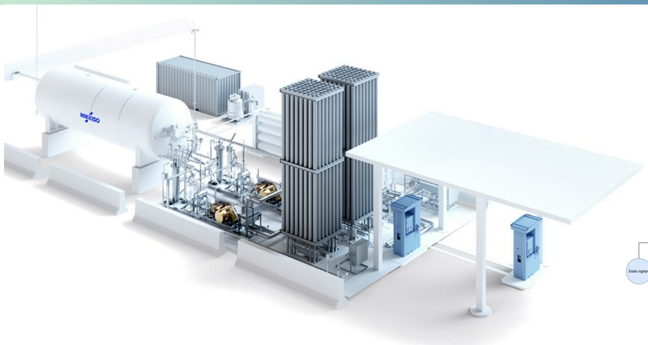

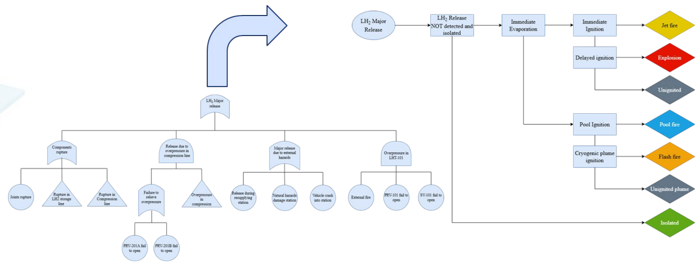

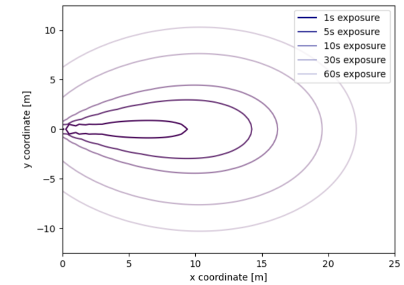

Quantitative Risk Assessment of hydrogen releases in a hydrogen fueling station with liquid hydrogen storage

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

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

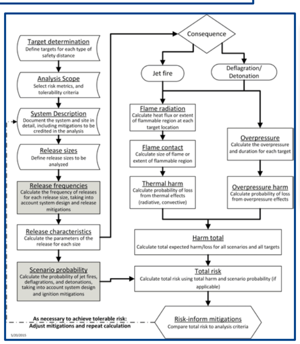
2017

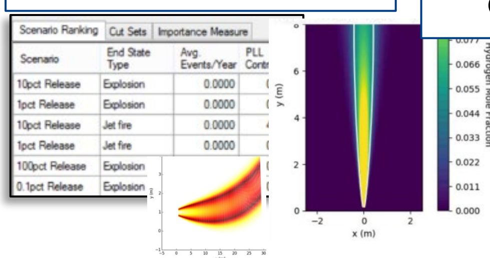
2019
- Pipeline corrosion model
- H2 Storage Risk & Reliability Gap Study

2021
- LH2 On-site storage QRA
- SIPPRA algorithms
- PHM & QRA Data requirements for LH2 storage
- BaNTERA pipeline excavation damage model
- H2FC Forklift QRA

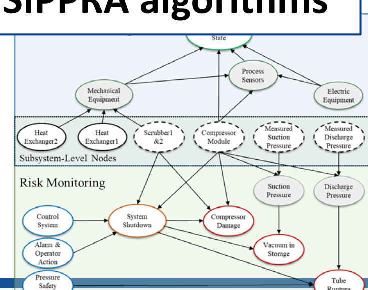
2023
- LH2 fueling station QRA
- HyCReD fueling reliability data collection framework

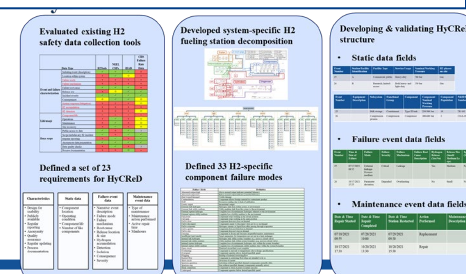
2025
- PEM Electrolyzer QRAs





HYRAM
HYDROGEN RISK ASSESSMENT MODELS





QRA on a Hydrogen fueling station with LH_2 storage

Objective: Identify risks of hydrogen releases in a fueling station with LH_2 storage through a QRA

- Systematic methodology developed for QRA of unintended hydrogen releases
- Minor and major releases of GH_2 and LH_2

System description and QRA scope

↓

Hazard identification

↓

Causal modeling of release events

↓

Model quantification

↓

Consequence characterization

↓

Harm analysis

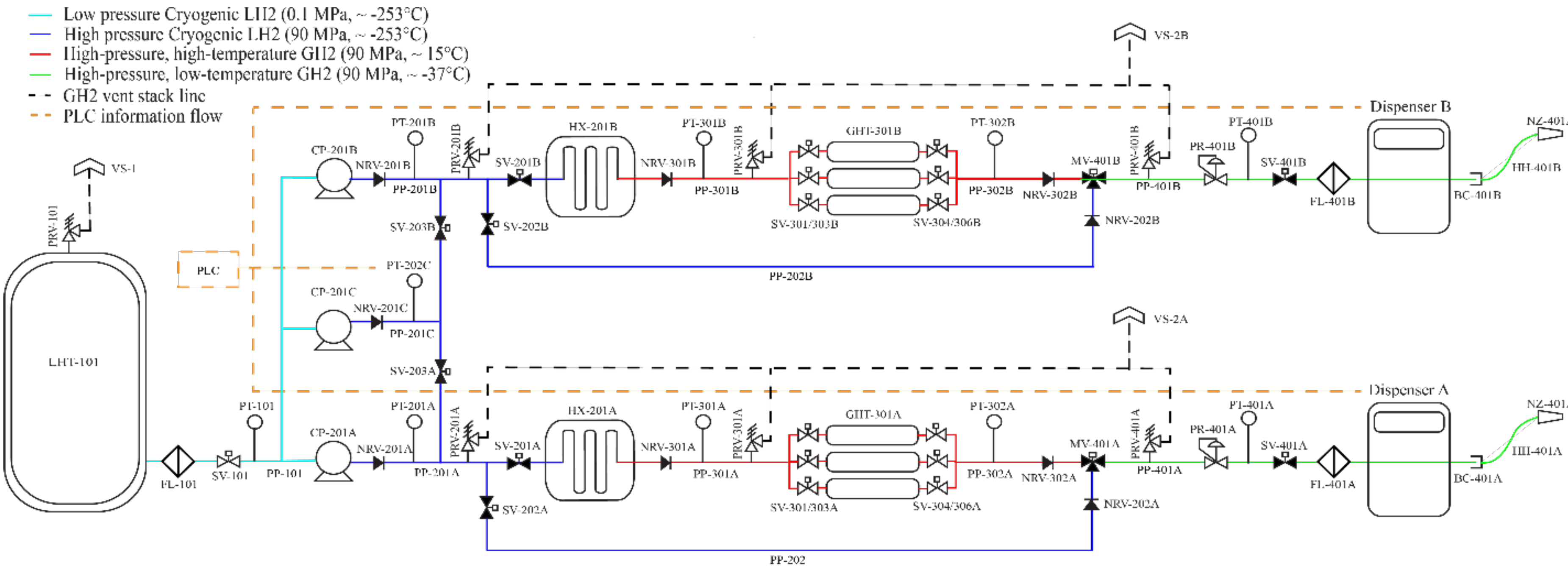
↓

Risk assessment

Mosleh, S., Schaad, C., Yang, R., & Groth, K. M. (2025). A methodology for quantitative risk assessment of a high-capacity hydrogen fueling station with liquid hydrogen storage. International Journal of Hydrogen Energy, 112, 544-553.

Example station defined for QRA

- High-capacity station with LH_2 storage



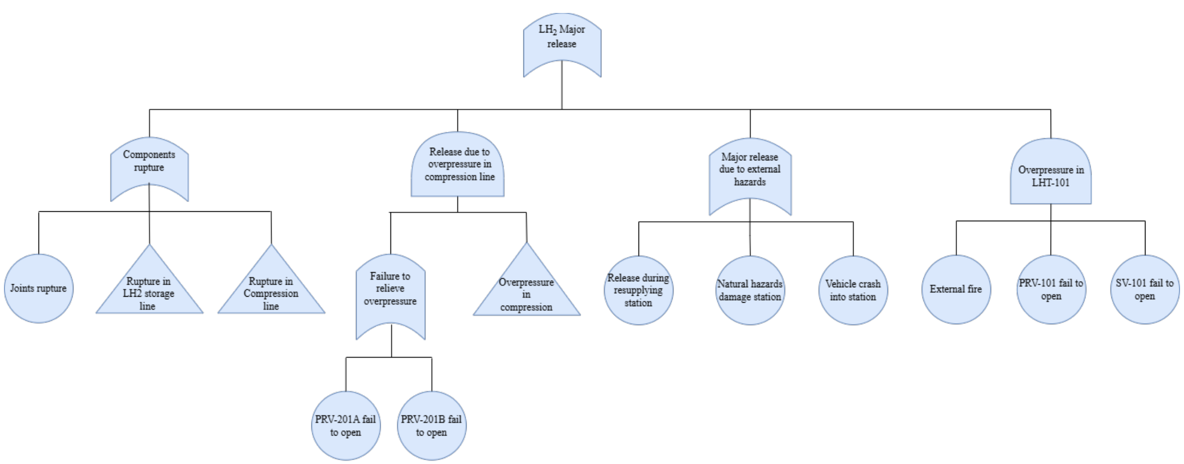
LH_2 storage → LH_2 compression and vaporization → GH_2 storage → GH_2 dispensing

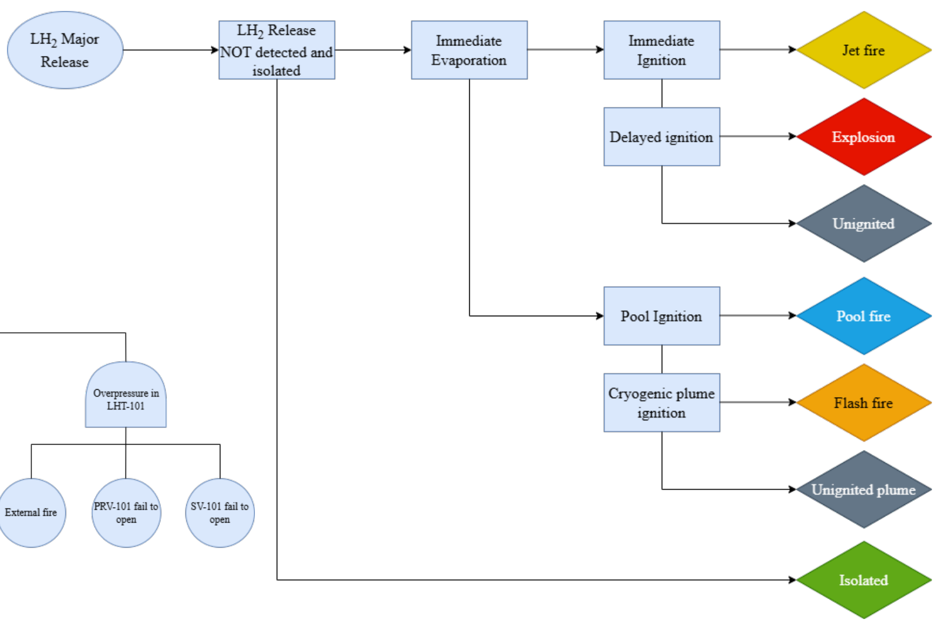
Mosleh, S., Schaad, C., Yang, R., & Groth, K. M. (2025). A methodology for quantitative risk assessment of a high-capacity hydrogen fueling station with liquid hydrogen storage. International Journal of Hydrogen Energy, 112, 544-553.

Method: Causal modeling of hydrogen release scenarios

Fault trees (FT) for pathways to hydrogen release event

Event sequence diagrams (ESD) from release event





Methods: Risk metrics and importance measures

- **Risk analysis metrics:**
  - Average Individual Risk (AIR) $$AIR = \sum_n \sum_j \left(f_{nj} \times c_{nj}\right)$$
  - Fatal Accident Rate (FAR) $$FAR = \frac{\sum_n \sum_j \left(f_{nj} \times c_{nj}\right) \cdot 10^8}{N_{pop} \cdot H}$$

f_{nj}: frequency of scenario
c_{nj}: consequence (fatalities) of scenario
N_{pop}: exposed population
H: annual exposure hours

- **Importance measure analysis:**
  - Risk reduction worth (RRW) is used to measure importance of events

$$I_i^{RRW} = \frac{F_s\left(Q(t)\right)}{F_s\left(Q(t) \mid Q_i(t) = 0\right)}$$

$F_s\left(Q(t)\right)$: system unreliability
$F_s\left(Q(t) \mid Q_i(t) = 0\right)$: system unreliability when event i is completely reliable

Data for parametrizing FT and ESD

Reliability data banks were used to quantify FT and ESD:

- **HyRAM** + (*Hydrogen Reliability Assessment Models*):
  - Release probabilities gaseous hydrogen components (piping, valves, tanks, etc.)
  - Hydrogen ignition probabilities
  - Dispensing failure events probabilities
- **PDS** data handbook (*Reliability data for safety equipment*):
  - PLC and sensor failures
- **OGP** (*Oil & Gas Producers*) 434:
  - Release probabilities for LH_2 filter, pump and vaporizer

- Sufficient release data for GH_2 components but noted lack of data for LH_2 components & non-leak failure modes of GH2 components.
- Oil & Gas data used as best approximate

Method: Consequence analysis

- **Consequence characterization**: estimation of thermal radiation and overpressure caused by hydrogen ignition scenarios
  - Physics-based simulation for GH_2 release and ignition
  - Empirical models used for LH_2 release magnitude and ignitions

HyRAM+
Hydrogen Plus Other Alternative Fuels Risk Assessment Models

Data processing and visualizations done with Python

- **Harm analysis**: estimation of human harm probability
  - Tsao & Perry model for thermal harm
  - Eisenberg lung damage model for overpressure harm

Results: frequency of hydrogen release scenarios

- Event sequence diagram results:

GH_2 Release scenario	Probability per year
	Major release
Isolated release	1.04×10^{-2}
Unignited release	1.47×10^{-4}
Jet fire	8.48×10^{-6}
Explosion	4.09×10^{-6}
Harmful scenarios (total)	1.26×10^{-5}

LH_2 Release scenario	Probability per year
	Major release
Isolated release	4.13×10^{-3}
Unignited release	6.36×10^{-5}
Unignited plume	7.01×10^{-6}
Jet fire	5.15×10^{-7}
Explosion	2.55×10^{-7}
Pool fire	7.15×10^{-8}
Flash fire	7.08×10^{-8}
Harmful scenarios (total)	9.13×10^{-7}

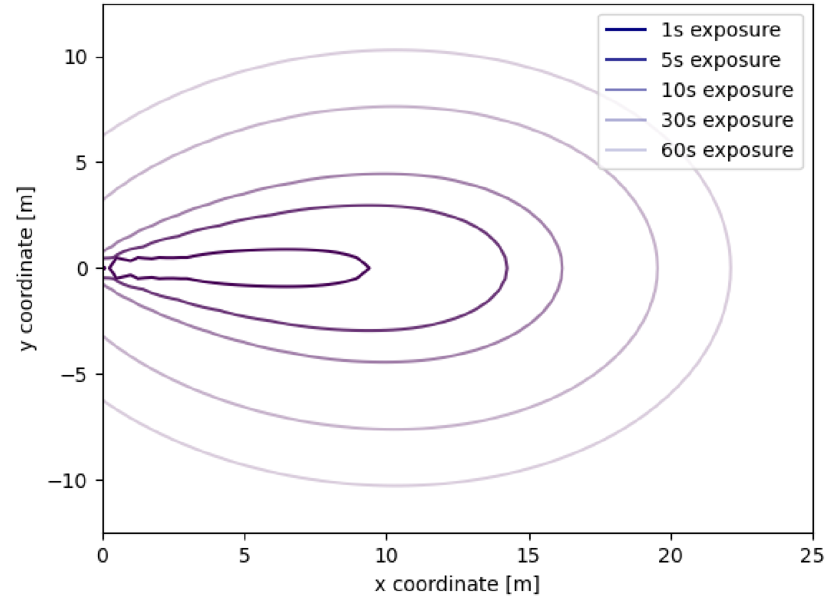
GH_2 ignition scenarios more probable than LH_2 ignition scenarios

Within ignition scenarios, a jet fire would be the most common

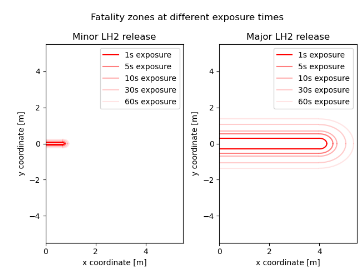
Schaad, C., Mosleh, S., Yang, R., & Groth, K. M. (2025). Quantitative Risk Assessment of hydrogen releases in a hydrogen fueling station with liquid hydrogen storage. International Journal of Hydrogen Energy, 112, 111-120.

Results: Consequence modeling (jet fires)

- Fatality zones of GH_2 jet fire:
  - GH_2 release flame length:
    - Minor release: 0.2 [m]
    - Major release: 18.6 [m]



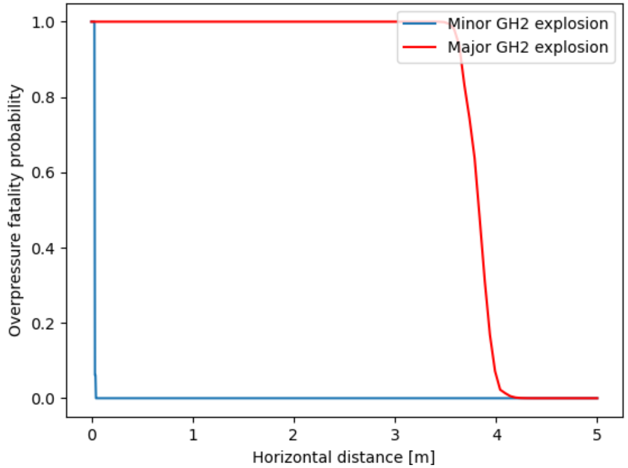
- Fatality zones of LH_2 jet fire:
  - LH_2 release flame length:
    - Minor release: 0.7 [m]
    - Major release: 4 [m]



Schaad, C., Mosleh, S., Yang, R., & Groth, K. M. (2025). Quantitative Risk Assessment of hydrogen releases in a hydrogen fueling station with liquid hydrogen storage. International Journal of Hydrogen Energy, 112, 111-120.

Results: Consequence modeling (deflagration explosions)

- Fatality radius for GH_2 explosions
  - Minor release: < 0.1 [m]
  - Major release: 3.8 [m]



- Fatality radius for LH_2 explosions
  - Minor release: < 0.1 [m]
  - Major release: < 0.1 [m]

Consequences of major GH_2 releases have a large magnitude than for LH_2

Schaad, C., Mosleh, S., Yang, R., & Groth, K. M. (2025). Quantitative Risk Assessment of hydrogen releases in a hydrogen fueling station with liquid hydrogen storage. International Journal of Hydrogen Energy, 112, 111-120.

Results: Risks of hydrogen releases

- Risk evaluation metrics:

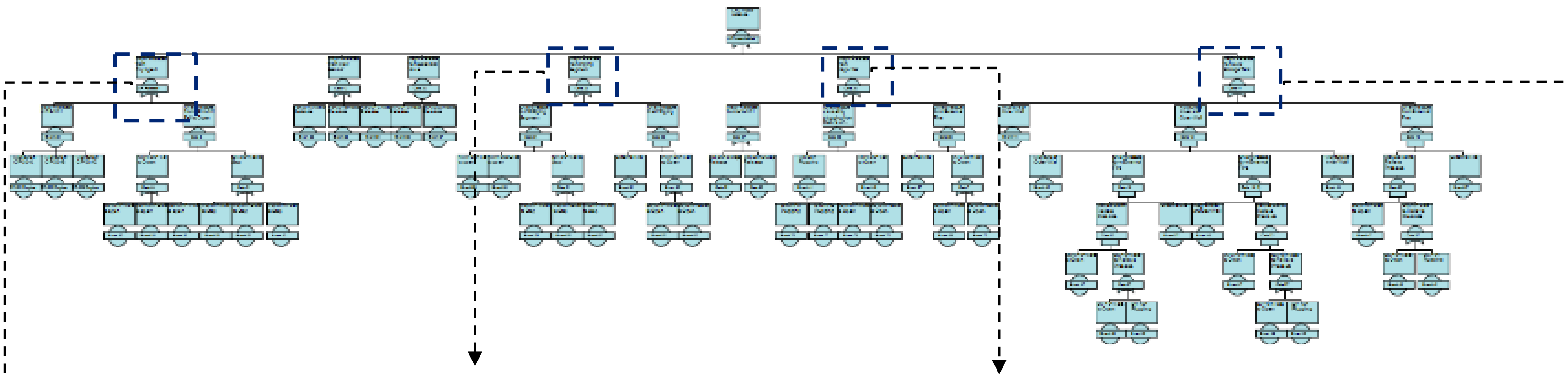
Release type	Risk metrics	
	FAR	AIR
LH_2 major	4.70×10^{-2}	5.15×10^{-7}
GH_2 major	7.70×10^{-2}	3.36×10^{-5}
Station total	$\mathbf{1.24 \times 10^{-1}}$	$\mathbf{3.41 \times 10^{-5}}$

  - AIR is **below the risk limit** set by the European Integrated Hydrogen Project (1×10^{-4}/year) but **above** fire fatality rate in conventional gasoline (2×10^{-5}/year) [NFPA 2].

AIR is ~70% higher than conventional gasoline fueling stations

Schaad, C., Mosleh, S., Yang, R., & Groth, K. M. (2025). Quantitative Risk Assessment of hydrogen releases in a hydrogen fueling station with liquid hydrogen storage. International Journal of Hydrogen Energy, 112, 111-120.

Example: FT for Major release of LH_2



Release from Piping Segment:
- Overpressure in Pump Segment:
  - Valve fail to open & Pump fail to stop
- Overpressure in HX Segment:
  - External fire & PRV fail to open

Release from Vaporizer:
- Component rupture
- Overpressure from plugging
  - Debris accumulation from degraded cryogenic pump
- Overpressure form an external fire

Release from Cryogenic Pump:
- Overpressure event: Valve fail to open
- Component rupture

Release from LH2 Storage Tank:
- Overpressure event: external fire & failure of PRV & SV
- Rupture of inner & outer wall

Results: Importance measure analysis

What are the best **opportunities for reducing risks**?

- Risk reduction worth (RRW) is used to measure importance of events

Release type	Event (Top 5 only)	RRW
LH_2 major	H_2 sensors fail to detect release	6.37
	CP-201 rupture	1.19
	FL-101 rupture	1.16
	SV-101 fail to close	1.13
	HX-201 rupture	1.09
GH_2 major	H_2 sensors fail to detect release	22.28
	Release from any component rupture	1.87
	Natural hazards	1.03
	Station loss of power	1.03
	PLC failure	1.02

- Improving H_2 leak detection is the best option for reducing risks in station
- Improvements to reliability & inspection of valves, pumps, filters has significant risk-reduction potential

Schaad, C., Mosleh, S., Yang, R., & Groth, K. M. (2025). Quantitative Risk Assessment of hydrogen releases in a hydrogen fueling station with liquid hydrogen storage. International Journal of Hydrogen Energy, 112, 111-120.

Remaining knowledge gaps

- Reliability data for hydrogen components is still inadequate:
  - Cryogenic hydrogen pumps
  - Cryogenic valves & piping components
  - Cryogenic hydrogen vaporizers

- Several gaps on LH_2 release modeling:
  - Probabilities of ignition
  - Physics-based simulations
  - Characterization of cryogenic vapor cloud magnitude and ignition

HyFIRE-BN: Bayesian Network for Modeling Hydrogen Ignition Probability

Comprehensive musti-factor causal model that **considers the impact of varying conditions** internal to and surrounding the hydrogen system to **make an informed estimate of ignition probability**.

Methods

Results of hydrogen ignition experiments and studies

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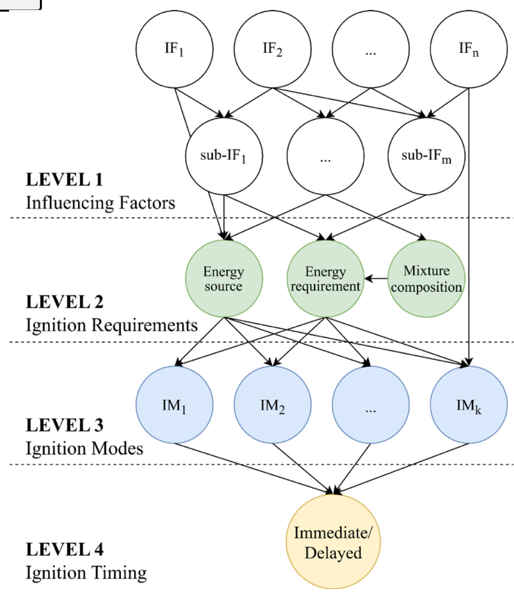
Causal modeling of risk-relevant influencing factors

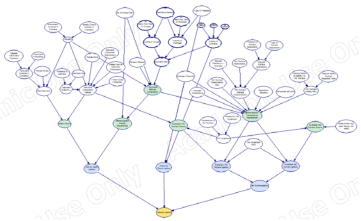
\+

System understanding and logic modeling



Results

Customizable system conditions and parameters



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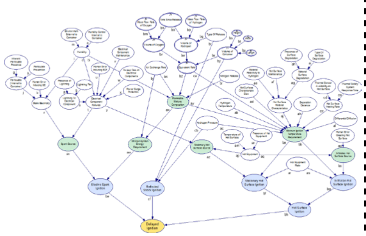
Consideration of multiple influencing factors and their relationship to ignition



Informed Ignition Probability

Federica Tamburini, Samantha E. Wismer, Valerio Cozzani, K. M. Groth, “Bayesian Network Model for Assessing Hydrogen Ignition Probability.” Submitted to: *Reliability Engineering & System Safety*

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 project achievements

- Identified causal pathways for both GH_2 and LH_2 releases
  - Frequency of mayor releases: 1.48×10^{-2} per station-year
  - Frequency of mayor ignition events is lower: 1.35×10^{-5} per station-year
- Estimated magnitude and consequences of releases to customers and operators of hydrogen fueling station
  - AIR is 70% higher than in conventional gasoline fueling stations
- Identified opportunities for reducing risks:
  - Reliable H_2 gas detectors are critical for reducing risks
  - Reliability improvements for key equipment: Valves, LH_2 pump and filters

Thank you!

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SYRRA

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Properties of releases

	LH_2 release magnitude	
	Minor	Major
Release mass flow [kg/s]	0.00083	0.02778
Prob. immediate evaporation	0.9	0.9
Prob. for pool/flash fire	0.013	0.013
Prob. immediate ignition	0.008	0.008
Prob. delayed ignition	0.004	0.004

	GH_2 release magnitude	
	Minor	Major
Release mass flow [kg/s]	0.000147	1.47
Prob. immediate ignition	0.008	0.053
Prob. delayed ignition	0.004	0.027