APPLICATION OF PIPELINE QRA METHODOLOGIES TO HYDROGEN PIPELINES IN SUPPORT OF THE TRANSITION TO A DECARBONISED FUTURE

Aslam, A[1], Curson, N[2]
[1] Centre of Engineering Excellence, Penspen, Richmond, UK, a.aslam@penspen.com
[2] Centre of Engineering Excellence, Penspen, Richmond, UK, n.curson@penspen.com

ABSTRACT

Hydrogen is expected to play a key role in the decarbonised future of energy. For hydrogen distribution, pipelines are seen as the main method for mass transport of hydrogen gas. To support the evaluation of risk related to hydrogen pipelines, a revised QRA methodology is presented based on currently available and industry accepted guidance related to natural gas. The QRA approach is primarily taken from HSE UK's MISHAP methodology [1]. The base methodology is reviewed, and modifications suggested to adapt it for use with hydrogen gas transport. Compared to natural gas, it was found that the escape distances for hydrogen (based on the degree of heat flux) were lower. However, as for the overall risk, for both individual and societal, the case with hydrogen was more severe close to the pipeline. This was driven by the increased ignition probability of hydrogen. The approach may be used as part of the review and appraisal process of hydrogen projects

1.0 INTRODUCTION

As the energy transition gathers pace on the backdrop of increasing concern around climate change and need to decarbonise, the use of hydrogen as an energy source is seen as a key enabler. The case for hydrogen has been assessed for some years and now firm steps are being taken to make the hydrogen economy a reality. Various pilot schemes around the world have been completed or in progress, such as HyNet, Acorn Hydrogen and H21 in the UK. As part of the hydrogen economy, its transportation via pipelines is expected to play a key role to connect the supply side with end-point users.

To facilitate onshore pipeline developments, a Quantitative Risk Assessment (QRA) is widely used in natural gas and liquid pipeline transportation. Introducing hydrogen as an alternative fuel, its transportation via pipelines could be as a mixture with natural gas or pure hydrogen. The latter may require new pipelines primarily owing to issues of steel embrittlement, although this is still an area of ongoing research. In both cases, to support the evaluation of hydrogen pipeline transport, a QRA methodology is presented. The primary source is HSE UK's MISHAP [1] methodology for which Penspen have an in-house software tool for pipeline QRA assessments. The MISHAP approach is discussed in this paper with modifications for use with hydrogen based on latest industry literature.

It is noted that hydrogen pipeline transport is relatively less understood than natural gas transport with various research activities currently underway or planned, such as consequence modelling (specifically jet fire models for hydrogen-methane mixtures). Further maturity in the understanding of hydrogen transport, either as a mixture or on its own, is expected to affect QRA methodologies. This paper presents a robust methodology to support concept project evaluation based on state-of-the-art techniques and knowledge.

2.0 THE QRA PROCESS

The use of QRA for onshore pipelines is standard practice in the UK and elsewhere. The general methodology is well established in industry to identify and manage risks. Figure 1shows a typical QRA process with the key steps.

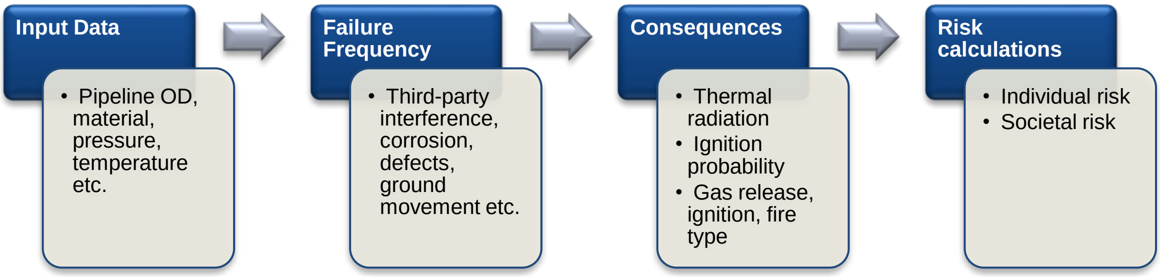

Figure 1 Typical QRA Process

3.0 INPUT DATA

Most of the input parameters can be used directly as is the case with natural gas; this includes pipeline size, coatings, terrain etc. However, there are a few parameters that are affected by the introduction of hydrogen and are discussed below.

3.1 Pipeline Pressure

The operating pressure is a key input parameter for a QRA. The energy density by volume of hydrogen is approximately a third of that for natural gas. However, hydrogen's density is ~8 times lower meaning its volumetric flow rate (for the same pressure drop) is higher – see Table 1 (mass flow rate for hydrogen is still lower compared to natural gas). It can be shown the net result is a small reduction in energy transported via hydrogen [8] [9]. Thus, based on an energy transport basis, the operating pressure is similar to that of current natural gas pipelines. There are other possible reasons why the pressure could be different; most likely the pressure would be reduced to counter the risk of embrittlement (which would need to be balanced with a consequent reduction in transported energy).

3.2 Pipeline Material

The main concern from transporting hydrogen in steel in pipelines is embrittlement. This is a known failure mechanism, primarily from experience with "sour" hydrocarbons containing high hydrogen sulphide content. Causes of embrittlement are mainly related to the pipeline material and operating conditions, including hydrogen concentration. Embrittlement is characterised by a loss of ductility due to hydrogen diffusion into surface flaws resulting in increased sensitivity to fatigue. It is a time-dependent phenomenon with failure occurring at stress levels well below the yield limit [5] [10]. Higher pressures increase the risk of embrittlement. A combination of steel grade and operating pressure can be suitably selected for safer operation. If using existing pipelines, the material is a given and so the pressure may need to be reduced if embrittlement is found to be a potential issue. Embrittlement is more pronounced in higher strength steels. Indeed, the design of existing hydrogen pipelines is based on steel with low yield strengths and with low carbon and manganese content [10].

Figure 2 presents a summary of the UK NTS pipeline by steel grade [11]. This shows 89% of the NTS network is steel grade X60 or lower. 90% of the network operates between 70-80bar.

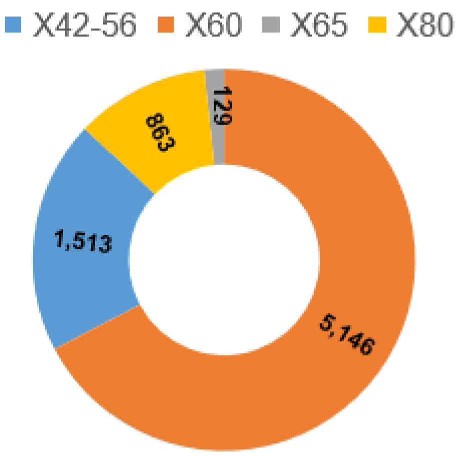

Figure 2 UK NTS Breakdown by Steel Grade (in km)

Based on limited research data, for a hydrogen-natural gas mixture with 25% molar volume of hydrogen embrittlement for X70 steel was not observed [2]. The QRA methodology presented herein assumes embrittlement is not a likely failure mechanism (whether in an existing pipeline or in a suitably designed new pipeline) and should be used with low strength steel grades (assumed to be X60 or lower).

3.3 Product

A comparison of key parameters for methane and hydrogen is presented in see Table 1. Of note, particularly for a QRA, is the increased flammability range, lower ignition energy and the higher heat of combustion.

Table 1 Methane & Hydrogen Properties

Parameter	Units	Methane	Hydrogen
Gas properties			
Molecular Mass	g/mol	16.04	2.016
Heat of Combustion (lower heating value)	kJ/kg	50,000	119,960
Higher Heating Value	kJ/m^3	39,800	12,700
Specific Heat Ratio	-	1.31	1.41
Combustion properties			
Stoichiometric Fuel Volume Fraction	%	9.5	29.5
Adiabatic Flame Temperature	K	2226	2380
Flammability limits	% vol.	5-15	4-75
Minimum Ignition Temperature	K	905	845
Minimum Ignition Energy	J	33×10^{-5}	2×10^{-5}

The wider flammability range and significantly lower minimum ignition energy combine to make hydrogen more hazardous. The ignition energy at the lower flammability limit is like that of methane, however, this rapidly reduces with increasing hydrogen concentration. Hydrogen has been reported to ignite even from unintended small static electricity discharge [10].

4.0 FAILURE FREQUENCY

Pipeline failure statistics, mainly for hydrocarbon transport, are well documented with various databases available; UKOPA being the main one for the UK [17]. There remains inherent uncertainty in the use of these statistics particularly for higher grade materials for which the available historical data is relatively sparse. Even with available data due care is required in its use for QRAs, with engineering judgment often used to make appropriate assumptions for the particular pipeline being assessed.

For hydrogen, given only a small number of hydrogen pipelines around the world exist, the available data is insufficient for direct use. The total estimated length of hydrogen pipelines is less than 0.1% of that for natural gas pipelines. Although there is some data for hydrogen failures, the majority of these are in process plants [12], and as such are not directly applicable for transmission pipelines.

A closer examination of pipeline failure statistics indicates the main source of failure is due to third-party interaction [13]. This threat is, generally, equally applicable irrespective of the transported medium. For the QRA calculation the assumption is to use the same failure statistics as for natural gas pipelines. It represents a suitable risk level to facilitate concept evaluation of hydrogen pipelines. The main concern with hydrogen being injected into existing steel pipelines designed for natural gas is material embrittlement and leakages. For new pipelines designed for hydrogen specifically, these concerns are assumed to be adequately addressed through design. Whilst the potential increased risk is acknowledged; this can be addressed on a case-by-case basis, depending on hydrogen concentration, pipeline history, mitigation measures etc.

Table 2 Failure Statistics for Gas Pipelines [13]

Source	3rd Party	Internal Corrosion	External Corrosion	Material – Construction	Cracking – SCC	Natural Causes, Geotechnical	Other - Unknown
EGIG	48%	0.5%	13%	17%	2.5%	8%	11%
UKOPA	22%	1%	20%	28%	16%	5%	8%
DOT-PRCI	43%	16%	14%	8%	1%	10%	8%
TRANSPERTO	67%	0%	33%	0%	9%	0%	0%

5.0 CONSEQUENCE

The HSE MISHAP guidance has the following key components for consequence analyses [1]:

- Gas release modelling (LOSSP model for gases)
- Fireballs
- Jet fire models

5.1 Gas Release

The gas release model (LOSSP) is considered appropriate for hydrogen gas. A comparison of the gas release rate for methane and hydrogen is shown in Figure 3. Owing to the reduced density of hydrogen, the release rate is approximately one-third that of methane.

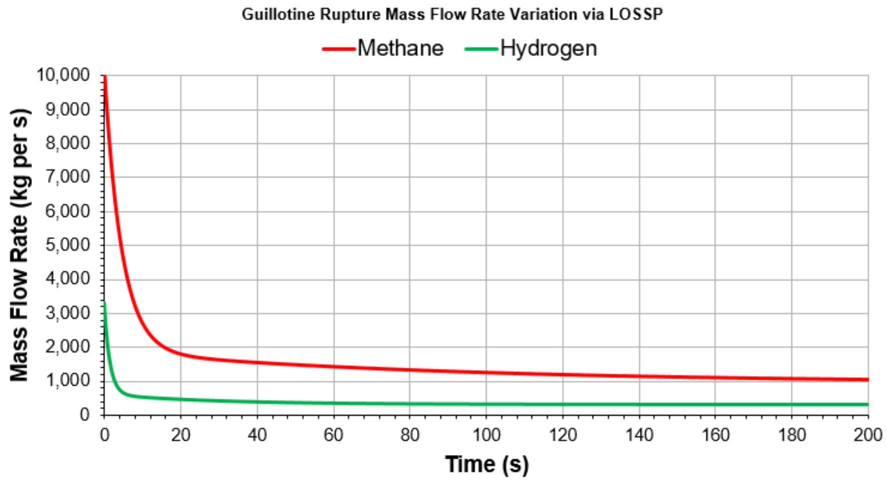

Figure 3 Mass Flow Rate Comparison – Full Bore Rupture (ID = 0.7m, 70 bar)

5.2 Fireballs

The MISHAP fireball model (“FBALL”) [1] is considered adequate for use with hydrogen. The surface emissive power (SEP) and the substance-specific A-factor (which relates the radius of the fireball to its mass) are suitably selected for hydrogen. The SEP value is not well defined for hydrogen based on a literature search and so the same value as for natural gas has been conservatively used in the model from the MISHAP guidance [1]. The “A-factor” is also not well defined in literature, although a value of 7.93 is used based on an existing study [18]. It is also noted that the fireball risk, compared to a jet fire, is relatively lower and thus does not materially impact the final result.

5.3 Jet Fires

There are two main jet fire models in MISHAP12 [1]; one specifically for natural gas (“PIPEFIRE”) and another for “other substances” (“JIF/MAJ3D”), though it is not stated whether this includes hydrogen. This is based on Chamberlain’s flame model, which employs a multi-point radiation source approach. The ASME B31.12 code for hydrogen piping and pipelines [14], presents an alternative methodology for jet fire radiation, which collapses the heat emitters into a single point emitter at ground level [6]. The methodology is the same as their natural gas model, found in ASME B31.8S [15], however it has been specifically adapted for hydrogen [7]. A comparison between the ASME and HSE MISHAP JIF/MAJ3D model for hydrogen was performed, which showed the ASME model is more conservative. Given the uncertainty with hydrogen, the ASME model was adopted to determine the jet fire heat flux, whilst the remaining methodology follows MISHAP guidance (for thermal dosage limits etc.). It is, however, noted that the ASME model has not been experimentally validated for hydrogen.

The ASME model is based on a study by the Gas Research Institute (GRI) [6], which was subsequently updated for other gases [7], from which the “potential impact radius” formula quoted in ASME B31.12 [14] and ASME B31.8S [15] is taken. The heat flux, I, from a jet fire flame from the ASME model is calculated as follows:

$$I = \frac{\eta . X_g . Q_{eff} . H_c}{4\pi r^2} \tag{1}$$

Where:

$\eta = combustion\ efficiency\ factor$

$X_g = emmissivity\ factor$

$H_C = heat\ of\ combustion\ in\ [kJ/kg]$

$r = horizontal\ distance\ from\ source\ to\ target\ [m]$

$Q_{eff} = gas\ release\ rate\ in\ [kg/s] = 2\lambda C_d \frac{\pi d^2}{4} p \frac{\varphi}{a_0}$

$\lambda = release\ decay\ factor$

$C_d = Gas\ discharge\ ratio$

$d = hole\ diameter [m]$

$\varphi = flow\ factor = \gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\ \ where\ \gamma = specific\ heat\ ratio$

$a_0 = sonic\ velocity\ [m/s]$

As part of the update for hydrogen, additional considerations for the combustion, release decay and emissivity factors were made [7]. Table 3 presents a comparison of these factors for methane and hydrogen.

Table 3 ASME Jet Fire Model Parameters – Methane vs Hydrogen [7]

Parameter	Methane	Hydrogen [6]
Combustion efficiency factor	0.35	
Emissivity factor	0.20	0.15
Release decay factor	0.33	0.24

ASME B31.8S [15] and ASME B31.12 [14] provide an equation for the "Potential Impact Radius" (PIR), which is based on the above formulation. The equation is setup to give the radius at the 1% fatality dosage (15.8kW/m^2). The equations as presented in the codes are:

$$Methane\ (B31.8S\ [15]) \qquad r = 0.69\sqrt{pd^2} \tag{2}$$

$$Hydrogen\ (B31.12\ [14]) \qquad r = 0.47\sqrt{pd^2} \tag{3}$$

$r = radius\ of\ impact\ (ft),\ p = pipeline\ segment\ maximum\ allowable\ operating\ pressure\ (psig), d = diameter\ of\ pipeline\ (in)$

From these equations, for the same diameter and pressure the implication is an approximate 30% reduction in the PIR value for pure hydrogen compared to methane (for a 20% hydrogen-natural gas mixture, there is <3% difference compared to methane). This comparison is presented to illustrate the difference based on existing codes. However, the proposed Penspen QRA methodology uses the thermal dosage limits as per HSE MISHAP guidance [1] and MISHAP is used for methane/natural gas comparison presented in the case study.

5.4 Ignition Probability

Compared to natural gas, hydrogen is significantly more flammable requiring a considerably lower ignition energy; approximately 1/15th of the natural gas value – see Table 1. Within the HSE MISHAP methodology there are 3 event trees presented; one for natural gas and two for other substances, primarily based on the minimum ignition energy (MIE) [1].

- Natural gas;
- R12 substances with MIE < 0.2 mJ; and,
- R12 substances with MIE ≥ 0.2 mJ.

Hydrogen is included in the R12 substances with a low MIE. However, this tree has flashfire as a possible consequence, which given hydrogen is intrinsically buoyant, flash fires are not applicable and so this event tree does not directly apply [4]. Furthermore, within the R12 substance family, there are other substances with much higher MIE and the event tree may not capture the increased ignition potential of hydrogen. For the QRA an adapted version of the MISHAP event tree for R12 low MIE is used where flashfire is discounted, and the ignition probability increased to reflect hydrogen's higher flammability. The total probability of an even resulting in any fire was increased by almost two-thirds compared to the default MISHAP values. The currently available guidance on ignition probability for hydrogen is not fully defined in literature and is an area of ongoing research. As part of the NaturalHy project, this aspect was assessed experimentally [20]; it was found that the probability of ignition is related to the equivalent ratio (a measure of the actual air/fuel ratio versus a stoichiometric reaction) and the energy level of the source. A degree of engineering judgment is required for use within a QRA framework. For a project, a sensitivity study is recommended to quantify the impact on the results and safety distances. This is further discussed in the case study.

6.0 RISK

To compute the individual and societal risk, the methodology of MISHAP is used [1], which is incorporated in the software. This includes the various dosage limits for which safety distances are computed and resulting individual and societal risk curves. The approach is generic and unaffected by the transported medium.

7.0 CASE STUDY

An example using the aforementioned methodology is presented. The following cases were considered:

- Full rupture with pure methane using HSE MISHAP methodology [1] throughout. Two diameters were considered; 157mm & 700mm.
- Full rupture with pure hydrogen using the ASME approach for jet fire modelling as detailed above, with the remainder based on HSE MISHAP [1], also with the same 2 diameters.

A summary of the key input parameters common to both methane and hydrogen scenarios is shown in Table 4, which are common to both the methane and hydrogen scenarios.

Table 4 Case Study – Input Parameters

Parameter	Units	Value
Operating Pressure	barg	71
Operating Temperature	°C	15
Pipeline Inner Diameter	mm (inch)	157 (6) & 700 (28)
Material Grade	-	X46
Land Type	-	Rural
Landslide Potential	-	Low
Pipeline Condition	-	Buried (no slabbing)

Table 5 presents a summary of the mass release rate results comparison for a full-bore rupture using HSE MISHAP LOSSP methodology. In addition, results from MISHAP FBALL for the fireball modelling is also presented, along with percentage differences. Due to the light nature of hydrogen the release rate is significantly lower, which also drives the fireball characteristics; the view factor is a function of fireball flame radius.

Table 5 Release Rates & Fireball Modelling – Results Comparison

ID (mm)	Contents	Release Rate (kg/s)		Fireball Mass (t)	Radius (m)	Duration (s)
		Initial	Steady-State			
157	Methane (100%)	523	73	1.3	33	5
	Hydrogen (100%)	170	24	0.2	23	4
	% difference	-67%	-67%	-86%	-31%	-31%
700	Methane (100%)	10,376	2,341	72.8	127	20
	Hydrogen (100%)	3,366	758	11.5	90	14
	% difference	-68%	-68%	-84%	-29%	-29%

Figure 4 shows the heat flux comparison for methane and hydrogen using MISHAP FBALL. As indicated, very close the pipeline the heat flux from hydrogen is slightly higher but then decreases beyond a distance of around 75m for the pipeline case considered.

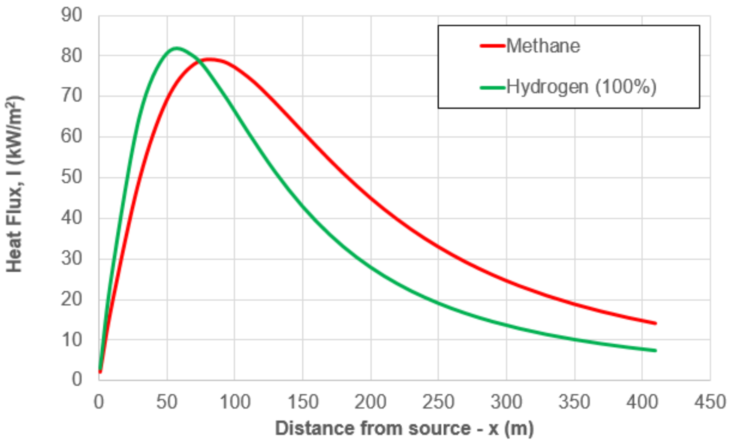

Figure 4 Fireball Heat Flux Comparison (MISHAP FBALL) (ID = 0.7m, 70 bar)

Table 6 presents a comparison of the escape distances, which are typically assessed in MISHAP. Note these are not safe distances but rather distances from which escape is possible in the absence of any available shelter. The results show a reduction for the pure hydrogen case for both the smaller and larger pipeline size. This is primarily driven by the reduced heat flux with hydrogen, due to the smaller fires as a result of the lower mass released rates from a hydrogen pipeline.

Table 6 Safety Distances from a Jet Fire – Results Comparison

ID [mm]	Contents	Spontaneous Ignition (m)	Piloted Ignition (m)	Standard Escape (m)	Vulnerable Escape (m)
157	Methane (100%)	35	53	15	57
	Hydrogen (100%)	28	37	13	30
	% difference	-20%	-31%	-15%	-48%
700	Methane (100%)	131	215	119	349
	Hydrogen (100%)	124	164	104	204
	% difference	-5%	-24%	-13%	-42%

Figure 5 presents a spatial comparison of the standard escape distance for a pipeline segment in a rural setting.

Figure 5 Standard Escape Distance – Methane (red) vs Hydrogen (green) (ID = 0.7m, 70 bar)

To fully assess the safety distance, the risk must be calculated which is typically performed for an individual and society. The methodology used for this is as per HSE MISHAP, which considers more than just ruptures but from three hole sizes.

Figure 6 presents the results for the individual risk for all four cases considered. The risk closer to the pipeline is higher for the hydrogen case. This is primarily driven by the increased ignition probability (built into the event tree). Further away from the pipeline, the risk from hydrogen reduces compared to methane, which reflects the reduced heat flux from hydrogen. The zero-risk distance for the 0.7m ID case for methane is 263m, whilst for hydrogen it is 165m, a reduction of 37%. The results for the small diameter (0.16m ID) are also presented, but the differences are less pronounced; 28% reduction in the zero-risk distance but only a relatively small increase in risk closer to the pipeline.

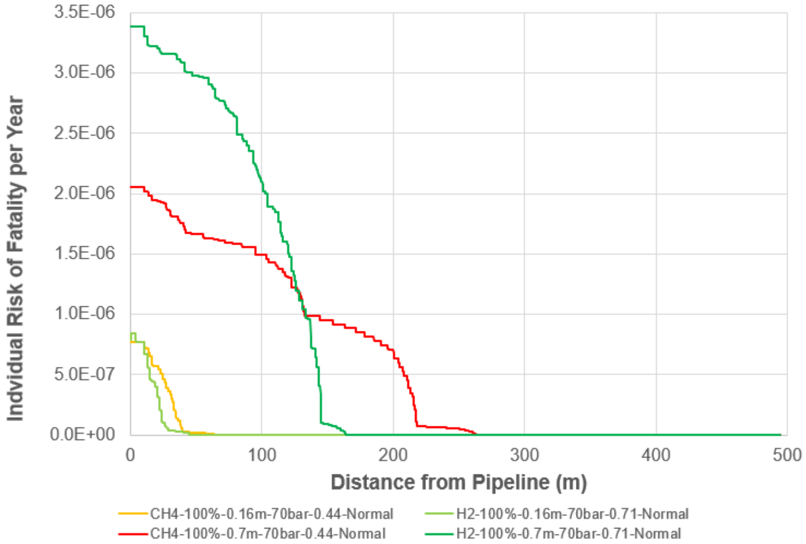

Figure 6 Individual Risk Results

Figure 7 presents the societal risk results against the IGEM TD1 criteria [19]. For the 0.7m ID cases, the societal risk from methane marginally exceeds the IGEM TD1 criteria, whilst for hydrogen the risk is even higher, which is again driven by the significantly higher ignition probability assumed in the event tree. (Note: the intention here is not to determine the absolute risk level to assess mitigations but rather to explore the differences.) The assumed ignition probability was 60% more (probability of all events resulting in a fire) for hydrogen to account for the lower minimum ignition energy and increased flammability range. This value is considered conservative. As noted before, however, it is a function of other factors, such as input energy, and as such would need to be reviewed and assessed on a case-by-case basis. For the small diameter pipeline, the risk for hydrogen is in fact lower than that of methane (ignition probability the same for both diameters).

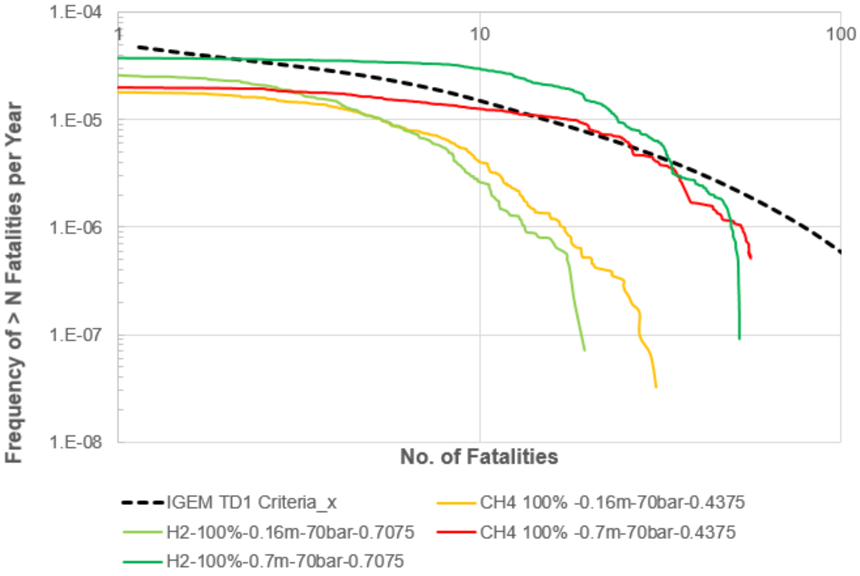

Figure 7 Societal Risk Results

8.0 CONCLUSIONS

A revised QRA methodology, based on the HSE MISHAP guidance, is presented for use with hydrogen pipeline assessments. The main amendment to the MISHAP guidance was made for the jet fire model for which an alternative single-source model used in the ASME codes is adopted. The results show an approximate 30% reduction in the escape distances for hydrogen transport, which is due to the reduced heat flux. However, the significantly higher ignition probability results in an increased individual risk with hydrogen close to the pipeline. The results showed an increased individual risk close to the pipeline with hydrogen, but the risk reduces faster compared to methane resulting in a lower risk further away from the pipeline. Though there is also an increased societal risk, it was only found for the larger diameter pipeline considered. Thus, the increase ignition probability of hydrogen is a key factor to be assessed and its value should be selected with due care.

As acknowledged, various elements are currently being researched further to better define use with hydrogen pipeline QRAs. The methodology presented provides a robust basis for QRAs of hydrogen pipelines based on existing and accepted industry guidance.

9.0 REFERENCES

1. HSE UK, Re-writing MISHAP: The development of MISHAP12 (RR1040), 2015
2. HSE UK, Injecting hydrogen into the gas network – a literature search (RR1047), 2015

3. HSE UK, Report on a Second Study of Pipeline Accidents using the HSE's Risk Assessment Programs MISHAP & PIPERS (RR036), 2002
4. HSE UK, Review of the event tree structure & ignition probabilities used in HSE's pipeline risk assessment code MISHAP, 2015
5. P.E. Dodds, S. Demoullin, Conversion of the UK gas system to transport hydrogen, International Journal of Hydrogen Energy, 2013
6. Gas Research Institute, M.J. Stephens, A Model for Sizing High Consequence Areas Associated with Natural Gas Pipelines (GRI-00/0189), 2000
7. C-FER Technologies, TTO Number 13 – Integrity Management Program – Potential Impact Radius Formulae for Flammable Gases Other Than Natural Gas Subject to 49 CFR 192, 2005
8. Siemens, Hydrogen Infrastructure – The Practical Conversion of Long-Distance Gas Networks to Hydrogen Operation (whitepaper), 2020
9. KU Leuven Energy Institute, The Use of the Natural Gas Pipeline Infrastructure for Hydrogen Transport in a Changing Market Structure, 2008
10. European Commission – Institute for Energy, Techno-Economic Assessment of Hydrogen Transmission & Distribution Systems in Europe in the Mediums & Long Term (2006)
11. National Grid, Hydrogen in the NTS – Foundation Research & Project Roadmap (2019)
12. International Journal of Hydrogen Energy – R. Mohammadam, E. Zarei, Safety Risk Modelling & Major Accidents Analysis of Hydrogen & Natural Gas Releases: A Comprehensive Risk Analysis Framework, 2015
13. ASME, S.B. Cunha, Comparison & Analysis of Pipeline Failure Statistics (IPC2012-90186), 2012
14. ASME B31.12, Hydrogen Piping & Pipelines, 2019
15. ASME B31.8S, Managing System Integrity of Gas Pipelines, 2018
16. NaturalHy, Process Safety & Environemental Protection 90 108-129, B.J. Lowesmith, G. Hankinson, Large scale high pressure jet fires involving natural gas & natural gas/hydrogen mixtures, 2012
17. United Kingdom Onshore Pipeline Operators' Association (UKOPA), UKOPA Pipeline Product Loss & Faults Report (1962-2018), 2020
18. NBS, J. Hord, Is hydrogen safe? Technical Note 690, 1976
19. IGEM/TD/2 Edition 2, Assessing the risks from high pressure Natural Gas pipelines, Communication 1764, Institution of Gas Engineers & Managers, 2013
20. NaturalHy / Loughborough University, G. Hankinson, H. Mathurkar, B.J. Lowesmith, Ignition energy and ignition probability of methane-hydrogen-air mixtures