Benchmark Exercise on Risk Assessment methods applied to a virtual Hydrogen refuelling Station

HySafe/HyQRA Benchmark QRA

TNO | Knowledge for business

International Conference on Hydrogen Safety

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Outline of the presentation

1. Objectives of benchmark in HyQRA
2. Definition of Benchmark Base Case and subjects of study
3. Results phase 1: used approaches and methodologies
4. Results phase 2: comparison of consequence modelling
5. Summary of conclusions

Objectives of HyQRA benchmark exercise

HyQRA was a work package of NoE-HySafe aiming at:

The development of a
"Methodology for Consistent Site Risk Assessment"

The sub-task "QRA studies" aimed at:

- identification of knowledge gaps in risk assessment -approach, methods, models and tools- for hydrogen installations
- exchange of views and experiences with the application of QRA for different applications and from different -regulatory or cultural- backgrounds

A benchmark exercise was set up in which the various approaches in QRA could be demonstrated by participating partners.

Description of benchmark case:

(virtual) Hydrogen Refuelling Station

HyQRA, background of Benchmark Base Case

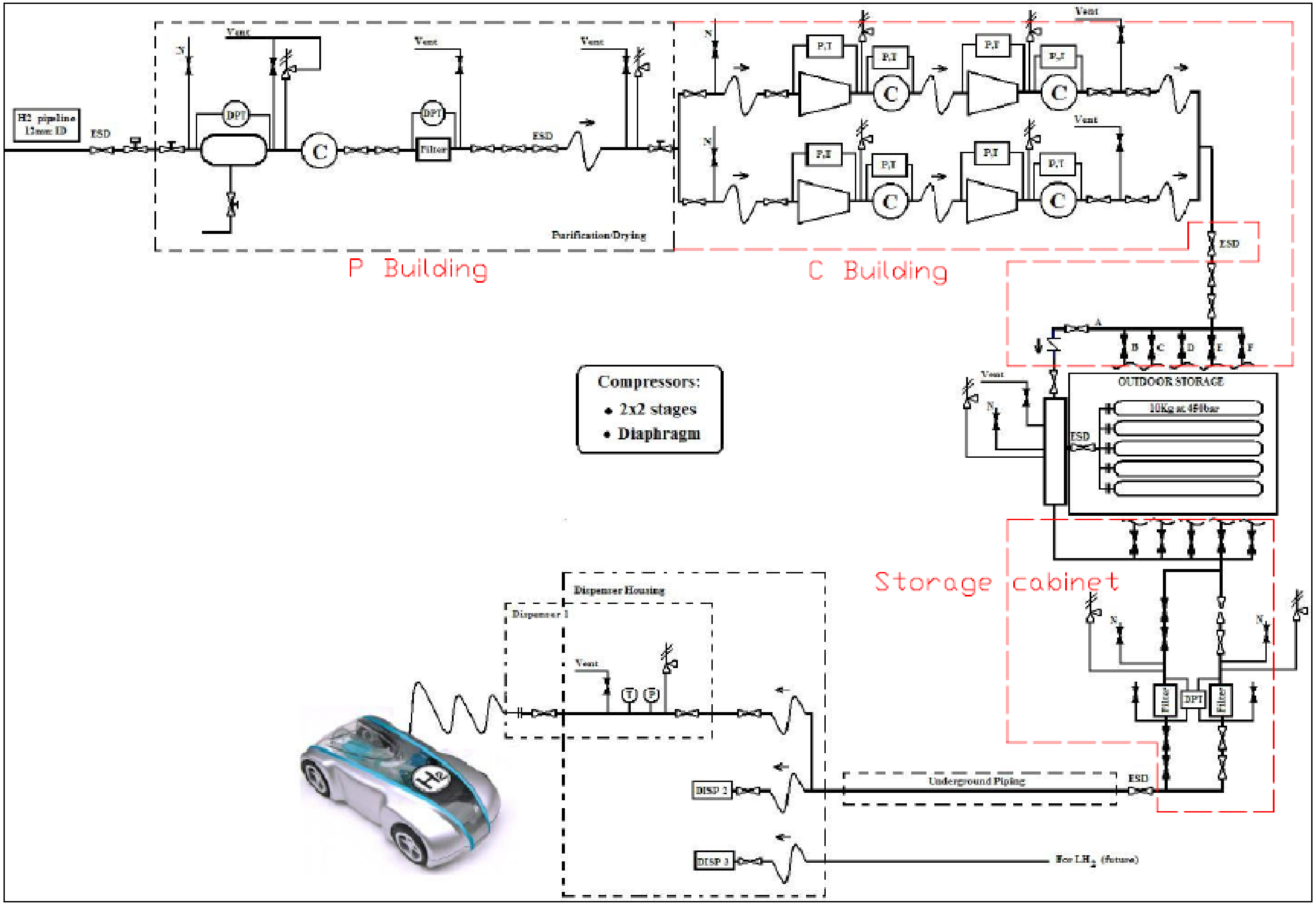
A reference installation was defined: a virtual hydrogen refuelling station, the so called ‘Benchmark Base Case’ (BBC):

- Lay-out; process and mitigation equipment
- Capacities and use (consumption, etc.)
- Surroundings: built-up areas, vegetation, numbers of public

With this virtual, somewhat simplified situation QRA approaches could be demonstrated that would provide:

- sufficient insight in the various risk analysis concepts, and
- flexibility to demonstrate risk approaches for both on-site as well as off-site risks.

Process Flow diagram of 'BBC-HRS'

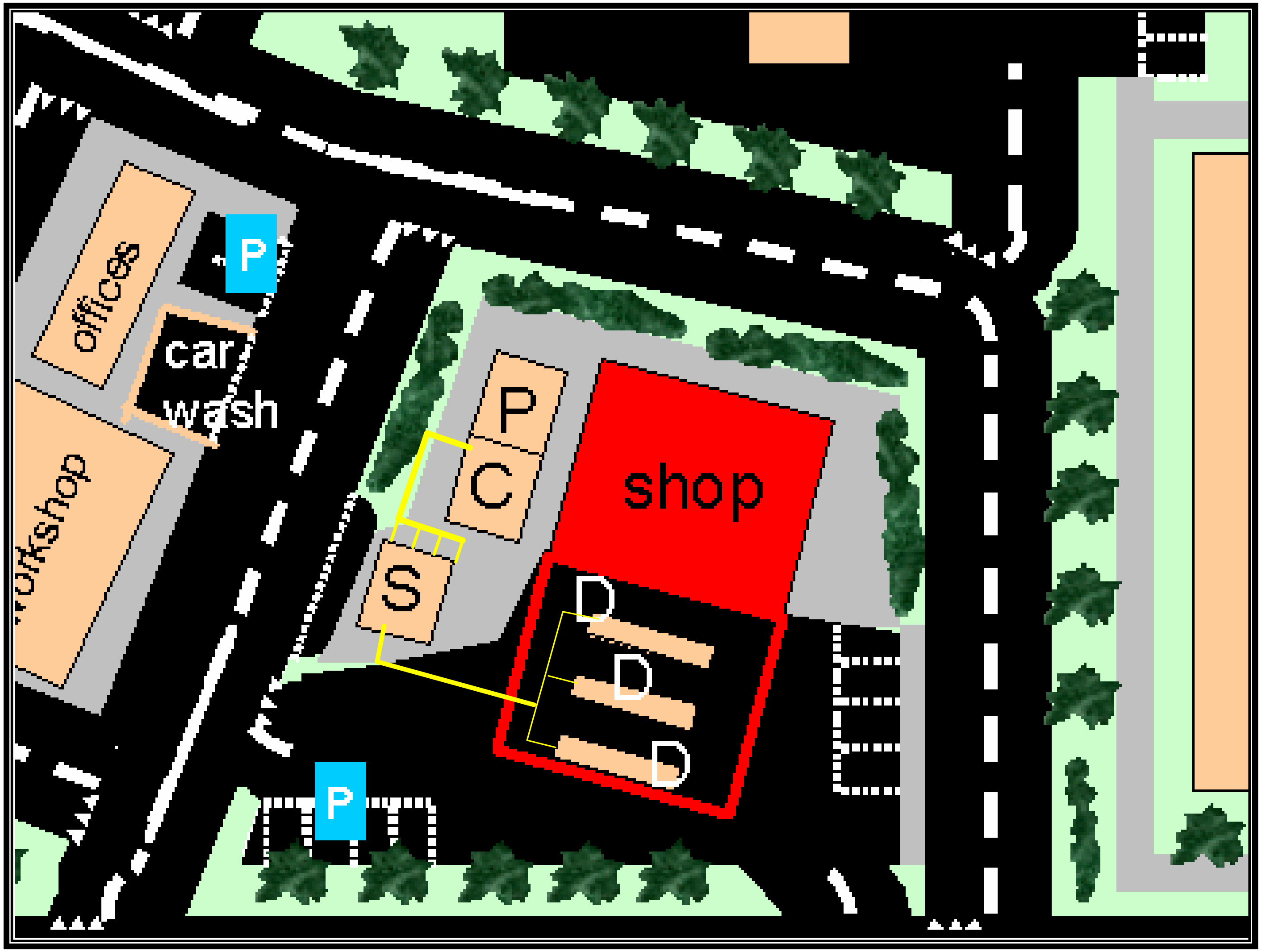


Design basis and capacities of ‘BBC-HRS’

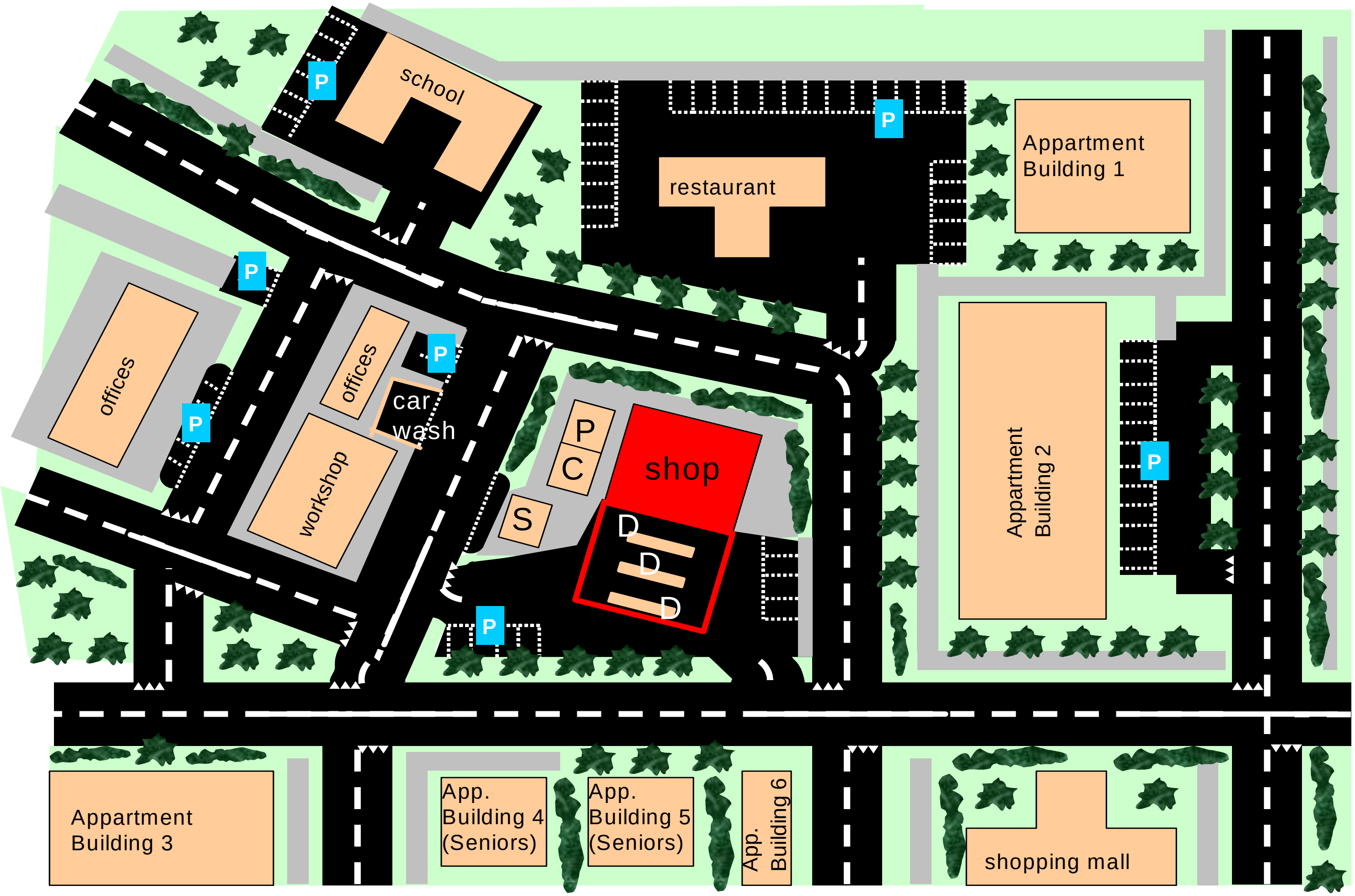
Table 2: Refueling Station Design Bases

Parameter	Values
Number of vehicles refuelled	60 per day
Amount of fuel per fill	4 kg
Driving per fill	250 km
Vehicle refuelling time	10 min/fill
Station average consumption	240 kg/day
Nominal dispensing capacity	0.4 kg/min
Typical fuel consumption (gasoline equivalent)	4 L/100 km

Lay-out of 'BBC-HRS'

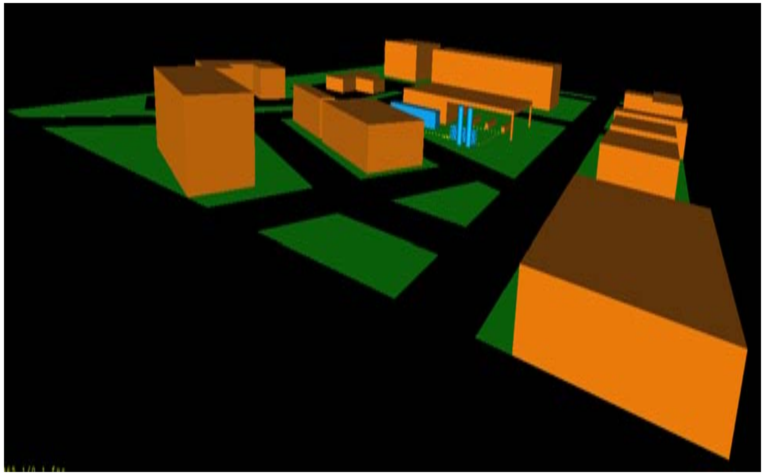


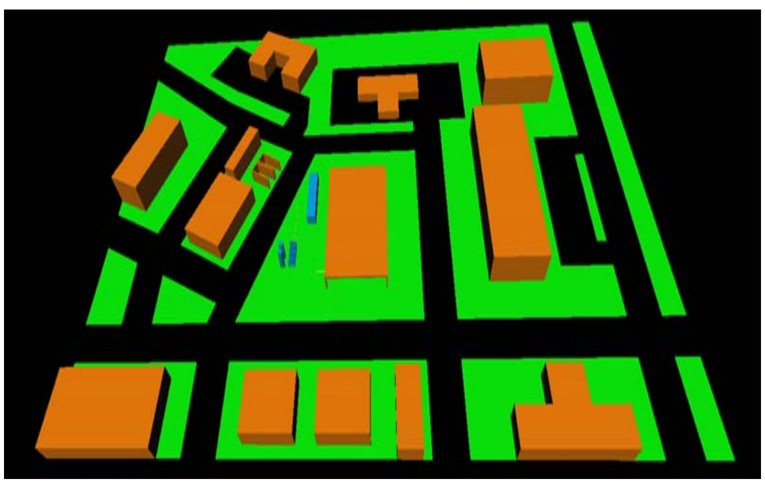
‘BBC-HRS’ and its surroundings

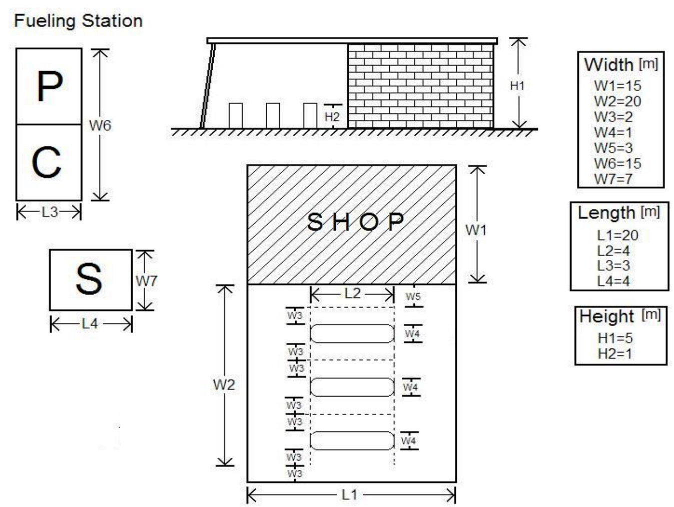


P = production; C = compressor; S = storage; D = dispenser   P = parking spaces

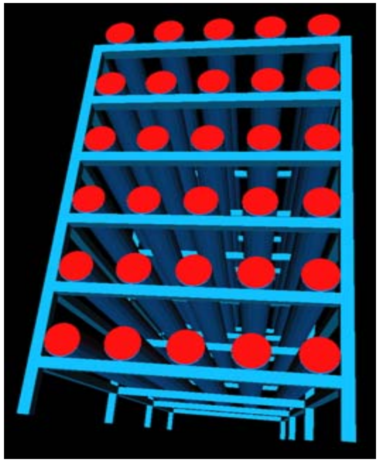
‘BBC-HRS’: 3D views + building’s dimensions

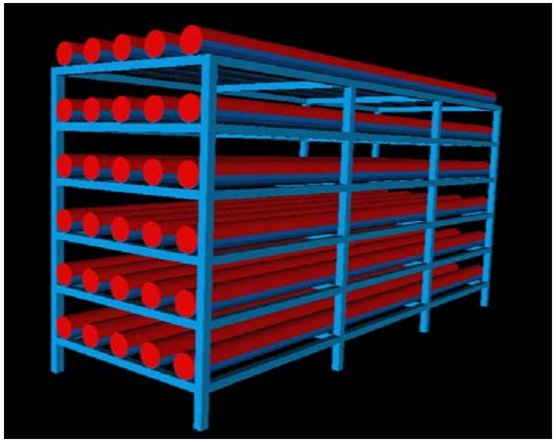


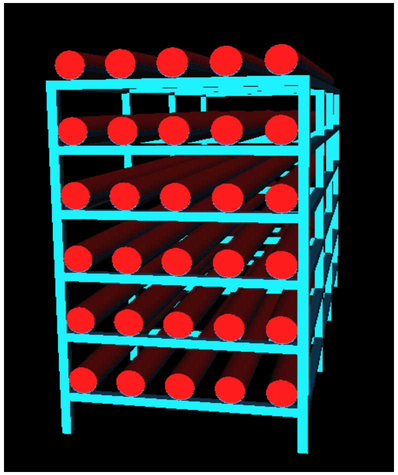


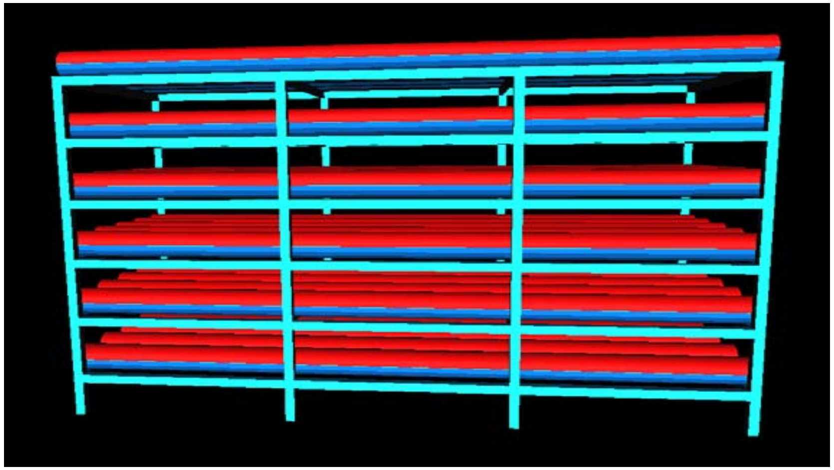


3D view of storage tanks package: 6 x 5 x 0.5 m^3



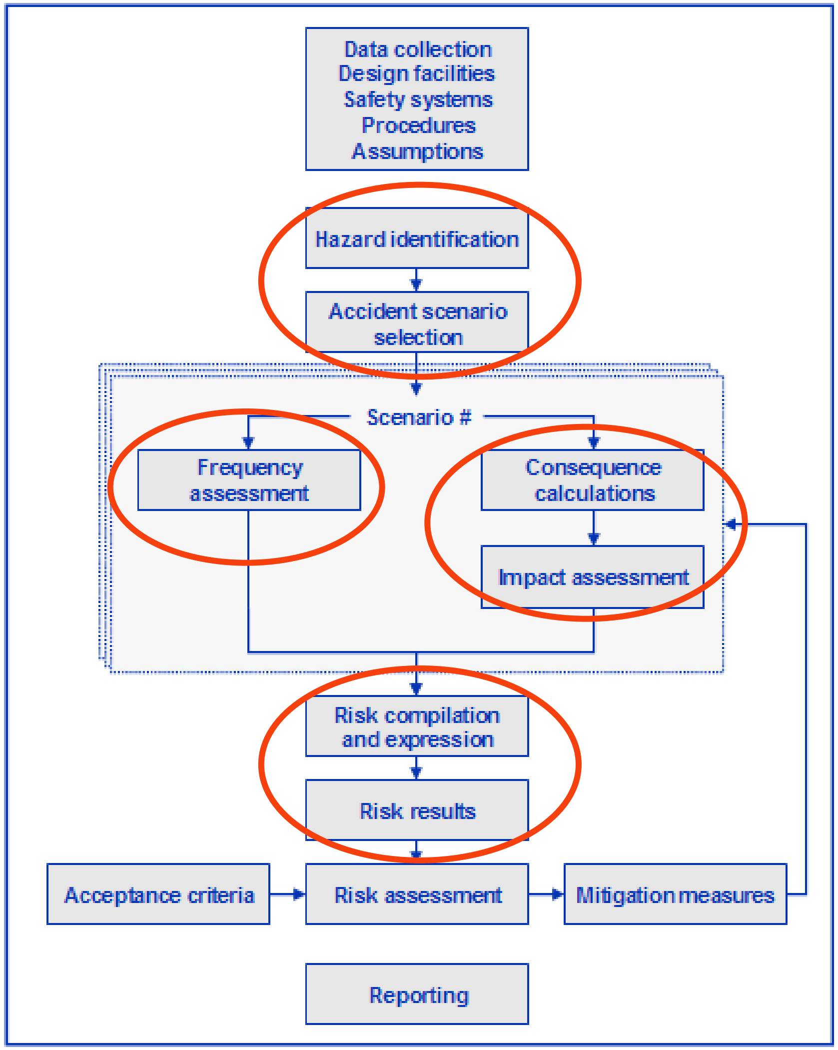






Instructions and data for Benchmark QRA

Classical scheme for quantitative risk assessment



Instructions for making QRA

- Initially full freedom: Participants were requested to conduct a QRA according to their own procedures and requirements, and to use models and data according their own practice: scenario definition, frequency assessment, ignition and consequence modelling and risk presentation.

- Some guidance data were given, on:
  - Failure frequencies for hydrogen equipment: figures suggested by SNL
  - Consequence criteria for personal injury and property damage
  - Distribution of persons, on-site and off-site
  - Climate conditions: three weather classes (F-1.5, D-5, quiescent), with equal distribution

Suggested data for failure frequencies of Hydrogen equipment (source: SNL)

Component	Mean Component Leakage Frequency		
	Small Leak	Large Leak	Rupture
Vessel	1E-3/yr	1E-4/yr	1E-5/yr
Pipe	5E-5/m-yr	5E-6/m-yr	5E-7/m-yr
Refueling Hose	0.1/yr	1E-2/yr	1E-3/yr
Pump	3E-3/yr	3E-4/yr	3E-5/yr
Compressor	3E-2/yr	3E-3/yr	3E-4/yr
Electrolyser	1E-4/yr	1E-5/yr	1E-6/yr
Vaporizer	1E-3/yr	3E-4/yr	5E-5/yr
Valve	1E-3/yr	1E-4/yr	1E-5/yr
Pipe Joints/Unions	3E-2/yr	4E-3/yr	5E-4/yr
Flange	3E-4/yr	3E-5/yr	NA
Filter	3E-3/yr	3E-4/yr	3E-5/yr
Instrument Line	1E-3/yr	3E-4/yr	5E-5/yr

Proposed damage criteria: explosion overpressure and thermal radiation

Effect	Effect level	Consequence to property	Consequence to people
Overpressure	10 mbar = 1 kPa	No or limited damage; possibly crack of windows	None
	30 mbar = 3 kPa	Break of window panes	Injuries by glass fragments
	100 mbar = 10 kPa	Severe damage to buildings	Serious injuries to people inside, few fatalities
	300 mbar = 30 kPa	Destruction of all buildings that were not designed to withstand explosions	Many fatalities
Thermal radiation	3 kW/m^2	Crack of glass, for prolonged exposure	Possibly pain; redish skin
	10 kW/m^2	Heating of structures; temperature and pressure increase in liquid/gas storages	Skin / tisse blisters, many 2^{nd} degree burns;some fatalities for 20 s exposure
	35 kW/m^2	Secundary fires, ignition of wood, textiles, etc.	100% fatalities

Output requested from each participant

- **Defined scenarios and methodology for identification**
- **Leakage rate and frequency**
- **Maximum gas cloud size, e.g. flammable volume, flammable mass, equivalent cloud size, cloud/jet extent to LFL**
- **Explosion consequences:**
  - **Frequency of explosion for different gas cloud sizes, and associated consequences (maximum pressure)**
  - **Area / distance for 1, 3, 10 and 30 kPa**
- **Fire consequences:**
  - **Jet fire dimensions and frequencies for different leak sizes**
  - **Area / distance for 3, 10 and 35 kW/m^2**
- **Extent of personal injury. Particularly fatality as dimension of risk.**
- **Risk figure(s)**

HyQRA: Nine organisations participated

Management group

Results Stage 1:

Comparison of approaches and methodologies

Overview of approaches and final results

(Intended) approach / contribution	**Partner**
Qualitative for scenario identification (e.g. HAZOP, Fault trees, system analysis). Detailed quantification of frequencies.	UNIPI, UPM, JRC
Semi-quantitative: Risk matrix	UNIPI, GexCon (different objectives)
Quantification of consequences only	HSL, NCSRD, GexCon
Full QRA: determination of individual & societal risk	DNV, TNO
Other, not related to Benchmark	UU

Methodologies applied and sources used

Parameter	**Source / model**	**Partner**
Scenario	System analysis + Fault trees, incl. ESD, human intervention, etc. Mainly generic release sizes Risk matrix for generic release cases Risk matrix, based on system analysis	UNIPI, UPM, JRC DNV, TNO GexCon UNIPI
Frequency	SNL data HyApproval Purple Book OREDA AIChE	DNV, UNIPI DNV TNO, UNIPI UNIPI UNIPI
Ignition	HySafe D71 Purple Book	UNIPI, DNV, JRC, Gexcon TNO
Consequences	Analytical (e.g. PHAST, EFFECTS) Numerical / CFD (e.g. ADREA-HF, FLACS, CFX-11)	DNV, HSL, UNIPI, TNO NCSRD, Gexcon, HSL, TNO

Comparison of two 'Risk matrix' approaches, used for different objectives!!

Table 1_ "Compensated" Risk matrix

Severity – S index	Likelihood – L index: 4 $F \geq 10^{-2}$ $F \geq 0.01$	3 $5 * 10^{-4} \leq F < 10^{-2}$ $0.0005 \leq F < 0.01$	2 $5*10^{-6} < F < 5 * 10^{-4}$ $0.000005 < F < 0.0005$	1 $F \leq 5*10^{-6}$ $F \leq 0.000005$
4			1.1.1.3/a 1.1.1.6/a 1.1.1.9/a 1.1.1.12/a 2.1.1.3/a 2.1.1.6/a 2.1.1.9/a 2.1.1.12/a 2.1.1.15/a 4.1.1.3/a 4.1.1.6/a 5.1.1.3	1.1.1.3/b 1.1.1.3/c 1.1.1.6/b 1.1.1.6/c 1.1.1.9/b 1.1.1.9/c 1.1.1.12/b 1.1.1.12/c 2.1.1.3/b 2.1.1.3/c 2.1.1.6/b 2.1.1.6/c 2.1.1.9/b 2.1.1.9/c 2.1.1.12/b 2.1.1.12/c 2.1.1.15/b 2.1.1.15/c 4.1.1.3/b 4.1.1.6/b 4.1.1.9/a 4.1.1.9/b
3	5.1.2.5	2.1.1.5/a 2.1.1.8/a 3.1.1.5 5.1.1.2 5.1.2.6	2.1.1.8/b 2.1.1.11/a 2.1.1.14/a 3.1.1.2 3.1.1.6 5.1.2.2 5.1.2.3	2.1.1.5/b 2.1.1.5/c 2.1.1.8/c 2.1.1.11/b 2.1.1.11/c 2.1.1.14/b 2.1.1.14/c
2	1.1.1.1/a 2.1.1.1/a 2.1.1.7/a 4.1.1.1 5.1.1.1	1.1.1.1/b 1.1.1.2/a 1.1.1.4/a 1.1.1.7/a 1.1.1.10/a 2.1.1.1/b 2.1.1.2/a 2.1.1.4/a 2.1.1.4/b 2.1.1.10/a 2.1.1.13/a 4.1.1.2/a 4.1.1.4 4.1.1.5/a	1.1.1.4/b 1.1.1.7/b 1.1.1.10/b 1.1.1.10/c 2.1.1.7/b 2.1.1.10/b 2.1.1.13/b 4.1.1.2/b	1.1.1.2/b 1.1.1.2/c 2.1.1.2/b 2.1.1.2/c 4.1.1.5/b
1	3.1.1.4 5.1.2.1 5.1.2.4			

LEGEND:

(red)	*NON ACCEPTABLE RISKS*: the events that fall in this region are non acceptable and more detailed analysis are recommended
(yellow)	*ALMOST ACCEPTABLE RISKS* or *ALARP* (As Low As Reasonably Practicable) *REGION*: the events that fall in this region are almost; nevertheless a more detailed analysis is recommended
(white)	*ACCEPTABLE RISKS*: for the events that fall in this region, the design and the management of the plant guarantee an adequate control of the risk. No need to proceed with more detailed analysis.

UNIPI:

- Matrix used for identification of relevant scenario's
- 4 x 4 matrix; with frequency quantified and damage expressed as magnitude of leak + location
- Result: > 60 out of 90 scenario's require further evaluation

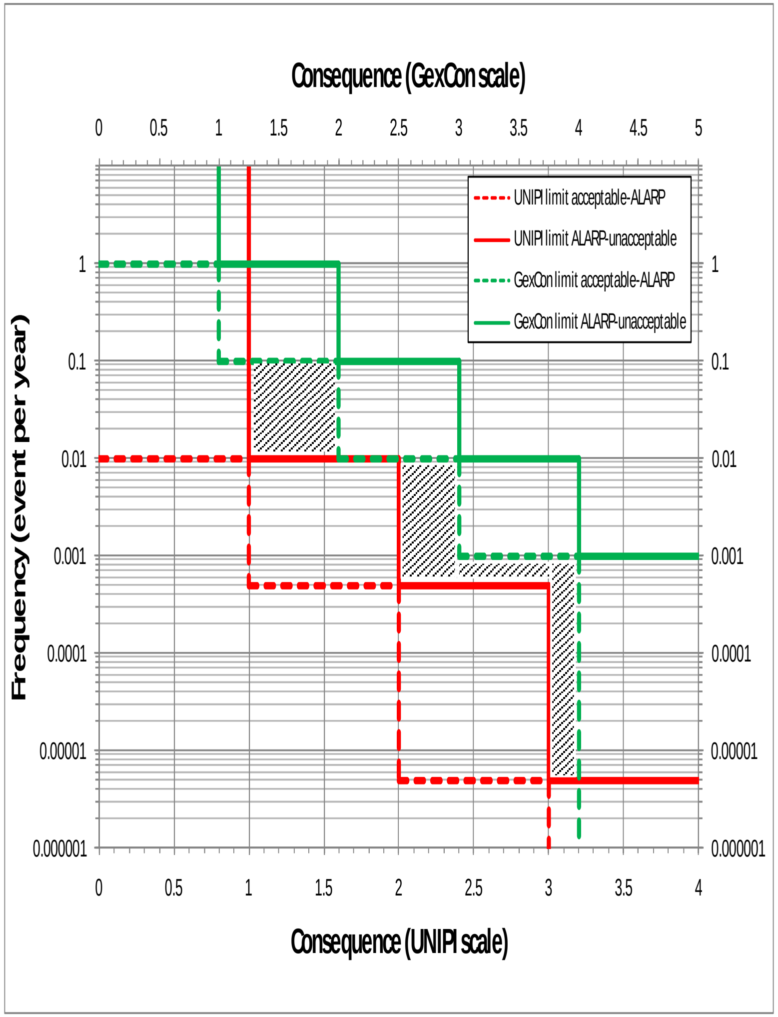
Consequence					
V	C	B	A	A	A
IV	D	C	B	A	A
III	29	7, 8, 9, 10, 15, 16, 17,18	C	B	A
II	1, 23	2, 24, 25, 26, 28, 30, 31, 32, 36, 39	D	C	B
I	4, 6, 22, 27, 38, 40, 44, 46, 47	3, 5, 11, 12, 13, 14, 19,20, 21, 22, 33, 34, 35, 41, 42, 43, 45	E	D	C
	I	II	III	IV	V
	Probability				

Gexcon:

- Matrix used for determination of (acceptability of) explosion risk
- 5 x 5 matrix, with both frequency and damage quantified
- Result: all (47) scenarios acceptable

Observations in risk matrix comparison

- Objectives of risk matrix in both studies were different
- Scale and grades of both damage and frequency differ
- As a consequence, also conclusions about acceptability are likely to differ (see graphs, by University of Ulster)
- Lessons:
  - Presentation of QRA results need careful explanation
  - Misunderstandings (‘red is wrong’) are easily created
  - Uniform criteria for acceptability should be encouraged



Main conclusions for Stage 1

- A big diversity is found in:
  - Methodologies applied for identification and analysis of unwanted events
  - Definition of risk figure and risk characterisation
  - Used data and tools to present risk
- Due to this scatter in approaches, a comparison of quantified results seemed hardly feasible; attempt was made for risk matrix, but difference in objectives made them incomparable
- Team concluded that a Stage 2 should be defined that would focus on a more limited scope of comparison: only consequence modelling for uniform scenarios

Results Stage 2:

Consequence assessment for defined scenarios

Instructions for consequence assessment

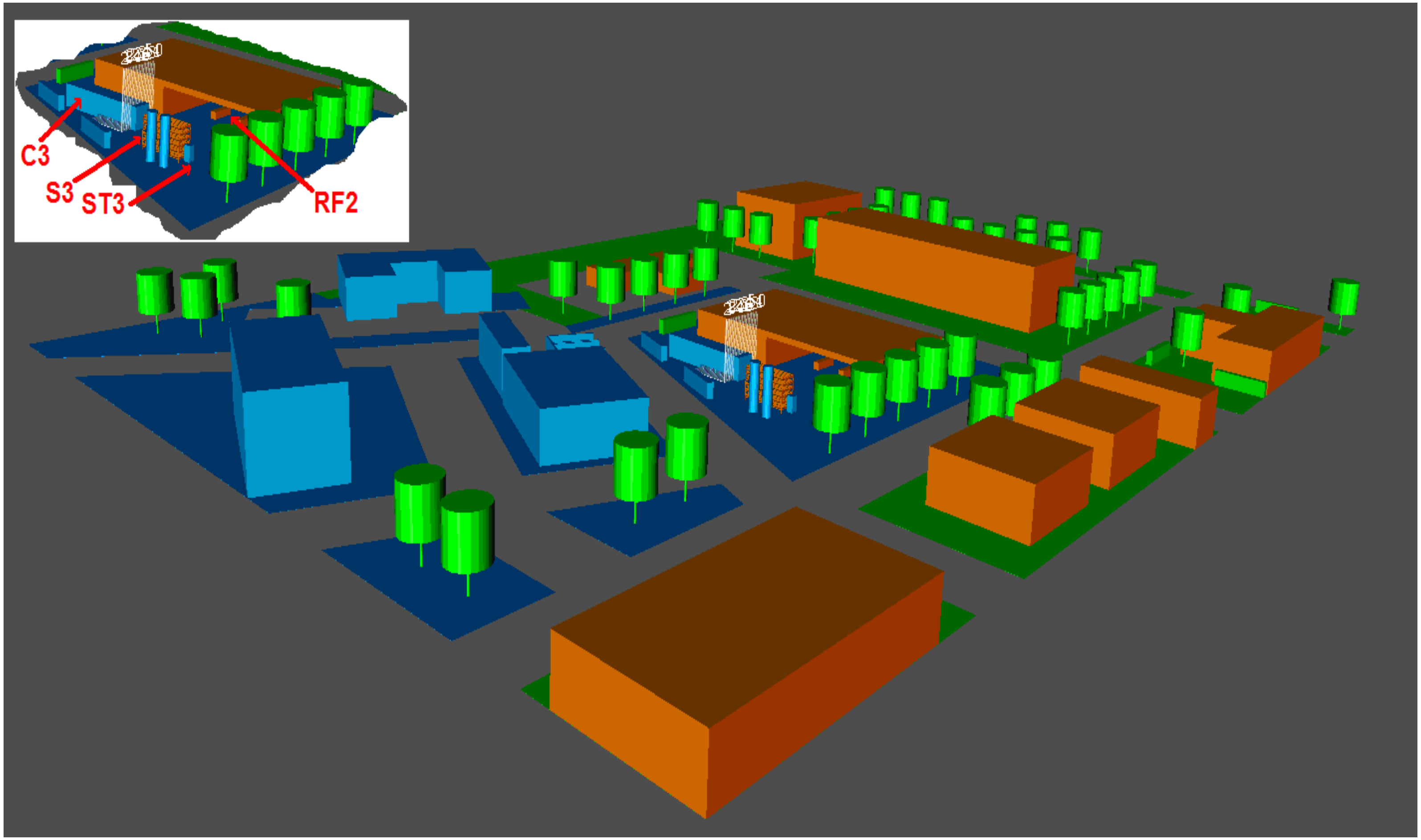
Four release scenarios, defined by:

- Location
- Leak size and release direction
- Weather / wind

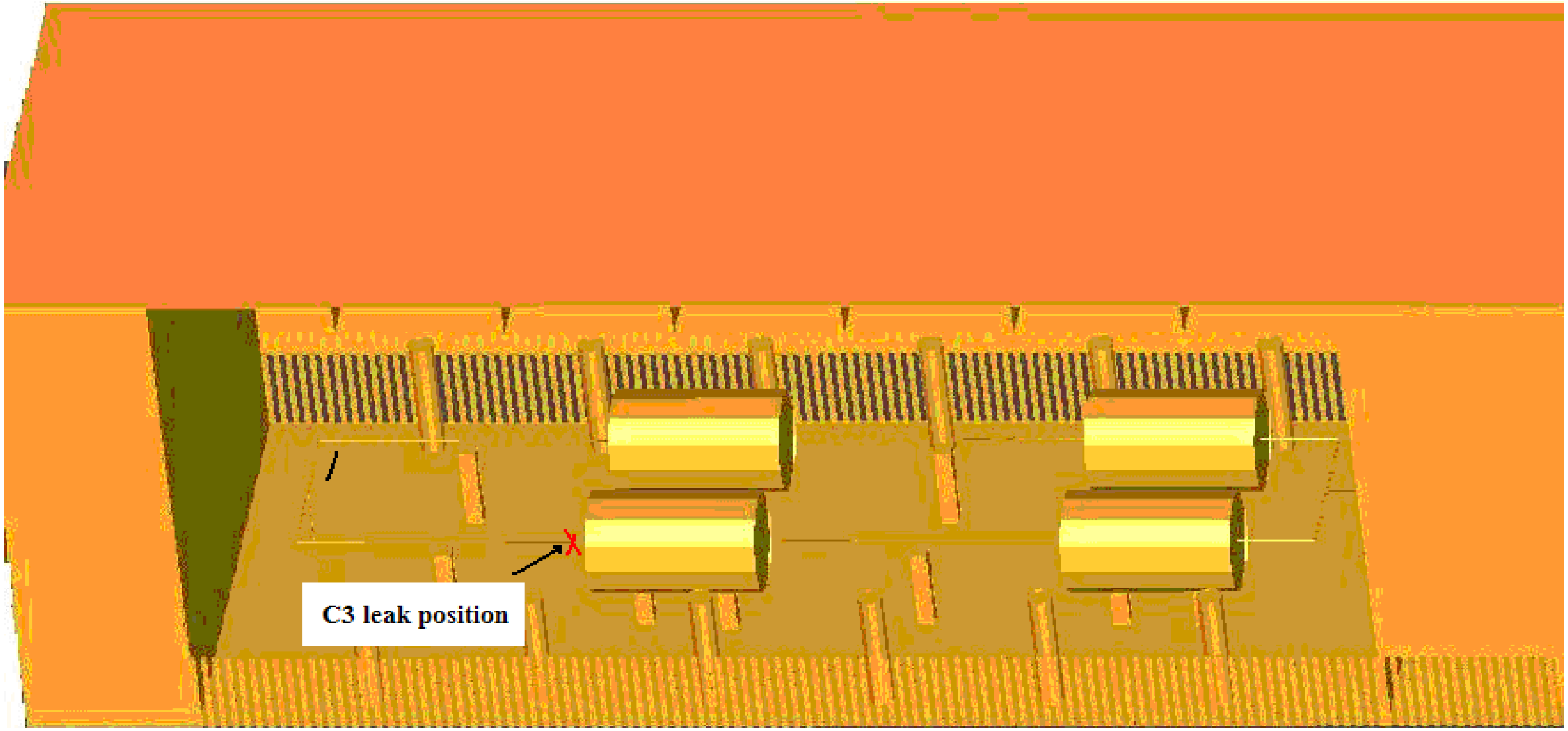
Requested output:

- Size or distance of consequence area: overpressure and/or radiation level
- Frequency of the accident

Release locations for consequence assessment



Case 1: C3, leak in Compression section

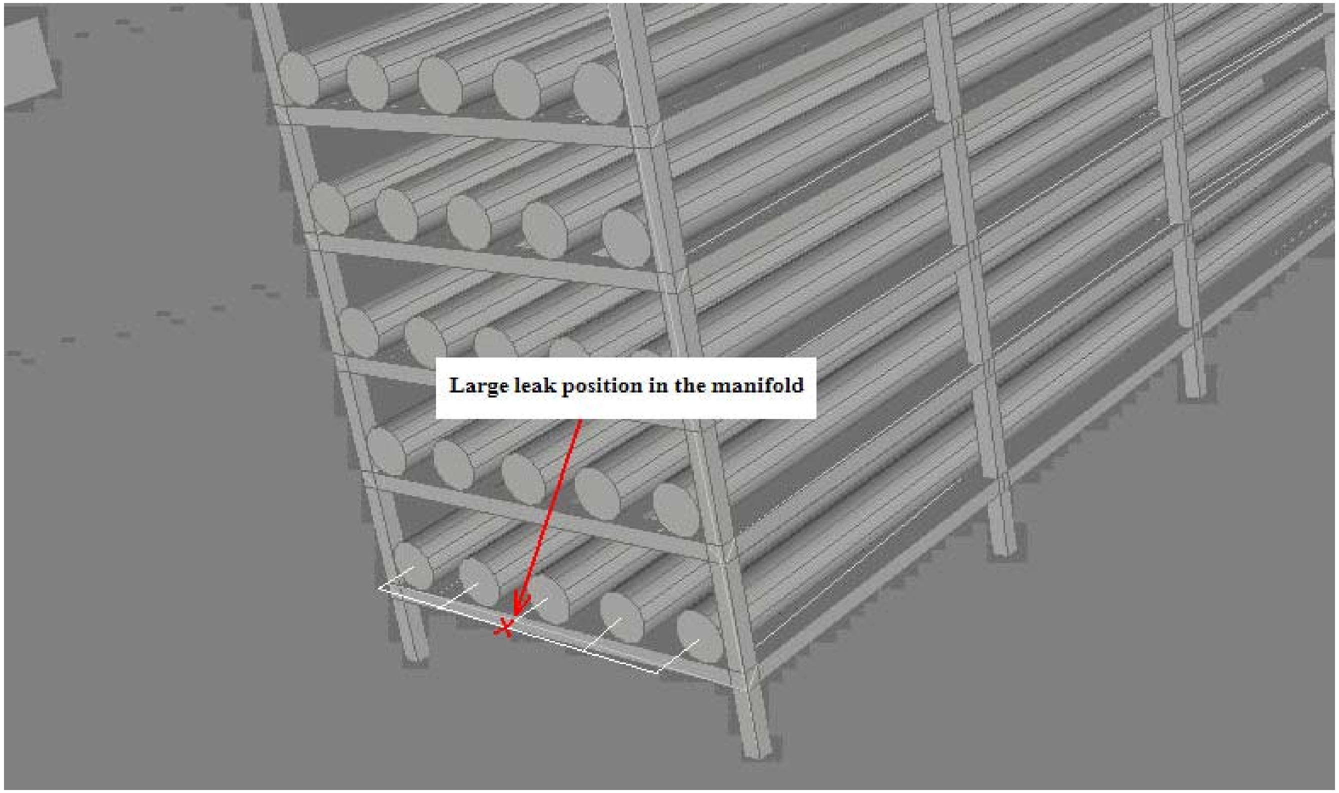


- Compressor building; volume ~ 67.5 m^3, with mech. venting in ceiling at 150 ACH
- 8 mm leak in vessel; p = 450 bar; volume 0.25 m^3 (~ 9 kg); horizontal leak
- To be addressed: Explosive mass; overpressure

Case 1: C3, leak in Compression section, RESULTS

Parameter	Unit	Analytical model					Numerical model		
		DNV	UNIPI	HSL	TNO	GexCon	NCSRD	GexCon	HSL
Model used		PHAST		PHAST + Excel	EFFECTS-8 + additional	Semi-quantit.	GAJET + ADREA-HF	FLACS + Analytical	GAJET + CFX-11
Location				in + out	in + out	indoor	indoor	indoor	indoor
Room volume assumed	[m^3]	67.5		67.5	63	67.5	63	67.5	67.5
Release rate	[kg/s]			1.1	1.1 (↓)	0.83	1.1 (↓)		1.37
Release duration t, to 10%	[s]			6.1	19		15		6.4
Released amount at t	[kg]			6.7	6.7		5.7		8.7
Max. concentration	[vol%]			98	85		43 - 55		
Time to Cmax	[s]			~ 6	12	10	~ 8		~ 6
Duration C > LEL	[s]			83	~ 100	39	50 - 150		
Flammable mass	[kg]			3.6	~ 4.4		1.7		1.8
Flammable volume	[m^3]	Building					57		60
Max. overpressure	[barg]	0.2		1.0	6 (TNT-eq.)	0.4		12	
Distance P = 0.3 barg	[m]			20	15	0.6			
Release rate fan exhaust	[kg/s]			0.25	0.19 (max)				
LEL extend outside	[m]							18 (vert.)	

Case 2: S3, leak in Storage section

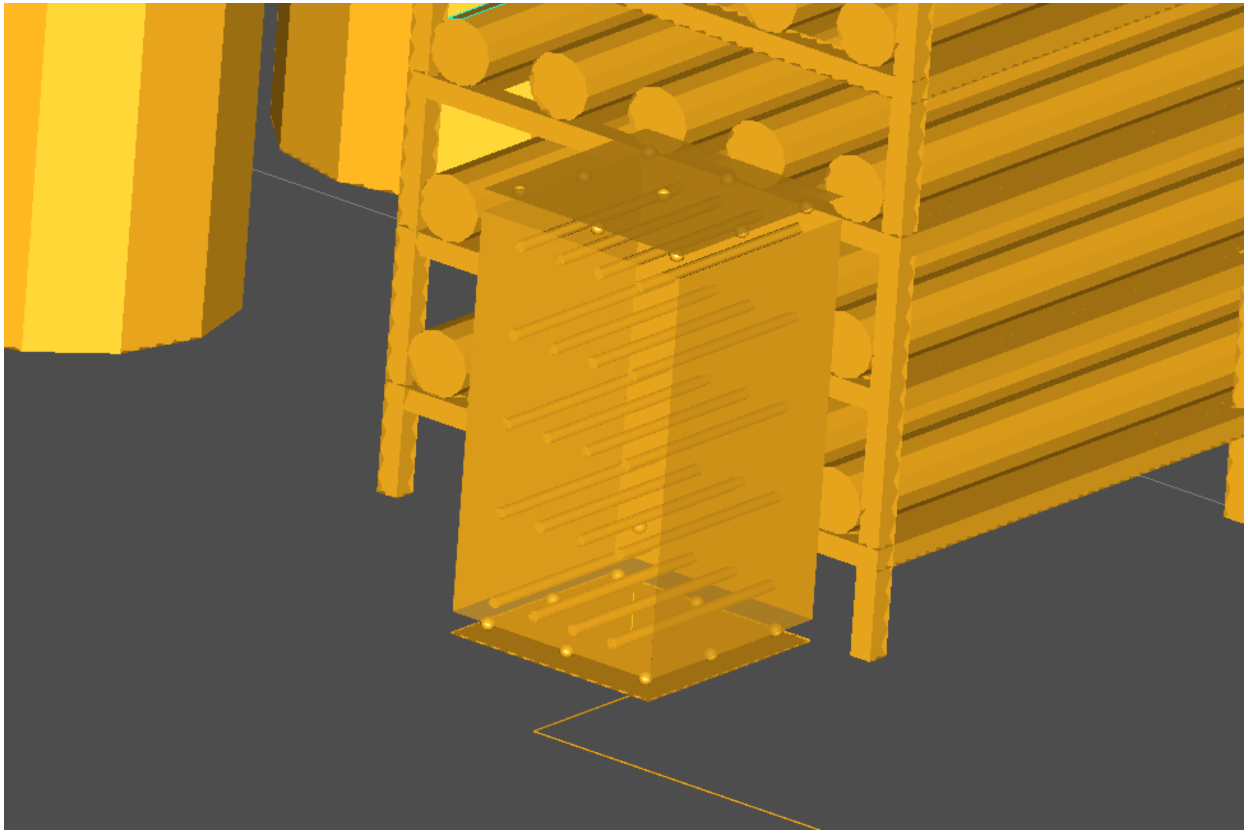


- Storage bank; p = 450 barg; volume 6x2.5 m^3 (~ 270 kg)
- 1.6 mm leak in one set of five cylinders (45 kg); downwards release
- Wind: u = 1.5 m/s
- To be addressed: distance overpressure 0.3 bar; radiation 35 kW/m^2

Case 2: S3, leak in Storage section, RESULTS

Parameter	Unit	Analytical model					Numerical model		
		DNV	UNIPI	HSL	TNO	GexCon	NCSRD	GexCon	HSL
Model used		PHAST	EFFECTS-7	PHAST	EFFECTS-8	Semi-quantit.	GAJET + ADREA-HF	FLACS	CFX-11
Location			outdoor, horizontal	outdoor	outdoor, horizontal	outdoor	outdoor	outdoor	outdoor
Release rate	[kg/s]	0.05	0.043	0.045	0.045 (↓)	0.029	0.047 (↓)		0.06
Release duration t, to 10%	[s]		1800	1550	4650		3680		'long'
Released amount at t			82	70	78.5		59.5		
Jet fire length	[m]		3.6	5.4	3.4				
Jet fire SEP	[kW/m^2]		98	100	104				
Distance 35 kW/m^2	[m]	not reached	4.5	not reached	3.5	4.0			
LEL length	[m]		36.4 (F1.5)	1.4 (h=0) 3.5 (h=4)	17 (D1.5) 44 (F1.5)	2.5		Ø = 8 m	
Time to Cmax	[s]				continuous	10	55	10	
Duration C > LEL	[s]				continuous	-	2700		
Flammable mass	[kg]	0.02	0.5 (F1.5)		0.29 (D1.5) 0.74 (F1.5)		0.16 (1.5) 0.20 (5.0)	0.08	0.06–0.07 (5.0)
Flammable volume	[m^3]						~ 33 (1.5) 38 (5.0)	16	11.3 – 15.4
Max. overpressure	[barg]							~ 0.01	
Fraction confined	[%]		50	50	25 (D1.5) 50 (F1.5)				
MEM curve	[-]		6	7	6				
Distance P = 0.3 barg	[m]	3.5	8.0	not reached	5.2 (D1.5) 9.0 (F1.5)	1.1			

Case 3: ST3, leak inside Storage Cabinet

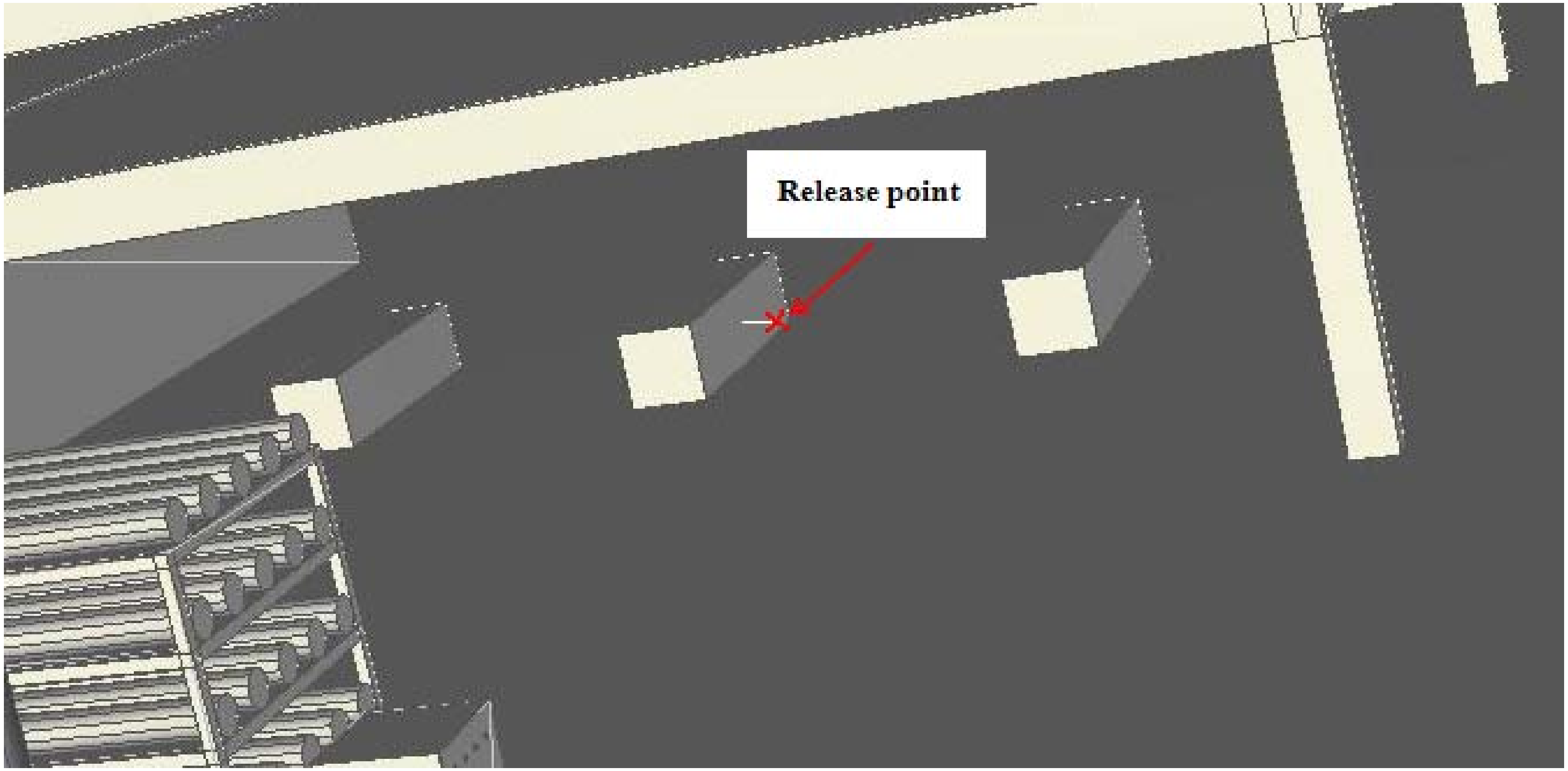


- Storage cabinet; p = 450 bar; not isolated 0.1 m^3 (~ 3.6 kg)
- 8 mm pipe rupture; horizontal release
- Wind: u = 1.5 m/s
- To be addressed: overpressure 0.3 bar; radiation 35 kW/m^2

Case 3: ST3, leak in Storage Cabinet, RESULTS

Parameter	Unit	Analytical model					Numerical model		
		DNV	UNIPI	HSL	TNO	GexCon	NCSRD	GexCon	HSL
Model used		PHAST	EFFECTS-7	PHAST + Excel	EFFECTS-8	Semi-quantit.	GAJET + ADREA-HF	FLACS	GAJET + CFX-11
Location				in + out		in + out	In + out	in + out	indoor
Release rate	[kg/s]	1.1	2	1.13	1.10 (↓)	3.24?	1.18 (↓)		1.42
Release duration t, to 10%	[s]			2.5	6.7		11	5	7.6
Released amount at t	[kg]			2.8	2.9		2.4		10.8
Jet fire length	[m]			18.1	14.9				
Jet fire SEP	[kW/m^2]			151	110				
Distance 35 kW/m^2	[m]	16		16	17.2	132?			
Distance to LEL (stability)	[m]			13 (h=0) 21 (h=5)	36 (D) 68 (F)		35	30	>6
Time to Cmax	[s]			2.5	~ 5.4 (D) ~ 9.4 (F)		8		2.5
Duration C > LEL	[s]				36		43	~25	
Flammable mass	[kg]	5.65	2 (F1.5) 6.6 (D5)	2.8	2.75 (D) 3.1 (F)		7.3		1.22
Flammable volume	[m^3]	132					940	450	62
Fraction confined	[%]		50	50	100				
MEM curve	[-]		8	7	8				
Max. overpressure	[barg]			1.0	2			~ 0.12	
Distance P = 0.3 barg	[m]	14	15.1 (F1.5) 22.5	15 early 10 late (30 m)	22	25.9			

Case 4: RF2, leak in Dispenser



- Dispenser
- 1.6 mm leak; 60 s continuous release, then system volume 0.15 m^3 (~ 5.4 kg); unconfined, downwards
- Wind: u = 5 m/s
- To be addressed: overpressure 0.3 bar; radiation 35 kW/m^2

Case 4: RF2, leak in Dispenser, RESULTS

Parameter	Unit	Analytical model					Numerical model		
		DNV	UNIPI	HSL	TNO	GexCon	NCSRD	GexCon	HSL
Model used		PHAST	EFFECTS-7		EFFECTS-8	Semi-quantit.	ADREA-HF	FLACS	
Location			outdoor		outdoor	outdoor	outdoor	outdoor	
Release rate	[kg/s]	0.05	0.048		0.043	0.034	0.047		
Release duration t	[s]		69		(65)		72	65	
Released amount at t	[kg]				2.8		3.2		
Jet fire length	[m]		2.6		2.4				
Jet fire SEP	[kW/m²]		193		208				
Distance 35 kW/m²	[m]	not reached	3.45		3.3	16.1			
LEL length	[m]		5.15		6.9 (D5) 16.3 (F5)	1		Ø = 5 m	
Time to Cmax	[s]				continuous	40	13	7	
Duration C > LEL	[s]				continuous		85		
Flammable mass	[kg]	0.02	0.019		0.036 (D5) 0.087 (F5)		0.23 (1.5) 0.19 (5.0)		
Flammable volume	[m³]						47 (1.5) 35 (5.0)	10	
Max. overpressure	[barg]				1.0			~ 0.02	
Fraction confined	[%]		50		100 (D5) 70 (F5)				
MEM curve	[-]		6		7				
Distance P = 0.3 barg	[m]	2.9	2.7		5.0 (D5) 5.9 (F5)	1.1			

Conclusions and remarks

Conclusions and remarks (1)

- The benchmark exercise has shown a wide scatter in approaches and results of (quantitative) risk analysis.
- There also appears difference in opinion on the need of, and scope for quantifying risks. Many of the differences have a historical / cultural background, as was also observed in earlier QRA benchmarks in the EU.
- For several partners, it appeared that detailed expertise exists for only part of all issues in a QRA (e.g. reliability analysis; CFD dispersion modelling). Consequently, possibilities to compare the full chain of QRA for each participant were limited.
- Comparison of the application of the Risk Matrix approach has pointed out the necessity to adopt uniform risk scaling and acceptance criteria to ensure the uniformity and comparability of QRA studies for hydrogen applications. The same will probably hold for other QRA approaches.

Conclusions and remarks (2)

- Much interesting data has been collected in this exercise, but it appeared difficult to draw definitive conclusions from comparisons:

  - There is (still) no uniform definition of relevant and credible scenarios for hydrogen installations.

  - Considerable differences in the effects were observed, particularly in overpressures.

  - Consequence modelling in this task was limited to relatively small events. The effects of catastrophic events were not considered. These would likely result in (much) bigger differences in consequences, or unveil knowledge gaps in our understanding of the behaviour of hydrogen releases, including liquid hydrogen.

Conclusions and remarks (3)

- Not all original objectives could be realised. The HyQRA benchmark exercise was conducted in the final stage of the NoE-HySafe program. Due to time constraints, not all information underlying the quantitative data could be evaluated.
- There is a continuous need for exchange of knowledge and experience. Continuation of this activity should therefore be encouraged, in order to reduce the apparent uncertainties and differences in risk appreciation.
- Our Benchmark Base Case (BBC) may be recommended as a reference for future work in this field.

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Thank you for your attention!

Reactions to

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