Concept Risk Assessment of a Hydrogen driven High Speed Passenger Ferry

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Abstract

A concept risk assessment of a hydrogen and fuel cell driven high speed passenger ferry has been performed. The study focused on fatality risk related to the hydrogen systems on the vessel, both during operation and while moored in harbour overnight. The main objective with the study was to evaluate whether the risk related to the hydrogen systems is equivalent to that of conventionally fuelled vessels and can be considered acceptable according to the requirements of the IGF-code (International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels). Since hydrogen behaves differently than other flammable gases, some adjustments to existing models and vulnerability criteria have been proposed. The conclusion of the study is that the estimated risk related to hydrogen systems is relatively low, and much lower than the expected acceptable risk tolerance level of 0.5-1.0 fatalities per 10^9 passenger km. Furthermore, for the overnight mooring in harbour the estimated risks are well within acceptable limits. The work presented is part of a maritime case study performed within MoZEES, a Norwegian research centre for environmentally friendly technology and zero emission transport.

Keywords

Risk assessment, safety, high speed passenger ferry, hydrogen, PEM fuel cell

1 Introduction

According to the United Nations Development Programme greenhouse gas (GHG) emissions continue to rise and are now more than 50 % higher than their 1990 level. The UNFCCC Paris Agreement of 2016 has defined ambitious and challenging national targets for GHG emission cuts to limit contributions to climate change from man-made activities. In Norway, the largest source of GHG emissions is the transport sector [1].

In April this year the International Maritime Organization (IMO) adopted a new strategy on reduction of GHG emissions from ships [2]. For the first time IMO envisage a reduction in total GHG emissions from international shipping, which should peak as soon as possible, and to reduce annual GHG emissions by at least 50 % by 2050, while at the same time pursuing efforts towards phasing them out entirely.

There is also an urgent need to reduce local emissions. This has resulted in a decision by the Norwegian Parliament to implement regulations to reduce emissions from cruise ships and other ships trafficking tourist fjords, and the decision to implement a requirement for zero emission cruise ships and ferries in the world heritage fjords as soon as technically possible, and at latest within 2026.

Zero emission propulsion using batteries that are fast-charged during docking is a good and cost-effective solution wherever the crossing time is short, electrical power is available at the docking sites, and the ship design is not very weight sensitive. However, most ships do not fit into this category.

Another zero-emission alternative is proton exchange membrane fuel cells (PEMFC), fuelled by hydrogen produced via electrolysis from renewable electricity. A 250-350 bar hydrogen storage tank is about five times lighter than a maritime battery system. This results in longer range or lower ship weight, which makes it an alternative for a wider range of applications. However, hydrogen technology also has challenges, mainly fuel cell system cost and cost of hydrogen fuel and refuelling infrastructure. In addition, the use of hydrogen as fuel may require a completely different ship design to fulfil safety requirements.

Today's PEMFC systems are an expensive solution, at costs of 3000 $/kW or even higher. However, it's projected that production costs will rapidly fall with increased annual production rate [3]. This means that fuel cell system cost reduction is now depending mainly on mass production benefits, and not technological development. Even at less than 10000 units of 80 kW per year, keeping in mind that a ship will have hundreds of kW, or even MW, of installed power production, the PEMFC may have lower life cycle cost than diesel engines for selected applications.

To achieve profitability in the hydrogen production and refuelling infrastructure it is essential to ensure a certain scale, high utilization and regular sales over its depreciation period. With regular sales around 500 to 1000 kg/day hydrogen from electrolysis may be cost competitive with bio-diesel [4].

The case study presented in this paper was based on a concept design for the high-speed light craft (HSLC) illustrated in Figure 1.1 [5]. The ship is a medium sized passenger ferry with a capacity of 100 passengers, has a light weight carbon fibre hull, rated speed of 28 knots, hydrogen storage capacity of 450 kg, and installed propulsion power of 1.2 MW. The reference route goes from Florø in the Western part of Norway and has a distance of 113 nautical miles per day, which yields a hydrogen consumption of about 380 kg per day.

Figure 1.1 – Illustration of GKP7H2 hydrogen fast passenger ferry and planned daily routes [5]

High-speed light weight passenger ferries are applications where there is a great potential for hydrogen and fuel cells to compete commercially with diesel and internal combustion engines. The following elements work in favour of zero emission hydrogen solutions:

- High speed light craft (HSLC) is one of the least energy-efficient modes of transport, and the emissions per passenger per travelled distance are very high. At the same time HSLCs are an essential part of an efficient public transport system along the Western Norwegian coast
- HSLCs normally operate on fixed daily routes with only one point of refuelling, which minimizes the need for new hydrogen refuelling infrastructure
- HSLCs have high energy demands, which can be met by cost-efficient hydrogen supply options (>400 kg H2 per day); the hydrogen consumption by one single HSLC is sufficient to ensure a large and predictable demand
- In Norway the operation of HSLCs are normally regulated by public tenders with a contract period of up to 10 years, which gives a predictable income for the fuel cell ferry operator and hydrogen supplier
- HSLCs normally have at least one stop near a city or a densely populated area. If the hydrogen production and refuelling infrastructure is established in such areas it is possible to also supply other smaller consumers, such as passenger cars, taxis, buses, trucks, forklifts, and small fishing vessels, which eventually could lead to a sustainable local hydrogen economy

However, before a business case for hydrogen driven HSLCs can be made, the risk and safety of a concept ship design should be assessed. Risk assessments for other transport applications such as light duty vehicles [6], buses in tunnels [7] or hydrogen refuelling stations [8] have been performed in the past. The methodologies have similarities, but for a ship the installed hydrogen equipment and number of passengers may be orders of magnitude larger, and the assessments will be different. Today there does not exist any dedicated rules and regulations for the use of hydrogen and fuel cells on ships, nor does there exist a standard risk assessment methodology for the use of hydrogen and fuel cells in maritime transport applications. This is the main motivation for this study.

2 Risk assessment

A detailed concept risk assessment was performed by Lloyd's Register Risk Management Consulting [5]. A summary of this study is provided below.

2.1 Methodology - Risk assessment approach

The methodology and key elements for the risk assessment approach taken in this study are shown in Figure 2.1. The risks associated with the concept hydrogen system ship design where identified in a preliminary hazard identification (pre-HAZID) workshop with all the stakeholders, including a ship builder, ferry operator, and key hydrogen technology suppliers.

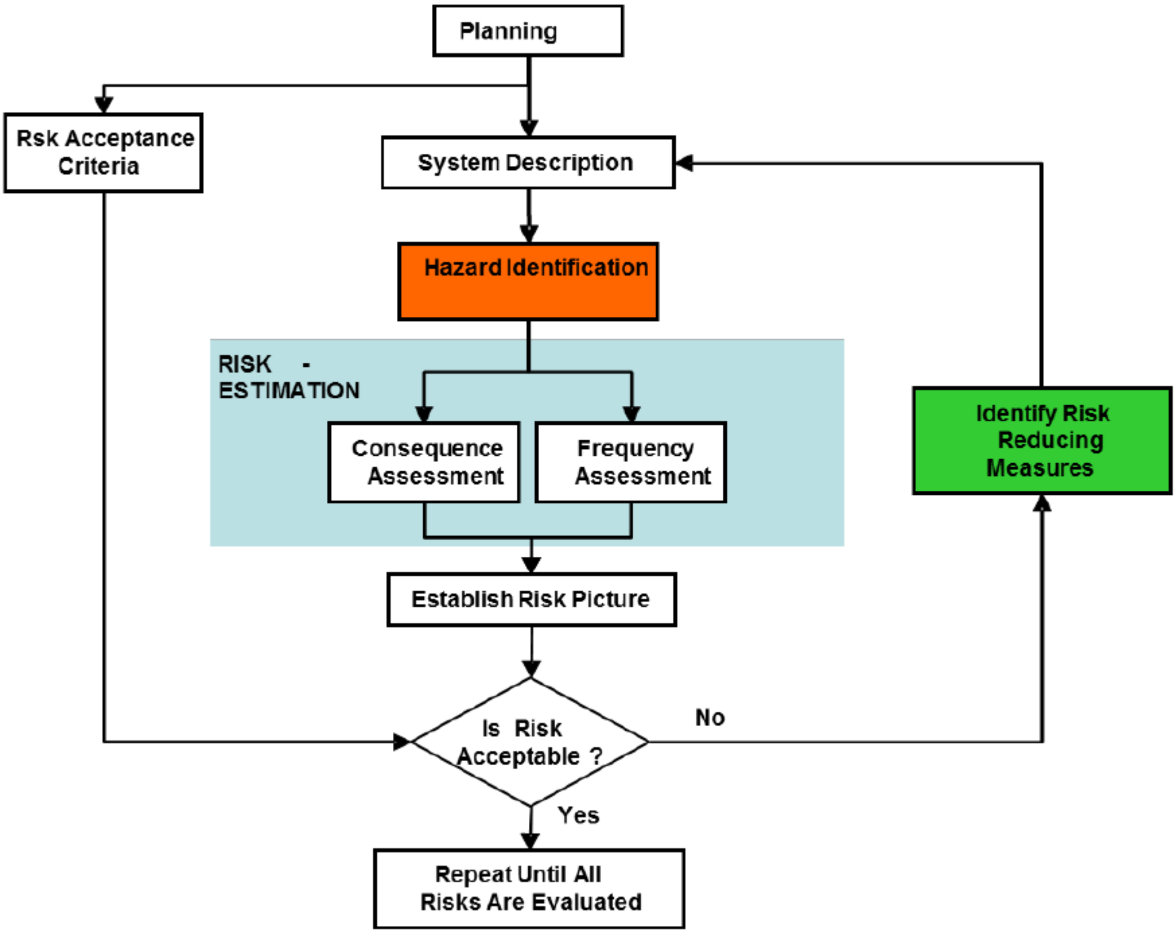

Figure 2.1 – Schematic overview of assessment approach

2.2 System description

Since this is still a concept vessel there are some uncertainties regarding the system design parameters. Hence, several assumptions on the design of the hydrogen systems needed to be made, as described below.

2.2.1 Storage system

The storage system consists of three 8300 litre Type IV composite tanks rated at 250 bar with a total hydrogen capacity of 450 kg. The tanks are connected to the tank connection spaces and to the vent mast by emergency valves.

2.2.2 High pressure piping

The high-pressure piping comprises the tank connection spaces, piping from storage tanks to pressure reduction valves, bunkering connection and valves to vent mast. A number of valves, filters and joints/connections are assumed. After bunkering the pressure is at 250 bar, typically decreasing to 50 bar during the daily cycle. Pipes are assumed to have 12mm inner diameter. When connected to tanks, the inventory is very large (up to 450 kg), while after ESD valves have closed the size of segments will be marginal and a release would be quickly stopped.

2.2.3 Low pressure piping

Low pressure distribution piping at 10 bar(a) includes two fuel lines with piping from pressure reduction valves to fuel cells, including emergency valves to vent stack. A certain number of valves and joints/connections are assumed included and pipes are assumed to have 12mm inner diameter. The expected hydrogen flow rate is 13.3 g/s in each fuel line.

2.2.4 Fuel cell units

There are 16 identical fuel cell units, each with power rating 50-100 kW, each contained in a volume of 0.75m x 0.75m x 0.52m, and each with hydrogen consumption of approximately 1.67 g/s. Pipes into the fuel cells units have 10 bar(a) pressure and assumed inner diameter of 5mm. No details of the pipes, valves and instruments inside the fuel cell unit have been available.

2.2.5 Vent mast

The vent mast enables controlled release of hydrogen in an emergency or error situation where there is a need to empty the hydrogen tanks. The vent mast should be dimensioned with capacity to evacuate the storage tanks effectively in case of a fire that may threaten their integrity. It is important to ensure that such a controlled release will not lead to risk for injuries or fatalities. It was assumed that the vent mast is dimensioned to accommodate a maximum release rate of 400-800 g/s. An inner diameter of 150-200 mm was assumed to limit the velocity of the flow out of the vent mast.

2.3 Rules and regulations

2.3.1 IGF-code - Alternative design approach

For hydrogen fuel cell vessels no dedicated class rules exist. Hence, the alternative design approach described in the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF-code) [9] must be applied. Passenger safety is an important aspect of the IGF code requirements which are enforced by the Norwegian Maritime Authority (NMA). The main IGF-code requirements are:

- Safety of the fuel systems must be equivalent to that achieved with new and comparable conventional oil-fuelled main and auxiliary machinery
- A risk assessment must be performed to assess risks arising from the alternative design
- An explosion assessment must be performed
- Consequences from one event shall remain local and not escalate to other parts of the vessel or threaten ship stability

The term "equivalent to new and comparable" is not very precise. In the period 1970-1994, The Institute of Transport Economics (TØI) estimated an average 0.6 fatalities per 10^9 passenger km with ferries and fast passenger boats along the Norwegian coast, Ref. [10]. In 2002 there was a requirement that a vessel utilizing new technologies should demonstrate a safety level not more than 1.0 fatality higher per 10^9 passenger km compared to a vessel with the safest conventional fuel technology for the same route. Assuming that other aspects than type of fuel may be important for, or dominate, the passenger risk, the additional passenger risk from the non-conventional (hydrogen) systems should then not exceed 1.0 fatality per 10^9 passenger km. For the vessel concept analysed in this case study that is operating 30h per week a fatality risk level of 1.0 per 10^9 passenger km would correspond to an individual fatality risk per annum (IRPA) of ~$7x10^{-5}$ for a person being at the ferry all the time when in operation, and an IRPA of $4x10^{-4}$ if being on a boat in operation 24/7. As the general tolerance for accidents in the society has decreased and safety levels have improved over the past 15-50 years, this type of risk acceptance criterion would likely be set somewhat stricter today.

2.3.2 DSB consultation distances

It may also be recommended to convince the relevant port authorities that risks related to the vessel when moored in harbour are limited and acceptable. Fuel onboard a vessel for its own propulsion should normally be expected to be sufficiently safe so that there would be no concerns regarding where the vehicle or vessel is located when not in operation. For hydrogen, being a fuel for which there is limited experience in society, it could be relevant to evaluate DSB (Directorate for Civil Protection) requirements [11] regarding area planning and exclusion zones against the potential risk contribution from a vessel spending e.g. 16-18h a day in harbour. These regulations apply for stationary facilities with flammable materials stored and are meant to protect the general population against major hazards. The following zones shall be established around a facility handling hazardous materials:

- Inner consultation zone (IRPA>10^{-5}) - Mostly within an area controlled by the activity itself, but could also include public areas where people are temporarily passing by
- Middle consultation zone (IRPA>10^{-6}) - Area surrounding the inner consultation zone where other activities are allowed; area includes office buildings, industry, public transportation quays, rail stations etc.
- Outer consultation zone (IRPA > 10^{-7}) - Homes and shops are allowed
- Beyond outer zone (IRPA < 10^{-7}) - Hotels, hospitals, schools and other vulnerable operations are allowed

For the vessel in this case study this type of evaluation is not required (except potentially related to the bunkering assessment), still evaluations could be of value and possibly relevant on the location where the ferry is moored in-between trips, in particular overnight. On other destinations the time spent in harbour will be very short, so that the risk contribution per year will be marginal.

2.3.3 Hydrogen bunkering

The bunkering of hydrogen was not included in the scope of work for this risk assessment and is left for future work. Nevertheless, it can be mentioned that the safety related to hydrogen bunkering should follow the principles of ISO 20519:2017 for LNG-bunkering [12]. This standard requires an inner safety zone to be established as well as a monitoring and security area. In addition, the hazardous area zones and DSB consultation zones (if risk based approach is used) shall be established for the hydrogen bunkering location. The bunkering in this study is assumed to take place at a separate location with no passengers present and should therefore not need to be included in the IGF risk evaluations.

2.3.4 Hazardous area classification

A hazardous area zoning must be performed according to the IEC 60079-10-1:2015 standard [13]. In these evaluations the properties of hydrogen must be considered, in particular the strong buoyancy of gaseous hydrogen. Here it is important to follow the wording of the standard, rather than the simplified prescriptive version in IGF-code and class rules. Otherwise, the defined zones may become too extensive and give unnecessary limitations to operation.

2.4 Hydrogen release frequencies

2.4.1 Leak frequencies

Data on leak frequencies from the hydrogen systems was taken from the Sandia National laboratories HyRAM-manual [14]. This data is based on experience from the oil and gas (O&G) industry, with some adaptations to hydrogen. The hydrogen equipment leak frequencies proposed by Sandia were similar to the release statistics from the North Sea O&G industry (ref. leak frequency models from SHLFM [15] and PLOFAM [16]), except for filters where there was a major deviation. The filter leak frequencies used in this study were therefore reduced by a factor of 25.

2.4.2 Catastrophic rupture frequency

The predication of catastrophic rupture of hydrogen storage cylinders where calculated with failure frequencies by LaChance et al. [17].

The annual tank catastrophic rupture frequency is of the same order as recommended in the TNO Purple Book for stationary pressurized storage cylinders [18], which recommends a catastrophic failure rate of 10-6/y "applicable to static, vibration free, pressure vessels operating under conditions of no corrosion (external or internal) and thermal cycling, i.e. typical storage pressure vessels". For process vessels and reactor vessels, with assumed more challenging operational modes, a frequency 10 times higher is proposed. While recognizing that safety level for hydrogen equipment is generally to a higher standard than average in industry, the special character of hydrogen with very high pressures combined with small molecules aggressively weakening many materials, and not least the challenging marine environment and motion of the vessel should justify the proposed frequencies for tank rupture.

2.5 Ignition probability model

Ref. [19] concludes that ignition probabilities are comparable for methane and hydrogen for concentrations below 10%. However, it has been shown that there is a difference in ignition energy for these two gases [20]. Only for concentrations around 6% in air minimum ignition energy seems to be comparable, while for higher concentrations the ignition energy for hydrogen is lower.

In some previous studies it has been assumed that hydrogen and methane with identical molar release rates will give same size of flammable cloud [19]. This is not in line with observations or model predictions made by Lloyd's Register, which predicts around 10 times larger flammable plume volume. In Ref. [21] where hydrogen and methane jets are compared the flammable length is 3 to 3.5 times longer with hydrogen. Assuming similar diameter/length relation this gives a 30-40 times larger volume for similar mass flow rate (7-9 times for similar molar flow rate, similar to the Lloyd's Register model predictions). Thus [19] may be non-conservative on this point.

The HyRAM manual [14] proposes ignition probabilities for hydrogen releases as recommended in [19]. A step function with 3 levels is used as illustrated in Figure 2.2. The relation only depends on the initial release rate and does not consider gas accumulation by confinement or extensive congestion. It could be assumed that ignition probability will increase if the gas is trapped at a flammable concentration inside confinement or congestion, both because the ignitable volume may become larger with slower removal of gas, and because the flammable cloud will remain in place longer. Another factor is that the cloud will be less turbulent so that less ignition energy will be required.

Based on the above Hansen [5] proposed an alternative ignition model:

1) OGP-ignition probabilities for methane inside oil platforms (Table 21) [22] for moderate release rates are increased by a factor of 3 for comparable flammable cloud sizes (at H_2 flow rates < 125 g/s)
2) Release rate reduction by a factor 40 will give comparable flammable cloud sizes. I.e. the flammable volume of a 25 g/s hydrogen release is comparable to that of a 1 kg/s methane release
3) A continuous model is used giving 3 times higher ignition probability per cloud size for releases less than 125 g/s, 30% ignition probability for a 1.25 kg/s release, and 100% probability for ignition for releases above 12.5 kg/s

   $P_{ign\_hydrogen\_jets}$ = Minimum (1.0; 0.55 x rate$^{0.87}$; 0.267 x rate$^{0.52}$)

4) 2/3rd of the ignition probability is assumed to be immediate (same as HyRAM), but immediate is interpreted to be within 1 second. For high release rates this may lead to generation of explosion overpressure. 1/3rd of the ignition probability is assumed delayed to a steady-state worst-case cloud size for free jet releases. For releases in enclosed volumes the delayed ignition probability per second is proposed distributed with a halftime of 60 seconds using the following relation:

   $P_{ign\_delayed}$ (t) = P_{delay}(vol) x ($e^{(1-t)/60} - e^{-t/60}$) with

   P_{delay}(vol) = 0.00384 x vol(t)$^{2/3}$

   with vol(t) being the flammable volume (m^3) at time t (second)

In Figure 2.2 the proposed ignition probability is compared to the step model currently applied in the HyRAM-tool. The proposed model is under development and future adjustments are likely.

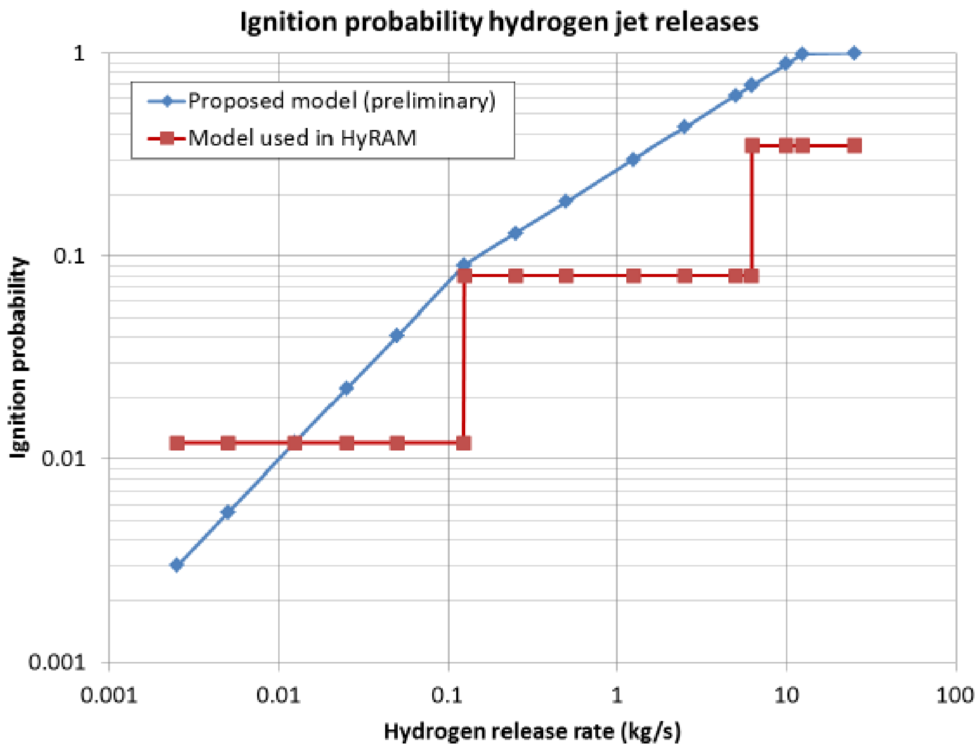

Figure 2.2 – Proposed ignition probability for hydrogen jet releases, compared to HyRAM model proposed in [19]

2.6 Vulnerability thresholds

The proposed vulnerability thresholds used in this study were based on the OGP 434 risk assessment directory [22]. Due to the special properties of hydrogen some important adjustments are proposed:

1) Hydrogen emits about half the radiation compared to methane for the same combustion energy and has around 1/4th of the combustion energy at the lower flammable limit (LFL). At concentrations < 8% any flames will only propagate upwards (not sideways or downwards), so the risk for a person inside a 4-8% hydrogen plume to be burned or exposed to high radiation levels should be very low. It is therefore proposed to adjust the fatality criterion for flashfires to concentrations above 8% hydrogen (i.e. downward combustion flammability limit). This is still considered a conservative assumption.
2) A 10% fatality risk from projectiles is proposed for regions with overpressure above 0.20 bar
3) To simplify the radiation dose calculations, and considering that people will often manage to move away from localized radiation exposure, the jet-fire fatality criterion for short exposure time (35 kW/m^2) was assumed
4) Hydrogen explosion loads, in particular hydrogen pressure vessel burst scenarios, will typically have a significantly shorter duration (pressure impulse) than the explosion loads considered when developing pressure fatality criteria. For this reason, an impulse criterion is proposed so that the explosion loads must exceed a pressure criterion $P>P_c$ and an impulse criterion $I_c > P_c \times \Delta t$ with Δt=10ms. This impulse criterion is still well within the TNO Green book pressure/impulse 50% fatality probability [23].

2.7 Consequence modelling

The hydrogen risk assessments made in this study was performed using a suite of worksheet based consequence models developed by Lloyd's Register. The models for LFL-distance and jet-fire radiation (function of pressure and hole size) are consistent with tabulated values from NFPA-2 [24]. Models for flammable cloud volumes, explosions pressures (deflagration, detonation and vessel burst) were also included. For the explosion energy estimated equivalent Q9 and Q8 volumes are used for deflagration and detonation energies [25]. The consequence models in the worksheet have some limitations, particularly if the presence of geometry (congestion/confinement) is important. Then more accurate CFD-calculations are applied to calculate dispersion [26, 27] and to predict pressures from deflagration, vessel burst and detonation [28].

3 Calculation

3.1 Scenario selection and frequency assessment

3.1.1 Storage system

The expected frequency for loss of hydrogen containment for various hole sizes were taken from literature [14] resulting in the scenarios shown in Table 3.1. The assumed frequency for the catastrophic failure of one of the three tanks is of the order 1 per million years. It was assumed that tank failures will not occur simultaneously in several tanks, thus each event is related to failure of one tank only. The scenarios considered in this study are marked with “X” in Table 3.1.

Table 3.1 – Scenarios related to storage tanks, frequencies shown are total for the system of 3 tanks

Storage tanks		P	V	Dia	Hole size distribution (% of cross-section)					
	#	bar	m^3	mm	0.01%	0.1%	1%	10%	100%	Total
Frequency / year	**3**	**250**	**8.3**	**1000**	**3.54E-6**	**2.99E-6**	**2.04E-6**	**1.17E-6**	**6.27E-7**	**1.04E-5**
Leak rate	Indicative			kg/s	**1.0**	**10**	**100**	**1000**	**6000**	
Duration	Half-time			s	**150**	**15**	**1.5**	**0.15**	**0.025**	
Vessel burst	Shockwave effects				N/A	N/A	(X)	X	X	
Jet/flash fire	Incl. vessel burst radiation				X	X	X	X	X	
Explosion	Incl. vessel burst combustion				X	X	X	X	X	

The failure mode of composite tanks was discussed during the pre-HAZID workshop, where it was argued that no catastrophic failures had been observed during extensive testing of 250 bar tanks (bonfire and impact/projectiles). The authors of this work do not have sufficient insight to evaluate whether the tests performed can conclusively rule out catastrophic failures. For CNG-tanks on buses there have been incidents with catastrophic tank rupture both due to impact [29] and impinging jet fire [30]. Even if CNG tanks may be significantly weaker than hydrogen tanks it is hard to rule out the possibility of a catastrophic tank rupture scenario. These scenarios are therefore kept in this assessment.

3.1.2 High pressure piping

The high-pressure piping release rates are conservatively based on maximum nominal system pressure. When connected to tanks, the hydrogen inventory is up to 450 kg, while after ESD valves closing there will only be 2 g H_2 for each meter of pipe, and the release is quickly stopped. Any leak will therefore continue until it is successfully detected and isolated. Since the details on the automatic shut-down systems were unknown, conservative values for leak durations were assumed. The resulting scenarios with assumed frequencies are summarized in Table 3.2.

Table 3.2 – Scenarios related to high pressure piping systems

HP Systems		P	V	Dia	Hole size distribution (% of cross-section)					
	#	bar	m^3	mm	0.01%	0.1%	1%	10%	100%	Total
Valves	16	250	-	12	9.14E-2	1.20E-2	1.59E-3	6.61E-4	2.38E-4	**1.06E-1**
Joints	50	250	-	12	3.53E-3	1.78E-4	3.90E-4	3.48E-4	3.11E-4	**4.75E-3**
Filters	5	250	-	12	7.54E-3	3.20E-3	2.88E-3	1.37E-3	1.35E-3	**1.63E-2**
Pipes	10	250	-	12	8.78E-5	4.57E-5	1.80E-5	9.12E-6	6.43E-6	**1.67E-4**

Frequency / year	total	250	-	12	1.03E-1	1.54E-2	4.88E-3	2.39E-3	1.91E-3	1.27E-1
Leak rate				g/s	0.15	1.5	14.8	148	920	
Duration	Half-time (s)				Until detection and isolation			1000	160	
Vessel burst					N/A	N/A	N/A	N/A	N/A	
Jet/flash fire					X	X	X	X	X	
Explosion					X	X	X	X	X	

3.1.3 Low pressure piping

The release frequencies for the low-pressure piping were estimated similarly to the high-pressure systems and are of the same order of magnitude. Due to ~25 times lower release rates (maximum 36 g/s) consequences would be of much less concern. Details are can be found in [5].

3.1.4 Fuel cell units

Since no details of the inside of the fuel cell unit were available, two "instruments" were assumed when estimating leak frequencies. In addition, there are leaks expected from the fuel cell stack which is accounted for by doubling the leak frequencies inside unit. The total estimated scenario frequency for leaks inside the FC-systems is of the order 0.5 per year, with maximum leak rate of 6.2 g/s. Primarily explosion scenarios (inside FC compartments) are considered relevant for safety of people, fire scenarios will be confined inside the units and should not put people at the vessel at risk. If a strong explosion tears open a fuel cell unit, there is a possibility for a jet flame. Details on the scenario assessment can be found in [5].

3.1.5 Vent mast

Since all segments except the tanks have very low hydrogen inventory, the situation of main concern is where the tanks must be emptied due to a detected fire threatening the tanks. Whether there are other situations requiring tanks to be emptied to vent mast is not clear. The scenarios to be considered are jet fire and explosion resulting if the vented hydrogen is ignited during venting.

The frequency of intended releases is difficult to estimate since it may not only be activated in emergency situations, but potentially also by error. Since it is assumed that by design an activation of the vent mast should not lead to risk for injuries or fatalities (i.e. the consequence is insignificant), there is no need to estimate this frequency.

3.2 Consequence assessment

In this section a consequence assessment is carried out for the scenarios described in Section 3.1. Outdoor scenarios giving consequences (hazard distance for potential fatality) less than 1m are not considered. This includes hydrogen leak rates below 2 g/s.

3.2.1 Storage system

In Table 3.3 the results from a screening consequence assessment can be found for the storage system scenarios. For each release rate estimated fatality distances are listed.

Table 3.3 – Scenarios related to storage tanks – estimated fatality distances

Storage tanks		Hole size distribution (% of cross-section)					
	Criteria (fatality rate)	0.01%	0.1%	1%	10%	100%	Total

Leak rate	Indicative		kg/s	**1.0**	**10**	**100**	**1000**	**>>1000**	
Duration	Half-time		s	**150**	**15**	**1.5**	**0.15**	**0.025**	
Frequency / year	**250 bar**	**8.3m^3**	**1.0m**	**3.54E-6**	**2.99E-6**	**2.04E-6**	**1.17E-6**	**6.27E-7**	**1.04E-5**
Vessel burst	0.50 bar (50%)			N/A	N/A	23 m (12.5m)#			
Vessel burst	0.35 bar (15%)			N/A	N/A	29 m (18m)#			
Vessel burst	0.20 bar (10%)			N/A	N/A	40 m (36m)#			
Delayed ignition probability				0.089	0.29	0.33	0.33	0.33	0.24
Explosion frequency / year ¤				**3.15E-7**	**8.82E-7**	**6.80E-7**	**3.90E-7**	**2.09E-7**	**2.48E-6**
Explosion	0.50 bar (50%)			6 m	21 m	21 m	21 m	21 m	
Explosion	0.35 bar (15%)			8.3 m	25 m	25 m	25 m	25 m	
Explosion	0.20 bar (10%)			10.8 m	37 m	37 m	37 m	37 m	
Immediate ignition probability				0.18	0.59	0.67	0.67	0.67	0.48
Early explosion frequency / year (1s) ¤				**6.30E-7**	**1.76E-6**	**1.36E-6**	**7.80E-7**	**4.18E-7**	**4.95E-6**
Early explosion	0.50 bar (50%)			3.9 m	8.5 m	18.5 m	21 m	21 m	
Early explosion	0.35 bar (15%)			4.6 m	9.9 m	22 m	25 m	25 m	
Early explosion	0.20 bar (10%)			6.8 m	14 m	32 m	37 m	37 m	
Total ignition probability				0.27	0.88	1.00	1.00	1.00	0.72
Fire frequency / year				**9.45E-7**	**2.65E-6**	**2.04E-6**	**1.17E-6**	**6.27E-7**	**7.43E-6**
Jet/flash fire 8%	35 kW along (100%)			16 m	57 m	Less hazard than blast			
Jet fire	35 kW radial (100%)			5 m	21 m	Less hazard than blast			

¤ Early explosion and delayed explosions are assumed to be deflagrations, but could potentially be detonations for the more severe scenarios. If so, the explosion hazard distances may be 2.7 times longer.

 # Distance in bracket corresponds to impulse criterion (0.01s x pressure criterion). For the deflagrations/detonations the energy will be higher and impact of impulse criterion lower.

For a well-defined gas cloud or gas release scenario blast pressures from deflagrations, DDT and detonations can be modelled, e.g. using the FLACS CFD model [28]. Still it is challenging to estimate the explosion pressure from a deflagration or detonation that can occur as a result of a hydrogen tank burst, since the cloud shape and concentration distribution will depend on the failure mode of the tank and how well the hydrogen has mixed with air at the moment of ignition. The worst-case tank burst scenario is 150 kg hydrogen at 250 bar. Predictions from the LR hydrogen safety screening tool (Figure 3.1) show that >100 mbar pressures could be feared at 50m distance, however, the duration of the blast wave is short and the impulse is limited. A CFD simulation (Figure 3.2) modelling blast waves from a vessel burst (no ignition) was performed with the ferry placed in a setting similar to Florø harbour, with businesses, shops and a hotel in the vicinity. Reflected pressures of 150-200 mbar onto the buildings 60m away across the harbour were predicted. While the pressure level may seem high, the duration is short (10-20 ms), and while such loads could give damage to buildings it is not foreseen that the integrity of the building would be threatened. Extensive window scattering with potential risks to people behind might be feared.

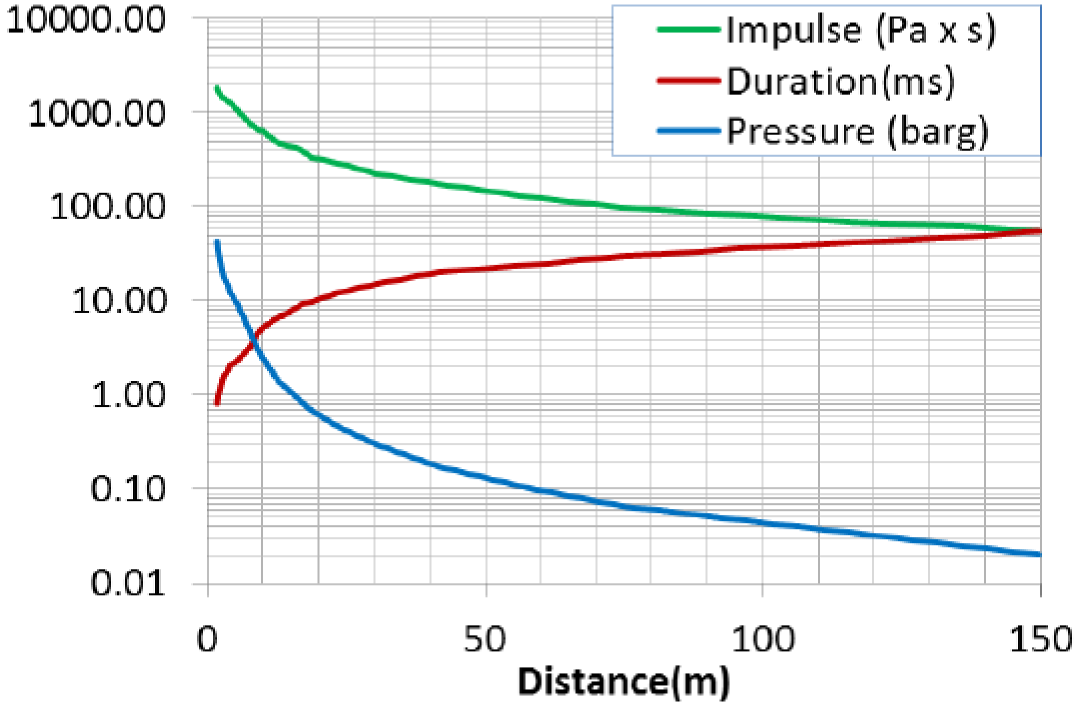

Figure 3.1 – Predicted tank burst consequence for catastrophic tank rupture according to LR screening tool for hydrogen safety

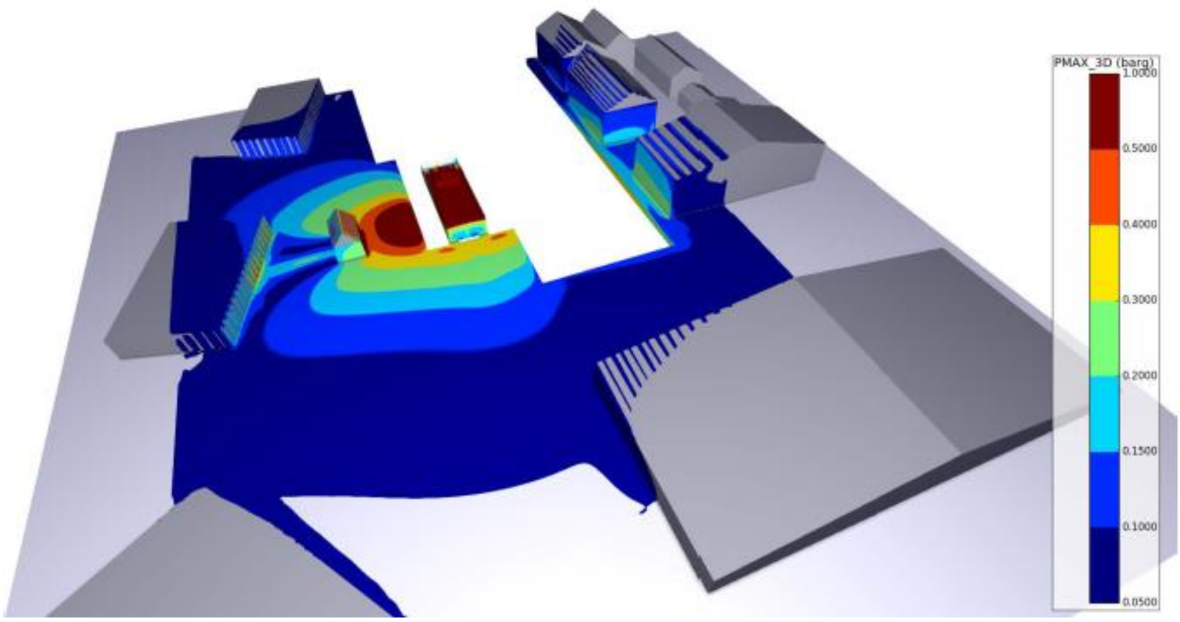

Figure 3.2 – FLACS CFD-calculation of pressure distribution after tank rupture (no ignition) in a setting similar to Florø harbour

As mentioned in Section 3.1.1 more knowledge is needed to assess the rupture scenario frequency. These types of scenarios are often not included when calculating separation distances [17, 24]. Furthermore, the tank is not likely to be full when rupturing. If refuelling occurs at noon, the tanks are likely to be half full during overnight rest. If the rupture is a consequence of fire exposure, it is likely that venting has been ongoing for several minutes before rupture occurs. If the tank pressure is halved, the blast pressure level distances and duration at a given distance may be reduced by around 20%.

To be conservative, the burst scenarios are included in this risk assessment, considering both blast waves from rupture and deflagration blast waves. With a better insight in the tank testing performed it could be possible to revisit the assumptions regarding potential for catastrophic tank failure.

3.2.2 High pressure piping

The estimated consequences for the high-pressure piping scenarios are found in Table 3.4. The jet fire from a full bore release gives the maximum fatality hazard distance, at 20m. It is recommended that vertical walls are installed around the tank connection space (TCS), to ensure that any hydrogen gas release is diverted upwards. If this is done, the potential fatal radiation distance for the worst-case release scenario is reduced to 5 meters in lateral direction. For the 10% hole size scenario, the upper hazard distances for blast will conservatively be applied. It is assumed that the release will lead to a significant reactive cloud accumulation within the TCS. The severity of this scenario can likely be reduced based on a CFD-assessment when design details are available.

The main consequence for the vessel in a worst-case explosion event is a possibility for broken windows. However, robust marine design against wave loads should make windows survive explosion blast loads originating from the roof, as these will have short duration and low impulse. Also, the origin and propagation direction of the blast waves gives a limited exposure to the passenger cabin windows.

Table 3.4 – Scenarios related to high pressure systems – estimated fatality distances

HP Systems				Hole size distribution (% of cross-section)					
	Criteria (fatality rate)			0.01%	0.1%	1%	10%	100%	Total
Leak rate	Indicative		g/s	**0.15**	**1.5**	**14.8**	**148**	**920**	
Duration	Half-time		S	**Until detection and isolation**			**1000**	**160**	
Frequency / year	**250 bar**	**-**	**12 mm**	**1.03E-1**	**1.54E-2**	**4.88E-3**	**2.39E-3**	**1.91E-3**	**1.27E-1**
Delayed ignition probability				0.000	0.001	0.005	0.033	0.085	0.002
Explosion frequency / year				**8.86E-6**	**9.88E-6**	**2.29E-5**	**7.88E-5**	**1.62E-4**	**2.83E-4**
Explosion	0.50 bar (50%)			-	-	-	0-5m #	5.5 m	
Explosion	0.35 bar (15%)			-	-	-	0-7m #	7.5 m	
Explosion	0.20 bar (10%)			-	-	-	0-9m #	10 m	
Immediate ignition probability				0.000	0.001	0.009	0.066	0.170	0.004
Early explosion frequency / year (1s)				**1.77E-5**	**1.98E-5**	**4.58E-5**	**1.58E-4**	**3.25E-4**	**5.66E-4**
Early explosion	0.50 bar (50%)			-	-	-	0-5m #	5.5 m	
Early explosion	0.35 bar (15%)			-	-	-	0-7m #	7.5 m	
Early explosion	0.20 bar (10%)			-	-	-	0-9m #	10 m	
Total ignition probability				0.000	0.002	0.014	0.099	0.256	0.007
Fire frequency / year				**2.66E-5**	**2.96E-5**	**6.86E-5**	**2.36E-4**	**4.87E-4**	**8.48E-4**
Jet/flash fire 8%	35 kW along (100%)			-	-	2.6 m	8 m	20 m	
Jet fire	35 kW radial (100%)			-	-	0.3 m	1.5 m	5 m	

 # No pressure of concern expected for free jet, upper distance estimated is based on worst-case assessment of leak into ~3m x 2m x 1m semiconfined TCS. For more precise estimate CFD assessment should be performed.

3.2.3 Low pressure distribution piping

The probability for hydrogen release events with severe consequences from the low-pressure part of the piping is low, since it is installed outdoors and in a well-ventilated area. Hence, chances for severe incidents with fatal outcome seem negligible. The only scenario which might lead to fatality risk is the full bore release, but also here the risk for fatalities is very low. If the releases are shielded behind vertical walls that deflect upwards, jet fire fatality risk will be negligible. The only remaining scenario with some fatality risk is gas accumulation and explosion from a full bore release. This scenario can be evaluated with CFD simulations once the details of the final system design has been determined. Details of the assessment can be found in [5].

3.2.4 Fuel cell units

Low release rates are expected in the fuel cell cabinets, due to the low pressures and small pipe dimensions. Jet fire risk will not be an issue until after an explosion, and even in this case the hazards will be limited to a small area inside the fuel cell cabinet. Explosion risk is the main concern regarding person safety, but volumes of the cabinets are limited and hazard distances of no more than a few meters should be expected. The main potential hazard to people is likely to be projectiles from an explosion (cabinet door or other parts of the cabinet), from which the risk should be possible to minimize by design. It is therefore assumed that design will ensure zero risk for fatalities for incidents inside the fuel cells cabinets.

Inside the fuel cell cabinets a ventilation rate of 30 air changes per hour (ACH) is assumed. Scenarios with hydrogen concentration of 10% or less inside the fuel cell cabinets are considered harmless for explosion effects corresponding to a leak rate of 0.02 g/s.

Traditional safety approaches will aim at keeping concentrations below LFL (or 25-50% LFL average) with the help of ventilation. With a cabinet volume of less than 0.3m^3 only 1 g hydrogen is required to obtain average concentration of 4% (LFL). In order for a ventilation system to maintain the average concentration < 4% at a full bore release rate of 6.2 g/s, about 20,000 ACH would be required. This is not practically feasible. If all the fuel cell units were located within one single enclosure (e.g. 3m x 3m x 2m) with an average target concentration of 1% (25% LFL) the 6.2 g/s release scenario would require 1500 ACH. This is not practically feasible either. Hence, the most feasible approach may be to accept a small risk for explosions and make sure that the consequences from such explosions will be negligible outside the unit.

3.2.5 Vent mast

The vent mast is assumedly activated when there is a fire threatening the hydrogen tanks, and there is a need to empty the tanks as quickly as possible to limit the risk for a catastrophic failure. If the evacuation flow rate is very high, explosion pressures or radiation loads from the vent mast could be of concern. The results from the consequence evaluations for three vent rates considered are shown in Table 3.5.

Table 3.5 – Scenarios related to vent mast – estimated fatality distances

Vent mast		P	V	Mass	Orifice from tank into vent mast (mm)		
Storage tanks	3	250 bar	3x8.3m^3	450 kg	8.9mm	7.7mm	6.3mm
Leak rate					**800 g/s &**	**600 g/s**	**400 g/s**
Duration	Half-time leak rate 1 tank			150 kg	**125 s**	**165 s**	**250 s**
	Half-time leak rate 3 tanks			450 kg	**375 s**	**500 s**	**750 s**
Delayed ignition probability					0.079 ¤	0.068 ¤	0.055 ¤

Explosion	0.50 bar (50%)	5 m	3.5 m	-
Explosion	0.35 bar (15%)	7 m	4.5 m	-
Explosion	0.20 bar (10%)	9.5 m	8 m	3.5 m
Early ignition probability		0.158 ¤	0.136 ¤	0.111 ¤
Early explosion	0.50 bar (50%)	5 m	3.5 m	-
Early explosion	0.35 bar (15%)	7 m	4.5 m	-
Early explosion	0.20 bar (10%)	9.5 m	8 m	3.5 m
Jet fire probability		0.238 ¤	0.205 ¤	0.166 ¤
Jet fire	Lateral radiation 35 kW/m^2 (100%)	4.3 m	3.6 m	2.8 m

¤ Ignition probability may be exaggerated in our assessment as the releases takes place in a controlled direction into the open away from equipment and objects that could be ignition sources. On the other hand there is likely a fire event that causes emergency venting of tanks, and ignition of the flare from the same fire event may be credible. Other potential ignition sources could be charging of particles (snow, water/salt).

& Exact flow rates versus flow restriction orifices will have to be verified. With 12mm piping 800 g/s is expected to be near the maximum flow rate, thus to empty the tanks even faster larger pipe diameters may be required.

If the gas release is directed upwards with a momentum the explosion centre will be located several metres above the mast, far above sea, deck and quay. The pressure loads where people may be present are in this case likely below the 10% fatality threshold of 200 mbar. Furthermore, the hydrogen blast will have a short duration, and the impulses are therefore most likely lower than the impulse criterion in Section 2.6.

Based on the fatality risk predictions, and taking the limited fire resistance of composite tanks into consideration, it might be recommended to choose the larger maximum tank evacuation flow rate of 800 g/s. There may however be other aspects to consider. Windows in buildings, for example, may break at blast pressures in the order 20 mbar. Since evacuation of gas tanks is a safety measure which may happen not only during severe incidents, but possibly also in less severe situations or by mistake, one should design to avoid window scattering in the harbour or on the vessel itself. Estimated distances to 20 and 50 mbar overpressure from ignited vent stack with various sonic flow rates are as seen in Table 3.6. The estimates are based on TNO multi energy model [31] with plume explosion energy and source pressure estimated with LR screening models.

Table 3.6 – Indicative distances for blast pressures for ignited vent mast sonic releases

Sonic release rate	50 mbar	20 mbar
400 g/s	14 m	33 m
600 g/s	28 m	63 m
800 g/s	33 m	75 m

Potential blast effects should be studied more in detail using CFD-models before concluding on the final design. Larger gas mast exit vent diameter to obtain subsonic release is expected to reduce noise level during tank evacuation, and to reduce blast pressures significantly if the plume ignites.

4 Results and discussion

The risk associated with a hydrogen and fuel cell driven high speed passenger ferry is reported in this study. Two different risk assessments were made. Firstly, an assessment of the risk to passengers during operation, and secondly, a risk assessment with respect to DSB consultation distances for area planning while the ferry is moored in the harbour. The second study is not mandatory, but might provide useful insight for the authorities in the approval process.

The analyses made in this study show that there are very few scenarios that have the potential to threaten life of passengers or crew on board, or people in the harbour. Table 4.1 summarizes fatality risks for the scenarios that are of most concern.

Frequencies and fatality distances are transferred from Tables 3.3, 3.4 and a similar table from LP systems not shown in the article. Each line in Table 4.1 refers to one column of these tables, except for the tank rupture where more explosion scenarios are combined as mentioned in footnote of Table 4.1. The dominating scenario by frequency (first line of Table 4.1) comes from the 100% release scenario of Table 3.4, where 100% fatality risk is predicted within 5m radial distance from a jet-fire (axial radiation/flash-fire is not considered due to shielding walls around TCS), 50% fatality is predicted for TCS explosion pressures above 0.5 bar (delayed and immediate).

Table 4.1 – Summary of scenarios of concern for fatality risk

Scenarios of possible concern to crew, passengers or people in the harbour	Fatality rate versus predicted distances					
	Frequency	100%	50%	15%	10%	1% #
HP release in TCS						
• Explosion & fire – 920 g/s ¤	**4.87E-4/y**	**5m**	**5.5m**	**7.5m**	**10m**	**20m**
• Delayed ignition & fire 148 g/s	**2.36E-4/y**	**1.5m**	**5 m**	**7 m**	**9 m**	**18m**
LP release in TCS						
• Immediate ignition & fire – 36 g/s	**1.16E-5/y**	**0.6m**	**3m**	**4m**	**5m**	**10m**
• Delayed ignition & fire – 36 g/s	**5.80E-6/y**	**0.6m**	**5m**	**7m**	**9m**	**18m**
250 bar / 8.3m³ tank – burst or leak						
• Max. explosion distances¤	**3.35E-6/y**	**~15m**	**21m**	**25m**	**37m**	**74m**
• 1% immediate ignition	**1.36E-6/y**	**~10m**	**19m**	**22m**	**32m**	**64m**
• 0.1% immediate ignition	**1.76E-6/y**	**~5m**	**9m**	**10m**	**14m**	**28m**
• 0.01% hole size	**9.45E-7/y**	**~5m**	**6m**	**8m**	**11m**	**22m**

¤ Delayed ignition for 0.1%, 1%, 10% and 100% release case, plus 10% and 100% immediate ignition.

 # 1% fatality criterion for people in buildings exposed to 100 mbar overpressures, coarsely estimated to 2 x distance for 0.2 bar overpressure (incoming pressure, not reflected pressure used in this indicative estimate).

4.1 Risk estimate for ferry during operation

The main risks identified for a hydrogen ferry during operation are discussed below.

4.1.1 High pressure release in TCS

For the scenario with 920 g/s ignited release (frequency 4.87 x 10^{-4}/y) no direct fatality risk to passengers or crew located indoor is expected. While people inside a normal house might be at some risk at a distance 20m away, it is assumed that the marine design of the bridge will be sufficiently robust to leave crew unharmed. The same applies for the passengers below deck. It is unclear whether the hydrogen systems and second train of fuel cells would remain operative after such an incident and the vessel may in this case have to rely on battery powered propulsion until assisted by other vessels. Similar considerations can be done for the 0.1% and 0.01% tank scenarios with a total explosion frequency of $3.6x10^{-6}$/y. Total frequency for this category of scenarios is thus $4.9x10^{-4}$/y. With bridge unharmed and battery back-up expected to ensure propulsion to safety, this scenario is not expected to give risk for fatalities.

However, if the propulsion fails due to an incident affecting both fuel cell trains there could be a resulting fatality risk. By assuming a 10% probability for a scenario where the ferry needs to be abandoned, either due to loss of propulsion in bad weather or developing fire scenarios around tanks, this would correspond to a frequency for abandoning vessel scenario of $4.9x10^{-5}$/y when operating 24/7. However, the ferry is expected to operate about 18% of the time, which corresponds to one event every $8.8x10^{-6}$ year. If a fatality risk of 5% is assumed in an emergency evacuation (5 of 100 passengers) this would give $4.4x10^{-5}$ fatalities per year, or 0.006 fatalities per 10^9 passenger km (based on 7.67 million passenger km/year). It should be noted that the assumptions made here are very conservative. On the other hand, there might also be reliability issues related to the fuel cell system (e.g. sudden power and propulsion failure), which may increase the risk of fatality. This part of the study should be updated once more fuel cell operation data is available.

For the scenario with 148 g/s ignited release no harm to passengers, crew or vessel is to be expected. Unless the hydrogen systems automatically de-activates after an incident, it may be expected that half of the fuel cell system (the part not exposed to the incident) can continue its operation. No fatality risk contribution is assumed from this scenario.

4.1.2 Tank rupture scenarios

For the tank rupture scenarios (1%, 10% and 100%) severe damage to the vessel could be expected (total frequency of $3.84x10^{-6}$/y). Reinforcement of the roof and short duration of the blast impact can prevent collapse of the ceiling above the passenger cabin, but severe damage and fatality risk is to be feared at the bridge, and damage to most windows is to be expected. It is expected that the vessel will continue to float after such an incident, but the propulsion is likely to be lost which will cause the ferry to start drifting in an uncontrolled manner. For this assessment a fatality risk of 30% for the passengers and crew is tentatively proposed. Since the ferry is operating 18% of the time, the expected number incidents during operation per year is $7x10^{-7}$, which gives $2.1x10^{-5}$ fatalities per year, or 0.003 fatalities per 10^9 passenger km due to tank rupture.

4.1.3 Summary – risk to passengers and crew

Based on the above simplified considerations less than 0.01 fatalities per 10^9 passenger km are predicted from accident scenarios caused by the hydrogen systems. This is well below a possible tolerance level of 0.5-1.0 fatalities per 10^9 passenger km assumed. For a person staying on the ferry 24/7 during operation, the estimated fatality risk from hydrogen incidents would correspond to an IRPA of $3x10^{-6}$, which is one order of magnitude below the general IRPA for passing away by accident in society for the least exposed age groups (females 10-14 years old with a fatality rate of $7x10^{-5}$/y), while adult males have a general fatality risk more than 100 times higher than this predicted IRPA, see [11].

In summary, the preliminary risk assessment presented in this study indicates that the risks associated with the operation of a hydrogen and fuel cell driven high speed ferry are well within the expected tolerance criteria, and that the fatality risk will not be significantly higher than for a conventionally fuelled ferry.

4.2 DSB consultation distance evaluation related to time in harbour

Over a typical week of operation ferry is expected to be moored in the harbour for about 75% of the time. In addition, it is likely to bunker 1-2 hour per day at a dedicated facility in Florø. There is no requirement to estimate consultation distances according to [11]. Nevertheless, for the IGF risk evaluation, it may be of interest to know to what extent hydrogen related risk originating from the vessel would have been of concern for the harbour area planning if it had been a stationary installation. Consultation distances for two different system options were therefore evaluated. In the first option it was assumed that all hydrogen systems remain pressurized and connected to the tanks while the vessel is moored in harbour overnight. In the second option the connections to the tanks are closed so that no hydrogen can leak in case of an incident when moored.

In Figure 4.1 the estimated IRPA as function of distance from the incident is plotted for the two scenarios. The low frequency high consequence scenarios related to the tanks are identical for both, while the frequencies of near field consequences are higher with the systems pressurized and connected to tanks. If the vessel had been a stationary installation the following approximate consultation distances would result from a risk assessment:

1) Inner consultation zone (IRPA > 10^{-5}): Radius 11m from the TCS and tanks if hydrogen systems are kept pressurized and connected to tanks. No inner consultation zone if connection to tanks are closed when moored
2) Middle consultation zone (IRPA > 10^{-6}): Radius 22m from the tanks
3) Outer consultation zone (IRPA > 10^{-7}): Radius 38m from the tanks

The current assessment thus indicates that with all hydrogen systems except tanks disconnected when moored, the estimated risk would be broadly acceptable for a stationary installation at the selected location in Florø harbour. This conclusion would also hold for a combination of several similar vessels in harbour with separation distance 15-20m along the quay. Thus, while the DSB assessment for consultation distances is not required for a hydrogen fuelled passenger ferry, the assessment could help confirm that the risk from the vessel is acceptably low with regard to the IGF-requirements.

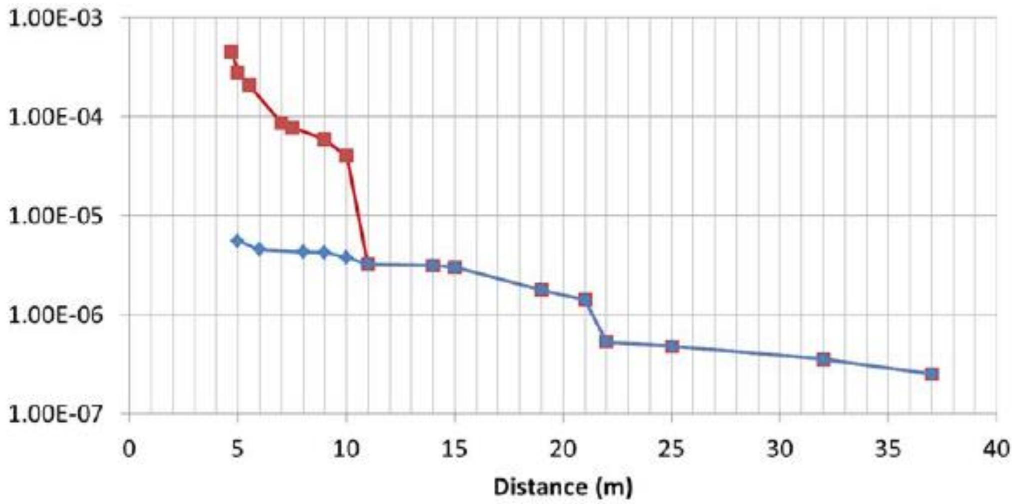

Figure 4.1 – IRPA as function of distance from hydrogen systems for vessel moored 75% of the time in harbour. Red curve shows estimated fatality risk if hydrogen systems are kept pressurized, whereas blue curve shows scenario if all systems except tanks are depressurized during the extensive time spent in harbour.

4.3 Proposed risk reduction measures

The following hydrogen system protection measures were assumed in the risk assessment made in this study, many of which can be regarded as recommendations for safe designs for future hydrogen and fuel cell driven high speed passenger ferries.

- A functioning fire detection and mitigation system that will initiate tank venting upon detection of fire threatening the tanks. This will reduce the risk for tank rupture. In specific PRD and T-PRD are not considered to be proper protection of larger tanks [6, 30] in the event of localized heat exposure
- Vertical walls around TCS to deflect jet fires upwards, and no confining cover to prevent significant gas accumulation during a release
- Fire protection and structural support below and to the sides of tanks to divert horizontal jet fires upwards, limit risk for tank rupture in case of fire, give additional protection to passenger cabin in case of tank rupture and offer additional resistance to external impact loads from collisions or projectiles. Passive fire protection around tanks should also be considered
- Weakened section on fuel cell cabinets to relieve pressure due to explosion, oriented in safe direction to limit projectile risk
- Minimize pipe diameters. Larger diameter piping will give higher release rates with expected more severe consequences
- It is assumed that a vent mast design is selected to allow high flow rates to empty the tanks as quickly as practically possible. There should be no risk for fatalities from emptying tanks to the gas mast, and ignited hydrogen plumes from venting should neither give damage to the vessel (including windows) nor to nearby buildings or windows in the harbour. An initial vent rate between 400 g/s and 800 g/s may be appropriate. Increased exit diameter for flow to remain sub-sonic can likely limit the consequences from an ignited event and allow larger releases

If the mitigation measures proposed above are adjusted, or not implemented, this may have a negative impact on the overall risk level.

4.4 Uncertainties

Among the major uncertainties in this study are the assumed frequencies for loss of containment scenarios. The frequencies used are considered realistic for hydrogen installations reflecting experience from oil and gas industry taking hydrogen specific aspects into consideration. A relevant question is to what extent these failure frequencies should be assumed influenced by the harsh marine environment and motion of the vessel.

The estimated consequences of the catastrophic tank ruptures are also highly uncertain. If the tank design prevents catastrophic rupture despite major impact loads or extensive fire exposure while at high pressure, there will be no pressure loads from vessel burst, and likely more limited explosion loads than assumed in this report. On the other hand, if the catastrophic rupture scenarios can take place, there is a possibility that the combustion scenarios from the fireball could undergo transition to detonation with 2.5-3 times higher hazard distances than assumed in this risk assessment. No literature on pressurized hydrogen tank rupture experiments at a realistic scale could be found for this study.

It can also be added that the detailed interpretation of the IGF alternative design risk target "equivalent safety level" is far from clear, and that there is a lack of detailed rules and standards for hydrogen applications. This will contribute to the overall uncertainty of the study.

4.5 Proposed adjustments to ignition models and vulnerability criteria

The maturity of risk assessment methodology for hydrogen in maritime transport applications is limited, and still under development. Several of the assumptions made in this risk assessment may need to be challenged, discussed, and possibly improved with experience, or verified through tests.

The existing ignition models for hydrogen risk assessments are far from satisfactory, for this reason a modified ignition model was proposed in Section 2.5. Due to limited documented events there will be significant uncertainties in this model. The modified model predicts a higher probability for ignition than the HyRAM-model, for example, and is therefore more conservative with respect to estimating hazards.

Blast loads for a given overpressure also tend to be a lot sharper for hydrogen, i.e. the pulse durations for a given overpressure will be shorter than the durations used as basis for the OGP fatality criteria. A higher tolerance both for people and structures to a given overpressure level can be expected. Some assumptions are done regarding robustness of the ferry (e.g. windows on the bridge or deck above passenger cabin) to short duration, high magnitude blast pressures. There are uncertainties related to such assumptions.

5 Conclusions

A risk assessment for a concept design of a hydrogen driven high speed passenger ferry has been carried out. The study focused on fatality risk related to the hydrogen systems on the ferry, both during operation and while moored in harbour overnight. The main motivation for the study was to evaluate if the risk related to the hydrogen systems could be considered acceptable according to the requirements of the IGF-code, i.e. equivalent to that of conventionally fuelled vessels. No bunkering assessment has been performed at this stage.

The conclusion of the study is that the estimated risk related to hydrogen systems seems limited, with less than 0.01 fatalities per 10^9 passenger km, and much lower than an anticipated risk tolerance level of 0.5-1.0 fatalities per 10^9 passenger km. Furthermore, the estimated risk was also well within acceptable limits for overnight mooring of the ferry in the harbour.

The study is an early system concept study. It is therefore expected that some of the assumptions will have to change as new details on a final system design becomes available. The final risk estimates can only be made when the final system design and operation profile have been determined.

6 Acknowledgements

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