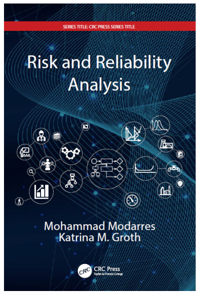
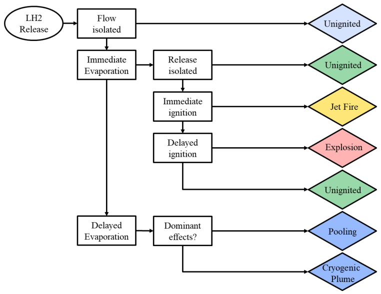
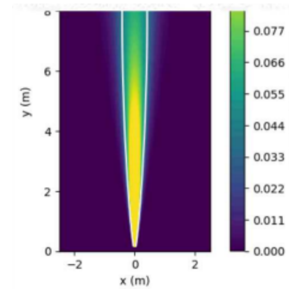






Managing risk and reliability in hydrogen systems: implications for fueling stations, forklifts, electrolyzers and beyond

Katrina Groth (kgroth@umd.edu)

Professor & Director, Reliability Engineering

Associate Director for Research, Center for Risk and Reliability

University of Maryland

Research supported by multiple sources. The views expressed herein are those of the authors and do not reflect the official policy or position of any sponsor.

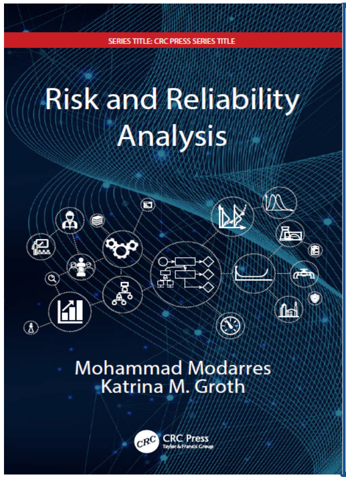
Fast Facts about UMD's Reliability Engineering program & Center for Risk and Reliability

4+12
Core, and Affiliate Faculty

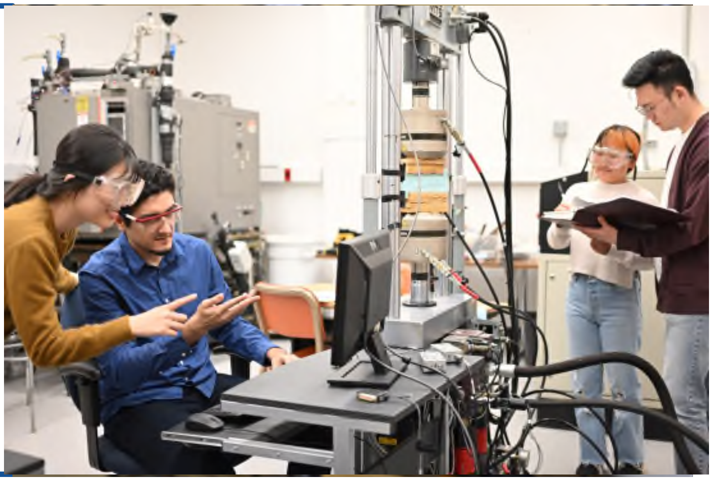
6
Cutting-Edge Research Laboratories

4
Degrees Offered (Ph.D. M.S., M.Eng, Certificate)

500+
Graduates since **1991**



- Systems Risk and Reliability Analysis Lab (SyRRA)
- Probabilistic Physics of Failure and Fracture
- Cybersecurity Quantification Lab
- Risk And Decision Analysis Lab (RADA)
- Design Decision Support Lab
- Risk-Informed Solutions in Engineering (RISE)

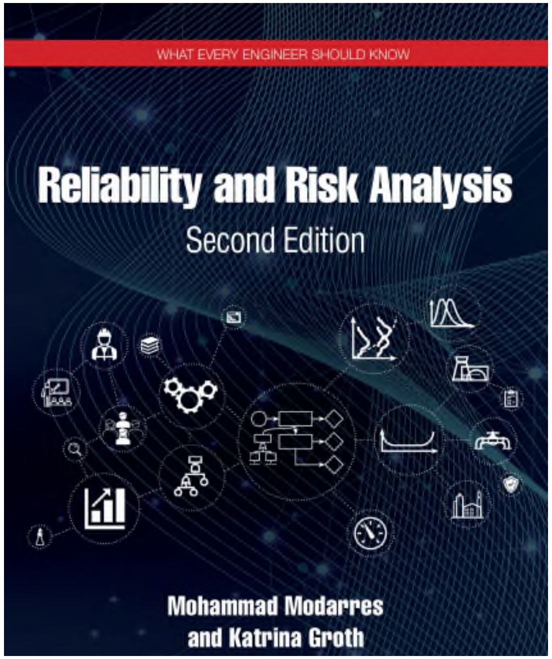


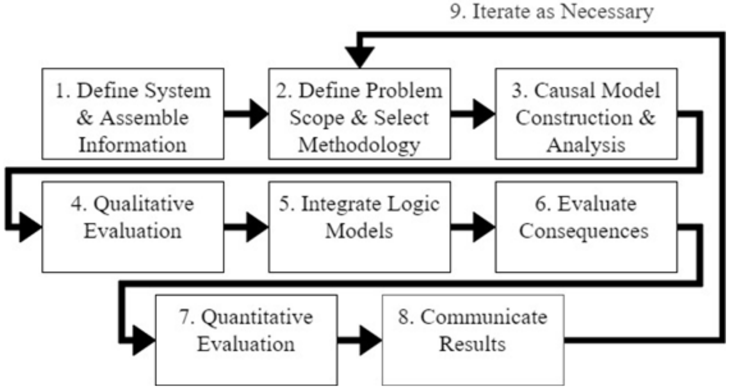
The **#1** Reliability Engineering program in the U.S. (Source: Scopus)

Reliability engineering & quantitative risk assessment (QRA): structured processes to support decision-making

SYRRA

- By building understanding of:
  - **What the system is supposed to do** (performance)
  - **The sources, causes, and likelihood of failures** (physics-based, human, computational, etc.)
  - **Priorities & strategies to reduce failure** (e.g., design, operation, maintenance)
- Offers the opportunity to identify & proactively change systems & practices throughout the lifecycle





Application areas for reliability engineering

Hydrogen is here – enabled by unprecedented national investment

Bipartisan Infrastructure Law

Includes $9.5B for clean hydrogen:

- **$8B** - regional clean hydrogen hubs
- **$1B** - electrolysis
- **$0.5B** - manufacturing and recycling

Inflation Reduction Act

Includes significant tax credits
(e.g., up to $3/kg for clean H2 production)

U.S. Goals

Reduce 50% U.S. GHG emissions by 2030
Net zero GHG emissions no later than 2050

Clean Hydrogen Production

- 10 MMT by 2030
- 20 MMT by 2040
- 50 MMT by 2050

Greenhouse Gas Reduction

- 10% reduction economy-wide

Economic Impact

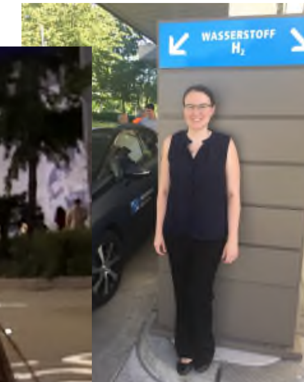
- 100,000 new direct / indirect jobs by 2030

A. JAMES CLARK SCHOOL OF ENGINEERING

U.S. DOE, "National Clean Hydrogen Strategy and Roadmap," U.S. Department of Energy, 2023

The hydrogen technology is global

Toronto,



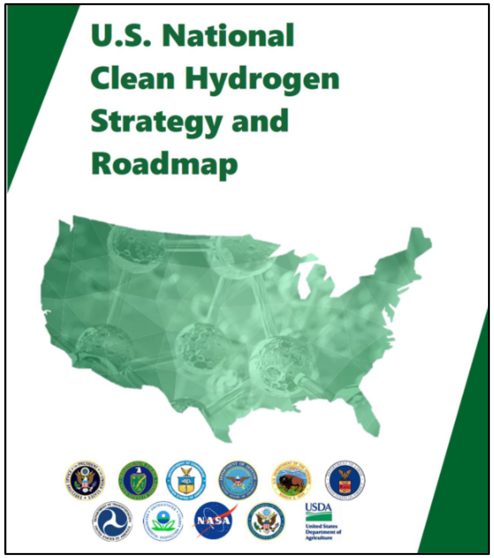
, Germany (2016)

Maryland, U

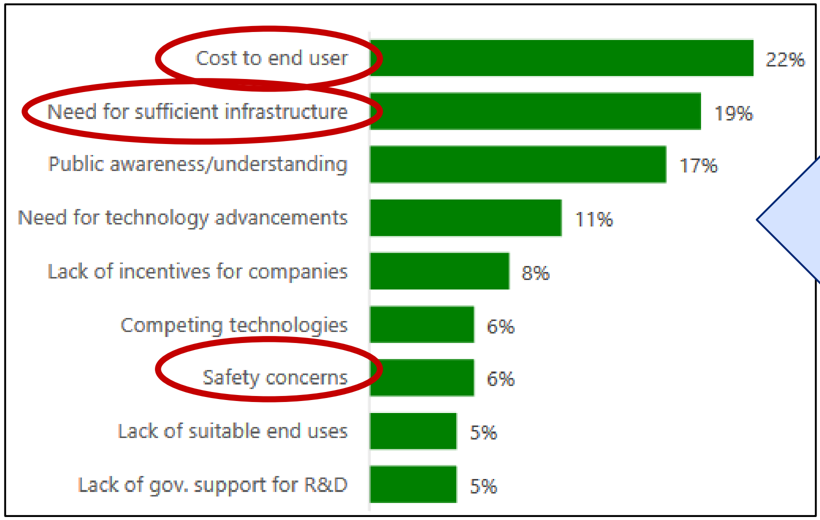
ryland, USA (2024)

Seoul, Korea (2025)

Safety & Reliability are a Key Barrier to H2 Deployments



- 2023 U.S. National Hydrogen Strategy identifies:
  - Reliability & risk assessment as key needs for enabling deployments.
  - Education: 100,000 new jobs by 2030



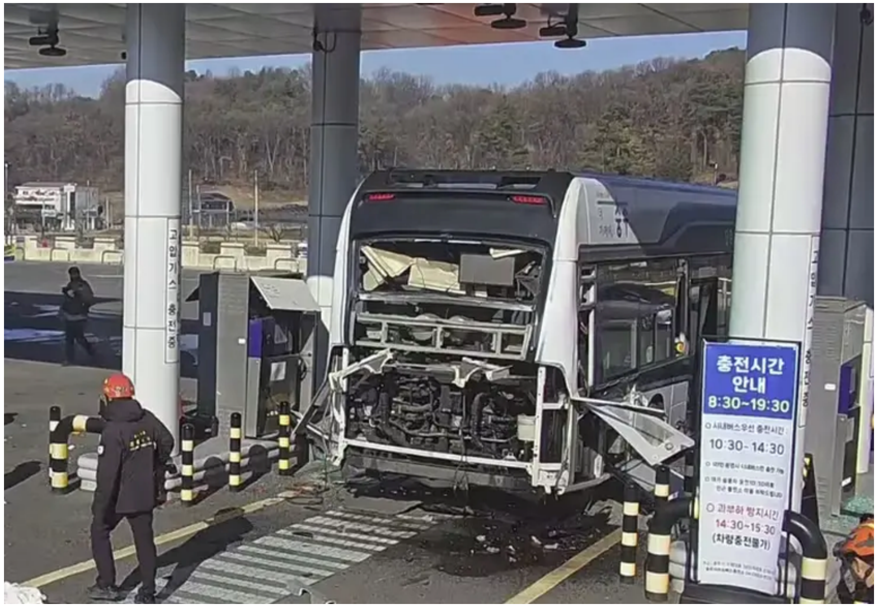
Survey at *2021 DOE Hydrogen Summit* shows that safety and reliability dominate the key barriers to public acceptance and market adoption.

Now we have the technology, but we do have some problems…

Fire engulfs new hydrogen bus and fueling station at Golden Empire Transit

Bus & Station Fire, Bakersfield, CA, Aug 2023

Norway fueling station explosion, June 2019
10 stations shut down for investigation



Bus fire, Chungju, Korea, Dec 2024

And it’s not just safety: the $100M problem is **reliability**

SYRRA

Los Angeles Times

CLIMATE & ENVIRONMENT

Refueling a hydrogen car in California is so annoying that drivers are suing Toyota

California USA, Aug. 2024

WIRED

BY KYLE YOUNKER BUSINESS NOV 19, 2024 8:00 AM

The Norwegian Company Blamed for California’s Hydrogen Car Woes

A civil fraud case reveals that the hydrogen fueling stations promoted by Toyota, Shell, and Chevron never worked in the first place.

USA, Nov. 2024

H_2

Widespread Breakdowns Cripple Hydrogen Stations in South Korea

By FCW Team
September 23, 2024 at 9:35 AM EDT

South Korea, September 2024

Hyundai recalls all 1,269 of its hydrogen-powered city buses in operation in South Korea due to new safety concerns

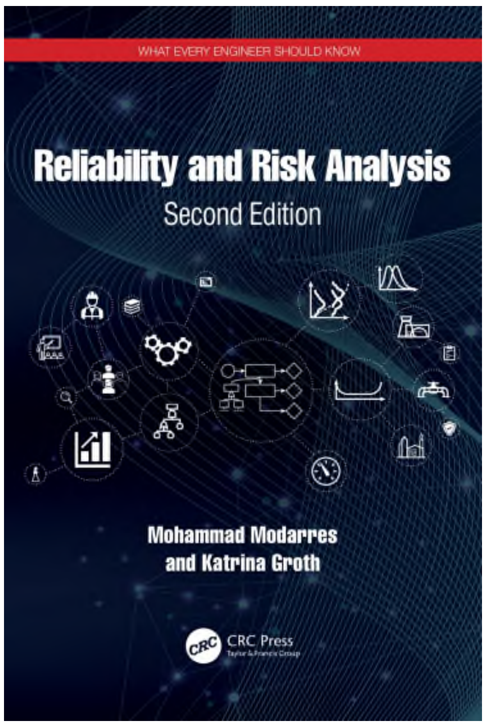
News comes several months after an Elec City bus exploded, seriously injuring a refuelling station worker

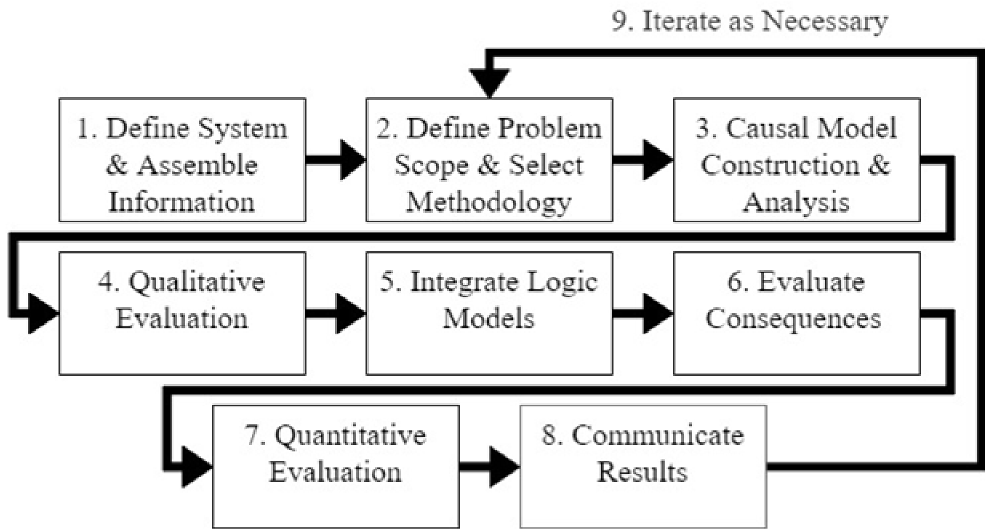
Seoul, Korea, May 2025

Bad approaches to dealing with potential failures (risk) & safety questions

SYRRA

Reliability engineering & risk analysis are part of the solution





Selected projects: 15 years of enabling safer hydrogen equipment & pipeline deployments

QRA for H2 indoor fueling for NFPA 2

QRA for H2 separation distances in NFPA 2

ISO 19880-1 incorporates QRA and HyRAM for safety distances & more

Pipeline corrosion model

LH2 On-site storage QRA

BaNTERA pipeline excavation damage model

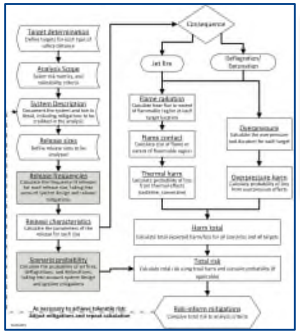
H2FC Forklift QRA

PEM Electrolyzer QRAs

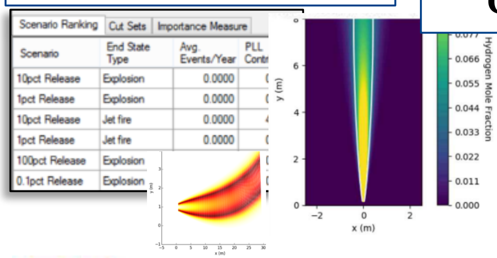
LH2 fueling station QRA

2010-2014 | 2015 | 2017 | 2019 | 2021 | 2023 | 2025

HyRAM algorithm

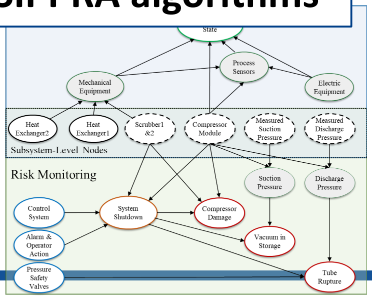


Public release of HyRAM 1.0



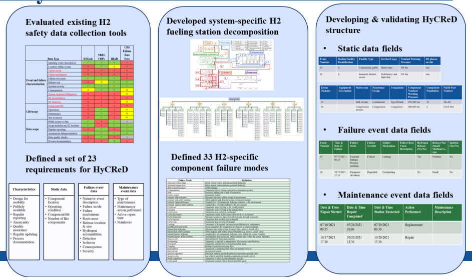
H2 Storage Risk & Reliability Gap Study

SIPPRA algorithms



PHM & QRA Data requirements for LH2 storage

HyCReD fueling reliability data collection framework



Major research activities include:

- Risk assessment (QRA) to establish codes & standards requirements
- Reliability & risk assessment (QRA) to establish risk tolerability & dominant risk contributions & mitigations
- Prognostics & health monitoring to enable reliability prediction and intervention
- Reliability modeling & failure analysis
- Reliability data collection to set priorities

HyRAM+: Making hydrogen safety science accessible through computational tools

SYRRA

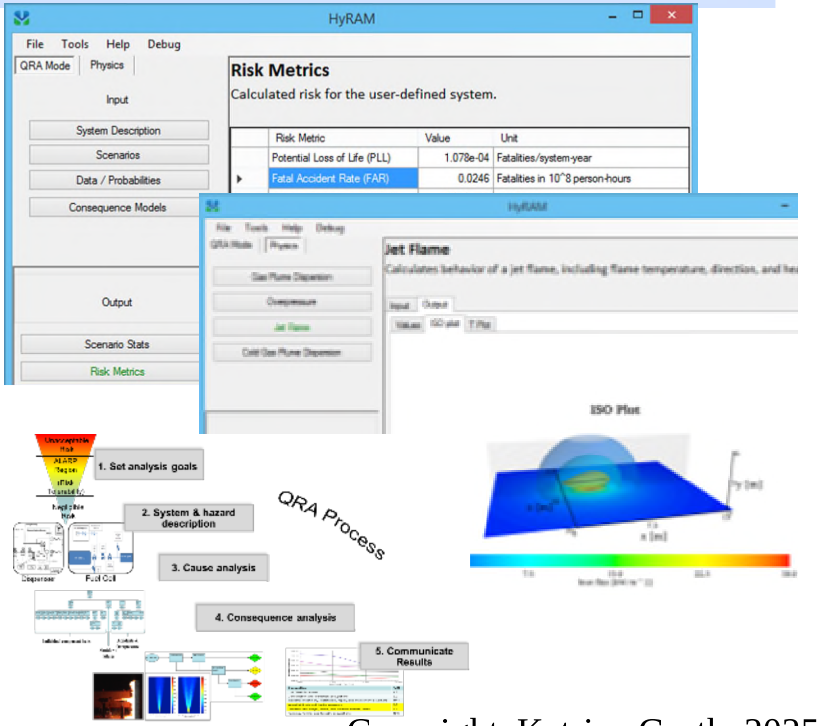
Sandia National Laboratories

HYRAM
HYDROGEN RISK ASSESSMENT MODELS

First-of-its-kind integration platform for state-of-the-art hydrogen safety models & data - **built to put the R&D into the hands of industry safety experts**

Core functionality:
- Quantitative risk assessment (QRA) methodology
- Frequency & probability data for hydrogen component failures
- Fast-running models of hydrogen gas and flame behaviors

Key features:
- GUI & Mathematics Middleware
- Documented approach, models, algorithms
- Flexible and expandable framework; supported by active R&D



Free at http://hyram.sandia.gov

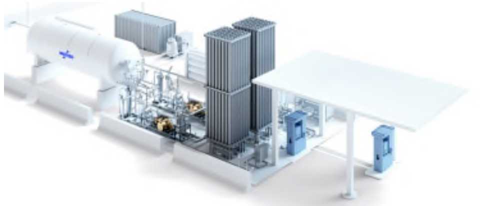
K. M. Groth and E. S. Hecht. Mar. 2017. "HyRAM: A methodology and toolkit for Quantitative Risk Assessment of hydrogen systems." *International Journal of Hydrogen Energy* 42.

Impact: QRA enabled safe deployment of hydrogen systems

- **QRA enabled the first US & International codes for H2 infrastructure**
  - *NFPA2 Ch. 7*: Established GH2 separation distances (SAND2009-0874)
  - *NFPA2 Ch. 10*: Calculated risk from indoor fueling (SAND2012-10150)
  - *NFPA2 Ch. 5*: Enabling Performance-based compliance option (SAND2015-4500)
  - *ISO 19880-1 Ch. 4*: Developed consensus approach for defining specific mitigations (e.g., safety distances) using regional criteria & requirements (2016)
  - *ISO 19880-1 Annex A*: Developed safety distance & mitigation examples (2017)

Advances in reliability engineering & safety for hydrogen systems will continue to drive the industry forward

Quantitative Risk Assessment of hydrogen releases in a hydrogen fueling station with LH_2 storage



Objective: Perform 1st full QRA on a high-capacity hydrogen fueling station with liquid hydrogen storage (LH_2), high-pressure cryogenic compression, and temperature control through GH_2 and LH_2 mixing.

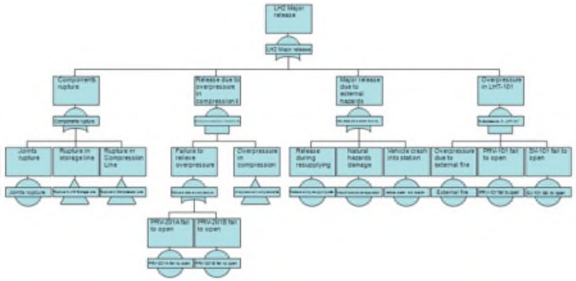
Qualitative Analysis: Design realistic high-capacity station & FMEA

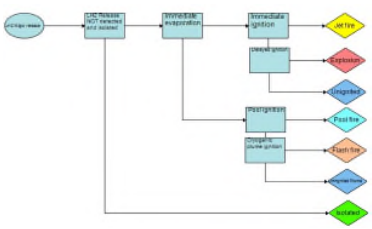
H2 Release Models: Develop fault trees for H_2 release scenario

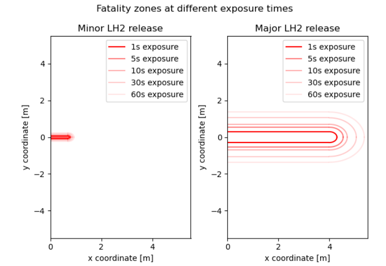
Event Sequence Models: model undesired scenario progression

Consequence Analysis: Fatal Accident Rate & Average Individual Risk

Probability Class		Severity Class: Minor	Moderate	Critical
	High	M	H	H
	Medium	L	M	H
	Low	L	L	M







Results:
Fully documented QRA to act as a baseline for safety of a liquid storage high-capacity H_2 fueling station

- **Most significant risk contributors:**
  - Cryogenic pump releases, H_2 sensor failure, Vaporizer ruptures, Filter ruptures, Valve fail. to close
- **FAR**: $1.24 \times 10^{-1}/year$
- **AIR**: $3.41 \times 10^{-5}/year$
- ($< 10^{-4}$ AIR threshold of EIHP2)

Implications & Impact:

- Provide basis for using QRA to enable reliability, siting, and standards development for liquid storage high-capacity H_2 fueling station
- Inform industry and stakeholders about **risks and mitigation options** for LH2 station designs and technologies.
- **Demonstrated AIR within risk-tolerability zone.**

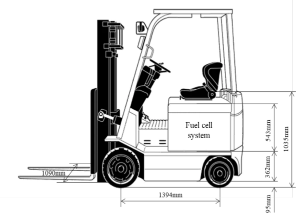
C.Schaad, S. Mosleh, R. Yang, K. Groth, "Quantitative Risk Assessment of hydrogen releases in a hydrogen fueling station with liquid hydrogen storage," *International Journal of Hydrogen Energy*, vol. 112, pp. 111–120, Mar. 2025.

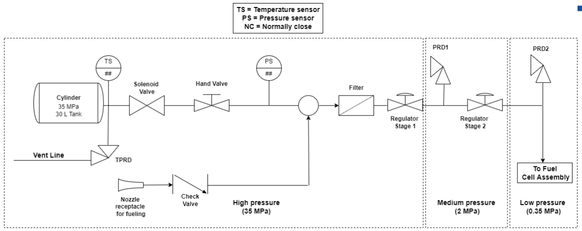
QRA of a hydrogen fuel cell forklift

- Over 40,000 H2 fuel cell forklifts currently operating in the U.S.
- QRA study to identify *failure causes, release scenarios, probabilities and consequences* of a hydrogen fuel cell forklift.
  - Building off QRA method applied for indoor hydrogen dispensers (used in NFPA 2)
- QRA method integrated three major data sources & validated H2 consequence models: HyRAM, CCPS PERD, OREDA

- **Shows extended types of impactful outputs possible from using QRA**:
- *Calculated worker risk (FAR)* and compared to U.S Gov't (BLS) data for industrial truck & material handling occupation fatalities.
- *Identified most risk-significant components* using importance measures analysis – potential to inform design modifications and/or codes and standards.

Generic H2 forklift system design



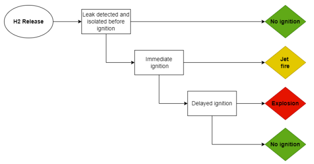


FMEA

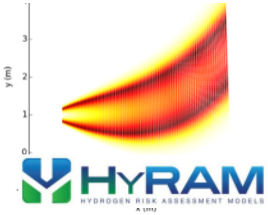
ID	Type	Function	Failure Mode	Cause	Local Effect	System Effect
	Tank (type III or IV)	On-board storage of gaseous hydrogen at 35 MPa	Rupture (Loss of fuel and fragmentation of container from overpressure beyond the 1.25x design pressure)	• External impact damage (crashes, road debris); • External or localized fire damage; • Inadequate design, testing, manufacturing, installation, or maintenance	• Explosive release of mechanical energy stored in gas and container; • Explosive release of container materials; • Potential asphyxiation hazard; • Collection of combustible mixture in closed environment;	• Immediate ignition of released fuel resulting in a jet flame hazard; • Delayed ignition of collected vapors, potential explosion or detonation hazard
			Leakage (Loss of fuel without substantial pressure drop)	• Degradation; • Seal failure; • External impact damage; • Inadequate design, testing, manufacturing, installation, or maintenance	• Potential asphyxiation hazard; • Collection of combustible mixture in closed environment;	• Immediate ignition; • Delayed ignition of collected vapors, potential explosion or detonation hazard

Full FMEA available upon request

Event sequences



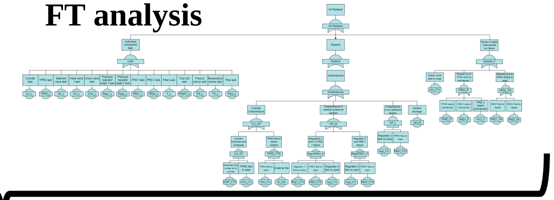
Release & flame simulations



Basic event frequencies

ID on Fault Tree	Description	Frequency (Failures/year): Median (HyRAM)	Mean	Lower 5%	Upper 95%	Reference
Cyl_L	Cylinder leak	2.30E-07	2.83E-07	6.93E-08	7.87E-07	[29]
Vent_L	Vent line leak		8.08E-07	3.89E-09	5.48E-06	[29]
TPRD_L	TPRD leak		2.60E-03	7.40E-04	5.38E-03	[36]
SV_L	Solenoid valve leak	4.80E-06	1.24E-05	3.30E-07	7.09E-05	[29]
HV_L	Hand valve leak	4.80E-06	1.24E-05	3.30E-07	7.09E-05	[29]
CHV_L	Check valve leak		8.29E-05	3.19E-07	3.32E-04	[36]

FT analysis



Total risk (FAR, AIR)

Release scenario	Pressure section	AIR, fatalities/forklift-year	FAR fatalities/100 million hours-driver	Expected fatalities/year
		Jet Fire		
Minor release	Low	0	0	0
	Medium	0	0	0
	High	0	0	0
Major release	Low	3.27×10^{-6}	0.16	6.53×10^{-2}
	Medium	2.74×10^{-6}	0.14	5.48×10^{-2}
	High	3.49×10^{-5}	2.77	1.11
Total		4.09×10^{-5}	3.07	1.23
		Explosion		
Minor release	Low	0	0	0
	Medium	0	0	0
	High	0	0	0
Major release	Low	1.41×10^{-6}	0.02	2.82×10^{-2}
	Medium	1.36×10^{-6}	0.07	2.72×10^{-2}
	High	2.67×10^{-5}	1.34	5.34×10^{-1}
Total		2.95×10^{-5}	1.42	5.90×10^{-1}

Component Risk Reduction Worth

High Pressure

Fault Tree ID	Description	Scenario(s)	I_{RRW}
F_L	Filter leak	All	1.720
TPRD_P	TPRD prematurely opens	All	1.399
TPRD_L	TPRD leak	All	1.328
CHV_FTC	Check valve failure to close	All	1.025
CHV_L	Check valve leak	All	1.007

Medium Pressure

Fault Tree ID	Description	Scenario(s)	I_{RRW}
PRD1_FR	PRD1 failure to reseat	All	1.874
PRD1_L	PRD1 leak	All	1.552
PRD1_P	PRD1 prematurely opens	All	1.212
Reg2_L	Regulator 2 leak	All	1.0013
Reg2_FTO	Regulator 2 failure to open	All	1.0009

Al-Douri, A., Ruiz-Tagle, A. & Groth, K. A Quantitative Risk Assessment of Hydrogen Fuel Cell Forklifts. *Int'l Journal of Hydrogen Energy* 2023. Doi: 10.1016/j.ijhydene.2023.01.369

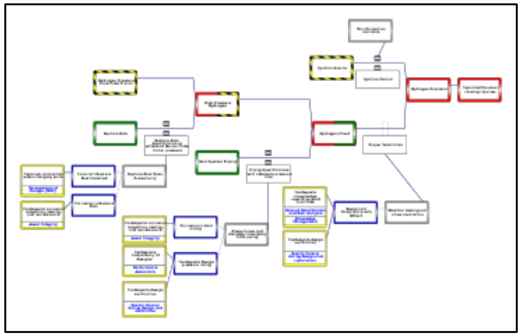
Evaluating the risk trade-offs of pressure relief devices in hydrogen systems

Pressure Relief Valves

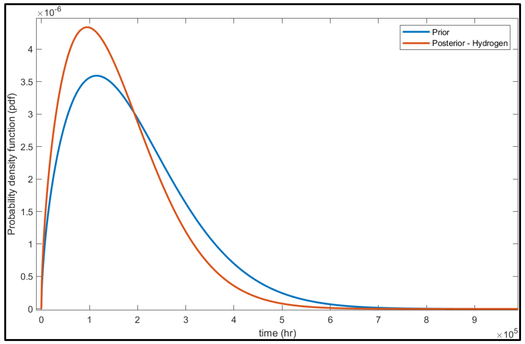
Burst or Rupture Disc

Objective: Define a probabilistic failure model for pressure relief devices (PRD) installed in hydrogen services to assess the risk trade-off they provide.

Establish risk management needs by identifying PRD incidents



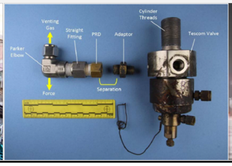
Define probabilistic failure models for PRDs installs on hydrogen systems



Assess the risk provided by PRDs in fueling station and evaluate trade-offs

- Previous studies have shown that PRDs do not receive the attention they need in regard to risk.
- Hydrogen introduces new challenges, and there are no models to evaluate the risk of PRDs






Implications & Impact:

- First of its kind in analyzing PRD risk profile, allowing the balance between risk control vs risk provided
- Inform industry and stakeholders about **risks and mitigation options** for PRDs
- Inform Code & Standards Committees on when to use PRDs as risk control mechanism.

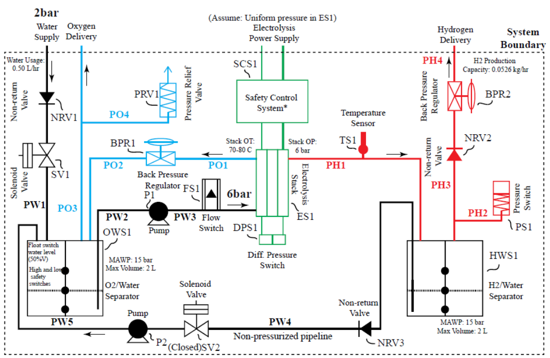
A. Jimenez and K. M. Groth, "Hazards Associated with Pressure Relief Devices in Hydrogen Systems," *Journal of Loss Prevention in the Process Industries*, vol. 91, p. 105380, Oct. 2024.

Early insights from QRA on H2 electrolyzers

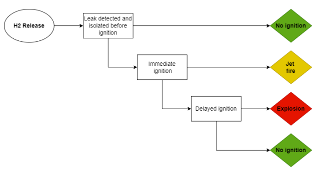
SYRRA

Objective: *Conduct QRA for an electrolyzer system to inform hydrogen technology development and QRA development to support hydrogen risk mitigation measures. In addition, the project seeks to identify input data gaps for hydrogen system QRA and any additional R&D needs in this topical area.*

Lab-scale PEM electrolysis system

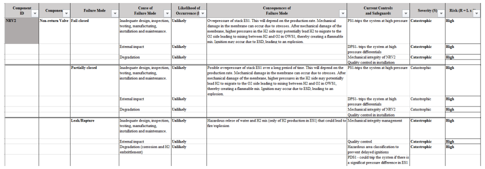


Event sequences



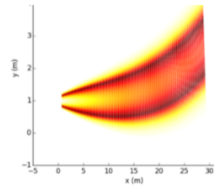
- For an H_2 release, **jet fires are twice as likely to occur vs. explosions**.
- The most risk-significant events for H_2 releases are:
  - **External** and **internal leakage** of hydrogen in **hydrogen-water separator**
  - **Flow restrictions** of the **non-return and solenoid valves** connecting the two gas-water separators
  - **External leakage** of hydrogen from **non-return valve, backpressure regulator,** and **piping** in H_2 production

FMEA



- **Water supply and separation** is the **highest contributor** to # of high-risk **scenarios** leading to an $\mathbf{H_2}$ **release**.
- **Electrolysis and $\mathbf{O_2}$ production contribute** to nearly **60%** of # of high-risk **scenarios** leading to $\mathbf{H_2}$**-**$\mathbf{O_2}$ **mixing**.

Release & flame simulations



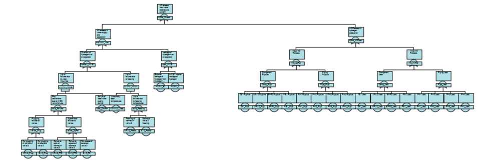
HyRAM HYDROGEN RISK ASSESSMENT MODELS

$$Pr_{thermal\ harm} = 2.56 \times 10^{-22}$$
$$Pr_{overpressure\ harm} = 0.95$$

Scenario Analysis & Total risk (FAR, AIR)

	AIR (fatalities/ electrolyzer-year-operator)	FAR (fatalities/ 100E+6 hours-operator)	Expected fatalities/year
Major H2 release leading to a jet fire	1.14×10^{-26}	2.82×10^{-22}	6.25×10^{-25}
Major H2 release leading to an explosion	2.03×10^{-5}	5.09×10^{-1}	1.12×10^{-3}
Total	2.03×10^{-5}	5.09×10^{-1}	1.12×10^{-3}

FT analysis



- In terms of frequency, $\mathbf{H_2}$**-**$\mathbf{O_2}$ **mixing is the most frequently-occurring top event** in electrolyzer operations (between a H_2 release, O_2 release, and H_2-O_2 mixing)

Importance measures analysis

Fault Tree ID	Description	I_{RRW}
HWS1_EL	External leak of hydrogen from hydrogen-water separator	3.62
HWS1_IL	Internal leak of hydrogen from hydrogen-water separator	1.36
SV2_Plug	Solenoid valve 2 plugged	1.00
SV2_FTO	Solenoid valve 2 fails to open	1.00
SV2_FC	Solenoid valve 2 fails closed	1.00

Early QRA results for electrolyzers show the importance of:

- **Mechanical integrity** and leak detection for electrolyzer stack, gas-water separators and valves
- **Preventing** freezing, plugging (flow blockage) in valves in H2-Water separation
- Increased interior volume and/or venting of H2 from the enclosure of the system

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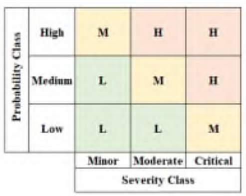
S. E. Wismer, A. Jimenez, A. Al-Douri, V. Grabovetska, and K. M. Groth, "PEM Electrolyzer Failure Scenarios Identified by Failure Modes and Effects Analysis (FMEA)," IJHE, Nov 2024.

Quantitative Risk Assessment of the Safety and Reliability of Proton Exchange Membrane Electrolysis for Hydrogen Production at Nuclear Power Plants

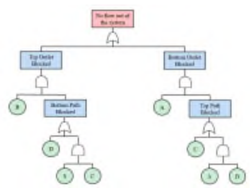
SYRRA

Objective:
Establish technical foundations and processes for assessing the safety of hydrogen production in nuclear power plant (NPP) applications by conducting and documenting a comprehensive QRA on a proton exchange membrane (PEM) electrolysis facility coupled to a NPP.

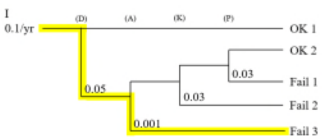
Task 1:
Conduct a **failure modes and effects analysis** on the PEM electrolyzer



Task 2:
Develop **fault trees** by functional group for risk critical scenarios



Task 3:
Create **event sequence diagrams** to model undesired consequences



Task 4:
Simulate and incorporate **consequence simulations** into ESDs

HyRAM
HYDROGEN RISK ASSESSMENT MODELS

Expected Results:
- **Fully documented QRA** for the safety and reliability of the PEM electrolyzer coupled to the NPP
- **Identification of the most risk significant components** from the PEM electrolyzer design
- Risk informed PEM electrolyzer **design and layout recommendations**

Impact:
- Ensure that siting the nuclear and hydrogen facilities together does not impose undue risk **through making early stage design and layout recommendations**
- Enable a **transition to decarbonized nuclear hydrogen production**, at scale, to support transportation, industrial manufacturing, and energy storage

NEUP Nuclear Energy University Program
U.S. Department of Energy

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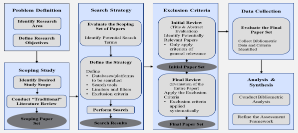
School of Engineering

Cryogenic pump reliability project: Objective & Motivation

- ***Objective***: *Develop mechanistic & computational understanding of the failure modes, behaviors, and mechanisms for cryogenic pumps and develop reliability models and methods to predict when these events will occur.*

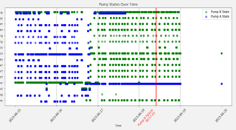
Data gathering and evaluation



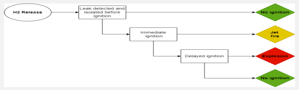
Available studies

Site Name	Site-01 Baltimore-MD	Site-02 Cocoa-FL	Site-03 Burlington-NJ	Site-04 Olney- IL	Site-05 Visalia-CA	Site-06 Perris-CA	Site-07 Dallas- TX	Site-08 Jefferson-MI
Observation Period	06/15/2023 – 6/21/2023 (7 days)	11/10/2023 – 12/04/2023 (25 days)	08/21/2023 – 12/19/2023 (140 days)	01/01/2023 – 02/27/2024 (422 days)	08/20/2021 – 02/19/2024 (913 days)	01/01/2023 – 02/29/2024 (424 days)	01/01/2023 – 02/29/2024 (424 days)	01/01/2023 – 02/29/2024 (424 days)
Period completeness	99.97%	99.92%	99.97%	92.83%	96.11%	82.53%	87.06%	90.84%
Sampling Rate	2 seconds	2 seconds	2 seconds	180 seconds	2 second	180 seconds	180 seconds	180 seconds
Dataset Dimensions (rows)	277,937	923,787	5,501,264	195,013	34,742,624	178,599	171,461	186,133
Size (Preprocessed)	3.7 MB	12.4 MB	68.3 MB	5.8 MB	400 MB	3.8 MB	4.4 MB	4.2 MB
Hours under cavitation	Pump A: 1.22 Pump B: 0	Pump A: 26.76 Pump B: 4.77	Pump A: 31.04 Pump B: 10.43	Pump A: 13.2 Pump B: 7.1	Pump A: 90.05 Pump B: 79.48	Pump A: 0 Pump B: 0	Pump A: 309.17 Pump B: 85.8	Pump A: 40.13 Pump B: 0
Preprocessing Status	Finished	Finished	Finished	Finished	Finished	Finished	Finished	Finished

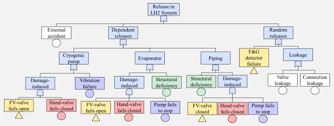
Activity logs



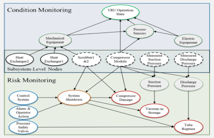
Data analysis



Event sequence diagram

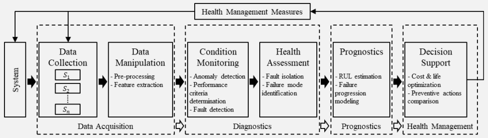


Fault tree

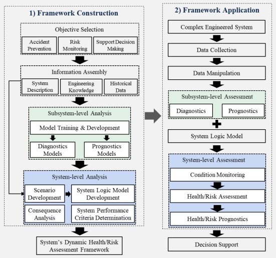


Bayesian network

Model development and reliability analysis



PHM model



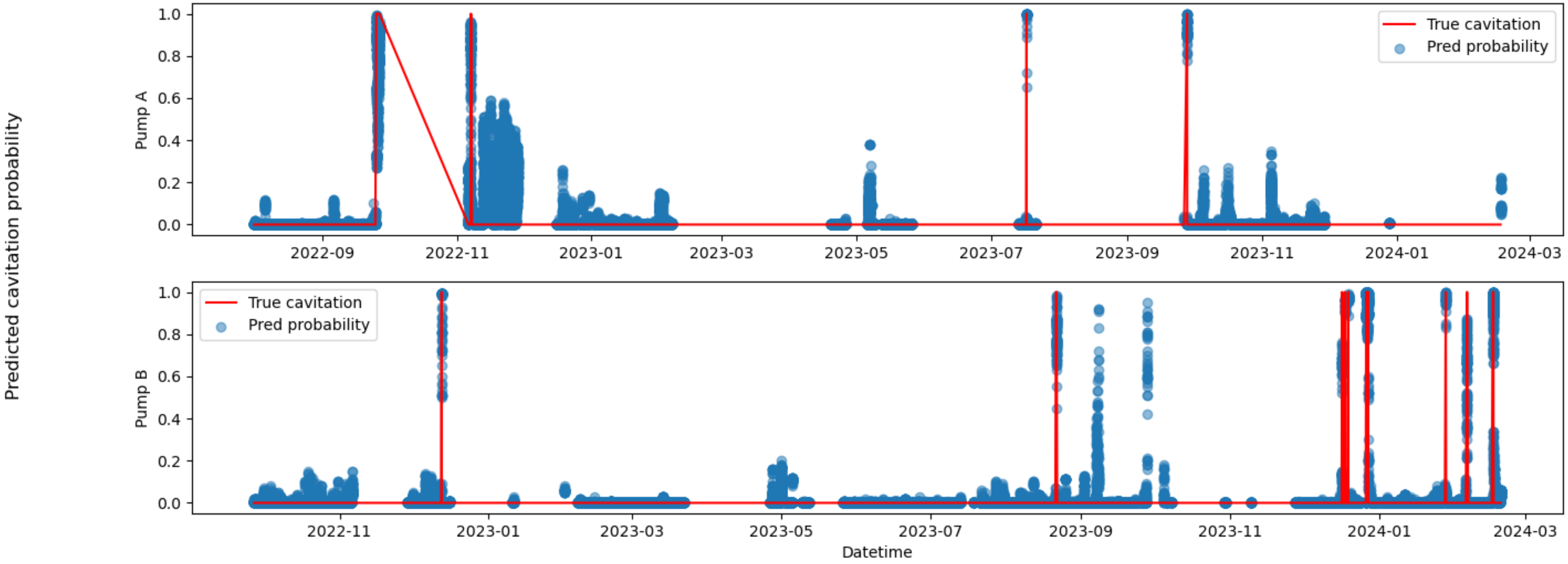
SIPPRA model

Advanced monitoring and maintenance practices

[Plug hydrogen storage and handling facility](#)

Cavitation data-driven machine learning model

Developed data-driven model for predicting cavitation from 3+ years of data with a handful of cavitation events



- Model is uncovering cavitation events that were undetected
- Cavitation events can be detected minutes earlier than previous algorithm
- This analysis uncovered a timing mismatch in maintenance records -- customer is correcting the record reporting.

A methodology for Risk and Reliability Prognostics applied to Hydrogen Fueling Stations

Research objective: Create a framework for system-level health state and risk prognostics on energy systems by fusing system understanding, causal logic and process data

Methods

Health state modeling for the components of the system

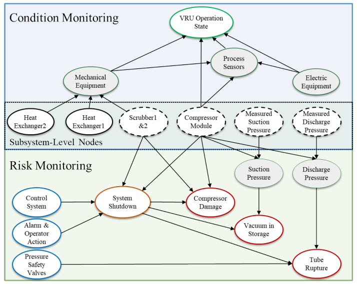
+

Causal modeling of risk-relevant events

+

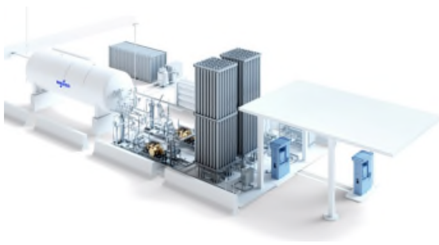
System understanding and logic modeling

SIPPRA: Systematic Integration of PHM and PRA framework for diagnosis and prognostics



Case study & Data

Hydrogen fueling stations



- +2 years of process data and maintenance records
- System design & documentation

Results

Computational and mathematical architecture

+

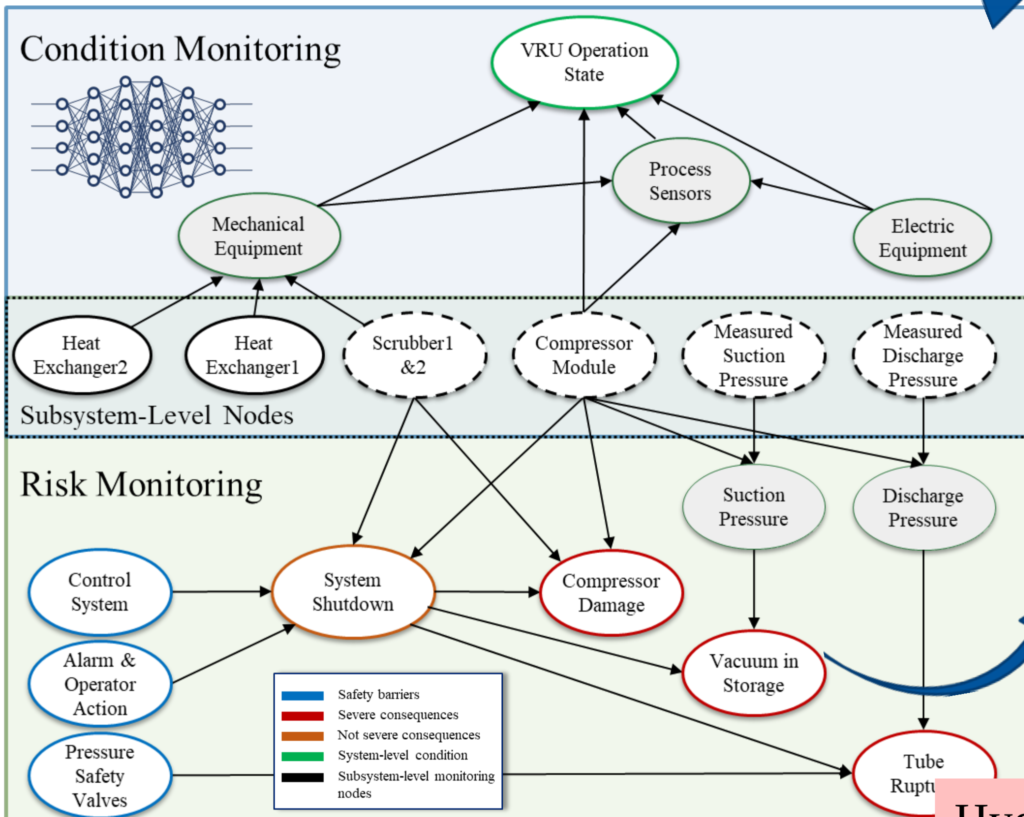
Develop SIPPRA as a software package and integrate into control system

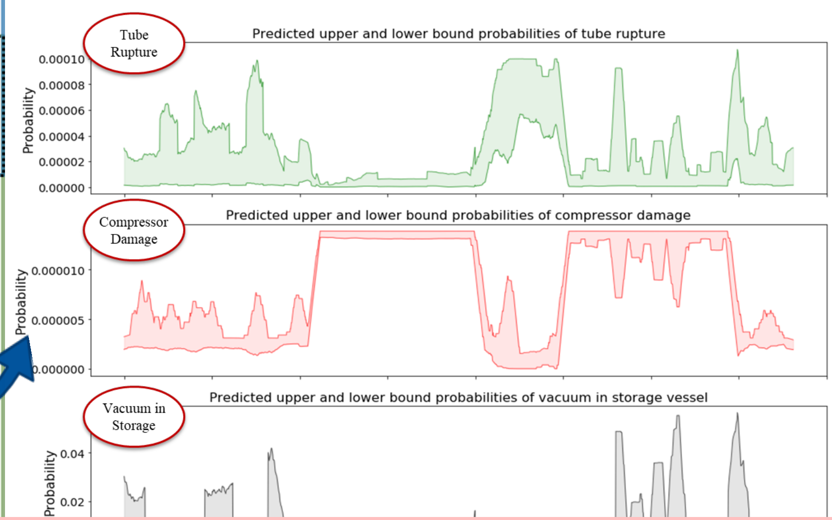
↓

Online system monitoring

This methodology will monitor system risk and estimate remaining useful life (RUL) of critical components, enabling more reliable operation and efficient maintenance planning

SIPPRA Example: day-to-day operations – risk monitoring of an oil & gas vapor recovery unit





Hydrogen system case study coming soon

Our new methods can dynamically monitor the risk of complex engineering systems

Moradi, Ramin, Sergio Cofre-Martel, Enrique Lopez Droguett, Mohammad Modarres, and Katrina M. Groth. "Integration of deep learning and Bayesian networks for condition and operation risk monitoring of complex engineering systems." Reliability Engineering & System Safety 222 (2022): 108433.

Research defining a Hydrogen Component Reliability Database (HyCReD)

Evaluated existing H2 safety data collection tools

	Data Type	H2Tools	NREL CDPs	HIAD	CHS Failure Rate Data
Event and failure characterization	Initiating event (description)	✓	✓	✓	×
	Location within system	×	✓	O	×
	Failure mode	×	×	×	×
	Failure mechanism	×	×	×	×
	Failure root cause	✓	✓	✓	×
	Release size	×	O	✓	✓
	Incident severity	✓	✓	✓	✓
	Consequences	O	✓	✓	O
	System response (Mitigation)	×	×	×	O
	H2 accumulation	×	×	×	×
	H2 detection	×	×	×	O
Life/usage	Component life	×	×	×	×
	Operations	×	✓	×	O
	Maintenance	×	✓	×	O
	Site inventory	×	✓	×	O
Data scope	Public access to data	✓	×	✓	?
	Scope includes any H2 incident	✓	×	✓	✓
	Regular reporting	×	✓	×	✓
	Anonymous data presentation	✓	✓	✓	✓
	Data quality checks	×	✓	×	?
	Process documentation	×	×	O	×

Defined requirements for HyCReD

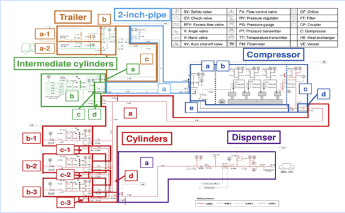
Characteristics
- Design for usability
- Publicly available
- Regular reporting
- Anonymity
- Quality assurance
- Regular updating
- Process documentation

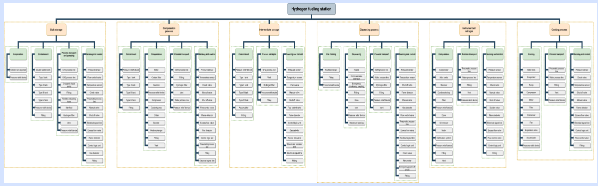
Static data
- Component location
- Operating condition
- Component life
- Number of like components

Failure event data
- Narrative event description
- Failure mode
- Failure mechanism
- Root cause
- Release location & size
- Hydrogen accumulation
- Detection
- Isolation
- Consequence
- Severity

Maintenance event data
- Type of maintenance
- Maintenance action performed
- Active repair time
- Manhours

Developed system-specific H2 fueling station decomposition





Defined hydrogen-specific component failure modes

Failure Mode	Definition
Abnormal output-high	Above normal output indicates potential failure(s)
Abnormal output-low	Below normal output indicates potential failure(s)
Bent/warped/damaged	Visible damage
Contamination	Component allows foreign material to contaminate product
Drift	Erroneous reading due to lack of calibration
Erratic output	Inconsistent output
External leak hydrogen	Hydrogen leak from within system to environment
External leak utility medium	Utility medium leak from the system to the environment
External rupture hydrogen	Complete loss of containment, hydrogen exhausts to the environment
External rupture utility medium	Complete loss of utility medium to the environment
Fail closed	Component stops working in the closed position
Fail open	Component stops working in the open position
Fail to close	Component does not close on demand
Fail to disconnect	Components meant to disconnect does not do so on demand
Fail to evaporate	Hydrogen remains in liquid form after passing through evaporator
Fail to operate	Component does not function on demand
Fail to stop	Component does not stop on demand
Freezing	Component is frozen and becomes inoperable/requires maintenance
Insufficient heat transfer	Target parameters for temperature are not met in a heat exchanger
Internal leak hydrogen	Hydrogen leak within system boundary (e.g. across a closed valve)
Internal leak utility medium	Utility medium leak within system boundary (e.g. across a closed valve)
Internal rupture hydrogen	Complete loss of containment, hydrogen stays within the system boundary
Internal rupture utility medium	Complete loss of containment, utility medium stays within the system boundary
Open circuit	Electrical circuit that is not complete
Overheating	Component is exposed to temperatures above design specifications
Overspeed	Component operates above desired/specified speed
Plugging	Buildup of material restricting flow
Restrict flow	Component is restricting flow when not intended to do so
Short circuit	Diversion of current
Spurious operation	Activation without specified demand (components normally idle)
Spurious stop	Stop without specified demand (components normally active)
Stuck connection	Component is stuck at point of contact (nozzle)
Underspeed	Component operates below desired/specified speed

Developed & validated HyCReD structure

- **Static data fields**

Event Number	Station/Facility Identification	Facility Type	Service/Usage	Nominal Working Pressure	H2 phases on site
25	A	Commercial, public	Heavy-duty	700 bar	Gas
26	B	Research, limited-access	Both heavy- and light-duty	350 bar	Gas

Event Number	Equipment Description	Subsystem	Functional Group	Component	Component Nominal Working Pressure	Component Population	P&ID Part Number
25		Bulk storage	Containment	Type III tank	250-300 bar	18	TK-103
26		Compression process	Compression	Compressor	400-680 bar	2	CO-E-49A

- **Failure event data fields**

Event Number	Time & Date of Failure	Failure Mode	Failure Severity	Failure Mechanism	Failure Root Cause Description	Hydrogen Release (Yes/No)	Release Size (Small/ Medium/Large)	Ignition (Yes/No)
25	07/17/2021 08:32	External leakage-Process medium	Critical	Leakage		Yes	Medium	No
26	10/17/2021 15:33	Parameter deviation	Degraded	Overheating		No	Small	No

- **Maintenance event data fields**

Date & Time Repair Started	Date & Time Repair Completed	Date & Time Station Restarted	Action Performed	Maintenance Description
07/18/2021 09:55	07/28/2021 10:00	07/29/2021 09:30	Replacement	
10/17/2021 17:30	10/20/2021 13:30	10/20/2021 15:30	Repair	

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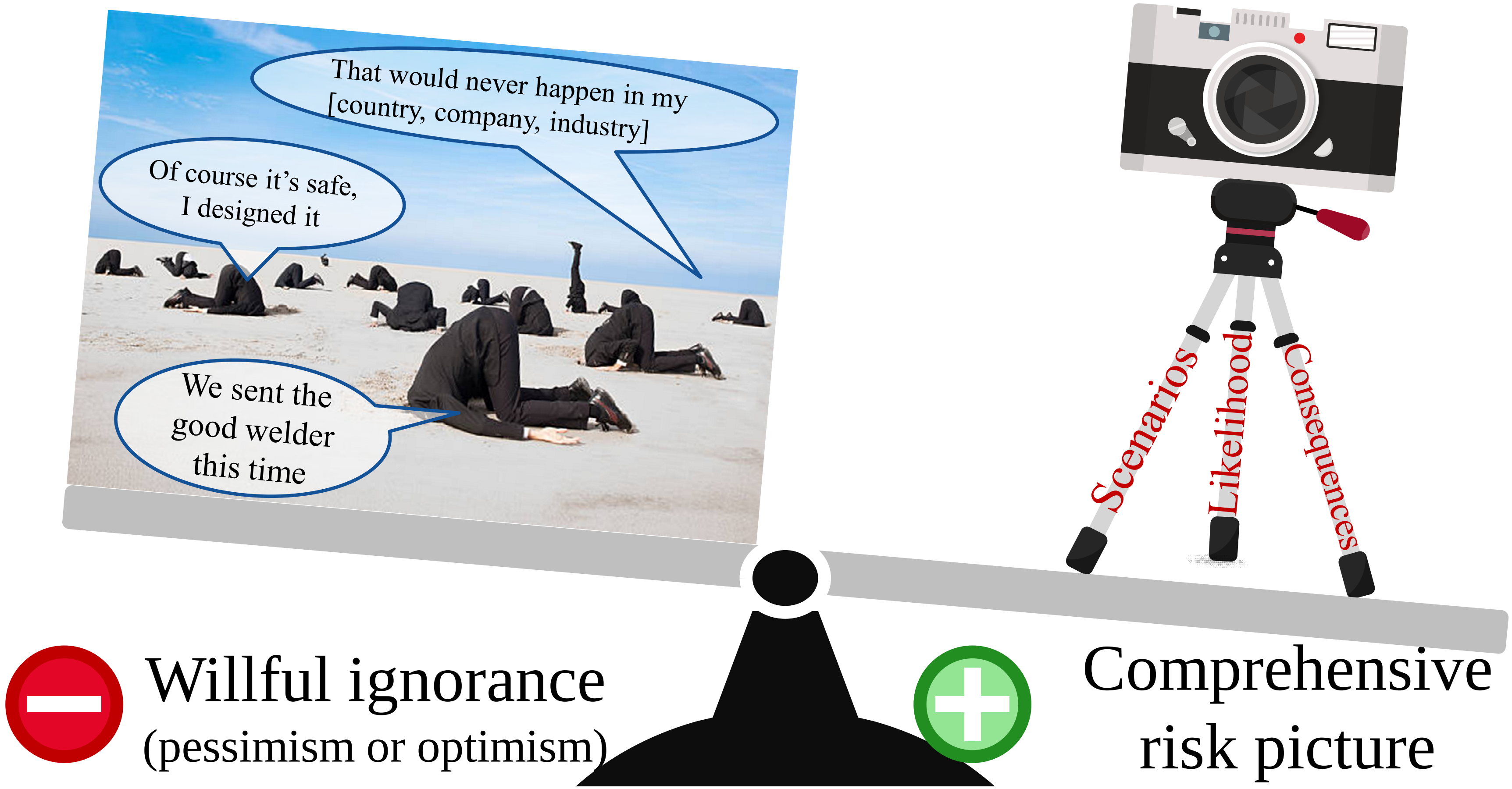
NREL NATIONAL RENEWABLE ENERGY LABORATORY

K.M. Groth, A. Al-Douri, M. West, K. Hartmann, G. Saur, W. Buttner. "Design and Requirements of a Hydrogen Component Reliability Database (HyCReD)," *International Journal of Hydrogen Energy*, 51D, pp. 1023–1037.

“Failures are the accidental experiments that contribute to the engineer’s experience…. Finding the true causes of failure often takes as much of a leap of the analytical imagination as original design concepts.”

-- Henry Petroski, *To Engineer Is Human: The Role of Failure in Successful Design*, 1992.

Principles: Why QRA?



Key takeaways & Closing thoughts

- Systems must be engineered for safety & reliability
- QRA & Process Safety *enable* hydrogen system safety
  - Need to scale-up QRA analysis as the industry matures to enable mitigation of early design/deployment issues
  - Opportunities to partner – what can we do together to advance the state of knowledge?

Advances in risk analysis & reliability engineering for hydrogen systems will continue to drive the industry forward

Acknowledgements – SyRRA Lab Members & Sponsors

SYRRA

NSF

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Office of Naval Research
ONR
Science & Technology

PHMSA
Pipeline and Hazardous Materials Safety Administration

plug™

GTI ENERGY

LCRI
LOW-CARBON RESOURCES INITIATIVE

EPRI
ELECTRIC POWER RESEARCH INSTITUTE

Department of Energy, United States of America

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

INL Idaho National Laboratory

SLAC NATIONAL ACCELERATOR LABORATORY

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BAM

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ASME
SETTING THE STANDARD

Research supported by multiple sources. The views expressed herein are those of the authors and do not reflect the official policy or position of any sponsor.

Thank you!

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Reliability Engineering
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Active research is supported by multiple sponsors.

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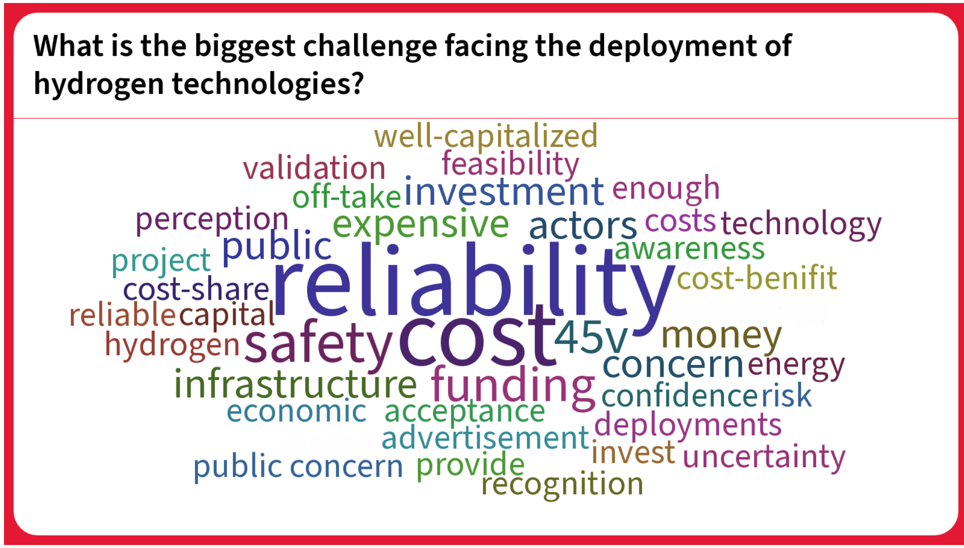
Center for Risk and Reliability



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