Integrated Design for Demonstration of Efficient Liquefaction of Hydrogen (IDEALHY)

Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

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Publishable Summary

Hydrogen is seen as an important energy carrier for the future which offers carbon free emissions at the point of use. In particular, hydrogen could be used to power vehicles using hydrogen fuel cell technology and thereby replace the use of petrol and diesel. In the absence of a hydrogen pipeline supply network, which would be costly and take considerable time to build, hydrogen could be supplied using road tankers. However, transporting hydrogen by road as a compressed gas is very inefficient and supplying liquefied hydrogen (LH2) by road tanker is seen as the most effective way forward in the medium term. This will require large quantities of LH2 to be produced, stored and transported for re-fuelling vehicles.

The IDEALHY project receives funding from the European Commission's 7th framework programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative. The project has the aim of developing a new hydrogen liquefaction process which will enable LH2 production to be undertaken at increased scale (50-200 tpd) and with significantly increased efficiency. The production of large quantities of LH2 and the subsequent road transportation and storage at vehicle re-fuelling stations (often in urban areas) present new challenges in terms of ensuring the safety of the public. For these reasons, as part of the IDEALHY project, the safety of the proposed production and supply system has been considered.

This report presents the results of two risk studies, using a qualitative risk matrix approach. The first considers the risk presented by the transport by road tanker to, and storage at, a refuelling station of LH2. The second considers the risk presented by the new IDEALHY liquefaction process operating at 50 tpd and storage at the liquefaction plant. Possible mitigation measures are also discussed.

Key Words

Liquid hydrogen

QRA

Accumulation

Dispersion

Fire

Explosion

BLEVE

Abbreviations

ach	Air changes per hour
barg	Shorthand for gauge pressure in bar
BBD	Building Burning Distance
BLEVE	Boiling Liquid Expanding Vapour Explosion
CFD	Computational Fluid Dynamics
DDT	Deflagration to Detonation Transition
HAZID	Hazard Identification
GH2	Gaseous Hydrogen
LFL	Lower Flammable Limit
LH2	Liquefied Hydrogen
LNG	Liquefied Natural Gas
LU	Loughborough University
LOC	Loss of containment
MR	Mixed refrigerant
RPT	Rapid phase transition
RTA	Road traffic accident
QRA	Quantitative Risk Assessment
QRM	Qualitative Risk Matrix
T	time
t	tonne
tdu	thermal dose units
tpd	tonnes per day
VCE	Vapour Cloud Explosion

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1 Background

Hydrogen is seen as an important energy carrier for the future which offers carbon free emissions at the point of use. In particular, hydrogen could be used to power vehicles using hydrogen fuel cell technology and thereby replace the use of petrol and diesel. However, to achieve this goal, vehicle re-fuelling stations would need to be supplied with large quantities of hydrogen on a regular basis. In the absence of a hydrogen pipeline supply network, which would be costly and take considerable time to build, hydrogen could be supplied using road tankers. However, transporting hydrogen by road as a compressed gas is very inefficient and, in the absence of a pipeline, supplying liquefied hydrogen (LH2) by road tanker is seen as the most effective way forward in the medium term. This will require large quantities of LH2 to be produced, stored and transported for re-fuelling vehicles.

At present the production of LH2 is generally at small scale (typically 2 to 5 tpd) [Krasae-in et al, 2010] and is very energy intensive. The IDEALHY project has the aim of developing a new hydrogen liquefaction process which will enable LH2 production to be undertaken at increased scale (50-200 tpd) and with significantly increased efficiency. IDEALHY receives funding from the European Commission's 7th framework programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative.

The production of large quantities of LH2 and the subsequent road transportation and storage at vehicle re-fuelling stations (often in urban areas) present new challenges in terms of ensuring the safety of the public. For example, in relation to the new large scale process for the production of LH2, there are a number of factors which may affect the hazard presented by the process plant, such as larger inventories of stored LH2, higher pressure operation, larger diameter pipework and the use of refrigerants such as hydrocarbon mixtures. Another specific option which is to be considered by IDEALHY is the possible integration of LH2 production with liquefied natural gas storage operations, so that the regasification of liquefied natural gas can be used as part of the pre-cooling of hydrogen. With regard to road transportation, transporting hydrogen as a liquid is significantly more efficient than as a gas in terms of the load carried per vehicle. From a safety stand point, this may be beneficial in terms of the reduced number of tanker deliveries, but may be detrimental since each tanker will have an increased capacity.

For these reasons, as part of the IDEALHY project, the safety of the proposed production and supply system has been considered. At this stage of development, the aim was to undertake qualitative risk studies of the new liquefaction process developed by the IDEALHY project and the subsequent road transportation of LH2 to re-fuelling stations. This will help identify the key areas which require further quantitative information or mitigation measures. Ultimately, operators need to be able to undertake quantitative risk assessments of their LH2 operations.

2 Introduction and Scope

The safety study comprised 3 steps: firstly to review existing knowledge and identify gaps; secondly to undertake two HAZID exercises, (one for the new liquefaction process and storage of LH2 and the other for road transportation and storage at a re-fuelling station); thirdly to consider the risks to workers and the public presented by these activities by performing qualitative risk studies.

A review of available information and two HAZID exercises have been undertaken [Lowesmith and Hankinson, 2012; Hankinson et al, 2013]. This report presents the qualitative risk studies for:

- The new liquefaction process producing LH2 at 50 tpd and storage at the production facility.
- The road transport of LH2 from the production facility to re-fuelling stations and storage at the re-fuelling stations.

2.1 IDEALHY Liquefaction Process and Storage at Production Facility

Figure 1 shows a diagram of the proposed liquefaction scheme and Figure 2 an initial plant layout. The process involves:

- The supply of gaseous hydrogen at an absolute pressure of 20 bar, and ambient temperature followed by compression to 80 bar.
- The passage of high pressure hydrogen through the vacuum insulated Pre-cool and cryogenic cold boxes where it is chilled and liquefied by a Mixed Refrigerant (MR) cooling circuit and a Helium/Neon (He/Ne) cooling circuit. It also passes through an adsorber to remove impurities and several catalyst beds to promote conversion to para-hydrogen.
- The Mixed refrigerant is a mixture of hydrocarbons and Nitrogen, typically, Methane (33%), Ethane (35%) Butane (22%), Propane (4%) and Nitrogen (5%). It operates at pressures between 3 and 26 bar and temperatures between 0 and 6 °C, with a flowrate of about 6 kg s^{-1}.
- Production of LH2 at a rate of 50 tpd (0.58kg s^{-1}) and transfer to a large storage vessel at the liquefaction plant capable of holding 2 weeks production of LH2 (700 t at 2 barg and temperature of about 24 K).
- If LNG was available to provide cooling, this would replace the MR cooling circuit

More information about the process can be found in other reports of the IDEALHY project.

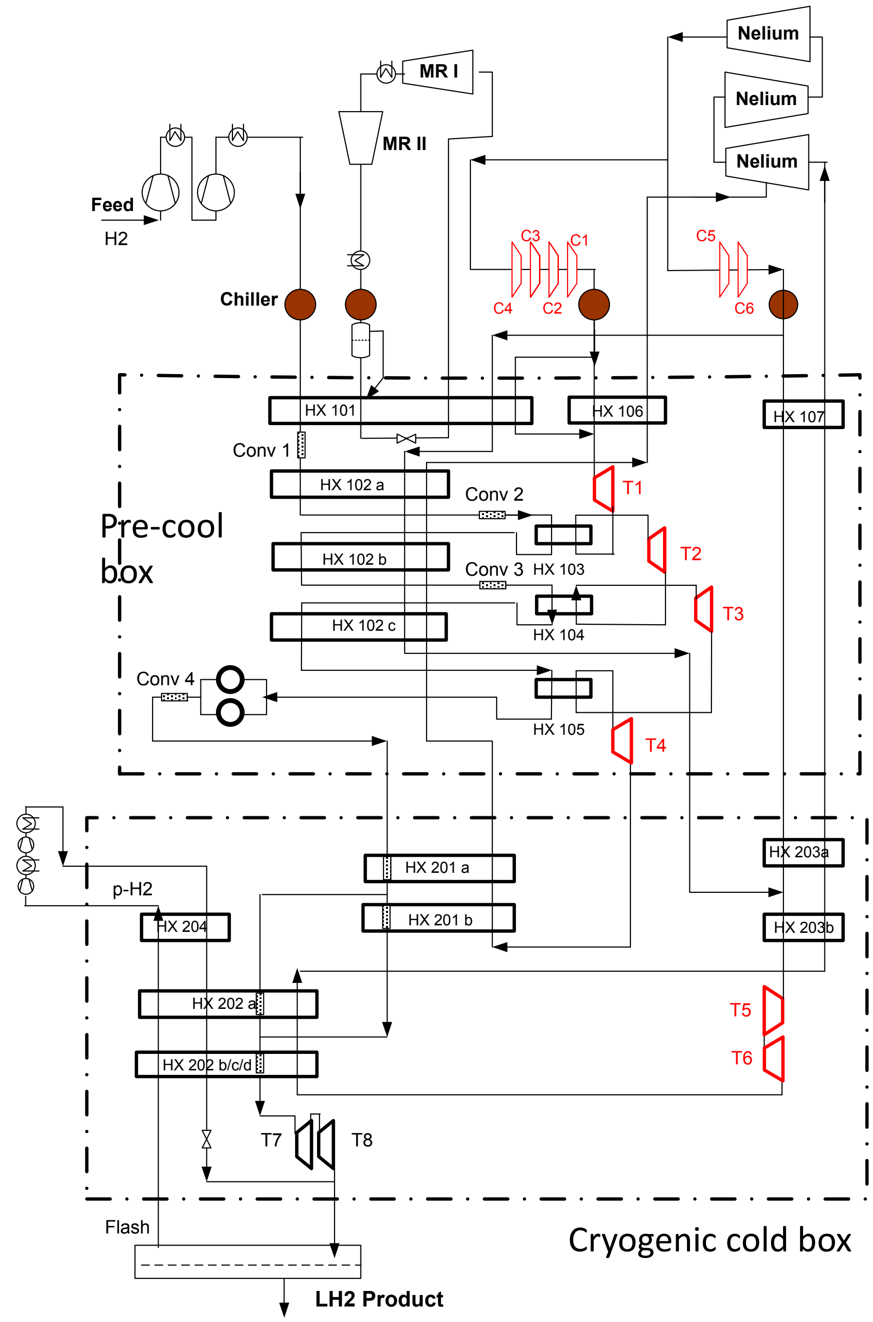

Figure 1: Diagram of the IDEALHY hydrogen liquefaction plant

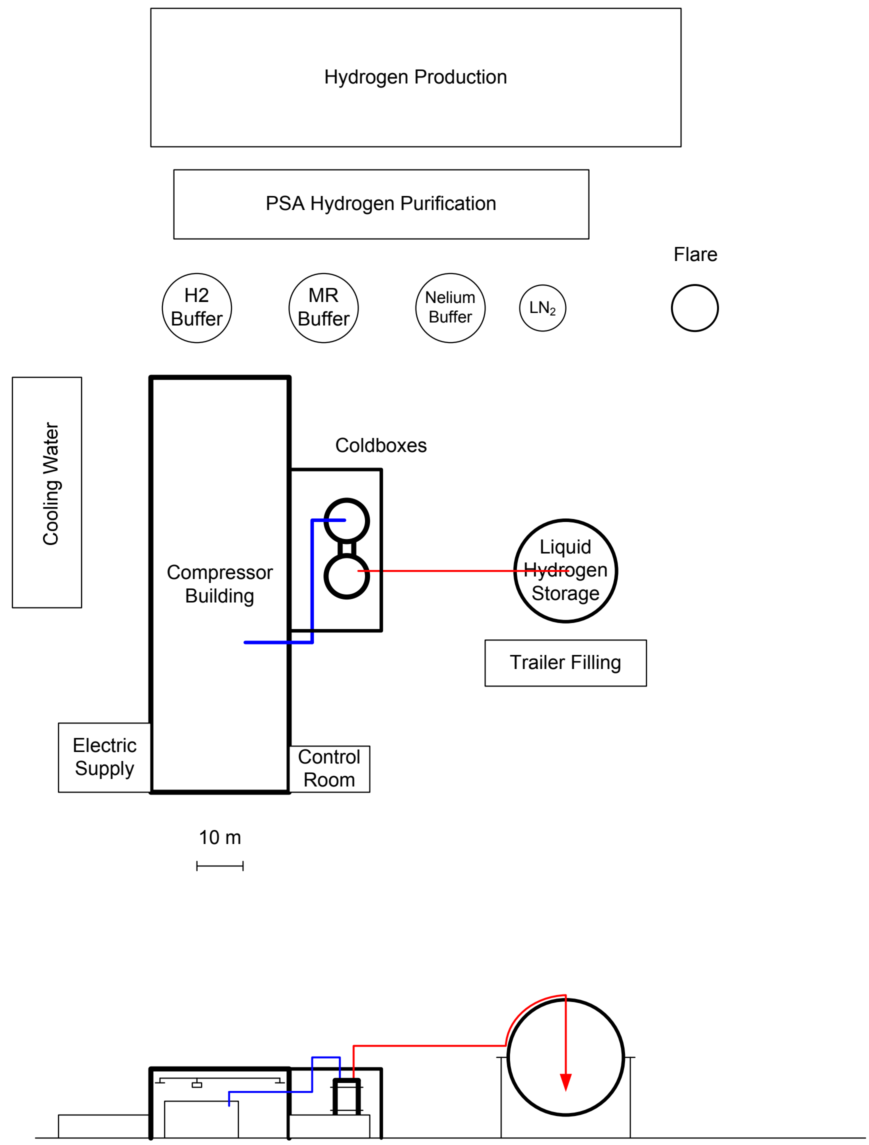

Figure 2: Proposed Plant Layout of the Liquefier

2.2 Road Transportation and Storage at a Re-fuelling Station

The assumption is that LH2 is transported in road tankers with a capacity of typically 3 t at a pressure of about 2 barg and temperature of about 25 K. This is then offloaded into a storage vessel at a re-fuelling station. The capacity of the storage will depend upon demand, but is likely to be in the region of 1 to 3 t. Currently, Shell operate a re-fuelling station in Berlin with a storage capacity of about 1 t. Pritchard and Rattigan [2010] report on a re-fuelling station in London which had a capacity of 3.5 t (closed in 2007) and other planned re-fuelling stations with capacities of up to 2.4 t. For the purposes of this risk study, a storage capacity of 3 t is assumed and a storage pressure of typically 2 barg at about 25 K.

3 Basics of Risk Assessment

3.1 Quantitative Risk Assessment

'Risk' is a measure of the number of the expected fatalities per year and, for a particular untoward event, is evaluated from the likelihood of an untoward event occurring and the consequences of that event, taking account of any mitigation measures in place. The 'consequences' are an assessment of the number of fatalities, based on a consideration of the hazard posed (for example, thermal radiation from a fire) and the number of persons likely to be within a hazardous region (for example, an area within which they would receive a dangerous dose of thermal radiation). So risk can be expressed as:

Risk (fatalities per year) = Frequency of the untoward event (per year)

x Hazardous area assessed from determining the consequences (m^2)

x Number of persons expected to be within the hazardous area (persons m^{-2})

x Likelihood that this level of harm would cause a fatality

In order to assess risk posed by a process plant (such as hydrogen liquefaction) or, for example, the transportation and storage of LH2 to a refuelling station in an urban location, a large number of potential untoward events must be considered. This may be achieved by performing a HAZID exercise to produce a long list of potential untoward events of varying severity and likelihood. The frequency and consequences of each event must be assessed and the risk associated with each untoward event totalled up to produce the overall risk. Two types of risk are usually considered: Individual Risk and Societal Risk.

- Individual Risk: The likelihood (per year) of an individual at a particular location relative to the hazardous activity becoming a fatality.

- Societal risk: This is a risk curve (or F/N plot) which displays the expected frequency of an untoward event capable of causing a pre-defined level of harm (usually fatality) to N or more people. It reflects the risk to society of the process under consideration.

This quantitative approach to risk assessment (QRA) is widely used in the oil and gas industry and often such QRAs are required by regulatory authorities. Acceptable and unacceptable levels of risk may also be prescribed by such regulatory authorities. For example, typically in the UK, the individual risk should not exceed 10^{-6} per year for members of the general population and if this is not the case, then appropriate mitigation measures must be considered, to either reduce the consequences or reduce the likelihood in order to reduce the overall risk.

3.2 Difficulties of QRA in Relation to LH2 Operations

3.2.1 Failure Frequency

It is likely that some regulatory authorities will require QRA for LH2 operations as they become more widespread. However, at the current time, the limited operational experience makes QRA extremely difficult. In particular, there is a lack of failure frequency data for hydrogen operations in general and for liquid hydrogen operations in particular. By contrast, for natural gas underground transmission pipelines there has been many thousands of kilometre-years operation and operators have collaborated to provide databases of failures which enable quantification of failure frequencies with reasonable accuracy, for example the EGIG database is based on a total pipeline exposure of over 3 million km yr. There is no database dedicated to hydrogen pipeline incidents. Furthermore, there is only around 1500 km of hydrogen pipeline in Europe compared to about 2 million kilometres of natural gas pipeline [Castello et al, 2005]. For non-pipeline hydrogen operations there is also a dearth of data and the limited extent of liquid hydrogen operations presents additional problems. The US hydrogen incident database [HIAD], whilst informative, is not yet comprehensive enough to provide quantitative failure frequencies for a range of hydrogen operations.

Failure frequencies from hydrocarbon operations are not suitable for application to hydrogen systems since the failure modes will differ and different standards of material selection and construction apply to hydrogen [Moonis et al, 2010]. These authors report that the usual way forward is to use related failure data and apply a rate modification factor to account for the impact of hydrogen. In the short to medium term this may be the only way forward to determine quantitative failure frequencies.

3.2.2 Ignition Probability

The wide flammability limits and low ignition energy suggest ignition probabilities will be significantly higher than for hydrocarbon releases. Astbury [2007] comments that the wide flammability limits combined with the very low ignition energy means basing safety on avoidance of ignition is almost impossible. However, evidence from experiments and incidents show that ignition does not always occur [Astbury and Hawksworth, 2005; Hankinson et al, 2013]. With the low ignition energy, there are numerous potential ignition sources for hydrogen [Lowesmith and Hankinson, 2012] including so-called 'spontaneous' ignition, generally associated with sudden gaseous releases, which has recently been attributed to shock-interactions at the exit [Dryer et al, 2007].

Without many years of extensive operational experience, it is not possible to determine reliable quantitative ignition probabilities, so some engineering judgement will be required. At this time, probably the best basis for estimating ignition probabilities is from reviewing hydrogen related incidents.

IAEA [1999] report on a review of 409 hydrogen related incidents (78.5% GH2, 20.8% LH2 and 0.7% hydrides) and noted that most finally ignited. In partially obstructed areas most cases resulted in an explosion or even detonation. IAEA also noted that 'spontaneous' ignition was possible following burst disk or safety valve failure resulting in a sudden release. Ordin [1974] reviewed 96 incidents (some GH2, some LH2) during NASA operations and overall concluded that 62% ignited for releases into the atmosphere but when the release was due to inadequate purging, this increased to 93%. 100% ignited for releases into confined spaces.

A review of LH2 incidents performed as part of IDEALHY [Hankinson et al, 2013] identified 18 LH2 incidents associated with road transportation and 39 LH2 incidents associated with storage/liquefaction. Overall, a release of hydrogen took place in 50 cases of which 24 ignited. The split between immediate ignition (fire) and delayed ignition (explosion) was about 50:50. Closer examination of the incidents overall is merited. Of the 18 transportation incidents, 11 were associated with burst disc rupture or opening of a relief valve. Two cases associated with storage tanks also involved burst disc failure or opening of a relief. Of these 13 cases, 3 were directly from a road tanker whilst in transit and none ignited. Of the remaining 10 cases, 4 ignited. The source of ignition was not identified, but the rapid release associated with these scenarios suggest that 'spontaneous', that is, shock-interactions as shown by Dryer et al [2007], was the most likely cause. This would be consistent with the observation in the IAEA report [1999] noted above.

Unexpected ignition of gas venting from a vent stack or vent valve was noted in a further 4 cases within the storage related incidents. These observations suggest that venting systems need to be designed on the assumption that ignition may take place and this factor taken into account in the siting and orientation of vent stack outlets. Closer examination of the storage related incidents also identified that 11 out of 13 releases into confined or semi-confined spaces resulted in ignition, whereas 9 out of 21 releases into the atmosphere ignited. It was also evident that large releases were much more likely to ignite than small releases.

In conclusion the following recommendations for ignition probability are made:

- For releases from burst discs or relief valves: 50%
- For releases to atmosphere: 50%
- For releases into confined regions: 100%
- For releases due to inadequate purging: 100%
- For large releases: 100%

3.2.3 Consequence Assessment

Due to the large number of cases to be simulated in any QRA, it is usual to use 'engineering type' consequence models rather than CFD. Such models are usually quick to run and require more limited definition of the geometry and release conditions. This is more practical for the simulation of generic releases in a typical geometry of the process being studied. However, mathematical models of all kinds are reliant upon experimental data for their development and validation. Experimentally derived input parameters, such as fraction of heat radiated for fires or vapour evolution rate for liquid spills, are needed for engineering type models and few such data exist for LH2 releases [Lowesmith and Hankinson, 2012]. Many such models were developed for the study of hydrocarbon releases and their applicability to hydrogen, especially LH2 may not be justified.

3.3 Qualitative Risk Matrix

For all the reasons outlined in Section 3.2, performing QRAs on the proposed liquefaction plant and storage, and the transportation and storage of LH2 at a refuelling station is not practical at this stage. In such circumstances, a qualitative approach can be used, producing a Qualitative Risk Matrix (QRM).

A QRM is a 2-dimensional presentation of the risk. On one side of the table, the likelihoods of the untoward events are categorised into a selected number of sub-divisions, which may be ranges of quantitative likelihoods or words such as 'possible', 'unlikely', 'very unlikely'. On the other side the consequences are categorised into a selected number of consequence bands according to the expected severity (number of fatalities and/or damage). Typically, one corner of the matrix (associated with relatively high consequence, not infrequent events will be coloured red indicating relatively high risk. The corner diagonally opposite will be coloured green, indicating low risk. Across the diagonal, a yellow band will indicate the region in which the risk may only be acceptable if As Low As Reasonably Practicable (ALARP). Cases falling in the red and yellow areas will merit more careful assessment, where the use of mitigation measures should be considered. The number of categories used in a QRM varies and the position of the central region may also vary in extent (see Figure 3).

4 LH2 Risk Studies in the Literature

There are limited studies of risk of LH2 operations in the literature. Details of a few are provided here.

Zhiyong et al [2011] presents a consequence assessment (no likelihoods considered) of accidental releases from a vehicle LH2 tank with an inventory of 3.5 kg. Continuous releases from hole diameters up to 10 mm were considered as well as catastrophic failures. Cold dispersion, fireballs, jet fires, flash fires and Vapour Cloud Explosions (VCEs) were considered using engineering type models. The largest hazard distance was for a catastrophic rupture resulting in a VCE and was about 42 m. A comparison with 700 bar compressed hydrogen storage was also made (assuming equivalent mass storage) and concluded that the hazard distances for LH2 were greater than for GH2 in the cases of catastrophic ruptures but less in the cases of continuous releases from holes. Another study of some of the hazards of LH2 and GH2 releases was undertaken by Rigas and Sklavounos [2005], where an event tree approach was used to identify untoward events. The key hazards for LH2 were cold gas dispersion, flash fire, jet fire, BLEVE, VCE and DDT. A CFD model was used to perform some dispersion calculations of relatively small spills (2 kg s^{-1} for 5 s duration) for both high pressure GH2 and LH2. The importance of the dense gas behaviour of cold hydrogen from LH2 spills was emphasised. There was no estimation of likelihood or risk in this study.

Kikukawa et al [2009] used a QRM to study LH2 refuelling stations encompassing tanker offloading, storage and dispensing of LH2 to vehicles. The LH2 tank of capacity 17 m^3 was assumed to be operating at 0.35 MPa (3.5 bar) and provided a refuelling capacity of 0.380 m^3 hr^{-1}. A QRM was used with 4 levels of likelihood described as "Improbable", "Remote", "Occasional" and "Probable". The severities of the consequences were divided into 5 categories of "Extremely Severe Damage", "Severe Damage", "Limited Damage" and "Minor Damage". No information on the harm criteria used was presented and little detail of the method of consequence assessment. Using a HAZID type approach 131 untoward events were identified and allocated to one of the cells in the QRM. Without mitigation, 88 cases fell into the ‘red’ region of the matrix and were deemed High Risk and 26 fell into the diagonal Medium Risk (possibly ALARP) region. After mitigation measures were applied, only 13 cases remained in the High Risk region, all of which were associated with “Improbable” events and 45 cases fell into the Medium Risk category.

IAEA [1999] summarises a risk assessment of LH2 transportation by barge carrying 15000 m^3 of LH2 on the Elbe river near Hamburg. Conceivable accident scenarios were grouped into just 4 release categories being

- Continuous release of GH2 through a safety valve
- Quasi-continuous or instantaneous release of a small fraction of the tank contents
- Continuous release of a large amount of the tank contents
- Instantaneous release of the entire inventory

They conclude that delayed ignition represents the worst case with a certain chance of VCE or even detonation. The quantified risk evaluation was deemed preliminary due to the many assumptions made due to the lack of better data and the use of models which do not realistically account for the behaviour of gaseous or liquid hydrogen. However, qualitatively, they concluded that the highest societal risk was found onshore for the population of Hamburg city with the highest individual risk for the ship’s crew. Collision with an encountering ship caused the highest total risk and collision with a crossing ship caused the highest risk for the onshore population.

IAEA [1999] also make reference to a safety assessment of a hydrogen liquefaction plant near Lille with a production rate of 10 tpd. A maximum accidental release rate of 1.9 kg s^{-1} was used representing rupture of an LH2 pipe. This resulted in a maximum dispersion distance of 200 m to the LFL. A safety distance of 238 m around the plant was deemed sufficient to protect offsite residential areas.

Perhaps the most relevant study is that performed by Moonis et al [2010] which included a qualitative risk study (and QRM) of the transportation of LH2 by railcar to an intermediate storage location and then onward transportation by road tanker to a refuelling station. Dispensing to vehicles as a liquid and as a high pressure gas was also included. In terms of the road tanker, an inventory of 2.5 t was assumed at 20 K and an operating pressure of 7 barg. The refuelling station storage tank was assumed to have a capacity of 1 t, at 20 K and operating at 5 bar (gauge). A top down HAZID for each section of the network being considered was undertaken and a list of generic releases identified (similar to that in the IAEA study described above). For road tankers, small and large leaks of 1 and 22.5 mm diameter respectively were considered. For the storage tank at the refuelling station the small and large leak sizes were 1 and 10 mm. Catastrophic rupture of the road tanker and storage tank were also considered. The study also included larger catastrophic failures associated with the intermediate storage up to a maximum of 200 t. The DNV software PHAST was used for the consequence modelling of dispersion/flash fire (distance to Lower Flammable Limit (LFL) of 4%), VCE, pool fires and jet fires. The authors noted the problems of consequence modelling since the models were developed for hydrocarbons and their validity for hydrogen is questionable. In particular, difficulties in determining the potential for DDT in explosion events and assessing flame length and radiative characteristics of hydrogen jet fires. The authors note that the inability to consider DDT may result in hazard distances which are not sufficiently precautionary. Nevertheless, some very large hazard distances were predicted for VCEs and flash fires following catastrophic failures of tanks, up to 40 km in the case the 200 t tank failure followed by a flash fire. The 200 t inventory was not included in the

QRM, the largest inventory being 40 t representing intermediate storage, for which the greatest hazard distance was 16 km for the case of catastrophic failure leading to a VCE.

For the QRM, Moonis et al [2010] adopted 7 levels of likelihood being:

- Extremely Unlikely
- Very Unlikely
- Unlikely
- Quite Unlikely
- Somewhat Unlikely
- Fairly Probable
- Probable

The severities of the consequences were classified into 6 categories being:

- Very Major, Catastrophic >100 fatalities
- Catastrophic, Overall 11 to 100 fatalities to workers and/or public, International media exposure
- Extremely Serious, Overall 1-10 fatalities, worker fatality, major injury to public. National news, prosecution and fine
- Major, Serious Injury to worker (permananent disability). Injury to public
- Serious, Significant Injury to worker. Minor injury to public. Adverse local publicity
- Minor, Minor Injury to work. Few complaints

Not surprisingly, the highest risk cases were catastrophic failures and large continuous releases, although no cases fell into the ‘red’ region of the QRM.

5 Approach to Assessing Risk for this Study

5.1 The QRM

For this study, two separate QRMs were developed.

- A QRM for the transportation of LH2 by road tanker to a refuelling station, offloading and storage at the refuelling station (but excluding dispensing to vehicles).
- A QRM for the supply of high pressure hydrogen by pipeline to a liquefaction plant, the liquefaction process and storage at the production facility.

These are described in Sections 7 and 8 respectively. The proposed QRM is shown in Figure 3. As can be seen 5 categories of likelihood and severities of consequences are proposed, which are:

Likelihood categories:

- 1: Extremely Unlikely (about 10^{-9} per year)
- 2: Unlikely (about 10^{-7} per year)
- 3: Possible (about 10^{-5} per year)
- 4: Very Possible (about 10^{-3} per year)
- 5: Probable (about 10^{-1} per year)

Consequence categories:

- 1: Slight Effect (slight injury or health effect, no damage)
- 2: Minor Injury (minor injury or health effect, minor damage)
- 3: Major Injury (major injury or health effect, moderate damage)
- 4: Up to 3 fatalities (or permanent disability, major damage)
- 5: More than 3 fatalities (or massive damage)

QRM			Consequence Severity				
			1	2	3	4	5
			Slight Effect No Damage	Minor Injury Minor Damage	Major Injury Moderate Damage	Up to 3 Fatalities Major Damage	More than 3 Fatalities Massive Damage
Likelihood	5	Probable	Low	Medium	High	High	High
	4	Very Possible	Low	Medium	Medium	High	High
	3	Possible	Low	Low	Medium	Medium	High
	2	Unlikely	Low	Low	Low	Medium	Medium
	1	Extremely Unlikely	Low	Low	Low	Low	Medium

Figure 3: The QRM used for this risk study

5.2 Identifying the Untoward Events and the Cases for Consequence Assessment

Two HAZID exercises were performed [Hankinson et al, 2013] with the partners of the IDEALHY project. For the transportation of LH2 by road tanker and storage at a refuelling station 60 untoward events were identified. For the liquefaction of hydrogen and storage at the production plant, 43 untoward events were identified. Following the HAZID, the potential consequences of each untoward event were considered. In many cases, the outcome of a particular untoward could vary according to the actual size of release which results, whether or not ignition occurs, the height and/or direction of the release, and the location of the release (eg a confined or open area). For example, an untoward event "Road tanker hits overhead object such as bridge" has a range of potential consequences depending on the exact circumstances of the collision, from small gaseous release from the vent to total loss resulting in a large spill, dispersion and potential VCE in the event of delayed ignition or pool fire with immediate ignition. So in reality, there are many more than the 60 and 43 untoward events identified during the HAZIDs.

Using the list of untoward events, a list of generic consequence cases to be assessed was compiled, with the intention of encompassing all the possible hazardous outcomes of the untoward events. This is similar to the approaches taken by other workers [Moonis et al, 2010; IAEA, 1999]. For each untoward event, the possible size of release is considered and what the outcome will be depending on whether ignition occurs immediately or after a delay.

To encompass both HAZIDs, a list of 19 consequences (C1 to C19) cases was produced (Table 1). C1 to C9 and C13 were required to cover the transportation and storage at a refuelling station. Some additional cases, C10 to C19 were needed to cover all the untoward scenarios arising from the liquefaction of hydrogen and storage at the process plant. Within each case, a range of release sizes have been assessed and changes in other parameters were also studied, such as the release direction or height, resulting in a large number of consequence assessments (139). Overall, the type of consequence assessments required can be summarised as:

- Jet fires involving a continuous gaseous or liquid release (C1, C3, C5 (100mm), C10, C11, C14)
- Gas dispersion from continuous or instantaneous release of gas or liquid into the atmosphere and subsequent explosion (VCE) (C2, C4, C6, C15)
- Pool fires arising from an instantaneous spill of LH2 (C5)
- BLEVE of a tank due to external fire causing pressure rise leading to failure (C7)
- Gas accumulation within an enclosure potentially leading to a flammable mixture and then explosion (C9, C12, C19)
- Confined explosion within a vessel or pipework (C8, C16, C17, C18)
- Solid oxygen/hydrogen explosion within valve, pipework or vessel (C13)

Table 1: List of Generic Consequence Assessments

Case	Description	Range of conditions	Hazard prediction	No.
C1	Fire from ignited cold GH2 into atmosphere	Size:2, 5, 25 and 50 mm diameter. Direction: Vertical at 1 and 3m above ground. Horizontal at 1 and 5m above ground. Pressure: 2 and 8 barg Temperature: 25 K (2 barg) and 31 K (8 barg)	Fire size, Areas for BBD, 1800 tdu and 1050 tdu	32
C2	Delayed ignition of release of cold GH2 into atmosphere	Size:2, 5, 25 and 50 mm diameter. Direction: Vertical at 1 and 3m above ground. Horizontal at 1 and 5m above ground. Pressure: 2 and 8 barg Temperature: 25 K (2 barg) and 31 K (8 barg)	Cloud footprint and mass of fuel involved. Areas for range of Explosion overpressure levels	32
C3	Fire from ignited release of LH2 into the atmosphere	Size:2, 5, 25 and 50 mm diameter. Direction: Horizontal at 1 m above ground. Pressure: 2 and 8 barg Temperature: 24 K (2 barg) and 30 K (8 barg)	Fire size, Areas for BBD, 1800 tdu and 1050 tdu	8
C4	Delayed ignition of release of LH2 into atmosphere	Size:2, 5, 25 and 50 mm diameter. Direction: Horizontal at 1 m above ground. Pressure: 2 and 8 barg Temperature: 24 K (2 barg) and 30 K (8 barg)	Cloud footprint and mass of fuel involved. Areas for range of Explosion overpressure levels	8
C5	Total loss of tank contents without prior pressure rise and ignition of spill	Size: 100mm dia and instantaneous 3, 17.5 and 700 t. (3 t bunded and unbunded) Wind speed: 2 m s^{-1} Pressure: 2 barg Temperature: 24 K	Initial flashing, fireball event, pool formation, evaporation rate, pool fire size and areas for BBD, 1800 and 1050 tdu	7
C6	Total loss of tank contents without prior pressure rise and delayed ignition of spill	Size: 100mm dia and instantaneous 3, 17.5 and 700 t. (3 t bunded and unbunded) Wind speed: 2 and 6 m s^{-1} Pressure: 2 barg Temperature: 24 K	Initial flashing, pool formation, evaporation rate, cloud footprint and mass of fuel involved. Areas for range of Explosion overpressure levels	14
C7	BLEVE tank/tanker and ignition	Size: 3, 17.5 and 700 t. Pressure: estimated failure pressure Temperature: boiling point	Fireball dimensions. Areas for BDD,1800 and 1050 tdu	3
C8	Explosion in tank during commissioning/ decommissioning	Volume of storage tanks: 3, 17.5 and 700 t.	Confined explosion pressure rise and assessment of vessel failure	3
C9	Leak of cold GH2 into building or enclosure	Size: 5, 25 and 50 mm diameter. Enclosure: 12x20x5 m^3 and 30x90x15m^3 Pressure: 2 and 8 barg. Temperature: 25 K (2 barg) and 31 K (8 barg) Ventilation: 8 ach	Potential to reach flammable concentration. Confined explosion assessment.	12

Case	Description	Range of conditions	Hazard prediction	No.
C10	Fire from puncture in high pressure above ground GH2 pipeline outdoors.	Size: 5, 25 mm diameter and rupture of 112mm diameter pipeline. Direction: vertical. Pressure: 20 barg. Temperature: ambient.	Fire size, Areas for BBD, 1800 and 1050 tdu	3
C11	Fire from puncture in high pressure GH2 pipeline indoors	Size: 2, 5, 10 mm diameter. Direction: vertical. Pressure: 80 barg. Temperature: ambient. Enclosure: 30x90x15 m^3	Fire size, Areas for BBD, 1800 tdu and 1050 tdu	3
C12	Puncture in high pressure GH2 pipeline indoors and delayed ignition.	Size: 2, 5, 10 mm diameter. Pressure: 80 barg. Temperature: ambient. Enclosure: 30x90x15 m^3 Ventilation: 8 ach	Potential to reach flammable concentration. Confined explosion assessment.	3
C13	Solid O2/LH2 explosion in pipework/valve.		Damage assumed.	1
C14	Fire from leak of MR outside cool baox	Size: 10, 25 mm diameter. Direction: horizontal Pressure: 25 barg Temperature: 6 C	Fire size, Areas for BBD, 1800 tdu and 1050 tdu	2
C15	Leak of MR outdoors and delayed ignition.	Size: 10, 25 mm diameter. Direction: horizontal Pressure: 25 barg Temperature: 6 C	Cloud footprint and mass of fuel involved. Areas for range of Explosion overpressure levels.	2
C16	Leak from MR or H2 inside cool box and loss of vacuum.	Volume of cool box	Confined explosion pressure rise and assessment of vessel failure.	2
C17	Explosion in purifier.	Volume of purifier	Confined explosion pressure rise and assessment of vessel failure.	1
C18	Explosion in process pipework		Confined explosion. Damage assumed.	1
C19	Leak of MR in liquefier building and delayed ignition.	Size: 10, 25 mm diameter. Pressure: 25 barg Temperature: 6 C Enclosure: 30x90x15 m^3 Ventilation: 8 ach	Potential to reach flammable concentration. Confined explosion assessment.	2

5.3 Defining the Criteria for Harm

Criteria need to be set to determine the number of fatalities, injuries or level of damage that results from the fire or explosion event. For example, Zhiyong et al [2011] used a level of 9.5 kW m^{-2} for fire hazards and an overpressure of 0.07 bar. Moonis et al [2010] specified 12.5 kW m^{-2} for fires and 0.1379 bar for explosion overpressure to determine fatalities.

5.3.1 Harm Criteria for Fires

The harm caused by a fire depends on the radiation level and the duration of exposure. For harm to people, the thermal dose is given by $I^{4/3}$ TD in units of $(kWm^{-2})^{4/3}$ s (often referred to a thermal dose unit, tdu), where I is the radiation level (kW m^{-2}) and DT is the duration (s). It is also commonly assumed that people will find shelter within 30 s and so the duration of exposure to the radiation will be limited to that time. Based on approach widely adopted in the gas industry for pipeline risk assessment [IGEM/TD/2, 2008] the following harm criteria have been adopted:

- 1800 tdu within a duration of 30 s resulting in 50% fatality
- 1050 tdu within a duration of 30 s resulting in 1% fatality

In addition, 100% fatality is assumed for persons enveloped by flame.

At certain radiation levels, buildings may burn and not provide adequate shelter. Based on Hopkins et al [1993], in this assessment, the building burning distance (BBD), is the largest distance where:

$$\int_0^{1800} (I - 12)^2 \, dT = 17500$$

(The integral is restricted to a duration of 1800 s = 30 minutes on the assumption that the emergency services will arrive and intervene within this time). The building burning distance was determined all around the fire and hence an area within which buildings will burn was determined. In an urban environment, persons may escape from the side of the building away from the fire into another, and hence the level of fatalities within the building burning distance has been taken as 75%.

The maximum number of fatalities arising from the 3 criteria described above was taken.

Recognising that injury of other persons may accompany fatalities, or occur when no fatalities arise, it has been further assumed that if the assessment of fatalities results in less than 0.5 persons, this is taken as at least 1 person suffering ‘major injury’. If less than 0.1 fatalities, this is taken as ‘minor injury’ and if less than 0.01, as ‘slight effect’.

5.3.2 Harm Criteria for Explosions within Buildings

In the event of a release within a building a flammable accumulation may form and then ignite. If the concentration does not reach the LFL within 5 minutes, it is assumed that everyone will escape from the area. However, damage may still arise. The following damage levels have been assumed [Skelton, 1997]:

Overpressure (P) (bar)	Damage Level
$P \leq 0.07$	None
$0.07 < P \leq 0.25$	Minor
$0.25 < P \leq 0.4$	Moderate
$0.4 < P \leq 1.0$	Major
$P > 1.0$	Massive

However, if the explosion occurs within 5 minutes, it is assumed that persons are still present within the building and 50% fatality is assumed for overpressures up to 0.25 bar and 100% fatality over 0.25 bar.

5.3.3 Harm Criteria for Explosions Outdoors

Skelton [1997] also suggested casualty criteria for fatalities arising from explosions occurring outdoors. However, the levels are considered very conservative, particularly for persons who are outdoors, where survival is expected to be much better. Therefore, fatality levels have been halved, to reflect the proportion of persons outdoors and taken as:

Overpressure (P) (bar)	Casualty Level (%)
$P \leq 0.07$	0
$0.07 < P \leq 0.21$	5
$0.21 < P \leq 0.34$	12
$0.34 < P \leq 0.48$	35
$P > 0.48$	47

The number of persons subjected to each pressure level was determined and hence the total number of fatalities. In addition, a fatality level of 95% is assumed for persons engulfed by the flammable cloud.

As for the fire assessment, if the fatality assessment results in less than 0.5 persons, this is taken as at least 1 person suffering 'major injury'. If less than 0.1 fatalities, this is taken as 'minor injury' and if less than 0.01, as 'slight effect'.

5.3.4 Population Density

In order to assess the number of persons at risk of becoming a fatality within the hazardous region, the density of persons is required. For this work, an urban density of 2850 persons km^{-2} was assumed. For the liquefaction plant, a density of 200 persons km^{-2} was assumed. This represents a typical sparsely populated rural area and is considered appropriate for the liquefaction plant which is assumed to be located within a large industrial complex with controlled access for public and personnel. At this density, the liquefier building shown on Figure 1 would have less than one person within it. This is considered representative since during normal operation this building will generally be unoccupied. However, during maintenance or commissioning/decommissioning a greater number of persons may be present.

5.4 Assessing the Consequences

For the consequence cases C1 to C19, a total of 139 cases were assessed, covering a range of release sizes and scenarios. The extent of the hazardous areas were assessed and hence the number of fatalities, injuries or damage as determined by the criteria above.

Consequence assessments were performed using engineering type models. The fire assessments used models developed by Loughborough University (LU). Dispersion was assessed using the Shell FRED suite of models [Shell, 2012]. Vapour Cloud Explosions were assessed using the TNT method, which is generally regarded as unsuitable for modelling VCEs, since the complexity and extent of the congested region within the gas cloud affect the explosion overpressure and this cannot be assessed using the TNT method. However, for this study, where no knowledge of the congestion layout and extent is known, it provides a simple approach to ranking the severity of VCEs. Simple calculations were performed for confined explosions within vessels. More details of the consequence modelling and some examples are provided in Section 6.

5.5 Assessing the Likelihood

The likelihood of each untoward event identified in the HAZID was estimated using engineering judgement. For each untoward event, a range of outcomes could arise depending particularly on the size of release, but also whether ignited or not, whether horizontal or vertical etc. Therefore, a range of likelihoods were identified for each untoward event depending on the assumed size of release. In general, it was assumed that small releases were more likely than larger releases. Also, where human error could be involved, the likelihood of an untoward event is thought to be greater than cases of material or component failure. Where incidents have been recorded of a similar nature, this also indicates a higher likelihood than untoward events that have not been known to occur.

5.6 Assessing the Risk

By combining the likelihood category with the assessment of harm, allows each case to be allocated to one of the cells of the QRM. This is presented in Section 7 for the transportation of LH2 by road tanker to a refuelling station, offloading and storage at the refuelling station. Section 8 presents the QRM for the liquefaction process and storage at the production facility.

6 Consequence Assessments

6.1 Ignited Pressurised Continuous Releases (C1, C3, C5 (100mm), C10, C11, C14)

Continuous ignited releases of GH2, LH2 or MR have been modelled using a weighted multi-point source jet fire model developed by Loughborough University (LU) [Hankinson and Lowesmith, 2012]. In this model, the radiation emanates from a number of sources distributed along the flame axis and the received radiation is determined as a vector sum of the radiation from each individual point source. This jet fire model has been shown to predict incident radiation around hydrocarbon jet fires more accurately than other commonly used empirical models such as the single point source model and solid flame (view factor) type models. The length of the flame is provided by a correlation of net power of the release from Lowesmith et al [2007], which has been shown to be applicable to a wide range of gaseous and liquid hydrocarbon releases. Additionally, the model has been shown to be able to predict the flame length and radiation field around large scale hydrogen jet fires following high pressure ambient temperature hydrogen releases [Ekoto et al, 2012], as shown on Figures 4(a) and (b). These experiments also established that the fraction of heat radiated (F) for large scale hydrogen fires is similar to natural gas. Based on the literature review conducted for IDEALHY [Lowesmith and Hankinson, 2012], a value of 0.15 for F has been used for hydrogen fires with a release rate >0.1 kg s^{-1} and 0.075 for smaller releases.

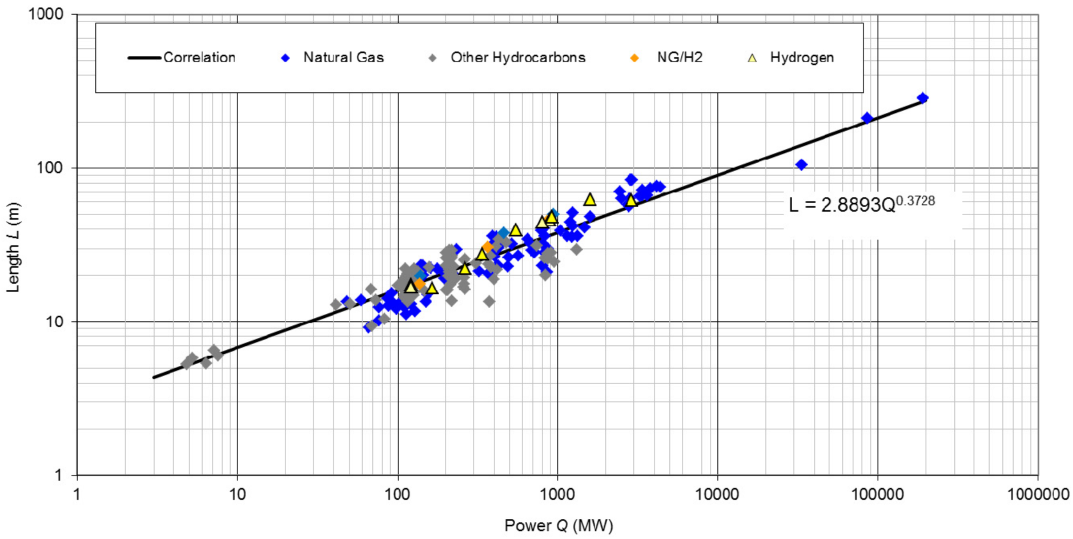

Figure 4(a): Correlation for Jet Fire Length compared with Hydrocarbon and Hydrogen Data

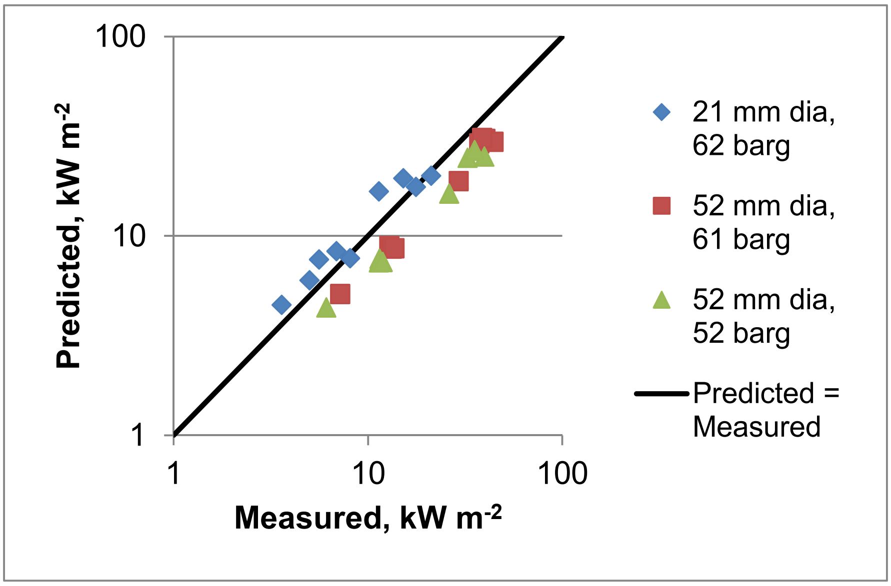

Figure 4(b): Predicted and Measured Radiation Levels around Hydrogen Jet Fire

6.1.1 Gaseous Jet Fires (C1, C10 and C11)

For C1, the cases encompass releases of cold GH2 from holes from 2 mm to 50 mm diameter at varying heights and directions and at a gauge pressure of either 2 or 8 bar (32 cases, see Table 1). The release rate was calculated using standard equations for compressible or incompressible flow, as appropriate. Various properties, such as gas density and specific heat capacity, were obtained from a thermodynamics package (GasVLe from DNV GL). The fire size and radiation was assessed as described above and the level of harm assessed as described in Section 5.3.1. The results are shown in Table 2 for cases in an urban environment and an environment representing a liquefaction plant.

As expected, more severe consequences arose for horizontal rather than vertical releases, for larger diameter releases, and for 8 bar releases rather than 2 bar releases. As can be seen, no fatalities (severity < 4) arise for releases of 25 mm diameter or less, with the exception of the horizontal 8 bar releases from a 25mm diameter hole in an urban environment (left hand side of table). Due to the lower population density on a process site, there is less risk presented to personnel (right hand side of table).

Cases C10 and C11 consider accidental releases from the hydrogen pipeline supplying the liquefaction plant at 20 bar (C10) and after compression to 80 bar (C11). The severity of the consequences for these cases are also summarised in Table 2.

6.1.2 Liquid Jet Fires (C3, C5 (100mm))

Case C3 considers LH2 released from holes of 2 to 50 mm diameter horizontally at 1 m above ground and at gauge pressures of 2 and 8 bar (8 cases, see Table 1). The release rate was calculated using a standard incompressible flow equation and various properties, such as gas density and specific heat capacity, were obtained from a thermodynamics package (GasVLe from DNV GL). A large continuous release of LH2 from a 100 mm diameter hole at 2 bar (C5) was also modelled in the same way.

The question arises, will all the released liquid vaporise and form a jet fire or will some LH2 drop-out and form a pool on the ground? Some flashing is expected on exit, dependent on the release pressure [Lowesmith and Hankinson, 2012]. In addition, radiation from the fire will increase the vaporisation. Large scale jet fires involving liquid hydrocarbons such as propane, butane, kerosene and oil have shown that little or no liquid drop out occurs [Lowesmith et al, 2007]. Furthermore, the density of LH2 is low compared to liquid hydrocarbons. Consequently, the drive pressure will readily result in jet break-up into small droplets. Therefore, it is considered that no liquid drop-out will arise. This conclusion is supported by the findings of HSL during recent tests involving releases of LH2, where drop-out occurred for unignited releases at a gauge pressure of 1 bar but not at 2 bar [Hall et al, 2013].

An example prediction of a LH2 jet fire and surrounding thermal dose is shown in Figure 5. Overall, due to the higher release rate from a liquid release, the severity of the consequences increases compared with similar cold GH2 releases as can be seen in Table 2. The large 100 mm diameter release from a storage tank (or tanker) of C5 is a high consequence event (at least category 4), see Table 2.

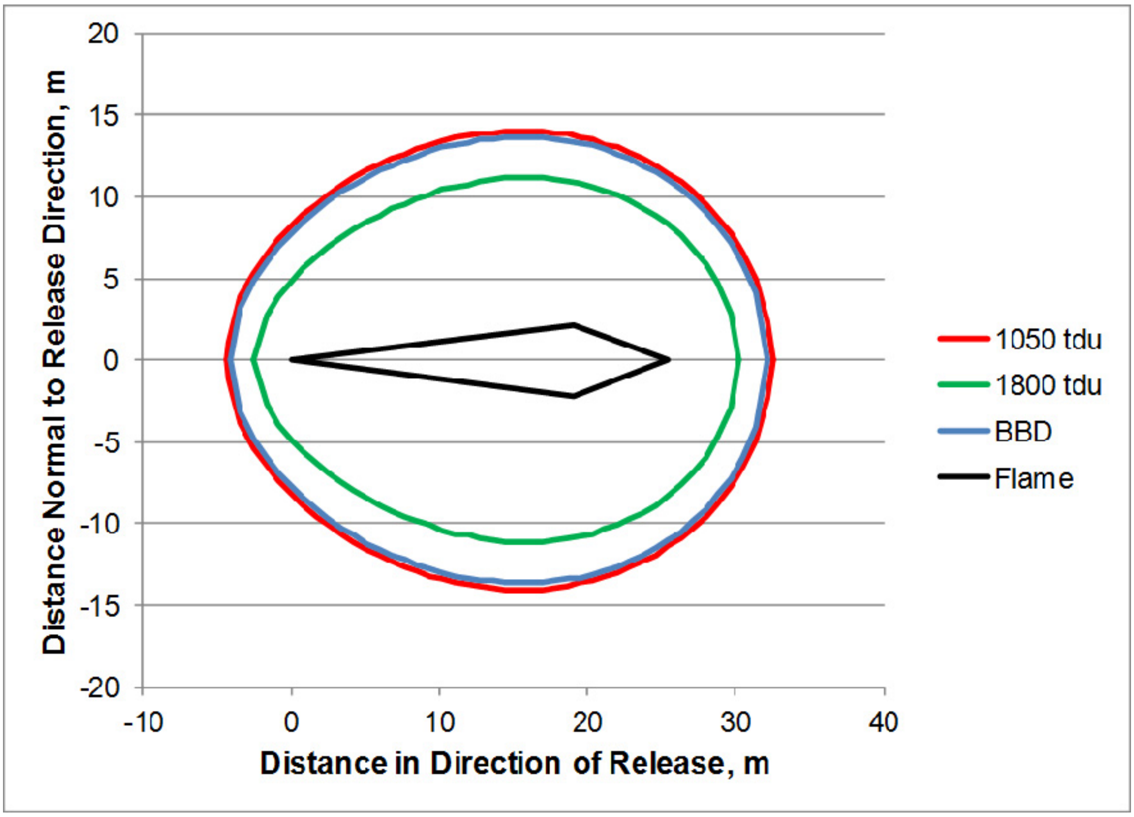

Figure 5: Example of the Radiation Hazard around a LH2 Jet Fire

6.1.3 2-phase Jet Fires (C14)

The C14 cases consider horizontal jet fires following a release of MR at 25 bar from a 10 mm or 25 mm diameter hole. The MR produces a 2-phase release. The Shell FRED package was used to calculate the release rate and calorific value. This data was used as input into the LU multi-point source jet fire model. A fraction of heat radiated of 0.2 was used. As shown on Table 2, these are low consequence events.

6.2 Unignited Pressurised Releases and Delayed Ignition of a Flammable Cloud (C2, C4, C6 (100mm), C15)

The FRED package was used to model these scenarios as a pressurised release. The results included the maximum length (downwind) and width (crosswind) of the plan view of the flammable plume. The height above ground of the lower and upper extent of the plume could also be estimated from the graphical output. FRED also provided the volume of the flammable cloud and the mass of fuel it contained.

The dimensions of the cloud enabled a 'footprint' area to be determined, within which casualties may arise as a result of engulfment, in accordance with the criteria specified in Section 5.3.3 and the appropriate population density. If the cloud was at high level (all above 2 m above ground), then the footprint was taken as zero for the purposes of assessing fatalities by flame engulfment.

Determination of the explosion overpressure following ignition of a flammable cloud is complex and depends upon many factors, such as the fuel involved and the geometry of the environment that the flammable cloud envelopes. Areas of congestion and/or confinement may lead to higher overpressures and flame acceleration through congestion can significantly increase the severity of a gas explosion. With hydrogen there is also the risk of Deflagration to Detonation Transition (DDT), which deflagration explosion models are not able to model. Therefore, assessing explosion overpressure hazards is not straightforward and usually requires a full description of the geometry of the region. However, for this qualitative risk study, generic release events have been considered and since the geometry of the environment may vary or be unknown. This difficulty was also recognised by Moonis et al [2010] in their qualitative risk study. For that study, explosions were modelled in a generic way using the TNO multi-energy method.

For this study, although not ideal, explosion overpressure has been determined using the TNT equivalence method based on the mass of fuel involved. This provided areas where differing pressure levels were experienced and the level of severity was determined using the criteria specified in Section 5.3.3 and the appropriate population density.

6.2.1 Unignited Pressurised Gas or 2-phase Releases and Delayed Ignition (C2, C15)

The C2 cases consider releases of cold GH2 from 2 mm to 50 mm diameter holes at varying heights and directions and at a gauge pressure of either 2 or 8 bar (32 cases, see Table 1). The resulting consequence severity bands for all 32 cases for the C2 type releases are summarised in Table 2 for both an urban environment and an environment representing a liquefaction plant. As for the fire scenarios (C1), the consequence severity is higher for larger releases (due to diameter or pressure) and for horizontal rather than vertical releases.

Leaks of MR at a liquefaction plant and delayed ignition were considered in case C15 in the same way and consequence severity bands summarised in Table 2, for a 10 mm and 25 mm diameter leak.

6.2.2 Unignited Pressurised Liquid Releases and Delayed Ignition (C4, C6 (100mm))

The C4 cases considered horizontal releases of LH2 at 2 and 8 bar from holes from 2 to 50 mm diameter holes. As discussed in Section 6.1.2, the question arises, will all the liquid vaporise or will a pool form? The difference here is that there is no flame providing back-radiation enhancing vaporisation. Nevertheless, it is argued that no liquid pool will form for releases at 8 bar (based on calculation of the flash fraction) . At 2 bar, liquid drop-out is also thought very unlikely for releases up to and including 50 mm diameter. The 100 mm release case of C6 was considered as potentially forming a pool using a liquid spill model as described in Section 6.3.

It was found that FRED was unable to model directly the pressurised liquid releases as the parameters for LH2 were outside allowable bounds for the model. Therefore, using standard equations, the mass outflow of liquid was calculated. This mass flowrate was then input into the FRED pressurised release model and taken to be gaseous in order to obtain a prediction of the flammable cloud dimensions and mass of fuel within it. The explosion severity was then assessed using the TNT method and the consequence severity assessed as described above at the start of Section 6.2. The results for the C4 cases are shown in Table 2. As can be seen, the consequence severity is higher than comparable releases of cold gaseous hydrogen, due to the increased mass release rate of the liquid releases. In an urban environment, releases of 25 and 50 mm are high consequence events (category ≥ 4).

6.3 Instantaneous Spills (C5, C6)

In the event of major loss of containment from a storage vessel or road tanker, a large spill of LH2 would arise. Storage vessels will probably be located within bunded areas, such that any spill would then be contained. However, unbounded spills could arise from a road tanker.

Due to the lack of a suitable model, a mathematical model has been developed by LU to determine the behaviour of such spills, predicting the pool size and the vaporisation rate from the pool, whether ignited or not. The model can be summarised as follows:

Immediately upon loss of containment, a certain amount will flash evaporate. The amount is determined as described in Lowesmith and Hankinson [2012], and for storage at a gauge pressure of 2 bar, is about 21%. The hydrogen which has flashed will either disperse or burn as a fireball depending on whether ignited or not. The remaining liquid is assumed to appear as a vertical cylinder with height equal to its diameter. This liquid then spreads out radially as a result of the conversion of potential energy into kinetic energy. During the spreading process, liquid evaporates as the result of heat transfer. For unignited pools, the heat transfer is primarily by heat conduction from the substrate [Verfonden and Dienhart, 2007]. An initial value of 100 kW m^{-2} is suggested which reduces with time (in proportion to $t^{-0.5}$) due to cooling of the ground [Takeno et al, 1994]. However, the edge of the pool is always spreading onto warm ground and receiving the maximum heat flux of 100 kWm^{-2} (until any bund wall is reached). If ignited, additional vaporisation occurs due to heat transfer by radiation from the flame onto the surface of the pool. This has been taken to be 70 kW m^{-2}, which was derived from a mass burning rate for large LNG pools of 0.14 kg m^{-2} s^{-1} from Pritchard and Binding [1992].

If not bunded, the pool is assumed to continue to spread until the pool depth is less than a particular value which depends on the substrate. A value of 10 mm has been used in this work. The selection of this depth, rather than a smaller value, has little impact on results in the case of a fire, since the remaining LH2 is consumed in a matter of seconds. In the case of an unignited pool the size of the pool continuously increases and will do so until the minimum depth determined by the substrate is reached. The variation with time of the amount of vapour being released into the atmosphere depends on the amount of LH2 spilled and hence on its duration. For the 3 t spill, the amount of vapour released continuously increases whereas for the 700 t spill, the amount reaches a maximum at about 94 s after which time it gradually reduces.

Figure 6 shows the spread of liquid during the early stages of an ignited, instantaneous release from failure of a 700 t storage vessel. In this example, it is assumed to be unrestricted (without a bund). Figure 7 shows that a pool of diameter of about 450 m is achieved in about 140 s. Such a large unrestricted release must be avoided and hence it is assumed that large storage vessels will be surrounded by a bund. However, an unrestricted release could occur from a 3 t road tanker.

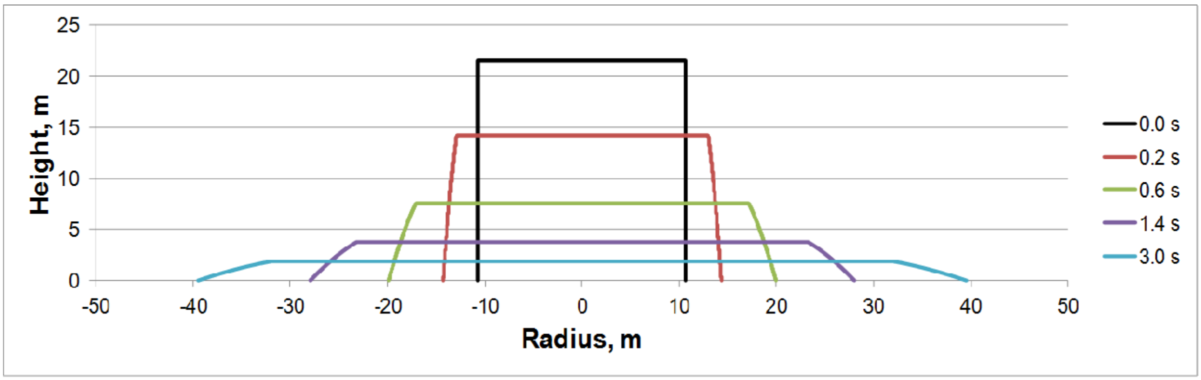

Figure 6: Pool Development in the Early Stages following 700 tonne Tank Failure (no bund)

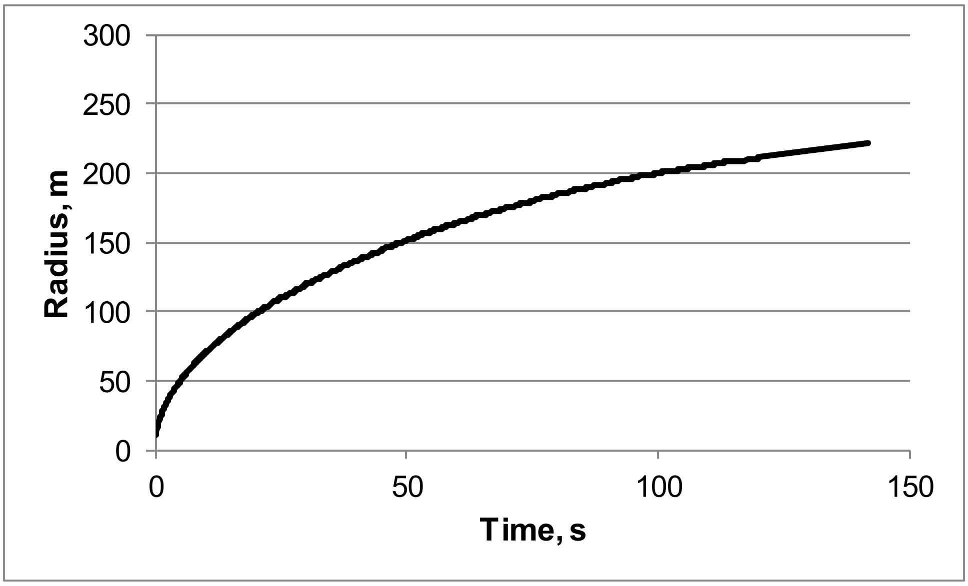

Figure 7: Predicted Pool Radius for an Unbunded 700t Tank Failure

6.3.1 Unignited Instantaneous Spills and Delayed Ignition (C6)

The C6 cases consider catastrophic failure of a storage vessel or tanker resulting in a liquid spill and delayed ignition. For the larger storage vessels (17.5 and 700 t), it is assumed that a bund will be used around the vessel. The 3 t case is considered both bunded and unbunded. As well as instantaneous spillage, a continuous spill from a 100 mm hole, representing major damage to the vessel is also considered.

For instantaneous spills which are not immediately ignited, the fraction which flashes is assumed to disperse and not contribute to the hazardous area.

For the spills into a bunded area, the LU model described above was used to predict the pool radius with time (reaching a maximum at the bund wall). The model also predicts a time varying evaporation rate. The Shell FRED model for dense gas dispersion was then used to predict the dispersion distance, using the pool size and evaporation rate as input. (However, this model was not designed for LH2 spills and would not run if the molecular weight of hydrogen was input, so a molecular weight of 15 kg $kmol^{-1}$ was input, although all other input data related to hydrogen). The FRED dense gas dispersion model is also a steady state model, so could not accommodate time varying evaporation rates. Therefore, the following process was adopted:

Using the results of the LU pool spreading model, the pool area at an arbitrary time T_0 was identified and the average evaporation rate up to T_0 calculated. These data were used as input into the FRED dense gas dispersion model and a steady state downwind distance to LFL predicted (D_1). Using the wind speed, the time (T_1) for the cloud to reach D_1 was calculated. If T_1 was not the same as T_0, then the process was repeated, using the LU pool model to identify the pool area at T_1 and the average evaporation rate up to T_1. Inputting the new values into FRED produces a new steady state downwind distance D_2, which is reached in T_2 seconds. Quite quickly, this procedure resulted in convergence and consistency between the two models. Following convergence, the output of the FRED model included the cloud footprint, volume and mass of fuel involved. The TNT equivalence method was then used to predict the distances to various overpressure bands and the overall level of severity was determined using the criteria specified in Section 5.3.3 and the appropriate population density.

As expected, these are high consequence events (category ≥4).

Using the above method, it was not possible to assess the instantaneous 3t spill which was unbunded, representing catastrophic failure of a road tanker. The reason was that such a spill is highly transient as the evaporation rate continues to increase as the pool gets larger and larger until the inventory runs out. The whole process lasts about 20 seconds. The associated dispersing cloud does not achieve a steady state condition and so the FRED dispersion model is not suitable. Therefore, the same consequence severity is assumed for an unbunded spill as a bunded spill.

The C6 cases also include a 100mm diameter continuous release. This was assumed to form a pool and the pool size and evaporation rate determined using a modified version of the spill model described at the beginning of Section 6.3. It was found that the pool reached a maximum of about 12 m in diameter with an approximately steady evaporation rate. These values were input into the dense gas dispersion model of FRED in order to determine the dispersion distance, cloud footprint and mass of fuel involved in a similar way to the instantaneous bunded spills described above. The TNT equivalence method was then used to predict the distances to various overpressure bands. The overall level of severity was determined using the criteria specified in Section 5.3.3 and the appropriate population density. As can be seen from Table 2, this resulted in a consequence severity of 4 or 5.

6.3.2 Instantaneous Spills and Immediate Ignition (C5)

The C5 cases consider instantaneous catastrophic failure of a storage vessel and immediate ignition. As noted above, upon loss of containment, a certain proportion of the spill will flash and, in this case, burn as a fireball. There is insufficient information available about the behaviour of hydrogen fireballs and no suitable model exists. Therefore, a model has been developed by LU based on the assumption that the behaviour of a hydrogen fireball will be similar to a hydrocarbon (methane) fireball of equal net energy. (This assumption is justified on the grounds that large scale hydrogen jet fires have been found to be similar to natural gas jet fires of equal net power).

The diameter of a fireball, the height the fireball achieves and the duration of the fireball are often modelled by empirical relationships based on the mass of fuel involved. From a review of such relationships by Casal et al [2001], three relationships were selected: $D = 6.14\ M^{0.325}$; $H=0.41\ M^{0.34}$ and $T = 0.75\ D$ (where D, M and T are diameter (m), mass (kg) and time (s)). For this work, the mass input into the equation was the equivalent mass of methane based on equal net energy.

The radiation emitted by a fireball is highly transient and can be approximated by a triangular shape, rising from zero to a peak value half-way through the fireball duration and then dropping back to zero at the end of the fireball. The fireball was then modelled as a sphere with hemi-spherical point sources all over the flame surface (the distributed point source approach as detailed in Hankinson and Lowesmith [2012], which was shown to be a more accurate method for calculating incident radiation at all locations around a flame). A fraction of heat radiated of 0.15 was taken, based on the fraction of heat radiated measured for large scale hydrogen jet fires.

The remaining liquid which is not involved in the fireball event forms a pool, which spreads and evaporates as described in Section 6.3 above. The radiation from the pool fire is predicted using a model developed by LU, which is a modified version of the FIRE2 pool fire model [Pritchard and Binding, 1992]. Once again, the LH2 pool fire is assumed to behave in a similar manner to an LNG pool fire of equivalent net power. The result of this assumption is that the length of the flame for a LH2 pool fire is longer than an LNG pool fire of the same diameter. The mass burning rate inferred for LH2 was $0.15\ kg\ m^{-2}\ s^{-1}$, for a large pool, which compares with a value of approximately $0.14\ kg\ m^{-2}\ s^{-1}$ measured for LNG [Pritchard and Binding, 1992]. The radiation emitted from the flame surface was determined using the distributed point source approach [Hankinson and Lowesmith, 2012]. Again, a fraction of heat radiated of 0.15 was assumed. However, a value of 0.25 was cited by Zabetakis and Burgess [1961] for LH2 pool fires.

For the instantaneous spill events of C5 (3, 17.5 and 700 tonnes), the radiation with time from the fireball event and pool fire were added (as vectors) and the hazardous areas to the specified dose levels (Section 5.3.1) determined in order to assess the consequence severity. Not surprisingly, for such large catastrophic events, the severity band for all these cases was 4 or 5 (see Table 2). Although the severity category was lower for the liquefaction site, this is as a result of the assumed much lower population density.

6.4 BLEVEs (C7)

A BLEVE (Boiling Liquid Expanding Vapour Explosion) arises when a liquid contained in a vessel is superheated (most likely due to an external fire event). The pressure may rise sufficiently that vessel failure occurs (due to the stress exceeding the vessel strength due to weakening of the vessel by the elevated temperature). The result is an instantaneous release of the entire contents. As such an event is associated with an external fire on the vessel, it is assumed that ignition will occur immediately and hence a fireball event involving the entire inventory of the vessel takes place. Missiles will also be generated from vessel fragments and overpressure will also be generated. However, it is usually the fireball event that dominates the size of the hazardous area.

For this study, BLEVEs with an inventory of 3, 17.5and 700 t were modelled using the LU fireball model described in Section 6.3.2. As expected, for these catastrophic events, the resulting severity assessments were all category 5 (see Table 2).

6.5 Gas Accumulation within a Building and Subsequent Explosion (C9, C12, C19)

In the event of a release within a building, a flammable gas accumulation may occur depending on the release rate, volume of the building and the ventilation rate. Once flammable, the potential for an explosion arises leading to flame engulfment of anyone within a building and the generation of overpressure.

A simple approach to modelling these cases has been taken. Firstly, the gas accumulation was assessed using the 'well-mixed' model, assuming uniform concentration throughout the building. A ventilation rate of 8 ach (air changes per hour) was assumed. The time to reach the LFL (4%) was determined and the time to reach a stoichiometric mixture. If a stoichiometric concentration could be formed, then the explosion overpressure was calculated at stoichiometric conditions assuming ideal gas behaviour and the adiabatic flame temperature. If a stoichiometric mixture could not be achieved, then the assessment of overpressure was performed at the maximum concentration that was possible (assuming this exceeded the LFL).

The consequence severity was then determined using the criteria specified in Section 5.3.2.

6.5.1 Cold GH2 into a Building (C9)

The 12 cases of C9 encompass releases at 2 and 8 barg from hole sizes from 5 to 50 mm diameter into a building representing a refuelling station (12 m x 20 m x 5 m) or into the building housing the liquefier (30 m x 90 m x 15 m). For the 5 mm diameter releases into the larger building it was not possible to achieve a flammable mixture and these cases resulted in severity category 1. For the smaller building with a 2 barg release, it took 8.7 minutes to reach LFL and so it was determined that no fatalities would occur. Nevertheless, the event was assessed as category 4 on the basis of the level of damage.

Many of the other cases of C9 resulted in high consequence events as summarised in Table 2.

6.5.2 Ambient Hydrogen into Liquefier Building (C12)

The 3 cases of C12 consider leaks (2 to 10 mm diameter) from the 80 barg pipeline supplying the liquefier, into the liquefier building. Only the 10 mm diameter case was capable of producing a flammable mixture (in 20 minutes), and achieved a maximum of 4.3%. The severity category was determined as 3 (moderate damage). The results are summarised in Table 2.

6.5.3 MR Release into Liquefier Building (C19)

Two cases of a release of MR into the liquefier building were considered (10 and 25mm diameter). Neither was capable of producing a flammable mixture (3%), and hence the consequence severity category was determined as 1.

6.6 Confined Explosion within a Vessel or Pipework (C8, C16, C17, C18)

These cases consider a stoichiometric flammable mixture within a storage vessel (C8), cold box (C16), purifier vessel (C17) or pipework (C18), such as might arise following inadequate purging. The mixture is assumed to ignite and the maximum overpressure was assessed by assuming ideal gas behaviour and using the adiabatic flame temperature. This overpressure was then compared with the calculated failure pressure of the containment vessel. In no case was vessel failure expected to occur. Nevertheless, some level of damage is to be expected which was estimated to be 'major' (category 4) or 'massive damage' (category 5). Explosions within pipework (C18) are expected to accelerate to result in detonation and cause failure. Again, this was classified as 'major' damage.

6.7 Solid O2/LH Explosion (C13)

In the event of air ingress, cold LH2 may cause solid oxygen deposits which can present an explosion hazard. The LH2/solid O2 is pressure sensitive and can result in an explosion, triggered by compression, such as within a valve seat. Such an event is expected to cause major damage (category 4).

Table 2: Consequence Severity Categories for Generic Assessments

Results:C1 CONSEQUENCE SEVERITY BAND (URBAN)				
Case	2mm	5mm	25mm	50mm
2bar V @1m	1	1	2	3
2bar V @ 3m	1	1	1	1
2bar H @ 1m	1	1	3	4
2bar H @ 5m	1	1	1	4
8bar V @1m	1	1	2	4
8bar V @ 3m	1	1	1	3
8bar H @ 1m	1	1	4	5
8bar H @ 5m	1	1	4	5
Results: C2 CONSEQUENCE SEVERITY (URBAN)				
	2mm	5mm	25mm	50mm
2bar V @1m	1	1	3	3
2bar V @ 3m	1	1	2	3
2bar H @ 1m	1	2	3	4
2bar H @ 5m	1	1	3	3
8bar V @1m	1	2	3	4
8bar V @ 3m	1	2	3	4
8bar H @ 1m	1	2	4	4
8bar H @ 5m	1	2	3	4
Results:C3 CONSEQUENCE SEVERITY BAND (URBAN)				
Case	2mm	5mm	25mm	50mm
2bar H @ 1m	1	1	4	5
8bar H @ 1m	1	2	4	5
Results:C4 CONSEQUENCE SEVERITY BAND (URBAN)				
Case	2mm	5mm	25mm	50mm
2bar H @ 1m	2	2	4	5
8bar H @ 1m	2	3	4	5
Results:C5 CONSEQUENCE SEVERITY BAND (URBAN)				
Case	3t no bund	3t bunded	17.5t	700t
100mm	5		5	5
instant	5	5	5	5
Results:C6 CONSEQUENCE SEVERITY BAND (URBAN)				
Case	100mm	3t	17.5t	700t
2m/s	5	5	5	5
6m/s	5	5	5	5
Results:C7 CONSEQUENCE SEVERITY BAND (URBAN)				
Case	3t no bund	17.5t	700t	
instant	5	5	5	
Results:C8 CONSEQUENCE SEVERITY BAND (URBAN)				
Case	3t	17.5t	700t	
	4			

Results:C1 CONSEQUENCE SEVERITY BAND (FACILITY)				
Case	2mm	5mm	25mm	50mm
2bar V @1m	1	1	1	1
2bar V @ 3m	1	1	1	1
2bar H @ 1m	1	1	2	2
2bar H @ 5m	1	1	1	2
8bar V @1m	1	1	1	2
8bar V @ 3m	1	1	1	2
8bar H @ 1m	1	1	2	3
8bar H @ 5m	1	1	2	3
Results: C2 CONSEQUENCE SEVERITY (FACILITY)				
	2mm	5mm	25mm	50mm
2bar V @1m	1	1	1	2
2bar V @ 3m	1	1	1	2
2bar H @ 1m	1	1	2	2
2bar H @ 5m	1	1	1	2
8bar V @1m	1	1	2	2
8bar V @ 3m	1	1	2	2
8bar H @ 1m	1	1	2	3
8bar H @ 5m	1	1	2	2
Results:C3 CONSEQUENCE SEVERITY BAND (FACILITY)				
Case	2mm	5mm	25mm	50mm
2bar H @ 1m	1	1	2	3
8bar H @ 1m	1	1	3	3
Results:C4 CONSEQUENCE SEVERITY BAND (FACILITY)				
Case	2mm	5mm	25mm	50mm
2bar H @ 1m	1	1	3	3
8bar H @ 1m	1	1	3	3
Results:C5 CONSEQUENCE SEVERITY BAND (FACILITY)				
Case	3t no bund	3t bunded	17.5t	700t
100mm	4		4	4
instant	5	5	5	5
Results:C6 CONSEQUENCE SEVERITY BAND (FACILITY)				
Case	100mm	3t	17.5t	700t
2m/s	4	4	4	5
6m/s	4	4	4	4
Results:C7 CONSEQUENCE SEVERITY BAND (FACILITY)				
Case	3t no bund	17.5t	700t	
instant	5	5	5	
Results:C8 CONSEQUENCE SEVERITY BAND (FACILITY)				
Case	3t	17.5t	700t	
	4	4	4	

Results: C9 CONSEQUENCE SEVERITY (Urban Building)			
Case	**5mm**	**25mm**	**50mm**
2bar,Small Vol	4	4	4
2bar,Large Vol	1	3	5
8bar,Small Vol	4	4	4
8bar,Large Vol	1	5	5

Results: C9 CONSEQUENCE SEVERITY (Facility Building)			
Case	**5mm**	**25mm**	**50mm**
2bar,Large Vol	1	3	4
8bar,Large Vol	1	4	4

Results:C10 CONSEQUENCE SEVERITY BAND (FACILITY)			
Case	**5mm**	**25mm**	**Rupture**
20bar V	1	1	2

Table 2 (cont'd): Consequence Severity Categories for Generic Assessments

Results:C11 CONSEQUENCE SEVERITY BAND (FACILITY)			
Case	**2mm**	**5mm**	**10mm**
80bar H	1	1	2

Results: C12 CONSEQUENCE SEVERITY (Facility Building)			
Case	**2mm**	**5mm**	**10mm**
80bar, LgVol	1	1	3

Results: C13 CONSEQUENCE SEVERITY (Urban)	
	4

Results: C13 CONSEQUENCE SEVERITY (Facility)	
	4

Results:C14 CONSEQUENCE SEVERITY BAND (FACILITY)		
Case	**10mm**	**25mm**
25bar H	1	1

Results: C15 CONSEQUENCE SEVERITY (FACILITY)		
	10mm	**25mm**
25 bar H	1	2

Results: C16 CONSEQUENCE SEVERITY (FACILITY)		
Case	**MR**	**H2**
Cool box	5	5

Results: C17 CONSEQUENCE SEVERITY (FACILITY)		
Case		**H2**
Purifier		**4**

Results: C18 CONSEQUENCE SEVERITY (FACILITY)		
Case		**H2**
Pipework		**4**

Results: C19 CONSEQUENCE SEVERITY (Facility Building)		
Case	**10mm**	**25mm**
25barg	1	1

7 Qualitative Risk Matrix of LH2 Transportation and Storage at a Re-fuelling Station

As described in Section 5.2, the list of 60 untoward events identified during a HAZID [Hankinson et al, 2013], identified a range of consequences within the generic list C1 to C9 and C13. The likelihoods were estimated as described in Section 5.3.

Based on the consequence assessments for these cases as described in Section 6, this enabled completion of a Qualitative Risk Matrix with 1093 entries. The number of cases falling with each area of the QRM is shown in Figure 8.

LH2 Transportation and Storage QRM			Consequence Severity				
			1	2	3	4	5
			Slight Effect No Damage	Minor Injury Minor Damage	Major Injury Moderate Damage	Up to 3 Fatalities Major Damage	More than 3 Fatalities Massive Damage
Likelihood	5	Probable	10	9	1	0	0
	4	Very Possible	92	17	6	1	0
	3	Possible	157	42	31	29	1
	2	Unlikely	154	72	42	35	23
	1	Extremely Unlikely	34	21	74	121	121

Figure 8: QRM for LH2 Road Transportation and Storage

Two of the 3 cases in the red area of the QRM are associated with horizontal venting at 5 m above ground of cold GH2 from a 25 or 50 mm diameter relief at 8 barg. The same releases in a vertical direction (from 3 m above ground) fell into the green (25 mm diameter) and yellow (50 mm diameter) regions, showing the benefits of venting vertically from an elevated position.

The third case in the red area arose from a vertical 8 barg gaseous release at 3 m above ground with delayed ignition. The consequence assessment did not suggest any fatalities, (category 3). However, the untoward event being considered was over-pressurisation due to failing to follow the procedure. Since such events were identified during a review of incidents, a likelihood of ~ 0.1 per year was estimated, (likelihood category 5). Hence the risk fell into the red area. It is possible that the likelihood has been over-estimated. Nevertheless, it emphasises the importance of compliance with procedures.

25% of the cases fell into the yellow region. In general terms, releases in the yellow region were usually associated with liquid rather than gaseous releases, as liquid releases result in increased mass flow rate, and the extent of a hazardous region is closely linked to the mass released. Furthermore, these releases were assumed to occur close to ground level. Some high pressure (8 barg) gaseous releases also fell into the yellow area, especially if the release was horizontal and near the ground.

As expected, high consequence events (such as catastrophic failure of tanks or the road tanker) fell into the bottom right hand corner of the QRM, indicating high consequence severity but very low likelihood. A BLEVE of a road tanker was the single most severe event and could cause fatalities within a 120 m radius.

8 Qualitative Risk Matrix of LH2 Liquefaction and Storage at Production Facility

Forty three untoward events identified during a HAZID [Hankinson and Lowesmith, 2013], were studied and the consequences assessed using the generic list of consequences

C1 to C19. The likelihoods were estimated as described in Section 5.3.

Based on the consequence assessments for these cases as described in Section 6, this enabled completion of a Qualitative Risk Matrix with 351entries. The number of cases falling with each area of the QRM is shown in Figure 9.

LH2 Transportation and Storage QRM			Consequence Severity				
			1	2	3	4	5
			Slight Effect No Damage	Minor Injury Minor Damage	Major Injury Moderate Damage	Up to 3 Fatalities Major Damage	More than 3 Fatalities Massive Damage
Likelihood	5	Probable	16	0	0	0	0
	4	Very Possible	104	9	1	0	0
	3	Possible	50	27	13	9	0
	2	Unlikely	41	38	10	4	3
	1	Extremely Unlikely	1	8	2	8	14

Figure 9: QRM for Liquefaction and Storage

It is assumed that the liquefaction plant is not in an urban area and is within an industrial complex with controlled and limited access. This means that a limited number of persons are at risk. The result was that most assessments did not give rise to fatalities, although potentially some injury could arise. 15% of the cases fell into the yellow area, compared with 25% for the QRM for transport and storage at a re-fuelling station.

Events that fell into the yellow region included gaseous releases at 8 barg from a 50 mm hole and LH2 releases from holes of 25 mm diameter and above, although no fatalities were predicted.

Fatalities only arose from large releases of hydrogen (≥ 25 mm diameter) into the liquefier building or from major or catastrophic failures of storage vessels. As for the QRM for transport and storage, the highest consequence event was a BLEVE of a storage tank (C7), which is an extremely unlikely event. However, the hazard range within which fatalities might occur could be 1 km and, as such, would probably extend outside the site boundary. Depending on the density of the local population around the facility, significant numbers of persons could be within this hazardous area. This emphasises the need to take appropriate mitigation measures to prevent such an event occurring.

Some mitigation of storage tank failures was already assumed within this QRM, as it was assumed that the storage tanks would be surrounded by bunds. This helps to reduce the hazardous region in the event of tank failure (category 4 in some cases). However, consideration should be given to the extent of the hazardous area and whether it extends beyond the site boundary. In which case, the consequence severity may increase to 5. In the event of tank failure and ignition of the spill (C6), the hazardous region will probably extend outside the site boundary, as it was of the order of 800 m in radius.

Some cases fell within the yellow region of the QRM with consequence severity 4 or 5, but without any fatalities. These were associated with explosion events inside the liquefier components or pipes. Although no persons are expected to be injured, major or massive damage could arise and hence the consequence severity was 4 or 5.

The generally lower risk and reduced fatalities for this QRM compared to that for the road transportation and storage at a re-fuelling station reflects the controlled environment expected for a liquefaction plant, with fewer people in the area, and greater control over events (for example, reduced risk of third party damage occurring).

In addition, much of the process is contained within a vacuum insulated box making limited opportunity for a flammable accumulation to form following a release. The process will also include detection systems to identify leaks at an early stage. Hence, during normal operation, conceivable untoward events are few. The greatest opportunity for the formation of a flammable mixture arise during commissioning or decommissioning of the process or storage vessels and during regeneration of the purifier, as inadequate purging could allow oxygen ingress to mix with fuel. At these times there are also likely to be more personnel present undertaking such operations.

9 Mitigation

In general terms, mitigation measures could be preventative, that is, measures taken to reduce the likelihood of an accidental release in the first place, or they could be ameliorative, that is, to make the consequences of a release less harmful. Preventative measures could include:

- Good design in general
- Well designed vent system
- Process monitoring (pressure, temperature, gas concentration)
- Safety detection systems for leaks
- Robust procedures and staff training
- Inter-locks to prevent non-compliance with procedures
- Minimum sizing of vulnerable components, such as transfer hoses

As noted in Section 3.2.2, vent systems should be designed assuming that ignition could occur. Venting vertically at high elevation reduces the hazard presented by vent stacks, whether ignition occurs or not. Vent systems also need to be well designed and located so that they have adequate capacity in the event of emergency blow-down or high venting rates in the event of over-pressurisation.

Ameliorative measures include the use of fire-fighting systems or fire/blast walls although care needs to be taken to ensure that mitigation of one hazard does not increase the severity of another – for example, the use of confining walls may reduce a fire hazard beyond the wall but its presence may increase the likelihood of gas accumulation and the severity of an explosion. The use of bunds around storage tanks will extend the duration of certain hazardous events (such as fires) but will reduce the hazard range and it is expected that bunding of large storage tanks would be undertaken.

10 Societal Risk

Although this study is a qualitative risk approach, as an indication of societal risk, the data for cases entered in the QRMs were used to generate a societal risk curve (see Section 3.1). For this purpose, failure frequencies were attributed to the likelihood categories as indicated in Section 5.1, namely:

- 1: 10^{-9} per year
- 2: 10^{-7} per year
- 3: 10^{-5} per year
- 4: 10^{-3} per year
- 5: 10^{-1} per year

The number of fatalities predicted for all the events with a consequence severity of 4 or 5 were then identified. Using this data, a societal risk curve for the road transportation and storage was generated as shown in Figure 10 below.

Figure 11 presents an indicative societal risk curve from the liquefaction and storage at the process site. Note that this does not account for additional fatalities outside the process site from the largest hazard distance events.

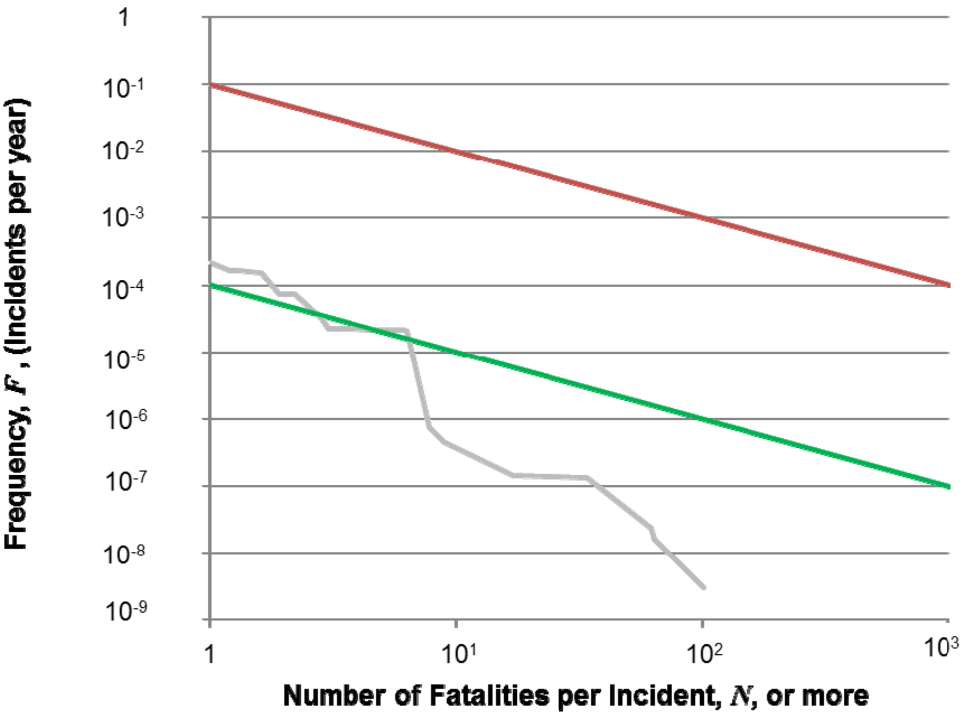

Figure 10: Indicative Societal Risk Curve for Road Transportation and Storage

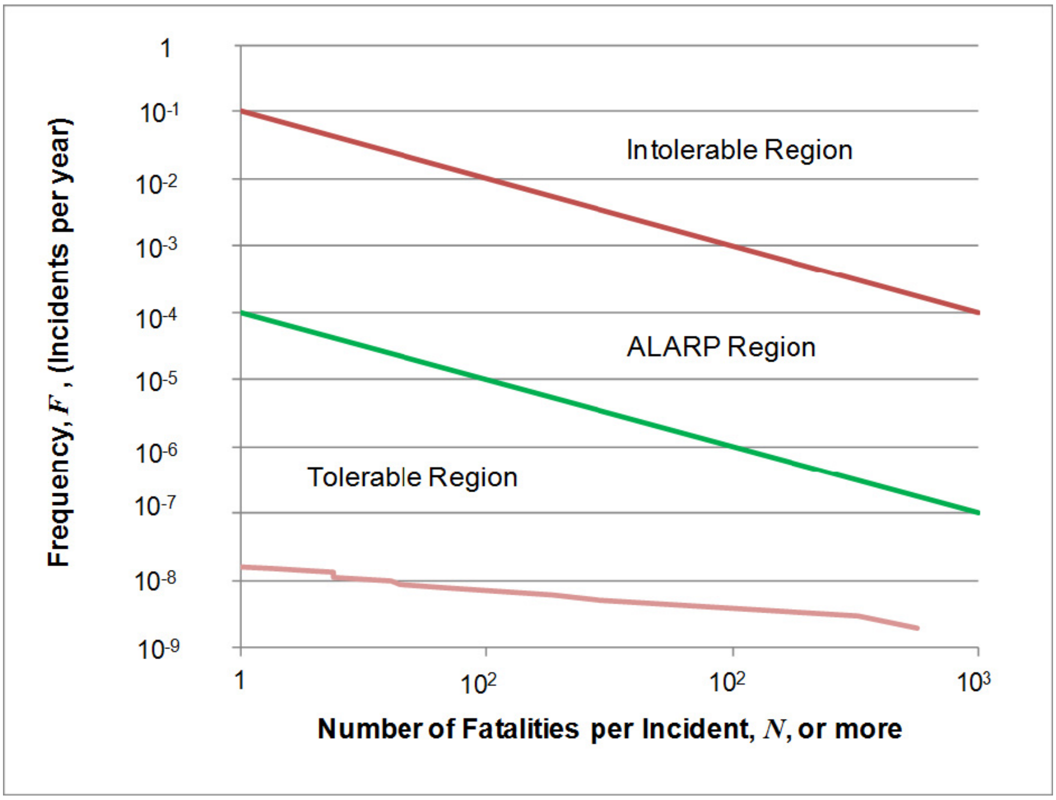

Figure 11: Indicative Societal Risk Curve for Hydrogen Liquefaction and Storage at the Process Site

11 Discussion and Conclusions

This qualitative risk assessment exercise for the liquefaction of hydrogen and its transportation to re-fuelling stations has highlighted some of the problems that will need to be addressed for a full quantitative risk study. In particular:

- The lack of available models that can be applied to LH2 releases
- The lack of large scale experimental data which could be used to develop and validate models to assess LH2 hazardous releases
- The lack of experimentally determined parameters needed by such models
- The lack of quantitative data on failure frequency and ignition probability
- The lack of ability to model explosions where the potential for DDT is significant

Nevertheless, the exercise has provided an indication of the relative risk and the areas in which to focus attention to reduce risk, most notably:

- The design (height and orientation) of vents
- Ensuring that procedures are followed (including use of inter-locks)
- Ensuring adequate purging during commissioning/decommissioning
- The avoidance of allowing large instantaneous and high mass flowrate releases

Compared to Moonis et al [2010], the extent of areas in which fatalities are expected from the most severe events was less during this study. This is probably due to the substantially different harm criteria adopted. For example, Moonis et al [2010] assume significant risk of fatality for an overpressure of 0.1379 bar, considerably lower than adopted for this study.

In conclusion, this qualitative risk study has identified that a higher risk is presented by the road transportation and storage of LH2 into urban areas compared to the liquefaction process and storage at the liquefier plant. This is due to a combination of factors including the higher population density in urban areas, the presence of third parties over which operators do not have control and manual operations (such as tanker offloading) where there is potential for procedures not to be followed.

Areas where additional information is needed in order to perform a quantitative risk analysis have also been identified.

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