National Aeronautics and Space Administration

Hydrogen Systems Risks and Reliability

Hydrogen Systems Risk and Reliability Workshop
Center for Risk and Reliability
University of Maryland

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13 September 2024

Hydrogen History

Sir Robert Boyle
Defined GH2 flammability limits

Jacques Charles
First Hydrogen Balloon Flight

1st Water Electrolysis Demonstration

William R. Grove
1st practical fuel cell

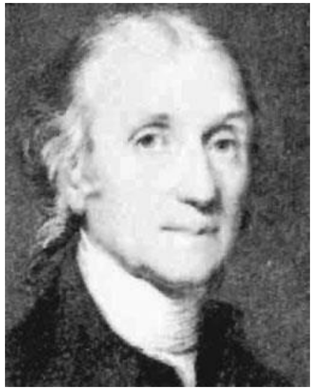
Sir James Dewar
Liquefies GH_2

Invents vacuum container

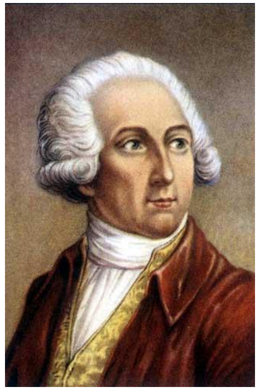
Dr. Herrick Johnston
Develops practical H_2 liquefaction process

1520 1673 1766 1783 1784 1789 1801 1839 1898 1903 1937 1938 1943

1st recorded observation of Hydrogen

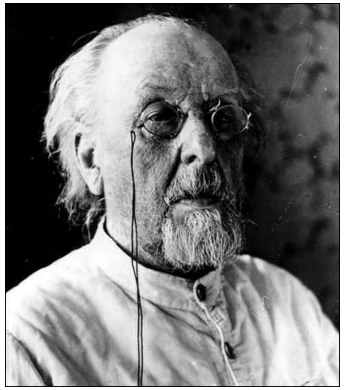


Henry Cavendish
Determined density and GH_2 flammability limits in air



Antoine Lavoisier
Measures GH_2 heat of combustion

Sir Humphry Davy
Demonstrated fuel cell principles



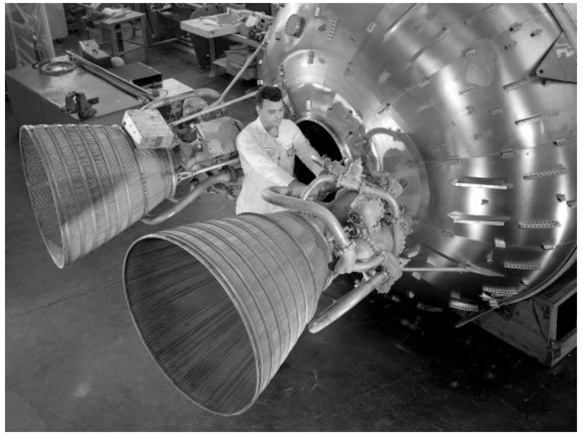
Konstantin Tsiolkovskiy
Proposes H-O as rocket propellant

Derives “Rocket Equation”

1st H_2-cooled Electrical Power Generator

240 km Rhine-Rhur H_2 pipeline (2 to 21 MPa)

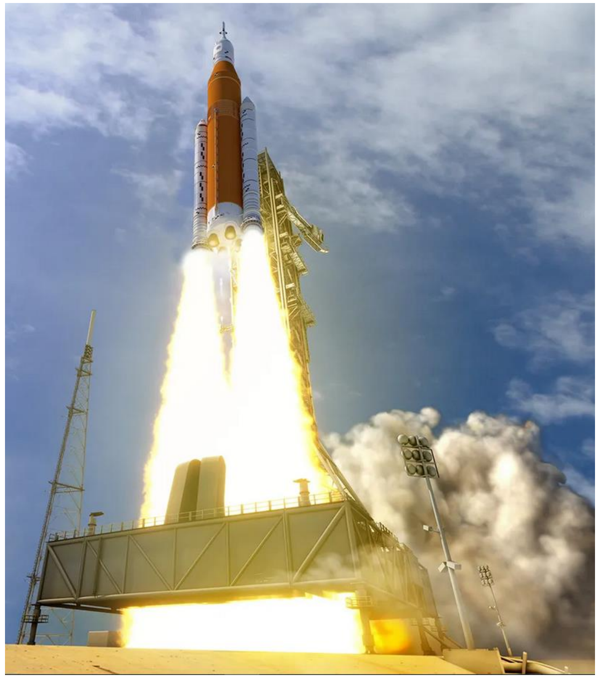
NASA Hydrogen Application: Rockets



A researcher prepares a Centaur 6A second-stage rocket for a series of vacuum tank tests

United Launch Alliance Delta IV Heavy rocket lifts off from Launch Complex 37 (8/12/2018).

Space Shuttle Discovery launces from Launch Pad 39B for flight mission STS-114.



NASA's Space Launch System (SLS) rocket launches from Launch Complex 39B (11/16/2022)

		Turbopumps			
		Centaur RL10	Delta IV RS-68	Shuttle RL-25	SLS RL-25
# Engines		2	3	3	4
Impeller Speed	RPM	31,500	21,000	35,360	35,360
Discharge Pressure	MPa (psi)	53.7 (7790)	165 (24,000)	44.9 (6515)	44.9 (6515)
Motor Mass Flow Rate	kg H_2 / s	2.7	15.4	68.5	68.5
Peak Vehicle Mass Flow Rate	kg H_2 / s	5.4	46.2	205.5	274

Enabling Hydrogen Rockets

Successful launches requires a complex infrastructure consisting of many Hydrogen systems

- Mobile refuelers to deliver Hydrogen from off-site producers
- Storage tanks to store Hydrogen until needed
- Transfer systems to move Hydrogen where it is needed
- Processes and Systems to safely move and use Hydrogen
- <u>***Trained People***</u> to execute procedures <u>***safely***</u>

Tanker trucks deliver liquid hydrogen (LH2) for the large sphere at NASA's Kennedy Space Center in Florida, Launch Pad 39B.

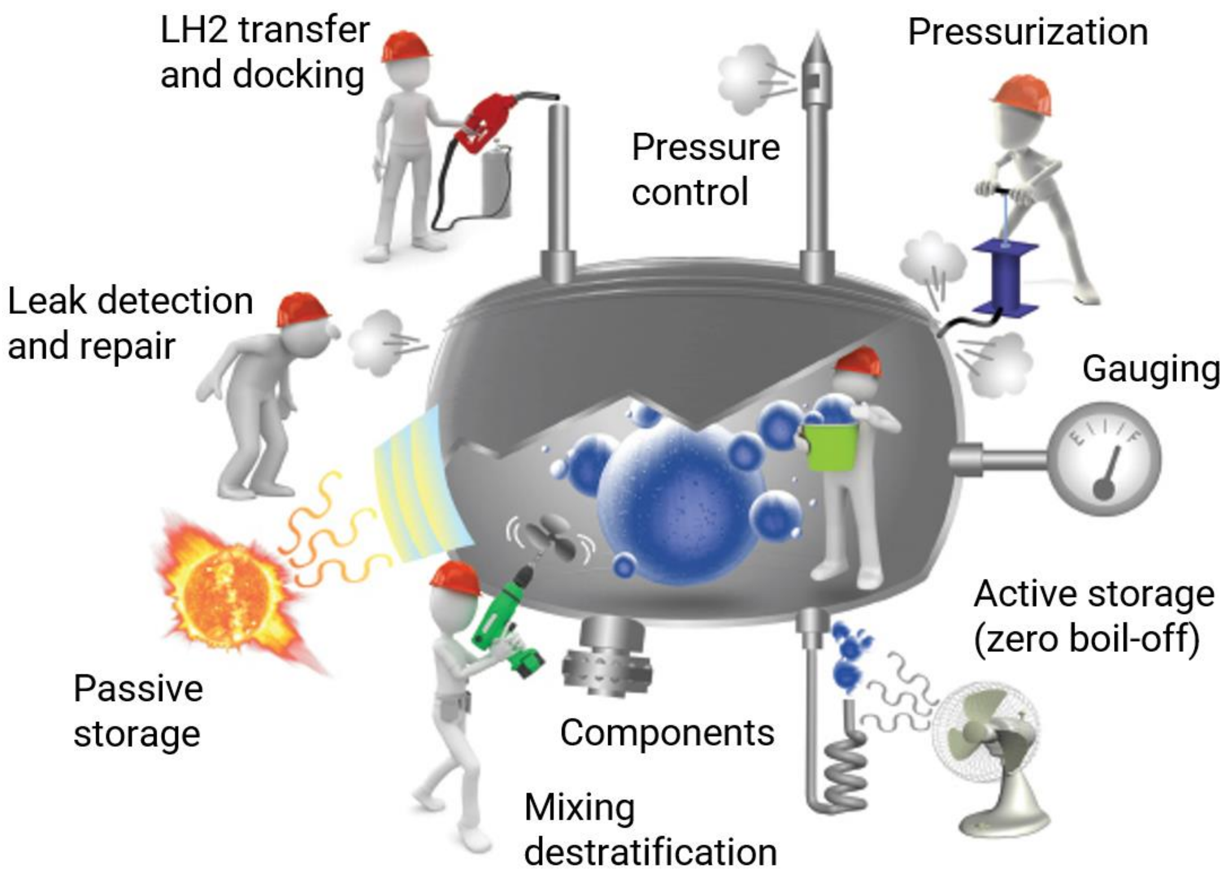
800,000 gal (3,3028 m^3)
LH2 Tank at Pad 39B

Launch Complex at NASA's Kennedy Space Center in Florida, Launch Pad 39B.

Using Hydrogen Safely

- Proper system design
  - Critical component redundancy
  - Active and passive safety devices
  - Multiple layers of safety
  - Fail-safe policy
- Proven practices and principles
- Personnel training and certification
- Design, safety, hazard, and operational reviews
- Careful system operation
- Quality control and maintenance programs
- Approved operating procedures and checklists and following them
- Personal protective equipment

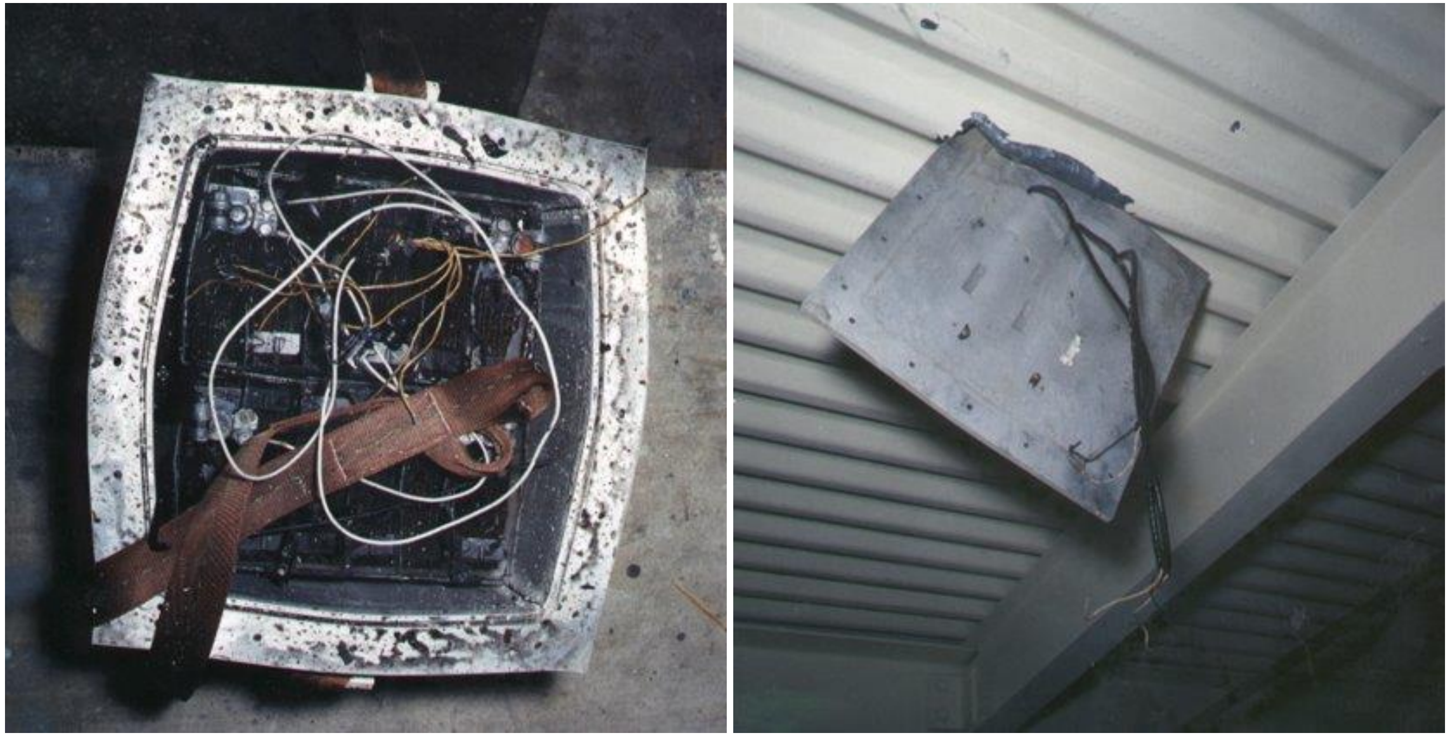
Managing Cryogenics



Hydrogen Accidents

Lewis' Rocket Engine Test Facility

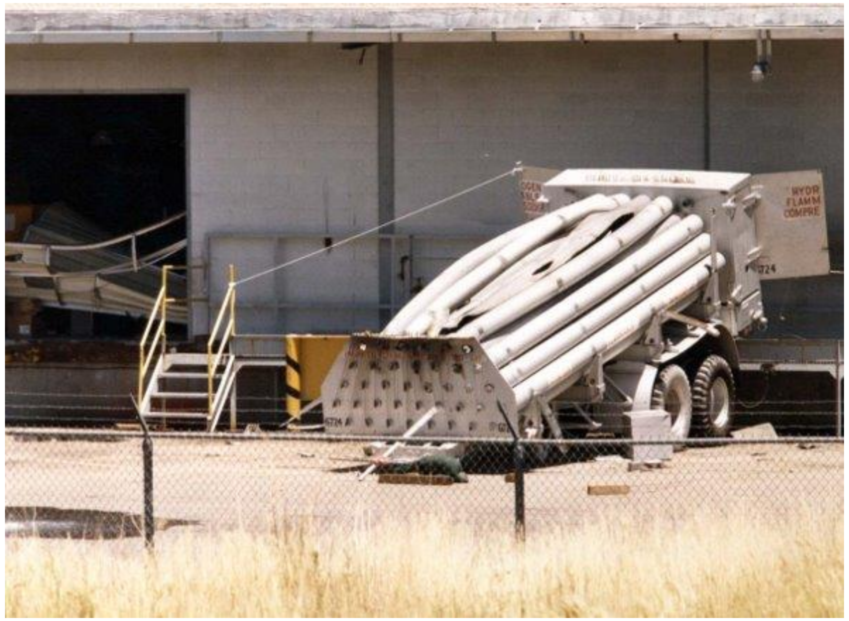
Damage following a test of high-energy fuels (4/27/1955)

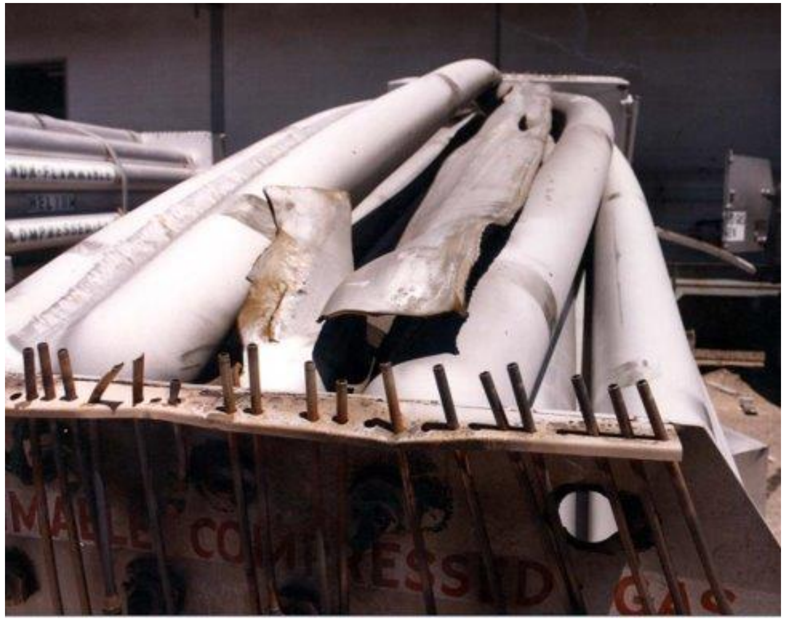


Battery Box Explosion at the Old JSC Water Immersion Facility

The box lid killed one worker and severely injured another. Post incident photos show lid puncturing a 35-ft-high concrete ceiling (above) and the battery box with two damaged batteries (left). (4/29/1972)

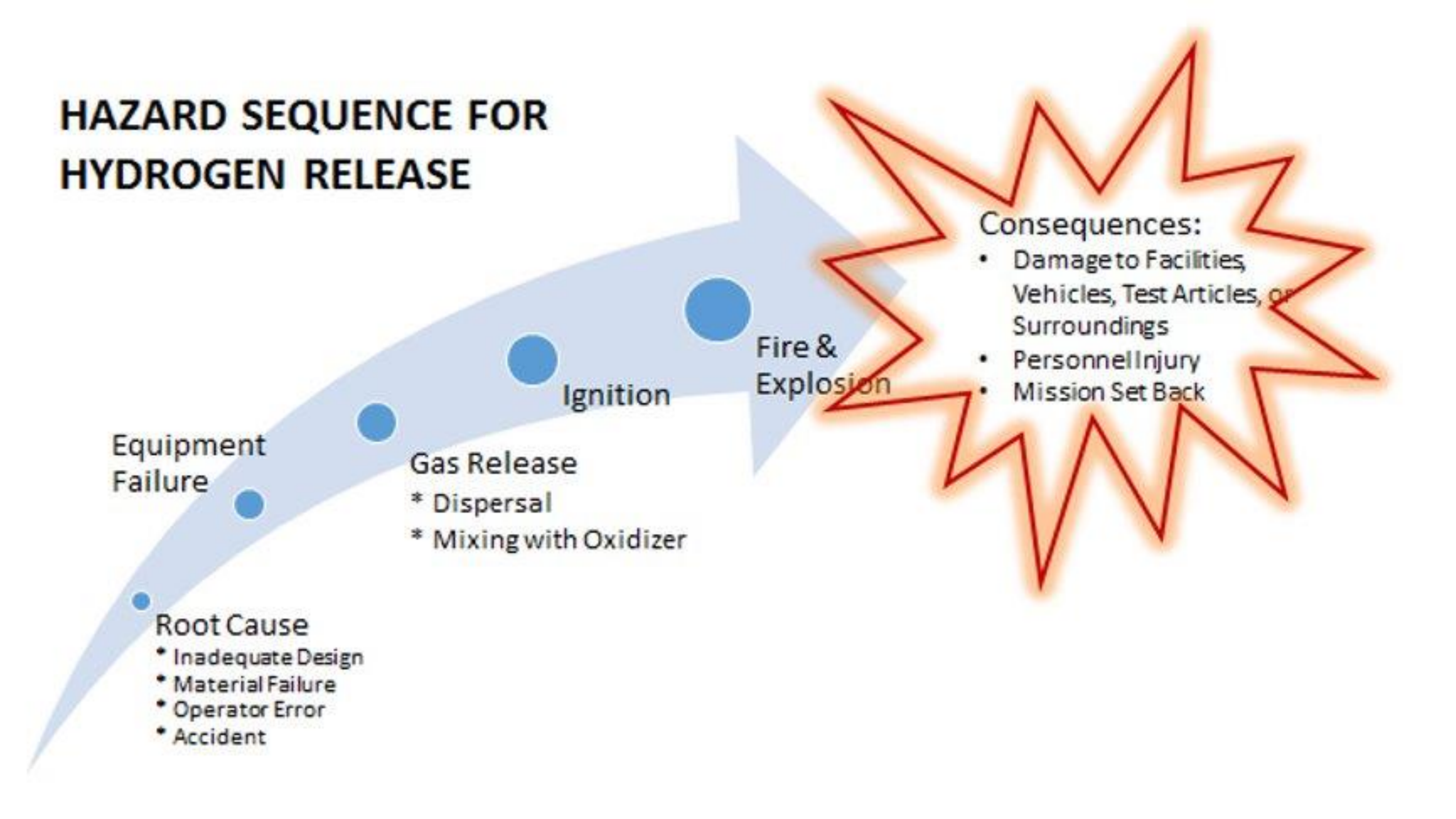
Hydrogen Accidents





Tube Trailer Explosion at the Los Alamos
A single point failure led to detonation of a high pressure (~550 psi) mixture of GOX and GH2 in the GH2 tubes.
Tubes and debris were scattered (one large piece of shrapnel landed 1250-ft away in the Los Alamos Town dump)
Two employees received severe burns resulting in 4 months of lost time.

Common Sequence of Events

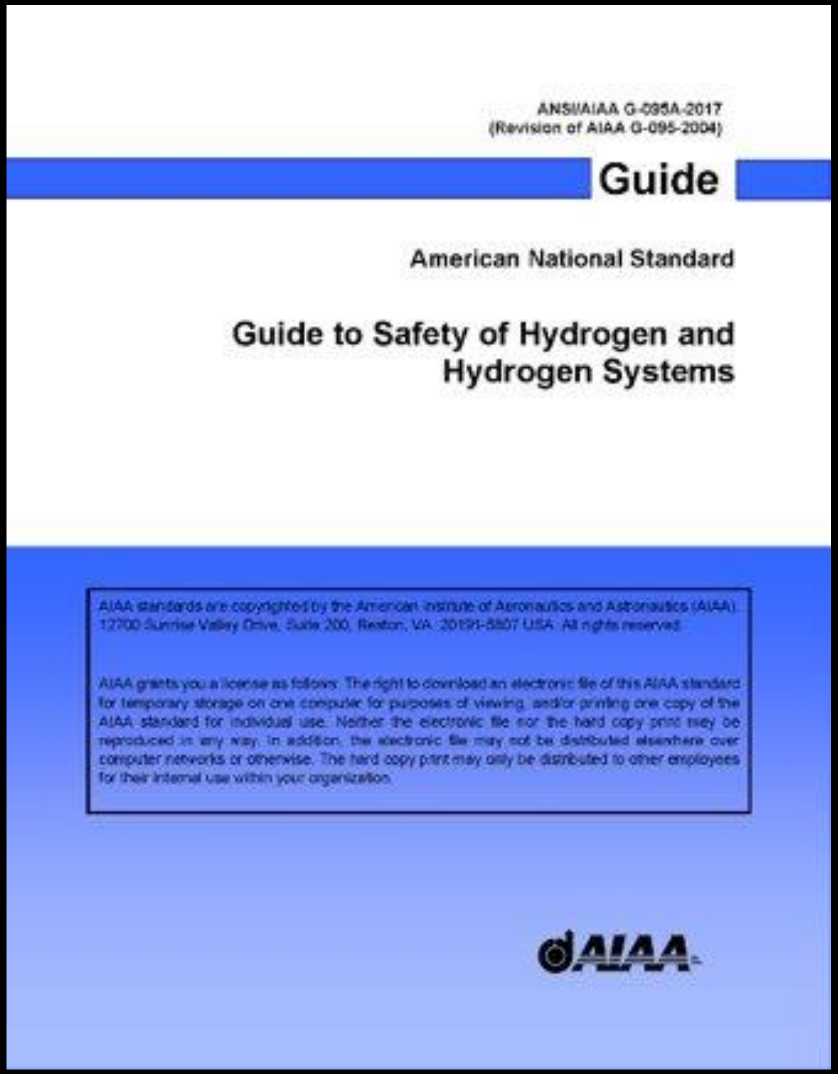


Hydrogen Design Guides and Standards

- Hydrogen practice combines art, engineering, and experience
  - No “cookbook” approach works for all systems / situations because:
    - ❖ Complex hydrogen behaviors
    - ❖ Constant changes in the state of the art, new applications
  - Technical judgment required to apply the appropriate codes and standards in the appropriate manner

- Multiple design consensus guides capture current knowledge
  - ANSI/AIAA G-095A-2017, Guide to Safety of Hydrogen and Hydrogen Systems
  - NASA/TM-2003-212059, Guide for Hydrogen Hazards Analysis on Components and Systems
  - NASA/TM-2016-218602, Hydrogen Embrittlement

- Multiple design standards capture current knowledge
  - NFPA 2 Hydrogen Technologies Code
  - NFPA 55, Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks. [Supersedes NFPA 50 A and 50 B]
    - ❖ NFPA 50A, GH2 Systems at Consumer Sites
    - ❖ NFPA 50B, LH2 Systems at Consumer Sites


ANSI/AIAA G-095A-2017
(Revision of AIAA G-095-2004)

Guide

American National Standard

Guide to Safety of Hydrogen and Hydrogen Systems

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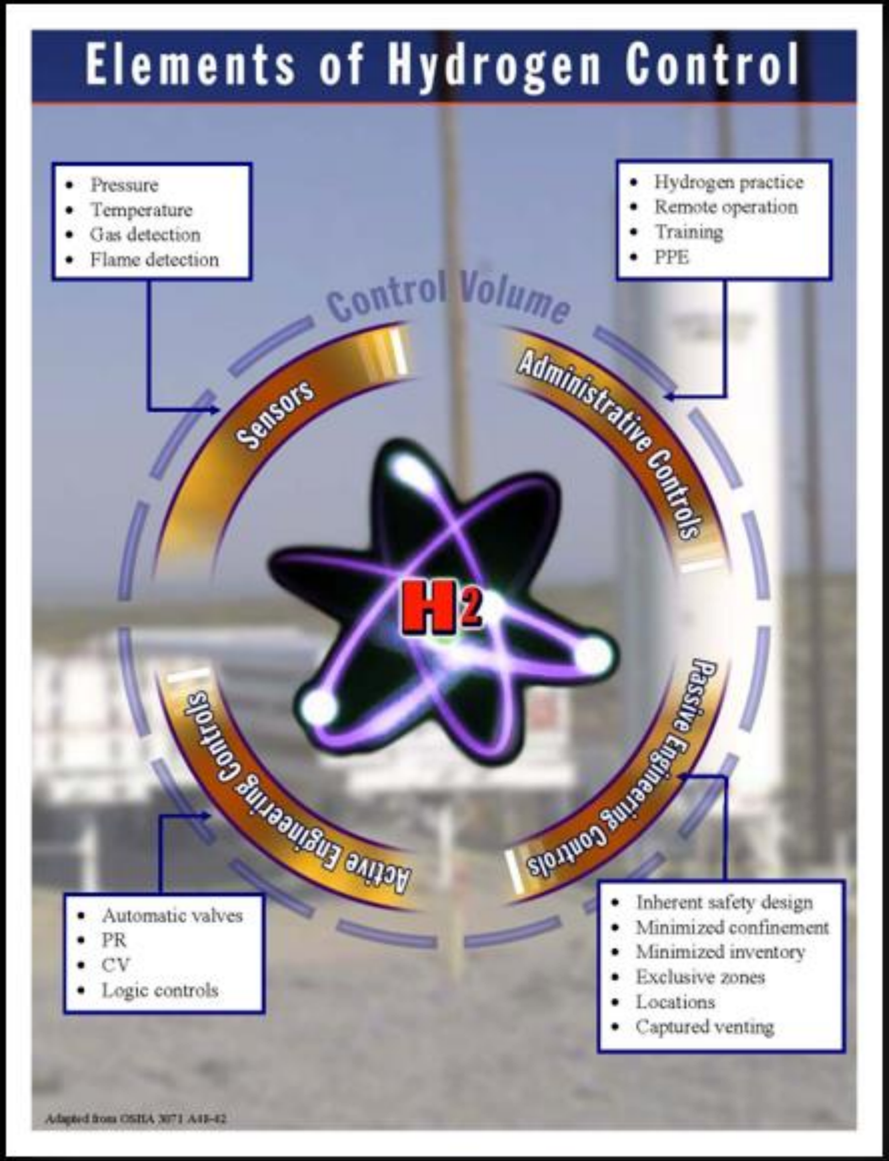
AIAA

The Department of Energy Hydrogen Safety Panel sponsored website resource: https://h2tools.org/

Hydrogen Pyramid of Practice

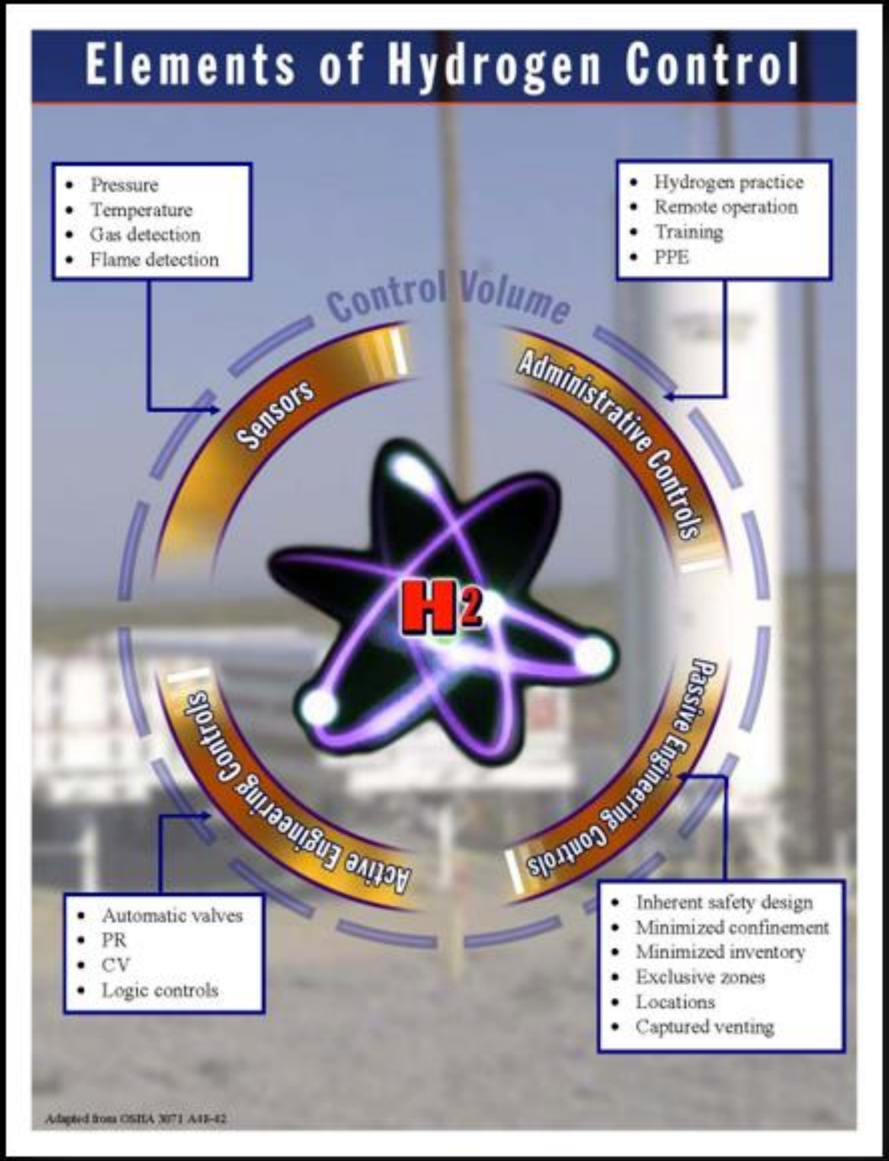
Risk and Risk Management

- Managing Risk is a persistent, iterative process throughout the project life-cycle
  - Identify potential negative events
  - Determine realistic probability of the events occurring
  - Implement measures to reduce the potential and/or consequences
  - Monitor the risks
  - Effectively communicate with the entire project team
- Effective communication
  - Appropriate audience
  - Clear, unambiguous content
  - Concise
  - Timely



Hydrogen Risk Assessment

- Hazards are not Risks
  - Hazard is a negative safety event
  - Risk is the likelihood of an undesirable event occurring
- Multiple Risks exist
  - Programmatic
    - ❖ Resources (Schedule, Budget, Staffing)
    - ❖ Regulatory
    - ❖ Scope Creep
    - ❖ Process Creep
  - Technical
    - ❖ Hardware Availability
    - ❖ Safety (Hazards)
    - ❖ Processes and Procedures
- Risk Management must be scoped to the project
  - Not all projects are equal
  - Hazards must be understood as part of a Risk Assessment
  - Lack of credible, statistically based information complicates hydrogen component / systems risk assessment



Hydrogen Hazard Assessment Protocol (HHAP)

Why Perform Hazards Assessments?

1) Use assessment to:
   - Improve designs
   - Evaluate safety
   - Analyze failures
2) Provide a formal assessment:
   - Ensure management oversight and "buy-in"
   - Written documentation
   - Reference for operations and future efforts

Systematically and objectively:

- Identify hazards
- Evaluate hazard consequences
- Evaluate hazard likelihood
- Identify mitigations
- Document and communicate
- Provide mechanism for control of hazards

Applied at all stages in a system's existence:

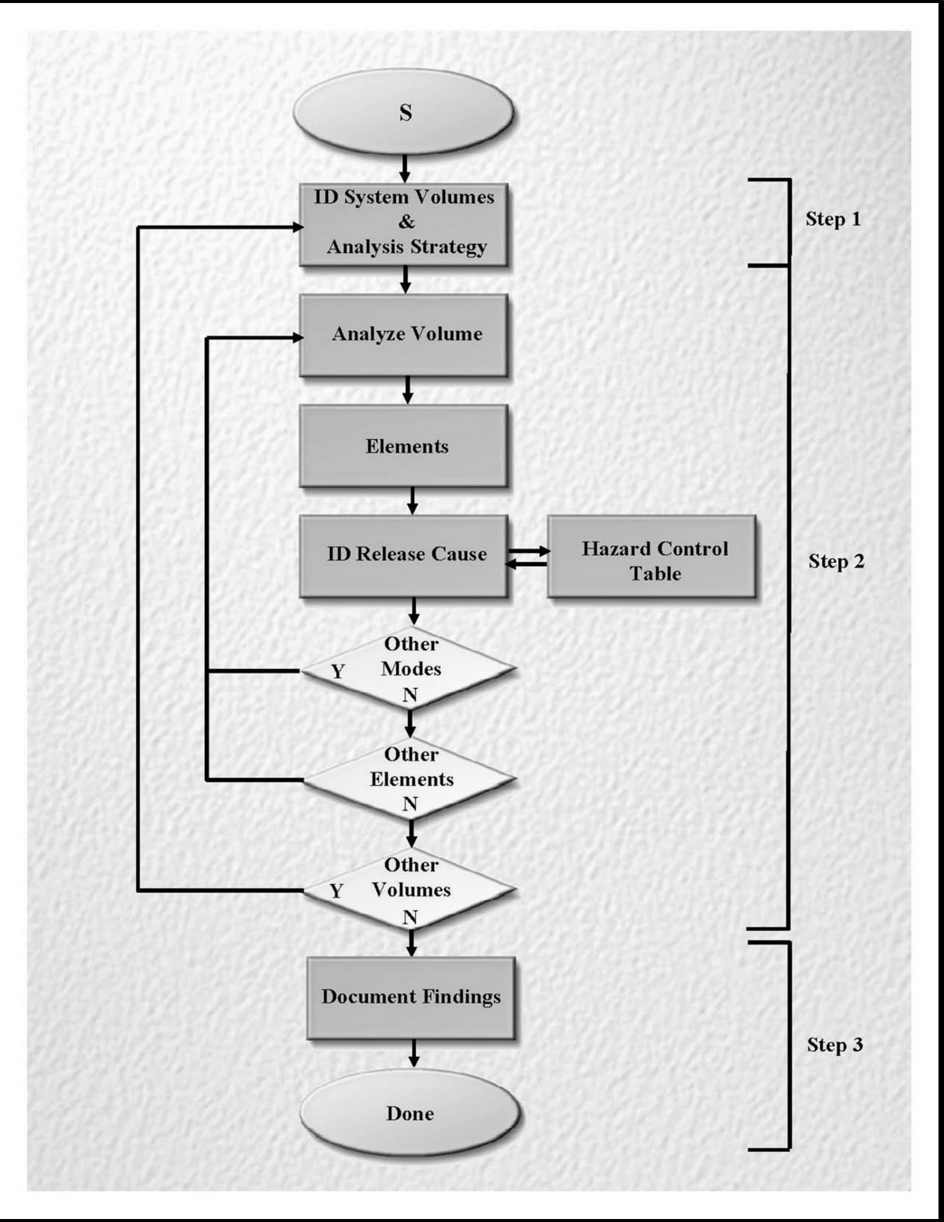
- Initial concept
- Design review
- Operations
- Modifications to design or operation
- Decommissioning
- Post-mortem analysis following a failure

Hazard assessment coupled with expert review is a primary component of *best* practice.

Hydrogen Hazard Assessment Protocol (HHAP)

- Determine the system elements for hydrogen analysis
- Discern the distinct volumes in which hydrogen is controlled
- Consider the volumes into which hydrogen or hydrogen related energies may be released unintentionally
  - Hydrogen ***always*** leaks
  - What is the leak rate?
  - What happens when it leaks?
- Prioritize order to consider which volumes and elements
- Identify attributes in common between volumes or elements to minimize effort (components, materials, functions, etc..)

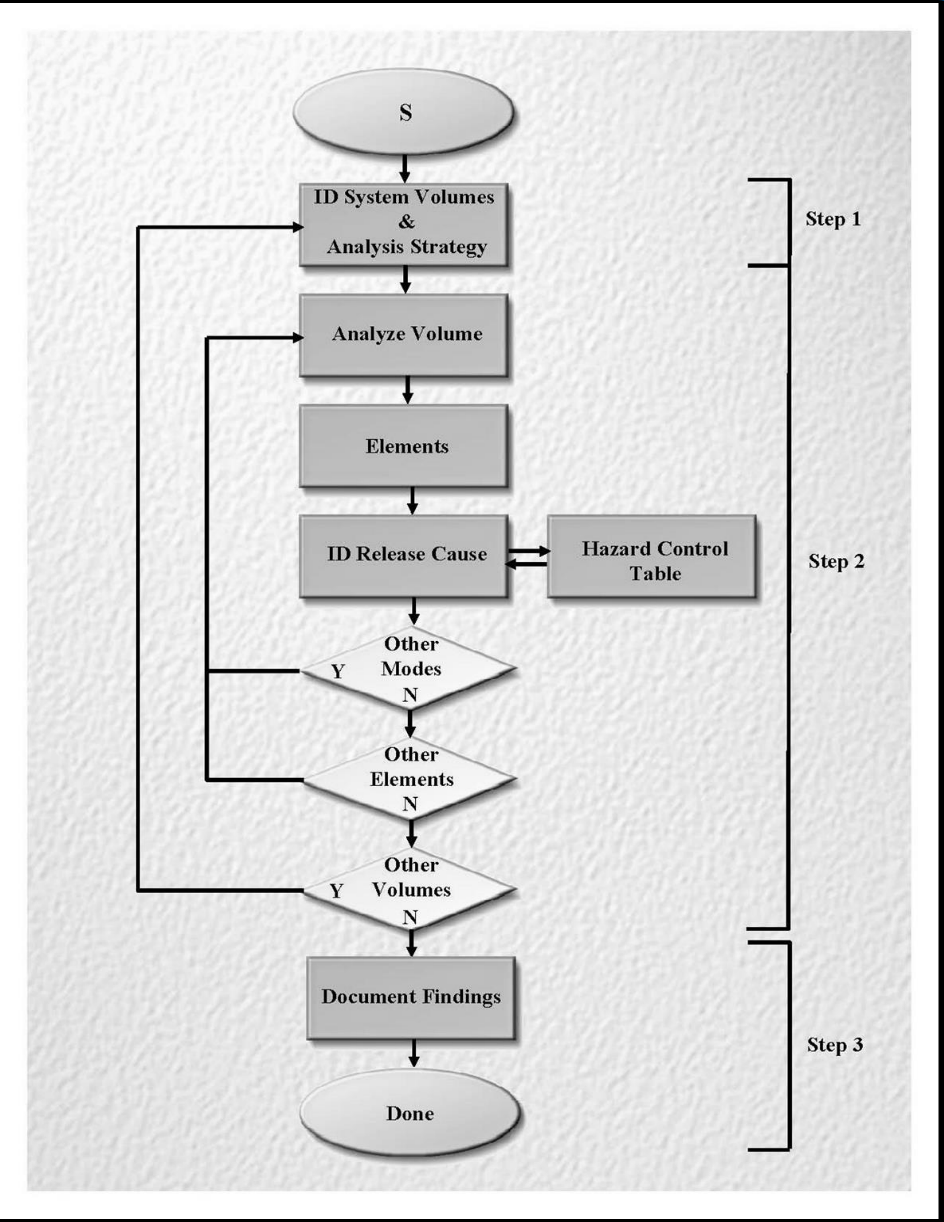
When unsure, FIND help!!!



Hydrogen Hazard Assessment Protocol (HHAP)

- Hydrogen hazards
  - Combustion
  - Pressure
  - Low Temperature
  - Material incompatibility
    - High permeability
    - Hydrogen Embrittlement**
  - Personnel Exposure
- Include operational procedures in the assessment
- Generate Mitigation plans to address hazards

When unsure, <u>FIND</u> help!!!



** Requires specialized training

Sample Hazard Control Table

Item	Release Cause	Seal fails on flange for pipe containing 30 psi, 100 K cold hydrogen gas					
1	Release Description	Cryogenic gas release into open space. No further confinement in exclusion zone					
Hazard Consideration		Existing Controls	Reaction Effect	Code	Recommended Action/Control	Final Code	STATUS
Non-Ignition Probabilities	Cold Exposure	Use appropriate PPE	None. Frostbite hazard mitigated	1 A	None	1 A	
	Gas/Liquid Release	Hydrogen gas detector above flange	Detector will trigger	3 A	None	3 A	
	Pressurized Release/Jet	None			None		
Probabilities for Combustion Processes	Heat	None			None		
	Flame	None	Ignition is possible and may be triggered by approaching personnel. Hazard would include burns	2 B	Upon alarm, appropriate safing procedures must be followed. Regardless of system status, personnel should approach with caution. Operational control prevents hazard to personnel	2 A	Accept, as noted
	Cloud Fire	None	Will dissipate	0	None		
	Jet Fire	None	Insufficient pressure	0	None		
	Deflagration	None	Insufficient mixture	0	None		
	Gas Detonation	None	No ignition source	0	None		
	Condensed Detonation	None	No mixture	0	None		
	Other		Not identified				

Code: 0 Not possible, 1 Remotely Possible, 2 Possible, 3 Probable, 4 Highly Probable

A Negligible, B Marginal, C Critical, D Catastrophic

Risk Scorecard

LIKELIHOOD					
5	10	16	20	23	25
4	7	13	18	22	24
3	4	9	15	19	21
2	2	6	11	14	17
1	1	3	5	8	12
	1	2	3	4	5
	CONSEQUENCE				

LIKELIHOOD		
5 Very High	**Qualitative:** Nearly Certain to occur.	**Quantitative**: Safety P ≥ 10^{-1} Technical P≥60% Schedule/ Cost P≥75%
4 High	**Qualitative**: Highly likely to occur.	**Quantitative**: Safety 10^{-2} ≤ P < 10^{-1} Technical 35% ≤ P < 60% Schedule / Cost 50% ≤ P < 75%
3 Medium	**Qualitative**: May occur.	**Quantitative**: Safety 10^{-3} ≤ P < 10^{-2} Technical 15% ≤ P < 35% Schedule / Cost 20% ≤ P < 50%
2 Low	**Qualitative**: Not likely to occur.	**Quantitative**: Safety 10^{-5} ≤ P < 10^{-3} Technical 2% ≤ P < 15% Schedule / Cost 5% ≤ P < 20%
1 Very Low	**Qualitative**: Very unlikely to occur.	**Quantitative**: Safety P < 10^{-5} Technical P < 2% Schedule / Cost P < 5%

TIMEFRAME (when mitigation needs to start)	
Near	0-4 months
Mid	4-9 months
Far	> 9 months

Example Values Shown - Every project has specific values

CONSEQUENCE		1 Very Low	2 Low	3 Medium	4 High	5 Very High
Safety	Personnel	No injury requiring treatment	Minor first aid treatment	Emergency medical treatment for non-permanent injury	Severe (incapacitating) injury or illness	Death or permanent disability
Safety	Assets	No critical asset damage. Minor non-critical asset damage	Minor Asset damage	Repair or replacement feasible. Moderate asset damage; no or limited threat to project success – impacts no more than 1 KPP	Major critical asset damage; impacts project success- multiple KPPs	Loss of critical asset; prevents project success
Safety	Environmental	Negligible OSHA / EPA violation – non- reportable	Minor reportable OSHA / EPA violation	Moderate OSHA / EPA violation which requires immediate remediation	Major OSHA / EPA violation causing temporary stoppage	Serious or repeat OSHA / EPA violations resulting in action terminating project
Technical		Negligible Performance Impact: KPPs satisfied, decrement in performance does not affect system design	Minor Performance Impact: KPPs satisfied, decrement in performance may require minor change to system design	Moderate Performance Impact: KPPs may need updated but does not affect state-of-the-art, decrement in performance may require system design change or operational limitations	Significant Performance Impact: KPPs will not be satisfied and design could underperform state-of-the-art, decrement in performance results in significant change to system baseline and/or operational limitations	Severe Performance Impact: KPPs will not be satisfied and design underperforms state-of-the-art, design is unsuccessful and will not meet mission requirements.
Cost		≤ $25K	> $25 - 50K	> $50-100K	> $100-250K	> $250K
Schedule		≤ 1 month impact to critical path / milestones	> 1 - 2 months impact to critical path / milestones	> 2 - 3 months impact to critical path / milestones	> 3 - 4 months impact to critical path / milestones	> 4 months impact to critical path / milestones or possible project cancellation

Risk Scorecard

Risk Title: < Succinct, descriptive title >	**Risk Owner:** < Owner >
Risk Statement: Given [condition, situation, hazard, etc.]; there is a possibility that [negative consequences].	
Context: [Provide background information to elucidate the situation. Be clear, concise, and exact.] ***Risk Initiator:* *< Risk Initiator >* *Date Initiated:*** *< Date>*	
Timeframe: Near	**Current Likelihood (L)**: 4 | **Current Consequence: Safety (Sa)**: 1 **Technical (Te)**: 3 **Cost (Co)**: 2 **Schedule (Sc)**: 2
Approach: Mitigate	**Trigger:** Trigger #1
Status:	

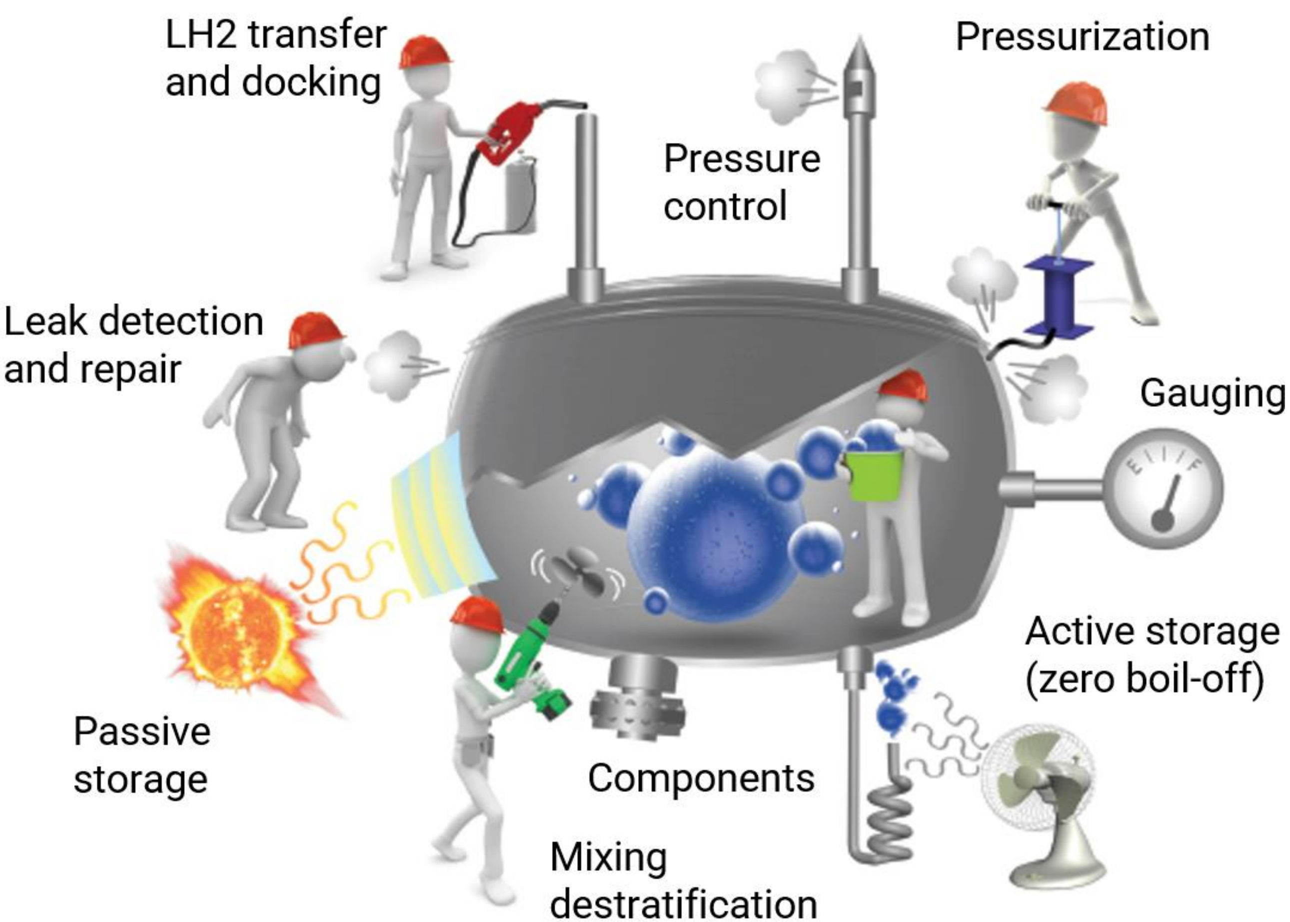
	Mitigation Task Description or Comments (C)	Actionee	Mitigation Cost	Mitigation Start Date	ECD	Li	Consequence				Success Criteria
							Sa	Te	Co	Sc	
	Initial LxC					4	1	4	3	4	
1	Initial Mitigation Step that reduced risk	Team Member	$ [TBD] k	< Date >	< Date >	2	1	3	2	2	< Metric for success evaluation >

	Watch Triggers	Actionee	Mitigation Cost	Mitigation Start Date	ECD	Li	Consequence				Success Criteria
							Sa	Te	Co	Sc	
2	Trigger #1	Team Member	$ [TBD] k	< Date >	< Date >						< Metric for success evaluation >
3	Trigger #2	Team Member	$ [TBD] k	< Date >	< Date >						< Metric for success evaluation >
4	Trigger #3	Team Member	$ [TBD] k	< Date >	< Date >						< Metric for success evaluation >

Review

- Hydrogen practice combines art, engineering, and experience
  - No "cookbook" approach works because there is no one solution to all situations
  - Use conservative approach
  - Search for and Recognize hazards and limitations
- Multiple design *consensus guides* and *standards* capture current knowledge and best practices
  - These are tools – Apply Engineering Judgement to most effectively apply these tools
- Don't take chances or shortcuts - The human factor is the most probable weak link in hydrogen operations.
- When in doubt, ***find help***!

Managing Cryogenics



Thank you for your attention.

Back-up