HYDROGEN APPLICATIONS

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RISK ACCEPTANCE CRITERIA

AND

RISK ASSESSMENT METHODOLOGY

Gerd P. Haugom, Company: DNV

Address: Veritasveien 1, Postal code: N-1322, City: Høvik, Country: Norway

Phone: +47 67 57 92 67, Fax: +47 67 57 99 11

e-mail: Gerd.Petra.Haugom@dnv.com

Harald Rikheim, Company: DNV/the Research Council of Norway

Company: the Research Council of Norway, Address: Postboks 2700 St. Hanshaugen, Postal code: 0131 City: OSLO, Country: Norway

Sandra Nilsen, Company: Norsk Hydro ASA

Address: P.O.Box 2560, Postal code:N-3907, City: Porsgrunn, Country: Norway

Abstract

The paper describes the development of risk acceptance criteria and risk assessment methodology for early phase introduction of hydrogen (H_2) applications. Hydrogen refuelling stations for hydrogen fuelled vehicles were used as case studies. This was done as a task in the European Commission funded research project European Integrated Hydrogen Project phase 2 (EIHP2). The EIHP2 shall provide input to regulatory activities on a European Union and global level facilitating the safe development, introduction and daily operation of hydrogen fuelled vehicles on public roads and their refilling at public hydrogen refuelling stations. The suitability of a risk based approach to development of standards and regulations is discussed.

Risk acceptance criteria are an important part of safety management and reflect the targeted safety level. Criteria must be established before conducting risk assessments to enable comparison against the desired safety level. Risk acceptance criteria based on general societal risk were developed, and the resulting risk acceptance criteria are described in detail.

Early phase introduction of hydrogen applications in the public domain is characterised by the lack of relevant, detailed technical information and historical incident and accident data. A method for risk assessments was developed to take into account hydrogen specific issues and early concept phase. The risk assessment methodology was then used for risk assessments of different concepts for hydrogen refuelling stations.

The conclusion discusses the suitability of the risk acceptance criteria and the risk assessment methodology based on experiences from the case studies. Keys to success are also presented.

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1 Introduction

The European Integrated Hydrogen Project phase 2 (EIHP2) is a European Commission funded research project, ref./1/. The EIHP2 provides input to regulatory activities on a European Union and global level facilitating the safe development, introduction and daily operation of hydrogen fuelled vehicles on public roads and their refilling at public hydrogen refuelling stations. The suitability of a risk based approach to development of standards and regulations is investigated in Work Package 5 Safety.

One task in Work Package 5 Safety of the EIHP2 was to assess the risks in the refuelling infrastructure for hydrogen fuelled vehicles, and to utilise the results as input and recommendations for the standardisation for hydrogen refuelling infrastructure. The risk assessments were concentrated on hydrogen refuelling stations. To facilitate this work, it proved necessary to develop a set of risk acceptance criteria and a suitable course risk assessment methodology.

2 Risk acceptance criteria

One task of EIHP2 was to assess the risks in the refuelling infrastructure for hydrogen fuelled vehicles. As part of this work in work Package 5 - Safety of the EIHP2 project, a set of safety acceptance criteria for hydrogen refuelling stations was developed and proposed. The full description of this work is available in the EIHP2 report "Risk acceptance criteria for Hydrogen refuelling stations" ref. /2/.

Quantitative risk acceptance criteria are an important part of enterprise risk or safety management systems, and should be established prior to performing quantitative risk analyses (QRA). Acceptance criteria are based on the established safety goals and quantification of these. Risk results from QRA of installations, plants, procedures etc. are compared with established risk acceptance criteria to determine whether the risk level is acceptable or not. If the estimated risk level is too high compared to the acceptance criteria, risk reducing measures need to be identified and implemented. Such criteria are also a suitable measure for establishment of safety distances.

2.1 Risk exposed persons

Risk acceptance criteria are established for all groups of people that can be exposed to accidents originating from a refuelling station. Different types of criterion are used for these groups. The groups are described in the following.

Third party

Third party risk considers how events on the refuelling station can affect areas outside the refuelling station boundaries and includes people living and working in the vicinity of the refuelling station or visiting/travelling through the neighbourhood. Both societal and individual (or geographical) risk measures should be considered (e.g. FN curves and risk contours).

Refuelling station customers (second party)

This will assess people visiting the refuelling station area to use the facilities. These people will be exposed to the risks at the refuelling station for a limited period of time, while visiting the facilities. Therefore, the risk contribution to each individual will be very low. However, it would be unreasonable to use this as an argument for not considering this risk.

Hydrogen refuelling station personnel (first party)

This includes personnel involved in operation, inspection and maintenance of the hydrogen and/or the conventional re-fuelling station. Generally, a higher risk level will be considered acceptable for this group than for Third party. An individual risk criterion, setting limits to the risk of each individual working at the station, is the most relevant.

Suggested detailed risk acceptance criteria

There are several alternative strategies for developing risk acceptance criteria. In this work the following three were evaluated:

1. Comparing with statistics from existing petrol stations, giving an historical average risk level
2. Comparing with estimated risk levels from risk analyses
3. Comparing with general risks in society.

It was decided to compare with general risks in the society, mainly due to lack of relevant statistics and risk analyses of existing petrol stations. This choice also satisfies the general criteria of assuring that the risk level associated with hydrogen applications should be similar to or smaller than the risks associated with comparable non hydrogen systems.

When comparing with the general risk in everyday life it is normal to use the natural fatality risk for the age group with the lowest individual fatality risk, ref./3/. This is for the age group between 5 and 15 years. Dutch data suggest a base death rate (i.e probability for a death to occur) of $1*10^{-4}$ per year for the age group 10 to 14 years. UK data suggest a base death rate of $2.8*10^{-4}$ per year for the age group 5 to 14 years. These data are from ref./3/. Based on this a base death rate is set at $1*10^{-4}$ per year.

Furthermore, process plants should not lead to more than a 1% increase in the natural fatality rate, i.e. $1*10^{-6}$ per year. This risk level is used as acceptance criteria by Dutch authorities, VROM, for process industry in general, see ref./4/ and by Australian authorities for LPG refuelling stations, see ref./5/.

The risk acceptance criteria suggested in the following are related to process related hazards only, and not other types of hazards such as robberies, collisions, sliding on ice, occupational hazards etc.

Third party (based on general societal risk comparison):

No residential area, third party working premises or public assembly area outside the station shall be exposed to fatal exposure levels caused by major accidents at the station of probability greater than 10^{-6} per year. If there are buildings surrounding the facility, fatal exposure due to collapse of these shall be taken into account.

And:

For the societal risk it is proposed to use the Dutch VROM criteria, ref./4/. This is a FN curve (Frequency of N or more fatalities, as function of N) as shown in Figure 1. If the calculated risk is above the curve, the risk must be reduced.

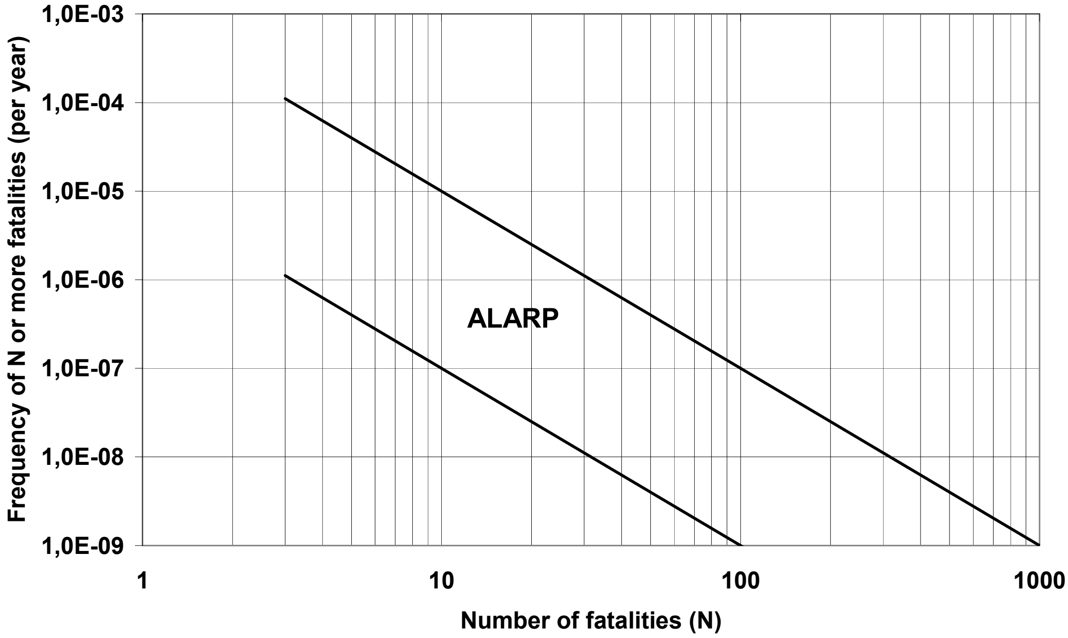

Figure 1 Societal risk curve, FN curve with ALARP region

The upper line in Figure 1 represents the risk acceptance curve. The region between this line and the lower line denotes the ALARP area (As Low As Reasonable Practical). For scenarios with risk levels (that lie) between these lines the risk should be reduced if practical, typically subject to cost benefit analysis. For scenarios with risk levels above the upper curve, measures to reduce the risk must be implemented.

The slope of the FN curve is designed to reflect the society's aversion to single accidents with multiple fatalities as opposed to several accidents with few fatalities.

Refuelling station customers

The probability of a major accident causing one or more fatalities among customers shall not exceed 10^{-4} per year.

Hydrogen refuelling station personnel

The *individual* probability of fatality caused by hydrogen-process related events on the refuelling station should not exceed 10^{-4} per year.

2.2 Risk acceptance criteria for coarse risk assessments

In the concept phase of e.g. refuelling stations it is more practical to use a coarser methodology, as for example a Rapid Risk Ranking (RRR), ref./6/, instead of a QRA. In this case a risk matrix is used instead of FN curves. A risk matrix is based on the numbers in a FN curve but allows for the uncertainty incorporated in RRR. The proposed risk matrix for H_2 refuelling stations is shown in Table 1.

Table 1 Risk Matrix, - the letters H, M and L denote risk levels High, Medium and Low respectively. The probability levels are further explained further in table 4.

		PROBABILITY (per year)				
		A (<0.001)	**B (0.01-0.001)**	**C (0.1-0.01)**	**D (1-0.1)**	**E (10-1)**
Consequence severity	**1 (Catastrophic)**	**H**	**H**	**H**	**H**	**H**
	2(Severe loss)	**M**	**H**	**H**	**H**	**H**
	3 (Major damage)	**M**	**M**	**H**	**H**	**H**
	4 (Damage)	**L**	**L**	**M**	**M**	**H**
	5 (Minor damage)	**L**	**L**	**L**	**L**	**M**

The risk levels correspond to the FN curve in Figure 1, where High is the unacceptable area, Medium is the ALARP area and Low is the acceptable area. The consequence severity categories, as presented in Table 3, have been developed for consequences to people (measured in injury, need for medical treatment, disability or fatality), as well as material and the environment.

Table 4 gives a detailed description of the probability level categories “A” to “D” applied in Table 1, i.e. the probabilities for the event consequences in table 3 to occur. Table 2 gives a more detailed explanation of the three risk categories and the following acceptance criterion:

Table 2 Description of risk levels High, Medium and Low.

Level	**Level name**	**Description**
H	High	High risk, not acceptable. Further analysis should be performed to give a better estimate of the risk. If this analysis still shows unacceptable or medium risk redesign or other changes should be introduced to reduce the criticality.
M	Medium	The risk may be acceptable but redesign or other changes should be considered if reasonably practical. Further analysis should be performed to give a better estimate of the risk. When assessing the need of remedial actions, the number of events falling into this risk level should be taken into consideration to assure that the risk is as low as reasonable practical (ALARP).
L	Low	The risk is low and further risk reducing measures are not necessary

Table 3 Consequence severity levels

Level	Description	Definition		
		People	**Environment**	**Material**
1	CATASTROPHIC	Several fatalities	Time for restitution of ecological resource such as recreation areas, ground water >5 years	Total loss of station and major structural damages outside station area
2	SEVERE LOSS	One fatality	Time for restitution of ecological resource 2 - 5 years	Loss of main part of station. Production interrupted for months.
3	MAJOR DAMAGE	Permanent disability Prolonged hospital treatment	Time for restitution of ecological resource < 2 years	Considerable structural damage Production interrupted for weeks
4	DAMAGE	Medical treatment Lost time injury	Local environmental damage of short duration < 1 month	Minor structural damage Minor production influence
5	MINOR DAMAGE	Minor injury Annoyance Disturbance	Minor environmental damage	Minor material damage

Table 4 Description of probability levels

Level	Description	Definition	Frequency of event occurrence
A	IMPROBABLE	Possible, but may not be heard of, or maybe experienced world wide.	About once per 1000 years or less
B	REMOTE	Unlikely to occur during lifetime/operation of one filling station	About once per 100 years
C	OCCASIONAL	Likely to occur during lifetime/operation of one filling station	About once per 10 years
D	PROBABLY	May occur several times at the filling station	About once per year
E	FREQUENT	Will occur frequently at the filling station	About 10 times per year or more.

3 Risk assessment methodology

In EIHP2 a coarse risk assessment methodology was developed and adopted for risk assessment of hydrogen refuelling infrastructure based on DNV and Norsk Hydro ASA inhouse methodologies for course risk assessment. The methodology applied - Rapid Risk Ranking (RRR) was used and adapted for analysis of hydrogen refuelling stations (ref./7/). RRR, which can be characterised as a preliminary hazard analysis, is suitable when an overview of risks in a system or object is required and the resources or time available is limited, and will often be the very first analysis method used when evaluating risks.

RRR is a simpler approach than a full quantitative risk analysis (QRA) and is particularly suitable in an early development phase where the available information is not detailed enough for a full QRA. Rapid Risk Ranking with the use of risk matrixes will yield the desired results for evaluation of the different concepts in an early phase. The methodology can be applied to for example a geographic area or a plant in an early project stage, but also when the facility is in actual operation.

By using the proposed methodology the relevant hazards for persons operating, refuelling and living in the vicinity of the station will be identified and risk ranked. The risk ranking is based on qualitative estimates of the probability for and the consequences of the identified hazards.

3.1 RRR Methodology

Figure 2 describes the different steps of RRR assessment.

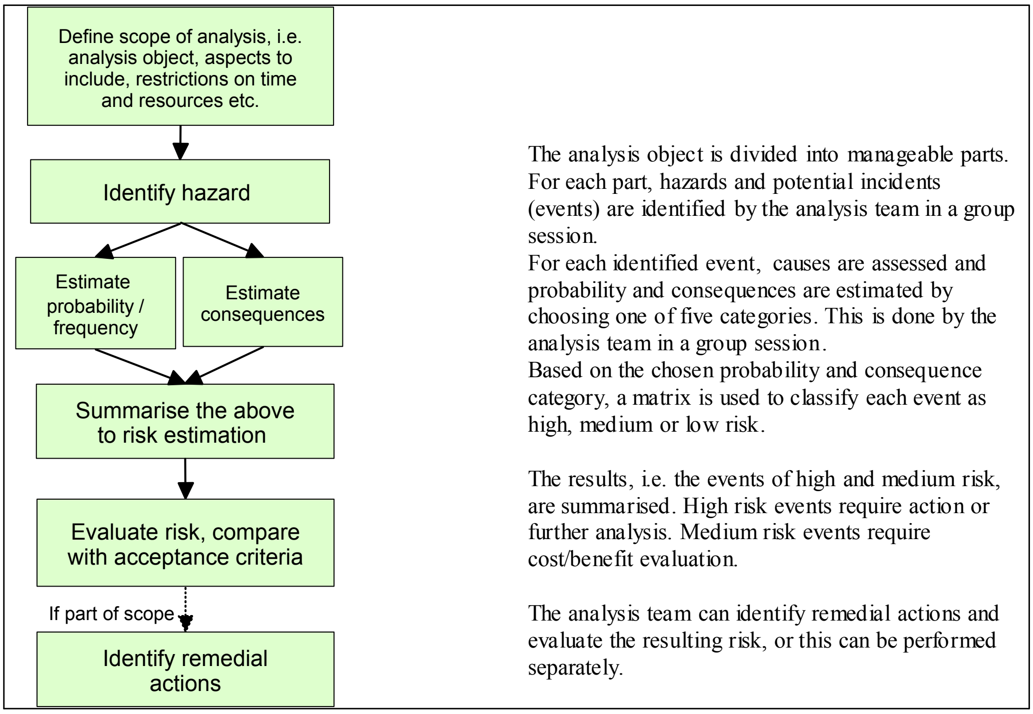

Figure 2 The different steps in the RRR methodology.

The hazard identification and the risk estimation are done as a group session. On beforehand the RRR facilitator and concept "owner" has defined the analysis scope and broken the process down into manageable parts.

3.2 System breakdown

To be able to identify all hazards and events, it may be necessary to split them into manageable parts, especially when the object is big or complex. In RRR this splitting up is normally geographical or related to process sections. An example of splitting for a hydrogen filling station based on pressurised hydrogen, where production of hydrogen also is included, can be as follows:

Process units

Storage of raw materials such as methanol, ammonia etc.

- Hydrogen production unit (typically within an enclosure)
- Drying/purification
- Compression unit
- Storage of hydrogen
- Dispenser unit

Activities

- Refuelling of buses/cars
- Operation, maintenance, transport etc.

Exposed to risk

- Operators
- Control rooms
- Cafeterias/kiosks
- Personnel working in cafeterias/kiosks
- People refuelling
- Residential areas
- etc.

Figure 3 illustrates one possible way of dividing a H_2 refuelling station into segments and sub systems. The actual selection of sub system elements will depend on factors as the scope of the analysis and the complexity of the planned refuelling station. Typically, elements with planned location within the same enclosure will be analysed together.

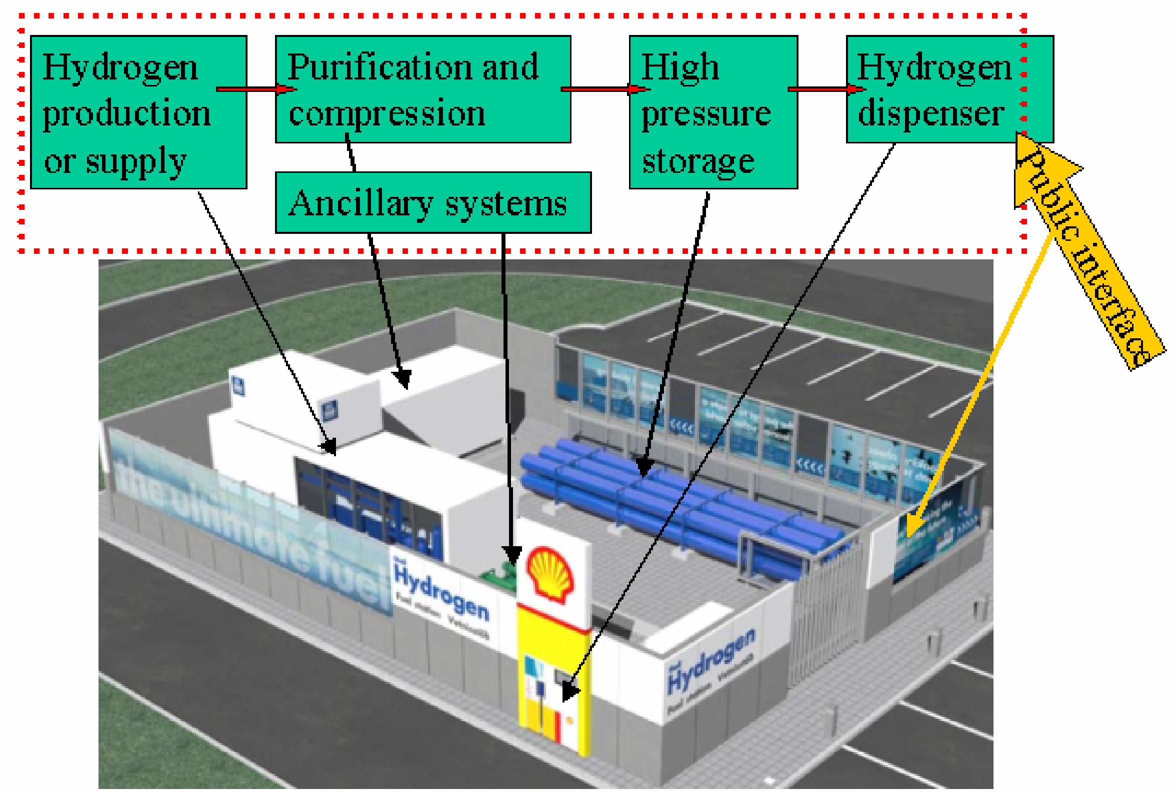

Figure 3 Example of segmentation for a H_2 refuelling station. The ECTOS hydrogen filling station at Reykjavik is used as example, ref./8/.

3.3 Group session

The risk analyses are performed as group sessions with experts and "owners" of the respective concepts who can provide the necessary knowledge and experience on the object being analysed. The goal is to identify and risk rank relevant hazards.

The team will normally consist of:

- a facilitator (team leader) with competence and experience in the method to be used will lead the analysis
- a recorder will report the results.
- team members (2-4 persons) who can provide necessary knowledge and experience on the object being analysed

The composition of the analysis team is very important. The quality of the results depend on the team being positive and open-minded, and on their knowledge, competence and experience.

The group will go through the following tasks:

- concept presentation
- hazard identification (HAZID)
- consequence and frequency estimation
- risk ranking

3.4 Concept presentation

The *concept presentation* should give the team members an overview of the different elements of the concept and the associated process. The information given in the concept presentation should include:

Process flow diagrams or other simplified block diagrams showing the principles of the filling station, including process conditions such as pressure, temperature and amount of hazardous materials

- Layout drawings
- Description of systems for detection and control of hazards/unwanted incidents
- Description of emergency systems and mitigation of hazards.

If the necessary information is not available, assumptions regarding these elements have to be made during the session. This alternative approach demands a lot of relevant experience from the team members to be successful.

3.5 Identification of hazards and potential incidents (HAZID)

After the concept presentation the group will do a structured Hazard Identification (*HAZID)* to identify relevant hazards and accident scenarios. It is important to review all parts of the process, operational modes, maintenance operations, safety systems etc. All hazards and possible accidental events in the analysis object must be identified. All findings should be recorded.

The analysis team's experience and imagination as well as accident reports and statistics etc. may be used. No hazards are too insignificant to be documented. "Murphy's law" must also be borne in mind, i.e. if something can go wrong, sooner or later it will.

There are different sources of hazards, for example:

- Mechanical
- Electrical
- Thermal
- Noise and vibration

- Material and substance (chemicals incl.)
- Ergonomics

Hazards to people, environment and material values may be identified.

The results of the group sessions are reported. A special report form was used for this purpose. For each identified hazard in different areas/systems, its cause, possible mitigation measures, consequence, probability and risk must be recorded. Comments may also be added.

3.6 Risk ranking

The risk is established as a combination of probability of a given consequence and a grading of the severity of the same consequence.

For each identified hazard, the group will assess the **probability of the hazard** occurring and the **severity of the related consequences**. This will enable a ranking of the hazards in a **risk matrix** (Table 1). The risk matrix with categories for consequence severity (Table 3) and probability (Table 4) is shown in the previous chapter. These results can later be used to compare different concepts and evaluate them against relevant acceptance criteria. These acceptance criteria are outlined in the previous chapter.

4 Experience from case studies

The risk assessment methodology was tested on the following set of case studies; i.e. different concepts for hydrogen refuelling stations:

- Gaseous H_2 production by water electrolysis, ref./9/.
- Gaseous H_2 production by methanol steam reforming, ref./10/.
- Gaseous H_2 production by ammonia splitting, ref./11/.
- Gaseous H_2 production by natural gas reforming, ref./12/.
- Compressed gaseous H_2 supplied from pipeline or truck, ref./13/.
- Liquefied H_2 supplied from truck, ref./13/.

All concepts could be assumed to have similar arrangements for compression, storage and dispensing to vehicles.

Very sparse technical input was available at the time of doing the analyses due to:

- Confidentiality aspects related to accident statistics and technical input
- Concepts were not finally designed
- Still some way to go until technical information is ready for some of the production units

This was especially the case with the methanol, ammonia and natural gas concepts which were conceptual designs with typical process details for the hydrogen generation unit known, while the information on how such systems will integrate in a hydrogen refuelling station was sparse. These analyses therefore concentrated on the hydrogen generation systems. More detailed information was available for some of the other concepts.

The lack of detailed information available made it difficult to identify detailed, very specific hazards. However, the more general hazards and conceptual issues could be successfully identified. As there is little or no operating experience available for the concepts analysed and relevant data is lacking, probabilities and consequences for the identified hazards had to a great extent to be based on expert judgement and experience from industry. Nevertheless, a number of relevant hazards with corresponding probabilities and consequences were identified. These results give a good foundation for further work, including an improved understanding of safety aspects of the concepts studied and a safety relevant basis for input to standardisation issues.

The results from the different concept studies are however very dependent on the participants. This means that the results are unsuitable for direct comparison of production concepts.
In theory, a better basis for comparison of different concepts based on RRR-results may have been achieved if all participants had been present at all RRR analyses. Due to practical aspects, e.g. requirements for specialist knowledge on the different hydrogen production methods, this was not possible, - or relevant, to achieve.

Relevant accident data have been difficult to obtain for estimation of risk due to the following reasons:

- Confidentiality aspects among the companies
- The available information is not detailed enough to give information about causes, source conditions, leak sizes, consequences etc.
- Existing hydrogen accidents data/statistics relate to an industrial rather than a retail environment
- Available existing accident data give little "technical" information, and it is therefore not possible to put available information about incidents into context i.e. volumes of H2 produced/delivered, distance traveled, man-hours worked etc.

The results were compared with the risk acceptance criteria. The results were qualitative, i.e. ranked with probability and consequence classes. Therefore they were compared with the risk matrix and not the quantifiable criteria, e.g. 3.party fatalities less than 10^{-6} pr. year. Presenting risk results in a risk matrix gave a good illustration of the risk levels.

The methodology gave good results in identifying high and medium risk hazards which must be addressed in further design work.

5 Conclusions

The risk acceptance criteria and risk assessment methodologies developed were tested on several relevant case studies. The quantitative risk acceptance criteria applied satisfies the general wish to secure that the risk level associated with hydrogen applications are similar to or smaller than the risks associated with comparable existing non hydrogen systems generally accepted in society.

The main purpose of the risk assessment approach adopted, i.e. the RRR technique, is to facilitate identification of main risk aspects, at and early development stage where design (and other) changes are still relatively easy and cost efficient to implement.

Main keys to success for the RRR technique include: the team composition and experience, information availability, and removal of information barriers (e.g. through confidentiality agreements) to secure open discussions.

A risk based approach to standardisation of hydrogen applications needs further work of several reasons. One important factor is the lack of specific and relevant data and experience. The development of quantitative risk acceptance criteria can be an important part of the foundation for the development of performance/risk based criteria into standardisation. A main strength of allowing performance based criteria in standards is to avoid unnecessary barriers against new and innovative solutions.

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