NTNU

Norwegian University of Science and Technology

NTNU ENERGY
Team Hydrogen

EIG CONCERT JAPAN
Connecting and Coordinating
European Research and Technology Development with Japan

Hydrogen Material Damage in a Safety Assessment Perspective

RAMS Seminar

3 November 2022
Trondheim, Norway

Alessandro Campari

Contents

H2
Hydrogen H2
zero emission

High Risk
Failure Rate
Low Risk
Consequence

Prevention of hydrogen-related accidents

Hydrogen has the potential to become the **energy carrier of the future**

Safety is the **major bottleneck** for a widespread rollout of hydrogen technologies

Hydrogen is:

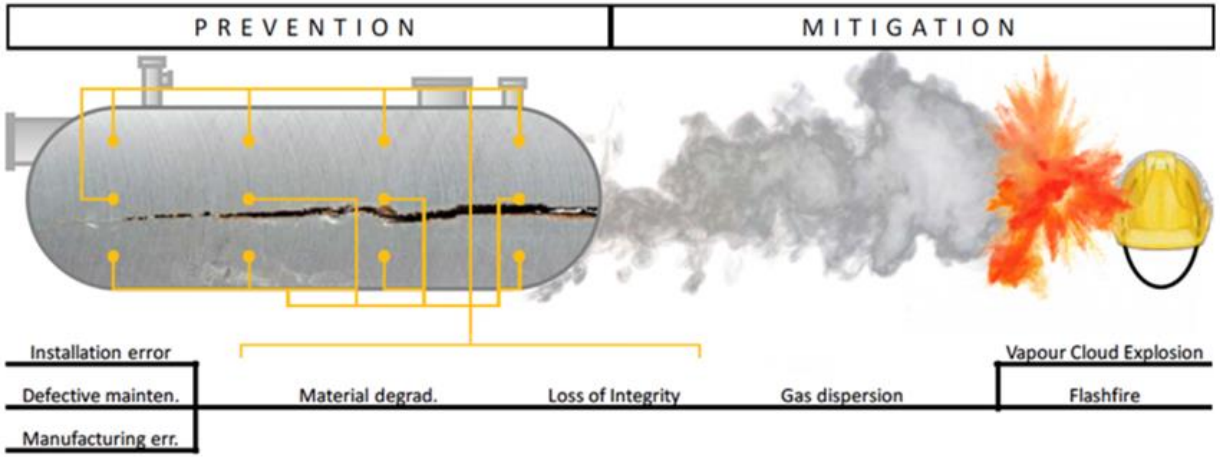
- Highly **flammable** and **explosible**
- Capable of **permeating** and **embrittling** metallic materials

Safety issues need **specific preventive approaches**

- **Inspection and maintenance** are vital to ensure the physical integrity of equipment in a hydrogen environment

- **Lessons learned** from past accidents are beneficial **to improve safety** for specific technologies

- Past accidents could be used as a basis to **develop mitigation strategies** in the future

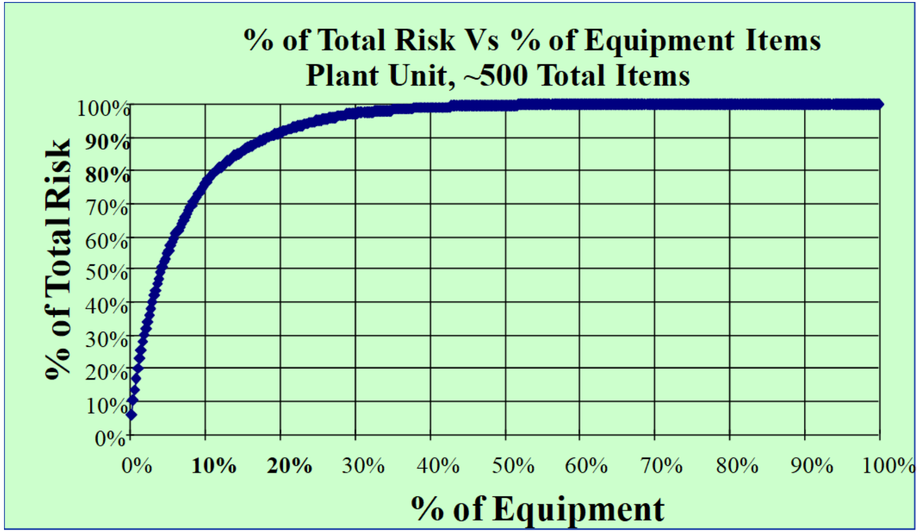


Risk-based Inspection

- **Risk is not equally distributed** among the individual pieces of process equipment

- A **large percentage of the total risk** of the plant unit is concentrated in a **small percentage of equipment items**

RBI aims at **prioritizing the inspection** and the maintenance **of high-risk components** to minimize the overall risk



- Risk assessment is based on **damage mechanisms** likely to occur

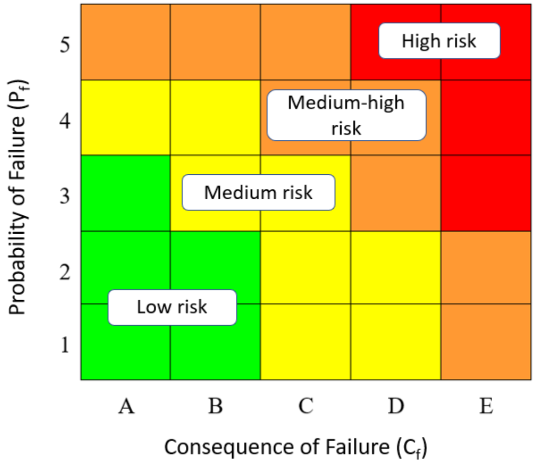
- **Risk of failure** of each component:

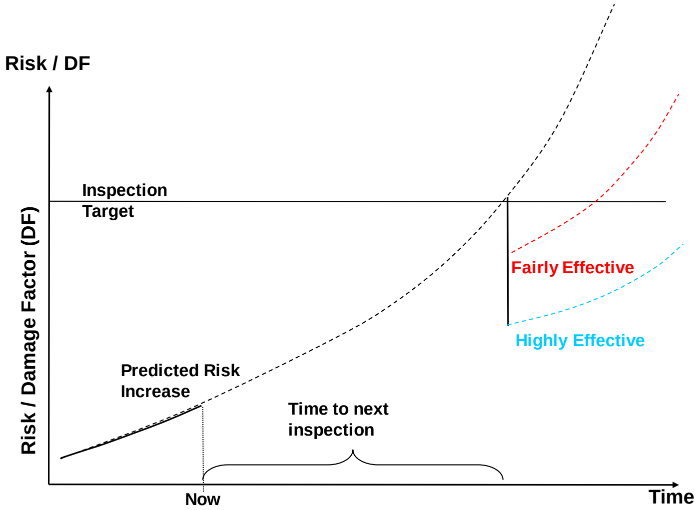
$$R(t, I_E) = P_f(t, I_E) \cdot C_f$$

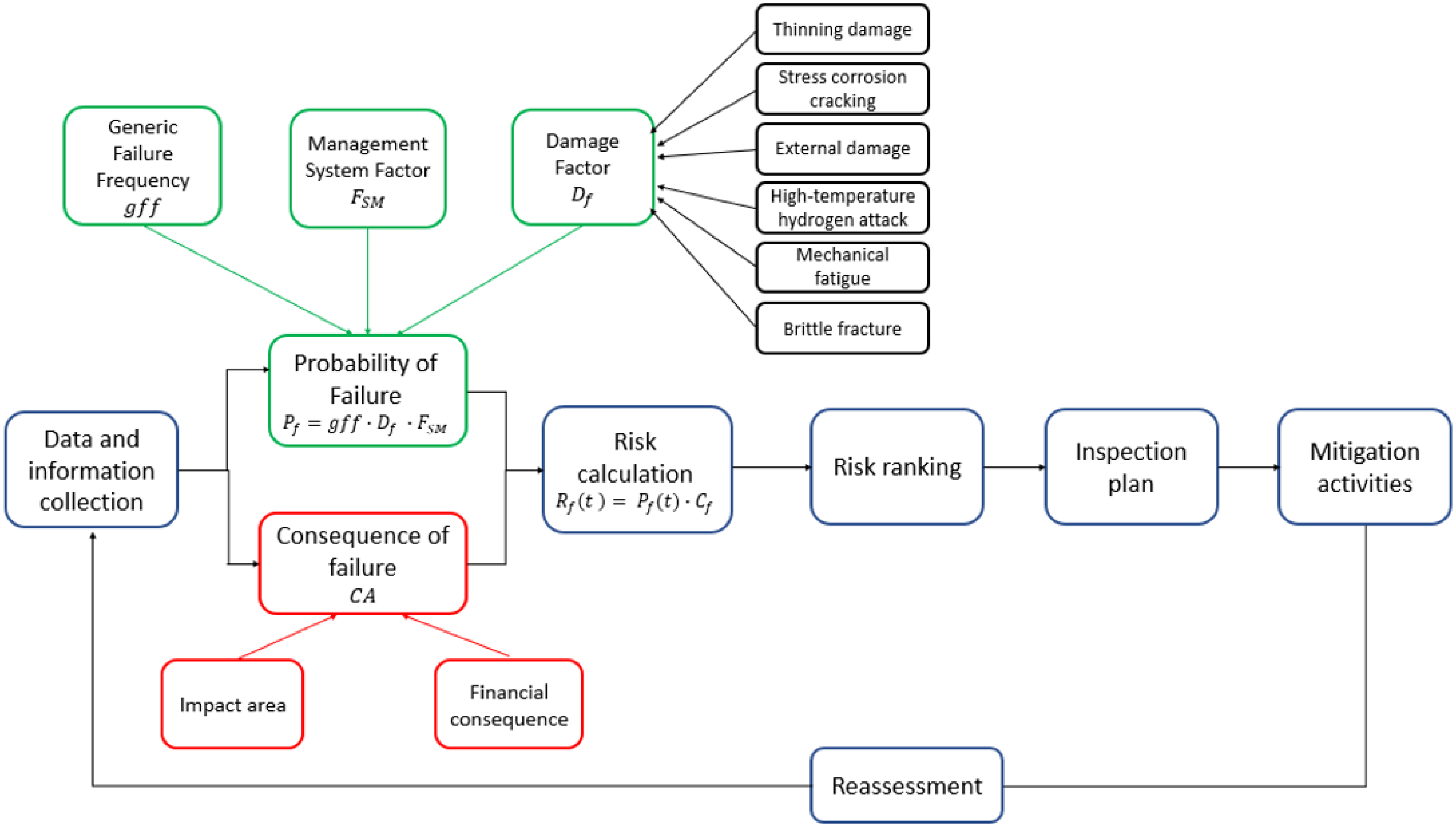
- **Probability of failure** of each component:

$$P_f(t, I_E) = gff \cdot D_f(t, I_E) \cdot F_{MS}$$

- Risk-based inspection planning has **never** been adopted **for equipment** operating **in pure hydrogen environment**





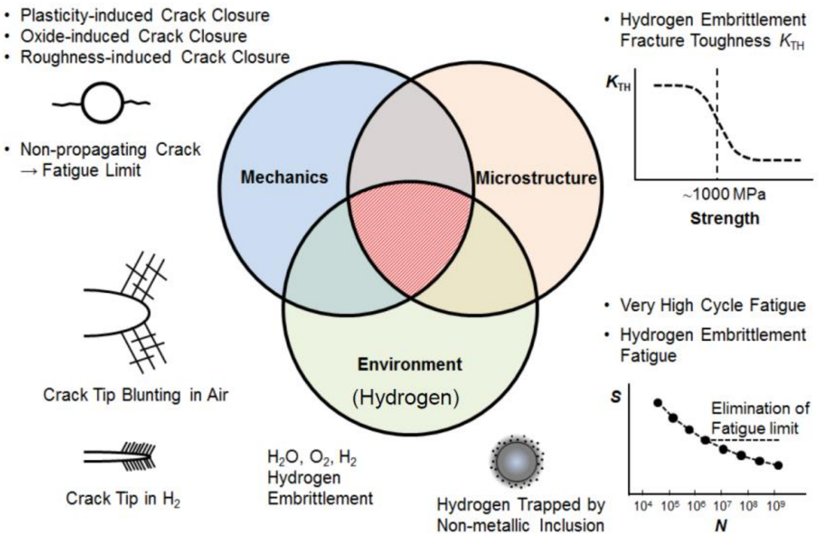

Thinning damage
Stress corrosion cracking
External damage
High-temperature hydrogen attack
Mechanical fatigue
Brittle fracture
Generic Failure Frequency gff
Management System Factor F_{SM}
Damage Factor D_f
Probability of Failure $P_f = gff \cdot D_f \cdot F_{SM}$
Data and information collection
Risk calculation $R_f(t) = P_f(t) \cdot C_f$
Risk ranking
Inspection plan
Mitigation activities
Consequence of failure CA
Impact area
Financial consequence
Reassessment

Hydrogen Embrittlement

- HE is a material degradation resulting from the combined action of **hydrogen** and **tensile stress**

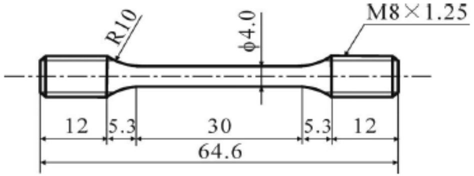
- HE occurs as a **synergistic effect** of three factors

- HE results in a reduction in the mechanical properties to an extent that could result in **catastrophic failure** of equipment

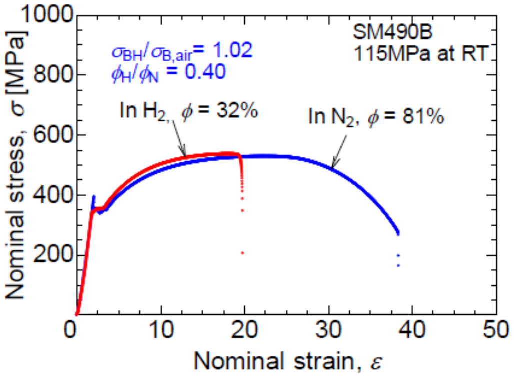


How does hydrogen degrade material's mechanical performances?

Loss of ductility

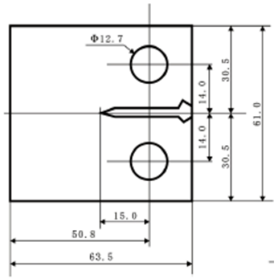


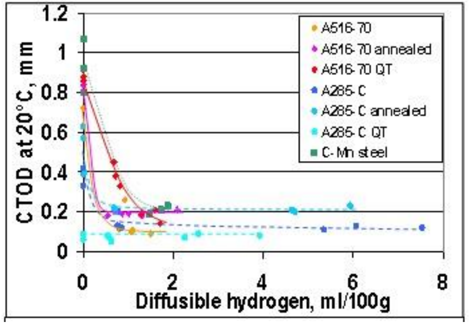
Tensile specimen



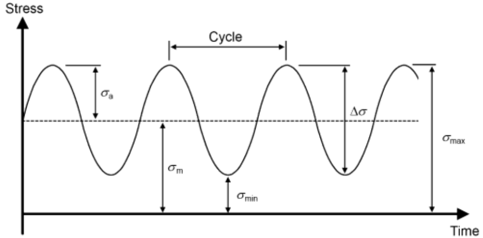
Stress-strain curve

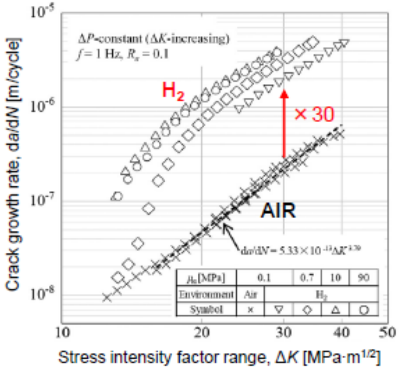
Reduction of toughness





Accelerated fatigue crack growth rate

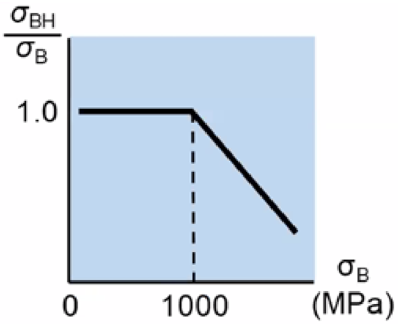




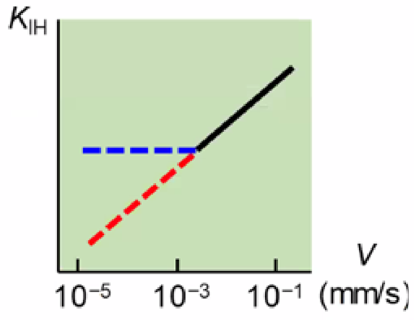
NASA, *Safety Standard for Hydrogen and Hydrogen Systems - Guidelines for Hydrogen System Design, Material selection, Operation, Storage and Transportation*, 2005

Material	Strength ratio, H_2/He: Notched[b]	Strength ratio, H_2/He: Unnotched	Unnotched ductility: Elongation, %: He	Unnotched ductility: Elongation, %: H_2	Unnotched ductility: Reduction of Area, %: He	Unnotched ductility: Reduction of Area, %: H_2
Extremely embrittled						
18Ni-250 Maraging Steel	0.12	0.68	8.2	0.2	55	2.5
410 Stainless Steel	.22	.70	15	1.3	60	12
1042 Steel (quenched and tempered)	.22	----	----	-----	----	----
17-7 pH Stainless Steel	.23	.92	17	1.7	45	2.5
Fe-9Ni-4Co-0.20C	.24	.86	15	.5	67	15
H-11	.25	.57	8.8	0	30	0
René 41	.27	.84	21	4.3	29	11
Electro-Formed Nickel	.31	----	----	----	----	----
4140	.40	.96	14	2.6	48	9
Inconel 718	.46	.93	17	1.5	26	1
440C	.50	.40	----	----	3.2	0
Severely embrittled						
Ti-6A1-4V (STA)	0.58	----	----	----	----	----
430F	.68	----	22	14	64	37
Nickel 270	.70	----	56	52	89	67
A515	.73	----	42	29	67	35
HY-100	.73	----	20	18	76	63
A372 (class IV)	.74	----	20	10	53	18
1042 (normalized)	.75	----	----	----	59	27
A533-B	.78	----	----	----	66	33
Ti-6A1-4V (annealed)	.79	----	----	----	----	----
AISI 1020	.79	----	----	----	68	45
HY-50	.80	----	----	----	70	60
Ti-5A1-2.5Sn (ELI)	.81	----	----	----	45	39
Armco Iron	.86	----	----	----	83	50
Slightly embrittled						
304 ELC Stainless Steel	0.87	----	----	----	78	71
305 Stainless Steel	0.89	----	----	----	78	75
Be-Cu Alloy 25	0.93	----	----	----	72	71
Titanium	0.95	----	----	----	61	61
Negligibly embrittled						
310 Stainless Steel	0.93	----	----	----	64	62
A286	.97	----	----	----	44	43
7075-T73 Aluminum Alloy	.98	----	----	----	37	35
316 Stainless Steel	1.00	----	----	----	72	75
OFHC Copper	1.00	----	----	----	94	94
NARloy-Z[c]	1.10	----	----	----	24	22
6061-T6 Aluminum Alloy	1.10	----	----	----	61	66
1100 aluminum	1.40	----	----	----	93	93

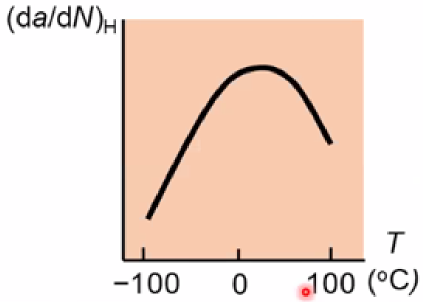
Practically important HE influencing factors



Material strength dependence



Load "speed" dependence



Temperature dependence

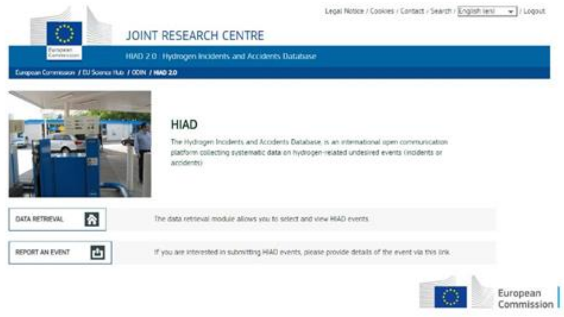
Hydrogen Incidents and Accidents Database 2.0

- HIAD 2.0 is a **public repository** developed by the **Joint Research Center** of the European Commission

- HIAD 2.0 includes report of **industrial accidents** related to hydrogen and its derivates

- The purpose is to facilitate the **exchange of lessons learned** to prevent similar accidents in the future

HIAD 2.0: home page



Spreadsheet	Parameters
Events	Classification, Physical consequences, Application stage, System involved, Region, Country, Date, Cause, Cause commented
Facility	Application stage, Application chain, Application, Storage medium, Storage quantity, Actual pressure, Design pressure, Location type, Location description, Operational condition, Pre-event summary
Consequences	Total number of injured persons, Total number of fatalities, Environmental damage, Currency, Property loss (onsite and offsite), Post-event summary, Official legal action, Investigation comments
Lessons learnt	Lessons learnt
Event nature	Emergency action, Emergency evaluation, Release type, Release substance, Release consequences, Release duration, Release rate, Release amount, Release pressure, Hole shape, Hole length, Hole width, Hole diameter, Hole area, Ignition source, Ignition delay, Detonation, Deflagration, High-pressure explosion, High-voltage explosion, Flame type, Cloud surface, Cloud volume, Flame length, Flame surface, Flame volume, Heat radiation
References	Sources, Documents

Business Intelligence for data mining

BI can boost the ability to **manage information access, identify data sources**, and **handle the information flow** within an appropriate architecture to assess user needs

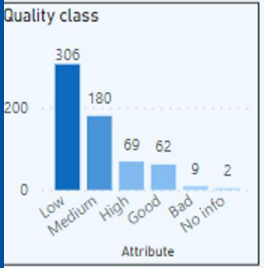
BI is based on the **extraction-transformation-loading** process:

1. Selecting the source
2. Transforming the source
3. Selecting the target
4. Mapping source attributes to target attributes
5. Loading the data

HYDROGEN INCIDENTS AND ACCIDENTS DATABASE - HIAD 2.0

Release type
All

Period
1894 2021

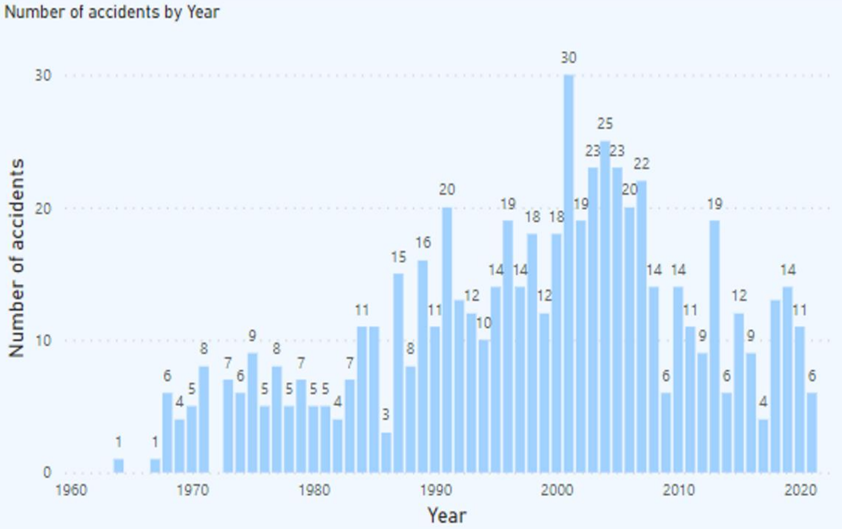


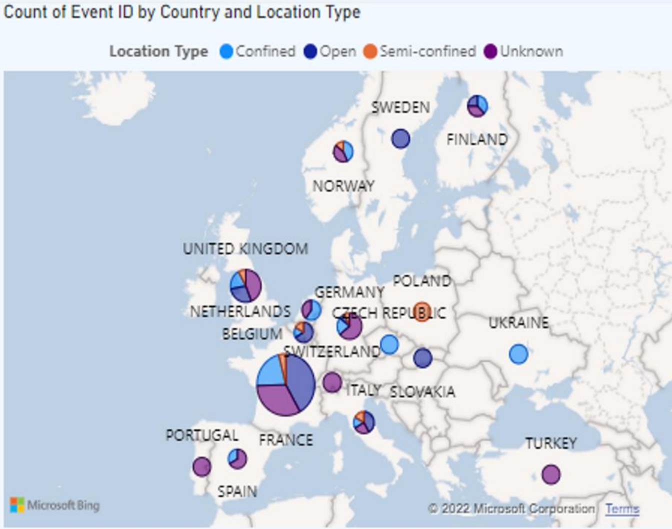
Substances
All

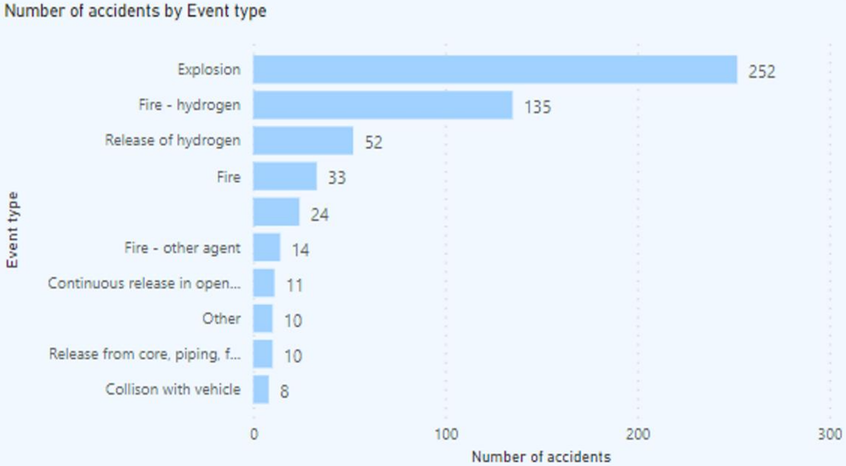
Release type
All

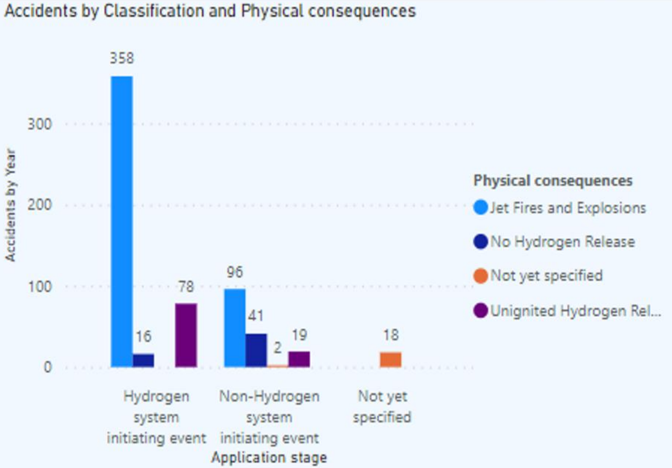
Cause
All

628
Total of Accidents

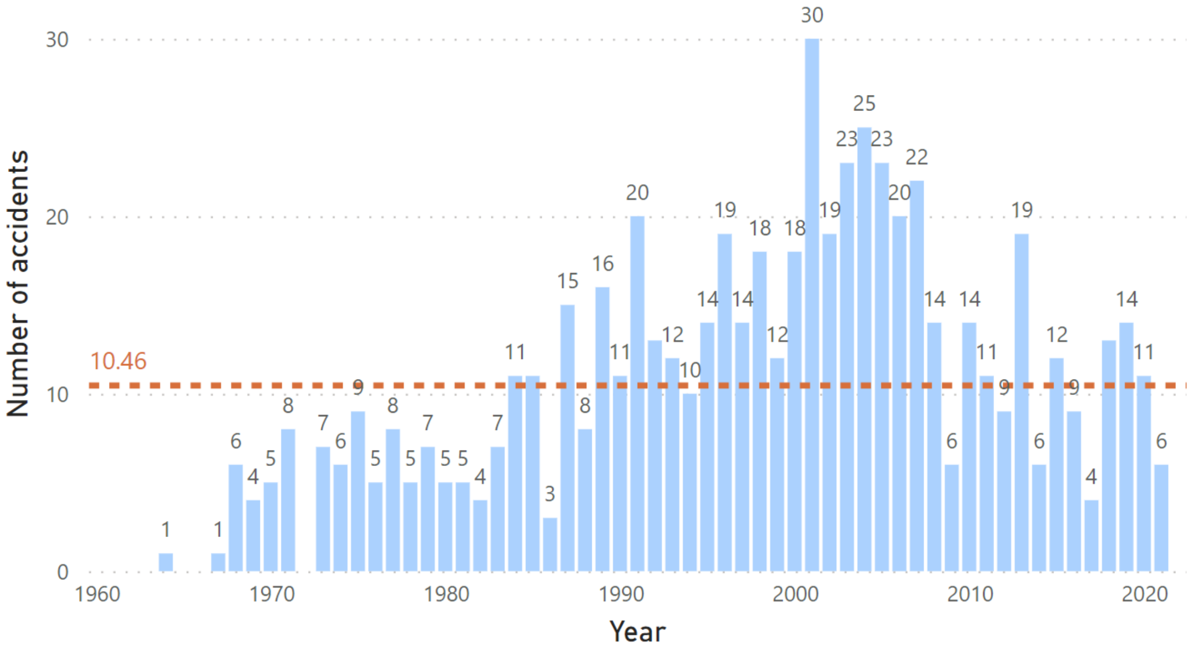








Reported undesired events over time



- What are the expected future trends?
- Is this trend representing the rollout of hydrogen technologies?

Geographical distribution of the events

- Is Europe the least safe continent for hydrogen technologies?
- Do every country follow the same rules regarding hydrogen accident reporting?

Fatalities and injuries per continent

Continent	Number of events	Fatalities	Fatalities per event	Injuries	Injuries per event
Africa	4	7	1.75	9	2.25
America	170	132	0.78	547	3.22
Asia	86	94	1.09	152	1.77
Europe	357	91	0.25	451	1.26
No reported	11	9	0.82	3	0.27
Total	628	333	0.53	1162	1.85

- **Europe** and **America** have the **highest number of events** reported
- Accidents reported in **Asia** and **Africa** have the **most severe consequences**
- There are **dissimilar regulations** across continents regarding industrial incident reporting
- In some countries, it is **not mandatory to report** hydrogen accidents unless they result in severe consequences

Accidents distribution by release type per country

Country	Release type				Total
	Confined	Open space	Semi-confined	Unknown	
France	37	64	7	55	163
USA	25	33	5	78	141
Not reported	8	12	2	64	86
UK	10	14	4	32	61
Germany	6	4	3	19	32
Canada	2	5	1	10	18
Italy	2	5	2	3	12
Japan	3	2	1	6	12
Finland	6	2	0	3	11
Norway	3	0	1	3	7
Total	102 (16.2%)	141 (22.5%)	26 (4.1%)	273 (43.5%)	542 (86.3%)

- The main **sources of information** for HIAD 2.0 are European and American databases
- There is a **different** magnitude of **adoption of hydrogen technologies** around the world

Distribution of events by field of application

Application stage	Events	Fatalities	Injured persons
Chemical and Petrochemical Industry	338	222	658
Other	113	26	178
Hydrogen Transportation and Distribution	69	9	126
Hydrogen Production	35	16	72
Road Vehicles	24	1	4
Not Reported	13	15	96
Laboratory and R&D	13	0	23
Non-Road Vehicles	9	8	7
Hydrogen Refueling Stations	8	0	0
Commercial Use	6	0	1

- **Chemical and petrochemical industries** have been historically the **biggest consumers** of hydrogen
- Hydrogen transportation is challenging due to its tendency to **permeate and embrittle** most metallic materials

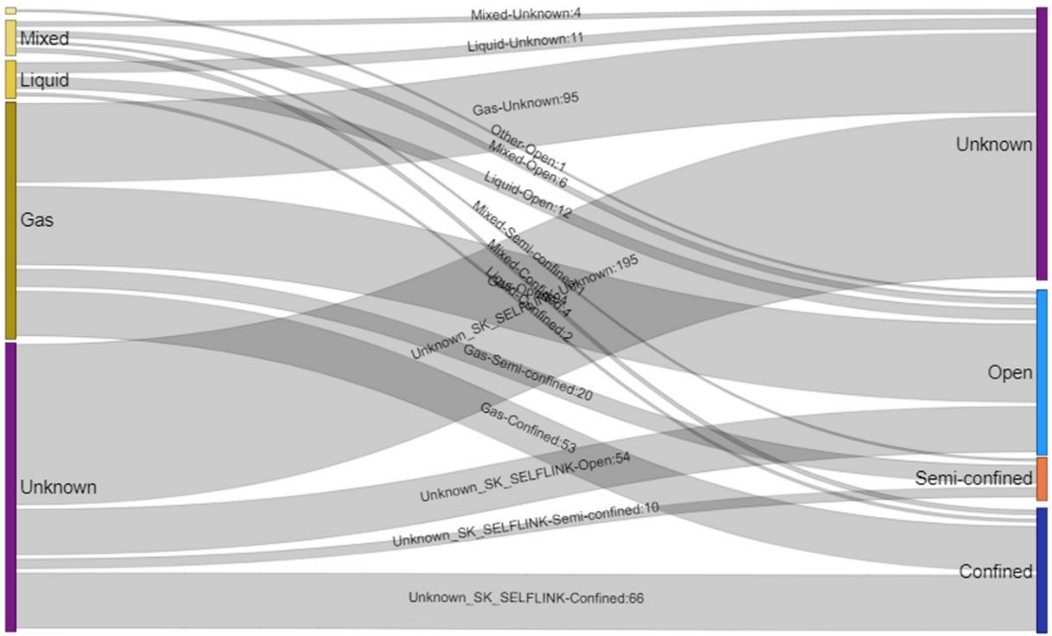
Distribution of events by cause category

Cause type	Number of events	Fatalities	Fatalities per event	Injured persons	Injuries per event
Technical / Mechanical	145 (23.1%)	39	0.27	144	0.99
Unknown	126 (20.0%)	73	0.58	150	1.19
Operational	121 (19.2%)	59	0.49	228	1.88
Human Error	59 (9.4%)	20	0.34	145	1.54
Organizational	57 (9.0%)	53	0.93	311	5.87
Environmental / External Causes	10 (1.6%)	15	1.5	91	9.10
Other Cause Categories	18 (2.8%)	7	0.39	16	0.89
Total	533 (85.1%)	266		1085	

- Technically-caused events are **frequent**, but have **limited consequences**
- Operational causes are related to **lack of inspection** or **inspections not tailored** toward hydrogen-induced degradations
- Improvements in the existing **RBI standards** are needed

Classification of events by release phase

- Most of the accidents are caused by gaseous releases
- Less than **1%** of the total share of hydrogen is used **in liquid form**
- LH_2 is used for **rocket propulsion**, **automotive**, and specific **industrial applications**
- Hydrogen is **stored outdoor**, **whenever possible**, to reduce the risk of explosions



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Conclusions

- Roughly **10%** of the accidents in HIAD 2.0 are caused by **material failures**
- **33%** of those are unambiguously **caused by hydrogen embrittlement**
- These event reports has been collected and analyzed
- Most of these events could have been **prevented** through proper **inspection and maintenance**

Steam methane reformers

LH_2 cryogenic vessels

Electrolyzers

Hydrogen pipelines

GH_2 cylinders

Thank you for your attention

Contact

Alessandro Campari: alessandro.campari@ntnu.no