TECHNICAL NOTE

Hydrogen Plant Siting Study

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1 Introduction

Gexcon has been hired by Green Hydro AS to make a safety assessment of a project to build a hydrogen plant near Tau in Rogaland.

The purpose of this document is to establish whether there are safety related reasons to exclude any of the options for the location of the facility. This assessment is based on the requirements for documentation and safety perimeters set in the act for prevention of fires and explosions and associated regulations.

The proposed locations are marked by yellow stars in the aerial photos below

Figure 1: Illustration of possible location of the hydrogen facility – Fiskå

2 Standards and regulations

2.1 Standards

Several international standards will apply to a hydrogen production facility.

- ISO/TR 15916:2015 “Basic considerations for the safety of hydrogen systems – 2nd edition 15.12.2015
- ISO 26142 “Hydrogen Detector Apparatus – Stationary Applications”
- ISO 22734-1:2008 “Hydrogen Generators Using Water Electrolysis Process”
- NS-EN ISO 80079 "Explosive atmospheres (ATEX)".

2.2 Regulations

In addition to being built in accordance with national and international standards the facility will be run in accordance to relevant laws and regulations. The Norwegian Directorate for Civil Protection (DSB) has issued a number of regulations based in the Fire and Explosion Prevention Act (Brann- og eksplosjonsvernloven).

2.2.1 Major incident regulations (Storulykkeforskriften)

Since a considerable amount of hydrogen will be stored at the facility, the European Seveso directives will apply. The Norwegian major incident regulation is made so that fulfilling it will also meet the requirements in the Seveso directive. The objective of the regulation is to prevent and mitigate major incidents in businesses handling dangerous materials. (FOR-2016-06-03-569).

Different materials are grouped based on their hazardous potential and the amount of the material kept at the facility. Facilities that store or handle dangerous materials may fall in to one of two categories:

1. Duty to notify according to §6, or
2. Complete and extensive safety documentation according to §9

Regardless of which category applies, the company will need to submit an application for consent to the DSB before activities can legally start on the facility. Threshold amounts for hydrogen storage are given in Figure 3 below.

KOLONNE 1		KOLONNE 2	KOLONNE 3
		Mengdegrense (i tonn) for	
Farlige kjemikalier	CAS-nummer[1]	Meldepliktig virksomhet, jf. § 6	Sikkerhetsrapport-pliktig virksomhet, jf. § 9
15. Hydrogen	1333-74-0	5	50

Figure 3 Extract from DSB regulations (2016), mass of dangerous goods handled leading to safety obligations

Attached to the major incident regulations is the “guidelines for risk assessment of facilities handling hazardous materials”.

The major incident regulations define influence zones that dictates what kind of activities and exposure time for humans are acceptable in the area around a facility These influence zones are defined as follows in Table 1.

Table 1: Influence zones according to the major incident regulation

Zone	Description
Inner	This is usually the facility site itself. In addition, it can include areas used for agricultural purposes. Only short-term human presence is acceptable, such as people passing through on already established hiking trails.
Middle	Public roads, railroads, docks and similar. Permanent places of work, such as industry or offices, is also acceptable in this zone. However, there shall be no hotels or residential buildings. Scattered residences may be accepted in some cases.
Outer	Residential areas and areas with access for the general public may be inside the outer zone, including shops.

2.2.2 Regulation – Handling of hazardous materials

This regulates design, construction and operation of systems and facilities handling hazardous materials, including pipework used for handling hazardous materials.

3 Methodology

As the layout and design of the plant is not yet known, and neither is the potential gas releases that may occur, at this time the effects of a hypothetical scenario will be considered. Because of this we have chosen a conservative approach.

In this case the qualitative assessment is that neither spread of hydrogen gas nor fire poses a threat to neighbours.

3.1 Explosion

The way a pressure wave moves in an open area is described by numerous sources. One technique that's frequently used is the "multi-energy" method described in 1993 by van den Berg and Lannoy [1]. According to the multi energy method beyond a certain distance from the explosion area the resulting pressure will always be the same, regardless of the initial explosion pressure. This is shown in Figure 1.

Influence zones are usually determined on the basis quantitative risk analyses. However, there is still insufficient data for hydrogen to make such calculations. This is why the alternative method given in «Retningslinjer for kvantitative risikovurderinger for anlegg som håndterer farlig stoff» [2] is recommended. These guidelines state that "in some instances, it may be beneficial to set the influence zones based on consequence assessment rather than risk contours". This is typically true for simple facilities where the 3rd party risk exposure is defined one unique incident. This document is referred to by the DSB on their website concerning major incident regulation.

The document assumes a pressure wave is capable of harming people and buildings. The threshold values for mortality and influence zones are given in Table 1, and discussed in section 6.

Table 2: Threshold values for mortality and influence zones

Pressure (mbar)	Description
20	Threshold value for outer zone
50	Threshold value for middle zone
74	50% mortality and threshold value for inner zone

The thresholds given in Table 2 is added as vertical lines in Figure 2 below, taken from van den Berg and Lannoy [1].

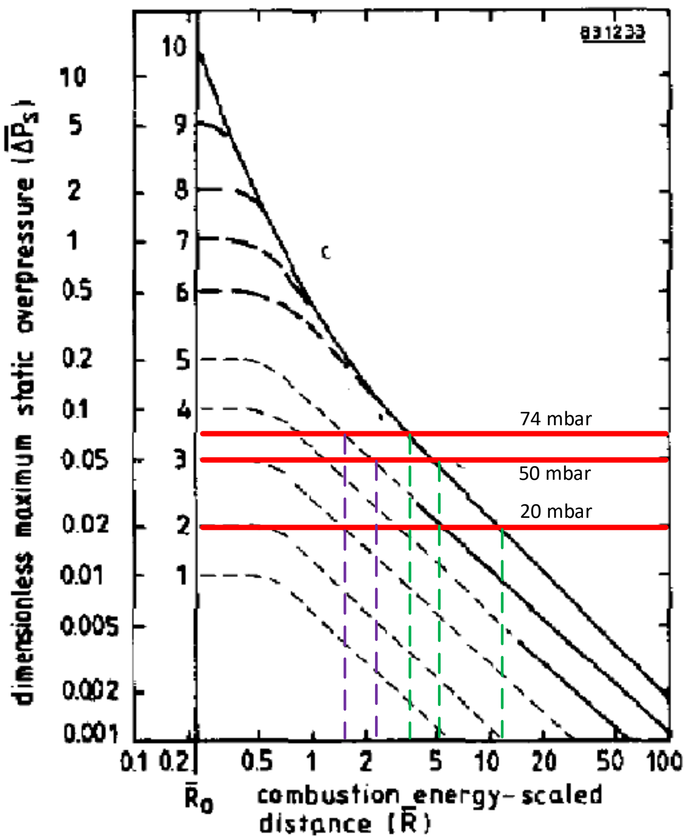

Figure 4: Hemispherical propagation of a pressure wave according to the multi-energy method

The initial pressure of the explosion can be chosen as a number between 1 and 10 where 1 is a weak explosion and 10 is a detonation. We use 5 for deflagration and 10 for detonation. Intensity level 5 represents a small to medium explosion with an explosion pressure of about 200 mbar. This corresponds well with combustion of a low concentration cloud of hydrogen with few obstacles to cause turbulence and should be understood as a lower limit for explosion frequency. The energy scaled radiuses $\bar{R}$ for intensities 5 and 10 can be read from Figure 1, and is given in Table 2.

Table 3: Combustion energy-scaled distances

Pressure (mbar)	Intensity 5	Intensity 10
20	5.96	11.40
50	2.34	5.07
74	1.59	3.62

Distance to the given pressure limits can be calculated by

$$r = \bar{R} \cdot \left(\frac{E}{p_a}\right)^{1/3}$$

where

E = combustion energy calculated by using the mass of hydrogen involved in the explosion multiplied by the specific combustion enthalpy of 141.8 MJ/kg
p_a = atmospheric pressure, 101 325 Pa.

3.2 Detonation

Under certain conditions of gas concentration and degree of turbulent combustion, hydrogen explosions can escalate from deflagration to detonation. This has the following effects:

1. While a deflagration typically uses the part of the gas cloud that consists of a flammable fuel-air mix, a detonation will involve a larger percentage of the fuel, thus increasing the total amount of energy released.
2. The flame front of a detonation moves at a much higher speed than that of a deflagration, the pressure is likewise increases. Pressures approaching 20 barg have been observed.

The facility should be designed in a way that prevents leaked gas from accumulating in high concentrations, to reduce the risk of detonation as much as practically possible. Should a detonation occur anyway, it will likely happen inside a building or similarly enclosed area that allows for gas accumulation. Designing buildings to withstand the load of a potential detonation is not feasible. This means a detonation will inevitably cause great damage to the facility.

However, with a potential for detonation, this effect should be taken into account when determining the extent of the influence zones.

3.3 Leakage from a pressurized system

A leak for a circular hole with a diameter of 3 mm in a pressurized system of 350 bar will have an initial leak rate of about 115 g/s. The leakage will dilute in air and relatively quickly develop a steady-state cloud of ignitable gas where the rate of dilution from the outer regions of the cloud balances the rate of supply from the leakage. Since the rate of combustion for concentrations between 4% (LEL) and 8% is quite low, it is taken that the part of the cloud contributing to an explosion if ignited, corresponds to the partial cloud with hydrogen concentration in excess of 8%.

According to calculations made in FRED the explosion contributing cloud will have a volume of 12,3 m^3 and that the hydrogen content is approximately 147 grams. Assuming that an explosion will consume all this hydrogen, the energy released will be 20.8 MJ.

The calculated distances from the explosion center to the damage limits will then be as given in Table 4.

Table 4 Calculated damage limit distances for a 3mm leakage from a 350 bar storage system

Pressure (mbar)	Description	Distance (m)	
		Deflagration	Detonation
20	Threshold value for outer zone	35.2	67.3
50	Threshold value for middle zone	13.8	29.9
74	50% mortality and threshold value for inner zone	9.4	21.4

As a sensitivity, leakage rates and associated influence zones have been calculated for hole sizes ranging from 1mm to 10mm. The calculated influence zone radii are shown in the figures below.

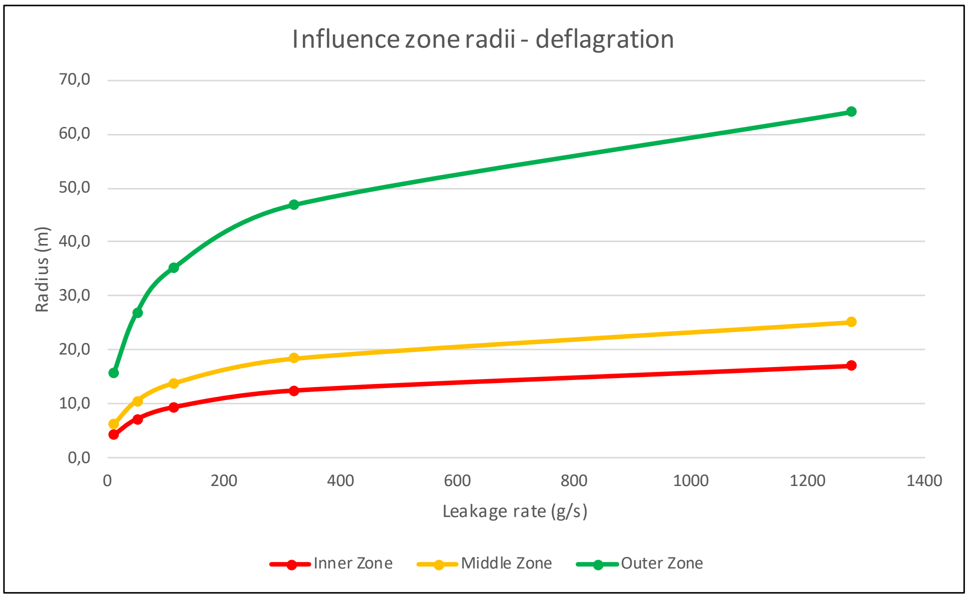

Figure 5 Influence zones for deflagrations

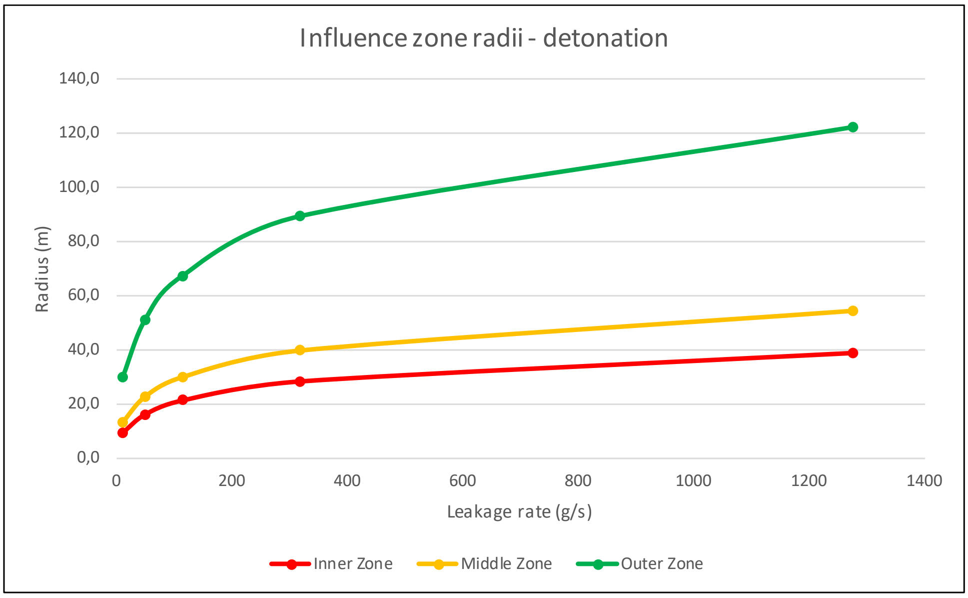

Figure 6 Influence zones for detonations

3.4 Release from cryogenic storage

The cryogenic storage will consist of double layer, vacuum insulated tanks and piping. Leakage of liquid hydrogen would only result from bot layers of containment being impaired, and this is deemed as an unlikely event. The loss of vacuum on the storage tank, however, will lead to a rise in pressure and temperature on the tank, and eventually cause the pressure safety valve to lift. A 10mm hole in the outer skin will give rise to a steady-state venting rate of approximately 100 g/s. The momentum and temperature of such a release will differ from the high-pressure leakages described above, so the influence zone radii will differ.

Table 5 Calculated damage limit distances for cryogenic tank venting

Pressure (mbar)	Description	Distance (m)	
		Deflagration	Detonation
20	Threshold value for outer zone	45.9	87.7
50	Threshold value for middle zone	18.0	39.0
74	50% mortality and threshold value for inner zone	12.2	27.8

4 Conclusion

Based on the calculations shown in sections 3.3 and 3.4 above, the influence zones emanating from loss of vacuum on the cryogenic storage with hydrogen cloud detonation are presented below, as yellow, orange and red circles. In addition, the detonation radius for the outer influence zone emanating from a 100 high-pressure leakage is indicate by a grey, dashed circle.

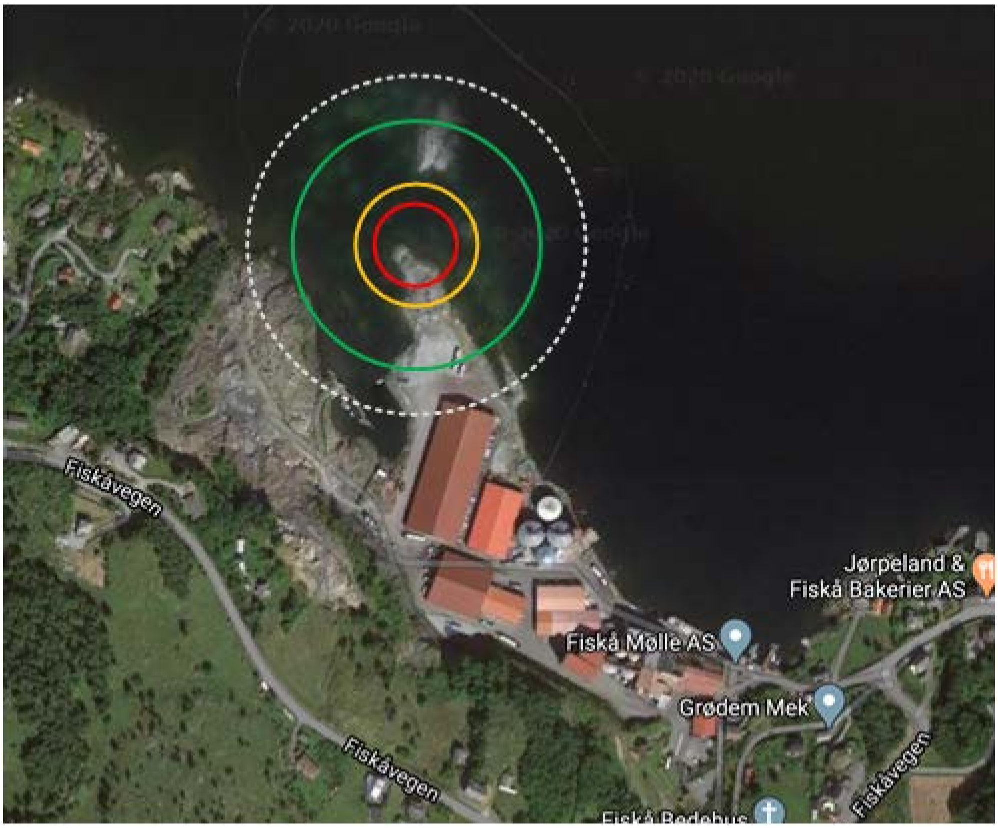

Figure 7 Influence zones at Fiskå

5 Process safety in design

To ensure a safe design, numerous steps must be taken in the planning phase of the project. This is to be aware of what risk elements will be present and to ensure sufficient barriers and procedures to keep the risks at an acceptable level, and that any mitigating measures are correctly implemented in technical systems, procedures and training.

Avoiding the most serious incidents, which in this case means detonation, should be a priority while developing process safety in the construction phase. This can be done by choosing a layout that prevents the accumulation of high-concentration hydrogen clouds, in addition to limiting the duration of any leaks by having good detection systems and well-placed emergency shutdown valves.

A report that documents that the risks are calculated and at an acceptable level is required by the major accident regulations. A general overview of the main steps of such a process is shown in Figure 9 below.

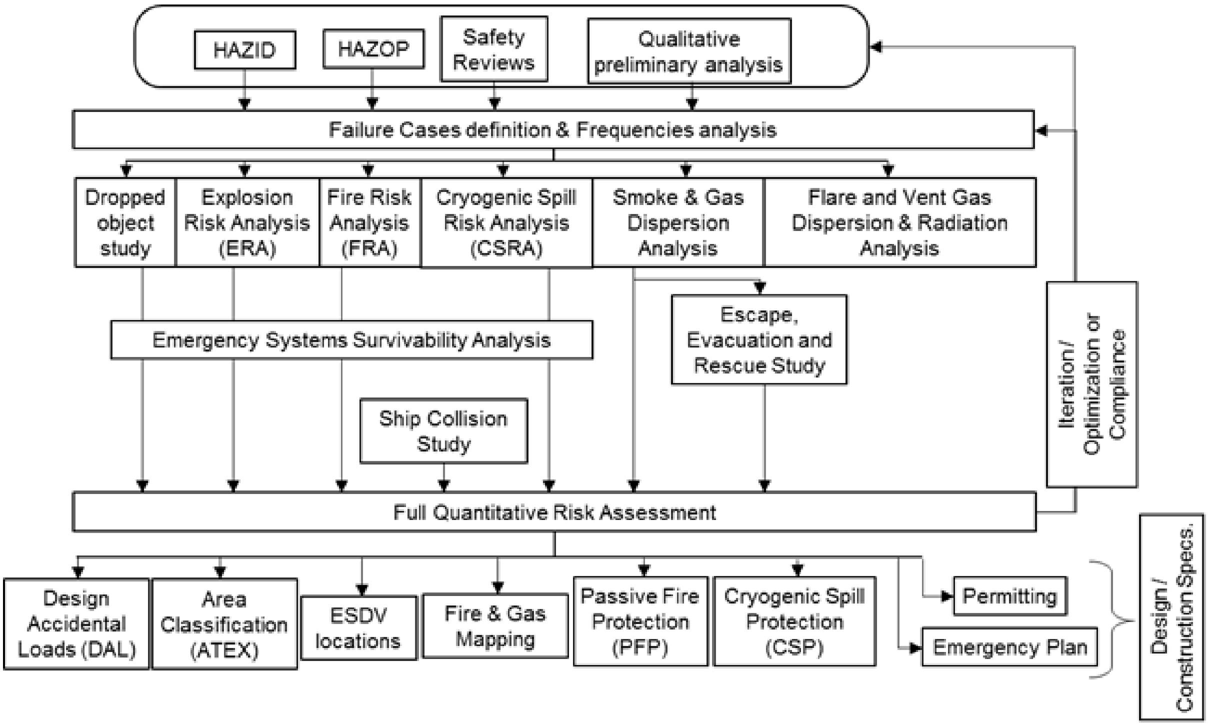

Figure 9 Typical activities related to process safety in an execution project

6 Discussion

74 mbar as a threshold for 50 % mortality is very low compared to most established references. We have still chosen this value because it is given in the guidelines on risk analyses given by DSB on their website. Therefore, this is likely the criterion the DSB will use when considering an application for consent, even though this is highly conservative.

In Gexcon's view it is natural that DSB is challenged on this criterion. We have not been able to find any resources supporting the claim that humans will be seriously injured or killed at this level of pressure. The only sensible explanation is that the pressure may turn objects into projectiles that, in the event they hit a human, cause injury.

In previous, comparable analyses Gexcon has used a limit of 5 % mortality of 200 mbar. This number is backed by the OGP [3] who in open areas recommend 350 mbar as a threshold of 15 % mortality and 500mbar for 50 % mortality.

7 References

[1] van den Berg, A.C. and Lannoy, A., “Methods for vapour cloud explosion blast modelling”, Journal of Hazardous Materials 34, 1993

[2] Lloyd’s Regisre, «Retningslinjer for kvantitative risikovurderinger for anlegg som håndterer farlig stoff», 18. oktober 2017

[3] OGP, «Risk Assessment Data Directory – Vulnerability of Humans», Rapport nr. 434-14, mars 2010.