JANUAR 2024
GRUNDARTANGI H2

Grundartangi Hydrogen project: Risk assessment report

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1 Introduction

This report is generated primarily to complete the Environmental Risk Assessment of the Grundartangi Hydrogen Project to provide quantitative risk assessment of the risk parameters maximum consequence distance (how far could serious injuries to people reach in case of major accidents), location specific individual risk LSIR (fatality risk isocurves round the premises), and societal risk (FN-curve, where number of people in the neighborhood is taken into account and combined with LSIR)

Credible accident scenarios are described and representative worst-case scenarios are selected based upon the conditions described in the Conceptual Design Study. Consequence distances to defined end points for toxic and heat radiation/explosion pressure effects are determined by using the commercial software from DNV GL, Phast/Safeti. Estimated accidental release frequencies are based upon the recognized Dutch guidelines, reference /1/. The number of persons on existing and future neighbor sites are estimated, and then combined with the frequencies and LSIR results in a risk calculation using Phast/Safeti.

The project covers facilities for the production of gaseous hydrogen by electrolysis, production of gaseous nitrogen by air separation, and production of liquid ammonia by reacting the produced hydrogen and nitrogen in a Haber-Bosch synthesis unit. The refrigerated liquid ammonia is stored in three atmospheric storage tanks and finally loaded on 30,000 m³ ship tankers. The electrolyzer, air separation and Haber-Bosch facilities are divided in three identical trains each of a capacity of 280 MW, hydrogen production of 5.0 t/h, and ammonia production of 26.8 t/h.

2 Dangerous substances

Three major dangerous substances on the Grundartangi site is identified. The substances, hydrogen, oxygen and ammonia are all covered by the EU Seveso Directive 2012/18/EU.

2.1 Hydrogen

Hydrogen is classified according to the European Regulation (EC) no. 1272/2008 as an extremely flammable gas, hazard statement H220, CAS no. CAS 1333-74-0.

In release cases the hydrogen could by ignition give either jet fires or flash fires (delayed ignition). Under certain circumstances (large gas cloud/congestion of equipment/physical objects) the flash fire could develop into an explosions and generate overpressures.

Hydrogen is flammable in a rather large interval compared to other flammable gasses, i.e. in the interval of 4-75 vol%.

2.2 Oxygen

Oxygen is classified according to the European Regulation (EC) no. 1272/2008 as a substance which may cause or intensify fires and being an oxidiser, hazard statement H270, CAS no. CAS 7782-44-7.

Oxygen is not flammable in itself, but if increased concentrations of oxygen appear by release, combustible objects can catch fire much easier than with normal concentrations of oxygen in the atmospheric air, e.g. clothing, and the fire itself will appear more intense.

2.3 Ammonia

Ammonia is classified according to the European Regulation (EC) no. 1272/2008 as a flammable gas even if the substance is very difficult to ignite in the open air, hazard statement H270, toxic by inhalation, hazard statement H331, very toxic to aquatic life, hazard statement H400, and toxic to aquatic life with long lasting effects. CAS no. CAS 7664-41-7. There are more hazard statements for ammonia, but only hazard statements of direct importance to the Seveso risk are mentioned

According to the above mentioned the main hazards related to ammonia are the toxic effects by inhalation and the toxic effects to aquatic life.

3 Credible accident scenarios

3.1 Hydrogen

Hydrogen is produced in the electrolyzers as a gas under atmospheric pressure. The gas is then cleaned and dried in subsequent equipment before being compressed to a pressure of 32 barg in a compressor unit. The compressed gas is then routed to the Haber-Bosch unit for ammonia synthesis, where the gas is mixed with nitrogen.

Credible accident scenarios are release of hydrogen due to leakages or ruptures of the equipment.

For the electrolyzers it may be caused by equipment failure due to material defects. For the piping and the involved cleaning and drying equipment releases may be caused by mechanical impacts by vehicles/cranes/drop of heavy objects, by ageing of gasket material or material defects. For the compressor it may be caused by wear and tear on sealings, unintended vibrations and material defects.

In all cases hydrogen would release from the closed systems. Such releases will have a very low probability, since equipment design must follow recognised standards. The standards are not yet specified. If a release has started gas detectors or other electronic equipment will ensure a quick automatic unit shut down.

The hazard from hydrogen is related to fire and explosion. To initiate a fire or explosion ignition sources shall be present. The design of the plant will take this into account by proper area classifications (ATEX classification) and administrative regulations to prevent existence of ignition sources. ATEX classification means site area classification according to the EU ATEX Directive. The purpose of the classification is to minimize the probability of having an ignition source if ignitable gasses should appear. By the area classification certain areas on the site are specified as classified (ignitable conditions could occur). A classified area will require special attention on controlling open fires and sparks and demand high quality electrical components.

Buildings with hydrogen containing equipment must be ventilated not to accumulate high concentrations of hydrogen in dead ends.

3.2 Oxygen

Although oxygen is produced along with hydrogen in the electrolysers it will not pay a significant role to risk. The oxygen is vented right after production to the atmosphere to a safe location, and it will consequently be dispersed in the atmosphere. The same can be said about the air separation units, where oxygen is produced along with nitrogen. The produced oxygen is vented to the atmosphere to a safe location.

3.3 Ammonia

Ammonia is produced in the Haber-Bosch unit by catalytic processes under high temperatures and pressures (Up to approx. 120 barg and 550 deg.C) to ammonia gas. After the reactor the gasses are cooled down until the ammonia is liquified. From a collecting vessel the ammonia is pumped at a temperature of -33 deg.C to storage. Three storage tanks in a common tank yard will each have a liquid capacity of approx. 17,600 m^3. The storage tanks will operate at a pressure slightly above atmospheric and a temperature of -33 deg.C. From the tanks liquid ammonia will be pumped to arriving ship tankers at the pier site for long distance transportation. The capacity of the tankers will be 30,000 m^3.

On the land side the major hazard of ammonia will be its toxic effect by inhalation. The Haber-Bosch unit is a typically chemical process unit, and by equipment type comparable to mineral oil refineries. Releases could take place, although probabilities are very low. The units will be designed according to recognised standard. The Haber-Bosch unit is a mature process with a long history.

Causes of release in the Haber-Bosch unit could be material defects, ageing of gaskets, mechanical impacts from dropped heavy objects, vibration of rotating equipment, and wear and tear. Release of ammonia gas will have a relatively low damaging potential. Release of liquid ammonia on the contrary have a much higher potential due to the very much higher mass of substance being released. In the Haber-Bosch unit liquid ammonia will appear as liquid under pressure, in which case a substantial part of the liquid promptly will evaporate after release to the open. This will give a large gas cloud. At the final station in the Haber-Bosch unit ammonia will appear as a cold liquid (-33 deg.C) at atmospheric pressure. This temperature will remain approx. at that level during pipe rundown to storage tank, the storage, and the ship loading. Release of cold liquid ammonia will start evaporation right away, but normally not as violent as compared to release of ammonia at higher temperatures. The release will anyway generate a gas cloud of ammonia, and the concentrations of ammonia near the release could be quite high with potential to severe injuries/fatalities.

Major releases will have a very low probability, since equipment design will follow recognised standards. If a release has started gas detectors or other electronic equipment will ensure a quick automatic unit shut down.

Releases at the loading point at the harbour could take place, in which case the liquid ammonia will be spilled on the sea surface and again result in significant evaporation and gas cloud generation. Apart from the effect on persons ammonia will partly be dissolved in the sea water. The spreading of ammonia in the sea water will depend on the flow pattern in the local part of the sea. Near to the release point aquatic life will suffer without doubt, but the experience from other cases is, that the ammonia will be diluted rather quickly and not result in long lasting effects. A literature review of the ammonia effects on fish can be seen in reference /5/.

Causes of releases at the pier could be leakage or rupture of the connection (marine arm), which normally is seen as the weakest point. Releases are though prevented by proper design following recognised standards. Should a release be initiated gas detectors and other electronic equipment will ensure automatic closure of valves and stop of the pumping. Apart from that the loading operation will be surveyed and controlled by dedicated people on land and on sea, who can push the emergency button if necessary.

4 Consequence calculations

In the figures below the results of consequence calculations are shown. Five different and supposedly most important scenarios for the external risk picture are identified and calculated for different weather conditions, release hole sizes and durations. Standard duration of a release is 30 minutes, but if safety instrumentation is available to cut off the flow, the duration is reduced to 2 minutes. The figures are the worst-case consequences for each effect type.

4.1 Flammable gas

In the figure below the dispersion for flammable gas to the calculated concentration. The contour seen below is defined by the scenarios including hydrogen calculations. The end point is ½LFL (lower flammability level). The contour shows how far worst-case flammable gas could be expected in an accident.

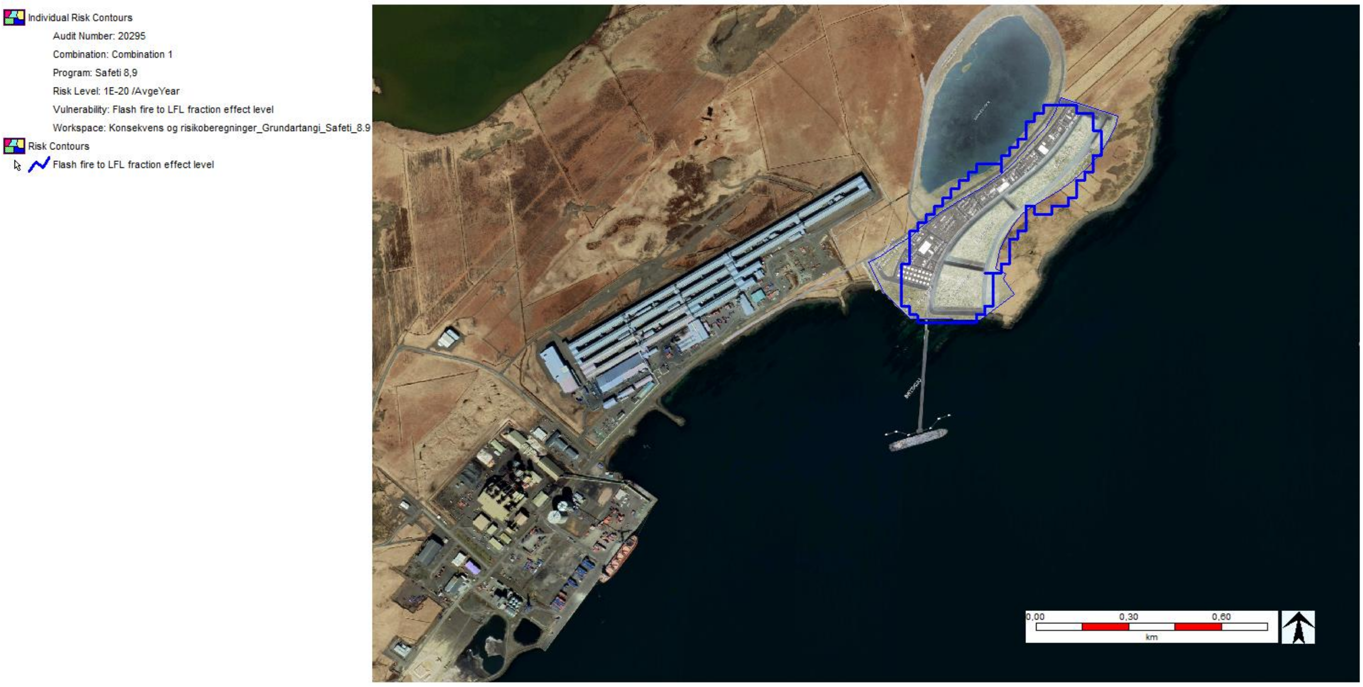

Figure 1 Dispersion of hydrogen to 0.5 LFL for all scenarios

4.2 Heat radiation

In the figure below, the heat radiation from jet fires can be observed from all the scenarios that include hydrogen releases. The end points for the figures shown are 4.7, 15 and 35 kW/m², where 4.7 kW/m² represents the lowest heat radiation level, which could result in serious injuries or even fatalities, while 15 kW/m² represents a radiation level, which could lead to domino effects on other pieces of equipment in a long time exposure, and while 35 kW/m² represent the domino level for short time exposure (<15 minutes).

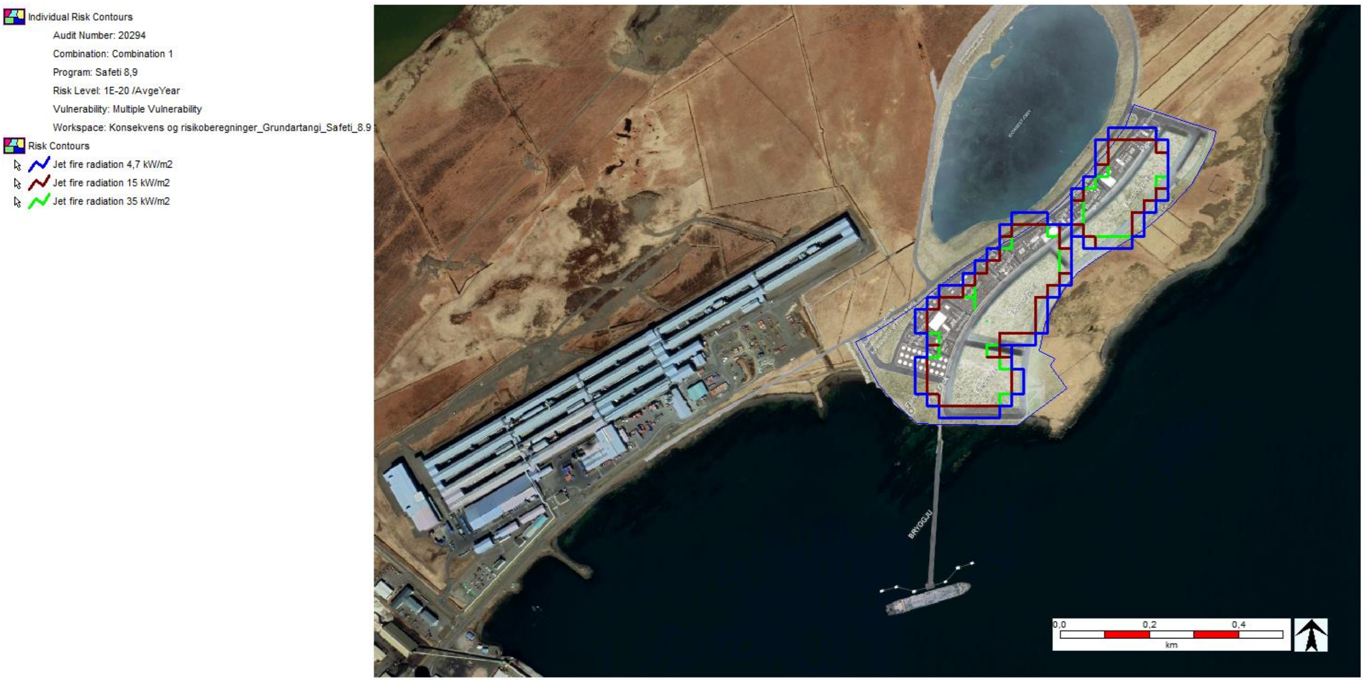

Figure 2 Heat radiation for jet fire for all scenarios
Blue coloured curve: heat radiation effect to 4.7 kW/m²
Dark red coloured curve: heat radiation effect to 15 kW/m²
Light green coloured curve: heat radiation effect to 35 kW/m²

4.3 Explosion overpressure

In the figure below the explosion overpressure can be observed for all the relevant calculations. The contour seen below is defined by the scenarios including hydrogen calculations. The end points are 0.05 bar and 0.2 bar overpressure. The 0.05 bar represents the lowest level, where exposure could lead to serious injuries or even fatality, while the level of 0.2 bar is the lowest level for domino potential.

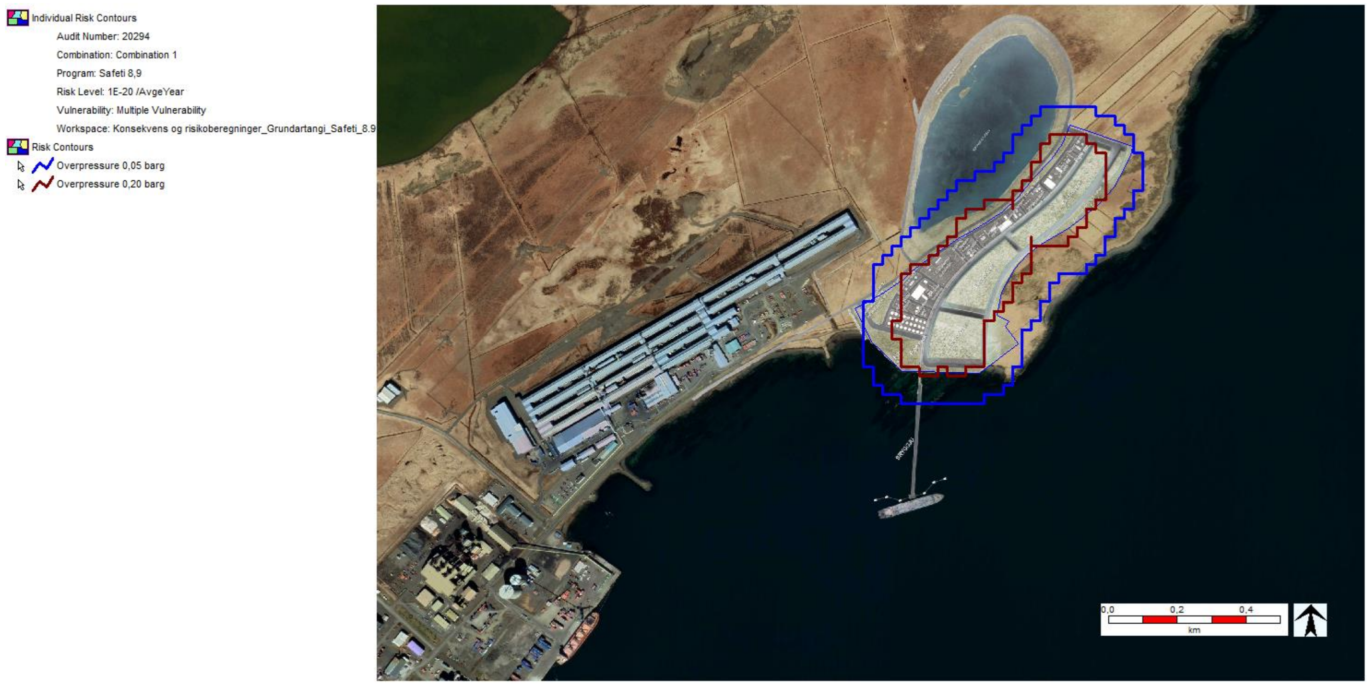

Figure 3 Explosion overpressure for all scenarios
Blue coloured curve: explosion overpressure effect to 0.05 barg
Dark red coloured curve: explosion overpressure effect to 0.20 barg

4.4 Toxic gas

In the figure below the distance that corresponds to a probability of death to 10% is covering all scenarios regarding ammonia. The probability of fatality is under the assumption, that the exposed person will stay at the point throughout the release period and being unprotected by any means, such as personal protection equipment or special clothing. The largest contribution comes from the ammonia release from the ship loading. The circle shown will be worst case at any time. In an actual release case only the part of the curve downwind is relevant.

Figure 4 Dispersion of ammonia for distances corresponding to 10% probability of death

An alternative way to present the worst-case scenario is to show how far a given concentration level can spread. In the figure below a concentration level of 2800 ppm ammonia is shown for different weather situations for the worst-case scenario. The green curve is 1.5F, red curve for 1.5D, the orange 5D and the light green is 10D. What can also be seen is the actual cloud, which is shown for a wind direction from the west. The level of 2800 corresponds to a death probability of 0.1% for a 10-minute exposure according to AEGL values.

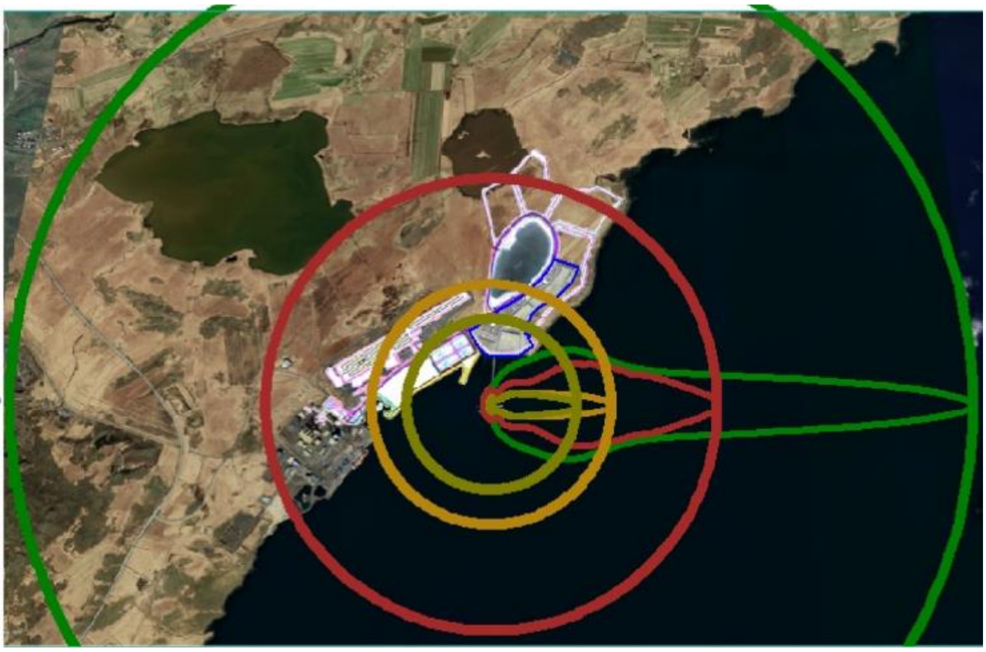

Figure 5 Dispersion of ammonia to a level of 2800 ppm

4.5 Maximum consequence distance

The maximum consequence distance for all consequence effects is defined from the ammonia release scenarios in paragraph 4.4. Therefore, the toxic effect from ammonia is the dominant one.

Figure 6 Maximum consequence distance for all scenarios

5 Risk calculations

5.1 Release frequencies

In the table below data for the scenarios are presented including the used frequencies. The used accidental release frequencies are based upon the Dutch guideline Reference Manual Bevi Risk Assessments, reference /1/ in the report. which is being used by numerous companies and consultants in the EU.

Duration is the assumed duration of the release. The maximum duration is assumed to be 30 minutes, after which the release may be stopped or exposed persons evacuated. This is a standard assumption. If the duration is specified shorter it means the Emergency Shutdown system ESD has stopped the process or the vessel is emptied before reaching 30 minutes.

The basic frequency is the frequency we read directly from tables in the Dutch reference. That may be a release frequency per meter pipe. The frequency is then corrected by the actual length of the pipe in question. In another case it could be the rupture frequency of a vessel. Since there are three identical Haber-Bosch trains, the basic figure is then multiplied by 3 to get the total frequency. The resulting frequency is as mentioned calculated. The assumption column is telling more in details which table figures are taken.

Table 1 Release Scenario Frequencies (ref. /1/)

Section	ID	Scenario	Material	Duration [sec]	Basic frequence per year	Length [m]	Number [-]	Resulted frequency per year	Assumptions/references
1. Pipeline downstream compressor	1.1	Rupture (unrestricted)	Brint	1800	1,00E-07	288	-	3,88E-07	Table 27 (75 mm< d < 150 mm)
	1.2	Leakage (unrestricted)	Brint	1800	5,00E-07	288	-	1,94E-06	Table 27 (75 mm< d < 150 mm)
	1.3	Rupture (restricted)	Brint	120	1,00E-07	288	-	3,84E-05	Table 27 (75 mm< d < 150 mm)
	1.4	Leakage (restricted)	Brint	120	5,00E-07	288	-	1,92E-04	Table 27 (75 mm< d < 150 mm)
2. High pressure separator in Haber Bosch	2.1	Rupture	Ammonia	Instantaneous	5,00E-07	-	3	1,50E-06	Table 13
	2.2	10 min emptying	Ammonia	600	5,00E-07	-	3	1,50E-06	Table 13
	2.3	Leakage	Ammonia	387	1,00E-05	-	3	3,00E-05	Table 13
3. Pipeline from ammonia synthesis to storage tank	3.1 (1)	Rupture (unrestricted)	Ammonia	1800	3,00E-07	199,2		6,98E-07	Table 27 (75mm < d < 150 mm)
	3.2 (1)	Leakage (unrestricted)	Ammonia	1800	2,00E-06	199,2		4,48E-06	Table 27 (75mm < d < 150 mm)
	3.3 (1)	Rupture (restricted)	Ammonia	120	3,00E-07	199,2		6,91E-05	Table 27 (75mm < d < 150 mm)
	3.4 (1)	Leakage (restricted)	Ammonia	120	2,00E-06	199,2		4,44E-04	Table 27 (75mm < d < 150 mm)
3. Pipeline from ammonia synthesis to storage tank	3.1 (2)	Rupture (unrestricted)	Ammonia	1800	3,00E-07	488,4		1,57E-06	Table 27 (75mm < d < 150 mm)
	3.2 (2)	Leakage (unrestricted)	Ammonia	1800	2,00E-06	488,4		1,03E-05	Table 27 (75mm < d < 150 mm)
	3.3 (2)	Rupture (restricted)	Ammonia	120	3,00E-07	488,4		1,55E-04	Table 27 (75mm < d < 150 mm)
	3.4 (2)	Leakage (restricted)	Ammonia	120	2,00E-06	488,4		1,02E-03	Table 27 (75mm < d < 150 mm)
3. Pipeline from ammonia synthesis to storage tank	3.1 (3)	Rupture (unrestricted)	Ammonia	1800	3,00E-07	880,8		2,74E-06	Table 27 (75mm < d < 150 mm)
	3.2 (3)	Leakage (unrestricted)	Ammonia	1800	2,00E-06	880,8		1,81E-05	Table 27 (75mm < d < 150 mm)
	3.3 (3)	Rupture (restricted)	Ammonia	120	3,00E-07	880,8		2,71E-04	Table 27 (75mm < d < 150 mm)
	3.4 (3)	Leakage (restricted)	Ammonia	120	2,00E-06	880,8		1,79E-03	Table 27 (75mm < d < 150 mm)
4. Ammonia storage tank	4.1	Brud	Ammonia	Instantaneous	1,00E-08	-	3	3,00E-08	Table 20
5. Ship loading	5.1	Rupture (unrestricted)	Ammonia	1800	3,00E-08	-	735	2,21E-07	Table 50 (loading arm)
	5.2	Leakage (unrestricted)	Ammonia	1800	3,00E-07	-	735	2,21E-06	Table 50 (loading arm)
	5.3	Rupture (restricted)	Ammonia	120	3,00E-08	-	735	2,18E-05	Table 50 (loading arm)
	5.4	Leakage (restricted)	Ammonia	120	3,00E-07	-	735	2,18E-04	Table 50 (loading arm)

5.2 Weathering

The calculations are carried out for four weather types:

1. wind speed 1.5 m/s, Pasquill stability class F
2. wind speed 1.5 m/s, Pasquill stability class D
3. wind speed 5 m/s, Pasquill stability class D
4. wind speed 10 m/s, Pasquill stability class D

Pasquill stability class F is an unfavorable weather condition with little vertical movement in the air and, accordingly, slow mixing of gas with air. F-weather is relatively rare, and then most often at night, assumed 12% of the time. Stability class D is a typical weather condition, and it results in faster mixing with air.

5.3 Population and traffic

On the west side of the plant there is an aluminium industry. It was assumed that 27 people are always (24 hours per day) present based on the personnel and the operational shifts of the company. On the east side it is assumed, that there will be a future industrial area and the population density assumed is 80 people per hectare, which is a fairly high and conservative value. During daytime hours 100 % will be present, while during night hours 20%. In all cases it was assumed, that out of the present employees 90% will be indoors. Night hours are set at as 60% of the total time, while the rest of the time (40%) is daytime.

5.4 Risk indicators

The main result of this report is the calculation and assessment of risk indicators. The risk indicators used are:

- Maximum consequence distance
- Location-specific individual risk (iso-risk contours)
- Societal risk (FN curves)

Acceptance criteria for the risk parameters are assumed to be in line with general practise within the EU.

5.4.1 Maximum consequence distance

Maximum consequence distance means the maximum distance(s) of accidents determined by a predefined cut-off impact criterion. The criterion will typically be a dangerous exposure in the form of heat radiation or explosion overpressure, corresponding to a probability of death of 1% for a person who is unprotected, outdoors. On the other side of the 1% lethality curve, the fatality risk is considered 0. Next level of effects could be irreversible injuries and discomfort.

In this study the maximum consequence distance is defined as the corresponding distance to a probability of death of 1% due to also toxic affect from ammonia release for the risk calculations.

The presentation of the nominal maximum consequence distance in a figure is though for a probability of death of 10%, which is accepted by authorities in Denmark. This is a little shorter than for a probability of 1%.

5.4.2 Location specific individual risk

The location specific individual risk refers to the fatality risk that a person who is unprotected and constantly in a particular geographical location. The location specific individual risk describes the geographical distribution of the company's risk. It is displayed using iso risk curves that show different predefined risk levels (e.g., 10^{-6} per year), and is independent of whether people or housing are present. Locations specific risk is used to assess whether individuals are exposed to more than an acceptable risk in the places where they may be staying (e.g., where they live or work). It does not in itself provide information about expected loss of life. Nor does it differentiate whether it is employees or the general population, who are exposed.

Location specific risk is considered acceptable if:

- The curve of location specific individual risk of $1 \cdot 10^{-5}$ per year does not exceed the company's area.

- In the area within the curve of location specific individual risk of $1 \cdot 10^{-6}$ per year there must not exist or be planned (in the zoning scheme) sensitive land use in the form of housing or other sensitive land use in the form of offices, shops, institutions, hotels or places where people regularly stay (e.g. railway stations, shopping centres, large car parks and sports facilities).

- Within the maximum consequence distance, there are no institutions that are part of the public emergency response (hospitals, fire and police stations), or institutions with people who are difficult to evacuate, and the acceptance criterion for the societal risk is achieved.

The acceptance criteria used are the same as in Denmark, which are in line with practice within the EU.

Figure 7 Location specific individual risk for Grundartangi Hydrogen

The curve of location specific individual risk of $1{\cdot}10^{-5}$ (purple colour) is well inside the company's fence and the $1{\cdot}10^{-6}$ (red colour) is slightly exceeding the company's fence but not affecting sensitive areas like offices or residencies. Therefore, the location specific risk is assumed to be accepted based on the criteria mentioned.

5.4.3 Societal risk

Societal risk defines the risk of a group of people being exposed to the consequences of an accident. This is expressed as a relation between the expected frequency of the accident and the number of people who could be fatally injured because of the accident. The societal risk is depicted by the so-called FN curve. Here, F is the (cumulative) frequency of accidents with more than N deaths. The result expresses the total expected losses. The calculation of the FN curve includes the probability of a number of accident scenarios, as well as an assessment of how many people may be exposed to the consequences of these scenarios, based on population density, workplaces and location protection (indoor or outdoor /1/). In Denmark, people at the SEVESO establishment are by definition not included in the social risk.

The societal risk, along with acceptance criteria, is depicted as curves in a double-logarithmic plot. As a starting point, acceptance criteria from the Danish Miljøprojekt 112 are used. Plot with acceptance criteria is depicted below.

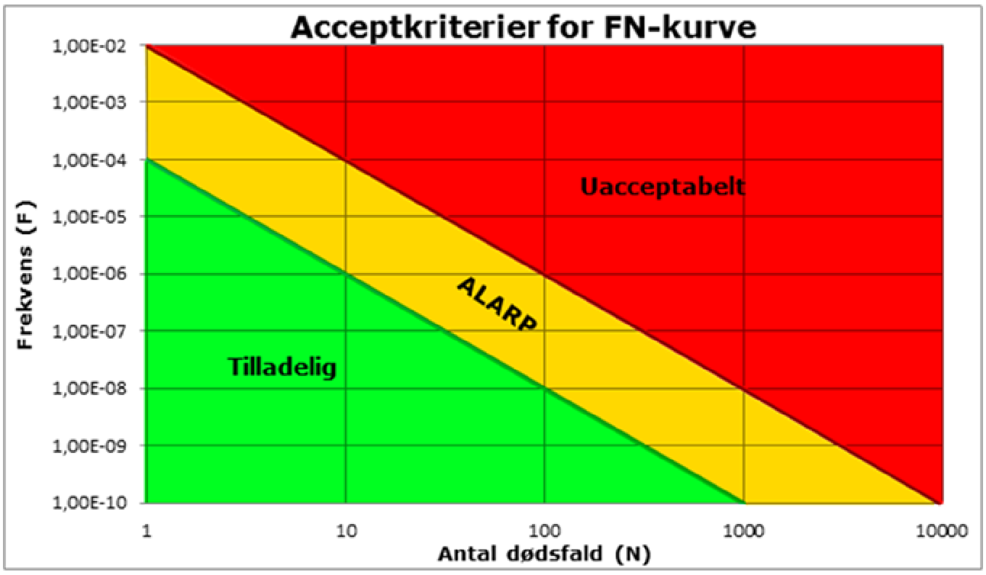

Figure 8 *Acceptance criteria for societal risk according to Miljøprojekt 112 and the Risk Manual.*

The plot for societal risk is divided into three zones: acceptable (green), unacceptable (red) and ALARP (yellow). If the curve of societal risk is completely within the acceptable range, the societal risk is most likely acceptable.

If at any point the curve of social risk reaches into unacceptable territory, it cannot be accepted by the authorities.

The range between acceptable and unacceptable risk is called the "ALARP" area (As Low As Reasonably Practicable). This means that risk must be reduced to a level that is as low as reasonably practicable.

Residences near the facility are a central input for calculating societal risk. Calculation of societal risk therefore requires mapping of the population and activities near the installation. As a starting point, the population should be mapped within maximum consequence distance. In practice, people staying near the periphery of maximum consequence distance is often of little importance for the calculation result.

The calculated societal risk curve for Grundartangi Hydrogen is put in the above acceptance figure format. Included in the calculations are all three phases of the project. The name Combination 1 on the Figure is just a random identification. In fact 4 curves are put in the figure. One figure is a base case including the existing population around the project area (e.g. Century Aluminium) and the planned development area northeast of the project area (area 1, assumed maximum population density 40/ha). The 3 other curves represents different population densities of the landfilling development area 2 to clarify the sensitivity. The populations densities used are either 5, 20 or 40 persons/ha. In all cases also the base case situation is included.

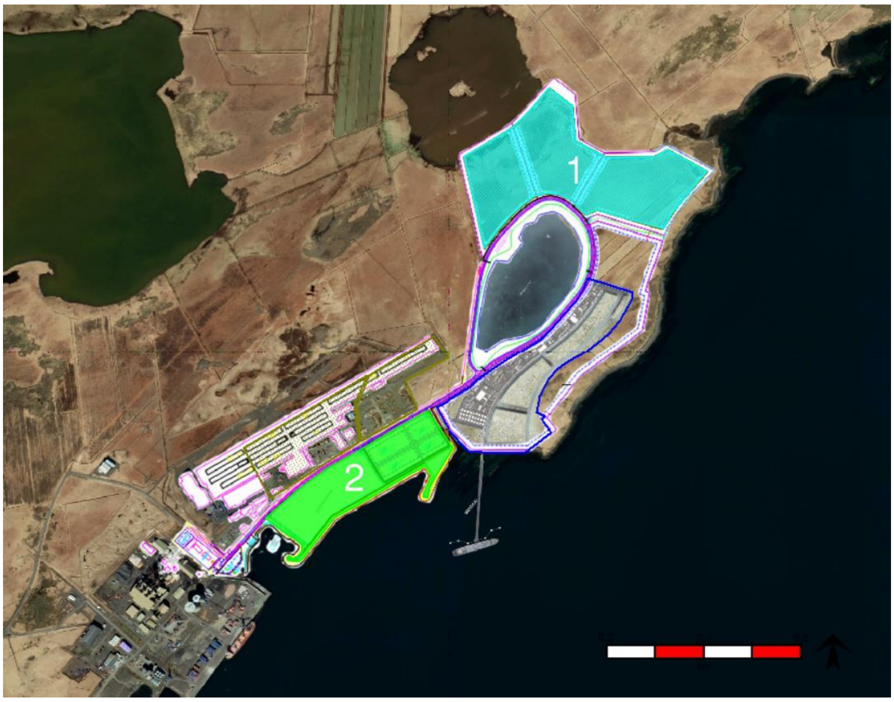

Figure 9 Development areas

For the sensitivity calculations 3 cases were assumed, each one with different population density leading to different number of people being present.

Table 2 Population data for calculations

	Hours	Area [m²]	Population [-]	Presence [-]	Total density [people/m²]
Basis case					
Industry northeast	Day	282921	905	0,8	0,004
Industry northeast	Night	282921	226	0,2	0,004
Sensitivity 1					
Industry northeast	Day	282921	905	0,8	0,004
Industry northeast	Night	282921	226	0,2	0,004
Industry west (low)	Day	148537	59	0,8	0,0005
Industry west (low)	Night	148537	15	0,2	0,0005
Sensitivity 2					
Industry northeast	Day	282921	905	0,8	0,004
Industry northeast	Night	282921	226	0,2	0,004
Industry west (intermediate)	Day	148537	238	0,8	0,002
Industry west (intermediate)	Night	148537	59	0,2	0,002
Sensitivity 3					
Industry northeast	Day	282921	905	0,8	0,004
Industry northeast	Night	282921	226	0,2	0,004
Industry west (medium)	Day	148537	475	0,8	0,004
Industry west (medium)	Night	148537	119	0,2	0,004

In the basis case it was assumed that the land on the northeast of the plant will be occupied from an industry, the nature of which is not known. A population density of 40 people/10000 m² was assumed leading to 1131 people. The distribution between day and night hours was 80% and 20% respectively.

In Sensitivity case 1, together with the population of the basis case, it was assumed that the land on the southwest of the plant will be occupied by industry/industries. In this first case, the population density was assumed 5 people/10000 m² leading to 74 people. The distribution between day and night hours was similar to the basis case.

In Sensitivity case 2, together with the population of the basis case, it was assumed that the land on the southwest of the plant will be occupied by industry/industries. In this second case, the population density was assumed 20 people/10000 m² leading to 297 people. The distribution between day and night hours was similar to above.

In Sensitivity case 3, together with the population of the basis case, it was assumed that the land on the southwest of the plant will be occupied by industry/industries. In this second case, the population density was assumed 40 people/10000 m² leading to 594 people. The distribution between day and night hours was similar to above.

The results for the societal risk for all the cases investigated are presented below.

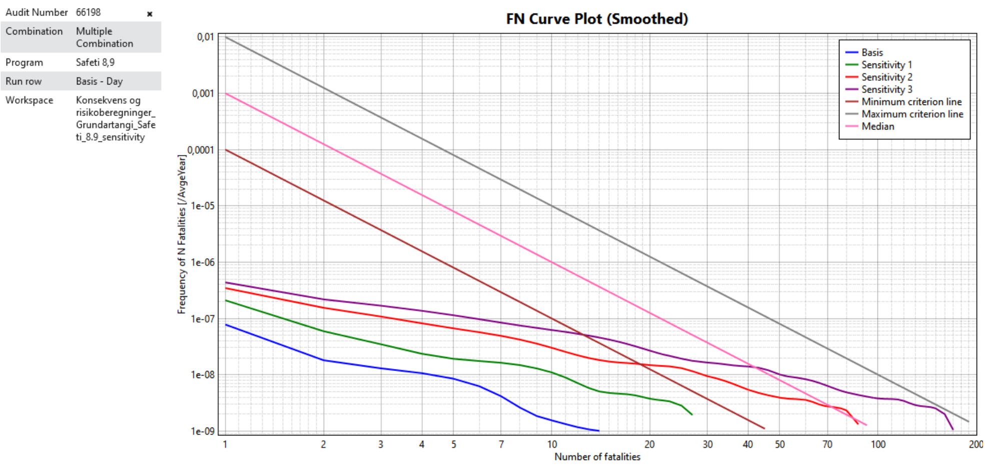

Figure 10 F-N curves for basis and sensitivity cases

The base case (blue colour) is below the minimum criteria, which means that it is immediately acceptable. In this case the maximum number of fatalities is 14 people with a frequency of $1{\cdot}10^{-9}$ per year. The same applies for sensitivity case 1 (green colour), for which the lowest population density was assumed for development area 2. In this case the maximum number of fatalities is 27 people with a frequency of $1{,}92{\cdot}10^{-9}$.

Sensitivity case 2 (red colour) with the intermediate population density falls inside the ALARP region. Here the maximum number of fatalities is 87 people with a frequency of $1{,}31{\cdot}10^{-9}$. Sensitivity case 3 (purple colour) with the highest population density falls just below the maximum criteria level. For this worst case, the maximum number of fatalities is 170 people with a frequency of $1{,}04{\cdot}10^{-9}$.

The societal risk level for the base case (blue) and the sensitivity 1 case (green) are both immediately acceptable. Sensitivity 2 case (red, 297 people on area 2) is touching the median of the acceptance lines and is considered acceptable provided implementation of all reasonable improvements can be demonstrated. The sensitivity 3 case (purple, 594 people on area 2) need more profound risk reduction to be acceptable, but it seems obtainable. Alternatively restrictions on the population density may be required.

6 Domino aspects

6.1 Hydrogen

Hydrogen will have the potential to develop an initiating incident into other escalating incidents, either by the heat flux from a jet fire or from the blast pressure from an explosion (deflagration/detonation)

6.2 Oxygen

Oxygen is vented to safe location, which is to a level above ground, where it could not affect people on the terrain. The exact height has to be determined in a later phase of the design work.

6.3 Ammonia

The hazard from ammonia is the toxic effect by inhalation or its toxic effect on aquatic life. Such an effect is not able to escalate an incident from one starting incident to another one.

6.4 Domino effects with neighbour industries

The consequence distances calculated for hydrogen are not able to create domino incidents in neighbouring companies. Neither are dangerous substances in those companies identified as potential causes of incidents at Grundartangi Hydrogen.

The criteria for domino effects are specified in chapter 4. For explosion pressures, that will be a level of 200 mbar, for heat radiation a level of 15 kW/m2 (long time exposure) and 35 kW/m2 (short time exposure, < 15 minutes). Toxic gas clouds cannot trigger domino effects. The domino distances are documented in the report figures 2 and 3, and the distances are too short to reach the mentioned companies.

7 Conclusion

The performed risk analysis of the Grundartangi Hydrogen Project reveals potential accident scenarios involving dispersion of toxic ammonia gas, heat radiation from hydrogen fires and explosion pressures from hydrogen explosions. All types could affect the surroundings of the project area. The effect distances from hydrogen scenarios are though relatively short with potential of serious injuries to persons in a distance of 50-150 meters from the project area. Distances to less severe injuries will be longer. The longer consequence distances come from ammonia accidents. The distance is presented as the so called LC10% distance for the worst-case scenario, which means a fatality probability of 10% if a person is standing in the gas cloud unprotected throughout the release. The calculated distance for the worst-case scenario is approx. 2 km. The probability of such an incident is though very small, approx. 2.2 x 10^{-7} per year. Distances to less severe injuries will be longer. It should be kept in mind, that the risk from the toxic effect from ammonia will only be relevant downwind, which means that the probability in any direction will be lower than the mentioned.

The consequence distances are acceptable, since there are no emergency institutions (hospital, fire or police station) or institutions with people difficult to evacuate within the curve of the combined maximum consequence distance.

The main risk parameter is the location specific risk, where distances and probabilities are combined. Even if ammonia releases could have long reaching consequence distances downwind, the probabilities are very low, which means that the risk is accordingly low. The location specific risk is considered to be relevant for EIA reporting. It is therefore recommended to include the figure of the location based risk in the EIA report.

The location specific risk is acceptable, since the location specific risk contour of 10^{-5} per year is within the project area itself and do not reach neighbour areas and the contour of 10^{-6} per year do not reach residential areas.

The second important risk parameter is the societal risk, where location based risk and population is combined. The population involved is from neighbour activities excluding people within the project area itself. Neighbour activities should include both existing (e.g. Century Aluminium) and planned activities. There are two development areas, one northeast of the project area and one landfilling project area southwest of the project area. The population density in the development area to the northeast is set at a level of 40 ha, which according to Dutch guidelines are covering medium industry area density. This density corresponds to totally 1131 persons. The population density on the land filling areas are more difficult to set, and sensitivity calculations have been performed with densities of 5, 20 and 40 respectively.

The societal risk is considered acceptable for existing population and development area 1 northeast of the project area. If the landfilling area

2 is included, there may be need of risk reduction, if the population density for that area is exceeding approx. 20 persons/ha. Risk reduction may be obtained by either risk reduction projects at Grundartangi Hydrogen, which is considered realistic) or by restrictions on the population density of the development area 2.

Potential domino effects between Grundartangi Hydrogen and neighbour companies have not been identified.

The risk of domino effects are acceptable. Domino effects from Grundartangi Hydrogen will not be possible according to the calculations done, and it seems unlikely, that potential domino effects on Grundartangi Hydrogen from the new development areas should show up. If so, that has to be regulated then by those projects.

The domino risk is acceptable.

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