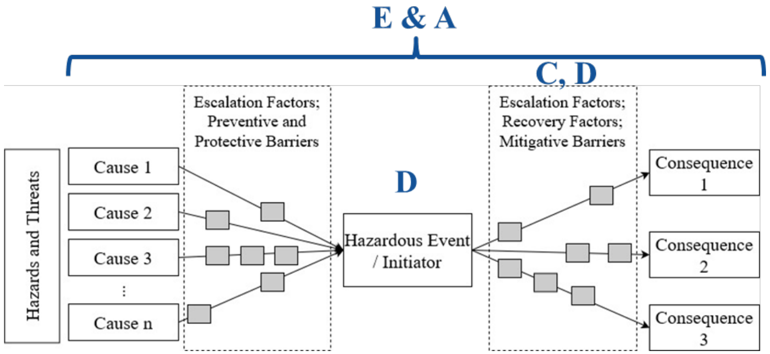

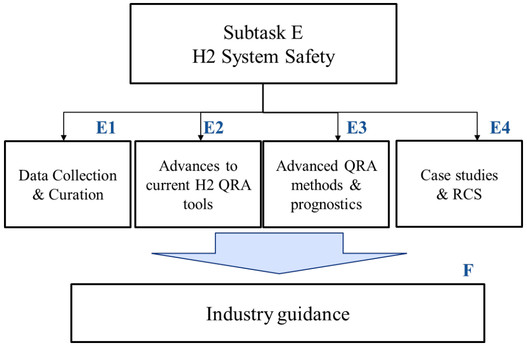
Subtask E
H2 System Safety

E1 Data Collection & Curation

E2 Advances to current H2 QRA tools

E3 Advanced QRA methods & prognostics

E4 Case studies & RCS

F Industry guidance

IEA TCP Task 43
Subtask E: Hydrogen System Safety

Prof. Katrina Groth

University of Maryland, Mechanical Engineering, Center for Risk and Reliability

ICHS 2023, Quebec City, Canada, 2023 Sept 19

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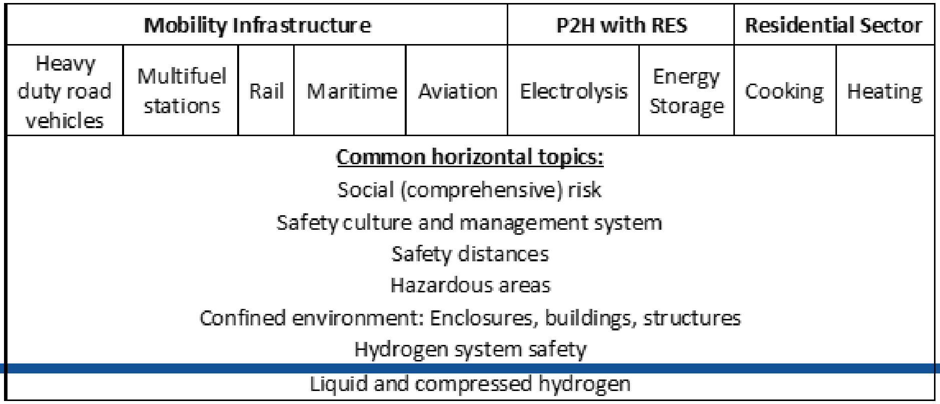
IEA Hydrogen TCP Task 43 Objectives

Task 43 “Safety and RCS of Large-Scale Hydrogen Energy Applications” (4th H2 safety task since Task 19 in 2004)

Specific Objectives & Framing

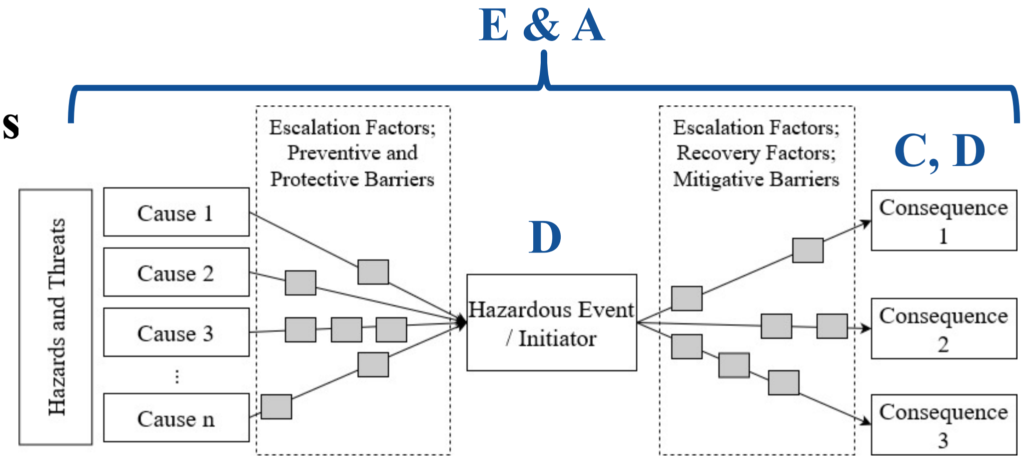
- Focus on large-scale compressed and liquid hydrogen energy systems and applications
- **Focus on common horizontal safety & regulatory attributes of emerging large-scale hydrogen energy systems and applications**
- Focus on developing uniform methodologies via case studies, available PNR and their results’ synthesis and analysis
- Focus on practical recommendations and solutions for industry, standardization, and regulatory bodies:
    - Inform relevant international and national RCS development activities
    - Help H2 industry with market deployment and establishment of best practices
- **Focus on the development of joint products such as peer-reviewed publications, educational and training materials, conference papers, white papers, reports, new work item proposals for standard development, etc.**



Mobility Infrastructure					**P2H with RES**		**Residential Sector**	
Heavy duty road vehicles	Multifuel stations	Rail	Maritime	Aviation	Electrolysis	Energy Storage	Cooking	Heating
Common horizontal topics: Social (comprehensive) risk Safety culture and management system Safety distances Hazardous areas Confined environment: Enclosures, buildings, structures Hydrogen system safety Liquid and compressed hydrogen								

IEA Task 43 Structure

- **Task 43 Safety and RCS of Large Scale Hydrogen Energy Applications**
  - Task Manager: Dr. Andrei V. Tchouvelev, Hydrogen Council
- **Subtask A: Social (Comprehensive) Risk;**
  - Prof. Tadahiro Shibutani, Yokohama National University (Japan)
- **Subtask B: Safety Culture and Management System;**
  - Nick Barilo, Centre for Hydrogen Safety / Nicolas Mey, Bureau Veritas (US, France)
- **Subtask C: Safety Distance Methodologies**
  - Subtask Leaders: Guy de Reals, Air Liquide / Richard Chang, Shell (France, UK)
- **Subtask D: Hazardous Areas Methodologies**
  - Subtask Leader: Dr. Stuart Hawksworth, Health & Safety Executive (UK)
- **Subtask E: Hydrogen System Safety**
  - Subtask Leaders: Prof. Katrina Groth, University of Maryland (USA)
- **Subtask F: Dissemination**
  - Subtask Leader: Dr. Andrei V. Tchouvelev, Hydrogen Council (Canada)



Subtask E participants

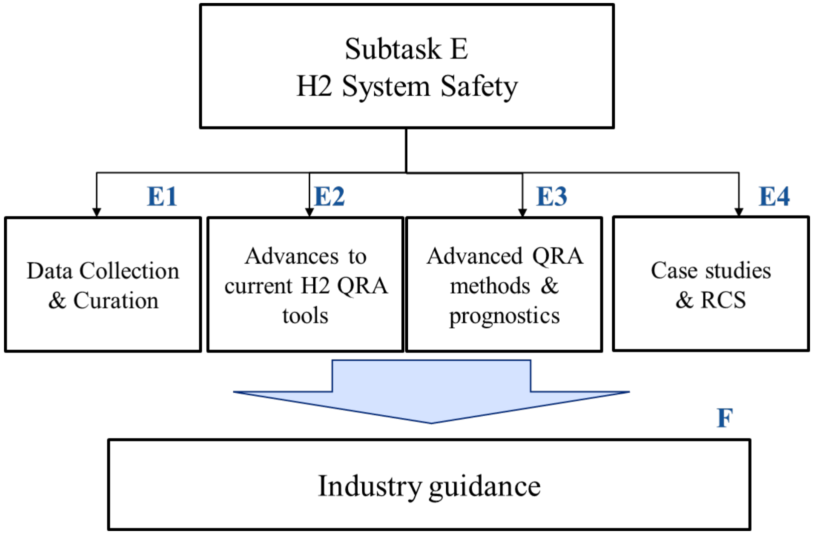
- Participating organizations were identified at the first Task 43 meeting in Buxton, UK in October 2022 and the second meeting in Golden, Colorado, USA in March 2023.
- The following organizations have engaged with Subtask E:

- Arup;
- Air Liquide;
- Airbus Operations Limited;
- Canadian Nuclear Labs;
- DGC a/s;
- DTU Construct;
- Engie;
- HSE;
- Hydrogen Council;
- ITM Power;
- Lifte H2 GmbH;
- Lloyd’s Register;
- Lund University;
- National Renewable Energy Laboratory (NREL);
- Norwegian University of Science and Technology (NTNU);
- Shell;
- University of Bergen (UiB);
- University of Maryland (UMD) Center for Risk and Reliability;
- University of South-Eastern Norway (USN);
- University of Stavanger (UiS);
- Ulster University, HySAFER Centre;

Join us – contact kgroth@umd.edu

Subtask E Scope is Hydrogen *Systems* Safety – from causes through consequences

- Objective: Provide a forum for exchange of scientific information regarding hydrogen system safety. The task addresses technical gaps pertaining to the safety, risk and reliability analysis of *hydrogen systems*.
- Emphasis on mechanical equipment, in confined environments (enclosures).
- June 1, 2022 – May 31, 2025



Subtask E
H2 System Safety

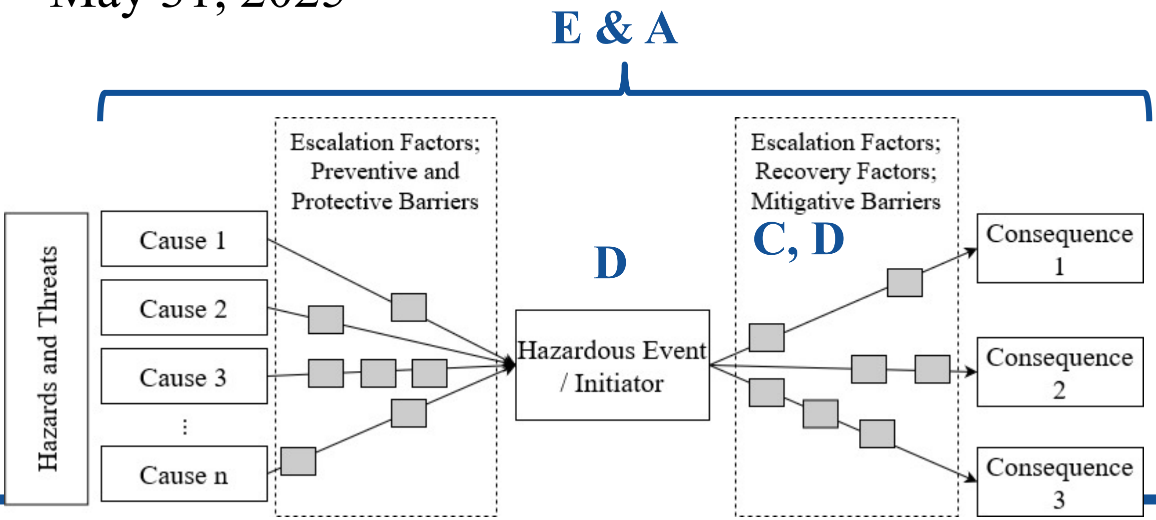
E1
Data Collection & Curation

E2
Advances to current H2 QRA tools

E3
Advanced QRA methods & prognostics

E4
Case studies & RCS

F
Industry guidance



E & A

Hazards and Threats

Cause 1
Cause 2
Cause 3
⋮
Cause n

Escalation Factors; Preventive and Protective Barriers

D

Hazardous Event / Initiator

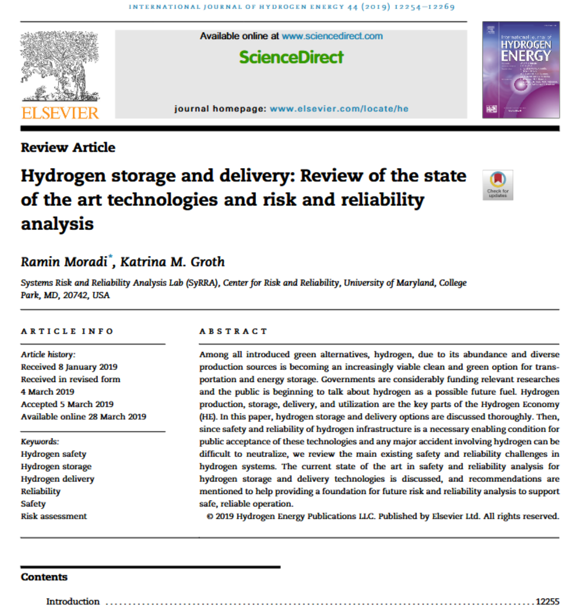
Escalation Factors; Recovery Factors; Mitigative Barriers

C, D

Consequence 1
Consequence 2
Consequence 3

Basis for subtask structure: Gap study on risk & reliability analysis for H2 storage & delivery (IJHE, May, 2019)

1. Current **reliability and safety data** is [still] inadequate & inaccessible
2. Current reliability, QRA, and safety modeling paradigms **(i.e., HyRAM) need to be matured**
3. H2 safety community needs to **modernize their approach to QRA**: embracing data, PHM, dynamic QRA.
4. Need for **more QRA case studies** (for H2 storage & delivery and beyond)



INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 44 (2019) 12254–12269

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Review Article

Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis

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Systems Risk and Reliability Analysis Lab (SyRRA), Center for Risk and Reliability, University of Maryland, College Park, MD, 20742, USA

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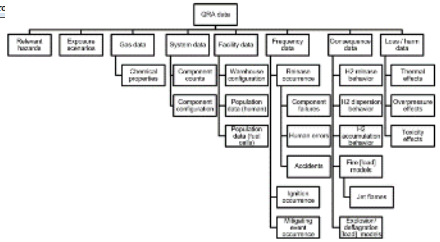
ABSTRACT

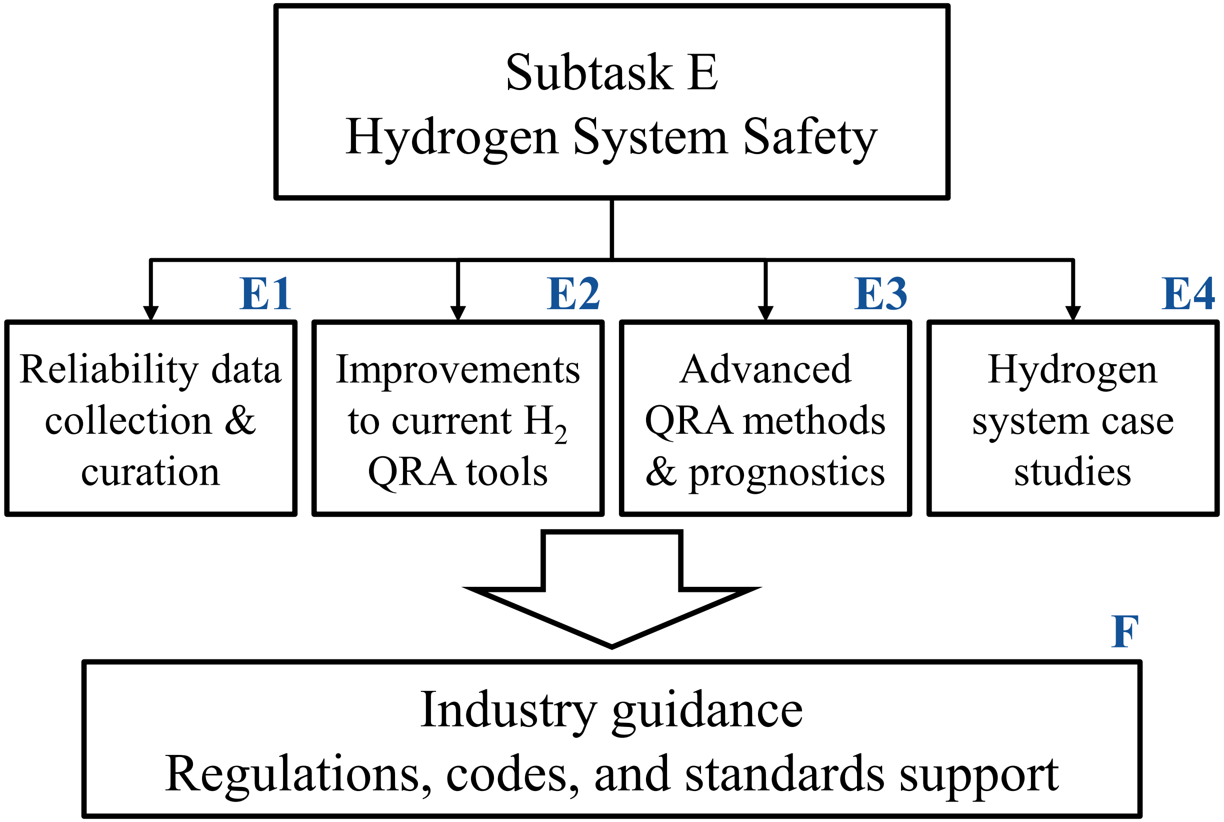
Among all introduced green alternatives, hydrogen, due to its abundance and diverse production sources is becoming an increasingly viable clean and green option for transportation and energy storage. Governments are considerably funding relevant researches and the public is beginning to talk about hydrogen as a possible future fuel. Hydrogen production, storage, delivery, and utilization are the key parts of the Hydrogen Economy (HE). In this paper, hydrogen storage and delivery options are discussed thoroughly. Then, since safety and reliability of hydrogen infrastructure is a necessary enabling condition for public acceptance of these technologies and any major accident involving hydrogen can be difficult to neutralize, we review the main existing safety and reliability challenges in hydrogen systems. The current state of the art in safety and reliability analysis for hydrogen storage and delivery technologies is discussed, and recommendations are mentioned to help providing a foundation for future risk and reliability analysis to support safe, reliable operation.

Contents



Moradi, Ramin, and Katrina M. Groth, **May 2019.** “Hydrogen Storage and Delivery: Review of the State of the Art Technologies and Risk and Reliability Analysis.” *International Journal of Hydrogen Energy*, 44(23): 12254–69. https://doi.org/10.1016/j.ijhydene.2019.03.041

Subtask Structure



Subtask E
Hydrogen System Safety

E1
Reliability data collection & curation

E2
Improvements to current H_2 QRA tools

E3
Advanced QRA methods & prognostics

E4
Hydrogen system case studies

F
Industry guidance
Regulations, codes, and standards support

Subtask E Active R&D Identified as of March 2023

- **E1 Reliability data collection framework for hydrogen systems**
  - UMD & NREL Developing HyCReD (Hydrogen Component Reliability Database) framework and corresponding probabilities – starting with fueling stations
    - Now published: see next slide
  - Lund University – Component leak data collection @ hydrogen stations in EU.
  - Hydrogen Council and CHS – Both setting up internal task teams to explore failure or leak database development.
  - Vysus and partners. - Developing leak frequencies and ignition probabilities under SAFEN project
  - Engie with many partners; MultHYFuel project, includes modeling sizes of hydrogen leaks from dispenser components
  - NREL, USN – Separate projects on experimental leak rate quantification and sensors and algorithms for leak detection

Approach: Research defining a QRA-usable HyCReD

Phase	***2018-2021***	***2021-2022***	***2022-2023***	***2023-2024***	***2024-2026***
Activities & Objectives	• ***Review existing H2 data sources*** • ***Identify best practices from similar industries***	• ***Develop H2-specific system decompositions*** • ***Develop H2 component failure modes***	• ***Database structure validation, feedback, and refinement***	• ***Partner with NREL & stakeholders to refine database structure*** • ***Develop a data quantification plan***	• ***Partner with industry sources to populate database***
Outputs *Completed & expected journal & conference publications*	• **Moradi & Groth (2019)** IJHE • **Correa-Jullian & Groth (2022)** IJHE • **West et al. (2022)** IJHE	• **West (2021)** M.S. thesis • **Al-Douri et al. (2022)** AIChE Spring Meeting	• **Hartmann et al. (2022)** CHS Americas Conf. • **Groth et al.** (IJHE 2023).	• **Al-Douri et al. (ICHS~2023)** • **Hartmann et al. (ICHS 2023)**	• **Potential (2026)** on database expansion & quantification

All papers are available from research team upon request

Hydrogen Component Reliability Database (HyCReD)

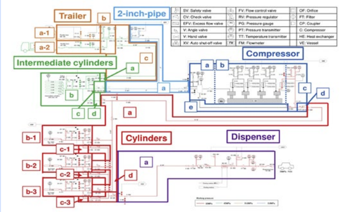
Evaluated existing H2 safety data collection tools

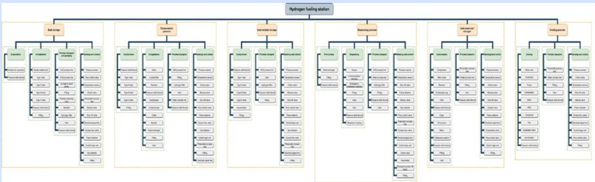
	Data Type	H2Tools	NREL CDPs	HIAD	CHS Failure Rate Data
Event and failure characterization	Initiating event (description)	✓	✓	✓	×
	Location within system	×	✓	O	×
	Failure mode	×	×	×	×
	Failure mechanism	×	×	×	×
	Failure root cause	✓	✓	✓	×
	Release size	×	O	✓	✓
	Incident severity	✓	✓	✓	✓
	Consequences	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 a set of 23 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

Developed system-specific H2 fueling station decomposition





Defined 33 H2-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
Internal leak utility medium	Utility med
Internal rupture hydrogen	Complete l
Internal rupture utility medium	Complete l
Open circuit	Electrical c
Overheating	Componen
Overspeed	Componen
Plugging	Buildup of
Restrict flow	Componen
Short circuit	Diversion c
Spurious operation	Activation
Spurious stop	Stop witho
Stuck connection	Componen
Underspeed	Componen

Developing & validating 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

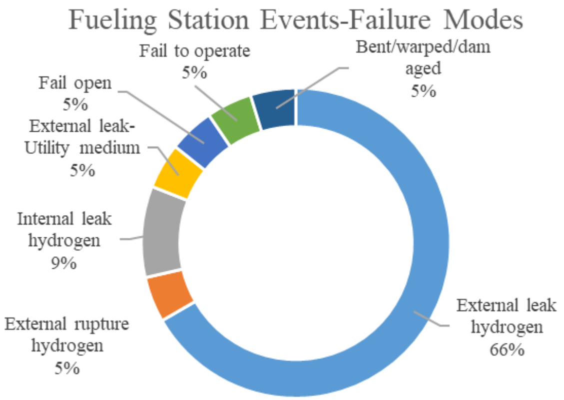
Date & Time Repair Started	Date & Time Repair Completed	Date & Time Station Restarted	Action Performed	Maintenance Description
07/18/2021	07/28/2021	07/29/2021	Replacement	

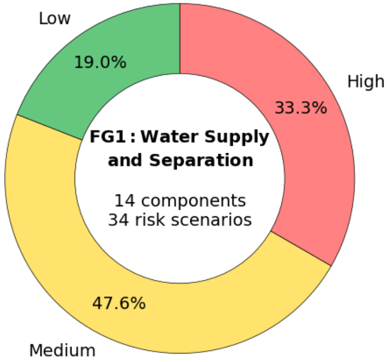
Active Research: Seeking data providers, contact K. Groth (UMD) or Bill Buttner, or Kevin Hartmann (NREL)

Katrina M. Groth, Ahmad Al-Douri, Madison West, Kevin Hartmann, Genevieve Saur, William Buttner. “Design and Requirements of a Hydrogen Component Reliability Database (HyCReD),” Accepted in *IJHE* 2023.

HyCReD + QRA will enable us to set priorities

- Calculate failure rates per failure mode and severity class
- Identification of components with highest failure frequencies and most impactful consequences (downtime).
- Identification which specific components & failure modes dominate the risk.
- Develop reliability-centered maintenance (RCM) plans





Population	Installations	Aggregated time in service (10^6 hours)		
17	8	**Calendar time**		**Operational time**
		0.7057		0.6296
Failure mode	**No. of failures**	**Failure rate (per 10^6 hours)**		
		Mean	**Std. Dev.**	**# of failures/service time**
Critical	128	220.34	273.35	181.39
	128	306.39	395.68	203.3
Degraded	149	242.6	216.05	211.15
	149	315.83	300.78	236.65
Incipient	132	132.29	309.17	187.06
	132	152.71	324.45	209.65
Unknown	2	2.78	2.93	2.83
	2	3.22	3.77	3.18
All modes	411	604.72	543.73	582.42
	411	777.05	742.96	652.78

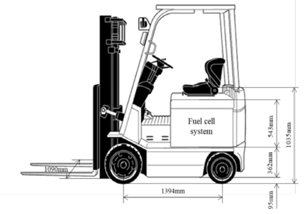
Subtask E Active R&D Identified as of March 2023

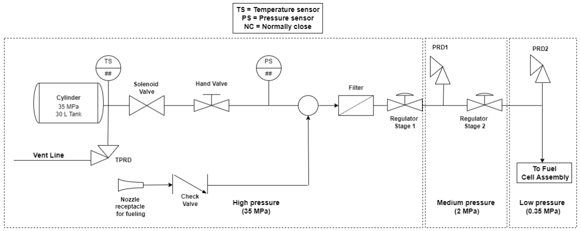
- **E2 Develop advances to current QRA tools**
  - Vysus, UMD: separate projects translating new data sources into inputs for QRA (HyRAM and PLOFAM)
  - Sandia: Currently on HyRAM+ 5.0
  - CNL: QRA toolkit with expads upon HyRAM+ with new models
  - Software efforts to incorporate models identified in task E1
  - UMD: Multiple projects identifying QRA gaps to guide extension to algorithms in HyRAM+ or other tools, including need for data development (see E1), for fault trees, physics of failure, and ignition modeling capabilities within tools.
  - NTNU, SUT, CIEMAT, NOHU, NU: SUSHy project accident scenario development and QRA studies
  - U. Roma Spiena and DTU – QRA methods for vehicles in road and rail tunnels and car parts
  - Lund – Models for H2 accumulation in enclosures
  - SINTEF et al – SH2IFT2 Experimental modeling campaign for hydrogen releases & fires
  - NTNU ELVHYS – Developing safety barriers and hazard zoning strategies
  - UiB and UiS – Enabling and benchmarking risk assessment for ships

Example: QRA of a hydrogen fuel cell forklift

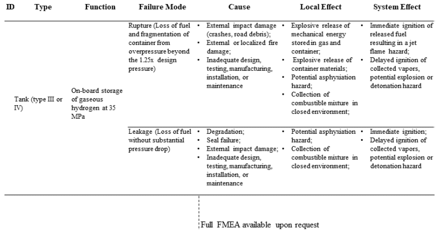
- QRA study to identify & prioritize *failure causes, release scenarios, probabilities and consequences* of a hydrogen fuel cell forklift.
    - Similar QRA method used for indoor hydrogen dispensers (in NFPA 2)
    - Used validated H2 consequence models (HyRAM) & three public data sources (HyRAM, OREDA, CCPS)
- Focus on:
    - *Identifying the most risk-significant components*
    - *Assessing whether risk is tolerable (comparison with BLS statistics)*
- Results could inform design modifications and/or codes and standards.

Generic H2 forklift system design





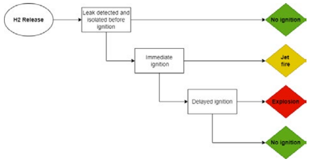
FMEA



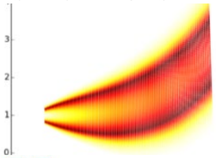
ID	Type	Function	Failure Mode	Cause	Local Effect	System Effect
	Tank (type III or IV)	On-board storage of gaseous hydrogen at 35 MPa	Rupture (Loss of fuel and fragmentation of container from overpressure beyond the 1.25x design pressure)	• External impact damage (crashes, road debris); • External or 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

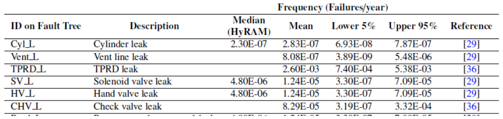
Event sequences



Release & flame simulations

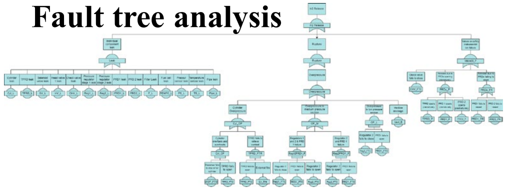


Basic event frequency data

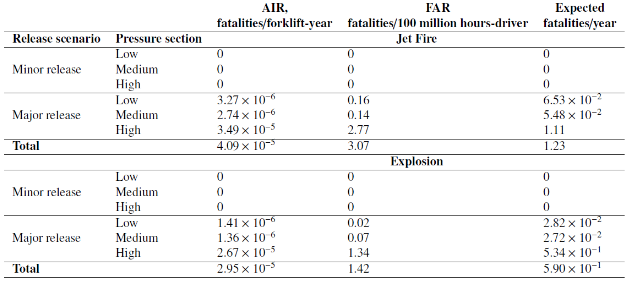


ID on Fault Tree	Description	Frequency (Failures/year) Median (HyRAM)	Mean	Lower 5%	Upper 95%	Reference
Cyl_L	Cylinder leak	2.30E-07	2.83E-07	6.93E-08	7.87E-07	[29]
Vent_L	Vent line leak		8.08E-07	3.89E-09	5.48E-06	[29]
TPRD_L	TPRD leak		2.60E-03	7.40E-04	5.38E-03	[36]
SV_L	Solenoid valve leak	4.80E-06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

Fault tree analysis

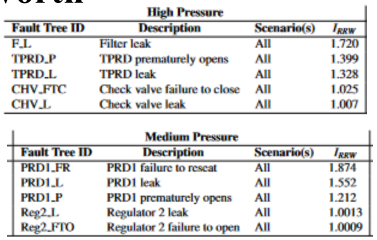


Total risk (FAR, AIR)



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

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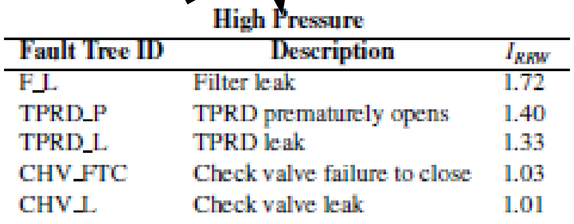
Al-Douri, A., Ruiz-Tagle, A. & Groth, K. A Quantitative Risk Assessment of Hydrogen Fuel Cell Forklifts. *Int'l Journal of Hydrogen Energy* 2023. Doi: 10.1016/j.ijhydene.2023.01.369

Insights from the forklift QRA

Conseq.	Scenario	Section	AIR	FAR	#Fatal/yr
Jet Fire	**Minor Release**	Low	0	0	0.00
		Medium	0	0	0.00
		High	0	0	0.00
	Major Release	Low	3.27E-06	0.16	0.07
		Medium	2.74E-06	0.14	0.05
		High	5.54E-05	2.77	1.11
	Total Jet fire		**6.14E-05**	**3.07**	**1.23**
Exposion	**Minor Release**	Low	0	0.00	0.00
		Medium	0	0.00	0.00
		High	0	0.00	0.00
	Major Release	Low	1.41E-06	0.07	0.03
		Medium	1.36E-06	0.07	0.03
		High	2.67E-05	1.34	0.53
	Total Explosion		**2.95E-05**	**1.47**	**0.59**
TOTAL	**Total**		**9.09E-05**	**4.54**	**1.82**

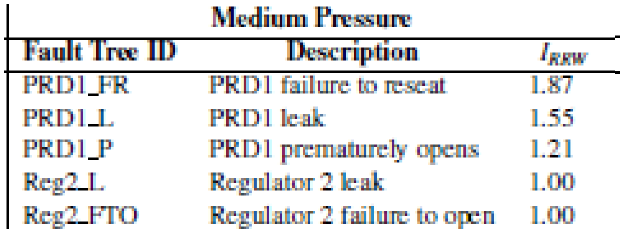
- **High-pressure section** contributes about **92% of** overall **Risk** values, **but low and medium pressure sections also contribute**
- AIR is < 1E-04 fatalities/forklift-year (within tolerability criteria – but close).
- FAR is > 0.295 fatalities/100M hours-driver (*above tolerability criteria*; BLS shows FAR of 2.95 for all material handling occupations).

- A handful of component failure modes offer greatest potential for risk reduction: PRDs, Regulators, FC, Filter
- PRD leaks, closure failures dominate facets of risk (beyond protective function).



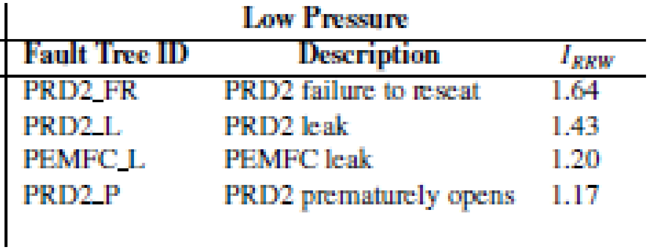
High Pressure

Fault Tree ID	Description	I_{RRW}
F_L	Filter leak	1.72
TPRD_P	TPRD prematurely opens	1.40
TPRD_L	TPRD leak	1.33
CHV_FTC	Check valve failure to close	1.03
CHV_L	Check valve leak	1.01



Medium Pressure

Fault Tree ID	Description	I_{RRW}
PRD1_FR	PRD1 failure to reseat	1.87
PRD1_L	PRD1 leak	1.55
PRD1_P	PRD1 prematurely opens	1.21
Reg2_L	Regulator 2 leak	1.00
Reg2_FTO	Regulator 2 failure to open	1.00



Low Pressure

Fault Tree ID	Description	I_{RRW}
PRD2_FR	PRD2 failure to reseat	1.64
PRD2_L	PRD2 leak	1.43
PEMFC_L	PEMFC leak	1.20
PRD2_P	PRD2 prematurely opens	1.17

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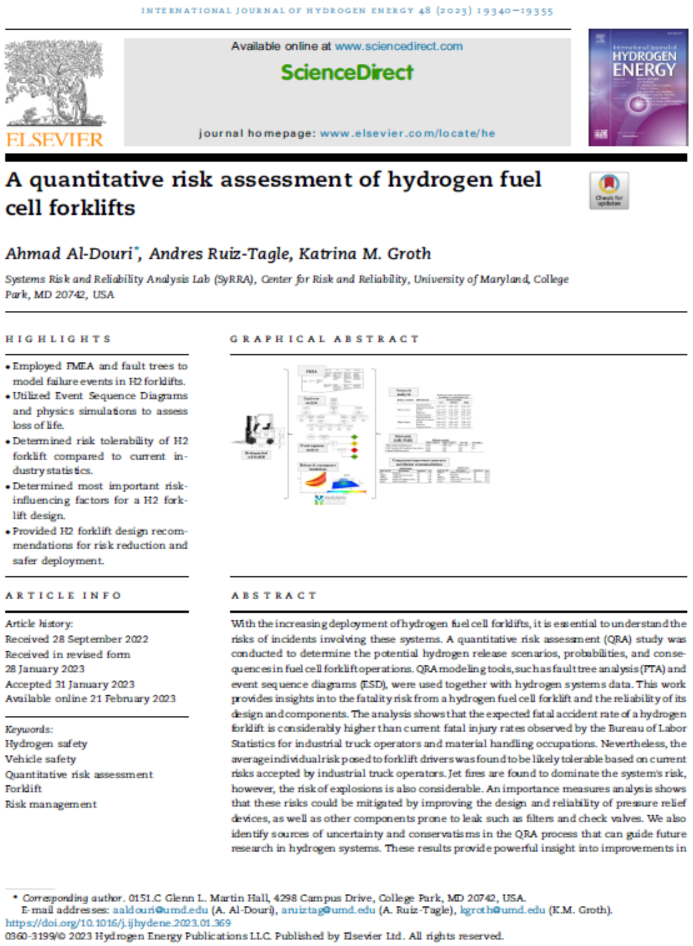
Key takeaways from forklift QRA

1. **Study number of PRDs and their positioning** in a forklift for risk-reduction purposes.
2. **Focus on** inspection, monitoring, and maintenance of the **filter and pressure relief devices** in a forklift's storage and delivery system.
3. **Minimize any containment of components prone to leakages or gas releases** (e.g., pressure relief devices, check valve, and filter), **even low pressure ->** ensure rapid, direct dispersion to mitigate potential explosion risks.
4. **Creating and maintain a database for H2 incidents & reliability data** to help identify major operational hazards and the most likely components to fail.

   See: HyCReD project



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A quantitative risk assessment of hydrogen fuel cell forklifts

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HIGHLIGHTS

- Employed FMEA and fault trees to model failure events in H2 forklifts.
- Utilized Event Sequence Diagrams and physics simulations to assess loss of life.
- Determined risk tolerability of H2 forklift compared to current industry statistics.
- Determined most important risk-influencing factors for a H2 forklift design.
- Provided H2 forklift design recommendations for risk reduction and safer deployment.

GRAPHICAL ABSTRACT

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ABSTRACT

With the increasing deployment of hydrogen fuel cell forklifts, it is essential to understand the risks of incidents involving these systems. A quantitative risk assessment (QRA) study was conducted to determine the potential hydrogen release scenarios, probabilities, and consequences in fuel cell forklift operations. QRA modeling tools, such as fault tree analysis (FTA) and event sequence diagrams (ESD), were used together with hydrogen systems data. This work provides insights into the fatality risk from a hydrogen fuel cell forklift and the reliability of its design and components. The analysis shows that the expected fatal accident rate of a hydrogen forklift is considerably higher than current fatal injury rates observed by the Bureau of Labor Statistics for industrial truck operators and material handling occupations. Nevertheless, the average individual risk posed to forklift drivers was found to be likely tolerable based on current risks accepted by industrial truck operators. Jet fires are found to dominate the system's risk, however, the risk of explosions is also considerable. An importance measures analysis shows that these risks could be mitigated by improving the design and reliability of pressure relief devices, as well as other components prone to leak such as filters and check valves. We also identify sources of uncertainty and conservatisms in the QRA process that can guide future research in hydrogen systems. These results provide powerful insight into improvements in

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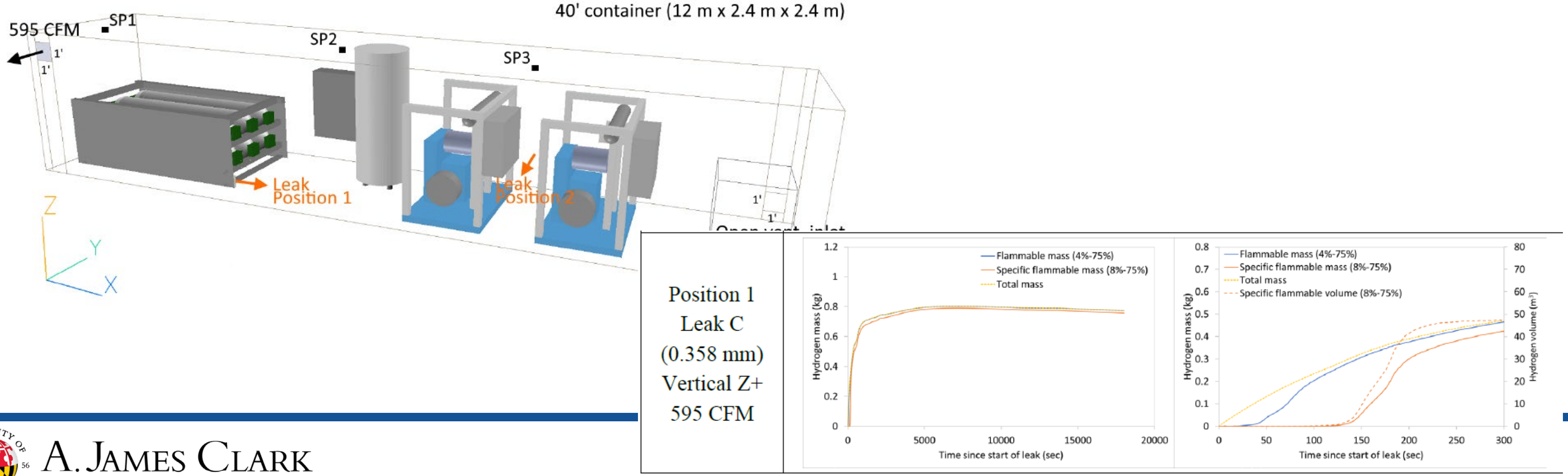
Subtask E Active R&D Identified as of March 2023

- **E3 Develop advanced QRA methods and prognostics and health monitoring (PHM) techniques**
    - UMD: SIPPRA project (Systematic Integration of PHM with Probabilistic Risk Assessment) – leveraging machinery data, machine learning & causality to enable system diagnosis and prognostics (SIPPRA)
        - Developing applications in pipelines, fueling stations
    - UMD & NREL Connection of PHM techniques and sensor monitoring to enable anomaly detection in LH2 on-site storage.
    - NTNU and partners: SUSHy developing digital twins and dynamic simulation for H2 fueling station systems

Subtask E Active Case studies

- **E4 System safety analysis of hydrogen technologies through case studies & RCS activities.**
  - Two key outputs are presented in other papers at this conference
    - Subtask A: Connection to Subtask A H2 storage example (ID227 @12pm)
    - Hydrogen Equipment Enclosure QRA study – (ID159 Th@8:50)
  - Many partners working on additional examples; too many to characterize. Subtask E focus: Developing QRAs for electrolyzers, enclosures, and fueling stations,



Position 1
Leak C
(0.358 mm)
Vertical Z+
595 CFM

Closing thoughts & takeaways

- Subtask E addresses a need for systems-focused approaches: Reliability engineering & risk analysis provide the technical basis for supporting decisions about H2 systems safety
- Recent studies suggest:
  - Need more studies on role of PRDs, filters, and check valves (reliability, inspection, monitoring, maintenance, and positioning).
  - Critical need for databases like HyCReD
- Do you have data to support active research?
  - **Reliability & maintenance info**: FMEA, FRACAS maintenance records, field data, monitors, sensor logs
  - **Operational monitoring logs & sensors**
- Interested in joining us?
  - Contact: kgroth@umd.edu

Thank you!

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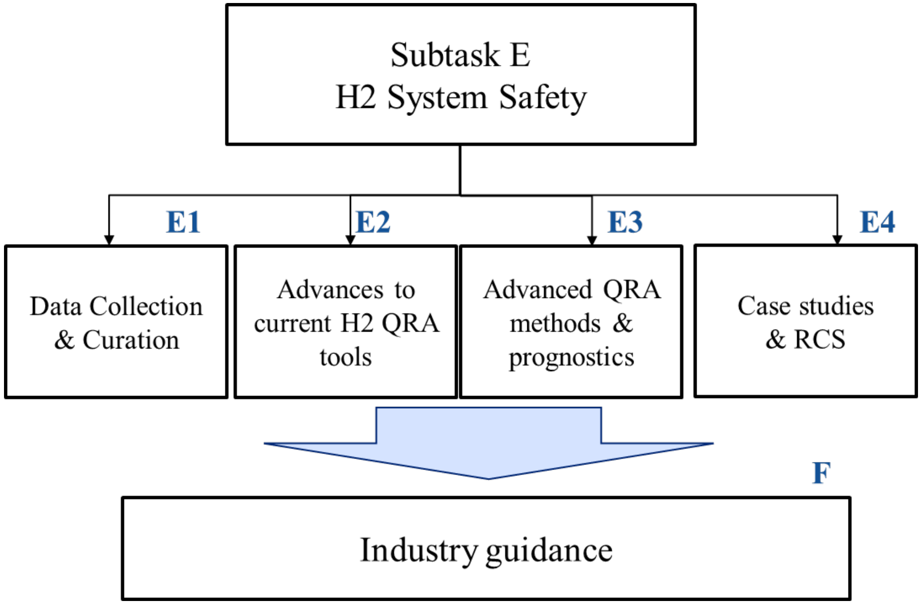
Systems Risk and Reliability Analysis Laboratory



Subtask E
H2 System Safety

E1 Data Collection & Curation

E2 Advances to current H2 QRA tools

E3 Advanced QRA methods & prognostics

E4 Case studies & RCS

F Industry guidance

A. JAMES CLARK
SCHOOL OF ENGINEERING