Aerospace Hydrogen Hazard Assessment

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Who We Are

NASA Johnson Space Center White Sands Test Facility

View north from SW corner of the White Sands Missile Range in southern New Mexico.

Our mission is to provide the expertise and infrastructure to test and evaluate spacecraft materials, components, and propulsion systems to enable the safe exploration and use of space.

Introduction

- Some perspective on managing hazards
- Unique aspects of aerospace systems
- Challenges of using hydrogen safely
- Hazard assessment
- Hazard assessment adapted to hydrogen systems

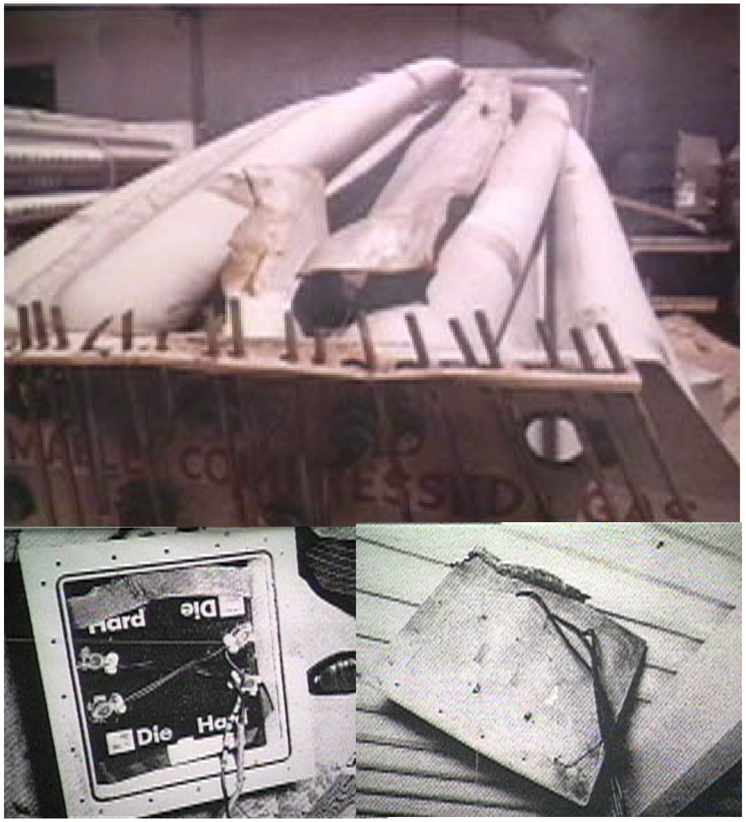
NASA White Sands Test Facility seen from space (see red arrow, lower center region).

What Is a Hazard?

Any event that creates a *condition* that can result in one or more of the following:

- Injury
- Damage to property, equipment, or environment
- Delay, loss of mission, or objective

May be considered a hazard.



Context for Managing Hydrogen Hazards

- Public expectations are formed from mature applications:
  - Technology and operations are fixed and well known
  - Users understand hazards and their safety expectations are met
- Hydrogen systems pose challenges:
  - Technology and operations are not fixed
  - Public expectations are based on specific experience with other energy technologies
  - General public's knowledge of H2 physical behavior ranges from incomplete to erroneous
- Management of hazards requires:
  - Knowledge of possible hazards
  - An approach based on an established practice

Context for Managing Hydrogen Hazards (Cont.)

Typical Elements of Safe Practice

Safe Hydrogen Use

Follow proper principles, practices, and procedures…

… by properly trained and motivated personnel

Inherent Safe Design

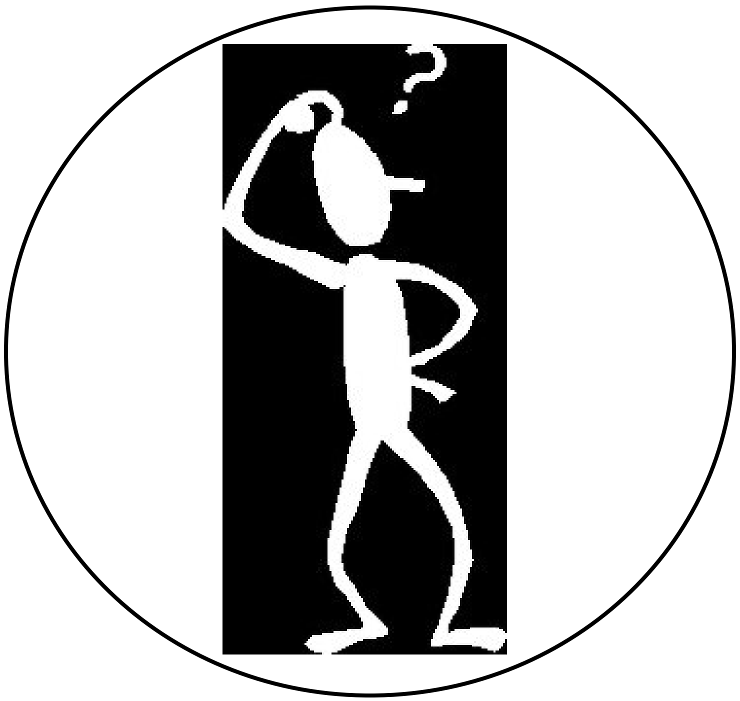
Codes & Standards

Proper Facility Siting

Managing a Hazard

Ignore it?

Eliminate it?



Control it?

Avoid it?

Prerequisites for Hazard Management

- Before hazards can be managed:
  - Identify hazards
  - Assess severity of consequences
  - Evaluate likelihood or risk
- This is a challenge for many hydrogen applications
  - Many applications are new
  - Industry systems and environment are different from those of commercial systems (lessons learned may not apply)
  - There is no extensive experience or historical information on the safety of new hydrogen applications.

Overview of Approaches to Hazard Assessment

- Approaches to hazard assessment
  - None (trial & error by default)
  - Prescriptive codes (from experience)
  - Proactive Prescriptive (derive code based on best available information prior to experience)
  - Assess basic principals, perhaps using predictive codes and models
- Caution: It is important to understand that existing codes apply to specific applications (for example, storage), and that codes and standards for new applications either do not exist, or are under development.

Hazard Assessment

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

- Hazard assessment can combine approaches
- May be applied at all stages in a system's existence:
  - Initial concept
  - Design review
  - Operations
  - Decommissioning
  - Post mortem analysis following a failure

Hazard Assessment Techniques

Step-wise methodologies have been developed to prevent failures in processes or facilities that deal with hazardous materials:

- Identify the facility/system
- Identify the hazards
- Conduct a hazard analysis
- Estimate the consequences of failures identified
- Estimate the frequency of occurrence of failures
- Estimate the risks
- Determine the acceptability of the risk(s)
- Develop strategies for preventing the failures and diminishing the adverse impact should failures occur

Some Methodologies and Tools

Methodology or Tool **(Source: Goldberg et. al.)**	**Advantages (A) and Limitations (L)**
Cause-Consequence Analysis	(A) Enables assessment of probabilities of coexisting faults or failures. End events need not be anticipated. Discrete levels of success or failure are distinguishable. (L) Addresses only on initiation challenge that must be foreseen by the analyst. May be very subjective as to consequence severity.
Directed Graph (Digraph) Matrix Analysis	(A) Allows the analyst to examine the fault propagation through several primary and support systems. Minimal cut sets, single-point failure, and double-point failures can be determined with less computer computation than with FTA. (L) Only identifies single point (singleton) and dual points (doubleton) of failure. Trained analyst, computer codes, and resources to perform this technique may be limited.
Energy Flow/Barrier Analysis	(A) Identifies hazards associated with energy sources and determines if barriers are adequate countermeasures. (L) Does not address coexisting system failure modes. Fails to identify certain classes of hazards, e.g., asphyxia in oxygen-deficient confined spaces).
Event Tree Analysis	(A) Enables assessment of probabilities of coexisting faults or failures. Functions simultaneously in failure and success domain. End events need not be anticipated. Accident sequences through a system can be identified. (L) Addresses only one initiating challenge that must be foreseen by the analyst. Discrete levels of success and failure are not distinguishable.

Some Methodologies and Tools (cont.)

Methodology or Tool	Advantages (A) and Limitations (L)
Failure Modes and Effects (and Criticality) Analysis	(A) Thorough methods of identifying single point failures and their consequences. A criticality analysis provides a risk assessment of these failure modes. (L) Can be extremely labor intense. Does not address coexisting failure modes.
Fault Tree Analysis	(A) Enables assessment of probabilities of coexisting faults or failures. May identify unnecessary design elements. (L) Addresses only one undesirable event or condition that must be foreseen by the analyst. Comprehensive trees may be very large and cumbersome.
Preliminary Hazard Analysis Probabilistic Risk Assessment	(A)Identifies and provides inventory of hazards and countermeasures. Provides methodology to assess overall system risks; avoids accepting unknown, intolerable, and senseless risk. (B)(L) Does not address coexisting system failure modes. Performing the techniques of this methodology requires skilled analysts. Techniques can be misapplied and results misinterpreted.
Risk Assessment Matrix Success Tree Analysis	(A) Provides standard tool to subjectively assess risk. Assesses probability of favorable outcome of system operation. (L) Only used to assess risk of hazards, does not identify hazards. Addresses only one desirable event or condition that must be foreseen by the analysis. Comprehensive trees may be very large and cumbersome.

Inductive and Deductive Logics

- Inductive Modeling
  - Involves reasoning from individual cases to a general conclusion
  - Induce the consequences of an event forwardly (bottom-up)
  - The scenarios for an initiating event, which can have undesired consequences, are defined first
  - Is useful in assuring that the analysis is broad enough to encompass all possible scenarios
  - In general, provides answers to the generic question, “What happens if ..?”

Inductive and Deductive Logics (cont.)

- Deductive modeling
  - Constitutes reasoning from the general to the specific
  - Deduce the causes of an event backwardly (top-down)
  - An event, for which causes are to be resolved, is defined first
  - Has the benefit of focusing the analysis on the undesired event
  - In general, answers the question, “What caused (or can cause) a failure or mishap to occur?”

Aerospace Hazard Assessment

- Some unique aspects of aerospace practice
  - Harsh operating environments
  - Large fuel inventories and severe consequences for failure
  - High performance requirements of flight systems
  - Combustion environments very different from the terrestrial environment (Low pressure, micro-gravity, high pressure, and cryogenic environments)
- Resulting requirements
  - Careful control on materials and systems to achieve high reliability
  - Evaluation for consequences of two independent faults
  - Inherently safe operation, auto-safe capability, and self contained (no reliance on outside systems or help)
  - Large exclusion zones for operation
- Aerospace systems are likely one-of-a-kind, each requiring individual hazard assessment

Challenges of Hydrogen Assessment

- Hydrogen is different from other fuels when inadvertently released, due the extent it reacts with its surroundings:
  - A leak at a point can grow into a cloud affecting a large area with potential combustion hazards
  - Large flammability range and low MIE promote interaction of released hydrogen with ignition sources
  - Cryogenic issues are distinct from gaseous issues (releases can begin heavier-than-air and warm to become buoyant)
  - Hydrogen combustion processes are often intertwined with the geometry of the physical system and surroundings, such that flame acceleration and development of dangerous overpressures can occur
- Complexity of phenomena can obscure identification of hazards

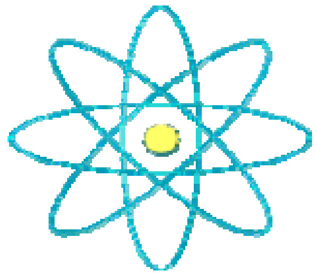
General Hydrogen Concerns

- The primary issues for hydrogen, in order of priority are:
  - Combustion Hazards
  - Pressure Hazards
  - Low Temperature Hazards
  - Hydrogen Embrittlement Hazards
  - Health Hazards

Physical Properties of Special Note

Gaseous Properties:

- **Asphyxiant, colorless, odorless, tasteless**
- **Lightest gas (15x less dense than air, can rise at rates up to 9 m/s)**
- **High diffusivity, low viscosity, small size**



Liquid (cryogenic properties):

- Non corrosive, Colorless Liquid (NBP 20.3 K)
- LH2: Condenses/Freezes all Gases Except He
- Liquid Density: 14x less dense than water
- Liquid Thermal Expansion: 23.4x that of water
- Gas Above Critical Temperature (33 K)
- **Equivalent Gas Volume Factor (@ NTP for NBP Liquid): 845.1 x**
- **Pressure (Liquid expansion in a fixed volume): 172 MPa**

Hydrogen Combustion Properties of Note

In most hydrogen combustion scenarios the “Fire Triangle” concept is not adequate.

- Flame is invisible in ambient light/produces little IR that can be perceived by human senses (emissivity < 0.1), and produces UV
- Flammability varies with mixture, initiation energy, pressure, temperature and combustion process
  - Under ambient conditions micro-joule sources can ignite sensitive mixtures
  - Broad range of flammable mixtures compared to most fuels
- Combustion process, hence overpressure and flame speed, dependent on surrounding geometry
  - Substantial flame acceleration possible for geometries with L/W > 8 or flow obstructions
  - Run up distances for DDT in sensitive mixtures ~ ½ meter
  - Deflagrations readily approach sound speed in unburned gases and detonation speeds > 1.5 km/s
  - For sensitive H2-air mixtures overpressures approach 8x in a closed vessel, 15x for deflagration and detonation, ~ 45 x for reflected detonation, and larger pressures in dead-headed spaces (pressure piling) are possible, where x ≡ initial gas pressure.

Condensed phase mixtures can be shock sensitive with TNT-like yields

Analysis Strategies for Hydrogen Combustion

- The basic strategy is to seek specific concentration data for mixture formation and ascertain the flammability
  - Below the flammability limit combustion does not occur
  - Lean mixtures burn incompletely and flames propagate poorly
  - With richer fuel concentrations ignited mixtures exhibit complete burning,
  - In more sensitive mixtures there is flame acceleration, and finally in very sensitive mixtures transition to detonation is possible

Analysis Strategies for Hydrogen Combustion

- Flammability, while a basic criteria, is not the only one that determines the likelihood for a particular combustion process, and hence consequences
- Some mixing scenarios involve conditions that create concentration gradients such as leaks or jets into open air filled spaces
- Use a conservative approach when there is insufficient information
  - Assume the worst case,
  - Or a stoichiometric mixture, even though it may not be the most likely

Analysis Strategies - Initiation

- Flammable hydrogen mixtures are readily ignited by a variety of initiation sources (sparks, hot surfaces, metal fracture, etc..)
- Best practice seeks to eliminate ignition sources wherever possible, so the first goal of hazard assessment is to ascertain where potential sources of ignition may arise, then assess their effect on the mixtures present.
- The strength of the ignition source does influence flammability. Powerful electric discharges will initiate combustion in mixtures at lower pressures over lower energy discharges.
- For detonation, more powerful sources of shock are required to initiate mixtures with larger cell sizes.
- Where mixtures are sensitive it is generally assumed that an ignition source will be present.

Factors in the Analysis of Release

- The quantities of materials that can mix
- The conditions (temperature, pressure, mixture composition)
- The rate of release
- Extent (size) of cloud/plume
- Extent of mixing with oxidizer in systems where oxidizer is present
- Degree of confinement as determined by presence of piping, ducts, turbulence inducing obstacles, surfaces, walls, or density gradients.
- Dimensions, volume
- The length to width (L/W) ratio to evaluate if conditions for flame acceleration are possible.

Water vapor cloud formed from 1500 gallons of hydrogen released into a 30 ft diameter pond in 30 seconds with a 7-8 mph wind NASA White Sands Test Facility (1980).

Bounding Criteria for Combustion Assessment

Bounding Conditions	Flammability Limit	Comments
LFL Air in Tubes, ID 0.8 – 7.5 cm	~ 3.9 - 5 %	Upward propagation, Ambient conditions
ID 0.9 – 7.5 cm	~ 6 - 7 %	Horizontal propagation
ID 1.4 – 21 cm	~ 8 - 9 %	Downward propagation
UFL Static Ambient Air	75 %	Upward propagation
UFL Static Oxygen	95.8 %	Upward propagation
Low Pressure Flammability Limit in Air	20 – 30 %	6 kPa absolute pressure 45 mJ spark in 2-liter vessel
Low Pressure Limit in Oxygen	30 – 60 %	3 kPa absolute pressure, ~1 J spark
Laminar Burning Velocity H_2-Air no confinement at 298 K	17%	1 m/s
Laminar Burning Velocity, H_2-Air, no confinement at 298 K (cont.)	42 %	3.5 m/s
	64 %	2.2 m/s
Flame Speed in Pipes, IDs 5-30 cm	< 10 %	No acceleration
H_2 - Air, 10 < L/D < 40	10 % to < 13 %	100 m/s to < 200 m/s, steady and insensitive to obstacles
	> 13 %	Velocity limited to sound speed of products (600 to 1000 m/s) – choked flow
	> 17 %	DDT and CJ velocities (1700 m/s)
Cell Size, Stoichiometric H_2 - Air	1.6 cm	Cell size increases for non stoichiometric mixtures
Cell Size, Stoichiometric H_2 – O_2	0.16 cm	Cell size increases for non stoichiometric mixtures
Solid air in Liquid Hydrogen	> 40 %	Highly shock sensitive. Detonable with effects similar to high explosives
Solid oxygen in Liquid Hydrogen	If % O_2 > % H_2	Shock sensitive for stimuli of 100 to 250 MPa (less than nitro-glycerine)

Source: Woods, McDougle, and Stewart [2]

Condensed Phase Issues

- LH2 spills dissipate by absorption of heat from the air and by heat transfer though gas near solid surfaces
- 40 % (LDL) solid air in LH2 is more shock sensitive than nitroglycerin (UDL is not known)
- LH2-Lox Mixing: Yield is proportional to surface area of mixing (WSTF drop tower/pan tests 1995)

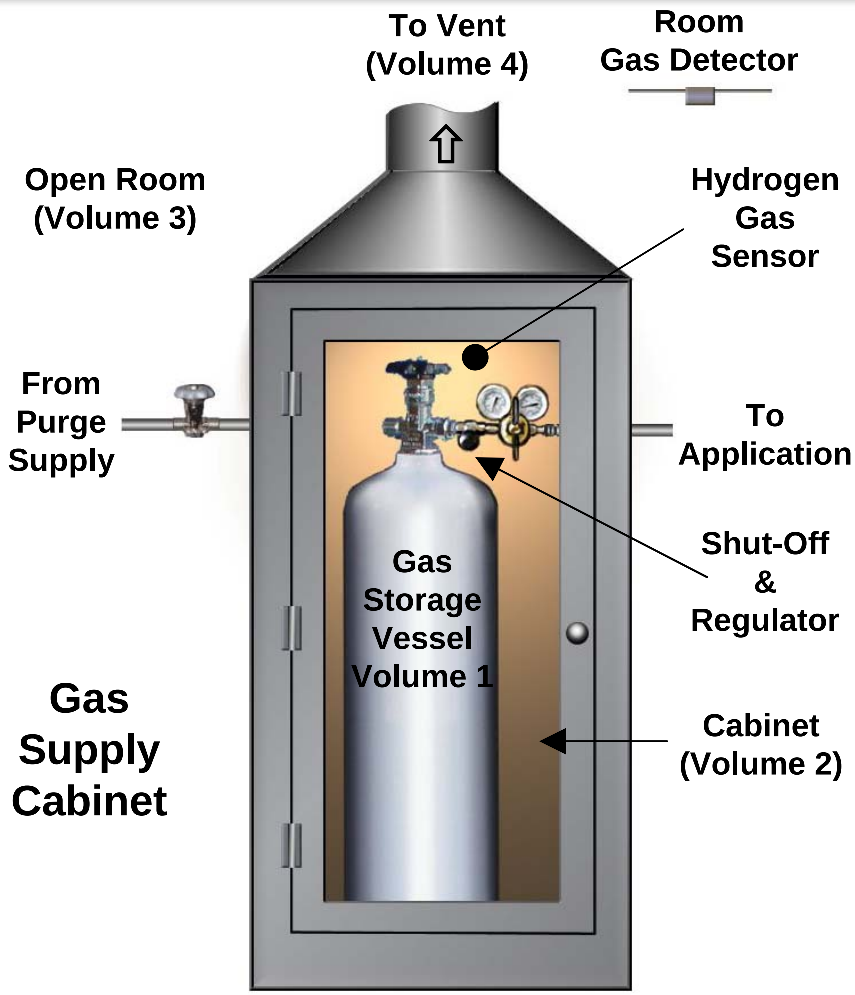
Explosion of 50 lb LOX/LH2 at High Energy Blast Facility (WSTF 1995)

HHAP – Basic Concept

- Typically a hydrogen event is defined by:
  - Unintended release of hydrogen derived energy (pressure or temperature differential),
  - Incursion of reactive material (causing mixing),
  - Release of hydrogen (causing mixing)

  into a volume or space.
- System layout, function and controls define volumes where the volumes of interest are:
  - Hydrogen-wetted portions of a system,
  - Interstitial spaces between components,
  - Environment surrounding the system.
- The procedure presented here provides suggestions for developing an analysis strategy, criteria for defining volumes, and a methodology for analysis.

Volumes in a Simple Scenario



Gas Supply Cabinet

Volume	Controls
1	Vessel walls, shut-off valve, regulator
2	Cabinet wall, purge, vent, gas sensor that controls purge and alarm
3	Gas detector in room, ventilation to code
4	Location to code, GH2 freely dissipates

Overview of Methodology

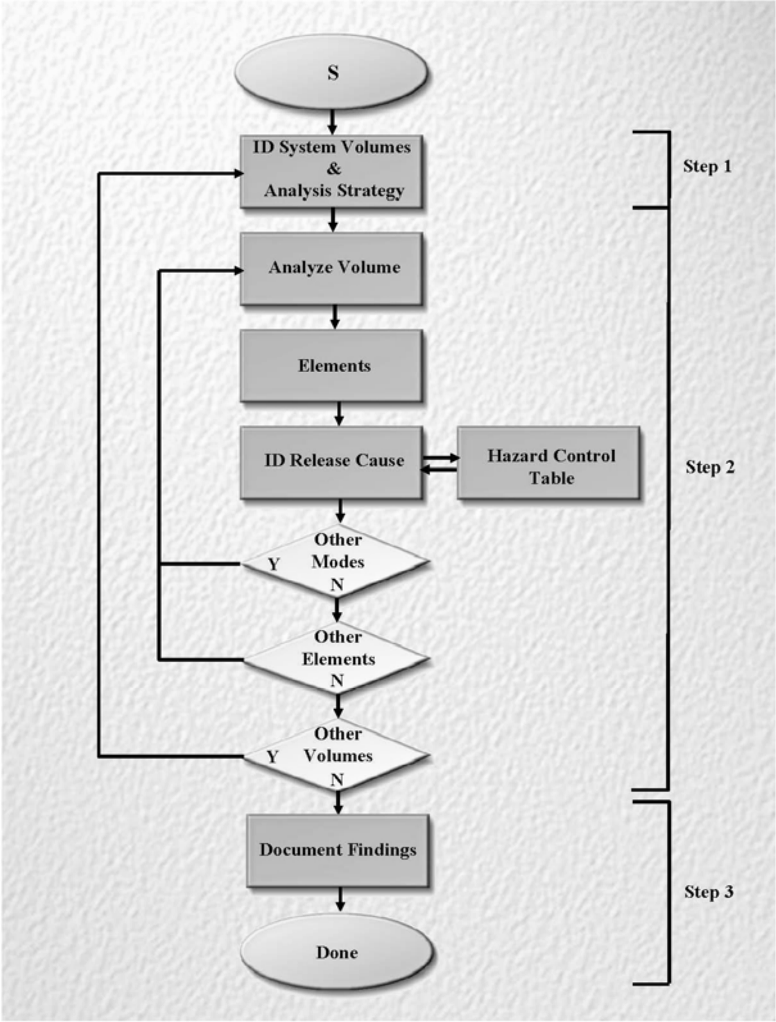
Methodology employs both inductive and deductive approaches. Process elements include:

- Identification of volumes for analysis
- Assessment of factors/potential causes that might contribute to an unintended release
- Evaluation of characteristics of the release within the volume
- Determination of potential hydrogen behaviors arising from the release
- Evaluation of consequences and associated risks
- Recommendations for mitigation

Assessment Process

STEP 1 – Analysis Strategy

- Determine which portions of a system require hydrogen analysis
- Discern the distinct volumes in which hydrogen is either controlled (wetted)
- Or into which hydrogen or hydrogen related energies may be unintentionally released.
- Prioritize which volumes and elements should be considered first.
- Identify attributes in common between volumes or elements to minimize effort



Assessment – Step 2

For a component:

- Identify the functional modes that involve hydrogen.
- Perform analysis of materials wetted by hydrogen.
- Look for circumstances and failure modes that can contribute to a hydrogen release.

For operations involving personnel look for:

- The potential for operator error
- Deviations from best practice that may lead to a hydrogen release
- Unnecessary exposure
- Interaction between elements, and kindling chain issues
- Other potential issues as required

Materials Assessment

COMPONENT ID	Flowmeter	**MANUFACTURER**	Rosemount	**MEDIA**	GH_2
PRESSURE RATING	335 psia	**MODEL NO.**			
NOTES					

MATERIALS OF CONSTRUCTION	
Metal / Softgood / Lubricant	Function within Component
300 series SS tubing	Inlet and outlet to fuel cell
321 SS	Sensor tubes
Nickel braze alloy	Braze weld for sensors
300 series SS	Housing
Fiberglass/epoxy	Printed Wiring (circuit) board
Copper wire	Sensor wiring
Varglass tubing	Copper wire covering

COMPONENT USE ENVIRONMENT

Use Scenario	Operating Conditions			Worst-Case Condition		
	Pressure	Temperature	Other	Pressure	Temperature	Other
Flight	250 psia	-70 to +100 °F		335	-70 to +190 °F	Per Spec.

Materials Assessment

POTENTIAL FAILURE CAUSES			PROBABILITY OF FAILURE				
Is this cause present?		Yes Or No	Leaks Externally	Leaks Internally Fails Open	Fails Closed	Generates Contaminants	Other
Properties of Component Materials	Diffusion/ Permeation	N					
	Chemical Reaction	N					
	Temperature Compatibility	N					
	Expansion/ Contraction	Y	2	N/A	N/A	N/A	N/A
	H-Embrittlement	N					
	Other	N					
System Conditions	Mechanical Stress / Vibration	Y	2	N/A	N/A	N/A	N/A
	Flow Regime	N					
	Deformation	N					
	Resonance	N					
	Liquid Lockup	N					
	Water Hammer / Surge Pressure	N					
	System Contamination	N					
	Liquid Air Formation	N					
	Other	N					

Probability Rating: **0** = Almost Impossible **1** = Remotely Possible **2** = Possible **3** = Probable **4** = Highly Probable

Mixing and Combustion

- Identify the cause of the hydrogen release
- Evaluate potential hydrogen mixture(s) that may arise within the volume
- Assess which potential effects for non-ignition and combustion events:
  - Evaluate possible non-ignition events
  - Fire, deflagration, detonation may all be possible
  - Evaluate potential combustion processes and effects in the context of the mixing event and scenario confinement
    - Evaluate flammability
    - Ignition mechanisms based on the elements and other ignition sources present in the volume.

Assessment Tasks

- Note controls or controlling factors that mitigate a hazard as well as circumstances that might interfere with the controls. Summarize the effect on potential reactions
- Assess the likelihood from ignition criteria
- Evaluate the severity of the reaction effect from established criteria
- Consider potential mitigations for unacceptable hazards and deleterious effects and note proposed controls.
- Assess mitigated reaction effects.

Assessment of Risk of Ignition

Ignition Rating	Code	Criteria	
		Characteristic Elements	Mixture Flammability
Not Possible	0	Not at all present	Nonflammable
Remotely Possible	1	All present Not at all present	Nonflammable Flammable
Possible	2	All present and active	Flammable
Probable	3	All present and some are strongly active	Flammable
Highly Probable	4	All present and all are strongly active	Flammable

Assessment Criteria for Event Severity

Rating	Code	Personnel Safety	System Objectives	Functional Capability	Example
Negligible	A	No injury to personnel	No unacceptable effect on production, storage, transportation, distribution, or use as applicable	No unacceptable damage to the system	There is no personnel access, kindling chain, or ignition probability greater than 0
Marginal	B	Personnel-injuring factors can be controlled by automatic devices, warning devices, or special operating procedures	Mission/Objective can be accomplished by using available redundant operational options, or resumed after acceptable repair	No more than one component or subsystem damaged. This condition is either repairable or replaceable within an acceptable time frame on site	There is a kindling chain, and ignition probabilities are greater than 0. In addition, access to the area is controlled in a formally documented procedure and barricades are used
Critical	C	Personnel may be injured (1) operating the system, (2) maintaining the system, or (3) by being in the vicinity of the system	Production, storage, transportation, distribution, or use as applicable impaired seriously	Two or more major subsystems are damaged. This condition requires extensive maintenance	There is a kindling chain, and ignition probabilities are greater than 0. In addition, access is limited by a shield or distance, but there are no formal access procedures or barricades used
Catastrophic	D	Personnel suffer death or multiple injuries	Production, storage, transportation, distribution, or use as applicable rendered impossible—major unit is lost	No portion of the system can be salvaged—total loss	There is a kindling chain, ignition probabilities are greater than 0, and direct exposure is required for operation

Sample Hazard Control Table

Item	Release Cause	Seal fails on flange for pipe containing 30 psi, 100 K cold hydrogen gas					
	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 and leak would likely disperse harmlessly	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

What is Achieved?

- HHAP organizes assessment around volumes into which hydrogen release can occur
- Inductive reasoning (FMEA) is used to systematically identify component or operational failures and their consequences
- Non-combustion and combustion hazards are recognized
- There is recognition that with hydrogen scenarios the combination of mixing specifics, of flammability, available ignition sources, surrounding confinement, and combustion process together define the hazard
- Hydrogen scenarios are systematically identified

What is Achieved?

- Mitigations built into the system are recognized
- Severity and qualitative risk are assessed
- If possible, new mitigations based on analysis are captured
- This information is systematically organized and documented

The end product is a tabulation of hazards and associated factors to facilitate decision making

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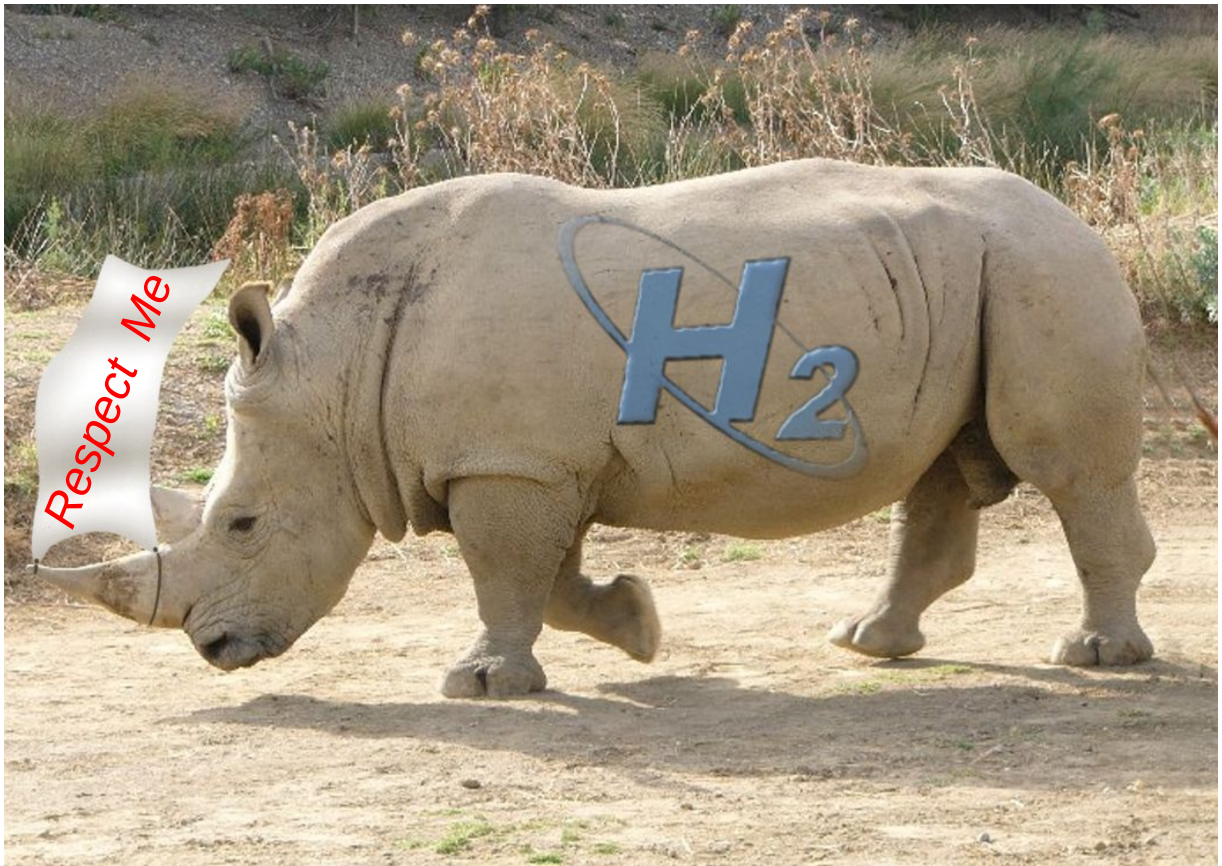

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