ASSESSMENT AND EVALUATION OF 3RD PARTY RISK FOR PLANNED HYDROGEN DEMONSTRATION FACILITY

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ABSTRACT

Potential risk exposure of 3rd parties, i.e., people not involved in the actual operation of a plant is often a critical factor to gain authority approval and public acceptance for a development project. This is also highly relevant for development of demonstration facilities for hydrogen production and refuelling infrastructure. This paper presents and discusses results for risk exposure of 3rd parties based on risk assessment studies performed for the planned Hydrogen Technology Research Centre, Hytrec in Trondheim. The methodology applied is outlined. Key assumptions and study uncertainties are identified, and how these might affect the results are discussed.

The purpose of Hytrec is to build a centre for research, development and demonstration of hydrogen as an energy carrier. Hydrogen will be produced both by reforming of natural gas with CO_2 capture and by electrolysis of water. The plant also includes a SOFC that will run on natural gas or hydrogen and produce heat and electricity for the Hytrec visitor centre. Hytrec will be located in a populated area without access control. Most of the units will be located within cabinets and modules.

The authors acknowledge the Hytrec project and the Hytrec project partners Statoil, Statkraft and DNV for their support and for allowing utilisation of results from the Hytrec QRA in this paper.

1.0 INTRODUCTION

This paper presents and discusses work undertaken to determine risk exposure of 3rd parties for the planned Hydrogen Technology Research Centre, Hytrec, in Trondheim, Norway. The Hytrec [1] project is a joint initiative between the companies Statoil, Statkraft and DNV. In addition the project has received financial support from the Research Council of Norway, and the Norwegian Ministry of Transport and Communications.

The QRA [2] work described and utilized in this paper is based on results from the QRA DNV performed as part of the Hytrec project. The objectives of the QRA studies were to identify and assess the main risk contributors associated with the operational phase, and to suggest potential risk reducing measures to achieve an acceptable risk level. Specific risk acceptance criteria were established for this study. These coincide with Statoil's acceptance criteria for individual risk.

This paper is based on rev.3 of the QRA and the corresponding design stage of Hytrec. The QRA was used actively to give recommendations regarding safe and cost efficient design. Several assumptions have therefore been changed between the 1st and the 3rd revision. The QRA was also utilized actively in the process to gain authority approval with the Directorate for Civil Protection and Emergency Planning (DSB).

2.0 DESCRIPTION OF THE HYDROGEN DEMONSTRATION FACILITY

Hytrec is a planned Hydrogen Technology Research Centre in Trondheim, Norway. The purpose of Hytrec is to build a centre for research, development and demonstration of hydrogen as an energy carrier.

The process plant part of Hytrec consists of the following modules:

- **SOFC.** Uses NG or H_2 in order to produce heat and electricity for the visitor's centre (Pressure ~ 100 mbarg, T ca 900°C).
- **Reformer -** Using NG in order to produce H_2. (Type not specified, P = 10 barg, T ~ 10-15 °C).
- **Electrolyser -** Using electrolysis of water to produce H_2. (Type not specified, P = 30 barg, ambient temperature.)
- **LNG storage and vaporizers.** Provides NG to the SOFC and Reformer units (P ~ 8 barg with an operating window of 5-12 bar, T = - 165 °C, volume 32 m^3, 12-13 ton CNG).
- **H_2 compressors** – Compresses H_2 produced by the Reformer and Electrolyser. (Type not specified, P ~ 200 barg)
- **H_2 storage -** Stores compressed H_2 (P ~ 200 barg).
- **H_2 refuelling station dispenser area** – Facilities for filling H_2 vehicles (P = 440 barg). (pump station)
- **Hydrogen pipeline to Marintek** – Provides supply of gas to Marintek (P = 6 barg, ambient temperature, 110 m long).
- **LPG storage units-** Provides possibilities of manipulating the composition of the applied gas from the LNG tank (LPG is only used by Marintek)
- **CO2 capture and storage module** – Captures the produced CO2 from the SOFC and H_2 production modules, and stores it for further and safe disposal.

As shown in Figure 1, hydrogen will be produced both by reforming of natural gas with CO_2 capture and by electrolysis of water. The plant will also include a SOFC for combined heat and power production. The SOFC, which will run on either natural gas or hydrogen, will produce heat and electricity for the Hytrec visitor centre.

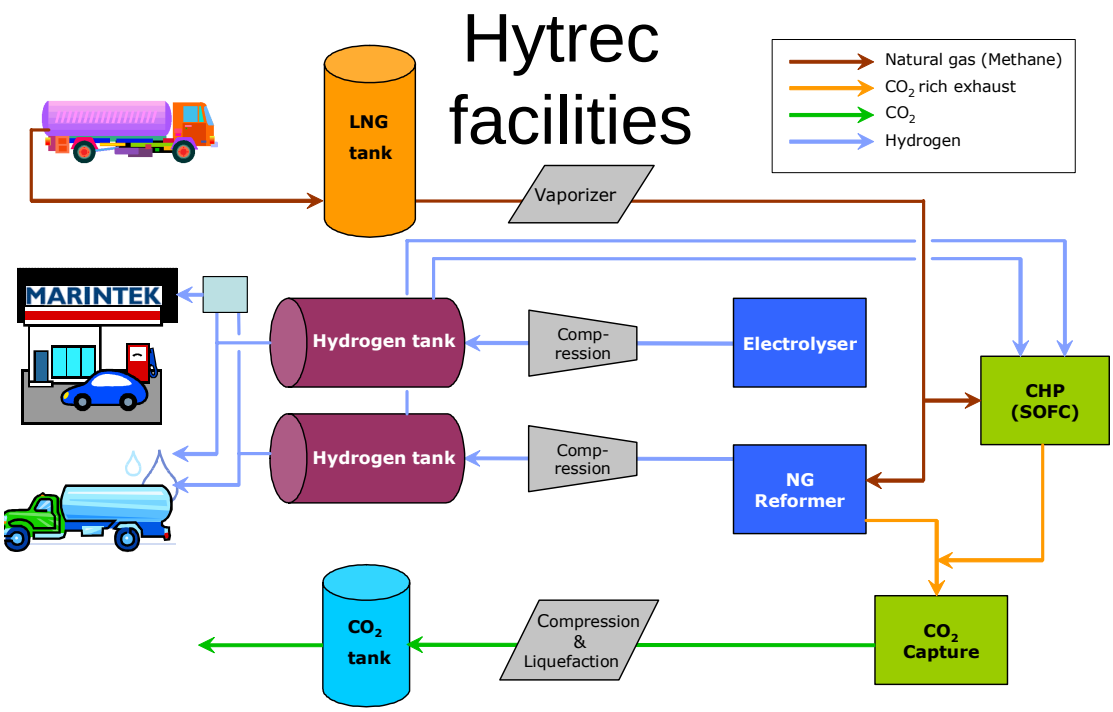

Figure 1. Main System Units and Flows.

Hytrec will be located in a populated area without access control. The hydrogen production and hydrogen storage will however not be accessible for the public. Most of the units will be located within cabinets and modules. An overview of the Hytrec layout is shown in Figure 2, while an overview of the production modules, which will be integrated with the visitor's centre, is show in Figure 3.

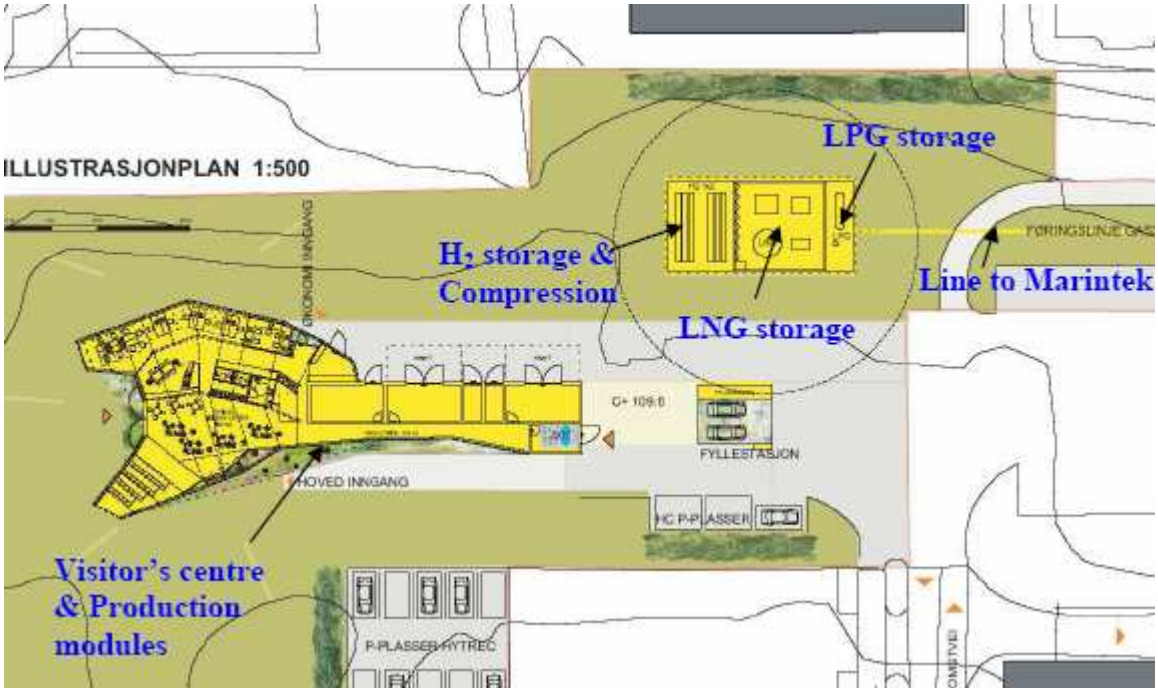

Figure 2. Principal overview of the Hytrec plant and refuelling station

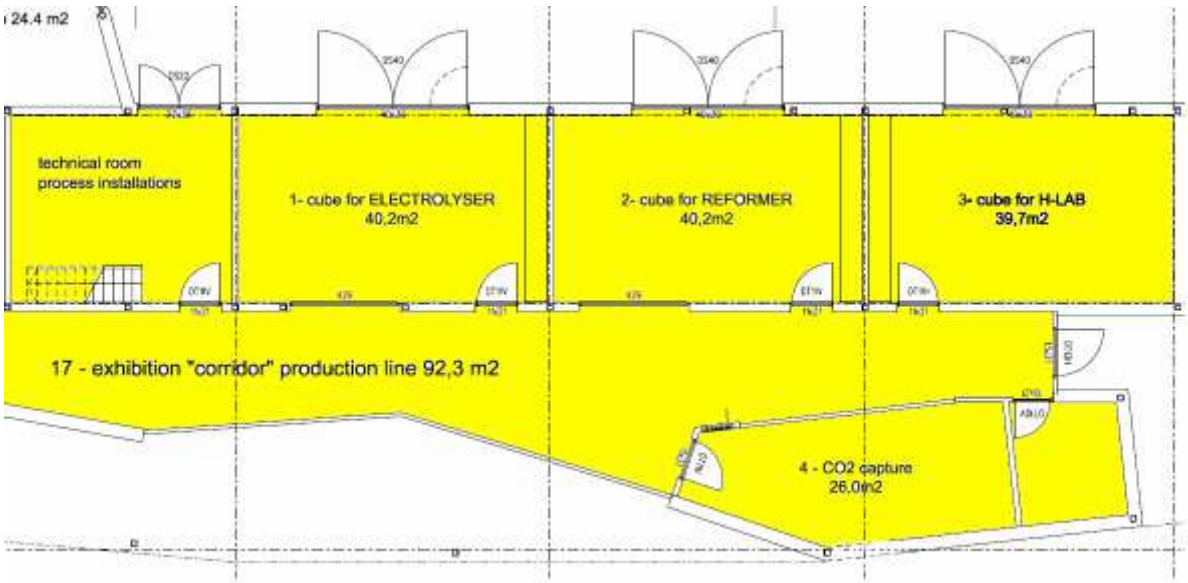

Figure 3. Principal overview of the production modules

3.0 METHODOLOGY

3.1 Risk Assessment

The methodology applied is a standard risk assessment approach as commonly applied within DNV for Quantitative Risk Assessments. Only 3rd party risk was estimated. This includes risk exposure onto residents, visitors and those not involved in activities at Hytrec. Assessment of risk exposure to Hytrec employees and customers at the hydrogen refuelling station were outside the scope of this risk assessment.

Figure 4 illustrates the QRA process, which is briefly described in the following.

Coarse hazard identification (HAZID) was performed at the kick-off meeting with the Hytrec project group. Additional potential hazards, within the defined scope of the QRA were identified through further in-house discussions within DNV.

Estimation of frequencies of the selected hazards was undertaken based on equipment count of PFD's for the different modules of the plant, and by using the DNV software LEAK[4]. LEAK is based on application of the UK (Health and Safety Executive) HSE Hydrocarbon Release Database (HCRD). The HSE database is established based on offshore hydrocarbon accidents. Lacking hydrogen specific data, the HSE database is considered as the most representative data currently available. The same approach to assess frequencies was selected in a recent QRA [5] in the HyApproval project.

The HySafe NoE [6] has an activity related to development of hydrogen specific incident and accident data, the HIAD database. This work is not yet sufficiently progressed to be utilized for estimations of leak frequencies for quantitative risk assessments.

Estimation of consequences of the selected hazards was undertaken by using the DNV software PHAST, and by separate explosion calculations. Maximum gas explosion overpressures were estimated by the COMEX programme. If necessary, the program NVBANG Version 3 was used to take the effect of different gases, possible walls being released during the explosion and venting of burnt gas in an early stage of the explosion into account.

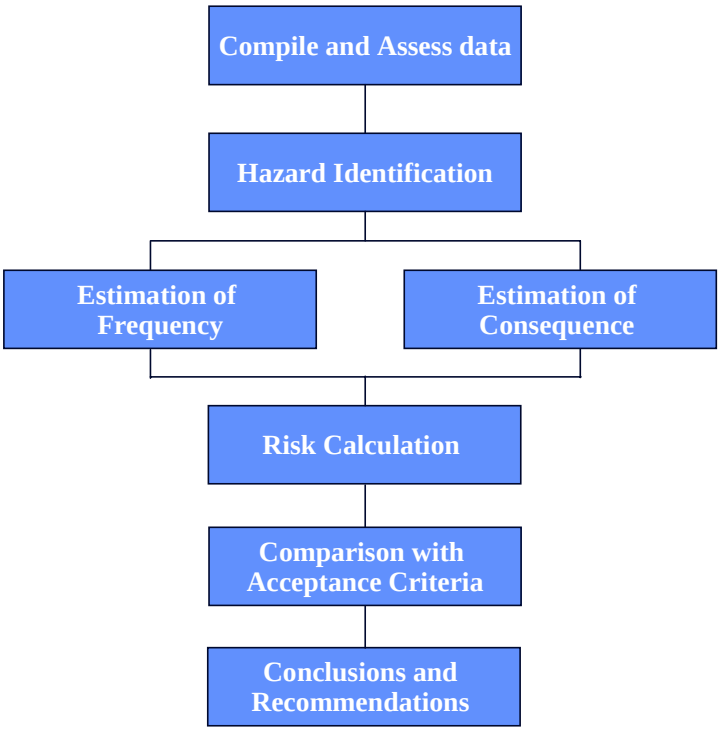

Figure 4. Quantitative Risk Assessment process

The risk calculations and overall risk assessment was undertaken by using an event tree approach.

Each end event from the event tree was assessed with respect to its potential of exposing 3rd party. In general, three factors were assessed:

- *Does the event have potential of exposing a 3rd party?* Some releases are too short to expose 3rd parties.
- *Presence fraction:* What is the probability of a 3rd party being present at the time of the accident?
- *Fatality fraction:* What is the probability of a fatal outcome if the accident has potential of exposing the person and the person is present at the time of the accident? This includes the probability of the release directed towards and exposing the 3rd party, probability of successful evacuation and probability of shelter from the heat radiation exerted by the fire.

Separate assessments were performed for all categories of 3rd parties.

3.2 Acceptance Criteria

Specific risk acceptance criteria were established for rev 3 of the Hytrec QRA considered in this study. These coincide with Statoil's acceptance criteria for individual risk. For individual risk, these criteria state that an individual risk of 1E-5 per year or less for the most exposed 3rd party is assessed to be acceptable.

Societal risk is commonly presented in a Frequency of N or more fatalities, as function of N curve (FN-curve). The slope of the FN-curve is designed to reflect the society's aversion to single accidents with multiple fatalities as opposed to several accidents with few fatalities.

Statoil's acceptance criteria for societal risk state that the FN-curve shall be within the maximum risk level illustrated in Figure 5. If the estimated FN curve lies within the As Low As Reasonable Practical (ALARP) region, risk reducing measures should be implemented if practical, typically subject to cost benefit analysis. This means that for a FN-curve within the ALARP area, risk reducing measures will be implemented, if they are cost effective with respect to the risk reduction that can be achieved. If the calculated risk is above the 'Maximum risk level' (illustrated in Figure 5), the risk must be reduced.

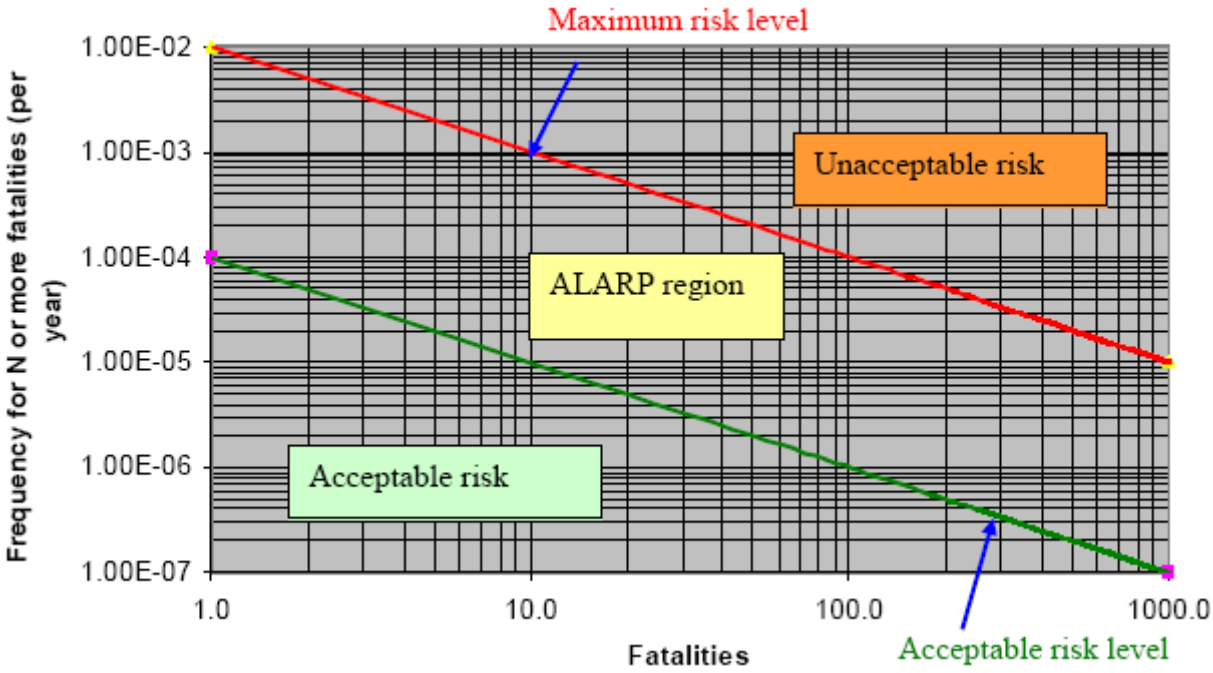

Figure 5. Risk acceptance criteria applied – societal risk.

4.0 KEY ASSUMPTIONS AND STUDY UNCERTAINTIES

4.1 Presence of 3rd party

3rd party is defined as visitors to Hytrec and inhabitants in the surrounding area that are not related to the operation of Hytrec. The most exposed 3rd party was assessed to be an inhabitant in the residential area. The different categories of 3rd parties were assessed separately. The presence fraction of each of the categories was estimated as follows:

Visitor: Present 4 hours per visit, 1 visit per year. Time will be spent 40% outdoors and 60% indoors.

Inhabitant (residential house): Present 20 hours per day, every day throughout the year.

Occasionally passing persons: People are assumed to be present in close vicinity of the plant. In average, it is assumed that a person is present 4 minutes every day throughout the year. This estimate is uncertain as no detailed research was undertaken.

Employees at adjacent offices: A person working at adjacent offices (NRK, Marintek) is assessed to be present 8 hours a day, 5 days a week. (based on standard working days).

Student at Marintek: A student at Marintek is assumed present 16 hours per day (day and evening, but not during night), every day of the year.

People working at the plant are defined as 1st party and were not included in the scope of this study.

4.2 Explosion Risk – ATEX Zone 2 Safety level

A key assumption to achieve the low explosion risk is that the cabinets and modules surrounding the SOFC, the reformer and the electrolyser are designed with a similar level of safety as if they were classified in accordance with ATEX Zone 2. This means that the results are based on assuming EX-equipment in cabinets and modules, double set of isolation valves and detectors, and sufficient ventilation to handle small leaks in the cabinets.

The structure and the façade of the building itself is assumed not specially designed against explosion overpressures, except for explosion venting panels in the roof of about 8 m^2 in each module. The justification for this is the low risk impact contribution from explosions in the production modules, which is caused by the ATEX Zone 2 classification safety assumptions.

4.3 Shielding walls

Shielding walls are assumed built around and between the outdoor modules in order to reduce the dispersion distance of ignitable gas as well as the jet fire length. This includes installation of shielding walls between the vaporizers (LNG and LPG) and the storage tanks. The exact design of the wall is not specified, but could consist of e.g. steel plates with perforations in order to give a transparent and see-through effect. Such a wall will cause impairment of gas releases and jet fires and therefore cause shorter dispersion and heat radiation distances.

4.4 Time to isolate hydrogen leaks

For hydrogen leaks in the indoor hydrogen production modules (Electrolyser and Reformer), the time to detect and isolate a leak was assessed to be in the order of 5 s. This assumption is based on quick-response gas detectors being installed inside the small electrolyser and reformer cabinets, giving very efficient hydrogen leak detection. In case a leak is detected, it is assumed that an automatic shutdown system that isolates the segments is initiated. It is assumed that the shutdown system (valve, actuator and logic system) satisfies certain reliability requirements related to probability of failure on demand. Further, a double set of detectors and isolation valves are assumed.

For outdoor modules there are certain uncertainties related to gas detection. It has therefore been assumed that steady state conditions with respect to dispersion distances are reached before the leak is successfully isolated. For the purposes of the QRA the isolation times only matters for the escalation probability, where the successful isolation of the release/fire is an important factor.

A system for automatic detection of hydrogen releases was assumed also for outdoor releases. In case a leak is detected, it is assumed that an automatic shutdown system that isolates the segments is initiated.

5.0 RESULTS

5.1 Individual risk

Table 1 below presents the risk results (per year) for a typical visitor and for the most exposed 3rd party, assessed to be an inhabitant in the closest residential area.

Table 1 Summary of risk results for individual risk to most exposed 3rd party (per year)[1].

Location of release	Module and leak size	IR –Visitor to plant (per year)	%-contrib	IR – Inhabitant (per year)	%-contrib
Indoor	Reformer NG (small)	Negl.	Negl.	Negl.	Negl.
	Reformer NG (large)	Negl.	Negl.	Negl.	Negl.
	Reformer H2 (small)	Negl.	Negl.	Negl.	Negl.
	Reformer H2 (large)	Negl.	Negl.	5.2E-09	2%
	SOFC (small)	Negl.	Negl.	Negl.	Negl.
	SOFC (large)	Negl.	Negl.	Negl.	Negl.
	Electrolyzer (small)	Negl.	Negl.	Negl.	Negl.
	Electrolyzer (large)	Negl.	Negl.	1.4E-09	1%
	Sub TOTAL	*Negl.*	*Negl.*	*6.6E-09*	*3%*
Outdoor	Filling station (small)	1.6E-10	2%	**1.4E-07**	**64%**
	Filling station (large)	7.8E-11	1%	1.1E-08	5%
	H_2 storage (small)	7.2E-10	8%	**5.1E-08**	**24%**
	H_2 storage (large)	6.4E-10	7%	7.0E-09	3%
	H_2 compr (small)	**1.3E-09**	**15%**	Negl.	Negl.
	H_2 compr (large)	8.0E-10	9%	Negl.	Negl.
	Marintek line (small)	Negl.	Negl.	Negl.	Negl.
	Marintek line (large)	5.5E-11	1%	Negl.	Negl.
	LNG and LPG storage (small)	Negl.	Negl.	Negl.	Negl.
	LNG and LPG storage (large)	**4.9E-09**	**56%**	1.6E-09	1%
	Sub TOTAL	*8.7E-09*	*100%*	*2.1E-07*	*97%*
GRAND TOTAL		**9. E-09**		**2. E-07**	

Escalated events are assessed to cause fatal impact up to 150 m away. People in surrounding buildings within this distance (NRK, NTNU, Tyholttårnet and Kindergarden) will therefore be exposed to risk, but the most exposed 3rd party is assessed to be an inhabitant as he is assumed present at his house almost the entire day. The risk to other 3rd parties is therefore lower than estimated for the inhabitant, as given in the table above.

Risk to inhabitant

As indicated in Table 1 above, an inhabitant, which is located in a house within 150 m of Hytrec was found to be the most exposed 3rd party. The individual risk to this person is estimated to be 2.E-7. This is assessed to be a low risk level.

Outdoors, only events causing escalation to either of the storage tanks (LNG, LPG or H_2) were found to expose the closest inhabitant. Isolated releases or initial events only cause 3rd party impact at shorter distances. More than half of the individual risk to the most exposed person (closest resident) originates

[1]Risk lower than the smallest risk mentioned in this table was considered negligible for presentation purposes. In many studies risk contributors smaller than E-09 are considered negligible.
All risk contributors have been considered in the risk calculations.

from the dispenser area (H_2 filling unit). The reasons for this include a high probability of ignition, and that the distance to the car being refuelled was found to be shorter than the flame length of the jet fire. If isolation fails (i.e. long lasting fire) and the jet is directed towards the car, the storage tank inside the car was assumed to rupture resulting in a BLEVE/Fireball causing sufficient fatal heat radiation to expose third parties. This is likely to be a conservative assessment. Escalation could also result in leak from the tank, not a catastrophic rupture. The risk estimate also depends on the number of refuelling operations. Performing more filling operations will increase the risk level.

The risk contribution from accidents originating indoors is very low. Due to the ventilation system in the cabinets, only explosions from large un-isolated releases (from the electrolyser or reformer unit) were found to cause sufficient explosion overpressure to cause fatal impact to inhabitants. Small releases (isolated and un-isolated) are assessed to only cause explosions that affect the immediate module. Large isolated releases are assessed to cause escalation out of the module, but not sufficient to expose inhabitants.

Risk to visitor:

The individual risk to a visitor at the H_2 plant is estimated to 9E-9 per year. The very low individual risk is achieved due to the short time one single visitor is present at the plant throughout a year. Personnel working at the plant is defined as 1st party and not assessed in this study.

The main risk contributor to visitors was found to be large LNG leaks from the storage module. It is assumed that visitors at the H_2 plant are evacuated before an initial event can escalate. Personnel should be evacuated further away than 150m, as this is the estimated impact radius from the worst case scenario.

5.2 Societal risk

The societal risk is defined as risk to the population (3rd party) in the vicinity of the plant. This is usually presented as a FN-curve represented by frequencies for N or more fatalities. The estimated FN-curve for Hytrec is presented in Figure 6 below, with Statoil's acceptance criteria included.

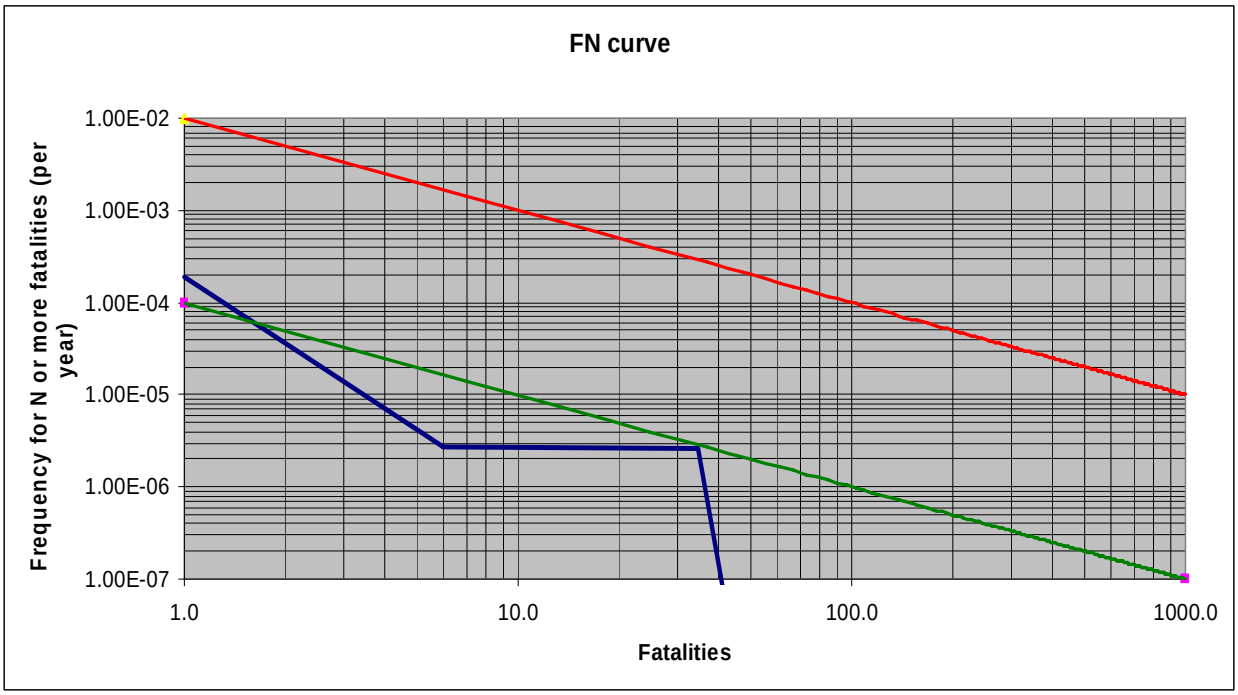

Figure 6 Societal risk, presented as FN curve.

A fatal accident is expected once every 5000 year. The estimated FN curve lies in the lower part of the ALARP-region. This indicates that the risk is low and acceptable, but also requires that measures are taken in order to reduce risk further if found cost-effective.

6.0 DISCUSSION

Although the results of this QRA shows risk results within the acceptance criteria applied, this should not be taken as a proof that hydrogen refuelling stations in general will be within defined risk acceptance criteria. The actual design and layout chosen including the specific assumptions related to safety systems will have great influence on the safety level. As this study focus on 3rd party risk only, the location of the hydrogen refuelling station and the related presence of people around the hydrogen refuelling station will affect the risk results.

Since the 3rd revision of the QRA considered in this paper further changes have been implemented that is considered to further improve the design and reduce the risk.

6.1 Key assumptions and study uncertainties

It should be noted that there are certain uncertainties associated with the risk estimates in this study. Key examples visualizing how certain study assumptions or uncertainties can affect results are given in the following.

Leak frequencies

Although being the 3rd revision of the Hytrec QRA, the results are still based on a conceptual design stage for the Hytrec plant. The QRA therefore had to be prepared without detailed information about the equipment to be installed. To take this into account and ensure that some conservatism was maintained in the estimates, frequency adjustment factors were applied.

There are also uncertainties associated with the use of the HSE accident database to estimate leak frequencies from hydrogen equipment. The HSE database is based on offshore accidents and hydrocarbon equipment. As relevant hydrogen specific incident and accident databases are not yet available for general hydrogen risk assessments purposes, the HSE database was assessed to be the most representative data source available.

Dispersion calculations

The dispersion modelling was undertaken with the DNV software PHAST, without taking possible effects of terrain, objects and other kind of obstructions into account. Assessments were undertaken to estimate the effect of shielding walls, but these were based on engineering judgement and not by utilization of sophisticated CFD tools. For scenarios with significant risk impact and influence on the total risk results, it is generally advisable to consider to use more complex tools like CFD tools to verify or correct certain results.

6.2 Acceptance Criteria

It is possible to set up and select acceptance criteria in different ways. In this case, the risk acceptance criteria was selected based on the risk acceptance criteria developed by one of the project partners.

The selection and interpretation of risk acceptance criteria might affect whether the risk results are interpreted as “acceptable” or not acceptable for a particular study. In this study a FN-curve was used to assess the acceptability for societal risk. It can be argued that this approach partly reflect

interpretation as further analysis and assessments are required when the risk fall within the ALARP region.

In this study, only acceptance criteria for 3rd party were included. Experience from other hydrogen refuelling station safety assessments [7] indicate that it might be challenging to meet risk acceptance criteria also for refuelling station customers (2nd party) and/or the hydrogen refuelling station personnel (1st party). The main challenges for one particular hydrogen refuelling station depend on a lot of different input parameters, and the conclusions from this study can therefore not be extrapolated to other hydrogen refuelling stations.

7.0 CONCLUSIONS

Although this QRA [2] gave risk results within the acceptance criteria applied, this should not be taken as a proof that the risk caused by hydrogen refuelling stations in general will be within defined risk acceptance criteria. It should be noted that since this is the 3rd revision of the QRA, changes implemented based on earlier versions of the QRA have contributed to improve the design and reduce the risk.

Generally it is recommended to use QRA results actively to optimize design and layout to achieve safe and cost efficient design and operation. It is recommended to assess the effect of potential risk reducing measures. Examples of relevant risk reducing measures are: reduction of the number of leak sources; control of ignition sources; optimise detection and shutdown systems, utilisation of alarms; evaluate the effect of passive fire protection; procedures for refuelling of hydrogen cars; establishment of emergency preparedness and contingency plans; design of ventilation systems and general routines and procedures for safe operation of the plant.

The QRA was also utilized actively in the process to gain authority approval with the Directorate for Civil Protection and Emergency Planning (DSB). Even the first QRA revision, was presented for DSB, for comments. This made it possible to implement the authority input at a very early design phase. The benefit was apparent when handing in the final approval application, as DSB at this point in time was familiar with the Hytrec project, and the required approval could be obtained faster than usual.

8.0 ACKNOWLEDGEMENTS

The authors acknowledge the Hytrec project and the Hytrec project partners Statoil, Statkraft and DNV for their support and for allowing utilization of results from the Hytrec QRA in this paper.

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