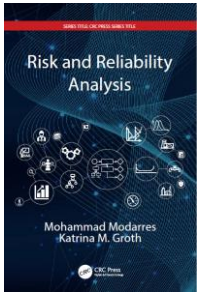

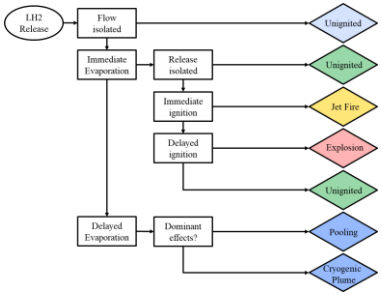

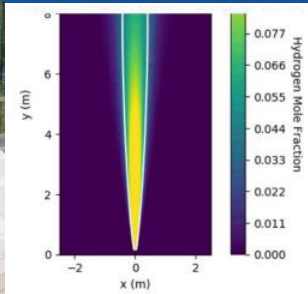

Enabling safety and reliability in hydrogen systems through reliability and risk analysis

Katrina Groth (kgroth@umd.edu)
Professor & Director, Reliability Engineering
Associate Director for Research, Center for Risk and Reliability
University of Maryland

HySchool
April 2026

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.

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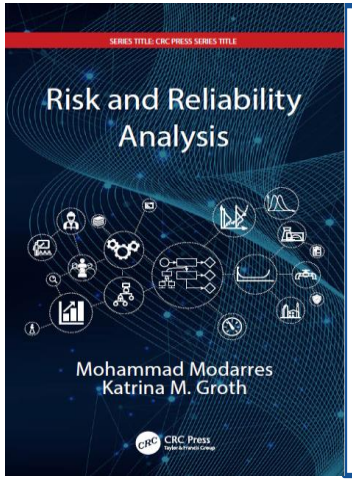
Fast Facts about UMD's Reliability Engineering program & Center for Risk and Reliability

16
Core, and Affiliate Faculty

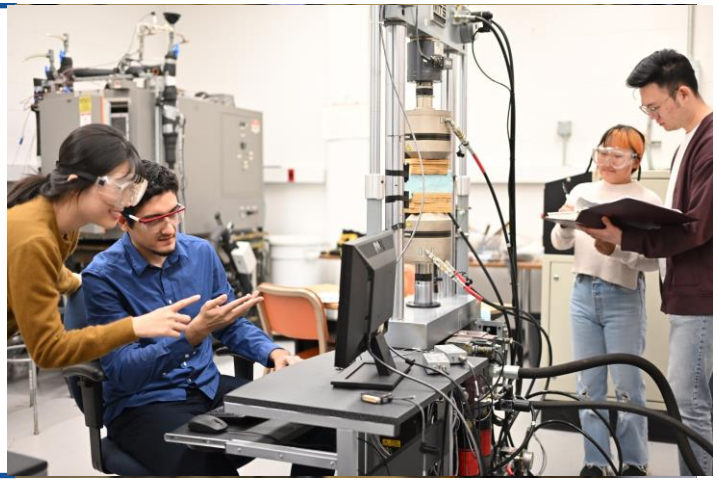
6
Cutting-Edge Research Laboratories

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)

Ph.D. & Postdoc openings for Fall 2026

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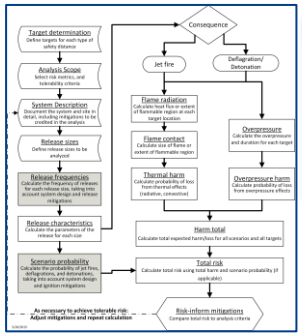
Selected projects: 15 years of enabling safer hydrogen equipment & pipeline deployments

SYRRA

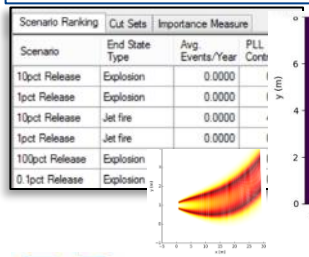
2010-2014

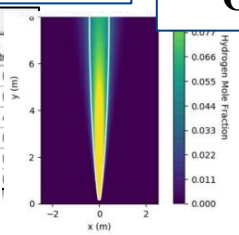
- QRA for H2 indoor fueling for NFPA 2
- QRA for H2 separation distances in NFPA 2
- HyRAM algorithm



2015

- ISO 19880-1 incorporates QRA and HyRAM for safety distances & more
- Public release of HyRAM 1.0





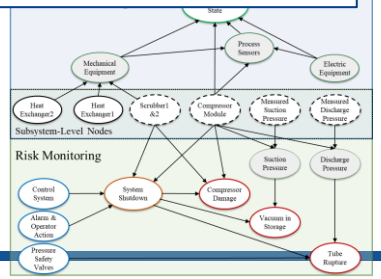
HYRAM
HYDROGEN RISK ASSESSMENT MODELS

2017

- Pipeline corrosion model

2019

- LH2 On-site storage QRA
- H2 Storage Risk & Reliability Gap Study
- SIPPRA algorithms

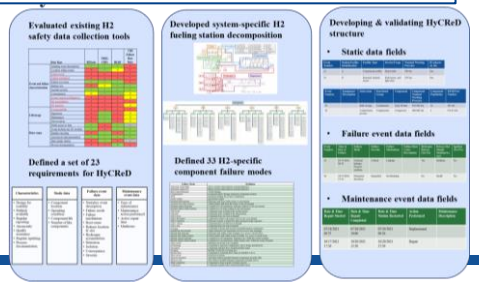


2021

- BaNTERA pipeline excavation damage model
- PHM & QRA Data requirements for LH2 storage

2023

- H2FC Forklift QRA
- LH2 fueling station QRA
- HyCReD fueling reliability data collection framework



2025

- PEM & SOEC Electrolyzer QRAs
- PRD hazard and risks study

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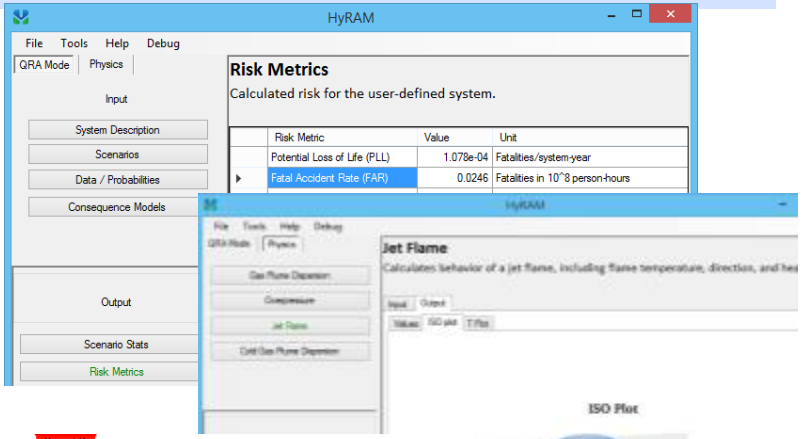
HyRAM+: Making hydrogen safety science accessible through computational tools

Sandia National Laboratories

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**

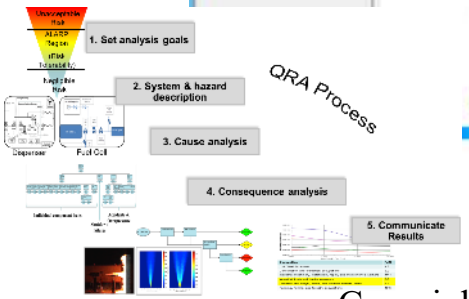


Core functionality:

- 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



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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

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Now we have the technology, but we have a big problem: reliability

Los Angeles Times

CLIMATE & ENVIRONMENT

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

U.S.A, 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.

U.S.A, Nov. 2024

H_2

Widespread Breakdowns Cripple Hydrogen Stations in South Korea

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

Listen 3:03

South Korea, September 2024

2024 UMD Workshop Result: Key challenges facing the deployment of hydrogen technologies

What is the biggest challenge facing the deployment of hydrogen technologies?

K. M. Groth, L. M. Reising, V. Grabovetska, and A. Ruiz, "Hydrogen Systems Risk and Reliability Challenges, Priorities, and Workshop Insights," *Hydrogen Safety*, 2(1).

A methodology for prognostics & risk monitoring for 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

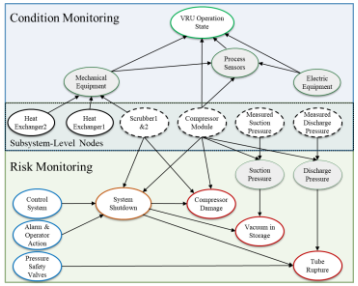
+

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

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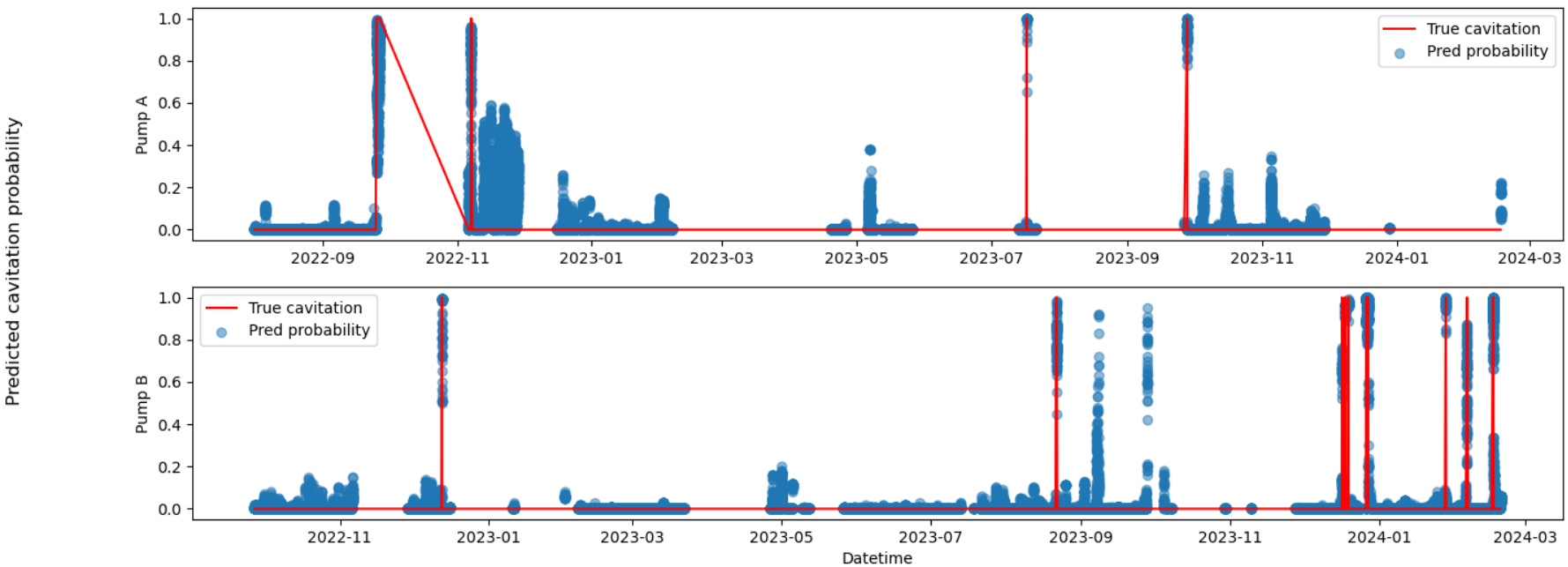
Cavitation data-driven machine learning model

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.

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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	Static data	Failure event data	Maintenance event data
• Design for usability • Publicly available • Regular reporting • Anonymity • Quality assurance • Regular updating • Process documentation	• Component location • Operating condition • Component life • Number of like components	• Narrative event description • Failure mode • Failure mechanism • Root cause • Release location & size • Hydrogen accumulation • Detection • Isolation • Consequence • Severity	• Type of maintenance • Maintenance action performed • Active repair time • Manhours

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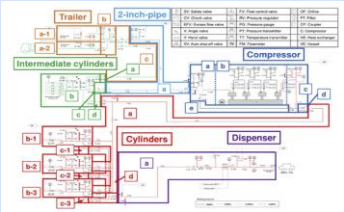
Developed system-specific H2 fueling station decomposition



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	

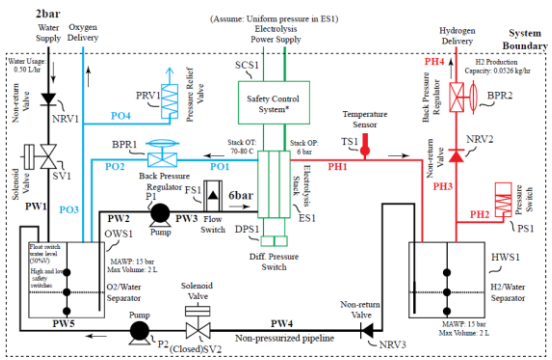
Active Research: Seeking data partners

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.

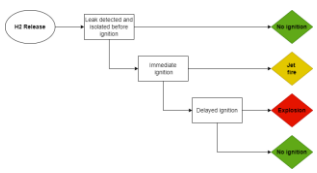
Early insights from QRA on H2 electrolyzers

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

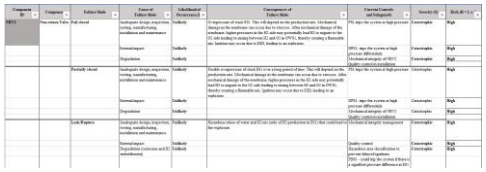


Event sequences



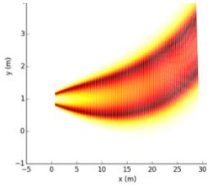
- For an H_2 release, **jet fires are twice as likely to occur vs. explosions**.
- The most risk-significant events for H_2 releases are:
  - **External** and **internal leakage** of hydrogen in **hydrogen-water separator**
  - **Flow restrictions** of the **non-return and solenoid valves** connecting 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 **H_2 release**.
- **Electrolysis and O_2 production contribute** to nearly **60%** of # of high-risk **scenarios** leading to **H_2-O_2 mixing**.

Release & flame simulations



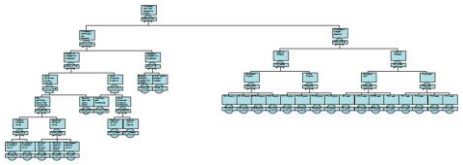
HyRAM
HYDROGEN RISK ASSESSMENT MODELS

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

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, **H_2-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

<u>Early QRA results for electrolyzers show the importance of:</u>

- **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.

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

Pressure Relief Valves

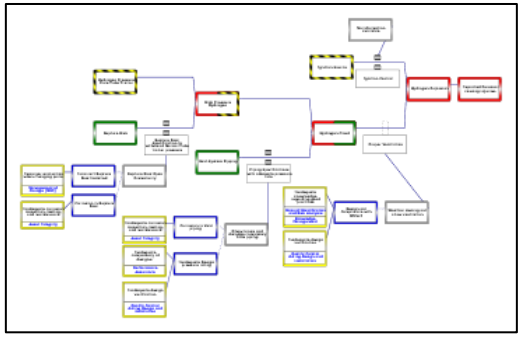
Burst or Rupture Disc

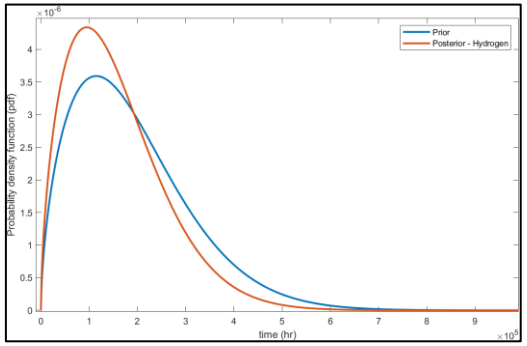
Objective: Define a probabilistic failure model for pressure relief devices (PRD) installed in hydrogen services to assess the risk trade-off they provide.

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.

Copyright, Katrina Groth, 2025

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.

A. Jimenez and K. M. Groth, "Evaluating the risk of pressure relief devices in hydrogen systems," *International Journal of Hydrogen Energy*, vol. 217, p. 153719, Mar. 2026.

Europe vs American Approach toward PRDs

USA

- 49 CFR Part 173, Subpart G
  - PRDs are need to follows CGA-S1.1
- CGA-S1.1 indicates that hydrogen tubes:
  - Single PRV (CG-7 or CG-11) at the end of the tube
  - Fusible trigger device (CG-10) at the end of the tube
  - Accept burst discs (CG-1, CG-4, CG-5) at either one or both ends

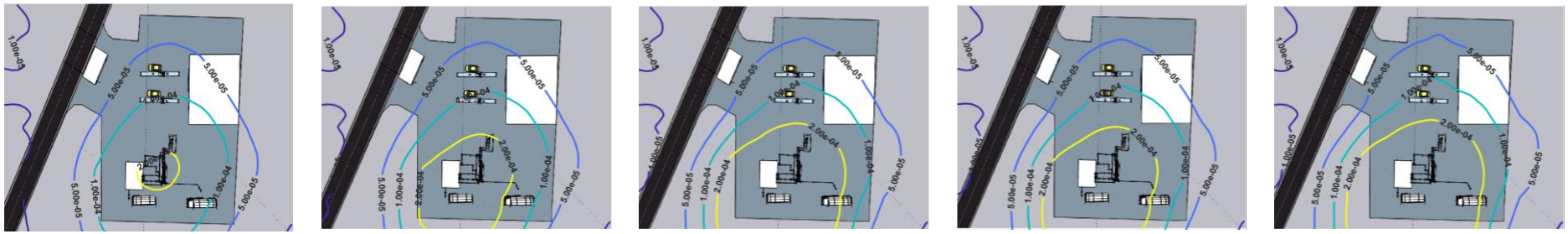
Europe

- European codes and standards does not require PRDs on any hydrogen transport
  - European Transportable Pressure Equipment Directive (TPED)
  - European transportable gas standard *EN 13807:2003 Transportable gas cylinders*
  - European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR)

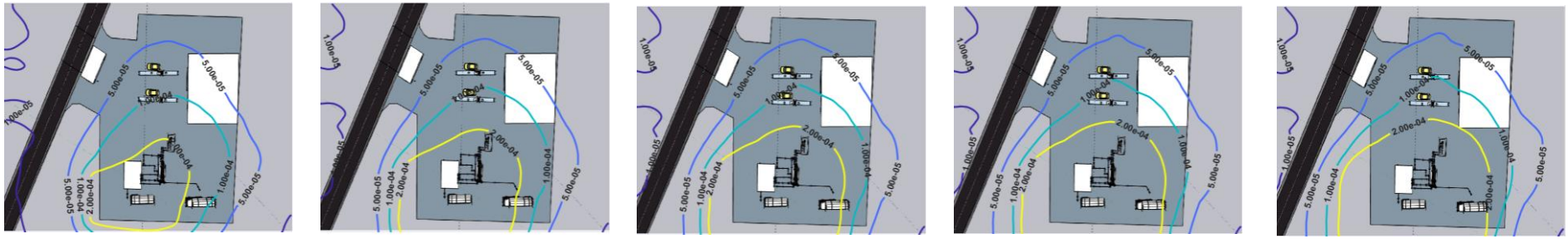
Results: Location Specific Individual Risk (LSIR)

Burst disc generates a larger contour near the tube trailer, indicating that a larger local risk is generated by burst discs in comparison with PRVs

Pressure Relief Valve (PRV)



Burst Disc



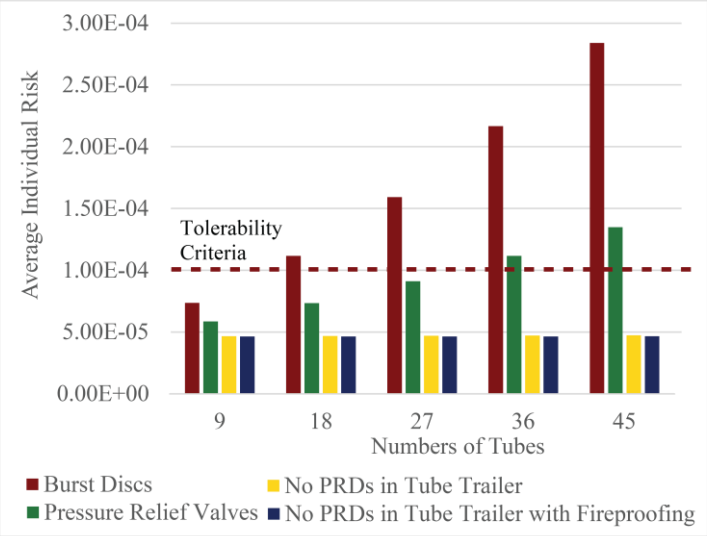
9 18 27 36 45

No. Tubes

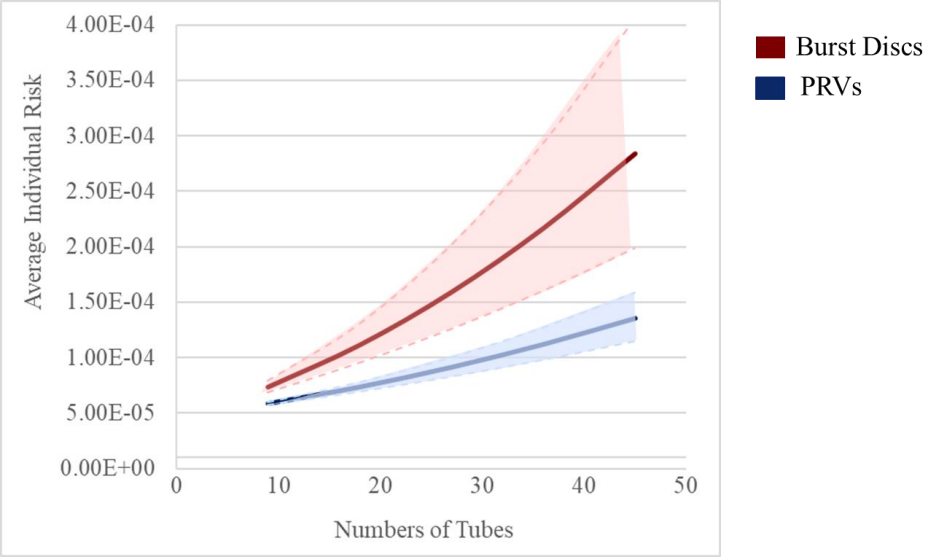
A. Jimenez and K. M. Groth, "Evaluating the risk of pressure relief devices in hydrogen systems," *International Journal of Hydrogen Energy*, vol. 217, p. 153719, Mar. 2026.

Results: PRVs Risk study suggests removing PRVs increases station safety

- Burst disc produces the highest risk in all cases, even exceeding the tolerability criteria in many cases.
- Cases without PRDs with the addition of thermal protection produced the lowest risk in each case, but the difference with cases with no PRDs without thermal protection only vary 2%



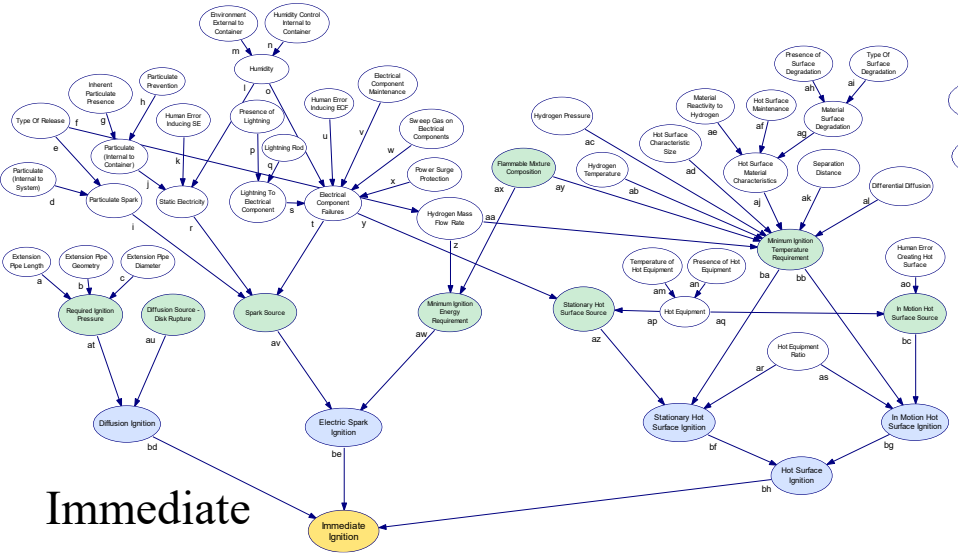
- There is a higher risk contributed by PRVs than their risk mitigation capability
- The European approach is a better solution from a risk perspective, as it produces lower risk than the American solution.

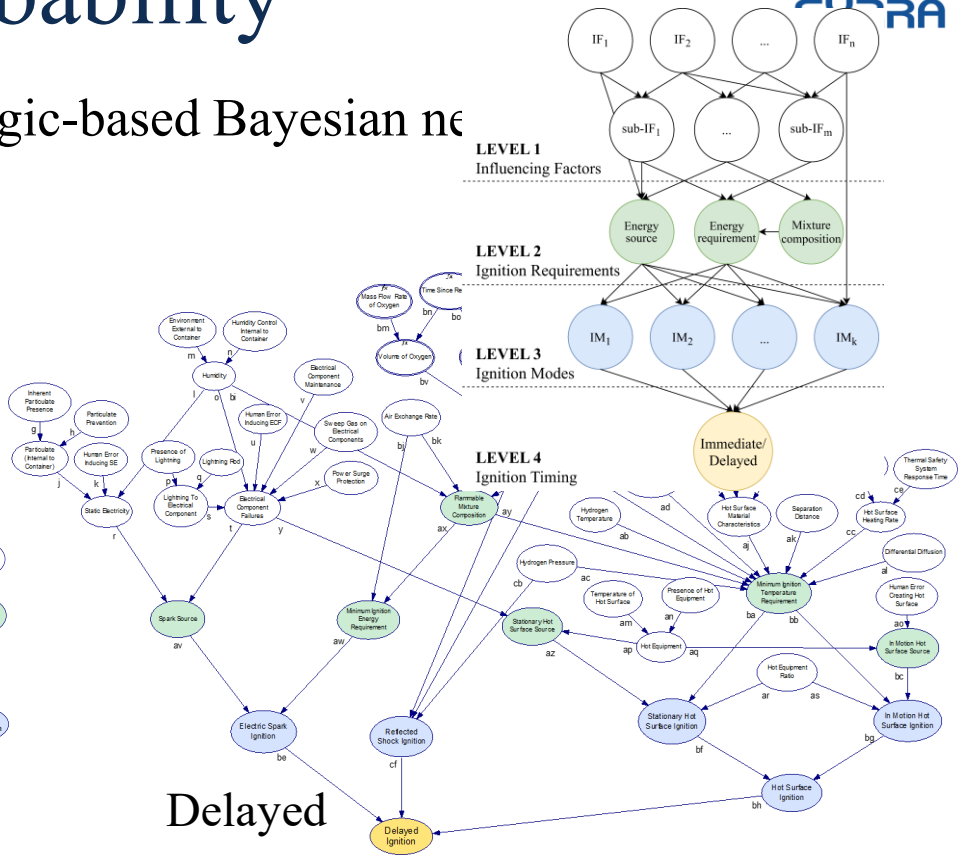


A. Jimenez and K. M. Groth, "Evaluating the risk of pressure relief devices in hydrogen systems," *International Journal of Hydrogen Energy*, vol. 217, p. 153719, Mar. 2026.

Bayesian Network for Modeling Hydrogen Ignition Probability

Research objective: Develop a causal logic-based Bayesian ne
calculating hydrogen ignition probability





Replaces overly simplified lookup tables to **consider the impact of varying conditions** internal to and surrounding the system to **make an informed estimate of ignition probability.**

Federica Tamburini, Samantha E. Wismer, Valerio Cozzani, and Katrina M. Groth, "Bayesian Network Model for Assessing Hydrogen Ignition Probability," *Reliability Engineering & System Safety*, p. 111959, Nov. 2025.

Ignition Probabilities of Case Studies

- These case studies illustrate:
  - The application of the model to generate immediate and delayed ignition probabilities for input into a QRA
  - The exploration of how design choices affect ignition probabilities
- Model validated through observed trends in changing ignition probability consistent with available experimental literature and the chemical and physical behavior

Case	Immediate		Delayed	
	Leak	Rupture	Leak	Rupture
Case 0 - Nominal	0.068	0.091	0.115	0.167
Case 1 - High Temperature Hot Surface	0.121	0.143	0.175	0.210
Case 2 - Internal and External Debris	0.071	0.115	0.117	0.168
Case 3 - Improper Maintenance	0.072	0.110	0.206	0.242
Case 4 - Poor Safety Design	0.074	0.108	0.304	0.336
Case 5 - Rupture Disk	-	0.803	-	-
Case 6 - Reflected Shock Ignition	-	-	-	0.205
Case 7 - Simultaneous Oxygen Release	-	-	0.118	0.172
Case 8 - Simultaneous Nitrogen Release	-	-	0.114	0.163
Case 9 - Human Presence	0.068	0.091	0.121	0.168
Case 10 - Human Error	0.104	0.124	0.186	0.236

Federica Tamburini, Samantha E. Wismer, Valerio Cozzani, and Katrina M. Groth, "Bayesian Network Model for Assessing Hydrogen Ignition Probability," *Reliability Engineering & System Safety*, p. 111959, Nov. 2025.

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

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Thank you!

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