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Summary: Det Norske Veritas have as a part of the IEAHIA Task 19 H2Safety performed Subtask A1 Risk Assessment Methodology Survey for risk assessment of hydrogen production, storage and/or refuelling stations.

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Executive summary

Det Norske Veritas, as part of the International Energy Agency (IEA) Hydrogen Implementing Agreement (HIA) Task 19 Hydrogen Safety Work Plan, has performed a Risk Assessment Methodology Survey for risk assessment of hydrogen production, storage and/or refuelling stations (Activity A1 of Subtask A Risk Management).

In total 11 example project have been received and reviewed, 6 qualitative approaches and 5 quantitative approaches.

The methods applied in the 11 case studies represent standard approaches to risk assessment, following the principles and guidance in a representative set of standards and guidelines.

It is in the details – not the risk analytical principles – the approaches differ slightly. It is however the details that determine the analyses' adaptability to the specifics of hydrogen risk. Such details are discussed in the survey.

The main findings from the survey are:

1. The selection and application of risk acceptance criteria for the example studies reflect the general practice for risk assessments, and are also adapted to most company guidelines and authority regulations. There are not made any particular adaptations to the acceptance criteria in order to reflect specificities of technologies or operation of hydrogen facilities. One aspect that could be considered here is the use of acceptance criteria that is suitable to communicate safety aspects to the public. The use of equivalence criteria, for example comparing the risk of using a hydrogen refuelling station with a usual petrol station, is in this context a good approach.

2. The review shows that specificity with respect to the concept and hydrogen risks in question is as high for the qualitative assessments as for the quantitative assessments.

3. An important development task is to develop a best practice for ignition probability modelling. The Dutch Guideline for Quantitative risk assessment (ref. 01) and the Joint Industry Project Time Dependant Ignition Intensity Model (ref. 02) proposes models for establishing time dependant ignition probabilities. These models should be used as input to establishing a best practice for ignition probability modelling for hydrogen.

4. The assessment of consequences from ignited hydrogen releases uses well established consequence calculation models. These models need however to be applied correctly in order to reflect the special features of hydrogen; lower radiant heat and more prone to explosions/detonations than for example methane and propane. This is reflected in some of the quantitative cases.

5. Two of the quantitative cases apply the Hydrocarbon Release Database collected and maintained by UK Health and Safety Executive as basis for establishing hydrogen release frequencies. The other 3 cases are using the Dutch "Purple book" (ref. 03), the EIGA code IGC 75/01/E/rev (ref. 04), and "Pipe failure probability-the Thomas paper revisited" by B.O.Y.-Lydell (ref 05). The Hydrogen Incident and Accident Database, initiated by HySafe, is very important in order to establish a high quality basis for estimating hydrogen release frequencies.

6. State-of-the-art risk analysis within the oil and gas industry may be identified by their ability to reflect the importance of the safety barriers in a technical system. It is important that risk analysis of hydrogen facilities also reflect the importance of the safety barriers. The IEC-standard "61508 Functional Safety of electrical/electronic/programmable electronic safety-related systems" has formed the basis for enhanced focus on ability of the safety systems to perform their safety functions. Features to reflect safety integrity level of the most important safety barriers for hydrogen facilities are necessary to include in a best practice for risk analysis.

7. Many hydrogen production, storage, and/or refuelling stations will have a wide interface between public users and the technical system. For the system to become accepted by the public it is important that the public risk perception is included both in the risk analysis and in the risk communication. The Canadian Q850 Risk Management Guideline for Decision-Makers contains sections on how to consider and include risk perception and risk communication in a risk analysis. These aspects are particularly important for technical systems that interface closely with public users and 3rd party, and implementation of these aspects should be considered for a best practice for risk analysis.

8. The case studies included focus on technical or operational aspects. The importance of human factors and safety culture for the risk level is not explicitly considered in the case studies.

1.0 Introduction and Scope

Det Norske Veritas (DNV), as part of the IEA HIA Task 19 Hydrogen Safety Work Plan, has performed a Risk Assessment Methodology Survey for risk assessment of hydrogen production, storage and/or refuelling stations (Activity A1 of Subtask A Risk Management).

The survey describes the steps of a risk assessment and show of how these steps are done in the received assessments. The scope and time frame does not allow detailed information on models used in the assessments and background information from databases and guidelines to be discussed.

The participants of Task 19 have been invited to share their experience from risk assessments performed in this area. In addition Partners have provided input on national regulatory regimes and guidelines. DNV has contributed in the data gathering in the same manner as the other Partners.

DNV has reviewed the examples gathered, and has performed a systematic review of the examples. In total 11 example project have been received and reviewed, 6 qualitative assessments and 5 quantitative assessments. Mitsubishi Heavy Industries (Japan) has contributed with one example project, University of Pisa with 2 examples, RIVM, Statoil, DNV with 5 examples and one example is collected from a literature search (California Energy Commission).

Qualitative assessments included:

1. Risk analysis of Refuelling Infrastructure, EIHP2, September 2003 (ref. 06)
2. Safety of Hydrogen Refuelling Stations, DNV 2003 (ref. 07)
3. Risk assessment of the Berlin Hydrogen Competence centre, DNV 2003 (ref. 08)
4. Failure modes and effects for hydrogen fuel options, California Energy Commission (ref. 09)
   http://www.energy.ca.gov/2005publications/CEC-600-2005-001/CEC-600-2005-001.PDF
5. Safety Study of Hydrogen Supply Stations for the Review of High Pressure gas Safety Law in Japan, Japan Petroleum Energy Center 2005 (ref. 10)
   http://conference.ing.unipi.it/ichs/Papers/400081.pdf
6. Risk analysis of Hydrogen Refuelling Station at Forusbeen (”Risikoanalyse av hydrogenfyllestasjon ved Forusbeen”) (ref. 11)

Quantitative assessments included:

7. Risk assessment of hydrogen production and filling station, DNV 2005 (ref. 12)
8. Risk assessment of hydrogen generation and storage facility, DNV 2005 (ref. 13)
9. External safety distances for hydrogen filling stations, RIVM (ref. 14) (Paper)
10. Synthesis of the Risk Assessment Analysis of a Compressed Hydrogen Filling Station, University of Pisa, November, 2005 (ref. 15)
11. Risk Assessment for Gaseous Hydrogen Refueling Station, University of Pisa, September 06-08, 2006 (ref. 16) (Presentation)

From Canada input on national guidelines on risk assessment has been received.

In addition Partners have reported three cases studies performed, for which DNV have not received documentation for. These studies are:

- Feasibility study for injection of hydrogen into the natural gas system to supply a recreation park with hydrogen.
- Basic safety study (second opinion) on the hydrogen filling station for the Amsterdam CUTE bus project.
- Risk assessment for gaseous hydrogen filling station

2.0 Nomenclature and definitions

The basis for this review is the IEC 300-3-9 Application Guide – Risk Analysis of Technological Systems. This basis has been used to define generic steps in risk analysis. These generic steps are reflected in the structure of the review. Definition of central terms is based on ISO/IEC Guide 73:2002 Risk Management – Vocabulary – Guidelines for Use in Standards.

RISK: The combination of the probability of an event and its consequence. The term risk is generally used only when there is at least the possibility of negative consequences.

RISK ANALYSIS is systematic use of information to identify sources and to estimate risk. Risk analysis provides a basis for risk evaluation, risk treatment and risk acceptance. The typical steps of a risk analysis are explained in chapter 2.1.

RISK CRITERIA is a terms of reference by which the significance of risk is assessed. Risk criteria can include associated cost and benefits, legal and statutory requirements, socio-economic and environmental aspects, the concerns of stakeholders, priorities and other inputs to the assessment.

RISK MANAGEMENT is coordinated activities to direct and control and organization with regard to risk.

In addition to these definitions, the term ALARP is applied as follows:

ALARP, i.e. As Low As Reasonably Practicable: The term ALARP is used to describe the process of evaluating the cost of risk reducing measures against the benefits of their implementation, and implementing all measures that are deemed reasonably practicable in the sense that the associated costs are in proportion to the benefits.

2.1 Risk analysis

In order to do a risk analysis a typical approach is first to identify the hazards, *Hazard identification*, and define *Acceptance criteria* for the identified hazards. At the hydrogen refuelling station the hazards may include hydrogen leakage in the dispenser, smoking, reckless driving, lack of maintenance, etc. When the risk related to the hazards is assessed the result should be compared to the acceptance criteria defined. If the results can meet the criteria the risk is by definition acceptable. On the other hand, if the result does not meet the criteria possible mitigation measures should be evaluated. The typical steps of a risk analysis from hazard identification to risk assessment are shown in Figure 1 and explained in this chapter.

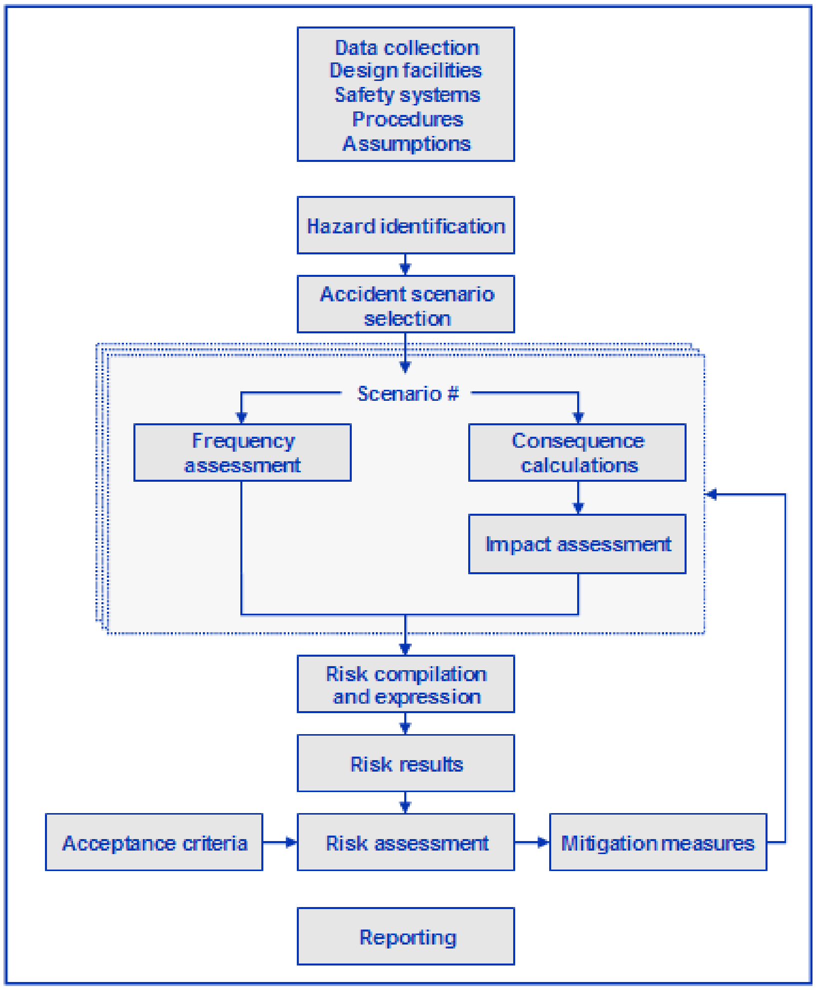

Figure 1: Generic steps in risk analysis

When the hazards are identified a set of accident scenarios is selected, *Accident scenario selection*. Each accident scenario is a result of one hazard or a combination of hazards. E.g. a scenario like hydrogen leakage may be caused by one or more of the following hazards; a rupture in the filling hose, leakage in the dispenser, pipe corrosion, or a vehicle damaging either the dispenser, filling hose or pipe.

So far the analysis has defined a set of scenarios, the next step is to analyse how frequent each scenario is likely to be occur. The *Frequency assessment* has to take into account the frequency of each hazard leading to this scenario. This is usually based on analysis of previous incidents experienced.

When a scenario such as a hydrogen leakage is realized a set of events e.g. jet fires, flash fires, and explosions, are possible results. For each of these events a set of conditions e.g. weather conditions, security measures, ignition sources, and congestion may determine the consequences. During the *Consequence calculation* the probabilities of each identified condition for each possible event is taken into account. The conception of effect is typically restricted to the measurable effect of e.g. an explosion or fire, and the result of the calculation could be the radius of the fire, 25kW/m^2 radiation border, etc. The practical consequences, such as person injury or death, damage to property, negative environmental or economic impacts are assessed in the next step, *Impact assessment*.

Having assessed both the frequency and the impact of a scenario, it is possible to compile and express the risk. The risk may be expressed by the probability of one or more effects. The results from the *Risk compilation and expression* are the *Risk results* which should be compared with the previously defined acceptance criteria to get an indication whether the risk is acceptable or not through the *Risk assessment* process. If the risk is not acceptable new *Mitigation measures* has to be introduced and the risk related to each scenario has to be analysed again.

3.0 Study basis

The following codes and standards on risk assessment have been applied as basis for review and discussion of the review of the example projects:

A. IEC 300-3-9, "Dependability management, part 3: Application guide – Section 9: Risk analysis of technological systems"
B. IEC 61508 – Functional safety of electrical/electronic/programmable electronic safety systems"
C. Control of Major Accident Hazards Regulations (United Kingdom), http://www.hse.gov.uk/comah/
D. Risk Management: Guideline for Decision-Makers, A National Standard of Canada, CAN/CSA-Q850-97;
E. Risk Analysis of Technological Systems, A National Standard of Canada, CAN/CSA/IEC 300-3-9-97;
F. CPR 18E - Guideline for Quantitative Risk Assessment," Committee for the prevention of Disasters (Netherlands) (ref. 01).

A-E represents normative descriptions of principles for risk analysis, while F is an extensive guideline for how to perform a quantitative risk assessment in practice. In addition the Canadian "Risk Assessment – Recommended Practices for Municipalities and Industry" also have been used for reference (ref. 17).

4.0 Introductory discussion of methods

Risk assessments can be classified as either qualitative or quantitative risk assessment methods. The included assessments are listed in chapter 1.0 Introduction and Scope.

A quantitative assessment estimates quantitative risk results. This will typically be a risk number for personnel (typically potential loss of lives per year), environment (frequency of categories of environmental damage per year) or property (frequency of categories of damage to property per year). A quantitative assessment may be used as a basis for cost benefit evaluations, since damage costs can be calculated from the estimated risk figures. Effect of mitigating measures can therefore also be evaluated in an economical perspective. Quantitative assessments will often be more time and resource consuming than a qualitative assessment. A certain level of detail in design is necessary to achieve a quantitative assessment with a reasonable level of accuracy. A simplified quantitative approach may however also be useful for early design and concept evaluations.

A qualitative method follows the same structure as the quantitative approach. The difference is that evaluation of frequency and consequences for the selected scenarios are evaluated qualitatively. Risk results may be presented as hazards placed in a frequency vs. consequence risk matrix. Figure 2 shows an example risk matrix. Qualitative risk assessments are often used to study concepts or operations that are not designed or planned in detail, in order to give a first screening of hazards and risk contributors.

		FREQUENCY (per year)				
		A (<0.001)	B (0.001-0.01)	C (0.01-0.1)	D (0.1-1)	E (1-10)
SEVERITY	1 (Catastrophic)	H	H	H	H	H
	2 (Severe loss)	M	High	H	H	H
	3 (Major damage)	M	Medium	H	H	H
	4 (Damage)	L	Low	M	M	H
	5 (Minor damage)	L	L	L	L	M

Figure 2: Risk Matrix

A combination of the two approaches is often named a semi-qualitative study.

The qualitative and quantitative example studies are reviewed in appendix I and II respectively, following the generic risk assessment structure described in chapter 2.1. A discussion of the risk assessment methods is presented in chapter 5.0.

5.0 Discussion and evaluation

The methods applied in the 11 case studies represent standard approaches to risk assessment, following the principles and guidance given in the guidelines presented in chapter 3.0.

It is in the details – not the risk analytical principles – the approaches differ slightly. It is the details that determine the adaptability specifics of hydrogen risk. Such details are further discussed below.

All case studies included are focusing on technical or operational aspects. The importance of human factors and safety culture for the risk level is not explicitly considered.

5.1 Risk acceptance criteria

The risk associated with a given activity or operation will often be evaluated against risk acceptance criteria. The magnitude of the identified risk compared to the risk acceptance criteria will form the basis for the further process; is there a need for further risk reducing measures or is the achieved risk level accepted as it is? The IEC 300-3-9 standard includes evaluation of risk tolerability as a step in the assessment process, but does not give guidance on how to define tolerability. It is because this standard's scope concentrates on elements of risk analysis only. It does not include further steps of risk assessment that include application of risk criteria (i.e. risk evaluation step). The standard, however, advises that the most suitable terms should be used to express risks, and implies that for example ALARP-type evaluations may be used to assess the tolerability of the expressed risk. This interpretation of the standard was used in the Canadian Hydrogen Safety Program projects. Canada adopted the IEC 300-3-9 standard as a National Standard of Canada in 1997 as CAN/CSA/IEC 300-3-9-97.

The Control of Major Accident Hazards (COMAH) Regulations in the UK applies the concept of risk tolerability, which is defined by an upper maximum level and a lower negligible level. The need for measures in the gap between these two bands shall be based on an ALARP-evaluation.

The Canadian Q850 Guideline for Decision Makers also mentions an earlier version of the ALARP-principle – ALARA – in the tolerable risk region, however, does not provide any clues how to apply it and does not mention "risk criteria". This standard focuses on the differences in risk perception among the stakeholders. This is a very important aspect in risk communication - in particular to the public and users.

In the review of risk assessment methods in chapters 8 and 9 it can be seen that four types of risk acceptance criteria have been applied:

Qualitative assessment:

a. Qualitative risk matrix
b. Equivalence criteria

Quantitative assessment:

c. Individual risk, 1st and 3rd party
d. Societal risk, 1st and 3rd party

Individual and societal risks evaluate the same hazards and consequences using different acceptance criteria. Individual risk is focusing on a person, while societal risk is focusing consequences. Societal risk takes into consideration the severity of accidents over time typically using an F-N curve, where F is frequency of accident and N is number of fatalities. The slope of such an F-N curve decides the aversion for large accidents, with many fatalities, versus small accidents, with few fatalities. 1st party is a person, or persons, who has decided to take the risk, typically the facility owner, operator, or site worker, while a third party is a person in the vicinity but not interest in the facility, and possibly not aware of the risks related to it, e.g. someone residing or working nearby.

The use of the risk matrix with areas representing high, medium and low risk is shown to be useful in order to discuss the risk associated to specific scenarios and failure modes. Each scenario can be represented as a single point in the risk matrix. Risk acceptance can then directly be evaluated, compared and calibrated to other scenarios and hazards. This will assist in quality assurance of the evaluations. Further the effect of mitigating measures can be effectively illustrated. If sufficiently effective frequency (or consequence) reducing measures are identified, the location of the relevant scenario in the risk matrix can be moved to a lower frequency category (or consequence category). One negative aspect of a risk matrix to keep in mind is that it evaluates the risk for individual accident scenarios but does not provide a mechanism to address the total risk.

The selection of acceptance criteria is important to both the quality of the risk evaluation process, and also for successful communication of the risk picture and effect of mitigating measures. The acceptance criteria must be selected according to the purpose and the users of the study. When the risk acceptance criteria are selected much of the format of the rest of the study is also determined. The risk matrix can also be used in quantitative studies and will also there be a strong tool to present the diversity of risk contributors.

In the reviewed studies acceptance criteria have been selected according to the level of design that has been available. For concept evaluations a qualitative approach is often selected, since the uncertainty in design makes quantitative assessments less applicable. Hazard identification in workshops with technical experts is then an efficient tool to perform a qualitative risk assessment, measuring and visualizing the results in a risk matrix.

The equivalence criterion is a strong tool to communicating risks to users that are not familiar with technical terms. The review of the hydrogen refuelling station (ref. 07) is a good example of such use, where the use of a hydrogen refuelling station shall represent the same risk level as a conventional petrol station.

The five quantitative studies evaluated in this survey use quantitative acceptance criteria in order to measure the risk levels for on-site personnel, 1st party, and general public, 3rd party, that may be exposed to the accidents originating from the hydrogen facilities. 4 of the quantitative studies are site specific. This makes it particularly worthwhile to analyse the potential impact to a 3rd party. The quantitative criteria are based on industry practice and/or relevant regulatory authority requirements for the given geographical locations. As an example, UK Health and Safety Executive, Shell, BP, Hydro and Statoil all have quantitative individual risk acceptance criteria for 1st party expressed as the theoretically expected number of fatalities per year. Corresponding quantitative criteria for 3rd party are also defined. The Hong Kong Risk Guidelines give individual and societal risk criteria for 3rd party population, as do the Dutch Ministry for Housing, Spatial Planning and The Environment (VROM). If the facility owners or operators themselves do not have established risk criteria, they will often apply criteria reflecting the industry practice.

To what degree the application of the ALARP principle is used is often a good way to measure the quality of the safety management process. Authorities tend to focus stronger and stronger on the activity owners' use of the ALARP principle in design and operation. Thus risk assessment methods that can document the steps in the ALARP process are useful. For the reviewed methods the ALARP focus is clearer in the qualitative studies, where the effect of risk reducing measures are illustrated by relocating the scenarios within the risk matrix.

The results in the quantitative studies are not applied in cost-benefit evaluations, but risk reducing measures are discussed based on the main risk contributors. The calculated risk levels are low compared to the acceptance criteria, both for 1st and 3rd party.

The selection and application of risk acceptance criteria for the hydrogen risk assessments reflect the general practice within risk assessments, and are also adapted to company and authority regulations. No adaptations to the acceptance criteria have been made in order to reflect specificities of hydrogen technologies or operation of hydrogen facilities. One aspect that could be considered here is the use of acceptance criteria that is suitable to communicate safety aspects to the public. The use of equivalence criteria, for example comparing the risk of using a hydrogen refuelling station with the known risk of a conventional petrol station, is a good approach in this context.

5.2 Specificity with respect to hydrogen risks

All the case studies are closely linked to the technical system they analyse. The identification of relevant hazards and failure modes are ensured by structured brainstorming workshop techniques like HAZOP, FMEA or HAZID. Such workshops utilise technology experts to work through the systems and activities in order to identify the hazards and failure modes that should be included in the further assessment. Single expert assessments can then be used to work further with these scenarios (case 8).

The review shows that specificity with respect to the concept in question is as high for the qualitative assessments as for the quantitative assessments. The additional feature of the quantitative assessments is that they further elaborate the frequency and consequences of the identified unwanted scenarios and provide an estimate of the total risk for comparison to a risk criterion.

The same can be seen if one looks at the specificity with respect to hydrogen risks. Generic characteristics for hydrogen such as low ignition energy/high ignition probability, low rate of radiant heat, higher tendency to detonation, deflagrations more severe etc. are discussed both in the quantitative and qualitative studies. These issues are however more challenging to handle for the quantitative studies, since validity of the assessments requires that the models used are able to reflect these characteristics.

Most of the case studies discuss or reflect the main recommendations from the EIHP2 Study on Risk Analysis for refuelling Infrastructure (ref. 06):

- *Minimise probability of hydrogen releases*
- *Quick and reliable detection systems – gas and fire*
- *Shutdown, isolation and depressurisation of system*
- *Prevent accumulation of hydrogen gas in pockets*
- *Avoid high levels of confinements*
- *Promote natural ventilation and gas release to safe location*

5.2.1 Ignition probability

The ignition probability for hydrogen is considered to be higher compared to hydrocarbon releases. This is reflected in 2 of the 5 quantitative assessments, case 7 and 8. The assessment of ignition probability considers both immediate and delayed ignition. Delayed ignition is critical to assess, since these incidents may result in a hydrogen vapour cloud explosion. Different approaches are used to calculate representative values. Case 7 uses a single value for immediate ignition probability, based on "Sourcebook for hydrogen applications" (ref. 18). Case 8 adapts the Cox, Lees and Ang ignition probability data[1] to hydrogen properties and by this attains hydrogen specific ignition probabilities for different release sizes. Case 9 and 10 applies the Dutch "Yellow book" (ref. 19). The nominal values for ignition probabilities differ significantly. This is partly due to technical differences in the concepts analysed, but the variations between the approaches also cause the values to differ. The ignition probabilities greatly affect the estimated risk level.

An important development task should therefore be to develop a recommendation for best practice for ignition probability modelling. The HySafe network has initiated such an approach based on the Joint Industry Project Time Dependant Ignition probability Model (ref. 02).

5.2.2 Fire and explosions

The assessment of consequences from ignited hydrogen releases uses well established consequence calculation models. These models need however to be applied correctly in order to reflect the special features of hydrogen; lower radiant heat and more prone to explosions/detonations than for example methane and propane. Calculation tools for gas dispersion (PHAST, Effects) are also applied in case 7, 8, 10, and 11, as a basis for both ignition probability modelling and consequence assessments.

5.3 Hydrogen leak frequencies

One of the recommendations from the EIHP2 study of Risk Analysis of Refuelling Infrastructure was to design the hydrogen facilities in so that the probability of hydrogen releases is minimised. For the risk assessment to be able to reflect the importance of these design work, the expected hydrogen leak frequency of different concepts need to be established.

Leak frequencies have always been a major source of uncertainty in risk analysis. 2 of the quantitative cases apply the Hydrocarbon Release Database collected and maintained by UK Health and Safety Executive as basis for establishing hydrogen release frequencies. This database contains hydrocarbon releases at off shore installations in the UK sector of the North Sea. The database is applied via DNVs leak frequency calculation software LEAK, in order to calculate leak frequencies per equipment unit and year. The other 3 cases are using the Dutch “Purple book” (ref. 03), the EIGA code IGC 75/01/E/rev (ref. 04), and “Pipe failure probability-the Thomas paper revisited” by B.O.Y.-Lydell (ref. 05).

No comprehensive collection of leak frequency experience has yet been published for onshore process equipment. Onshore risk analyses have traditionally used leak frequencies whose origin is obscure, typically dating from the 1970s, and which cannot be traced to any actual data from any specific group of plants.

During the 1990s, the offshore process industry made the most comprehensive collection of leak frequency data that is currently available in any industry, and this has now become the standard data source for offshore risk analyses (ref. 20). After careful consideration of the strengths and limitations of different data sources, and the expected differences in leak frequencies in offshore and onshore industries, DNV has concluded that it is appropriate to use the high-quality *offshore* data for *onshore* QRAs, until verifiable onshore experience becomes available.

The Hydrogen Incident and Accident Database, HIAD, initiated by the HySafe network is very important in order to establish a high quality basis for estimating hydrogen release frequencies. The development of the "Hydrogen Incident and Accident Database" (HIAD) is progressing under EU FP-6 Network of Excellence.

5.4 Applicability of methods as design input

A risk analysis shall be used as input to a design process for a facility. In order to achieve this, the analysis must be flexible and easy to update, it must be made ready to perform and report sensitivity studies, and the results must be traceable.

As discussed in chapter 3.0 the use of risk matrixes to illustrate the risk picture allows a quick and illustrative method to present changes in the risk picture. New scenarios or scenarios that are controlled by new mitigating measures can easily be introduced or excluded from the risk matrix. In a concept design phase the risk matrix method is therefore a very useful tool.

The traceability of the evaluation process is here dependant on the documentation and quality of the discussions in the workshops or by the technical expert. In order to make it possible for outsider to understand the conclusion and to follow the process, extensive hazard-logging is necessary. Several software tools exist for this use, for example DNV's EasyRisk.

The quantitative methods have the possibility to better qualify the nominal effect of design changes. These may be changes in pressure or mass flow, new or removed equipment, changed layout etc. All these are parameters that can be altered easily in three of the five quantitative cases. The traceability of quantitative studies is as for qualitative studies a question about good reporting practices. The danger about quantitative studies is that they become "black boxes", where justifications of the assessments are lacking. Chapter 5.6 in the IEC 300-3-9 standard for risk analysis presents a recommended table of contents for a risk analysis, to ensure traceability.

State-of-the-art risk analysis within the oil and gas industry may be identified by their ability to reflect the importance of the safety barriers in a technical system. It is important that risk analysis of hydrogen facilities also reflects the importance of the safety barriers in the analysis. The structure of the quantitative approaches has proven to be useful to document this. Risk modelling with event trees may show the importance of safety barriers, and the quality and condition of the barriers. For hydrogen facilities important safety barriers are (ref. 06):

- *Containment – avoid releases*
- *Gas detection*
- *Ignition source control*
- *Shut down and isolation of process segments*

The IEC standard 61508 "Functional Safety of electrical/electronic/programmable electronic safety-related systems" has formed the basis for enhanced focus on ability of the safety systems to perform their safety functions on demand. This will, for example, be the probability of the gas detection system to detect a critical gas leak on demand. Features to reflect safety integrity level of the most important safety barriers for hydrogen facilities are necessary to include in a best practice for risk analysis.

5.5 Applicability as operational tool for safety management

The reviewed studies were performed for design phases of projects, and hence the reporting of the analysis was not intended for operating personnel. However, if or when the projects are realised, it is important that the risk analysis is performed and documented so that it can be used by management and operating personnel as a safety management and planning tool in daily work.

The reviewed cases do not, for example, list *risk indicators* that can be used to *measure* the operational risk level. Such indicators can be a number of detected releases per year, a number of critical failures detected during inspections, reported external incidents etc. Such parameters will be useful input to the plant's SHE Manager.

Risk maps and description of particular hazards in the different sections of the facility will be useful for operators when they are planning inspection or maintenance jobs. Such information will also be important in training of personnel, and in communicating the safety philosophy of a facility.

For further work with a best practice for risk assessment of hydrogen facilities it is important to include features that facilitate use of the risk analysis for operating personnel.

5.6 Expressing risk results and risk communication

All hydrogen facilities assessed, except case 8, represent systems that will have a wide interface between public users and the technical system. Public risk perception should be evaluated both in the risk analysis phase and in the presentation of the risk. Risk communication to user groups is challenging. Although there is a potential for risk aversion in the user group related to new technologies, risk communication is an important tool for educating the users and promoting safe behaviour.

A study by Kuttschreuter, M and Gutteling, J.M. (ref 21), evaluating the experiences from introduction of the Dutch Digital Risk Map, concluded that the participants were able to understand and use digital risk maps and there were no reactions of extreme fear by participants. The study also indicated that increased risk awareness may promote safe behaviour and prevent panic reactions in a crisis situation.

The qualitative approaches presenting results in risk matrices is easy to communicate, since the areas of high (red), medium (yellow) and low (green) risk is intuitive. The same with the equivalence criterion, which makes it possible to compare the new activity to something familiar.

The quantitative approach often expresses risk as number of fatalities per year, which must be interpreted and translated into non-technical terms before being communicated to the public. Theoretically expected values for number of fatalities per year are difficult to communicate as a measure of safety. It is therefore important that the expression of risk results is adapted to the purpose and target group.

The Canadian standard CAN/CSA-Q850 Risk Management: Guideline for Decision-Makers contains useful sections on how to consider and include risk perception and risk communication in risk management. These aspects are particularly important for technical systems that interface closely with public users and 3rd party.

6.0 Main uncertainties in quantitative risk analysis of hydrogen installations

This chapter discusses uncertainties specific to QRAs of hydrogen installations. Uncertainties general for most QRAs such as uncertainty related to main assumptions, modelling parameters etc. are not discussed here.

The quality of the results you get out from a QRA (Quantitative Risk Assessment) is very dependent upon the quality of the input used in the risk assessment. A lot of the input used in QRAs is normally statistical data from historical incident databases. A challenge when performing risk analysis of hydrogen refuelling stations and other hydrogen installations is the lack of historical incident data for such installations. The lack of data is mainly due to the fact that the use of hydrogen as fuel for transportation is relatively new and the infrastructure technologies are under development and currently mainly applied in demonstration projects. The experience data available for hydrogen installations is therefore scarce. In order to build up a database of historical incidents on hydrogen installations, it is important to start collecting incident data and exposure data in line with what has been done for hydrocarbon equipment and systems in the offshore oil and gas industry.

At present the lack of hydrogen specific historical incident data result in a higher degree of uncertainty in QRAs for hydrogen installations compared to QRAs for offshore hydrocarbon installations where the statistical data basis is very good. To compensate for the missing high quality incident data basis a number of assumptions must be made and verified .

For comparison of results from QRAs for different installations performed by different parties it is beneficial if the assessments are based on similar methods and assumptions. DNV sees the need for further development of best practice methods and assumptions for estimation of:

- Leak frequencies
- Probabilities for failure of safety systems, including probabilities for human failure when operating equipment or safety systems
    - containment,
    - shutdown and isolation of process segments,
    - gas detection
    - ignition source control
- Ignition probabilities

Some activities on developing best practices for hydrogen QRAs and safety studies are ongoing. The most relevant ongoing activities in the European Network of Excellence HySafe is listed in the following:

- In HySafe WP 9 there is ongoing work on development of a best practice for estimation of ignition probabilities for hydrogen releases.
- The HySafe plans to develop a best practice for estimation of leak frequencies, to be used until historical frequency data becomes available.
- The HySafe project has undertaken significant work to develop the basis for a Hydrogen Incident and Accident Database (HIAD). The plan is to start collecting and systemising hydrogen incident data into the database, in order to over time develop a high quality historical hydrogen specific database.

6.1 Leak frequency assessment

In Quantitative Risk Assessments (QRAs) the leak frequencies for each process segment (isolable segment containing hydrogen or other flammable fluids) needs to be calculated. Until statistical frequencies are developed specifically for hydrogen equipment, incident frequencies must be estimated based on other data sources.

Throughout the years a number of databases and data collection projects have been initiated for several industries such as nuclear, offshore and onshore process, related to compiling release data for process equipment and systems. The data being publicly available today through reports and/or electronic databases varies a lot with respect to quality, quantity and application, and many of them contain old and outdated data. In DNV's work for the oil and gas operators in the North Sea (UK and Norway), we have been searching for the "state-of-the-art" regarding offshore process release data, and we concluded in co-operation with the operators that the UK Health & Safety Executive's (HSE) HydroCarbon Release Database HCRD holds such qualities that is required.

It is open for discussion whether it is relevant to use the hydrocarbon incident data in the HSE HCRD to calculate release frequencies for hydrogen, because:

- The hydrocarbon containing equipments in the offshore industry are generally of larger dimension than the hydrogen containing equipment on for example hydrogen refuelling stations. The typical pipe size in a hydrogen refuelling station is 12mm and this is very small in relation to offshore process pipes. Offshore 12mm is a typical instrument connection and this has a high leak frequency due to external damage, faulty connections etc.
- Operating pressures are typically much lower in hydrocarbon process equipment compared to equipment on a hydrogen refuelling stations.
- The offshore historical leak database incorporates causes for leaks such as corrosion in a marine environment, internal erosion, vibration from vessel motion and engine rooms etc. These are leak causes which are not relevant for hydrogen refuelling stations or other hydrogen installations.
- Inspection and maintenance intervals strongly influence how often leaks occur in process equipment, and may be different for hydrocarbon installations compared to hydrogen installations.
- Hydrogen installations may have problems with hydrogen embrittlement and diffusive leaks. The contribution from these two phenomena to the leak frequencies for hydrogen equipment should be investigated.
- Hydrogen installations use specialized connections and other equipment as well as the equipment dimensions generally being small compared to industrial plants and offshore installations. As an example the leak data on connections used in hydrogen application are not available in the HCRD database and standard flanges are used instead. Flanges are a relatively large source of leaks offshore, while the connections used for hydrogen are of high quality. However these connections are screw fittings and the integrity of these is very dependent on proper workmanship. For a hydrogen refuelling station other types of compressors may be used than what is typical for offshore installations, (e.g. a high pressure diaphragm compressor). This type is not available in the HCRD database and one will have to use data for e.g. a centrifugal compressor instead. A diaphragm compressor may have higher leak integrity than the centrifugal compressors but no data is available to support this.

As a conclusion the use of HSE offshore data for a H_2 installation is outside the validity and normal usage area for the HCRD database. The reason these data are used is the lack of data and information on hydrogen leaks, which makes it difficult to estimate realistic leak frequencies.

As mentioned in the introduction to this chapter there are ongoing activities in the European Network of Excellence HySafe on development of more apropriate leak frequencies for use in QRAs::

- The HySafe plans to develop a best practice for estimation of leak frequencies, to be used until historical frequency data becomes available.

- The HySafe project has undertaken significant work to develop the basis for a Hydrogen Incident and Accident Database (HIAD). The plan is to start collecting and systemising hydrogen incident data into the database, in order to over time develop a high quality historical hydrogen specific database.

6.2 Effect of safety systems

In a QRA efforts are made to include the risk reducing effect of the safety systems:

Effect of automatic gas detection:
The effect of automatic gas detection is normally included in a QRA by the "automatic detection probability" and the "time to initiation of shutdown". If there is an effective gas detection system the "automatic detection probability" will be high and the "time to initiation of shutdown" will be reduced compared to the opposite situation of no automatic gas detection system (where detection rely on manual detection only). It is however some uncertainty related to how effective the hydrogen detection systems are. More knowledge is needed with respect to:

- How probable is it that a well designed gas detection system will detect an indoor or outdoor leak?
- What characterizes a well designed hydrogen gas detection system?
- How fast will the gas detection system typically be able to detect a hydrogen leak?

Effect of process isolation and shutdown system:
An effective process isolation and shutdown system is normally included in a QRA by reduced release duration (due to limited inventory available in the leaking segment supplying the release) and by increased "shutdown probability".

As long as the detailed process design is known it is possible to estimate the segment inventories and estimate the release durations in a satisfactory way. However, there is some uncertainty related to the probability of successful shutdown:

- If there is automatic shutdown upon gas detection; what will the probability of failure on demand for the shutdown system be? Will the hydrogen shutdown system be similar to shutdown systems in the oil and gas industry, so that the high quality reliability data available for the oil and gas industry can be used?
- If the shutdown system relies on manual initiation the probability of shutdown failure will include the probability of human failure. Either the operator may not notice that there is a leak, or the operator may fail when attempting to initiate shutdown. How probable human failure is will depend on many factors such as; training of the operator, whether an operator is continuously monitoring the process or whether the operator is doing several other tasks on the same time, how easy and fast it is to initiate the shutdown system, if the operators have an aversion to shut down the system (will not have production loss), etc.

Effect of ignition source control:
An effective ignition source control system automatically shuts down ignition sources upon confirmed gas detection. The effect of ignition source control is normally included in a QRA by a reduced ignition probability for the scenario of successful detection and shutdown. The calculation of ignition probability for hydrogen releases is subject to a high level of uncertainty as discussed in Chapter.6.3.

Effect of containment:
If detailed design information about the containment is known (for example regarding the design of a storage tank) the integrity of the containment can be assessed in a satisfactory way.

6.3 Ignition probability assessment

In Quantitative Risk Assessments (QRAs) the probability of ignition of potential leaks are normally calculated per release scenario, based on ignition sources relevant each release scenario. Hydrogen has both a wider flammability range and, at high concentrations, a lower ignition energy than hydrocarbon gases, and hydrogen is therefore assumed to ignite more frequently. There is however a high degree of uncertainty related to how much easier hydrogen ignites compared to for example methane gas:

- Is the immediate ignition probability significantly higher for hydrogen than for hydrocarbon gas?
- Will hydrogen typically be ignited by the same ignition sources as for example methane gas or will the lower ignition energy result in ignition by other sources in addition?
- How will the increased flammability range affect the ignition probability?

Work has been initiated as part of the HySafe NoE to specify how an ignition model, the TDIPM(4), for hydrocarbon can be modified so that it can be used for hydrogen.

As mentioned in the introduction to this chapter the European Network of Excellence HySafe has ongoing work on development of a best practice for estimation of ignition probabilities for hydrogen releases.

7.0 References

1. "CPR 18E - Guideline for Quantitative Risk Assessment," Committee for the prevention of Disasters (1999)
2. JIP (1998), "Time Dependant Ignition Probability Model", DNV-report 96-3629
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7. Safety of Hydrogen Refuelling Stations, DNV-report 2003-0307, rev. 02, 2003
8. TOTAL BVG - Risk Assessment for the Berlin Hydrogen Competence Centre, DNV-report 2003-1541, rev. 01, 2003.
9. Failure Modes and Effects Analysis for Hydrogen Fuelling Options, California Energy Comission, CEC-600-2005-001, 2004
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12. HYTREC - Risk Assessment of Hydrogen Production and Filling Station, DNV-report 2005-1323, rev. 0, 2005
13. Quantitative risk assessment of proposed hydrogen facilities in Tuen Mun, DNV project no. K7605, Draft report, 2005
14. External safety distances for hydrogen filling stations, RIVM
15. Synthesis of the Risk Assessment Analysis of a Compressed Hydrogen Filling Station, University of Pisa, 2005
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20. "HCR99 – Hydrocarbon on Release database 1992-1999 (2000), UK Health and Safety Executive

21. Kuttschreuter, M and Gutteling, J.M., (University of Twente), The Dutch Digital Risk Map: First Experience With An Interface to The Public's Risk Perception, SRA Annual Meeting, 2004

22. Frank P Lees (2003), "Loss Prevention in The Process Industries – Hazard Identification, Assessment and control" 2nd edition

8.0 Qualitative methods

Qualitative assessments include:

1. Risk analysis of Refuelling Infrastructure, EIHP2, September 2003 (ref. 06)
2. Safety of Hydrogen Refuelling Stations, DNV 2003 (ref. 07)
3. Risk assessment of the Berlin Hydrogen Competence centre, DNV 2003 (ref. 08)
4. Failure modes and effects for hydrogen fuel options, California Energy Commission (ref. 09) http://www.energy.ca.gov/2005publications/CEC-600-2005-001/CEC-600-2005-001.PDF
5. Safety Study of Hydrogen Supply Stations for the Review of High Pressure gas Safety Law in Japan, Japan Petroleum Energy Center 2005 (ref. 10) http://conference.ing.unipi.it/ichs/Papers/400081.pdf
6. Risk analysis of Hydrogen Refuelling Station at Forusbeen (”Risikoanalyse av hydrogenfyllestasjon ved Forusbeen”) (ref. 11)

8.1	Definition of acceptance criteria
1	The acceptance criteria are semi-qualitative, and apply three risk levels: **High**: Unacceptable, detailed assessment should be performed to give better estimate. Mitigating measures should be introduced based on results from detailed assessment. **Medium**: Tolerable, but mitigating measures should be considered. **Low**: The risk is low and further risk reducing measures are not necessary. Each identified hazardous event is categorised according to defined levels for probability of occurrence and consequences. The risk is then interpreted as a combination of probability and consequence, and the combinations corresponding to high, medium and low risk are defined in a risk matrix. The acceptance level does not distinguish between different populations (1st party and 3rd party).
2	The acceptance criteria are qualitative equivalence criteria; “The conventional petrol station customer should neither be exposed to a significantly increased risk not be put to any inconvenience” (when introducing hydrogen refilling facilities at a petrol station). The acceptance criteria do only include users of the petrol station.
3	Three risk levels are defined (low, medium and high), based on a combination of probability and consequence for a given hazardous event. Probability and consequences were assessed qualitatively for each event, and presented in a risk matrix. Mitigating measures discussed and proposed for hazardous events at risk level medium and high.
4	No acceptance criteria were defined. Three risk levels are defined (low, medium and high), based on a combination of probability and consequence for a given hazardous event. Probability and consequences were assessed qualitatively for each event, and presented in a risk matrix.
5	The acceptance criteria are qualitative, and apply three risk levels: **High**: Risk is not acceptable. Remedial actions should be considered to reduce the risk to an acceptable level- **Medium**: In principle risk is not acceptable. Risk can only be accepted when risk reducing measures cannot be achieved by reasonable practical action. **Low**: Acceptable. Further risk reducing measures are not necessarily required. The acceptance criteria are established based on the European Integrated Hydrogen Project (EIHP2).
6	Three risk levels are defined; Unacceptable, Significant (ALARP), Non-significant. The levels are based on a combination of frequency and consequence for given hazardous events. Frequencies and consequences were assessed qualitatively and presented in a risk matrix.

8.2	Hazard identification
1	Hazard identification performed as an integral part of the risk assessment. A facilitator with competence in the assessment method leads a HAZID-workshop. The total size of the group will be 4-6 people, and 2-4 of these should be experts on the object being analysed. A list of generic risk to hydrogen refuelling station concepts was used as a trigger for the workshop discussions.
2	The HAZID was performed as single expert assessment, based on general process hazards.
3	The hazard identification was done as a multidisciplinary HAZID meeting, facilitated by a consultant with competence in the Structured What If Checklist (SWIFT) HAZID technique. The SWIFT study technique has been developed as an alternative to HAZOP when it can be demonstrated that circumstances do not warrant the rigor of a HAZOP.
4	The hazard identification was done as a multidisciplinary workshop. The workshop applied a top-down Failure Modes and Effects Assessments (FMEA) approach. One person had the role as FMEA facilitator, and 8 persons made up the expert team. The top down FMEA approach starts with a failure mode, and works out potential cause to the relevant failure, and the consequences.
5	The identification of relevant hazards and accident scenarios were identified through HAZOP and FMEA.
6	HAZID was performed using a list of leadwords and identifying possible deviations and problems relating to these. Examples include collisions, nearby fires, falling objects etc…

8.3	Accident scenario
1	High/medium risk scenarios evaluated based on consequence/probability
2	Scenarios were modelled as releases from the high pressure and low pressure parts from system, at different elevations and hole sizes. A Total of 9 scenarios were modelled.
3	All identified scenarios were evaluated in the risk matrix.
4	All identified failure modes were evaluated in the risk matrix.
5	Identification of relevant hazards and accidents scenarios which could occur on operation mode of hydrogen supply station.
6	The top event is a gas leakage leading to instant ignition (jet fire), delayed ignition (explosion) or no ignition (gas spreading). Typical dimensioning leakage is taken from the Scanpowers database Scanpower Data Dossier. For each deviation or problem identified an event analysis was performed. All identified events were evaluated in the risk matrix.

8.4	Consequence assessments for identified hazards: Evaluation of size of gas clouds, ignition probabilities, fires, explosions etc.
1	The consequence is graded according to the assumed severity for people, environment and material, and applies five consequence levels: **Catastrophic**: Several fatalities **Severe loss**: One fatality. **Major damage**: Permanent disability. Prolonged hospital treatment. **Damage**: Medical treatment. Lost time injury. **Minor damage**: Minor injury. Annoyance. Disturbance.
2	The consequence calculations for hydrogen leakages, dispersion and possible fires are modelled using PHAST. The expected human effects of radiation from flames are divided into four categories depending on the radiation. Ignition probabilities not assessed. The assessment is deterministic, in the sense that is evaluates the consequence from selected release scenarios.
3	The consequence evaluations are based on evaluation from the HAZID team as well as DNV's experience from previous risk analysis.

4	The consequences are rated in agreement with the FMEA team, and applies three levels: **High**: Potential for great harm or death if someone is present within the impact area. **Medium**: Harm would require some medical treatment to some pain or discomfort if someone is present within the impact area. **Low**: End user, if present, would not notice.
5	The consequence is graded according to severity of asset and human damage, and applies five levels: **Extremely serve damage**: collapse of nearby dwelling houses, one or more fatalities of pedestrian or dwellers. **Serve Damage**: major damage of nearby dwelling houses, one or more fatalities of customers or station workers. **Damage**: minor damage of nearby dwelling houses, injury and hospitalizing treatment. **Small damage**: windows broken, injury and medical treatment. **Minor damage**: no damages to nearby dwelling houses, minor injury.
6	Gas spreading is simulated by FLACS. Jet fires are simulated by TRACE. Explosions are not simulated, but the assumptions given may be verified by FLACS. The consequence assessment is qualitative and five levels of consequences are graded according to severity: **Critical**: Multiple fatalities and/or operation halt > 1 month and/or extensive material damages. **Serious**: One fatality and/or operation halt < 1 month and/or considerable material damages. **Significant**: Serious personal injury and/or operation halt < 7 days and/or material damages. **Minor**: Operation halt < 3 days and/or minor material damages **Negligible**: Operation halt < 1 day.

8.5	Frequency assessments – evaluation of frequency of identified hazards
1	The frequency assessment is qualitative, and applies five probability levels: **Frequent**: Will occur frequently at the filling station. **Probably**: May occur several times at the filling station. **Occasional**: Likely to occur during lifetime/operation of one filling station. **Remote**: Unlikely to occur during lifetime/operation of one filling station. **Improbable**: Possible, but may not be heard of, or maybe experienced world wide.
2	The frequency assessment is quantitative and is based on generic leakage data and equipment counting.
3	The frequency assessment is qualitative and is based on evaluation from HAZID team as well as DNV experience from similar equipment and medium.
4	The frequency is qualitative, and applies three occurrence levels: **High**: Almost certain to occur repeatedly. **Medium**: Likely to occur to rarely likely to occur. Low**:** Unlikely that failure would occur.
5	The frequency assessments is qualitative, and applies four levels: **Probable**: likely to occur several time in lifetime of one H2 station **Occasional**: likely to occur once in lifetime of one H2 station. **Remote**: unlikely to occur in lifetime of one H2 station **Improbable**: possible, but the probability is extremely low.
6	The Frequency assessment is based on info from meetings, on-site inspections, experience based on similar installations, going through regulations, performing simulations, and expert opinions. The frequencies assessment includes five levels: **Highly probable**: $> 10^{-1}$ no functional barriers

	Probable: **Less probable**: **Improbable**: **Highly improbable**:	$10^{-1} – 10^{-2}$ $10^{-2} – 10^{-4}$ $10^{-4} – 10^{-5}$ $< 10^{-5}$	one organisational barrier more than one organisational barriers one technical/physical and one organisational barrier two technical/physical barriers

8.6	Impact assessments – how does the consequences impact on personnel, environment and property?
1	Qualitative impact assessments included in the discussion of consequences.
2	Impact to personnel assess according to exposure to given heat radiation level.
3	Qualitative impact assessments included in the discussion of consequences.
4	Qualitative impact assessments included in the discussion of consequences.
5	Qualitative impact assessments included in the discussion of consequences.
6	Qualitative impact assessments included in the discussion of consequences.

8.7	Risk compilation and expression: Estimating the risk results
1	Qualitative compilation of frequency and consequence based on assessments in workshop.
2	Risk is not compiled. The assessment is deterministic, and gives a discussion of consequences from selected scenarios.
3	Qualitative compilation of frequency and consequence based on assessments in workshop.
4	Qualitative compilation of frequency and consequence based on assessments in workshop.
5	?????
6	The risk results are presented in the previously defined a risk matrix.

8.8	Risk results: Format and presentation
1	The risk result is a combination if severity and the probability and are presented in a matrix is used as a guideline to evaluate if the risk is acceptable for each hazard. The results can give useful input to further deign and development work including standardisation work.
2	The compression, storage and dispenser facilities are evaluated as representing the most serve consequences and thus also highest risk to people. Results presented as a summary discussion of the two design options.
3	The risk result is presented as a risk matrix. The evaluations are based on experience within the HAZID team as well as DNV's experience from similar equipment and medium.
4	The FMEA evaluation followed four major functions; supply, compression, storage and delivery. The results is presented in a risk-binning matrix which summarize\s the number of each of the nine frequency-consequence combinations.
5	The risk results are a combination of severity and the probability and are presented in a matrix before and after implementation of principal safety measures.
6	The risk results are presented in the previously defined a risk matrix.

8.9	Evaluation against acceptance criteria
1	The results from the hazard ranking in the risk matrix are used to compare the different concepts and evaluate them against the relevant acceptance criteria. The evaluation is qualitative.
2	The evaluation against acceptance criteria is a qualitative, and includes suggested mitigating measures proposed on "better safe than sorry" philosophy.
3	The evaluation against the acceptance criteria is qualitative.

4	No acceptance criteria defined.
5	The evaluation against the acceptance criteria is qualitative.
6	The risk is evaluated against the previously defined risk matrix cells.

8.10 Evaluation of mitigating measures	
1	The main general recommendation to control the risks is that the design, maintenance and operation of hydrogen refuelling stations should minimise the probability for leaks of hydrogen.
2	Recommendations for mitigating measures and their effects are discussed based on scenario evaluation. Recommendations are related segregation of people from the process and storage facilities, elevation of release points, ignition source control and detection systems.
3	The main recommendations are that the operational procedures (emergency procedures) and physical protection has to be improved. Effect of new mitigating measures on the risk level is evaluated qualitatively.
4	Planned mitigating measures included in assessment. Need for additional mitigating measures also included, but not the effect of these measures.
5	The principal safety measures are considering, general, material selection, compressor unit, dispenser unit and storage unit. Effect of new mitigating measures on the risk level is evaluated qualitatively.
6	Mitigating measures are proposed both for the risks appearing in the ALARP region and in general.

9.0 Quantitative methods

Quantitative assessments include:

1. Risk assessment of hydrogen production and filling station, DNV 2005 (ref 12)
2. Quantitative risk assessment of proposed hydrogen facilities in Tuen Mun, DNV 2005 (ref. 13)
3. External safety distances for hydrogen filling stations, RIVM (ref. 14)
4. Synthesis of the Risk Assessment Analysis of a Compressed Hydrogen Filling Station, University of Pisa, November, 2005 (ref. 15)
5. Risk Assessment for Gasoeus Hydrogen Refueling Station, University of Pisa, September 06-08, 2006 (ref. 16)

9.1	Definition of acceptance criteria
1	The acceptance criterion is quantitative, and states that maximum individual risk is a 1 x 10^{-5} fatalities per year. No acceptance criterion for societal risk is applied. The criterion is used for 3rd party, and for 2nd party.
2	Total Individual risk criterion defined as maximum $1x10^{-3}$ per year for facility. Hydrogen risk to represent maximum 10% of this, i.e. a maximum individual probability for loss of life of $1x10^{-4}$ per year. Negligible individual risk is $1x10^{-7}$ per year. ALARP region between maximum and negligible risk level. Societal risk criteria defined by an F-N curve (Accumulated Frequency of fatal accidents versus number of fatalities per accident). The F-N curves defines an unacceptable level, ALARP-region and an acceptable level.
3	SR: FN-curve. IR: No vulnerable objects such as dwellings, larger offices and hospitals are allowed within the 10^{-6} contour.
4	As developed by the Friuli Venezia Giulia Region within the risk analysis of the area of Trieste. Including three regions; Acceptable, ALARP, Non acceptable.
5	As stated by the "European Integrated Hydrogen Project (EIHP)" for hydrogen systems.

9.2	Hazard identification
1	The HAZID was performed as group discussion, evaluating the current concept against generic hydrogen and process hazards.
2	A survey and analysis of historical accidents at similar hydrogen facilities was conducted. The databases used were: • MHIDAS • HSELINE • ChemE Index – Loss prevention bulletin • IchemE Index – 100 largest losses Based on the accident review and an external HAZOP of the system detailed hazard identification was performed as a single expert assessment.
3	No HAZID included in report.
4	The methodology of hazard identification and accident scenario selection includes a Qualitative screening step including the following steps: • Historical analysis of incidents/accidents in similar plants • Identification of the related sources • Identification of the related consequences • Identification of operational phase incidents and accidents • Functional analysis, involving all possible deviations

	• Compilation of HAZID chart A 5*5 level Frequency and Damage classification chart and 3 risk acceptance levels (a risk matrix) are used in the process.
5	The methodology of hazard identification and accident scenario selection includes a Qualitative screening step including the following steps: • Analysis of the elementary functions • Identification of all the possible deviations • Identification of the related sources • Evaluation of the related consequences • Compilation of HAZID chart A 5*5 level Frequency and Damage classification chart and 3 risk acceptance levels (a risk matrix) are used in the process.

9.3	Accident scenario
1	Only scenarios that might expose most exposed individual.
2	The system was split into logical sub systems dictated by planned location of safeguards in the system. For these systems the generic hazards were discussed, and specific accident scenarios defined. A total of 14 accident scenarios were defined.
3	The Purple Book (Committee for preventing of disasters. Guidelines for quantitative risk assessment. The Hague: SDU 1999) is used in determinations of risk scenarios.
4	The initiating events identified in the HAZID are grouped, and from each group the event able to create the most critical scenario is chosen as a Reference Initiating Event, RIE.
5	This part is included in the Hazard identification.

9.4	Consequence assessments for identified hazards: Evaluation of size of gas clouds, ignition probabilities, fires, explosions etc.
1	The consequence assessments are divided into dispersion and explosion modelling, by utilising the DNV software PHAST and COMEX/NVBANG, respectively. COMEX is an empirical model developed on from a series of scale explosion tests. In connection with COMEX, NVBANG is used for calculating time-dependent overpressure. Ignition probability is analysed as immediate and delayed ignition, where delayed ignition takes into account exposure of ignition sources in the area.
2	Gas dispersions, jet fire sizes and fire ball sizes are calculated with the DNV tool PHAST (which is a part of the Safeti software package). Explosions assessments were performed in Safeti, and are based entirely on the TNO vapour cloud explosion correlation model. Missiles from rupture of storage cylinders were treated separately. Ignition probability was based on the Cox, Lees & Ang historical ignition probability data, modified with respect to: • Molecular weight of hydrogen compared to methane • Ratio of flammable range compared to methane Ignition probability of hydrogen is the treated as similar to methane, since most of the flammable vapour cloud is near the lower flammable limit, where ignition energy required is similar to methane.
3	The Yellow book (Committee for preventing of disasters. Methods for calculation of physical effects. The Hague: SDU 2005) is used for modelling the physical consequences of chemical releases such as discharge, dispersion and distances to heat radiation levels caused by fires. The Purple Book is used in determinations of the chance of direct ignition. H2 specific

	probabilities of ignition is neither used nor discussed in the report. The calculations were performed by the risk software called Safeti 6.42 from DNV.
4	The Yellow book (Committee for preventing of disasters. Methods for calculation of physical effects. The Hague: SDU 2005) is used for modelling the physical consequences. Event trees are used to calculate the probability for each event the scenario can lead to and the mechanisms that may have an influence on it. The software TNO Effects 4.0 was used to model the consequences of these events; Jet-fire, Flash fire, and Vapour Cloud Explosion.
5	Event trees are used to calculate the probability for each event the scenario can lead to and the mechanisms that may have an influence on it. PHAST modelling is used to simulate the consequences of these events.

9.5	Frequency assessments – evaluation of frequency of identified hazards
1	The frequency assessment is quantitative and is based on HSE database (hcr99), covering hydrocarbon releases from offshore installations in the UK sector. Adjustment factor are applied on leak frequencies, to cater for very small release rates.
2	The frequency assessment is quantitative and is based on HSE database (hcr99), covering hydrocarbon releases from offshore insallations in the UK sector. The failure frequency for type 3 hydrogen storage cylinders was estimated based on specific historical accident data for this kind of equipment. The OREDA Database (SINTEF Industrial Management, 1997) was used to estimate failure of protective systems.
3	The Purple Book and AMINAL is used in determinations of initial chance of failure.
4	Frequencies of pipeline break-up and rupture is based on “Pipe failure probability-the Thomas paper revisited” by B.O.Y-Lydell, Reliability Engineering & System Safety no68, 2000. Frequencies of catastrophic rupture of storage units are based on E&P Forum report no11.8/250, Quantitative risk assessment data sheet directory, October’96.
5	This is partly described only. IGC Doc 75/01/E/rev, “Determination of Safety Distances,” EIGA (European Industrial Gases Association)

9.6	Impact assessments – how does the consequences impact on personnel, environment and property?
1	The impacts from accidents are assessed for most exposed individual 3rd party (an inhabitant near the filling station). Impacts to 3rd party from explosion overpressures and heat radiation/flame exposure are assessed.
2	The impacts from accidents are assessed for 1st party and 3rd party. Impacts to 3rd party from explosion overpressures and heat radiation/flame exposure are assessed. Impacts from explosion overpressures, heat radiation from jet fires, heat dose received from fire balls, and impacts from missiles following rupture of storage cylinders.
3	The Green Book (Committee for preventing of disasters. Methods for determining possible damage. The Hague: SDU 1990) is used for modelling the impact of toxic and flammable effects on human beings.
4	Impact assessment is performed for Explosion, Jet-fire, and Flash fire. Ignition probabilities are based on “Loss Prevention in the Process Industries” P. Lees, 1980 (ref. 22). The probability of unavailability of pneumatic interception system is based on OREDA 92.
5	Impact assessment is performed for Explosion, Jet-fire, and Flash fire. Based on “Loss Prevention in the Process Industries” by Butterworth, 1983, page 526 and 599, Seveso directive

	as it is in force in Italy through the Ministerial Decree of 9th May 2001 (Mandatory), and the IGC Doc 75/01/E/rev (Not Mandatory)

9.7	Risk compilation and expression: Estimating the risk results
1	The risk was compiled from the frequency and consequence assessments using an event tree structure. The event tree structure combines facility specific input (e.g. population, ignition sources) with the frequency and consequence assessments and produces quantitative risk results.
2	The DNV developed risk assessment software tool Safeti was used to compile the frequency and consequence assessments into risk results. The model combines facility specific input (e.g. population, ignition sources) with the frequency and consequence assessments in an event tree structure, and produces quantitative risk contours, individual risk figures and hazard distances.
3	Risk was compiled using SAFETI 6.42.
4	The risk of each RIE is compiled using event tree structure.
5	The accepted value of Damage caused by a consequence at Frequency level 1 and 2 is compared to the maximum Damage level. The Frequency assessment is not very clear.

9.8	Risk results: Format and presentation
1	Risk was expressed as Individual risk per year (i.e potential loss of life per year) for 1st and 3rd party. The main risk contributor to 3rd party is assessed to be events escalating to the storage tanks (H_2 or LNG).
2	Risk was expressed as Individual risk per year (i.e potential loss of life per year) for 1st and 3rd party. No F-N curve for 3rd party societal risk was produced, since the 3rd party total risk was below the lowest Guideline level. The main risk contributor to 1st party is jet fire impingement on the hydrogen storage cylinders, causing cylinder hot rupture.
3	10^{-6} contour calculations were carried out for individual risk, and FN-curves for societal risk.
4	The results are based on the compilation above.
5	The results are based on the compilation above.

9.9	Evaluation against acceptance criteria
1	The risk is evaluated against the acceptance criteria for an individual risk of $1 \cdot 10^{-5}$ per year or less for that most exposed 3rd party, and was found acceptable.
2	The risk was evaluated against the quantitative acceptance criteria for 1st and 3rd party, and was found acceptable.
3	Comparing risk results with safety distances for gasoline and CNG, with the acceptance criteria.
4	All RIE events is evaluated, all but one event is acceptable, the last falls into the ALARP region.
5	The results are plotted in a log-log graph together with the acceptability borderlines.

9.10	Evaluation of mitigating measures
1	The risk reducing measures are related to reduce the risk to personnel as; physical protection, design and contingency plans. No sensitivity assessments were performed for proposed mitigating measures.

2	The risk reducing measures are related to reduce the risk to personnel as; fire detection systems, protection against jet fire impingement, escape ways, update emergency plans and safety management systems. No sensitivity assessments were performed for proposed mitigating measures.
3	N/A
4	All risk results were acceptable. No mitigation measures are evaluated.
5	All risk results were acceptable. No mitigation measures are evaluated.