HyApproval

WP2 – Handbook Compilation

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APPENDIX IV

Summary of Quantitative Risk Assessment performed for a Hydrogen Refuelling Station with on-site production

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Table of Contents

1 Introduction

As part of HyApproval WP4 Safety, Det Norske Veritas (DNV) performed a quantitative risk assessment (QRA) of an example case study hydrogen production and refuelling station (HRS), ref. /1/.

The main objectives of the QRA were to:

- **Demonstrate safety challenges relevant for today's technological development**
- **Demonstrate how detailed risk assessments can be used in order to manage risk associated with HRSs.**

The case study for the example HRS consists of the following modules:

- Electrolyser - using water and electrolysis to produce H_2.
- H_2 compressors – compresses H_2 from the electrolyser or the liquid hydrogen evaporator.
- CGH_2 (Compressed Gaseous Hydrogen) storage - stores compressed H_2.
- CGH_2 dispenser – facilities for refuelling CGH_2 to vehicles.
- LH2 (Liquid Hydrogen) tanker delivery
- LH2 storage, pump and evaporator – using LH_2 to produce CGH_2 and to supply the LH_2 dispenser. The LH2 is stored in an above ground tank.
- LH_2 dispenser – facilities for refuelling LH_2 to vehicles.

The HRS evaluated in this assessment is not a real station but an example case study HRS. Actual HRSs may be very different with respect to size (amount of hydrogen stored as well as number of refuelling operations per day), layout, amount, and quality of safety systems, whether equipment is located in closed containers or outdoors etc. The amount and type of equipment on a HRS will also differ. Many HRSs have either on-site hydrogen production or the possibility to evaporate trucked in liquid hydrogen not both, some HRSs have trucked in gas instead of gas production or evaporation, some HRSs have only gas dispensers or only liquid dispensers. The example HRS studied in this QRA is a standalone HRS, while some HRSs are integrated with refuelling stations for other fuels.

The HRS analysed in this QRA is an example virtual HRS, not a standard or representative HRS. For a real/actual HRS a separate detailed QRA will have to be carried out to reflect the risk at that actual station.

The example virtual HRS is based on available information about existing HRSs. Information like P&IDs and detailed description of the safety systems for HRSs with LH2 tanker delivery and liquid and gaseous dispensing have been obtained from the HyApproval partners Shell, ref. /2/, and Linde Gas, ref. /3/. The detailed input from the two partners has been used to create an "example virtual HRS". Detailed, specific up to date information about existing facilities has not been available for the production units (reformer and electrolyser). It has therefore been necessary to make a large number of assumptions regarding the design of the electrolyser and the reformer at the HRS in order to quantitatively assess the risk of these units. This approach also implies that the units are not optimised with respect to operational or process related criteria as would be the case for a real HRS.

The input and assumptions have large impact on the results of the Risk Analysis, and have therefore been verified by the HyApproval project partners during the assessment.

2 Conclusion

The QRA demonstrates the benefits of using a risk based approach to assess the risks associated with hydrogen installations. Advantages and recommendations related to utilisation of a QRA approach for HRS are summarised below:

- QRAs can be a very efficient risk management tool, particularly if used during the design of a HRS to evaluate different design solutions and optimise design with respect to both risk and economical aspects. For example to:
  - Optimise relative location of equipment, to prevent escalation and/or exposure of people to potential accidents
  - Optimise shutdown segment sizes
  - Assess the need for fire protection of equipment or support structure
  - Assess the need for designing buildings against explosion overpressures
- Based on the findings from a QRA, risk reducing measures can be suggested; the risk reducing effect of the measures can be evaluated and used as input to a cost benefit analysis.

3 List of abbreviations

ALARP	As Low As Reasonably Practicable
CFD	Computational Fluid Dynamics
CGH_2	Compressed Gaseous Hydrogen
DNV	Det Norske Veritas
H_2	Hydrogen
HRS	Hydrogen Refuelling Station
HSE	Health and Safety Executive
HAZID	Hazard Identification
LH_2	Liquid Hydrogen
P&ID	Process & Instrument Diagram
WP4	Work Package 4 (in the HyApproval Project)
QRA	Quantitative Risk Assessment

4 QRA Methodology

The methodology applied to assess the risk from the example hydrogen refuelling station to personnel working at the station, customers and third party is a standard risk assessment approach, as illustrated in Figure 4-1 below:

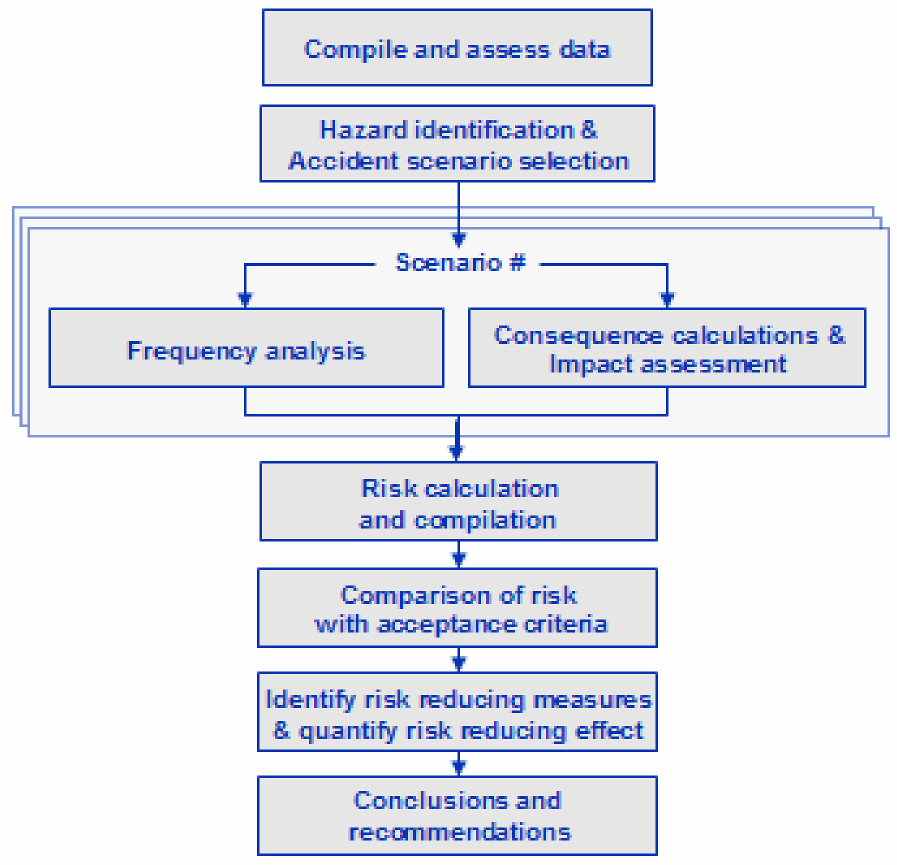

Figure 4-1 The QRA Process

Hazard Identification: The first stage of the assessment is hazard identification, where the primary objective is to identify major hazards that could have impact on the risk caused by the HRS. A hazard identification takes the form of a qualitative review of the plant to identify the major contributors to the total risk. It includes hazards specific to the relevant refuelling station, as well as hazards normal for typical hydrogen refuelling stations. A HAZID also includes identification of any specific operational aspects, which can be judged to influence the risk level.

A series of hazard identification meetings evaluating a typical hydrogen refuelling station were held by the HyApproval WP4 group at Ineris offices in Paris the 29th of March, the 23rd and 24th of May 2006. The hazards assessed in this report are based on the results from these meetings.

Frequency Calculations: The frequencies at which different hazards occur are calculated based on available statistical data. In cases where relevant statistical data for historical hydrogen incidents were unavailable, data for hydrocarbon incidents have been used, but adjusted to reflect the difference between hydrogen and hydrocarbons.

Consequence Calculations: Hazard consequences were assessed for each of the identified potential hazards. In general the consequences calculated for fire and explosion events consider the release potential should a hydrogen release occur, the potential for gas build-up and dispersion, as well as dimensions and duration of any resulting fire. Fire and explosion hazards may affect people in a variety of ways, primarily relating to impact of heat / radiation and explosion overpressures.

Risk calculation: The risk that each hazard represents is found by combining the hazard frequency and consequence. The risk assessments have been performed using an event tree approach. Risk have been calculated for 1st party employees at the HRS, 2nd party customers at the HRS and 3rd party outside the HRS who will be affected by accidents on the HRS. Through the risk assessment it is quantified which are the main risk contributors on the HRS. The main risk contributor should have a special focus in the risk reduction and ALARP process and with respect to safety management of the plant.

Comparison with the tolerable risk criteria: The risk results are compared with the selected criteria for tolerable risk . If the estimated risk level is too high compared to the tolerable risk criteria, risk reducing measures must be identified and implemented. If the risk level is found to be tolerable, risk reducing measures should be implemented if they are assessed to be cost effective.

Identification of risk reducing measures and quantify risk reducing effect: The safety systems and risk limiting design for the example HRS analysed in this QRA is assumed based on what is believed to be good practice and based on the knowledge about similar systems at existing HRSs. Several risk reducing measures have been identified as part of this QRA, including both technical and operational improvements. Some of these have been included in the assumed base case design. Additional risk reducing measures, not currently included in the basis for this study, are also proposed. The effects on risk by implementing selected risk reducing measures were assessed by performing sensitivity studies.

5 Results

The results presented below are for the defined base case with hydrogen supply from LH2 tanker delivery and production by water electrolysis.

It must be kept in mind that the HRS analysed in this QRA is an example virtual HRS, not a standard or representative HRS. For a real/actual HRS a separate detailed QRA will have to be carried out to reflect the risk at that actual station.

5.1 Risk to 1st party – employees at the HRS

The risk to 1st party is calculated in terms of individual probability of fatality per year.

The tolerable risk criteria used in the QRA for 1st party risk is:
The individual probability of fatality should not exceed 10^{-4} per year

The calculated risk to 1st party is below the defined project tolerable risk criteria.

For the HRS design assessed, the HRS personnel are most exposed to risk while they do the daily inspection of the production facility. The risk for personnel is low while they are inside the service building. Only the scenarios catastrophic rupture of a storage tank (gas or liquid) and full bore rupture of the loading hose during unloading from tanker are assessed to have potential (although with a small probability) to cause explosions strong enough to damage the service building and cause fatalities for people present within the building. Dispenser leaks give a low contribution to 1st party risk, since HRS personnel are not expected to be present in the immediate vicinity of the dispensers during refuelling.

Even though the risk to 1st party is tolerable, further risk reducing measures were suggested in the QRA, ref. /1/.

5.2 Risk to 2nd party – customers at the HRS

Risk to 2nd party is calculated in terms of probability per year of a major accident causing one or more fatalities among customers

The tolerable risk criteria used in the QRA for 2nd party risk is:
The probability of a major accident causing one or more fatalities among customers shall not exceed 10^{-4} per year. This is the total number of fatalities among customers per year caused by the HRS.

The calculated risk to 2nd party is below the defined tolerable risk criteria.

The dispensers are the dominating contributor to the risk for 2nd party. This is because the customers are assumed to spend much of their time at the HRS close to the dispensers. Incidents in the storage and production area will only give a small contribution to 2nd party risk.

Even though the risk to 2nd party is tolerable, further risk reducing measures were suggested in the QRA, ref. /1/. A very effective measure to reduce the risk to 2nd party is to encourage the customers to move away from the dispenser/vehicle interface during refuelling, ref. /1/.

5.3 Risk to 3rd party – Societal risk

Risk to 3rd party is calculated both in terms of:

- Probability (per year) of exposing residential area, third party working premises or public assembly area outside the station to fatal exposure levels caused by major accidents at the station.
- A FN curve (Frequency per year of N or more fatalities, as function of N). If the calculated risk is above the red curve the risk must be reduced. If the calculated risk is above the green curve the risk should be reduced if feasible.

The calculated exposure frequencies for 3rd party to fatal exposure levels caused by major accidents at the HRS are calculated for the following 3rd party premises:

- Residential house to the north of the HRS
- Office west of the HRS
- Office east of HRS

The tolerable risk criteria used in the QRA for probability (per year) of exposing 3rd party is:

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.

The 3rd party exposure frequencies are below the defined tolerable risk criteria.

The FN curve for the example HRS is showed in the figure below. The blue line is the FN curve for societal 3rd party risk around the HRS. The curve shows the accumulative frequency for N or more fatalities.

Most of the FN curve for the example HRS lies in the tolerable region (below the green line); only the part of the curve with the highest number of fatalities lies in the ALARP region (between the green and the red line).

It is therefore recommended to assess whether risk reducing measures to decrease the frequency of the accident causing the highest number of fatalities or to reduce the expected number of fatalities for the most serious accident are economically feasible. Risk reducing measures are suggested in the QRA, ref. /1/.

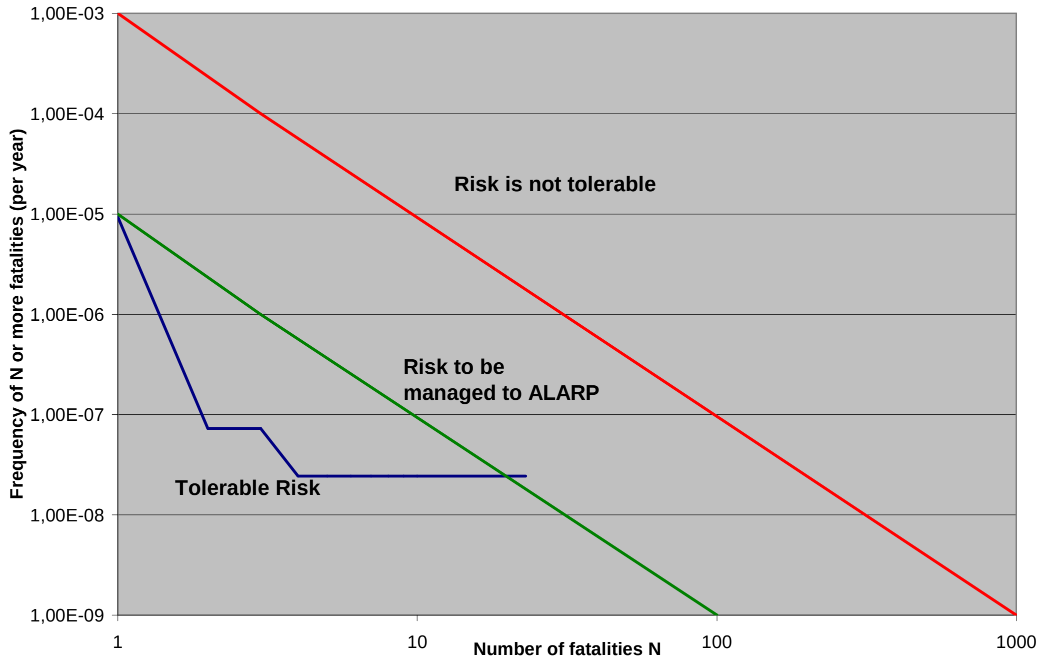

Figure 5-1 FN curve for the example HRS.

The main contributor to the risk of low number of 3rd party fatalities is full bore rupture releases from the unloading hose during unloading from tanker, followed by delayed ignition. Rupture of the liquid storage tank with immediate ignition and fires at the evaporator segment escalating to the storage tank also contribute to the risk of low number of 3rd party fatalities.

The only incident assessed to cause more than 5 fatalities among 3rd party is rupture of the liquid hydrogen storage tank followed by delayed ignition.

6 Uncertainties in QRAs of hydrogen applications

The quality of the results 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, but the HyApproval QRA has utilised the data sources available, ref. /1/. 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

A number of 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 are 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 project 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). Work is ongoing related to collecting and systemizing hydrogen incident and accident data into the database, in order to over time develop a high quality historical hydrogen specific database.

7 Recommendations for future use of QRA to assess risk at HRS

As part of the HySafe project WP9 there is ongoing work on developing a best practice for estimation of ignition probabilities for hydrogen releases. As of June 2007 a preliminary draft for an ignition model has been suggested, but this method is not finalized and has not been used in this study. However, before performing a QRA of future HRS, it is recommended that the newest results from HySafe and other sources are investigated.

As part of the HySafe project it is planned to develop a comprehensive Hydrogen Incident and Accident Database and develop a best practice for estimation of leak frequencies. However, before performing a QRA of an actual future HRS it is recommended to refer to more recent results and data from the HySafe project and other relevant sources.

In this example QRA detailed consequence assessments using CFD tools have been performed for a few selected scenarios; leaks from gas and liquid dispensers and leaks from unloading hose during liquid unloading from tanker. Other scenarios such as gas and liquid leaks in the production and storage area and tank ruptures have been assessed by simplified tools. In a future QRA of an actual HRS it is recommended that the most severe scenarios (which could be for example gas and liquid storage tank ruptures) are selected for detailed modelling. In many QRAs the most severe scenarios have low probability but severe consequence with potential of exposing 2nd and 3rd party relatively far away from the initial incident. The consequence of such scenarios will be very dependent on geometry effects, and the simplified consequence tools used in this analysis does not have the possibility of including geometry effects. By using CFD tools to model the potential incidents with most severe consequences, the layout of the HRS can be optimised to reduce the risk to 2nd and 3rd party.

The CFD results used in this example QRA are for simulations of similar (but not identical) geometries as considered in the study of the example HRS. The CFD results have been used as input to the QRA to illustrate how CFD results can be used in a QRA. However, for a QRA of an actual HRS it is recommended that consequence assessments are performed for the exact HRS geometry, as local geometry effects may affect the consequences of an incident significantly.

In this example QRA no detailed structural integrity assessments have been performed to determine the probability of explosions or fires escalating to other H2 containing equipment or damaging houses. If conservative assumptions regarding integrity of major equipment or structure supporting equipment (such as storage tanks) or integrity of houses (such as production containers or the service building) result in high risk numbers, detailed structural integrity assessments can be performed to determine the escalation risk in more detail.

8 References

/1/ HyApproval WP4 Deliverable D4.9. Quantitative Risk Assessment of hydrogen refuelling station with on-site production. Version Final (rev 4). 13th July 2007. Prepared by K. Holmefjord and G. P. Haugom DNV. Dissemination level PP – Restricted to other program participants included the Commission Services

/2/ Meeting between DNV and Shell the 17th of April 2007 at the Shell office in Den Haag. Review of detailed documentation (including P&IDs) for existing HRS

/3/ Meeting between DNV and Linde the 18th and 19th of April 2007 at the Linde site in Lohof. HRS site visit and review of detailed documentation (including P&IDs) for existing HRS

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