BENCHMARK EXERCISE ON RISK ASSESSMENT METHODS APPLIED TO A VIRTUAL HYDROGEN REFUELLING STATION

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ABSTRACT

A benchmarking exercise on quantitative risk assessment (QRA) methodologies has been conducted within the project HyQRA, under the framework of the European Network of Excellence (NoE), HySafe. The aim of the exercise was basically twofold: (i) to identify the differences and similarities in approaches in a QRA and their results for a hydrogen installation, between nine participating partners representing a broad spectrum of background in QRA culture and history, and (ii) to identify knowledge gaps in the various steps and parameters underlying the risk quantification.

In the first step, a reference case was defined: a virtual hydrogen refuelling station (HRS) in virtual surroundings comprising housing, school, shops and other vulnerable objects. All partners were requested to conduct a QRA according to their usual approach and experience. Basically, participants were free to define representative release cases, to apply models and frequency assessments according their own methodology, and to present risk according to their usual format. To enable inter-comparison, a required set of results data was prescribed, like distances to specific thermal radiation levels from fires and distances to specific overpressure levels. Moreover, complete documentation of assumptions, base data and references was to be reported.

It was not surprising that a wide range of results was obtained, both in the applied approaches as well as in the quantitative outcomes and conclusions. This made it difficult to identify exactly which assumptions and parameters were responsible for the differences in results, as the paper will show.
A second phase was defined in which the QRA was determined by a more limited number of release cases (scenarios). The partners in the project agreed to assess specific scenarios in order to identify the differences in consequence assessment approaches. The results of this phase provide a better understanding of the influence of modelling assumptions and limitations on the eventual conclusions with regard to risk to on-site people and to the off-site public.
This paper presents the results and conclusions of both stages of the exercise.

1. INTRODUCTION

Quantitative risk assessment (QRA) is one of the tools that is often used in risk-informed decision-making on determination of safety distances, risk reduction measures and land-use planning around activities in which hazardous materials are involved. QRA is being used in environmental permit applications, in regional planning and in emergency response preparation for risks caused by either industrial activities or transport.

It is a known fact from earlier benchmark studies on risk assessment for technological hazards that the concepts of QRA differ between the various EU Member States, as does the field of application of QRA. The philosophy on whether quantitative criteria on (and probabilities of) unwanted events and consequences should be applied in political decision-making, differs from country to country.

For the safe application of hydrogen, there is another complicating factor in that there are knowledge gaps in several elements of the QRA: which scenarios are relevant or credible to include?; how should these scenarios be determined in a given situation?; which probabilities shall be assigned to these scenarios?; what is known about the sensitivity and probability of ignition of hydrogen?; and how should the effects and consequences of a hydrogen escape be modelled? Are current practices of QRA for chemical industry or oil & gas industry appropriate for hydrogen applications as well?

It is for these and other questions that the project HyQRA was defined under the scope of the NoE HySAFE, sponsored with the support of the EU 6^{th} Framework Programme. The objectives of HyQRA were broken down into two main activities:

(1) To identify knowledge gaps in risk assessment modelling and to achieve mutually agreed parameters to be applied in the underlying steps in a QRA;

(2) To conduct a benchmark exercise to identify the differences and similarities in risk assessment approaches and in risk expressions, as applied by different participants in the HyQRA project.

As it was agreed to start the project with the benchmark study, that expectedly would also reveal the current knowledge gaps in underlying steps of QRA, and due to the limited duration of the HySafe initiative, only the activities under the second objective could be completed. This paper describes the conduct, results and conclusions of the benchmark exercise.

2. CONDUCT OF THE BENCHMARK EXERCISE

In total, nine partners from seven countries participated in the HyQRA project and in the benchmark exercise: Det Norske Veritas (DNV, Norway), University of Pisa (UNIPI, Italy), Universidad Polytécnica de Madrid (UPM, Spain), National Centre for Scientific Research Demokritos (NCSRD, Greece), GexCon AS (Norway), Joint Research Centre (JRC, The Netherlands), Health and Safety Laboratory (HSL/HSE, United Kingdom), University of Ulster (UU, Northern Ireland), and TNO (The Netherlands).
A management group was formed by three partners: UNIPI, GexCon and TNO.

For the so-called Benchmark Base Case (BBC) a virtual hydrogen refuelling station (HRS) and its surroundings were defined at the beginning of the exercise. The BBC is described in section 3. It is important to highlight that the aim of the proposed benchmark exercise is not so much to be exhaustive in the number of scenarios or to obtain an ‘absolute value’ of the risk of this HRS, but to focus on a limited number of equipment to see how each of the partner’s QRA methodologies would handle scenarios for this equipment. This way it would be possible to evaluate to what conclusions the benchmark exercise will lead to: differences in the used QRA methodologies, including assumptions made and knowledge gaps.

The exercise itself comprised two stages:

Stage 1: To conduct a QRA according to everyone's own approach and practice, including identification of release scenarios, probability analysis, consequence analysis and risk estimation. A set of requested output was defined, like distances to lethality criteria and damage due to specified levels of thermal radiation and explosion overpressures; see Table 1. Values were also suggested with regard to failure frequencies and weather class distribution. Participants were left free to use the given values or to apply numbers from their own data. Population data was provided for those who decided to conduct societal risk assessment.

Stage 2: To conduct consequence analysis for a limited number of predefined scenarios (release cases), and to provide results in a predefined format of consequence levels. The aim of this exercise was to identify the differences in the subsequent steps of consequence modelling, whether it is through analytical or through numerical models. Actually, this stage was added when the first results of stage 1 showed such a wide range of methods, results and applied risk dimensions, that quantitative inter-comparison would hardly be possible.

Table 1: Consequence criteria for thermal radiation and overpressure

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 / tissue blisters, many 2nd degree burns; some fatalities for 20 s exposure
	35 kW/m^2	Secundary fires, ignition of wood, textiles, etc.	100% fatalities

3. DESCRIPTION OF THE BBC HYDROGEN STATION

For the Benchmark exercise, a so-called 'generic' or 'virtual' hydrogen refuelling station was defined, for delivery of compressed gaseous hydrogen only. It should be underlined that the adopted system is not representative of all hydrogen stations, even if main assumptions related to hydrogen production/supply rate, storage volume, pressure, equipment dimensions are quite similar to existing stations. The intention is to solemnly use it as an example to test different methodologies of QRA and to highlight the differences in assumptions and approaches and to identify the knowledge gaps.

Therefore, a not too complex station was suggested by limiting the scope of the equipment taken into account. For the scope previously discussed, the BBC station is limited to:

- Hydrogen supply from an external source
- Compression
- Storage and gas distribution
- Hydrogen dispenser (including dispenser-vehicle interface)

The system description comprises both a simplified piping and instrumentation diagram (P&ID) of the hydrogen equipment and their capacities, as well as the geometry of the station's construction and of buildings and vegetation in its direct surroundings. This would enable a satisfactory study detail for each partner, whether his/her approach is aimed at on-site system safety and reliability or at major incidents with potential risk to the off-site public. Not all equipment is described in full detail; a true situation would probably be more complex in its instrumentation etc. Part of the equipment and/or components present at the station will only be treated as 'obstacles' (building constructions) in cloud dispersion. According to the exercise instructions, it was assumed that they would not contribute to the initiation of hydrogen release or any other event.

In Figure 1, a simplified P&ID of the station is given. The relevant equipment and some properties are:

A. Hydrogen supply: It is assumed that hydrogen arrives at the station by pipeline at low pressure (4 barg) from an external source.
B. Purification and compression: At the intake of the station, hydrogen gas first passes a purification section (P) and is then lead into the compression section (C). In (C), the hydrogen is compressed to 450 barg, in two stages. The sections (P) and (C) are placed in two separate containers (LxWxH = 7.5x3x3 m, each), both with forced ventilation in the ceiling at 150 ACH (air changes per hour). For air intake, louvres are supplied in the lower part of the 7.5 m long walls.
C. Hydrogen storage: The outdoor storage section comprises a so-called storage cabinet and six banks of storage cylinders. The storage cabinet (dimensions LxWxH = 1x1x2 m) holds the piping to and from the storage banks, including valves and control equipment. The storage banks consist of six layers of five horizontal cylinders of 0.5 m^3 each. There are 30 cylinders in total, holding 15 m^3 of hydrogen at 450 barg pressure (approx. 560 kg).
D. Hydrogen dispenser: There are three points of delivery of hydrogen to cars (only two of them assumed in use), through dispenser units located underneath a canopy (roof). The hydrogen gas is delivered from the storage to the dispenser via piping in a below grade trench. Rate of delivery to the car is 0.4 kg/min.

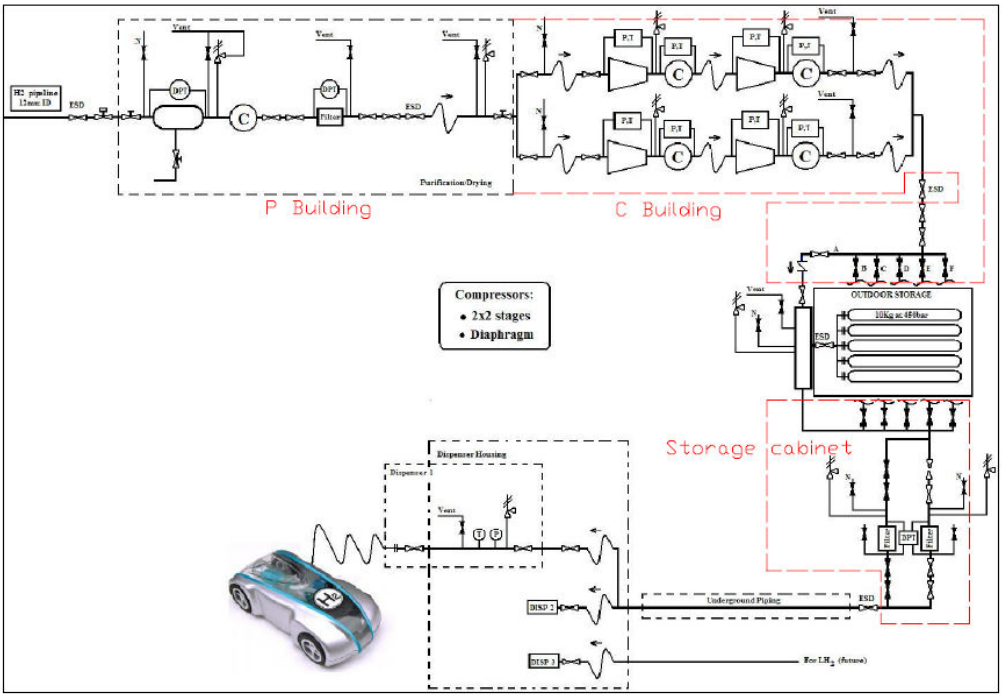


Figure 1. Simplified process scheme of the BBC refuelling station

Further dimensions of the units and piping were also supplied, including data on hydrogen leak detection and installation shutdown.

Figure 2 shows the plot plan of the station and its surroundings. Population data was given in numbers of people present in apartments, school, offices, etc., as well as on-site persons (clients, HRS personnel), including the day-/night patterns of presence. This data would enable partners in the exercise to conduct societal risk assessment.

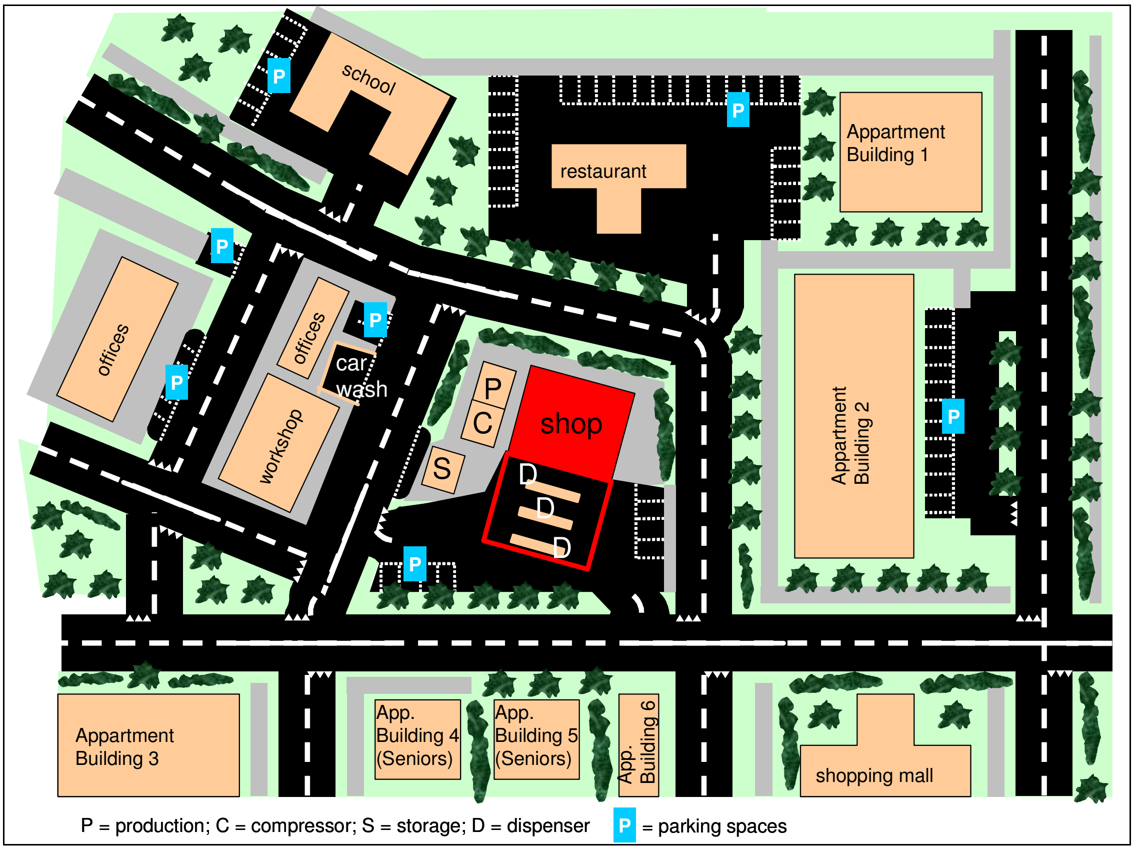


Figure 2. Layout of BBC refuelling station and its surroundings

4. BENCHMARK STAGE 1: APPROACHES FOLLOWED AND RESULTS

4.1 Risk assessment approaches

The scheme for the classical risk assessment procedure is given in Figure 3.

The basic philosophy is that RISK is, in its simplest definition, 'the combination of consequence (severity) and likelihood (frequency) of an unwanted event'. Consequently, quantification of risk comprises two main factors: the consequences of an incident and the probability that these consequences will occur. In assessment of risk of an activity, the total risk is the sum of probability times consequences of all unwanted events. In the quantification of risk, different approaches are followed. There is a wide palette of requirements and practices.

In the first group of approaches, most attention is paid to the determination of the probability of failure and to demonstrate that safeguards and procedures will ensure high reliability of a system and a sufficiently low probability that something will go wrong. Usually, detailed fault tree and event tree assessments are part of such studies. Probability of failure is often derived from literature data, in in fault trees specific data on inspection intervals, time of repair, etc. are included to make the risk values as system specific as possible.

At the other side of the palette, one will find practices which are fully deterministic in the assessment of potential consequences: injury or fatality to people, damage to constructions and assets. Most attention is paid to substance properties, physical behaviour, dispersion modelling and damage assessment.
And finally, there is the requirement of a 'full QRA' in which both approaches are combined, resulting in quantification of individual risk and societal risk, and where the outcomes of risk assessment are used as a more or less decisive tool in environmental permitting and land-use planning.

The preferred practices of each participating partner are, in most cases, determined by their background, history, national regulatory requirements, and available assessment tools. Moreover, each approach has its own type of outcome, e.g. consequence distances, risk matrix, list of critical equipment, values for probability of loss of life, individual risk contours, etc.

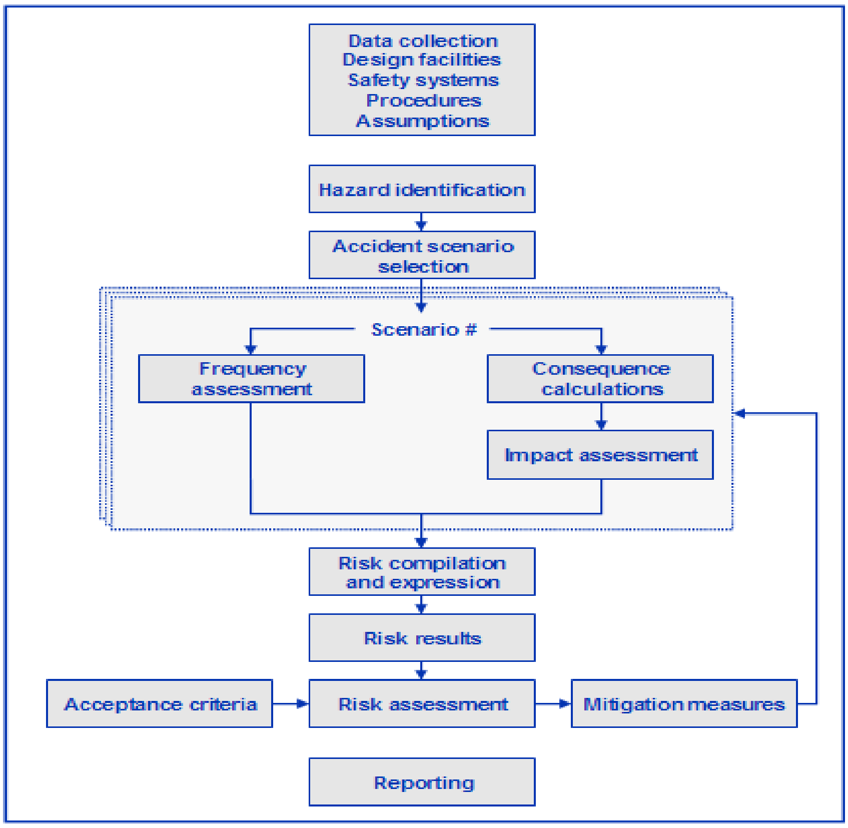


Figure 3. Scheme for classical quantitative risk assessment

4.2 Input for the benchmark exercise: approaches

Through an extensive questionnaire, an inventory was made of the approaches that each partner followed in their analysis. The questionnaire involved issues like: method for identification of scenarios, basis for frequency determination, ignition probabilities, methods for modelling of releases and their consequences both indoor and outdoor, nature of end-results, etc.
The inventory showed a wide variety of applied methodologies and tools. Table 2 gives a condensed overview of the results of this inventory.

Table 2. Summary of results of QRA provided by various partners

(Intended) approach / contribution	HyQRA Partner
Qualitative (e.g. HAZOP, Fault trees, system analysis); frequencies (partly) quantified	UNIPI; UPM; JRC
Semi-quantitative (e.g. risk matrix)	UNIPI + NCSRD; GexCon
Quantification of consequences	HSL; NCSRD; GexCon; UNIPI
'Full' QRA: individual and societal risk	DNV, TNO
Other, not directly related to the Benchmark	UU

Some observations of these results revealed:

- Two partners conducted the study mutually: UNIPI and NCSRD. The first step, identification of relevant release scenarios, was done by UNIPI using HazId, fault trees and risk matrix. The identified relevant cases were forwarded to NCSRD for consequence assessment, through numerical CFD modelling. In parallel, UNIPI also conducted consequence calculations for a set of scenarios, using an analytical modelling tool.

- Partners that followed the basically qualitative approach used extensive details in the assessment of failure probabilities in the system. Also human factors (successful intervention) were given due attention. The objectives in this approach are mainly focussed on the identification of criticality in the design and operation of the installation and on the reliability in mitigating measures. The comparison of results is quite a complicated, not straightforward exercise.

- Partners applying the risk matrix approach (UNIPI and GexCon) used this method primarily as a screening tool to identify which scenarios should be taken forward into a more detailed evaluation of consequences. A remarkable observation was that one group (UNIPI) identified over 20 scenarios in the 'red' segment of the risk matrix, while the other (GexCon) concluded that all the events scored in the 'green' area, meaning that the risk level would be acceptable and no further risk reducing measures are needed. UNIPI had obtained the result after the evaluation of a so-called compensated risk matrix with the inclusion of mitigation measures like emergency shutdown systems (ESD), non-return valves (NRV), alarms, sensors, etc.. GexCon notes that the risk matrix figures have not been updated based on the consequence results for the four chosen scenarios (Phase 2); they would probably be somewhat different if FLACS results were used. A more in depth analysis of the used criteria by the two participants revealed that considerable differences exist in the scales of both the severity and the likelihood parameters between the two contributions. Consequently, the decision of whether a scenario falls in the 'green' area or in the 'red' one appears to differ due to variation in the division of the axes. Any conclusions about the differences in the risk matrix outcome should therefore be made with this consideration in mind.

- In consequence analysis, both analytical modelling as well as CFD tools were applied. Since there were differences in the first steps of the analyses (scenario definition) already, comparison of eventual results between three to five partners appeared hardly feasible. Moreover, the available analytical tools appeared not appropriate to perform consequence assessment for indoor releases, e.g. inside the compressor section, and for accounting for obstacles. This, in turn, made it difficult to compare these scenarios with the ones for which CFD modelling was applied.

- Determination of individual and societal risk levels, as obtained through 'full QRA', was only done by DNV and TNO. Also these results showed considerable differences. An in-depth comparison has not been completed, but one of the main differences seems to be in the figures for delayed ignition probability. Both partners however calculated a relatively high societal risk for the external public. Scenarios involving catastrophic failures and large releases, together with the use of analytical consequence models for dispersion assessment, not suitable for accounting for the buoyancy effects of hydrogen, are likely causes for calculating large consequence areas.

4.3 Input for the benchmark exercise: methods, tools and data

Table 3 gives an overview of the methodologies and data sources that were used in the different consecutive steps in the QRA process.

Table 3. Data sources and models used by various partners

Parameter	Source / model	HyQRA Partner
Scenario definition	System analysis, including ESD etc.	UNIPI, UPM
	Mainly generic leak sizes	DNV, TNO
	Risk matrix for generic release cases	GexCon
	Fault trees	JRC
Frequencies	SNL data (provided for the project)	DNV, UNIPI, GexCon
	HyApproval	DNV
	Purple Book	TNO, UNIPI
	OREDA	UNIPI
	AIChE	UNIPI
Ignition probability	EIHP 2, in HySafe D71	UNIPI, DNV, JRC
	TDIIM	GexCon
	Purple Book	TNO
Effects modelling	Analytical (codes: EFFECTS, PHAST)	DNV, HSL, UNIPI, TNO
	Numerical / CFD (codes: ADREA, FLACS, CFX-11, PANEPR)	NCSRD, GexCon, HSL, TNO

The variation in the estimated failure frequencies and event probabilities appears quite wide. This seemed to be partly caused by the fact that several partners conducted detailed reliability analysis, and accounted risk reduction factors to ESD's, NRV's and human intervention. Others relied mainly on initial failure frequencies from generic databases. Within the scope and time constraints of the HyQRA project, the 'how, what and why' of the respective assumptions could not be evaluated, but they certainly have had a significant impact on the results.

Also the adopted values for ignition probabilities seem to spread considerably. Table 4 shows a summary of the reported numbers. The adopted 'no ignition' probabilities vary from p = 0 – 0.85. This appears to be one of the parameters that are not suffiently understood for hydrogen, as yet.

Table 4. Probability of ignition of hydrogen cloud, as adopted by different partners

Partner	Dependency	Direct ignition	Delayed ignition	No ignition	Source
DNV	Release rate / amount	In: 0.05 Out: 0.30	In: 0.10 – 0.20 Out: 0.10 – 0.30	In: 0.75 – 0.85 Out: 0.40 – 0.60	?
UNIPI	In / outdoor	0.50	0.50	-	Hysafe D71, EIHP2
UPM		0.30 – 0.50		0.50 – 0.70	HySafe D71, EIHP2
Gexcon		0.19	0.05	0.76	HySafe D71 EIHP2; TDIIM
TNO	Release rate / amount	0.20	0.80	-	Purple Book

4.4 Conclusions from Stage 1

In the first evaluation of the results obtained in Stage 1, it was concluded that the benchmark exercise would not be able to throw light on the most relevant (differences in) risk modelling, and on which a quantitative comparison could be useful. Particularly it appeared difficult to compare results of consequence assessments. Not all partners could deliver results as defined in the initial instructions, for reasons of unavailability of the appropriate tools or insufficient expertise in the expected type of outcomes, but also due to time and budget constraints.

Consequently, the set of data and results that can be used for comparison purposes is very narrow: often only in data pairs. A further evaluation of single parameters seems still feasible, though outside the time schedule and budgets of HySafe. Drawing overall conclusions and recommendations for future QRA practice from this exercise alone appears to be quite a challenge.

5. BENCHMARK STAGE 2: COMPARISON OF CONSEQUENCE MODELLING RESULTS

In the project evaluation of the initial results of stage 1, it was decided to focus the scope of further comparison on consequence assessment only, by defining a limited number of mutually agreed release cases. These scenarios were defined quite strictly, in terms of system conditions, weather conditions, leak location and size, and even leak direction (horizontal or downward). Also the requested output was defined, e.g. to provide the distance to thermal radiation of 35 kW/m^2 or to explosion overpressure of 0.3 bar. Also the frequency of occurrence of these consequences was requested to be reported.
Six partners agreed to participate in the part of the exercise: DNV, UNIPI, HSL, TNO, GexCon, and NCSRD.

The various scenarios and the results of the exercises will be described hereafter. The four defined scenarios (see also Figure 4) are:

1. C3: 8 mm leak in an intermediate vessel in the compression section (450 barg)
2. S3: 1.6 mm leak in one set of storage cylinders (bottom layer)
3. ST3: 8 mm pipe rupture inside the storage cabinet
4. RF2: 1.6 mm leak in a disperser unit (underneath canopy of HRS).

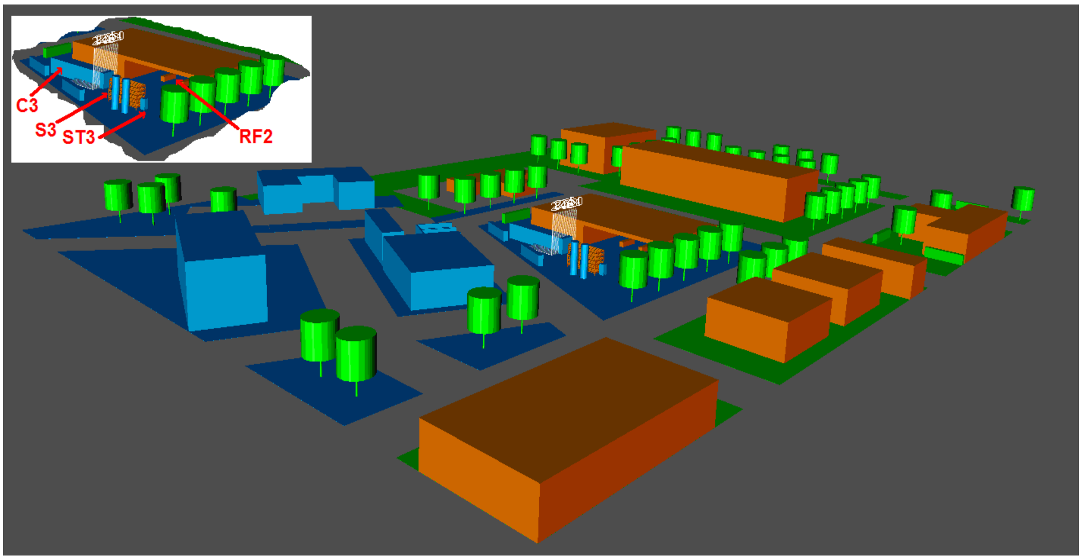
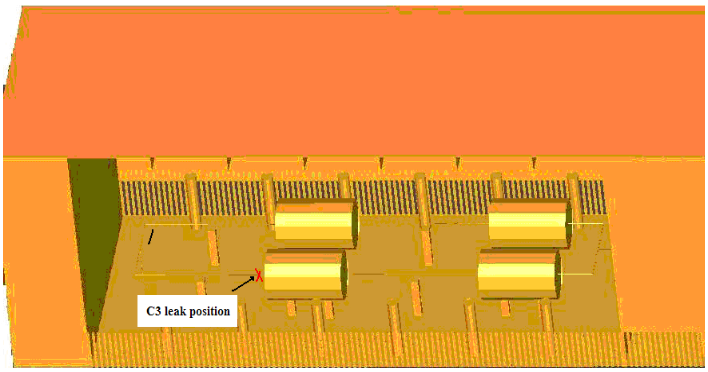


Figure 4. Three dimensional overview of refuelling station with surroundings; upper left shows locations of the four reference scenarios for the modelling benchmark

5.1 Results for Scenario C3

The definition of Scenario C3 is presented in Figure 5.



Compressor building

- Room volume ~ 67.5 m^3, with mech. ventilation in ceiling at 150 ACH
- Scenario: 8 mm leak in vessel; volume 0.25 m^3; p = 450 barg; horizontal leak
- Requested: Explosive mass; overpressure

Figure 5. Scenario description C3: Compressor building

Results of consequence modelling were submitted by five partners; four results were given for analytical models (DNV, HSL, GexCon and TNO), and three for CFD models (NCSRD, GexCon and HSL). The results are summarized in Table 5.

Table 5. Results of consequence modelling for Scenario C3.

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

Parameter	Unit	Analytical model					Numerical model		
		DNV	UNIPI	HSL	TNO	GexCon	NCSRD	GexCon	HSL
Room volume assumed [1)]	[m^3]	67.5		67.5	63	67.5	63	67.5	67.5
Release rate [2)]	[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 [3)]	
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.)	

Notes to Table 5:

1) The dimensions (length) of the compressor room were misinterpreted by some partners. Consequently, they assumed room volume of 63 m^3, in stead of 67.5 m^3.
2) The symbol (↓) means that the release rate decreases with time; the given values are the initial (maximum) ones.
3) Gexcon's value of an overpressure of 12 barg is explained by assuming the C-building to have 'strong walls', potentially resulting in a confined vapour cloud explosion with reflections / acceleration due to obstacles. A DDT could have occurred also.

Some observations in this scenario are discussed here.

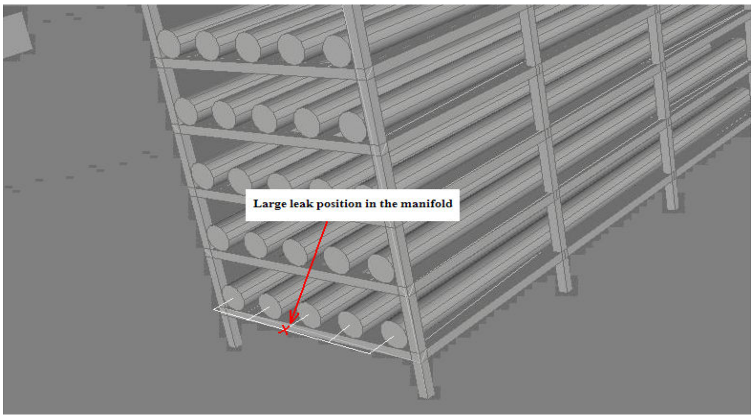
In the analytical modelling by TNO and HSL, the H_2 concentrations inside the building were calculated by assuming ideal mixing in the room and transient increase and decrease of H_2 due to room ventilation. Numerical modelling provides a more detailed result of H_2 concentrations as a function of time and indoors location.
The differences in the initial and intermediate results are not very large. Values of release rate, release duration, duration of flammable mixture, and even of flammable mass differ slightly (generally within a factor of 1.5 – 2).

The calculated explosion overpressures however cover a very wide range, from 0.2 barg to 12 barg. Differences are probably attributed to each analyst's assumptions with regard to the integrity of the room construction. The lower value (0.2 bar by DNV) assumes that the container wall will fail at this low pressure, and that pressure is then relieved. The highest values (12 barg by GexCon and 6 barg by TNO) probably assume a high integrity of the building, or a very steep pressure increase and a too slow response of the walls to fail.

Only in three cases (HSL, TNO and GexCon), an attempt was made to assess possible effects outside the container, that is downstream the vent opening. The analytical models yield no external effects, due to plume rise of the exhaust gas.
These aspects have not (yet) been evaluated in more detail. Particularly the differences in the overpressure results in enclosed areas are an indication of the need for further investigation.

5.2 Results for Scenario S3

The definition of Scenario S3 is presented in Figure 6.



Storage bank

- Scenario: 1.6 mm leak in one set of cylinders; volume 2.5 m^3; p = 450 barg; downwards release
- Wind: u = 1.5 m/s
- Requested: distance overpressure 0.3 bar; radiation 35 kW/m^2

Figure 6. Scenario description S3: Storage bank

Results of consequence modelling were submitted by six partners. Five results were given for analytical models (DNV, UNIPI, HSL, GexCon and TNO), and three for CFD models (NCSRD, GexCon and HSL). The results are summarized in Table 6.

Table 6. Results of consequence modelling for Scenario S3.

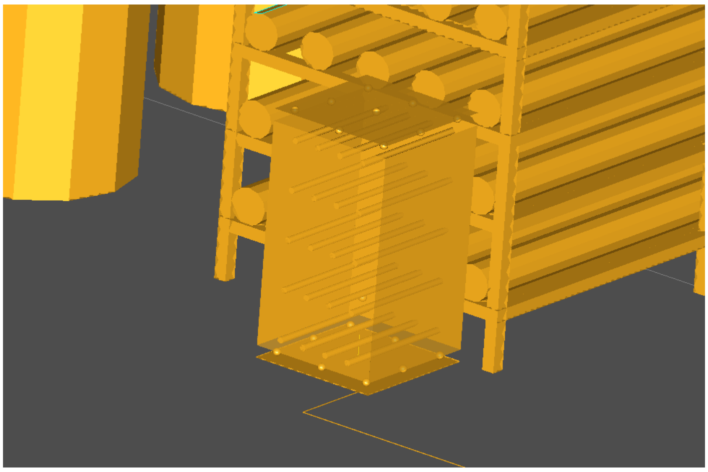
Parameter	Unit	Analytical model					Numerical model		
		DNV	UNIPI	HSL	TNO	GexCon	NCSRD	GexCon	HSL
Model used		PHAST	EFFECTS-7	PHAST	EFFECTS-8	Semi-quantit.	GAJET + ADREA-HF	FLACS	CFX-11
Location			outdoor, horizontal	outdoor	outdoor, horizontal	outdoor	outdoor	outdoor	outdoor
Release rate [2)]	[kg/s]	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 [1)]	[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 [1)]	[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 [1)]	[m^3]						~ 33 (1.5) 38 (5.0)	16	11.3 – 15.4
Max. overpressure	[barg]							~ 0.01	
Fraction confined [1)]	[%]		50	50	25 (D1.5) 50 (F1.5)				
MEM curve	[-]		6	7	6				
Distance P = 0.3 barg [1)]	[m]	3.5	8.0	not reached	5.2 (D1.5) 9.0 (F1.5)	1.1			

Notes to Table 6:
1) Values given in between brackets (..) indicate the atmospheric conditions (stability, wind velocity) or release height (h) for which the given dispersion results have been determined.
2) The symbol (↓) means that the release rate decreases with time; the given values are the initial (maximum) ones.

Some observations for Scenario S3 are:
There is not too much difference in the results for the source term (release rate and duration), and also jet fire lengths and radiation levels do not differ significantly.
Bigger differences occur, again, in the dispersion modelling (determination of flammable mass) where the results scatter over more than an order of magnitude. An obvious difference is that the analytical models assume release in horizontal direction; these models are not appropriate to model vertically downward, colliding jets. There is however no indication that the numerical models are clearly more consistent in this case. Overpressure distances are only given for the analytical models. The distance to p = 0.3 bar varies roughly from 0 - 9 metres.

5.3 Results for Scenario ST3

The definition of Scenario ST3 is presented in Figure 7.



Storage cabinet

- Scenario: 8 mm pipe rupture; volume 0.1 m^3; p = 450 barg; horizontal release
- Wind: u = 1.5 m/s
- Requested: overpressure 0.3 bar; radiation 35 kW/m^2

Figure 7. Scenario description ST3: Storage cabinet

Results of consequence modelling were submitted by six partners. Five results were given for analytical models (DNV, UNIPI, HSL, GexCon and TNO), and three for CFD models (NCSRD, GexCon and HSL). The results are summarized in Table 7.

Table 7. Results of consequence modelling for Scenario ST3

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 [2)]	[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

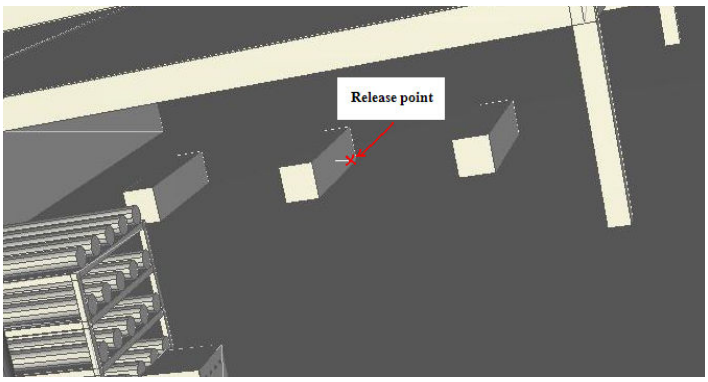
Parameter	Unit	Analytical model					Numerical model		
		DNV	UNIPI	HSL	TNO	GexCon	NCSRD	GexCon	HSL
Jet fire length	[m]			18.1	14.9				
Jet fire SEP	[kW/m^2]			151	110				
Distance 35 kW/m^2	[m]	16		16	17.2	132			
Distance to LEL (stability) [1)]	[m]			13 (h=0)	36 (D) 68 (F)		35	30	>6
Time to Cmax [1)]	[s]			21 (h=5)	~ 5.4 (D) ~ 9.4 (F)		8		2.5
Duration C > LEL	[s]			2.5	36		43	~25	
Flammable mass [1)]	[kg]	5.65	2 (F1.5)		2.75 (D) 3.1 (F)		7.3		1.22
Flammable volume	[m^3]	132	6.6 (D5)	2.8			940	450	62
Fraction confined	[%]				100				
MEM curve	[-]		50	50	8				
Max. overpressure	[barg]		8	7	2			~ 0.12	
Distance P = 0.3 barg	[m]	14	15.1 (F1.5) 22.5	15 early 10 late (at 30 m)	22	25.9			

Notes to Table 7:
1) Values given in between brackets (..) indicate the atmospheric conditions (stability, wind velocity) or release height (h) for which the given dispersion results have been determined.
2) The symbol (↓) means that the release rate decreases with time; the given values are the initial (maximum) ones.

The provided results in this scenario confirm the earlier observations.
The source rates and the thermal radiation distances do not differ much between partners that have submitted results. A clear exception is the result of GexCon. The cause for their high release rate needs to be determined, because this seems to cause the big consequence results as well, particularly the thermal radiation distance.
Distances for overpressure p = 0.3 barg have only been reported from analytical models. Since some partners reported distances from the release location, and others from the location of (delayed) ignition after cloud drift, the results are difficult to compare without detailed evaluation.

5.4 Results for Scenario RF2

The definition of Scenario RF2 is presented in Figure 8.



Dispenser

- Scenario: 1.6 mm leak; 60 s continuous, then volume 0.15 m^3; unconfined, downwards
- Wind: u = 5 m/s
- Requested: overpressure 0.3 bar; radiation 35 kW/m^2

Figure 8. Scenario description RF2: Dispenser

Results of consequence modelling were submitted by five partners. Four results were given for analytical models (DNV, UNIPI, GexCon and TNO), and two for CFD models (NCSRD and GexCon). The results are summarized in Table 8.

Table 8. Results of consequence modelling for Scenario RF2

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	$[kW/m^2]$		193		208				
Distance 35 kW/m^2	[m]	not reached	3.45		3.3	16.1			
LEL length [1)]	[m]		5.15		6.9 (D5) 16.3 (F5)	1		Ø = 5 m	
Time to Cmax [1)]	[s]				continuous	40	13	7	
Duration C > LEL	[s]				continuous		85		
Flammable mass [1)]	[kg]	0.02	0.019		0.036 (D5) 0.087 (F5)		0.23 (1.5) 0.19 (5.0)		
Flammable volume [1)]	$[m^3]$						47 (1.5) 35 (5.0)	10	
Max. overpressure	[barg]				1.0			~ 0.02	
Fraction confined [1)]	[%]		50		100 (D5) 70 (F5)				
MEM curve	[-]		6		7				
Distance P = 0.3 barg [1)]	[m]	2.9	2.7		5.0 (D5) 5.9 (F5)	1.1			

Notes to Table 8:

1) Values given in between brackets (..) indicate the atmospheric conditions (stability, wind velocity) or release height (h) for which the given dispersion results have been determined.

For this outdoor scenario, the numerical models (NCSRD and GexCon) seem to give higher results in flammable mass, than the analytical models. Differences are as high as one order of magnitude. Overpressure distances for p = 0.3 bar are only given by partners using analytical models. Conclusions with regard to the probable outcome of numerical modelling are not available.

For most of the other parameters (source term, radiation, etc.) too few data is available to enable a useful comparison.

6. CONCLUSIONS

The benchmark exercise has shown that big differences (still) exist in the approach of QRA and in the nature of results that are obtained. The differences are partly caused by historical and cultural reasons, like the background of the risk analysts and regulatory requirements in the different Member States in the EU. This has also determined the tool development and the emphasis on the different issues of what risk assessment comprises: consequences, likelihood and risk acceptance criteria.

Particularly the second part of the HyQRA benchmark exercise has shown that considerable differences exist in the results of modelling consequences for, even very straightforward, specified events. Some of these were due to limitations in the software used, in particular some of the analytical models. Particularly the results of dispersion calculations (e.g. dimension of flammable cloud; explosive mass) show wide scatter. Surprisingly, this scatter does not result in an obvious clustering of numerical results versus analytical results. It is a fact that the analytical dispersion models were applied for short distance predictions for which these models are not well validated. Given this limitation, there is no evidence from the limited available data that CFD modelling will provide a better prediction of the buoyant gas behaviour of hydrogen in open air than analytical models would. At short distances and/or in confined areas, numerical models are expected to provide more realistic results. A further evaluation of these results is certainly recommended.

The authors hope that opportunities will be found to draw more conclusions from this exercise through a confrontation of all partners with the results. Probably, the exercise and the individual (yet unpublished) background reports contain much more information than could be evaluated in this paper. Conclusions about uncertainties in modelling and basic data could be more comprehensive if definitions, objectives and tools of risk assessment were more harmonised and (instructions on) a benchmark analysis had less degrees of freedom. Also further validation of the appropriateness of consequence models (analytical versus numerical) for hydrogen is strongly recommended. The results of this benchmark exercise may be shared in an international platform like the IEA Hydrogen Implementation Agreement (HIA), as a basis for further harmonisation in risk analysis methods and practices.

7. ACKNOWLEDGEMENTS

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