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Safety and Asset Reliability for Hydrogen Electrolysis Panel Discussion

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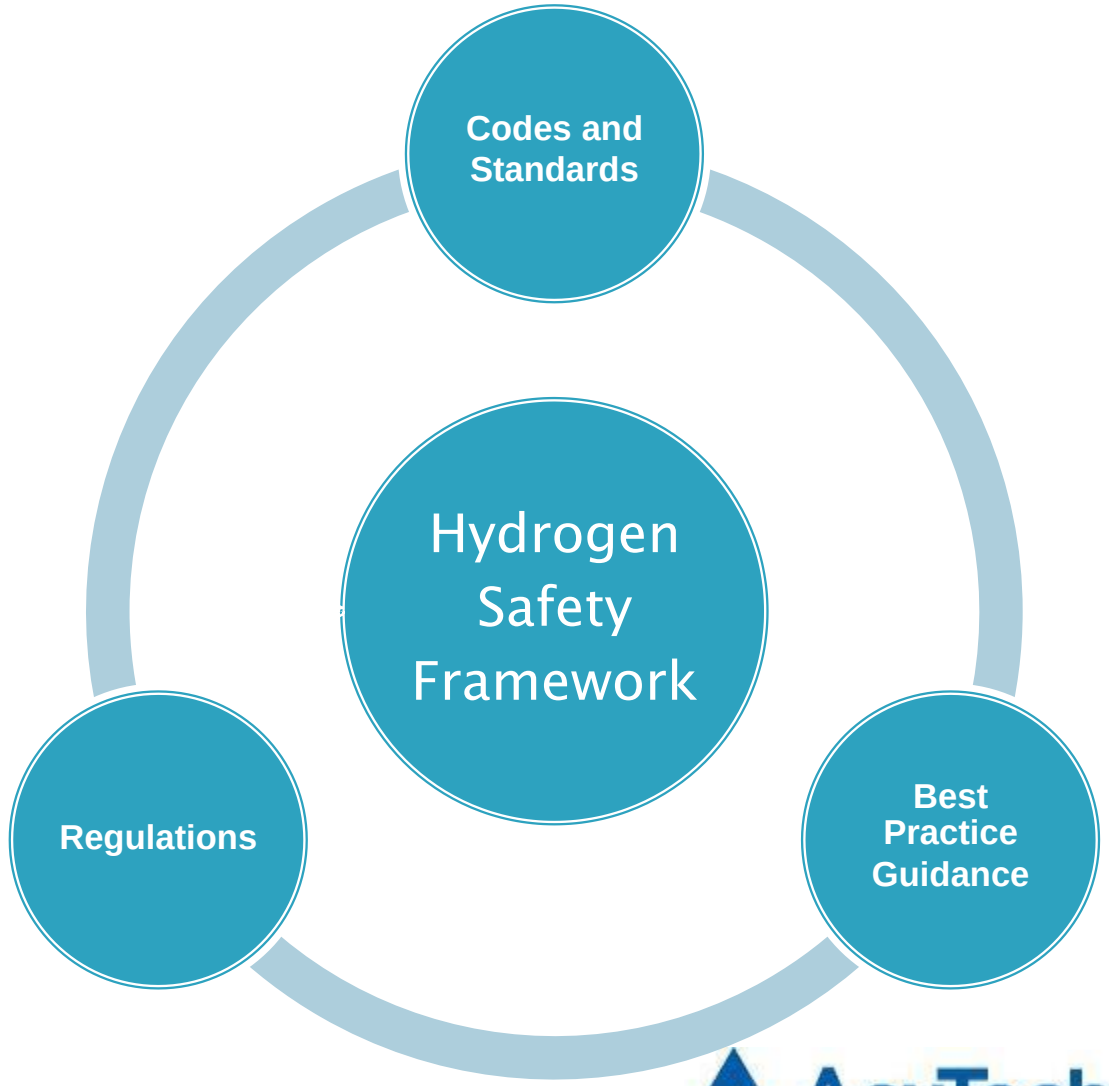
Phoenix, Arizona

Hydrogen Industry Safety Approach

- As we build out the hydrogen industry applications there will be an unprecedented integration of hydrogen into many aspects of industrial and non-industrial uses.
- There is a network of global regulations, engineering standards, codes, and guidance for best practices for hydrogen safety.
- Following good design codes and standards is not considered best practice for good safe plants and operations.



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Hydrogen Industry Safety Approach

- Process safety in addition is the “gold standard” for safety management of hazardous chemical processes
- PSM regulations v voluntary mgmt system
- Vary depending on the country of operation and their regulatory frameworks.
- **Gaps?** –
  - Others may operate in countries that do not have a PSM regulation or they may be excepted by threshold quantitates or exemptions as fuel.
- **Recommendation** - Producers, suppliers, facility operators, users, and their contractors and employees would all benefit from an industry approach to voluntary PSM

Causes of Accidents in the Chemical Industry

A.Human error

- Failure to follow safety protocols
- Slips in operations
- Inadequate maintenance practices
- Design or manufacturing defects

- **Root causes may include:**
  - Inadequate training
  - Process safety competency gaps
  - Poor communication
  - Lack of supervision
  - Lack of change control

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Causes of Accidents in the Chemical Industry

B. Equipment failure

C. Natural events

- Earthquakes
- Extreme weather conditions

- **Possible Contributing factors:**
  - Lack of safety culture
  - Cost-cutting measures
  - Inadequate emergency response plans

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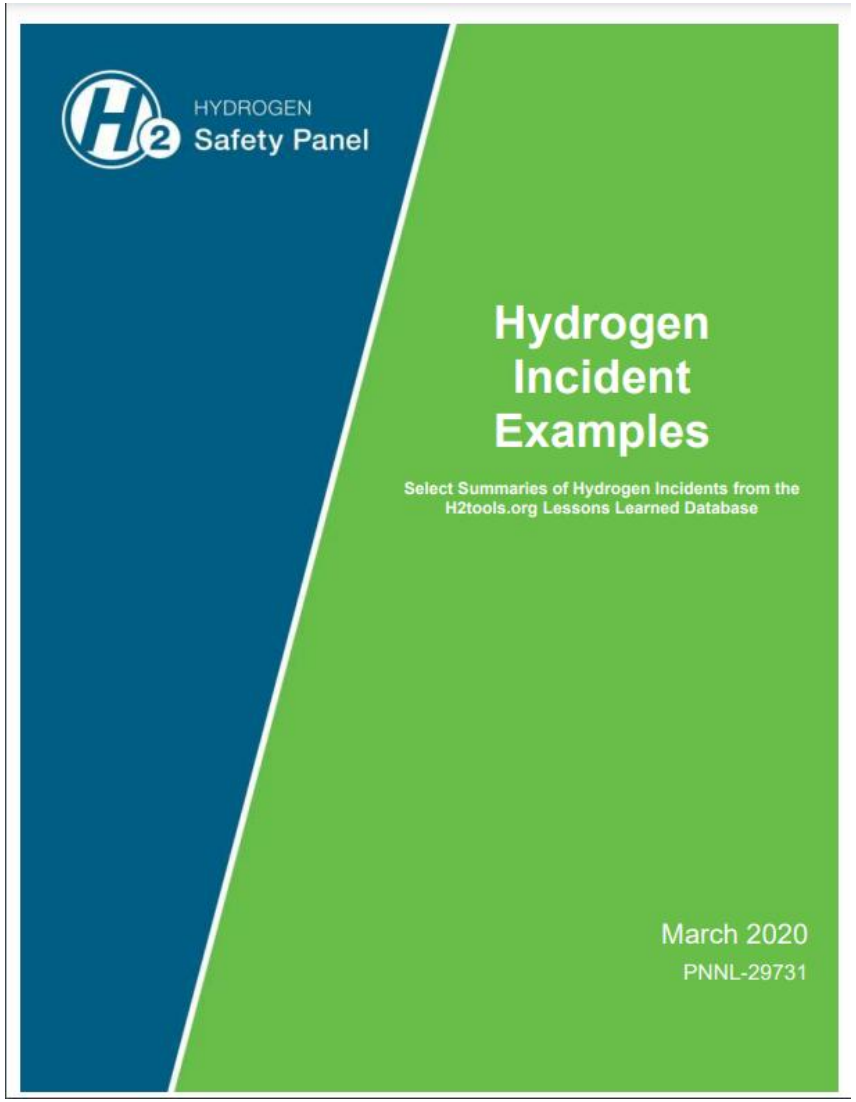
US DOE Hydrogen Safety Panel – Hydrogen Incident Examples



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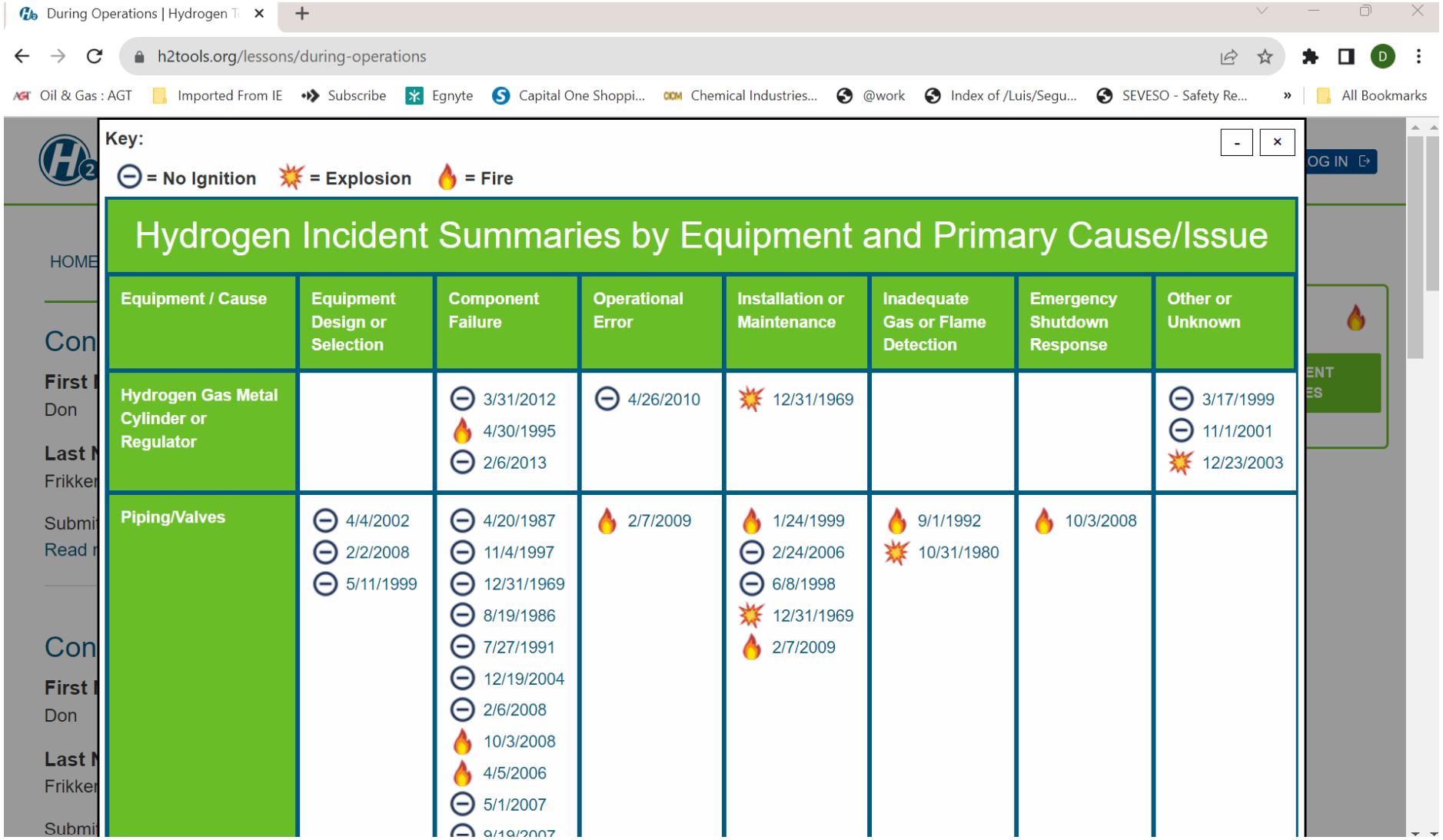

During Operations | Hydrogen T

h2tools.org/lessons/during-operations

Oil & Gas : AGT | Imported From IE | Subscribe | Egnyte | Capital One Shoppi... | Chemical Industries... | @work | Index of /Luis/Segu... | SEVESO - Safety Re... | All Bookmarks

Key:

= No Ignition = Explosion = Fire

Hydrogen Incident Summaries by Equipment and Primary Cause/Issue

Equipment / Cause	Equipment Design or Selection	Component Failure	Operational Error	Installation or Maintenance	Inadequate Gas or Flame Detection	Emergency Shutdown Response	Other or Unknown
Hydrogen Gas Metal Cylinder or Regulator		3/31/2012 4/30/1995 2/6/2013	4/26/2010	12/31/1969			3/17/1999 11/1/2001 12/23/2003
Piping/Valves	4/4/2002 2/2/2008 5/11/1999	4/20/1987 11/4/1997 12/31/1969 8/19/1986 7/27/1991 12/19/2004 2/6/2008 10/3/2008 4/5/2006 5/1/2007 9/19/2007	2/7/2009	1/24/1999 2/24/2006 6/8/1998 12/31/1969 2/7/2009	9/1/1992 10/31/1980	10/3/2008	

https://h2tools.org/

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US DOE H2Tools Website Incident Summaries - Trends

Hydrogen Incidents… Seeing the Common Thread

CENTER FOR Hydrogen SAFETY
Connecting a Global Community

- **Electrolyzer**
  - Personnel did not fully understand the interrelation of electrolyzer membrane gas permeability, membrane degradation, and dynamic operating range
- **Hydrogen Vehicle Fueling Station**
  - Assembly error of an end plug for the high-pressure hydrogen tank
- **Hydrogen Transport**
  - Incorrect pressure relief devices installed during maintenance
- **Hydrogen Tanker Loading**
  - Unauthorized repair and failure to follow procedures
- **Hydrogen Bus Fueling Station**
  - Incompatible pressure relief device installed

Courtesy of Gangwon Fire HeadQuarter

Damage from Electrolyzer Incident

Courtesy of Nick Barilo, Director, Center for Hydrogen Safety

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Hydrogen Safety Challenges

- Scaling at a rapid pace
- Propensity for hydrogen to leak and high potential for ignition; oxygen hazards
- Overpressure explosion hazards when hydrogen is released into confined or congested areas or internal explosions where hydrogen and oxygen may interface
- Lack of operating experience
- Unfamiliar technology to many engineers and operators
- Range of operating parameters (P, T, power density, lifespan)
- Novel technology developments expected as the industry evolves
  - Operating history and safety and reliability data is lacking
- Balance of plant (BOP) components can differ across electrolyzer stack designs
- Design codes and standards are developing

Example – Compressed Gas Association Process Safety Management and EPA Risk Management Guidance Document

- The U.S. Occupational Safety and Health Administration (OSHA) Process Safety Management (PSM) standard and the U.S. Environmental Protection Agency (EPA) Risk Management Program (RMP) rule require that some U.S. industrial gas facilities comply with these regulations".
- **P-28: OSHA Process Safety Management and EPA Risk Management Plan Guidance Document for Bulk Liquid Hydrogen Supply Systems**
- This publication is designed to help owners and operators of liquid hydrogen bulk tanks comply with PSM and RMP rules in addition to the requirements of CGA H-5, Standard for Bulk Hydrogen Supply Systems (an American National Standard). CGA H-5 refers to NFPA 55, Compressed Gases and Cryogenic Fluids Code, for the minimum setback distances between bulk hydrogen systems and exposures.
- **P-29, Guideline for Application of OSHA PSM and EPA RMP to the Compressed Gas Industry.**
- More details about the application of OSHA PSM and EPA RMP to hydrogen supply systems and other compressed gas and cryogenic fluid systems can be found in CGA

CGA
Compressed Gas Association
The Standard For Safety Since 1913

Process Safety Management Systems – License to Operate

- There is a strong business case for implementing process safety management systems – the value is in preventing the loss of lives, preserving the integrity of operations and protecting the environment.
- Safety management systems are well developed over the past 50+ years
- It takes years of development to make a PSM system effective and diligence to sustain that level

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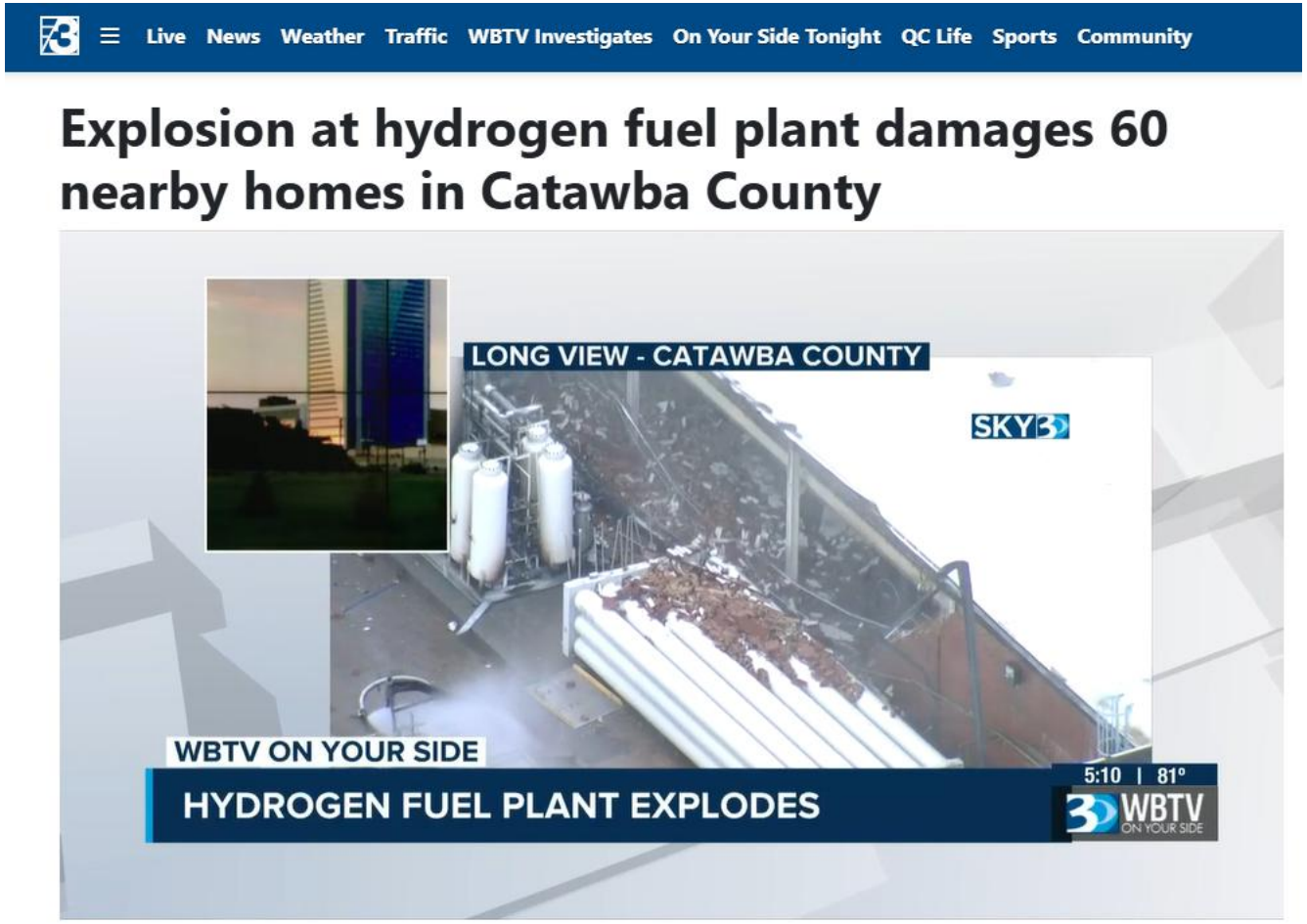
Long View North Carolina, OneH2 Hydrogen Tube Trailer Filling Facility, 4/7/2020



Hydrogen Quantity: 50-60kg

Quoted from: [Explosion at hydrogen fuel plant damages 60 nearby homes in Catawba County]

Officials say all 44 OneH2 employees have been accounted for. It's unclear how many, if any, employees were inside the facility at the time of the explosion.

It appears the explosion happened near the back, outside part of the building, according to officials. **Damage was reported to the building and about 60 surrounding homes.**

Fire officials say **the homes were inspected and one was deemed uninhabitable**. All the other homes suffered "mostly minor damage from the explosion."

Lynn Brigsbee's home was the one heavily damaged. by the explosion.

"95 percent of my windows are gone," she said.

Lynn was on the sofa when the blast happened less than 100 yards away.

Long View North Carolina, OneH2 Hydrogen Tube Trailer Filling Facility, 4/7/2020

Title	Long View, North Carolina, USA One H2 hydrogen tube trailer production and filling facility	
Date	4/7/2020	
Description	While the exact cause is unknown, it is generally accepted that hydrogen was released from a failure within a compressed hydrogen storage system. The failure resulted in the formation of a hydrogen/air mixture which subsequently ignited, apparently in a relatively open area.	
Incident Type	Structural damage to a wall of the company's facility as well as to nearby residences.	
Contributing factors	Confinement - Outdoor storage equipment was located close to the wall of the facility. Weak fire barrier walls - The facility walls were not designed to withstand the level of overpressure caused by ignition of the released fuel. Insufficient separation distance - Offsite risk had not been adequately assessed with the distance from nearby houses to prevent damaging overpressure levels at those locations. Mechanical integrity - The vent system may not have been adequately supported.	
Estimated Hydrogen Quantity	50-60 kg	
Impact	Community - damage to residences Property - equipment damage, structural damage to facility wall Local News media coverage	
Technical References		
Media Coverage	Explosion at hydrogen fuel plant damages 60 nearby homes in Catawba County	Catawba County, North Carolina
Incident's relevance	Sites where facilities have fire barrier walls constructed next to hydrogen equipment.	
PSM Elements found as contributing factors	Risk Assessment, Siting	

Safety Culture for Hydrogen Industry

- ***There is a need for continuously diligent hydrogen safety culture*** to improve overall performance
- It must be the foundation of the operating philosophy
- We believe enhancing culture is key to a potential breakthrough in more effective program results.

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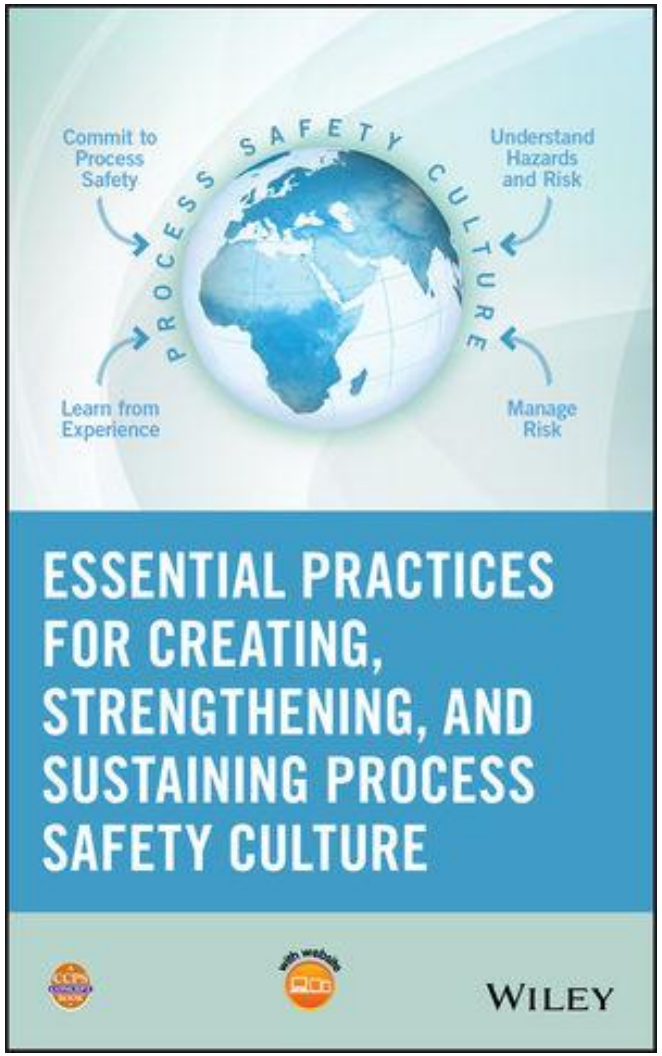
Core Principles of Process Safety Culture

- Establish an Imperative for Safety
- Provide Strong Leadership
- Maintain a Sense of Vulnerability
- Understand and Act Upon Hazards/Risks
- Empower Individuals to Successfully Fulfill their Safety Responsibilities
- Defer to Expertise
- Ensure Open and Frank Communications
- Foster Mutual Trust
- Combat the Normalization of Deviance
- Learn to Assess and Advance the Culture



CCPS Guidelines PSM Culture (2017)

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Conduct of Operations – Principles[1]

- Conduct of Operations (COO) is the embodiment of an organization's values and principles in management systems that are developed, implemented, and maintained to:
  - 1) structure operational tasks in a manner consistent with the organization’s risk tolerance
  - 2) ensure that every task is performed deliberately and correctly
  - 3) minimize variations in performance

1 “Conduct of Operations and Operational Discipline – For Improving Process Safety in Industry”, CCPS, Wiley, 2011

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Conduct of Operations and Operational Discipline Contribution to Major CSB Incidents

Conduct of Operations and Operational Discipline – Primary Findings
A2, A5, A10 C3, C11, C12, C18, C26, C43, C50, C57, C58 D9 J2, J19, J28, J38, J49, J50, J51, J52, J53, J54, J55, J56, J57, J58, J61, J63, J67, J70, J72, J73, J114, J127, J130, J147, J151, J165, J171, J174, J178, J180, J182, J183, J188, J190, J192, J208, J209, J211, J217, J243, J247, J248, J259, J262, J270, J271 S3, S4, S5, S13, S14
Conduct of Operations and Operational Discipline – Secondary Findings
A6, A7 C13, C15, C20, C24, C27, C28, C60, C76 D7, D19 J21, J22, J24, J25, J32, J35, J40, J64, J65, J75, J76, J91, J108, J109, J116, J119, J128, J129, J131, J133, J162, J163, J170, J176, J181, J184, J185, J186, J212, J237, J253, J261 S1, S10, S12, S15

	Investigation
C1.	Arkema Inc. Chemical Plant Fire
C2.	Acetylene Service Company Gas Explosion
C3.	AirGas Facility Fatal Explosion
C4.	AL Solutions Fatal Dust Explosion
C5.	Allied Terminals Fertilizer Tank Collapse
C6.	Barton Solvents Explosions and Fire
C7.	Bayer CropScience Pesticide Waste Tank Explosion
C8.	Bethlehem Steel Corporation Gas Condensate Fire
C9.	Bethune Point Wastewater Plant Explosion
C10.	BLSR Operating Ltd. Vapor Cloud Fire
C11.	BP America Refinery Explosion
C12.	BP Amoco Thermal Decomposition Incident
C13.	CAI / Arnel Chemical Plant Explosion
C14.	Carbide Industries Fire and Explosion
C15.	Caribbean Petroleum Refining Tank Explosion and Fire
C16.	Chevron Refinery Fire
C17.	CITGO Refinery Hydrofluoric Acid Release and Fire
C18.	Combustible Dust Hazard Investigation
C19.	ConAgra Natural Gas Explosion and Ammonia Release
C20.	CTA Acoustics Dust Explosion and Fire
C21.	D.D. Williamson & Co. Catastrophic Vessel Failure
C22.	Donaldson Enterprises, Inc. Fatal Fireworks Disassembly Explosion and Fire
C23.	DPC Enterprises Festus Chlorine Release
C24.	DPC Enterprises Glendale Chlorine Release
C25.	DuPont Corporation Toxic Chemical Releases
C26.	DuPont La Porte Facility Toxic Chemical Release
C27.	E. I. DuPont De Nemours Co. Fatal Hotwork Explosion
C28.	Emergency Shutdown Systems for Chlorine Transfer
C29.	Enterprise Pascagoula Gas Plant Explosion and Fire
C30.	EQ Hazardous Waste Plant Explosions and Fire
C31.	ExxonMobil Refinery Explosion
C32.	First Chemical Corp. Reactive Chemical Explosion
C33.	Formosa Plastics Propylene Explosion
C34.	Formosa Plastics Vinyl Chloride Explosion
C35.	Freedom Industries Chemical Release
C36.	Georgia-Pacific Corp. Hydrogen Sulfide Poisoning
C37.	Hayes Lemmerz Dust Explosions and Fire
C38.	Herrig Brothers Farm Propane Tank Explosion
C39.	Hoeganaes Corporation Fatal Flash Fires
C40.	Honeywell Chemical Incidents
C41.	Imperial Sugar Company Dust Explosion and Fire
C42.	Improving Reactive Hazard Management
C43.	Kaltech Industries Waste Mixing Explosion
C44.	Kleen Energy Natural Gas Explosion
C45.	Little General Store Propane Explosion
C46.	Macondo Blowout and Explosion
C47.	Marcus Oil and Chemical Tank Explosion
C48.	MFG Chemical Inc. Toxic Gas Release
C49.	MGPI Processing, Inc. Toxic Chemical Release
C50.	Morton International Inc. Runaway Chemical Reaction
C51.	Motiva Enterprises Sulfuric Acid Tank Explosion
C52.	NDK Crystal Inc. Explosion with Offsite Fatality
C53.	Oil Site Safety
C54.	Packaging Corporation of America Hot Work Explosion
C55.	Partridge Raleigh Oilfield Explosion and Fire
C56.	Praxair Flammable Gas Cylinder Fire
C57.	Pryor Trust Fatal Gas Well Blowout and Fire
C58.	Sierra Chemical Co. High Explosives Accident
C59.	Sonat Exploration Co. Catastrophic Vessel Overpressurization

See www.csb.gov for incident investigation reports

1 "Driving Continuous Process Safety Improvement from Investigated Incidents", CCPS, Wiley, 2021

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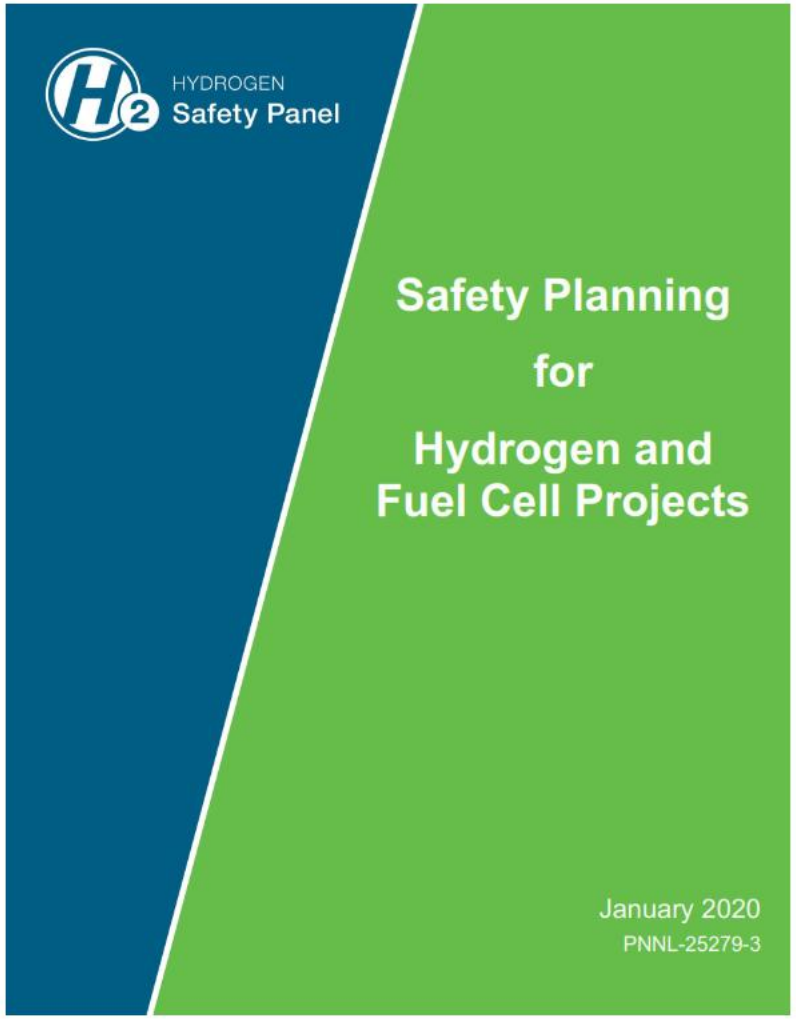
CCPS Risk Based Process Safety v OSHA PSM v HSP Safety Plan

Table 2.1. Comparison of RBPS elements to OSHA PSM elements.

CCPS RBPS Element	*OSHA PSM/EPA RMP Elements*
Commit to Process Safety	
1. Process Safety Culture	
2. Compliance with Standards	Process Safety Information
3. Process Safety Competency	
4. Workforce Involvement	Employee Participation
5. Stakeholder Outreach	Stakeholder Outreach (EPA RMP)
Understand Hazards and Risk	
6. Process Knowledge Management	Process Safety Information
7. Hazard Identification and Risk Analysis	Process Hazard Analysis
Manage Risk	
8. Operating Procedures	Operating Procedures
9. Safe Work Practices	Operating Procedures Hot Work Permits
10. Asset Integrity and Reliability	Mechanical Integrity
11. Contractor Management	Contractors
12. Training and Performance Assurance	Training
13. Management of Change	Management of Change
14. Operational Readiness	Pre-startup Safety Review
15. Conduct of Operations	
16. Emergency Management	Emergency Planning and Response
Learn from Experience	
17. Incident Investigation	Incident Investigation
18. Measurement and Metrics	
19. Auditing	Compliance Audits
20. Management Review and Continuous Improvement	



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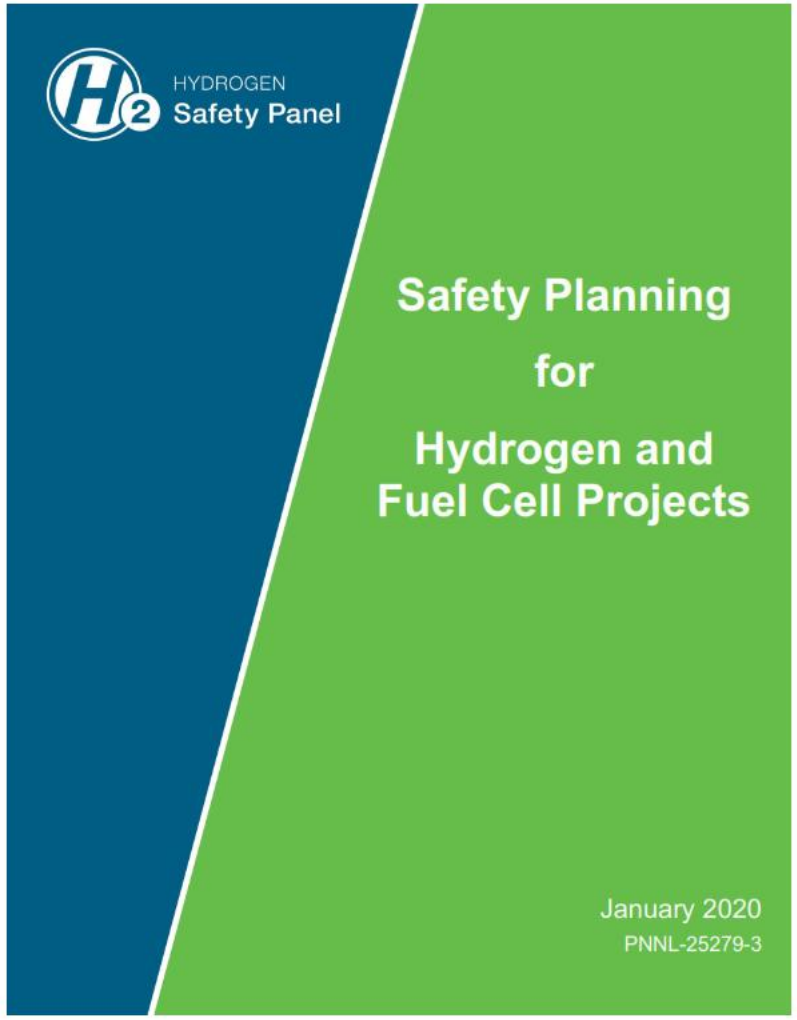
CCPS Risk Based Process Safety v OSHA PSM v HSP Safety Plan



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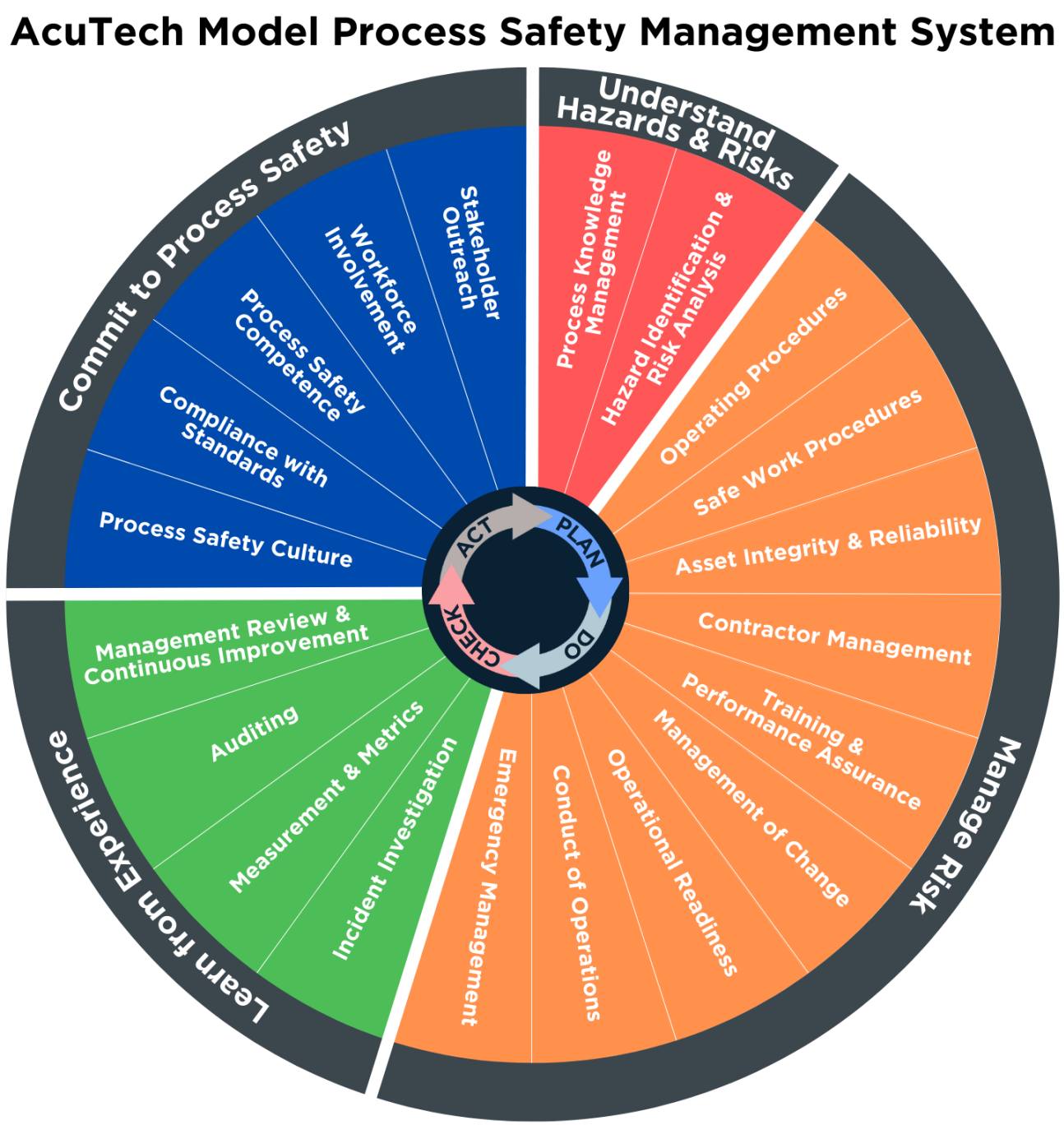
Model Risk Based Process Safety Management System

- Based on AIChE CCPS Risk Based Process Safety Model
- 4 Pillars
  - Commit to Process Safety
  - Understand Hazards & Risks
  - Learn from Experience
  - Manage Risk
- 20 elements
- Plan Do Check Act (Deming Cycle)



Based on four underlying pillars supported by the 20 elements of the Center for Chemical Process Safety (CCPS) Risk Based Process Safety Model.

Presentation Summary

- Hydrogen incidents are occurring due to preventable causes and contributing factors that speak to the need for process safety frameworks
- Industry experience of over 40 years of PSM has shown that it has positively changed the way safety is managed
- The application of a PSM framework to hydrogen operations can apply throughout the lifecycle and ecosystem
  - Manufacturing of hydrogen.
  - Transportation.
  - Use of hydrogen as a fuel
- It is recommended to influence the industry for to ensure hydrogen safety through a modern process safety framework

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