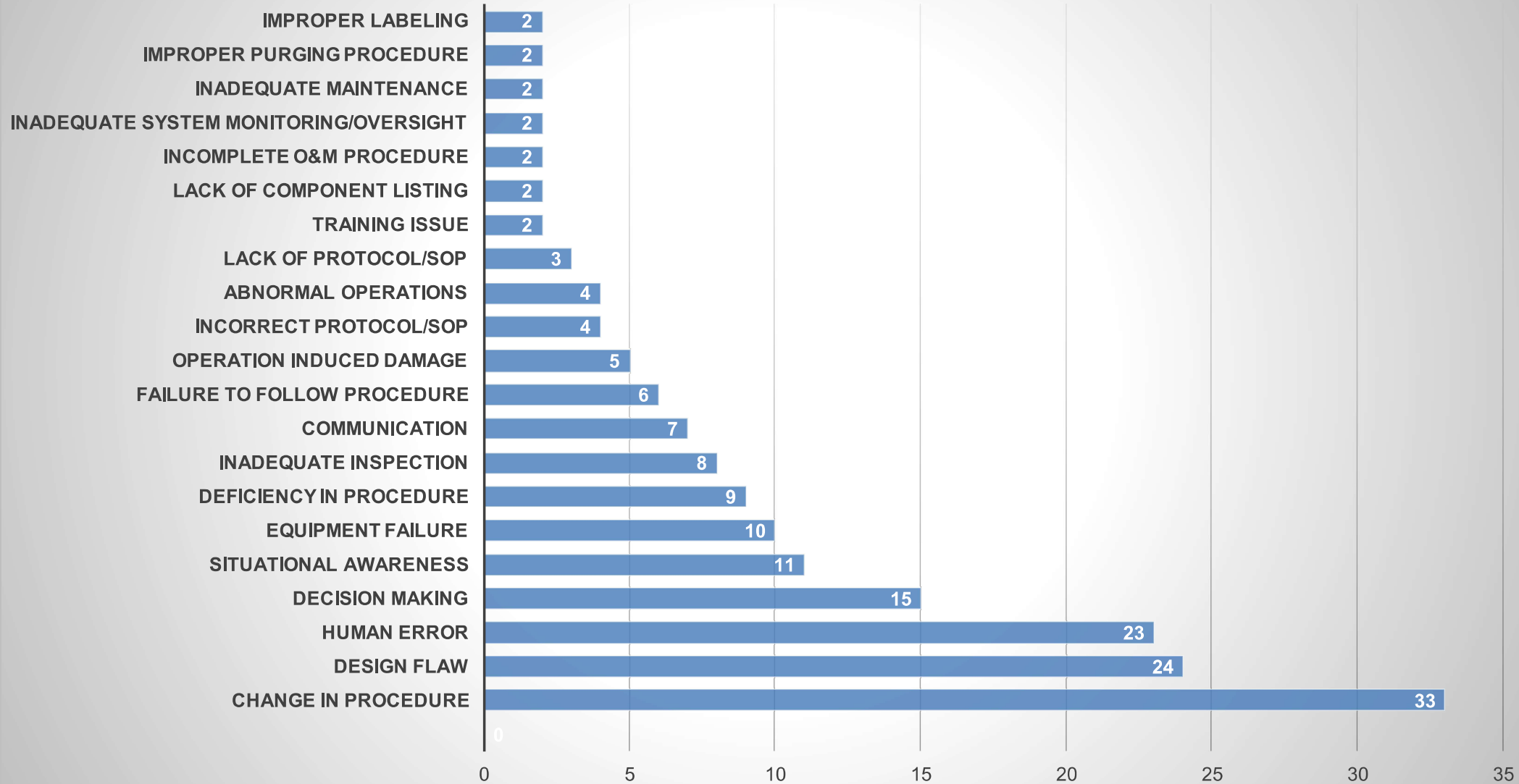
- ▶ A semi-truck's 100-gallon compressed natural gas tank exploded while firefighters attempted to extinguish the flame
  - Nine firefighters were injured during their response to a natural gas-powered semi-truck fire.
- ▶ The storage system's similarities to hydrogen highlight the need to ensure first responders have the information necessary to mitigate hydrogen incidents safely
- ▶ The US National Transportation Safety Board is currently investigating the incident



Video from ABC7, Los Angeles

**What Have We Learned?**

## H2Tools Lessons Learned Contributing Factors for 176 Events





# General Learnings from H<sub>2</sub> Incidents



- ▶ Human factors play a significant role in incidents... either causing or significantly contributing to the incident's impacts
  - Implement a strong safety culture
  - Utilize engineering controls before administrative controls



- ▶ Share what you have learned from an incident
  - Sharing is needed to help the industry avoid similar incidents, and transparency helps instill public confidence



- ▶ Help First Responders minimize the consequences of incidents by providing:
  - Training and knowledge resources for first responders before an incident occurs
  - Prompt information and support to the incident commander to help them understand the fuel and hazards

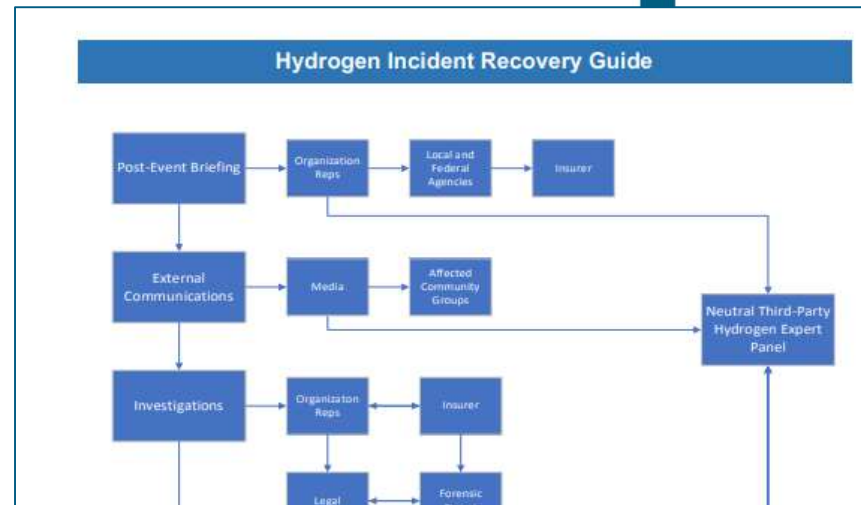
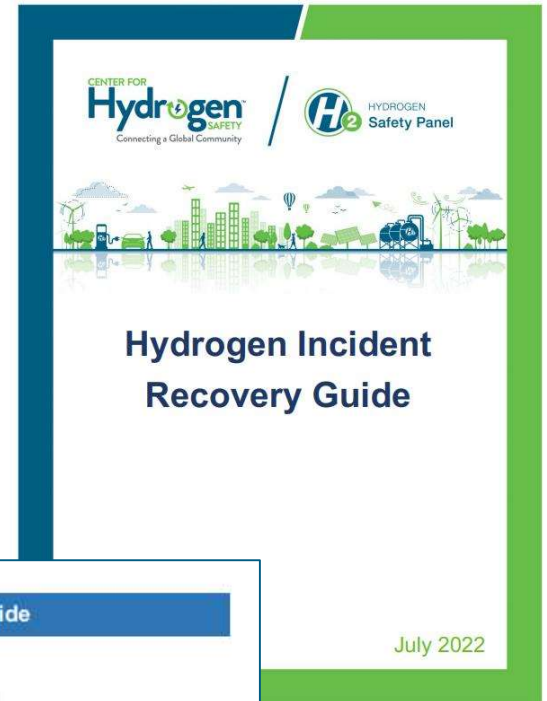


- ▶ Plan ahead for how to respond to an incident
  - Include crisis management and internal/external communication
  - Incident recovery

# Hydrogen Incident Recovery Guide

- ▶ Published July 2022
- ▶ Provides practical guidance with a checklist to help an organization recover from a hydrogen incident and return to normal operations
- ▶ Applies to the post-event recovery phase
- ▶ The can be tailored to meet the specific needs of the organization

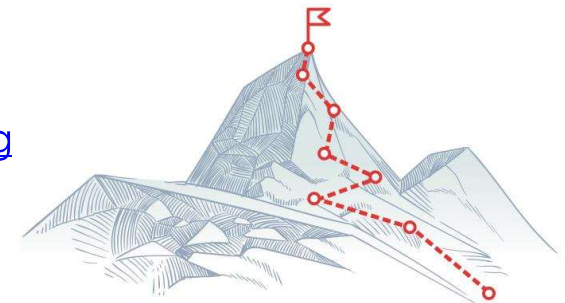
Status	Recovery Topics	Interfaces (Note A)	Appendix Reference
	1. ESTABLISH/ACTIVATE a recovery coordination team		E.1
	a. IDENTIFY members of recovery coordination team		A
	b. IDENTIFY points of contact for external communication		B
	c. OBTAIN initial post-event briefing from organization management and/or first responder lead	(i)	
	d. COMMUNICATE post-event briefing to appropriate individuals	(i) (ii) (iii) (iv) (v) (vii)	E.2
	2. VERIFY incident scene is safe, contained, and secured, and evidence is preserved		E.3
	a. PRESERVE incident scene by signage and physical barriers		
	b. RESTORE basic infrastructure utilities to site (electricity, water, heating, ventilation, air conditioning, plumbing, etc.) as needed and when safe to do so without affecting preservation of event scene evidence		



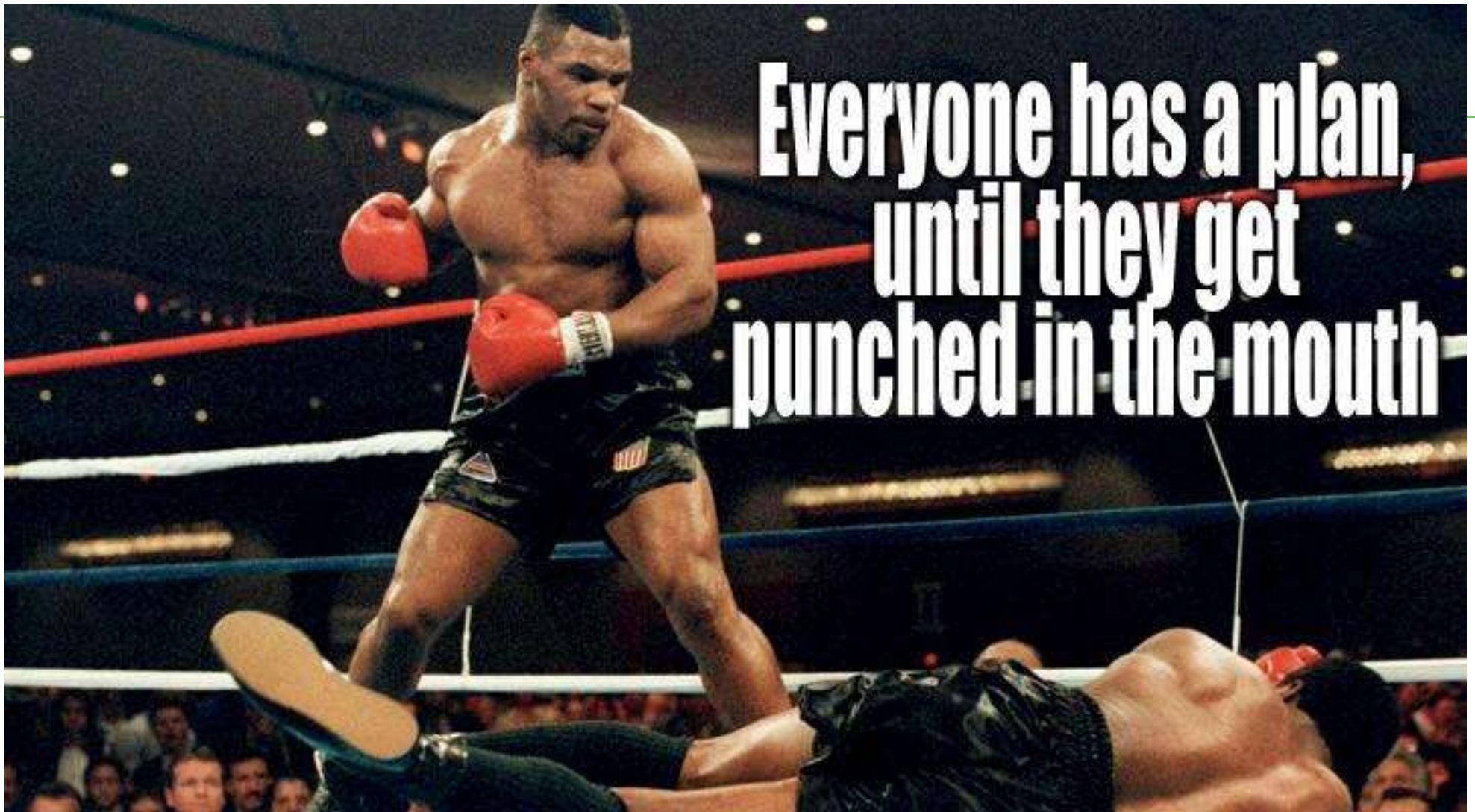
Scan for PDF

# Conclusions

- ▶ Incidents will occur, but let's minimize their frequency and impact
- ▶ **Sharing of information is critical**
  - Why? It helps everyone and transparency bolsters industry confidence
  - Please let us know about more recent incidents – [hsp@h2tools.org](mailto:hsp@h2tools.org)
  - For incidents from more than 5 years ago, use the input form on H2Tools at [https://h2tools.org/lessons?search\\_api\\_fulltext=](https://h2tools.org/lessons?search_api_fulltext=)
- ▶ **Information sharing has obstacles**
  - Barriers to getting information – shame, potential litigation, lack of seeing the value
  - Barriers to applying learnings – how does an organization know about an incident and may not see why they need to consider learnings



*The best way to avoid the negative consequences of an incident is to avoid the incident. And remember, if you don't have the resources to prevent an incident, how will you have the resources to recover?*



# Thanks for Your Attention

## Nick Barilo

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**Extra Slides**

# Other Recent Incidents



- ▶ Austria Cylinder Explosion – No update
  - Overpressure of 350 bar cylinder from a 900 bar supply source
- ▶ Golden Empire bus fire
  - Still under investigation
- ▶ Gaseous H<sub>2</sub> trailer TPRD activation incidents in Southern California
  - Three separate incidents over a several-month period
    - During trailer loading - resulted in fire and vent system failure
    - The trailer was parked during a delivery
- ▶ H<sub>2</sub> bus bridge impact incident in Netherlands  
<https://www.persbureaudrenthe.nl/drenthe/bus-te-hoog-of-brug-te-laet-bij-wijster/>
- ▶ Hose Issues
  - Reports of at least one H<sub>70</sub> dispenser hose failure in Korea
    - Upon inspection of other sites, additional precursor damage found
    - Short-term – additional inspections have been put in place while additional RCA is being conducted
- ▶ Deflagration within a compressor enclosure



Netherlands Bus Accident

# A Few Hydrogen Transportation Considerations

- ▶ Gas
  - During transport under high-pressure
  - Equipment can be installed or reinstalled incorrectly
  - Must be designed to ensure proper venting during roll-over incident... vent lines on front and back
- ▶ Liquid – over the road travel time and pressures are important to avoid venting while traveling
  - Tank going liquid full can result in activating rupture disk and discharging liquid
  - Proper vessel design is critical
  - Proper transfer techniques are important
- ▶ Minimize impact of accidents during transport
  - Location of manifold and how it is protected
  - Tubes don't move and manifold adequately protected
  - Valves closed during transport
- ▶ Fill and transfer activities
  - Issues with hoses
  - Leaks and improper connections



Credit: KTLA



# Keep First Responders Informed & Prepared

## ► 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 (<https://tinyurl.com/yxfy66rp>) and video-based training courses (<https://tinyurl.com/y64q48ck>)
- Classroom and hands-on operations-level training
- Trainer material (PowerPoint slides with speaker notes)



*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.*