Presented at FABIG Technical Meeting 111 "From Research to Practice: Insights From Recent Projects on Hydrogen & Ammonia Safety", 24 March 2026.
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Probabilistic models delivered by SAFEN and HICON

24.03.2026 Ingar Fossan

SAFEN Safe Energy Carriers

Closing knowledge gaps, sharing learnings and developing risk-based methodologies for hydrogen, ammonia and CCS facilities

Status: JIP started Q1 2022, Phase 2 2023-2025
Phase 3 starts Q2 2026!

Schedule: Phase 3 (1,5 years)

Funding: Industry partners and consultancies (in-kind)

Budget: 10 MNOK for Phase 1
23 MNOK Phase 2, X MNOK Phase 3

Project owner: Safetec

Partners: Consultancies, Authorities, Energy companies /Asset owners

SAFEN Phase 1 → **SAFEN** Phase 2 / **HICON** Hydrogen Ignition Control → **SAFEN** Phase 3

March 2022 · *Sep 2023* · *Jan 2024* · *Des 2025* · *Jul 2027*

Knowledge	Models	Application
Incident data	Leak frequency process equipment	Recommendations for application of SAFEN results • Use cases • Design of facilities/ installations • Standards and guidelines
Failure analysis	Leak frequency transfer operations	
Task analysis	Leak frequency storage tanks	
Experiments	Ignition probability H2 and NH3	

SAFEN Phase 3

II – Data and task analysis
Analyse data and human tasks

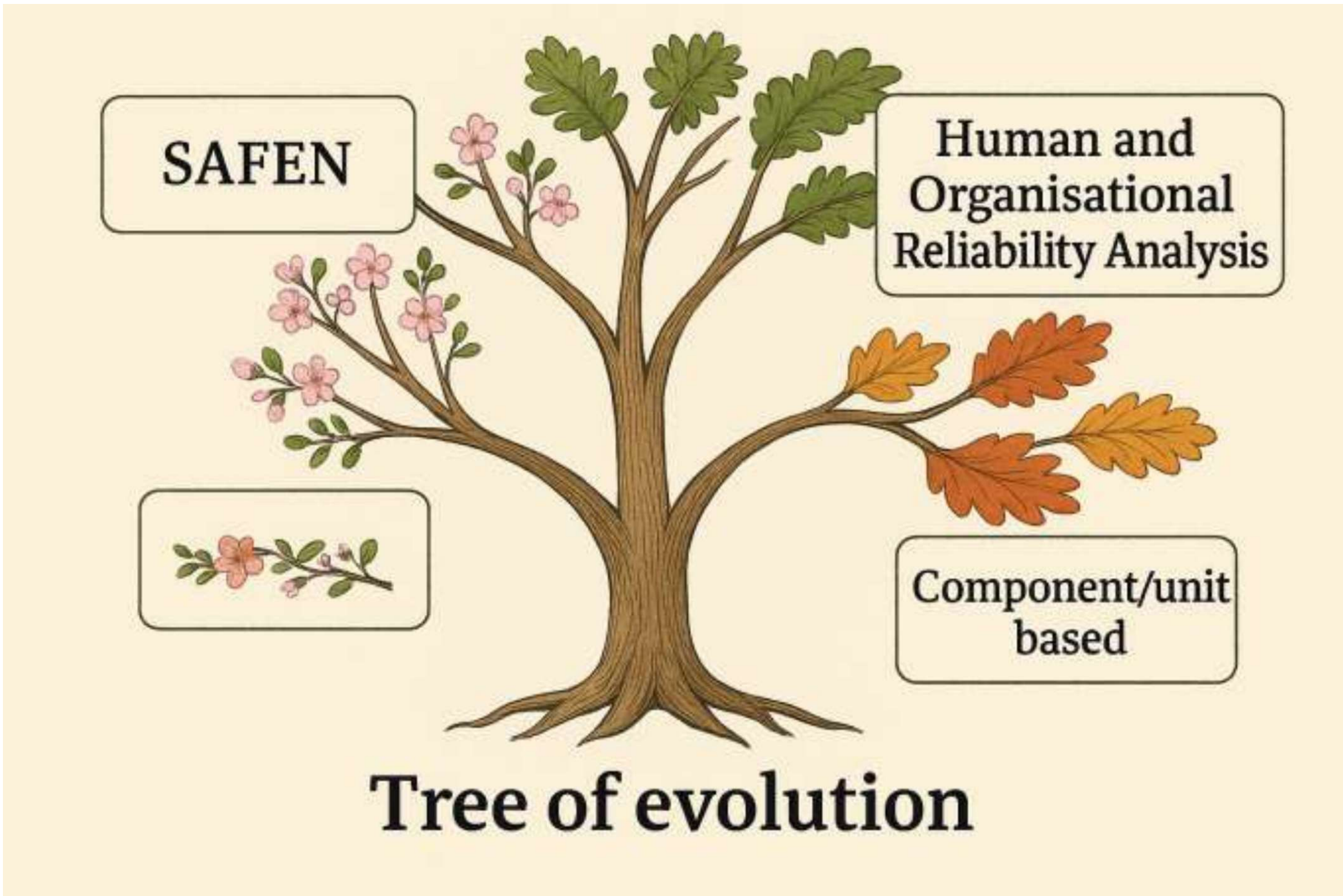
III – Model improvement
Improve SAFEN models, guidelines, advice for design and operation

I – Use case analysis
Quantitative risk analysis (QRA) of use cases
Application and testing of SAFEN models

IV – Scenario & consequence modelling
LoC scenario modelling and interface to consequence modelling

Project management and administration

Dissemination


SAFEN
Human and Organisational Reliability Analysis
Component/unit based
Tree of evolution

SAFEN

Statements frequently found in QRA's before SAFEN

«It is recommended to reduce the number of valves to reduce the risk for fires in the process area»

«It is recommended to reduce the number of flanges and fittings to reduce the risk for explosions in the hydrogen storage»

«It is recommended to reduce the number of instruments to reduce the risk for fires in the process area»

«It is recommended to reduce the number of transfer operations to reduce the risk for toxic exposure to third parties.

Conclusions hopefully found in QRA's after SAFEN

«It is recommended to implement DB&B arrangements towards all parts of the system likely subjected to maintenance while system is on stream»

«It is recommended consistently adhere to vendor requirements on installation of flanges and fittings. Rigorous procedures must be established and installation can only allowed by personnel with approved experience and competence»

«It is recommended to verify that all instruments are adequately supported such that they cannot fail due to fatigue»

«It is recommended to ensure that valves cannot be operated manually under a transfer operation causing fluid hammer»

«It is recommended to ensure that all receiving storage tanks are equipped with dedicated overfill protection system»

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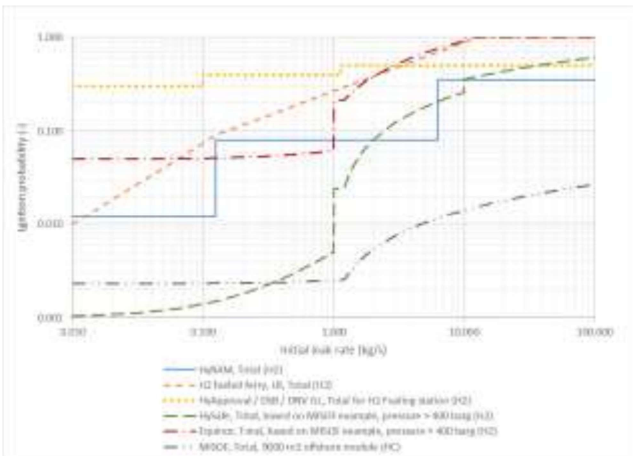
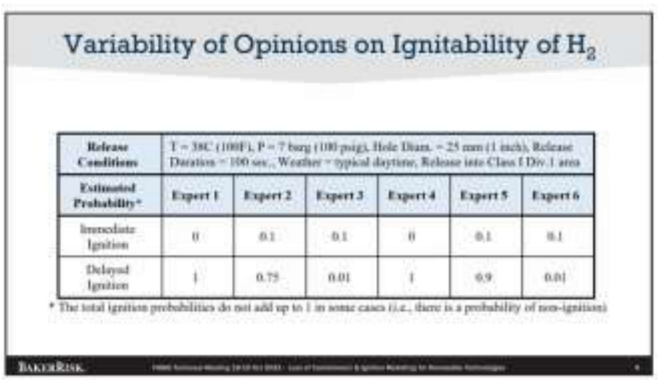
Statements frequently found in QRA's before SAFEN

«Ignition probability is 10% at your facility»





Release Conditions	T = 38C (100F), P = 7 barg (100 psig), Hole Diam. = 25 mm (1 inch), Release Duration = 100 sec., Weather = typical daytime, Release into Class I Div.1 area					
Estimated Probability*	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6
Immediate Ignition	0	0.1	0.1	0	0.1	0.1
Delayed Ignition	1	0.75	0.01	1	0.9	0.01

* The total ignition probabilities do not add up to 1 in some cases (i.e., there is a probability of non-ignition)

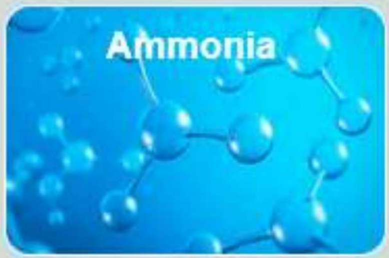
Conclusions hopefully found in QRA's after SAFEN

«The likelihood for ignition at your facility can be reduced by:

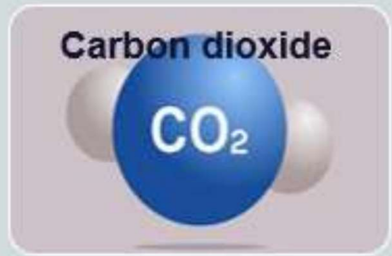
- *extending ATEX zone*
- *use of Non-Ex equipment only inside habitat*
- *eliminate the potential for generation of impacts*
- *enhance reliability of barriers controllling formation of explosive atmosphere within process equipment*
- *use slow closing valves instead of rupture disc for emergency release to hydrogen vent (to avoid diffusion ignition)*
- *…*

We have some data – but rarely with quantitative description of population!

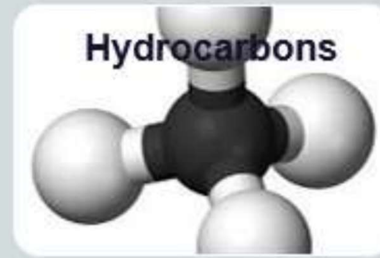
- HIAD
- H2-rich process streams leaks from 3 onshore oil & gas facilities
- Various literature sources, scientific articles and reports
- HyRAM prop. data.
- KHK, Japan



- 3 ammonia facilities
- ZEMA database
- Technical Safety BC in Canada
- Various literature sources, scientific articles and reports

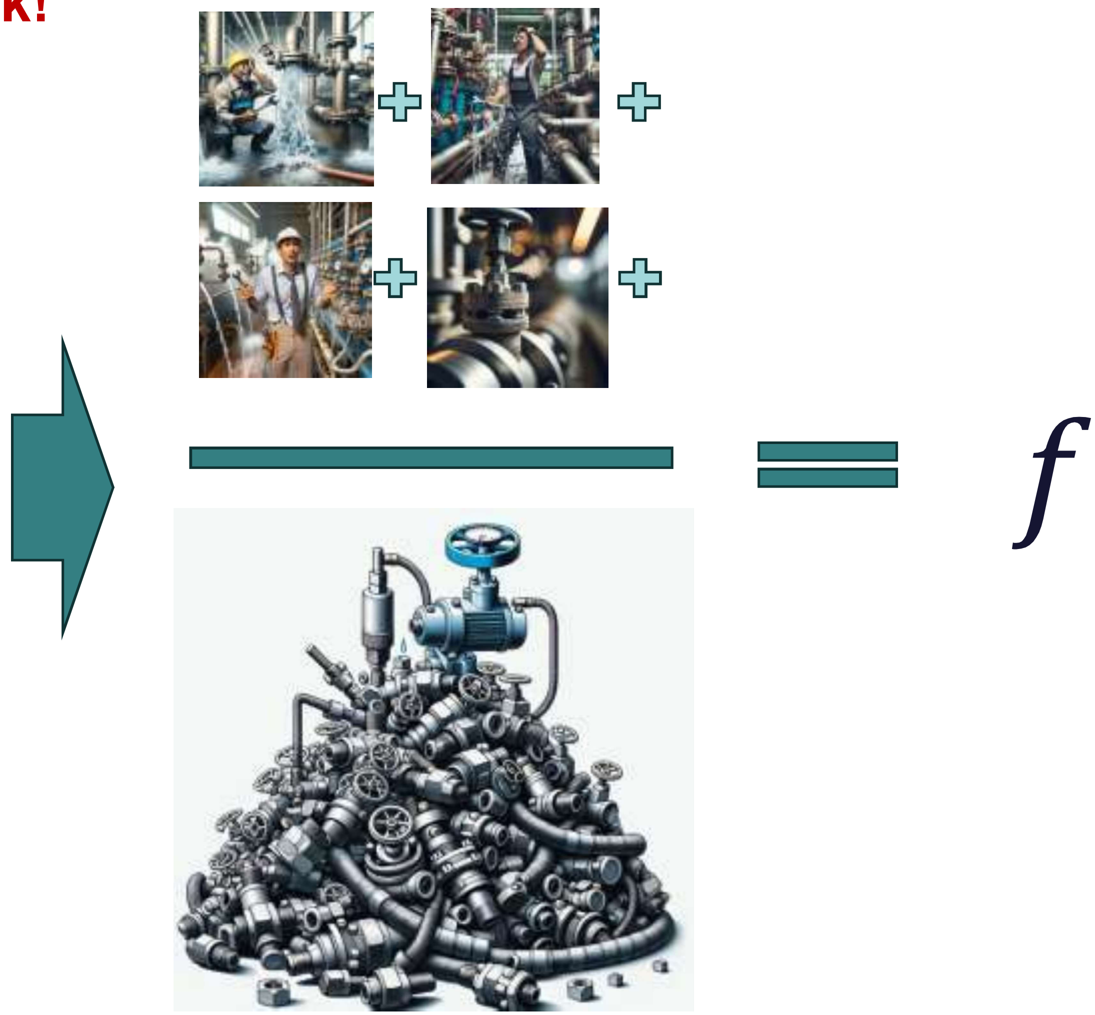


- ARIA database (Bureau for Analysis of Industrial Risks and Pollution of the French Ministry of Environment)
- Various literature sources, scientific articles and reports



- Norwegian O&G experience offshore/ onshore since about 1992
- UKCS (HCRD) since 1992
- Various literature sources, scientific articles and reports

Classical modelling principle does not work!



Why do we say so – anecdotal information

"The most probable cause of the diesel leakage was fatigue fracture in the feed pipes for a fuel injection pump due to the pump being loose. AIBN is of the opinion that insufficient job specification in the ***shipping company's maintenance system had contributed to the fuel injection pump not being sufficiently fastened*** *and to the indicator valve not being sufficiently insulated."*

aibn

REPORT Sjø 2013/02

REPORT ON THE INVESTIGATION OF A MARINE ACCIDENT NORDLYS LHCW - FIRE ON BOARD DURING APPROACH TO ÅLESUND
15 SEPTEMBER 2011

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Why do we say so – anecdotal information

ased new video from a hydrogen truck explosion in Colton that left one person dead and another injured.

alif. (KABC) -- Police have released new video from a hydrogen truck
n Colton that left one person dead and another injured.

International Association for Hydrogen Safety (HySafe)
3,095 followers
1w •

CALIFORNIA: **One dead, one seriously injured in hydrogen explosion involving truck trailer**

HySafe is saddened to report that one person has died and another has been seriously injured following a hydrogen explosion in Colton, California, approximately 55 miles east of Los Angeles.

According to local media reports:
- The explosion occurred at around 10:45 pm local time on Tuesday in a truck storage area.
- The blast involved a parked truck trailer containing compressed hydrogen canisters.
- At least two trucks at the site were reportedly carrying hydrogen cylinders.
- The explosion buckled the perimeter fence and ignited a fire that engulfed one truck and a nearby car.
- Firefighters extinguished the blaze within approximately 20 minutes.
- One individual was later found deceased at the scene.
- A second person sustained serious injuries, believed to be burns.

Reports indicate that technicians may have been working on hydrogen-containing trucks at the time of the incident. The precise cause of the explosion has not yet been confirmed, and an investigation is underway by local authorities.

The trailer involved reportedly belonged to Pilot Company, which has stated that it has temporarily suspended compressed hydrogen operations and is cooperating fully with investigators.

Hydrogen transport and mobile storage present distinct safety challenges compared to ...as cylinders, particularly ...for:

...systems

...injured individual.

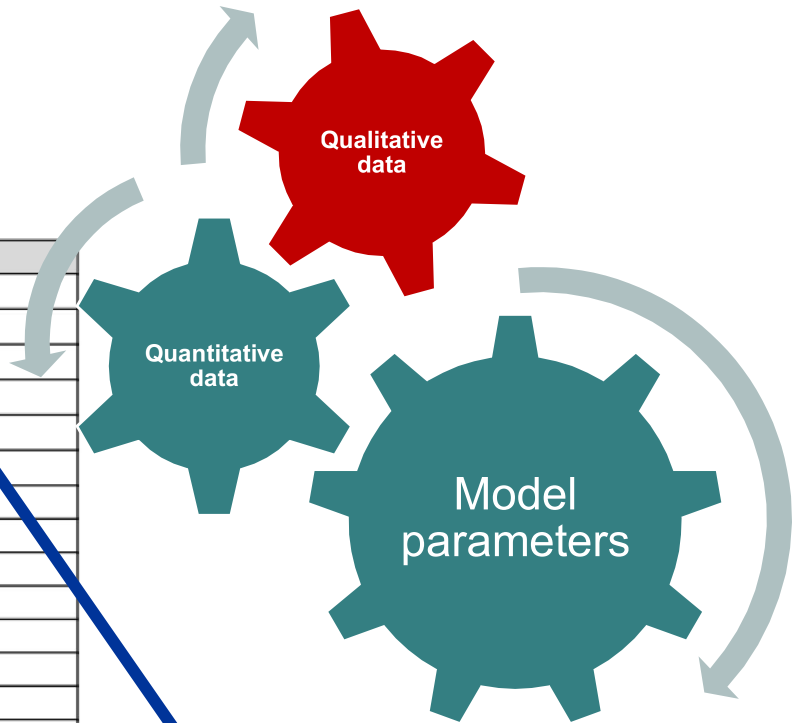
HySafe will continue to follow developments and share verified information as the investigation progresses.

Reports indicate that technicians may have been working on hydrogen-containing trucks at the time of the incident. The precise cause of the explosion has not yet been confirmed, and an investigation is underway by local authorities.

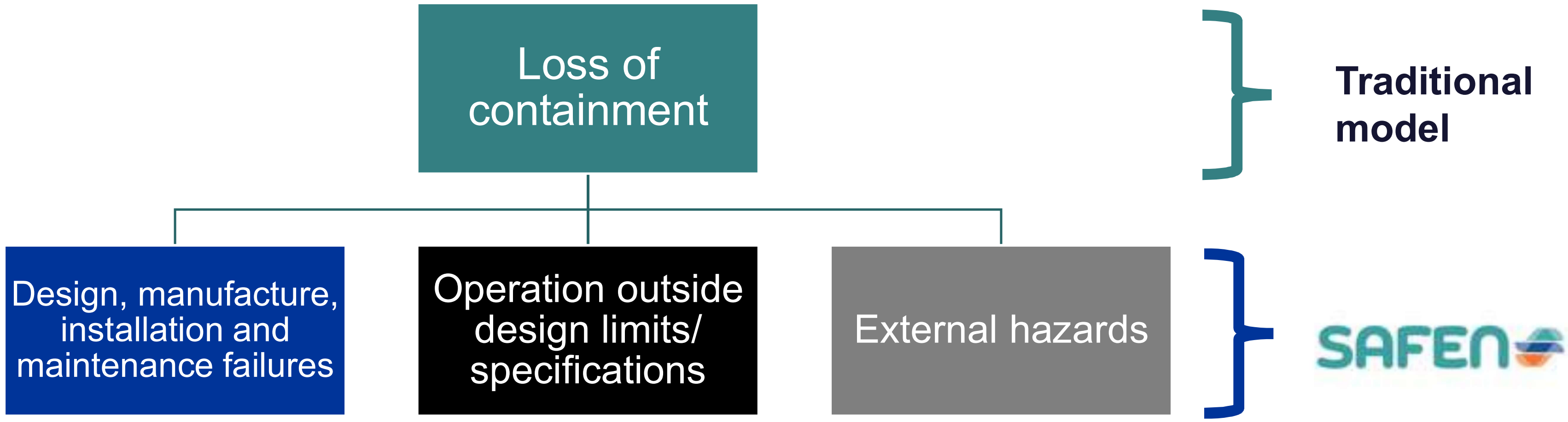
We have been digging deep!

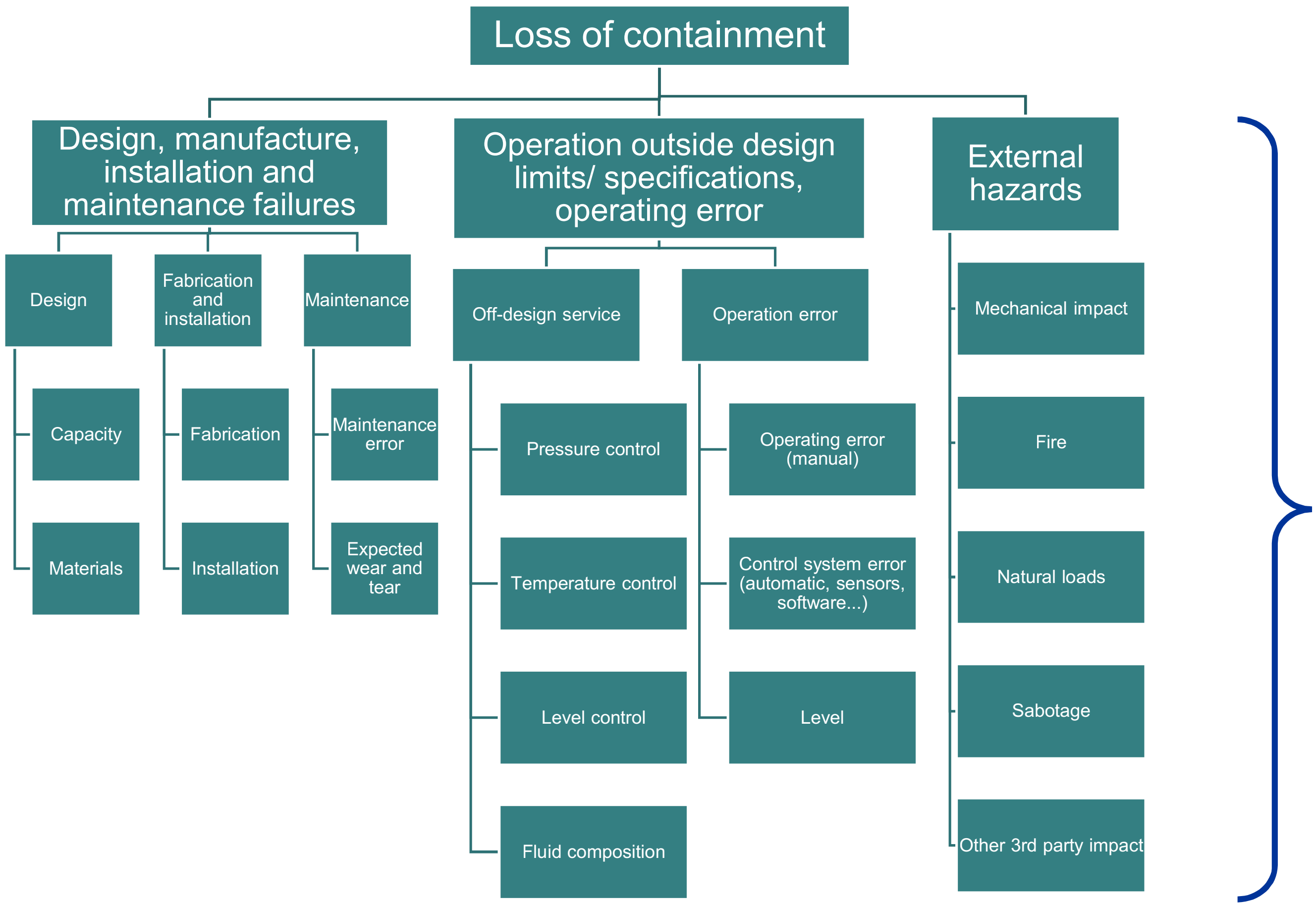
Report no.	Title
ST-000580-000	SAFEN model's validity: Knowledge, data and uncertainties
ST-000580-001	Failure frequencies for sets of identical units or operations
ST-000580-002	Fluid specific failure frequencies
ST-000580-003	Failure frequencies for tubing and fittings
ST-000580-004	SAFEN leak frequency model for vessels and storage tanks
ST-000580-005	Insights from incident data for modelling of leak frequencies
ST-000580-006-A	SAFEN LoC model - Framework for SAFEN LoC model
ST-000580-006-B	SAFEN LoC model - Failure cases for the SAFEN LoC model
ST-000580-006-C	SAFEN LoC model - The SAFEN LoC model
ST-000580-009	Loss of Containment due to material handling
ST-000580-010	Review of ammonia accidents in eMARS
ST-000580-011*	Review of hydrogen accidents in eMARS
ST-000580-012	Catastrophic tank failures in eMARS
ST-000580-013	Ammonia paper OSHA fatal accidents
ST-000580-013	Review of ammonia accidents in the OHSA database
ST-000580-014	Additional ammonia incidents
ST-000580-015 *	Review of hydrogen accidents in OSHA and NTSB
ST-000580-016 *	HIAD - Electrolysis incidents
ST-000580-017 *	Hydrogen industry incidents review (HIAD 2.1)
ST-000580-018 *	Hydrogen transport incidents review (HIAD 2.1)
ST-000580-019	Ammonia incidents in the Japanese HPGS database
ST-000580-020	SAFEN leak frequency model for transfer operations
ST-000580-021	Stakeholders' expectations to risk modelling
ST-000580-023	SAFEN leak frequency model for process systems
ST-000580-024	SAFEN leak frequency model for pipelines
ST-000580-100	The SAFEN project and models – a short introduction
ST-17462-3	WP2 SAFEN database outline report (update of SAFEN Phase 1 report with results from SAFEN Phase 2)

* in cooperation with HICON



A. Correct
B. Tube end not closing gap in fitting
C. Tube end excessively rounded off
D. Excessive torque


Loss of containment
Design, manufacture, installation and maintenance failures
Operation outside design limits/ specifications
External hazards
Traditional model


Loss of containment
Design, manufacture, installation and maintenance failures
Operation outside design limits/ specifications, operating error
External hazards
Design
Fabrication and installation
Maintenance
Capacity
Materials
Fabrication
Installation
Maintenance error
Expected wear and tear
Off-design service
Operation error
Pressure control
Temperature control
Level control
Fluid composition
Operating error (manual)
Control system error (automatic, sensors, software...)
Level
Mechanical impact
Fire
Natural loads
Sabotage
Other 3rd party impact

Loss of containment

- Design, manufacture, installation and maintenance failures
- Operation outside design limits/ specifications
- External hazards

Design, manufacture, installation and maintenance failures

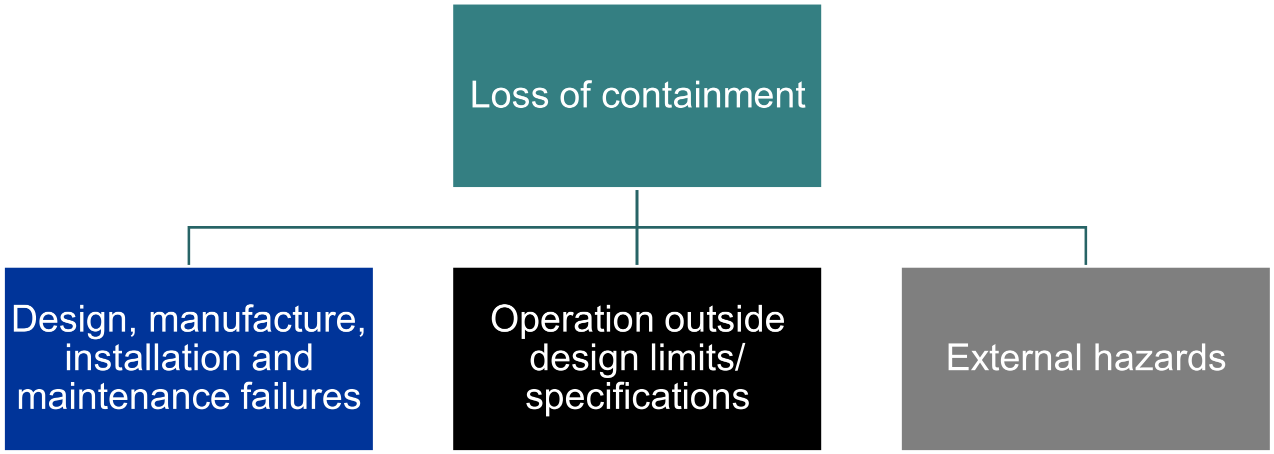
- P1110 Design and fabrication related causes
- P1101 Failure of valve body seals and gaskets
- P1102 Failure of gaskets and seals in piping systems and equipment
- P1103 Failure of instrument
- P1104 Failure of tubing and fitting systems
- P1106 Maintenance failure
- P1105 Degradation of pipes and pipelines
- V1101 Vessel failure due to degradation
  D1101 Pipeline - degradation
- MH1110 Design failure

Operation outside design limits/ specifications

- P1207 Operational failure
- P1209 Failure of pumps
- T1201 Transfer operation – Fluid hammer
- T1202 Transfer operation - Overfilling
- T1203 Transfer operation - Drain and vent failure
- T1204 Transfer operation - Connection failure
- T1205 Transfer operation - Valve line-up
- V1202 Vessel failure due to operational failure and overload
- V1205 Vessel failure due to internal explosion
- D1202 Pipeline - operational
- MH1207 Operational failure

External hazards

- P1310 Process systems – external hazards
- T1305 Transfer operation - Dislocation
- V1303 Vessel failure due to external hazard
- D1303 Pipeline - external hazards
- MH1303 External hazards



$$F_{total} = F_I + F_{II} + F_{III}$$

$$= \sum_i F(\text{failure case related to I})_i + \sum_j F(\text{failure case related to II})_j + \sum_k F(\text{failure case related to III})_k$$

Defining the failure cases

A failure case format is being defined

- Qualitative description of scope and limitations
- Equipment
- Failure mechanisms and causes
- Likely consequences (hole sizes, etc.)
- Risk mitigating measures
- References to analysis and additional information

"Failure case is a category of loss of containment scenarios with a similar set of circumstances characterising the chain of events. The commonalities are typically related to failure mechanisms, causes, equipment, systems and operations involved, but other aspects may also apply.

The scenarios falling into a failure case category does not have to possess similar attributes on all parameters mentioned. For example, some failure cases are weighted towards the failure mechanisms, while others are weighted towards the faulty state of the equipment involved. The term failure case is used at various levels when categorizing similar types of scenarios. The failure case categories used in the SAFEN loss of containment frequency models are defined more specifically to avoid disambiguation."

9.2 V1202 Vessel failure due to operational failure and overload

Vessel failure due to operational failure and overload			ID V1202
Loss of containment due to tank (shell) failure resulting from overload. Overload typically means that the pressure exceeds the capacity of the vessel. Note that tank failure due to other conditions such as too low pressure, too steep pressure gradients and too low/too high temperature is possible. Internal explosion or other chemical reaction is not included in this context.			
Industry, system, equipment and component			
Storage tank or process vessel, pressurised or atmospheric			
Faults			
Vessel	Rupture of vessel or large leak.		
Vent	Excessive or abnormal release through vent		
Inventory	Full inventory can be released, small releases are not considered in this context. For pressure vessels, inventory may exceed normal operating inventory.		
Hole size	For overpressure scenarios, full ruptures are likely. Hole equal to nozzle diameter is also possible.		
Failure mechanisms		Failure causes	
3.1 Control failure 3.2 No signal/ indication/alarm 3.3 Faulty signal/ indication/alarm	3.5 Software error 4.0 Electrical failure 5.4 Other unit/cascading failure	3.1 Off-design service 3.2 Operating error	The failure is operational in the sense that the control of the process fails. This may be due to operator or equipment failure (sensors, transmitters, valves)
Specific assessment of failures			
HAZOP	Specific analyses identify critical operations and failures		
Type	Tank designs (single containment, double containment, full containment, etc.) is generally not governing for this failure case.		
Management failures	4.1 Documentation error 4.2 Management error	Training and education. Weaknesses in procedures, specifications, etc.	
Other circumstances	It is assumed that HAZOP, pressure protection analysis and other relevant analyses to identify and correct system weaknesses. Human factors including control room response to alarms, etc. are vital.		
Risk mitigation	Robust solutions chosen, e.g. high design pressure, wide operational temperature interval. Ensure reliable pressure and temperature monitoring.		
Model Outline			
A generic (control) failure frequency may be applicable. For double containment and full containment solutions, the frequency for catastrophic failure due to operational failure should be evaluated for the specific configuration/solution and the specific scenario.			

HICON Model framework

- An equivalent framework for assessment of ignition probability will leverage the coupling between ignition control barrier design and ignition probability modelling
- The **Ignition Case** concept has been established

A category of ignition sources and/or ignition mechanisms with corresponding causes described by a set of similar circumstances.

The circumstances leading to ignition can be related to a single component, the system or driven by ongoing activity.

Key differentiators between ignition cases are the location of the ignition source and at what time the ignition occurs.

Loss of containment

Design, manufacture, installation and maintenance failures

Operation outside design limits/ specifications

External hazards

- P1110 Design related causes
- P1101 Failure of valve body seals and gaskets
- P1102 Failure of gaskets and seals in piping systems and equipment
- P1103 Failure of instrument due to installation error
- P1104 Failure of tubing and fitting systems
- P1106 Maintenance failure
- P1105 Degradation of pipes and pipelines
- P1207 Operational failure
- P1209 Failure of pumps
- P1310 Process systems – external hazards

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Loss of containment

- Design, manufacture, installation and maintenance failures
- Operation outside design limits/ specifications
- External hazards

V1101 Vessel failure due to degradation

V1202 Vessel failure due to operational failure and overload

V1303 Vessel failure due to external impact

V1205 Vessel failure due to internal explosion

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Loss of containment

- Design, manufacture, installation and maintenance failures
- Operation outside design limits/ specifications
- External hazards

T1201 Transfer operation – Fluid hammer

T1202 Transfer operation - Overfilling

T1203 Transfer operation - Drain and vent failure

T1204 Transfer operation - Connection failure

T1205 Transfer operation - Valve line-up

T1305 Transfer operation - Dislocation

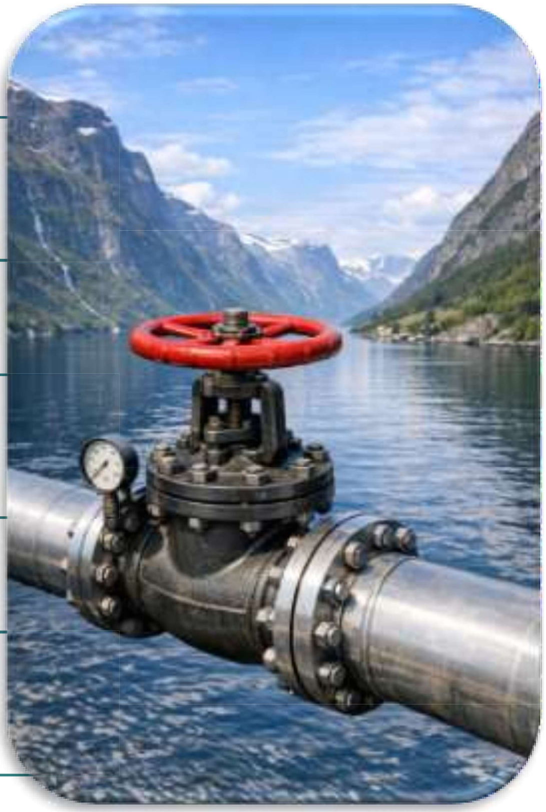
Loss of containment

- Design, manufacture, installation and maintenance failures
- Operation outside design limits/ specifications
- External hazards

D1101 Pipeline failure due to degradation

D1202 Pipeline failure due to operational overload

D1303 Pipeline failure due to external hazards



Loss of containment

- Design, manufacture, installation and maintenance failures
- Operation outside design limits/ specifications
- External hazards

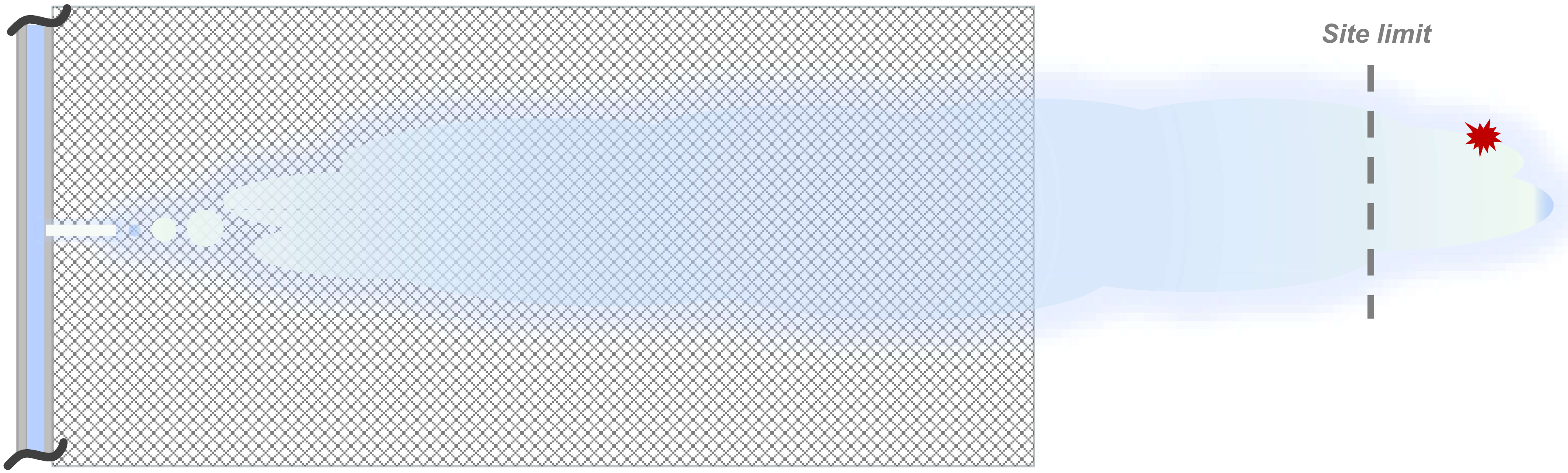
MH1110 Design, manufacture, installation and maintenance failures

MH1207 Operation outside design limits specification

MH1303 External hazards

Ignition cases

- IC1001 Internal ignition
- IC1002 Internal ignition in vent system
- IC2001 Ignition of cold vent
- IC2002 Ignition due to high process fluid temperature
- IC2003 Event ignition of LoC Failure cases
- IC2004 Ignition of LH2 leaked onto/in water
- IC3001 Ignition by jet release
- IC3002 Ignition in classified area – fixed equipment
- IC3003 Ignition in classified area - temporary Non-Ex equipment
- IC4001 Ignition outside classified area - fixed Non-Ex equipment
- IC4002 Ignition outside classified area - hot gas point sources
- IC4003 Ignition outside classified area – activity
- IC5001 Ignition outside facility premises



Inside system
- *ignition inside electrolyzer*
- *diffusion ignition in vent*
- *ignition inside reactor/vessel*

Ignition at nozzle/outlet
Autoignition due to high T
Failure mechanism and ignition mechanism related
e.g., failure of pump or compressor leading to electrostatic
Thunderstorm/blizzard/snow discharge

Ignition by jet release
- *mechanical impact*
- *generation of electrical discharge*
- *LH2 into water*

Ignition inside classified area
- *faulty Ex equipment*
- *introduction of* ***non-Ex equipment***
(vehicles, tools, activity)

Ignition outside classified area
- *fixed non-Ex equipment (e.g., transformer)*
- *temporary non-Ex equipment*
- *Hot gas point (flare, exhaust)*
- *Vehicles*

Ignition outside site
- *anything…*

Time

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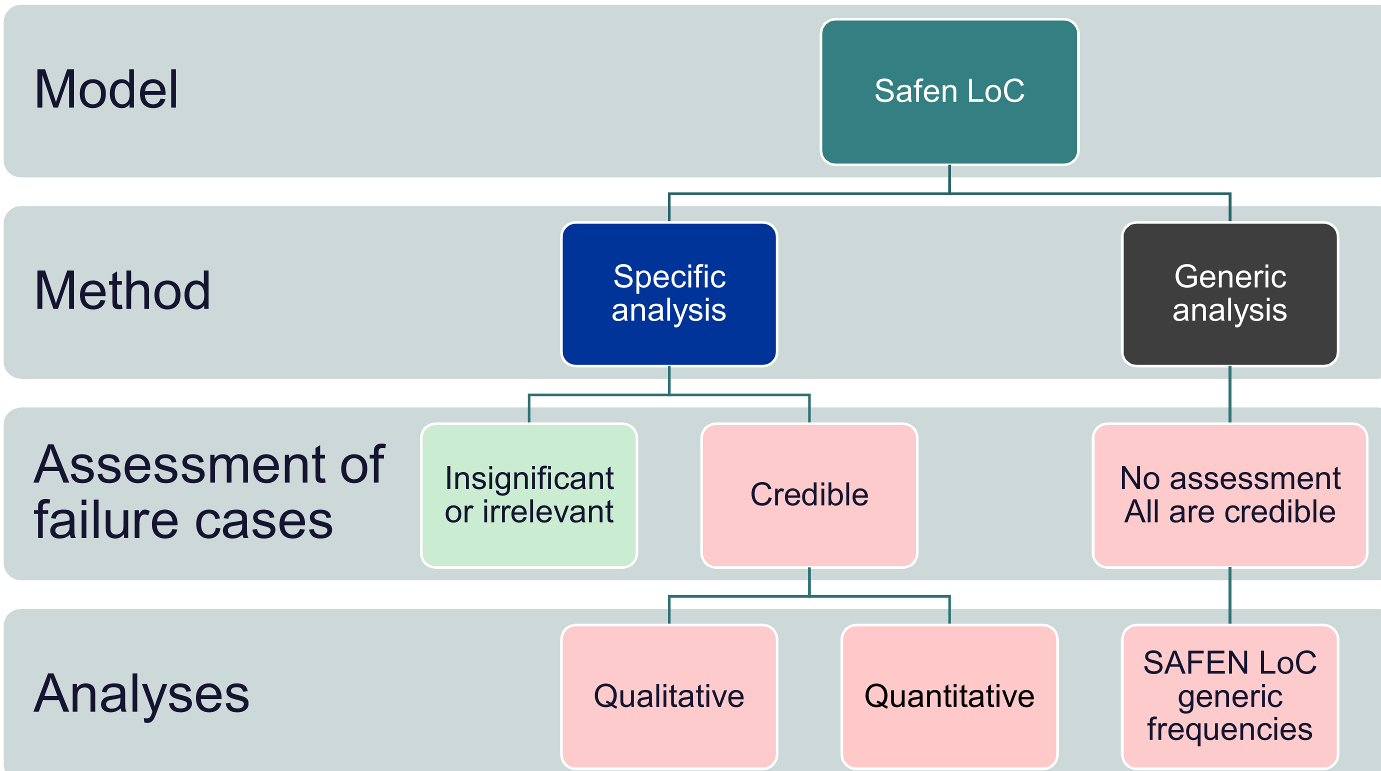
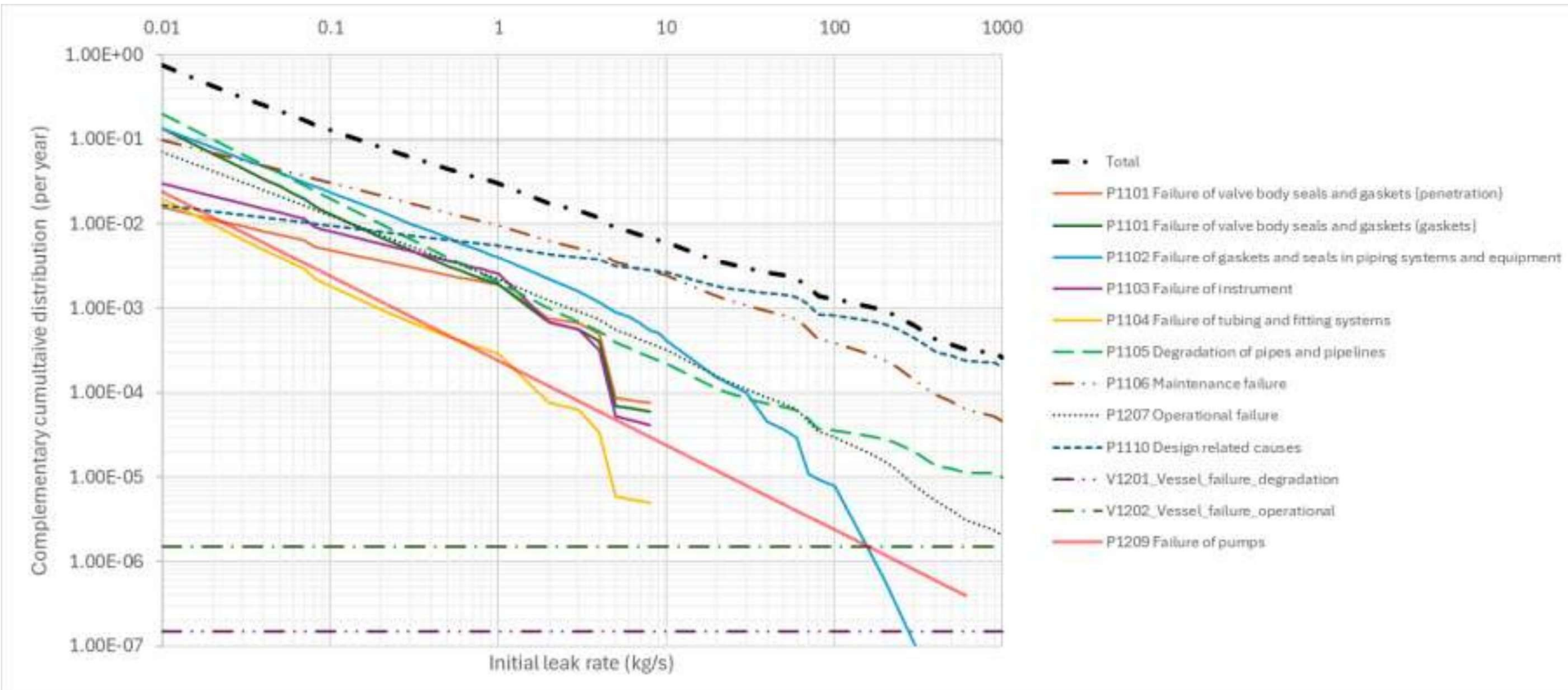
Methodology for assessment of failure cases



$$\text{Loss of containment frequency} = \sum_i F(\text{failure case})_i$$

Typical offshore installation
- The SAFEN model enable better analysis



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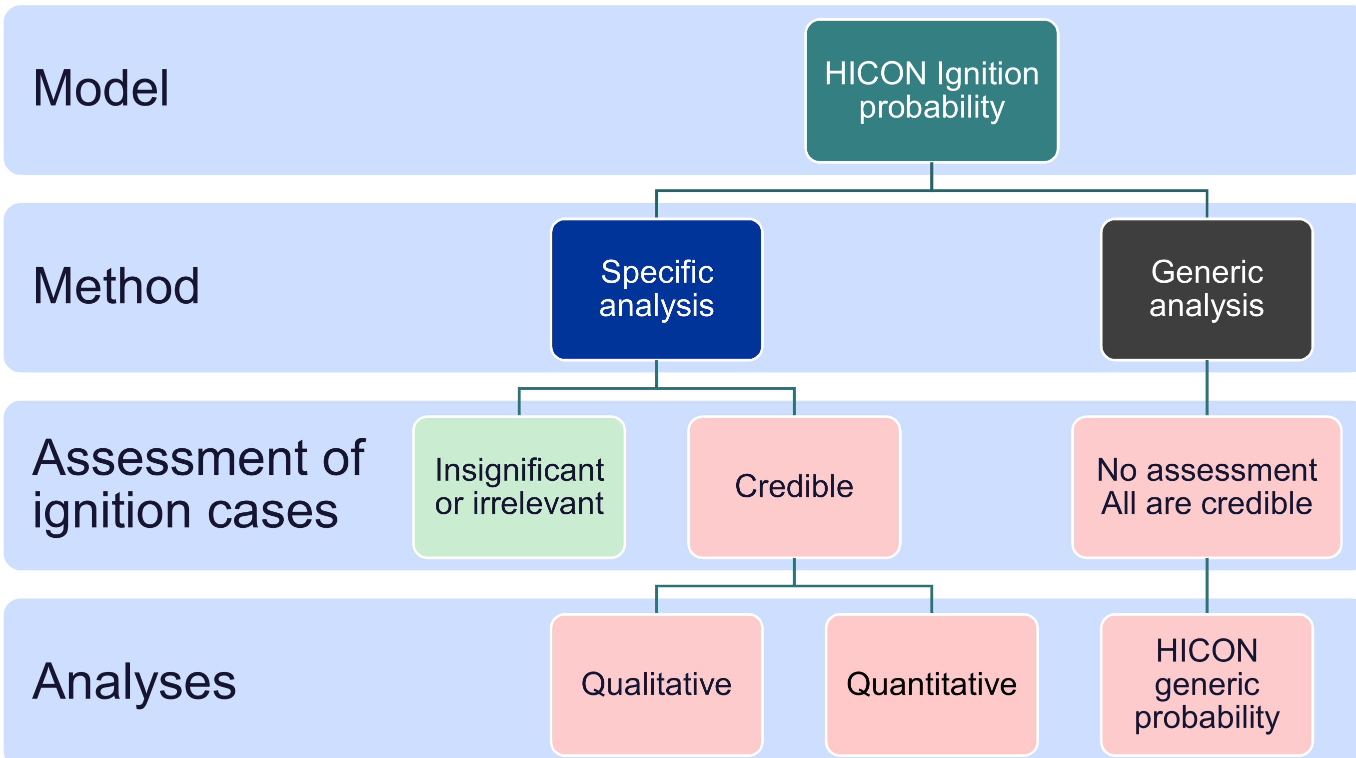
Methodology for assessment of ignition cases



$$\text{Ignition probability} \bigcup_i I(\text{Ignition case })_i$$

General equation for LoC modelling

$$F_{Total}(N) = f \cdot N$$

- f is the generic failure frequency (for $N = 1$)

$$F_{Total}(N) = \beta \cdot f + (1 - \beta) \cdot f \cdot N$$

- β is the common cause factor (ref. reliability engineering)

$$\boldsymbol{F_{Total}(N) = \beta \cdot f + (1 - \beta - \varepsilon) \cdot f \cdot N^{k} + f \cdot \varepsilon \cdot N}$$

- $\boldsymbol{k}$ is the exponent that describe the relation between the number of components or operations and the total loss of containment frequency, $F_{Total}(N)$
- $k = 1$, $\beta = 0$ and $\varepsilon = 0$ is generally applied in quantitative risk modelling, which means the LoC frequency is proportional to the number of components.

Pros and cons
The proposed model is flexible and can be applied to mimic system behaviour as required.

It may be hard to quantify the parameters β and k based on data and other evidence

Remember that $k = 1, \beta = 0$ and $\varepsilon = 0$ is a quantification as well

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Scaling with the number of operations

- The same equation is applied (for process accidents, vessels, fluid transfer, and material handling)

$$F_{Total}(N) = \beta_i \cdot f + (1 - \beta_i - \varepsilon_i) \cdot f \cdot {N_i}^{\kappa_i} + \varepsilon_i \cdot f \cdot N_i$$
Type equation here.

- Identical or similar operations
  - Technically, the same design means design failures are not proportional to the number of units
  - Operationally, parallel use or similar operational regime

	Generic model	Specific model (similar units and/or operations)
Values β can possess:	$\frac{1}{2}$	$\frac{2}{3}$
Values κ can possess:	$\frac{1}{2}$	$\frac{1}{3}$
Values ε can possess:	5%	1%

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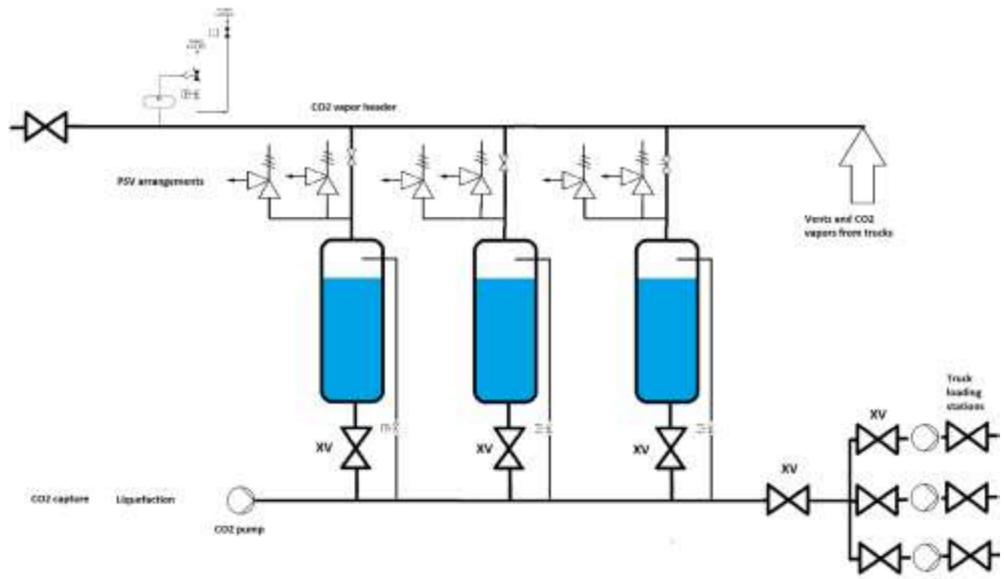
Example: CO2 storage



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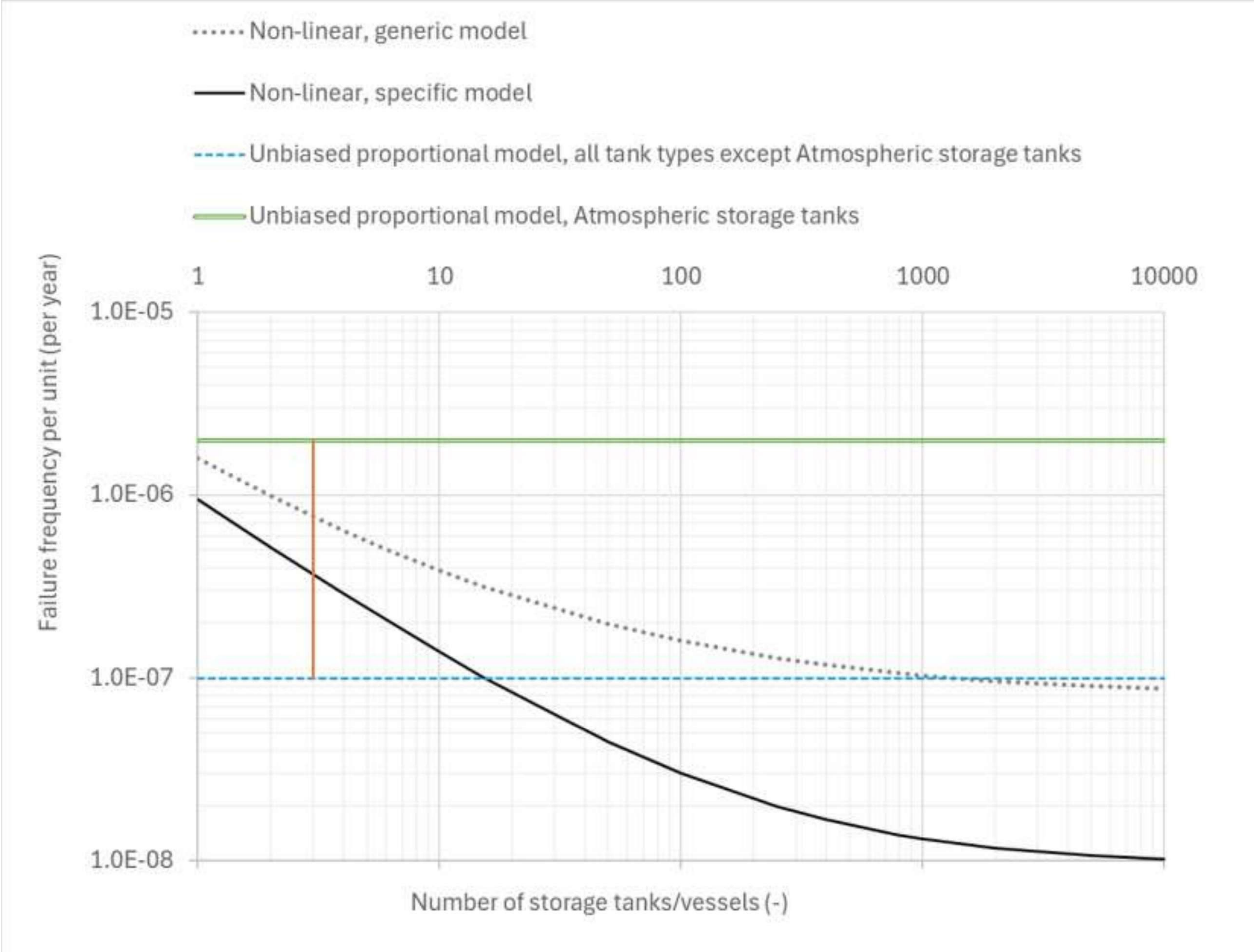
Non-linear, generic model
Non-linear, specific model
Unbiased proportional model, all tank types except Atmospheric storage tanks
Unbiased proportional model, Atmospheric storage tanks
Failure frequency per unit (per year)
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1
10
100
1000
10000
Number of storage tanks/vessels (-)

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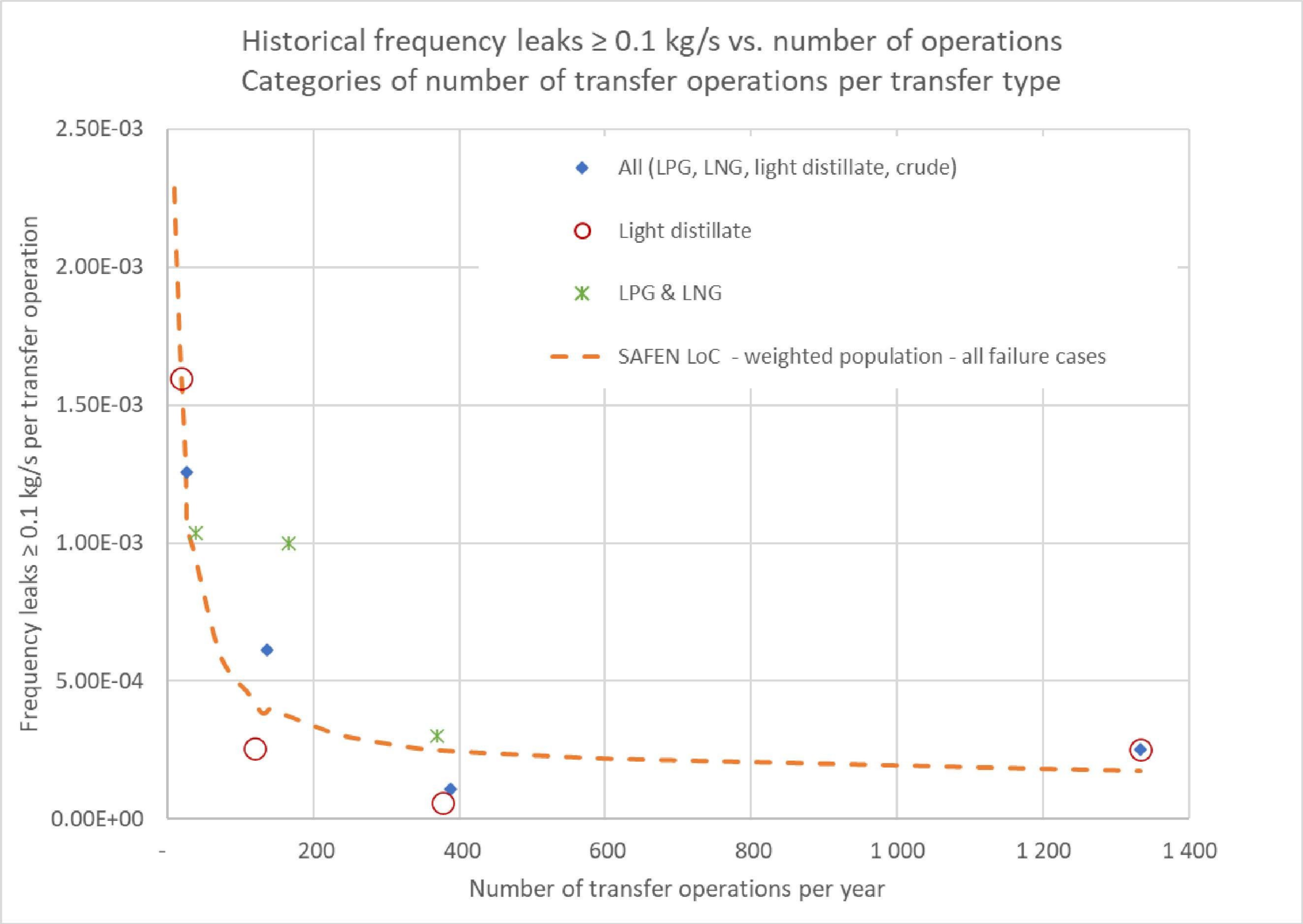
Historical frequency leaks ≥ 0.1 kg/s vs. number of operations
Categories of number of transfer operations per transfer type
Frequency leaks ≥ 0.1 kg/s per transfer operation
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
-
200
400
600
800
1 000
1 200
1 400
Number of transfer operations per year
All (LPG, LNG, light distillate, crude)
Light distillate
LPG & LNG
SAFEN LoC - weighted population - all failure cases

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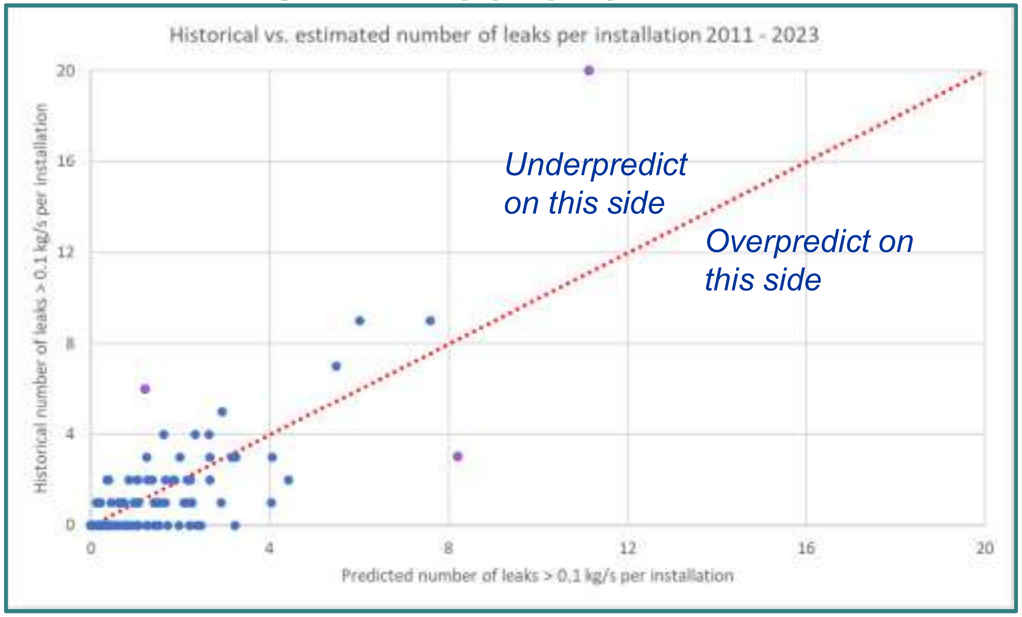
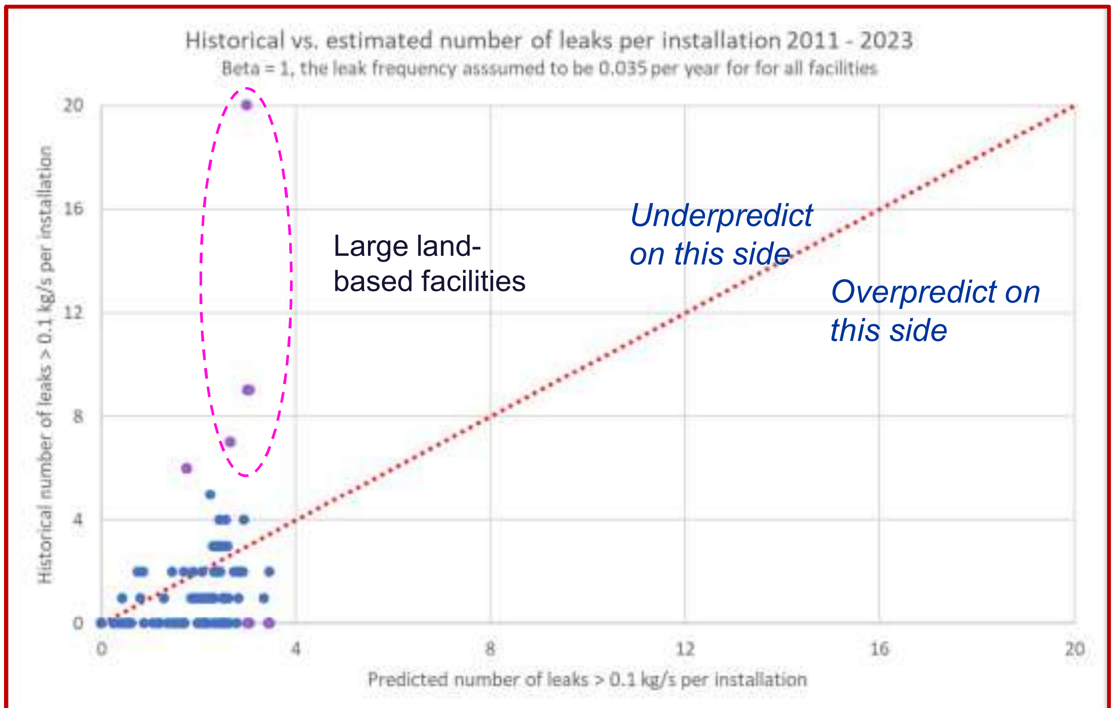
Presented at FABIG Technical Meeting 111 "From Research to Practice: Insights From Recent Projects on Hydrogen & Ammonia Safety", 24 March 2026.
See https://fabig.com/publications-and-videos/technical-presentations-videos/technical-meeting-111/ for all presentations and presentation recordings.

SAFEN Generic



- **90% confidence interval**
  - 2 out of 99 facilities underpredicting
  - 1 out of 99 facilities overpredicting

ß = 1, all common



- **90% confidence interval**
  - 5 out of 99 facilities underpredicting
    4 of these large land-based facilities
  - 6 out of 99 facilities overpredicting

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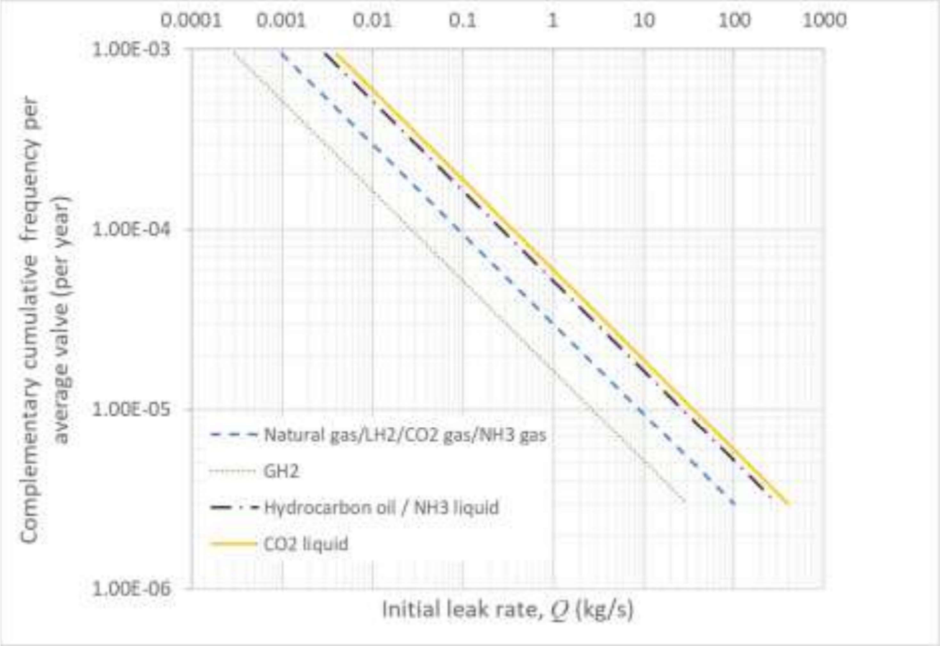
Frequency – leak rate dependency

- For some failure cases, a range of leak rates is possible.
- LoC data indicate rate-frequency relations as shown, and such relations are used to model LoC frequencies and corresponding release rates
- Simplistic model reflecting fluid properties
- The main difference is density – high density means higher frequency for the same initial leak rate
- Pressure is not the driving parameter: hole size not a parameter



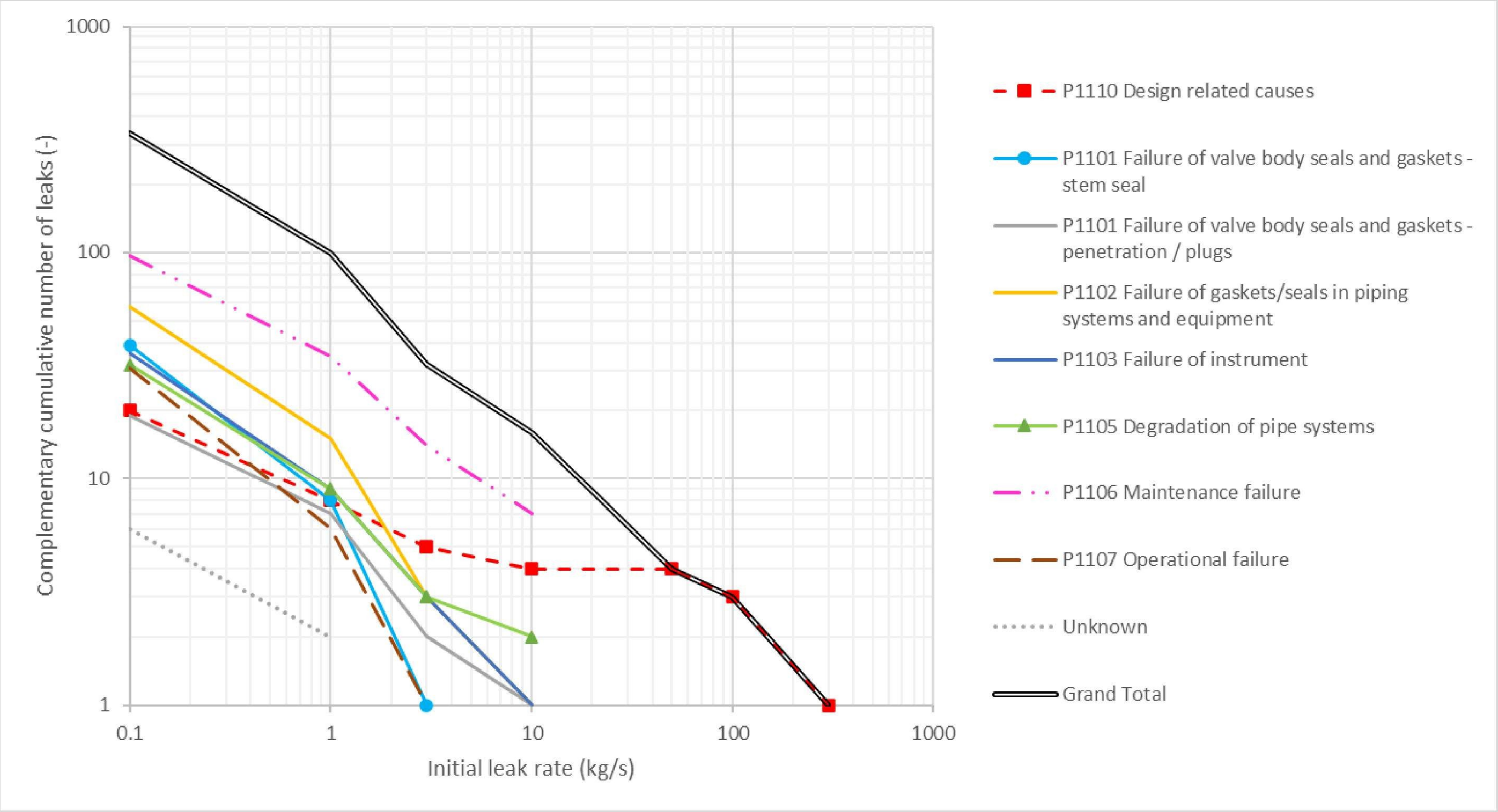
$$f_{i,c}(Q) = \begin{cases} \left(a_i \cdot \left(\frac{Q}{R_c}\right)^{m_i} + a_{i,R}\right), & 0 < Q \leq Q_{i,R} \\ 0, & Q_{i,R} < Q \end{cases}$$

Combining the leak rate relation and the leak frequency model

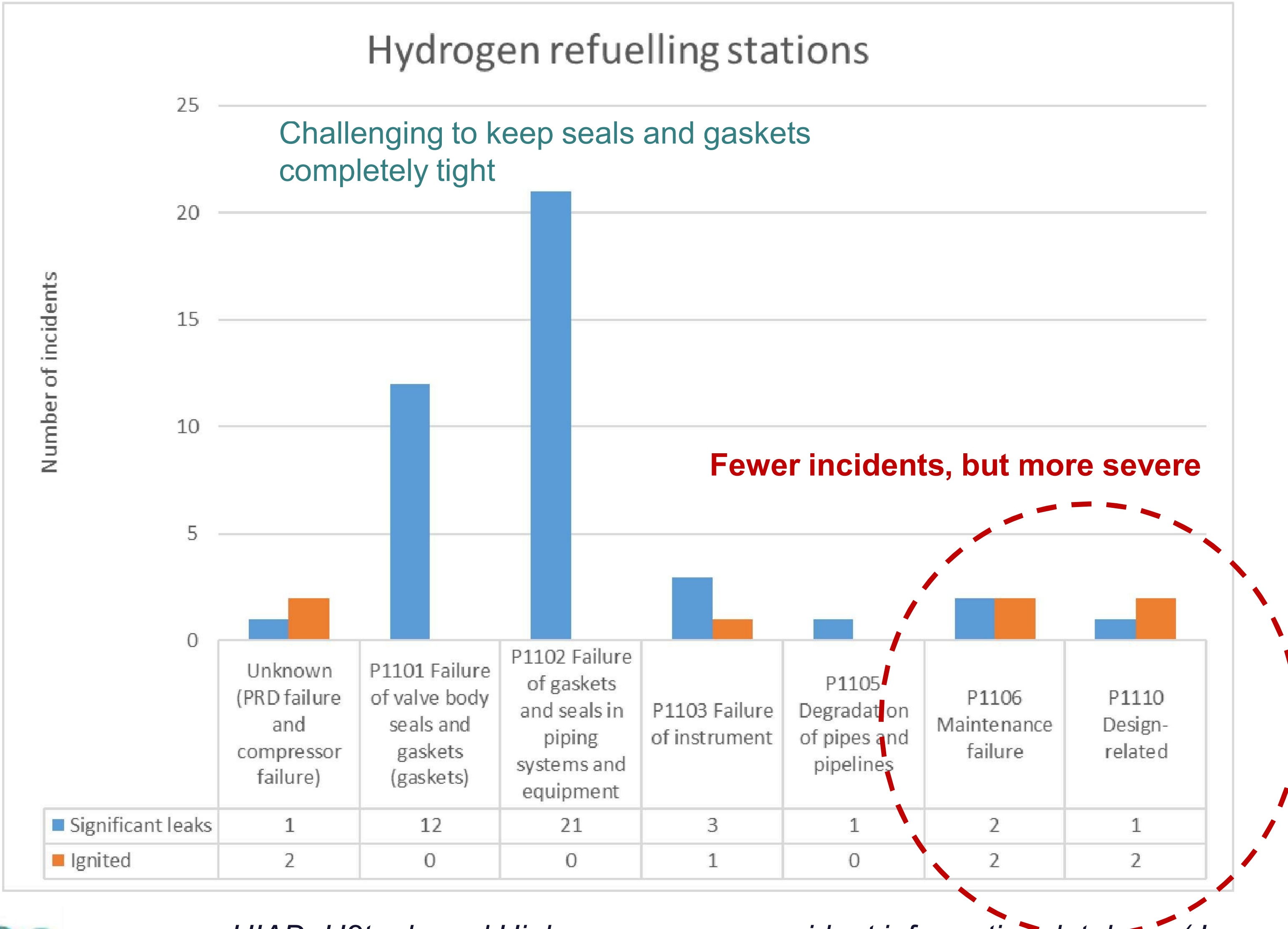
$$F_{Total,i,c}(Q, N_i) = \begin{cases} \left(a_i \cdot \left(\frac{Q}{R_c}\right)^{m_i} + a_{i,R}\right) \cdot \left(\beta_i + (1 - \beta_i - \varepsilon_i) \cdot {N_i}^{k_i} + \varepsilon_i \cdot N_i\right), & 0 < Q \leq Q_{i,R} \\ 0, & Q_{i,R} < Q \end{cases}$$

SAFEN

Distribution per failure case and initial leak rate – Norwegian oil and gas data



Distribution per failure case and initial leak rate – Incidents covering hydrogen refuelling stations



	Unknown (PRD failure and compressor failure)	P1101 Failure of valve body seals and gaskets (gaskets)	P1102 Failure of gaskets and seals in piping systems and equipment	P1103 Failure of instrument	P1105 Degradation of pipes and pipelines	P1106 Maintenance failure	P1110 Design-related
Significant leaks	1	12	21	3	1	2	1
Ignited	2	0	0	1	0	2	2

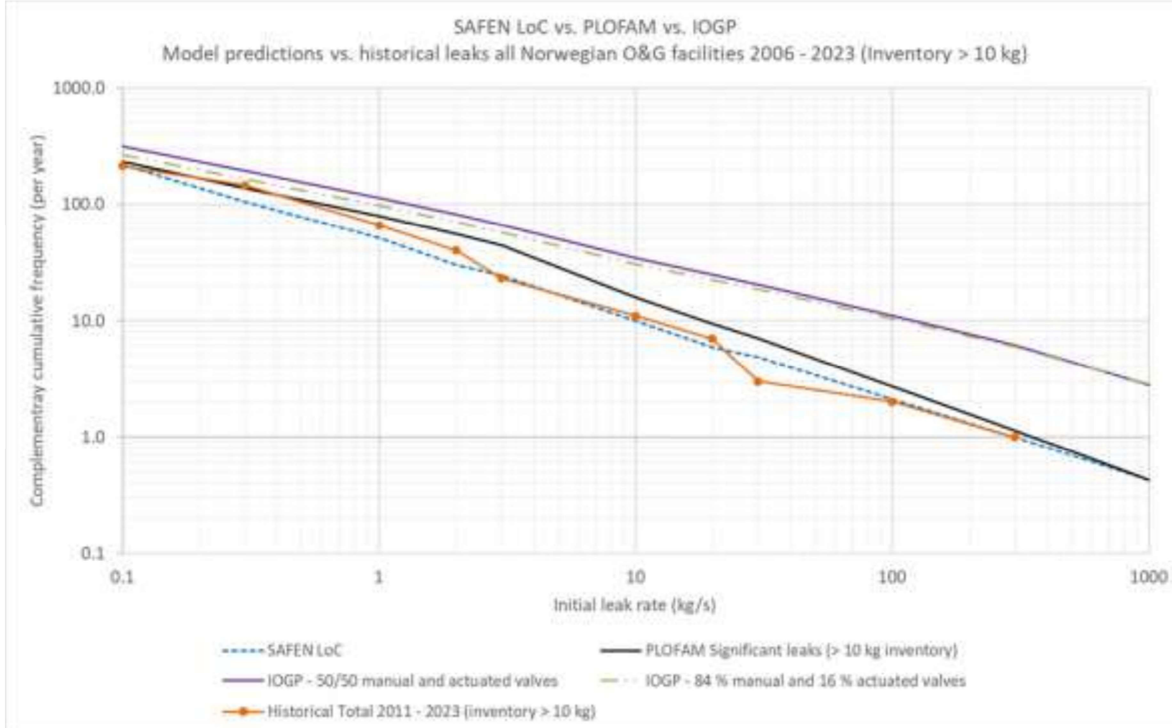
HIAD, H2tools and High pressure gas accident information database (Japan (KHK))

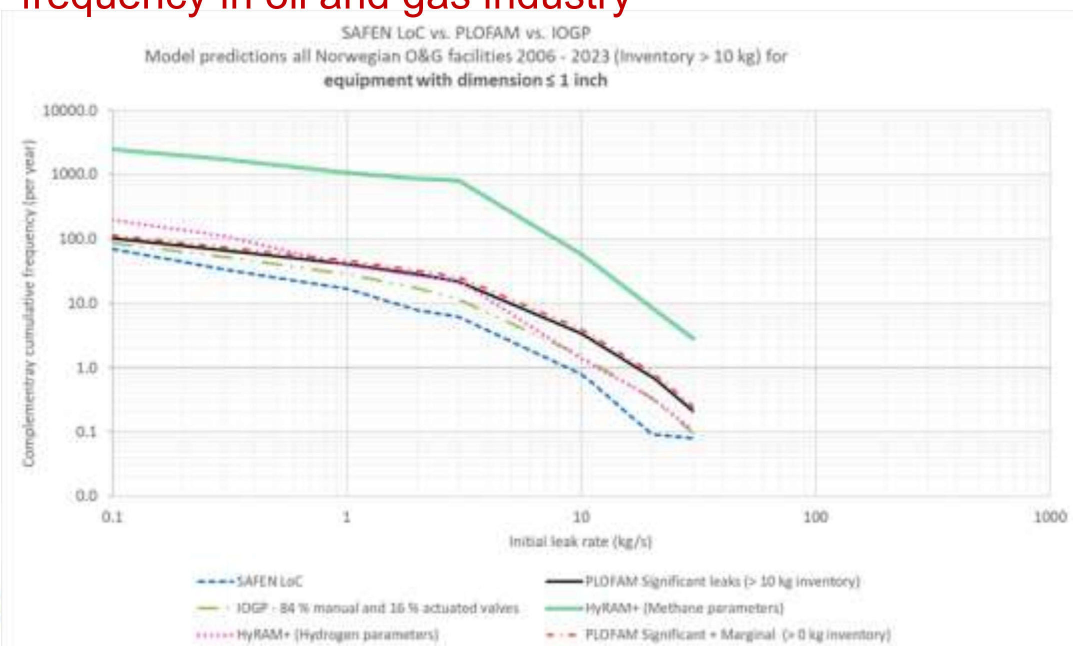
Performance O&G data

SAFEN LoC reproduces oil and gas data in line with PLOFAM

Thus, it can be concluded that

only valve counts and equipment dimension required to reproduce historical loss of containment frequency in oil and gas industry

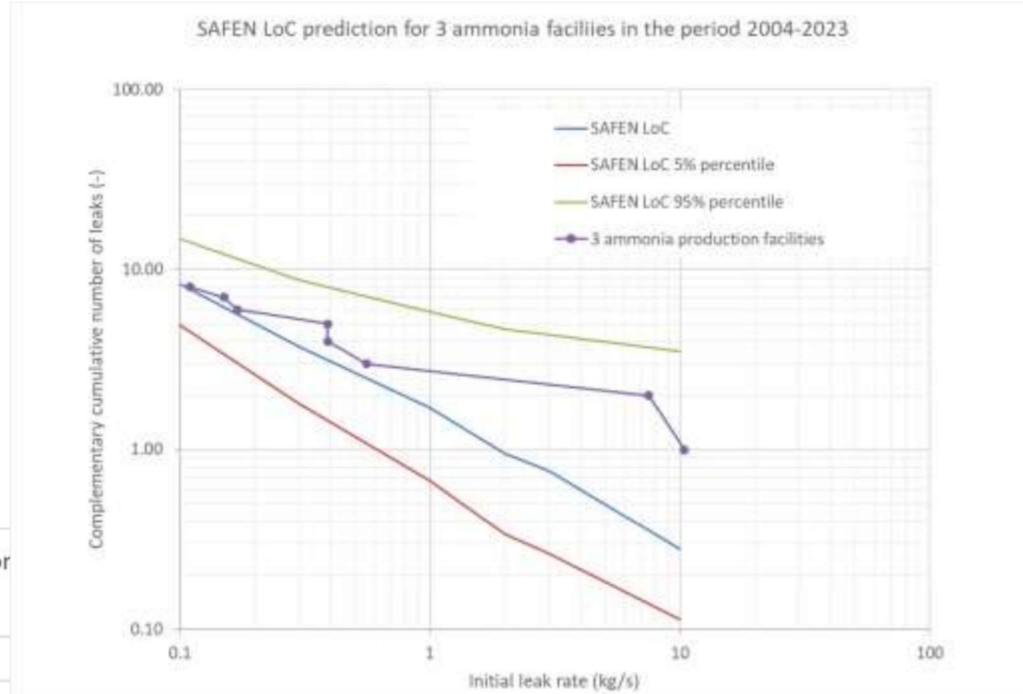


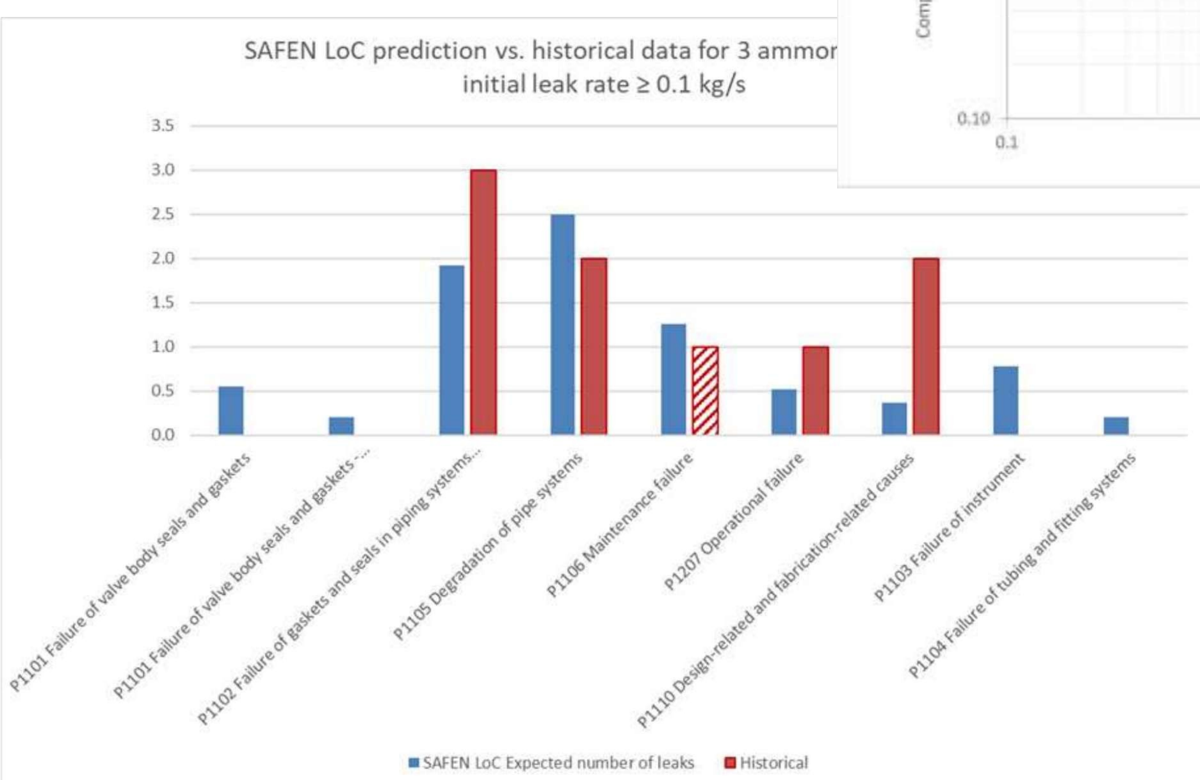


HyRAM+ for hydrogen in line with other models when only looking at equipment with dimension ≤ 1”

Performance independent data ammonia manufacturer used for validation

SAFEN LoC estimates historical frequency!





SAFEN LoC estimates contributing failure cases!

SAFEN

SAFEN Phase 3

II – Data and task analysis
Analyse data and human tasks

III – Model improvement
Improve SAFEN models, guidelines, advice for design and operation

I – Use case analysis
Quantitative risk analysis (QRA) of use cases
Application and testing of SAFEN models

IV – Scenario & consequence modelling
LoC scenario modelling and interface to consequence modelling

Project management and administration

Dissemination

Thank you!

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