SAFETY CALCULATIONS FOR EMERGING TECHNOLOGIES

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ABSTRACT

As part of executing 25 hydrogen-based Power to X (PtX) projects, our team of Safety consultants has completed safety and risk assessments for a number of hydrogen production developments. Drawing on this experience we will present the importance of making comparisons between hydrogen specific data sources such as HyRAM, and conventional oil and gas data sets and calculation methods to ensure that project design is carried out to the most appropriate data and provides a robust solution to demonstrate risks are managed. This presentation will be based on case studies where Fire and Explosion Risk Assessments (FERA) and Quantitative Risk Assessments (QRA) were conducted. The frequency calculations for these assessments used the release frequencies and ignition probabilities provided in HyRAM. However, it is noted that the HyRAM ignition probabilities are derived from a correlation from oil and gas assessments in the 1990s. The oil and gas approach has moved on from this data source, and now derives ignition probabilities based on the type of facility and fluid characteristics. To address this evolution, a comparison was made between the leak frequencies for equipment in hydrogen service and established oil and gas release frequencies from IOGP. In addition, a comparison between the HyRAM recommended ignition probabilities and the correlations used for oil and gas (from OEUK, formerly UKOOA) was conducted. By taking this approach, it was confirmed that the UKOOA data was more conservative, and sensitivity calculations were carried out. It was also noted that, as hydrogen technologies are emerging, there is a level of uncertainty around the data and comparisons must be regularly made to ensure the most appropriate basis for calculations is used.

1.0 NOMENCLATURE

CH_4	Methane
EI	Energy Institute
FB	Full Bore
FEED	Front End Engineering Design
FERA	Fire and Explosion Risk Assessment
H_2	Hydrogen
HC	Hydrocarbon
HSE	Health and Safety Executive
HyRAM	Hydrogen Risk Assessment Models
in	inch
IOGP	International Association of Oil and Gas Producers
LPG	Liquified Petroleum Gas
m^2	Square Metre
mm	millimetre
OEUK	Offshore Energies UK

P_{ing}	Probability of Ignition
PtX	Power to X
QRA	Quantitative Risk Assessment
UK	United Kingdom
UKOOA	United Kingdom Offshore Operators Association

2.0 INTRODUCTION

Hydrogen has gained significant attention as a potential clean and renewable energy carrier due to its high energy density and low carbon footprint. However, processing and storing hydrogen safely is a challenge due to its high reactivity and flammability. Hydrogen can ignite at very low concentrations in air, making its release a significant safety concern in projects involving hydrogen processing, storage, and transportation.

Given the increase in Hydrogen projects, 28% growth in global hydrogen demand over the last decade [1], there is a growing need for consistent and reliable data to be made available to aid design decisions for Hydrogen projects.

In the field of technical safety for the energy sector (including oil and gas and energy transition), quantitative risk assessments, including FERA and QRA, are important tools to aid decisions through all project phases. To carry out formal quantitative risk assessments, industry approved data for release/ leak frequencies for process equipment, storage facilities and pipelines handling hazardous fluid is required. Additionally, ignition probabilities or calculation methods used to determine the potential hazardous outcomes from a release are also a key variable.

Guidelines for the preparation of quantitative risk assessments where the objective is to establish risk contours around plants handling hazardous substances including hydrogen are presented in the technical report Guidelines for Quantitative Risk Analysis of Facilities Handling Hazardous Substances [2]. The report provides a comparison between the various databases available for leak frequencies and ignition probabilities depending on the hazardous substance. For Hydrogen projects, [2] recommends using Sandia National Laboratories HyRAM release frequencies and ignition probabilities [3]. However, there is some uncertainty around this data as some special fluids are likely to affect the leak frequency, for example due to known corrosion or other damage mechanisms, but no other frequency models are validated for hydrogen leaks [2].

To address this uncertainty, a comparison was made between the leak frequencies for equipment in hydrogen service and the established oil and gas release frequencies from IOGP Process Release Frequencies [4] (based on UK HSE Hydrocarbon Release Database). In addition, a comparison between the HyRAM recommended ignition probabilities and the correlations used for oil and gas based on the Energy Institute UKOOA correlations [5] was conducted.

This comparison was performed to support FERA and QRA studies carried out for an onshore large-scale Green Hydrogen Project during the FEED phase.

3.0 COMPARATIVE ASSESSMENT

3.1 Leak Frequency Comparison

HyRAM calculates the annual frequency of a hydrogen release for release sizes of 0.01%, 0.1%, 1%, 10%, or 100%. These release sizes are relative to the pipe flow area [3].

The parameters for frequency of random leaks for individual components used in this comparison are based on Table 2-2 in [3], with frequency calculations based on the geometric mean (median) as a more consistent metric of central tendency for the distribution. The default values are generic hydrogen-system leak frequencies developed on statistical analysis by J. Chance et al [6] where data from different sources was collected and combined using a Bayesian statistical method.

The IOGP release frequency data [4] is given as a function of both hole size and equipment dimension in the form of different classes, where representative hole (or release) sizes range from 1mm to > 150mm.

The IOGP data is built on the UK HSE Hydrocarbon Release Database which is based on the number of incidents recorded per year from offshore facilities in the UK.

The comparison of data from both models required both sets to be in the same format. In HyRAM the leak size is presented as a percentage of the equipment size (or diameter), whereas in IOGP (as well as other databases), this is based on hole size ranges (e.g.: 3 – 10 mm). To ensure the comparison is consistent, the hole sizes selected for the assessment (5mm, 25mm, 100mm and FB) were extrapolated against the percentage leak size of the HyRAM data to find the representative leak size percentage in HyRAM data as follows:

Table 1. Approximate Hole Sizes (mm) Based on Equipment Sizes for HyRAM frequencies.

Leak size HyRAM [3]	Equipment Size (Diameter) (in)						
	0.75	1	2	3	6	8	20
0.01%	0.002	0.003	0.005	0.01	0.02	0.02	0.05
0.1%	0.02	0.03	0.05	0.08	0.15	0.20	0.51
1%	0.2	0.3	0.5	0.8	1.5	2.0	5.1
10%	1.9	2.5	5.1	7.6	15.2	20.3	50.8
100%	19	25	51	76	152	203	508

Table 2: Cumulative Leak Sizes (%) for Nominal Hole Sizes (mm)

Hole Size (mm)	Equipment Size (Diameter) (in)						
	0.75	1	2	3	6	8	20
5	26.2%	19.7%	9.8%	6.6%	3.3%	2.5%	1.0%
25	100.0%	100.0%	49.2%	32.8%	16.4%	12.3%	4.9%
100	-	-	100.0%	100.0%	65.6%	49.2%	19.7%
FB	-	-	-		100.0%	100.0%	100.0%

The HyRAM release frequencies were extrapolated using the calculated leak size percentages calculated for the nominal hole sizes (Table 2). The HyRAM release frequency per nominal hole size is given in Table 3.

Table 3: HyRAM Release Frequencies (p/year) per Nominal Hole Size (mm)

Component	Hole Size (mm)	Equipment Size (Diameter) (in)						
		0.75	1	2	3	6	8	20
Compressors	5	2.10E-01	2.10E-01	2.10E-01	2.10E-01	2.10E-01	2.10E-01	2.10E-01
	25	3.00E-05	3.00E-05	1.32E-04	1.64E-04	1.97E-04	2.05E-04	2.20E-04
	100			3.00E-05	3.00E-05	9.88E-05	1.32E-04	1.91E-04
	FB					3.00E-05	3.00E-05	3.00E-05
Total		2.10E-01	2.10E-01	2.10E-01	2.10E-01	2.10E-01	2.10E-01	2.10E-01
Cylinders (Pressure Vessel)	5	3.10E-06	3.10E-06	2.79E-06	2.76E-06	2.46E-06	2.42E-06	2.35E-06
	25	2.10E-07	2.10E-07	3.06E-07	3.37E-07	3.68E-07	3.76E-07	3.90E-07
	100			2.10E-07	2.10E-07	2.75E-07	3.06E-07	3.62E-07
	FB					2.10E-07	2.10E-07	2.10E-07
Total		3.31E-06	3.31E-06	3.31E-06	3.31E-06	3.31E-06	3.31E-06	3.31E-06

Component	Hole Size (mm)	Equipment Size (Diameter) (in)						
		0.75	1	2	3	6	8	20
Filters	5	7.49E-02	7.49E-02	6.80E-02	6.80E-02	6.11E-02	6.11E-02	6.11E-02
	25	6.90E-03	6.90E-03	6.90E-03	6.90E-03	6.90E-03	6.90E-03	6.90E-03
	100			6.90E-03	6.90E-03	6.90E-03	6.90E-03	6.90E-03
	FB					6.90E-03	6.90E-03	6.90E-03
Total		8.18E-02	8.18E-02	8.18E-02	8.18E-02	8.18E-02	8.18E-02	8.18E-02
Flanges	5	8.65E-02	8.65E-02	8.65E-02	8.65E-02	8.65E-02	8.65E-02	8.65E-02
	25	1.50E-05	1.50E-05	2.74E-05	3.14E-05	3.54E-05	3.64E-05	3.82E-05
	100			1.50E-05	1.50E-05	2.34E-05	2.74E-05	3.46E-05
	FB					1.50E-05	1.50E-05	1.50E-05
Total		8.66E-02	8.66E-02	8.66E-02	8.66E-02	8.66E-02	8.66E-02	8.66E-02
Hoses	5	1.61E-03	1.61E-03	1.49E-03	1.48E-03	1.36E-03	1.35E-03	1.31E-03
	25	7.30E-05	7.30E-05	1.16E-04	1.30E-04	1.45E-04	1.48E-04	1.54E-04
	100			7.30E-05	7.30E-05	1.02E-04	1.16E-04	1.42E-04
	FB					7.30E-05	7.30E-05	7.30E-05
Total		1.68E-03	1.68E-03	1.68E-03	1.68E-03	1.68E-03	1.68E-03	1.68E-03
Joints	5	8.76E-05	8.76E-05	8.12E-05	8.11E-05	7.47E-05	7.45E-05	7.42E-05
	25	6.00E-06	6.00E-06	6.40E-06	6.52E-06	6.65E-06	6.68E-06	6.74E-06
	100			6.00E-06	6.00E-06	6.27E-06	6.40E-06	6.62E-06
	FB					6.00E-06	6.00E-06	6.00E-06
Total		9.36E-05	9.36E-05	9.36E-05	9.36E-05	9.36E-05	9.36E-05	9.36E-05
Pipes	5	1.57E-05	1.57E-05	1.49E-05	1.49E-05	1.41E-05	1.40E-05	1.39E-05
	25	6.40E-07	6.40E-07	7.92E-07	8.42E-07	8.91E-07	9.03E-07	9.25E-07
	100			6.40E-07	6.40E-07	7.43E-07	7.92E-07	8.81E-07
	FB					6.40E-07	6.40E-07	6.40E-07
Total		1.64E-05	1.64E-05	1.64E-05	1.64E-05	1.64E-05	1.64E-05	1.64E-05
Valves	5	6.57E-03	6.57E-03	6.54E-03	6.53E-03	6.50E-03	6.50E-03	6.49E-03
	25	1.50E-05	1.50E-05	2.97E-05	3.44E-05	3.91E-05	4.03E-05	4.25E-05
	100			1.50E-05	1.50E-05	2.49E-05	2.97E-05	3.82E-05
	FB					1.50E-05	1.50E-05	1.50E-05
Total		6.58E-03	6.58E-03	6.58E-03	6.58E-03	6.58E-03	6.58E-03	6.58E-03
Instruments	5	1.42E-03	1.42E-03	1.27E-03	1.26E-03	1.11E-03	1.09E-03	1.06E-03
	25	1.10E-04	1.10E-04	1.50E-04	1.62E-04	1.75E-04	1.78E-04	1.84E-04
	100			1.10E-04	1.10E-04	1.37E-04	1.50E-04	1.72E-04
	FB					1.10E-04	1.10E-04	1.10E-04
Total		1.53E-03	1.53E-03	1.53E-03	1.53E-03	1.53E-03	1.53E-03	1.53E-03

The Leak frequency totals per component for HyRAM and those for IOGP release data are compared for the equivalent equipment size / diameter. A summary is presented in Table 4.

Table 4: HyRAM vs IOGP Total Release Frequencies (p/year) per Components and Equipment Diameters

Component	Equipment Diameter	0.75 in	1 in	2 in	3 in	6 in	8 in	20 in
Compressors	IOGP			5.82E-03	5.82E-03	5.83E-03	5.83E-03	5.83E-03
	HyRAM		2.10E-01	2.10E-01	2.10E-01	2.10E-01	2.10E-01	2.10E-01
Cylinders	IOGP			6.42E-04	6.42E-04	6.42E-04	6.42E-04	6.42E-04
	HyRAM	3.31E-06	3.31E-06	3.31E-06	3.31E-06	3.31E-06	3.31E-06	3.31E-06
Filters	IOGP			1.83E-03	1.83E-03	1.83E-03	1.83E-03	1.83E-03
	HyRAM	8.18E-02	8.18E-02	8.18E-02	8.18E-02	8.18E-02	8.18E-02	8.18E-02

Component	Equipment Diameter	0.75 in	1 in	2 in	3 in	6 in	8 in	20 in
Flanges	IOGP			7.69E-06	7.69E-06	1.24E-05	2.16E-05	3.26E-05
	HyRAM	8.66E-02	8.66E-02	8.66E-02	8.66E-02	8.66E-02	8.66E-02	8.66E-02
Hoses	IOGP							
	HyRAM	1.68E-03	1.68E-03	1.68E-03	1.68E-03	1.68E-03	1.68E-03	1.68E-03
Joints	IOGP							
	HyRAM	9.36E-05	9.36E-05	9.36E-05	9.36E-05	9.36E-05	9.36E-05	9.36E-05
Pipes	IOGP			2.52E-05	2.52E-05	1.55E-05	1.59E-05	1.88E-05
	HyRAM	1.64E-05	1.64E-05	1.64E-05	1.64E-05	1.64E-05	1.64E-05	1.64E-05
Valves	IOGP			2.59E-04	2.59E-04	1.72E-04	1.85E-04	2.30E-04
	HyRAM	6.58E-03	6.58E-03	6.58E-03	6.58E-03	6.58E-03	6.58E-03	6.58E-03
Instruments	IOGP		1.97E-04	1.97E-04				
	HyRAM	1.53E-03	1.53E-03	1.53E-03	1.53E-03	1.53E-03	1.53E-03	1.53E-03

Notes:

1. No IOGP data for anything less than <2".
2. IOGP data for 1" is only for instruments.
3. HyRAM data - based on release size as a % of the total equipment size.
4. IOGP Valves Frequency in comparative table = Manual + Automatic valve frequencies.
5. No IOGP data for hoses and joints (included as other equipment).
6. Pressure Vessels included within cylinders component category

Overall HyRAM release frequency data are higher than that suggested by the IOGP for similar equipment items and components, with the exception of cylinders (pressure vessels). Therefore, HyRAM release frequencies are considered to provide a more conservative approach.

With regards to the project application, once the release frequencies were combined with the system parts counts to obtain the initiating frequency, the total release frequency for the facility based on the HyRAM dataset was 200% higher than the IOGP equivalent. This higher initiating frequency could increase the fire and explosion event frequency and drive the requirement for additional safety considerations such as equipment spacing or fire and explosion protection which can impact the overall project expenditure.

3.2 Ignition Probability Comparison

The ignition probability values used in HyRAM [3] are based on historical ignition probability data for methane from Cox, Lees, & Ang ignition probabilities [7], which have been modified for hydrogen based on the approach described in Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) for LNG Facilities [8].

As is the case for hydrocarbon ignition probabilities, hydrogen ignition probabilities are based on release rate values. The approach described in Reference [8] to modify the ignition probabilities in Reference [7] so they are suitable for hydrogen is replicated below:

- Reducing the leak flow ranges by a factor of 8, to allow for differential molecular weights of CH_4 vs H_2 (16 vs 2 g/mol respectively), which directly affects the size of flammable cloud.
- Increase ignition probabilities by 16%, to allow for the ratio of the flammable range of H_2 vs CH_4. Allowing that 15 - 75 vol% constitutes only 16% of total cloud size above lower flammability limit (from modelling).
    - This value is based on the difference between the ratio of the flammable range of H_2, 18.75, and the ratio of the flammable range of CH_4, 2.86, giving Δ15.89 (~ 16%).

- Immediate to delayed ignition probabilities are assumed to have a ratio of 2:1, and total ignition probability is immediate and delayed probabilities added together.

The Cox, Lees, & Ang ignition probability [7] values for gas and the respective release rates are given in Table 5.

Table 5: Cox, Lees, & Ang Ignition Probabilities for Gas [7]

Release Rate (kg/s)	Ignition Probability
<= 1	0.01
1 – 50	0.07
> 50	0.3

The values shown in Table 6 are the representative values for hydrogen ignition probabilities from HyRAM [3, 8].

Table 6: HyRAM – Ignition Probabilities for Hydrogen

H_2 Release Rate (kg/s) (HC release rate / 8)	Ignition Probability (HC P_{ing} + 16%)
< 0.125	0.01
0.125 - 6.25	0.08
> 6.25	0.35

Based on the approach described in [8], the ratio of immediate to delayed probabilities is given as 2:1. The representative values for immediate and delayed ignition probabilities are given in Table 7.

Table 7: HyRAM – Immediate and Delayed Ignition Probabilities

H_2 Release Rate (kg/s)	Probability Immediate Ignition	Probability Delayed Ignition
< 0.125	0.008	0.004
0.125 - 6.25	0.053	0.027
> 6.25	0.23	0.12

While the ignition probabilities data from Cox, Lees, & Ang ignition probabilities [7] is widely used, Cox, Lees and Ang state that it was speculative only [9].

A review by the United Kingdom Operator's Association (UKOOA), the Energy Institute (EI) and the Health & Safety Executive (HSE) of the ignition probabilities data and models available at the time (2002); which includes Cox, Less and Ang, Classification of Hazardous Locations, 1990; concluded that the typical approach of adopting very generic mass release rate-based correlations for the probability of ignition was overly simplistic and may lead to unrealistic or very conservative estimates of risk in some situations. Further, some of the correlations in use did not reflect more up to date historical ignition probability data and knowledge.

It was generally recognised that there was a need to take better account of the types of plant, substances, process conditions and ignition source characteristics, and recent work on the dispersion of flammable vapours in ventilated areas and work on ignition source characteristics and overland ignition modelling [10].

Based on this need, an ignition probability model was developed to provide a means to estimate the overall ignition probability and an approximate time/location distribution for a specific release scenario.

This model can also give an insight in to the main ignition factors and allows sensitivity analysis and 'what-if' analysis, which may help risk analysts and designers to change the plant layout or process conditions to reduce the ignition potential [10].

The resulting UKOOA ignition probability model [5] assesses the probability of ignition of hydrocarbon releases for use in offshore and onshore QRA by combining established data and methods on gas build up, gas dispersion, area ignition source characteristics, etc. The model estimates the volume or area of flammable gas or liquid in a given plant area, and then combines this with suitable ignition source densities to calculate the overall ignition probability. The model has been structured to consider the ignition of hydrocarbons within the immediate plant area where the leak occurs, and any additional probability of ignition were the flammable vapour cloud or liquid to spread to adjacent plant areas or beyond [10].

The characterisation of each area's ignition sources is based on selecting one of 17 generic types covering a wide range of plant and onsite and offsite land use types, including areas subject to hazardous area classification and the use of Ex rated equipment. These include various plant module types and equipment levels, and onsite and offsite general areas covering industrial, urban and rural locations [10].

Given the H_2 ignition probabilities recommended by HyRAM are based on the speculative Cox, Lees and Ang approach, an analysis of this versus the alternative UKOOA ignition probability was conducted. The results of this analysis is presented below.

The UKOOA ignition probability model [5] provides correlations for a variety of plant and pipeline scenarios, this analysis was based on an onshore ignition scenario based on the definition in IOGP Ignition Probabilities data directory [11] for large gas plant:

- 'Large Plant Gas LPG' Scenario 8 – Releases of flammable gases, vapour or liquids significantly above their normal boiling point from large onshore outdoor plants (plant area above 1200 m^2, site area above 35,000 m^2) [11].

This correlation was selected as most appropriate due to the nature and applicability to the Green Hydrogen Project facilities which consisted of a large onshore facility.

Table 8: UKOOA Scenario 8 – Ignition Probabilities

Release Rate (kg/s)	Ignition Probability
0.1	0.0011
0.2	0.0014
0.5	0.002
1	0.0025
2	0.005
5	0.0125
10	0.025
20	0.05
50	0.125
100	0.25
200	0.5
500	0.65
1000	0.65

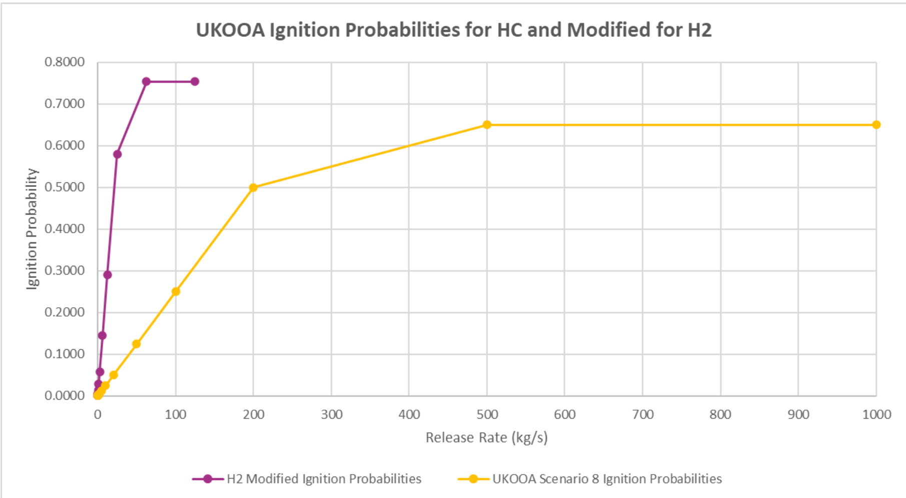
To account for differences between hydrocarbon and hydrogen, the release rates and ignition probabilities were modified as per the approach described in [8]. The modified UKOOA ignition probabilities, including immediate and delayed are given in Table 9.

Table 9: UKOOA Scenario 8 – Ignition Probabilities Modified for Hydrogen

H_2 Release Rate (kg/s) (HC / 8)	H_2 Ignition Probability (HC P_{ign} + 16%)
0.0125	0.0013
0.025	0.0016
0.063	0.0023
0.125	0.0029
0.25	0.0058
0.63	0.015
1.25	0.029
2.5	0.058
6.25	0.145
12.5	0.29
25	0.58
62.5	0.75
125	0.75

A comparison between the UKOOA ignition probability vs release rate values for hydrocarbon gas and those adapted for Hydrogen are shown in Figure 1.

Figure 1: UKOOA Ignition Probabilities for HC Gas and Modified for H_2



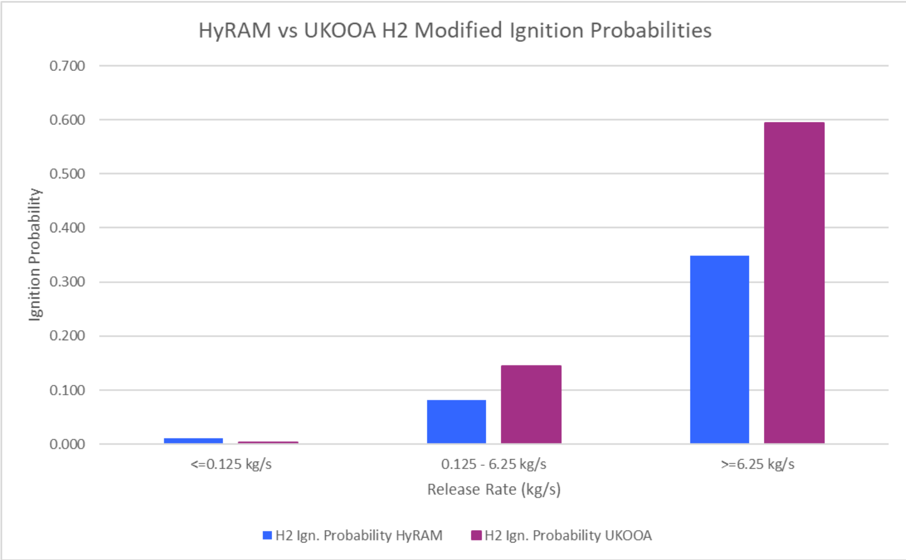
The representative values for immediate and delayed ignition probabilities are given in Table 9 based on a ratio of 2:1 as per approach described [8].

Table 10: UKOOA Scenario 8 – Immediate and Delayed Ignition Probabilities Modified for Hydrogen

H_2 Release Rate (kg/s)	Probability Immediate Ignition	Probability Delayed Ignition
< 0.125	0.0019	0.0010
0.125 - 6.25	0.097	0.048
> 6.25	0.40	0.20

The comparison between ignition probability models is shown in Figure 2.

Figure 2: Overall Ignition Probabilities Comparison



4.0 CONCLUSIONS

HyRAM release frequency data suggested for Hydrogen modelling is higher than that suggested by the IOGP for oil and gas projects.

The derivation of release frequency data for HyRAM is based on default values by combining data from different sources statistical analysis, whereas the derivation of leak frequencies presented in IOGP applications are based on practical data. However, the HyRAM model is the most established model for Hydrogen leaks.

HyRAM ignition probability data is derived from the Cox, Lees, & Ang ignition probability [7] values for gas and the respective release rates modified for Hydrogen, to account for the smaller molecular weight of hydrogen vs methane, the release rate values are reduced by a factor of 8, and the ignition probabilities are increased by 16% to allow for the ratio of the flammable range of H_2 vs CH_4 and allowing that 15 – 75 vol % constitutes only 16% of total cloud size above lower flammability limit.

The ignition probabilities derived for use in HyRAM are based on gas ignition probabilities which are no longer used extensively in oil and gas projects as these were replaced by correlations generated for type of fluid, facility and release rate, such as the UKOOA ignition probability model [5]. A comparison between both ignition probability models was conducted, the same modification for hydrogen approach was applied to the release rate and ignition probabilities given for Gas in the UKOOA ignition probability model [5].

The comparative results show the H_2 modified UKOOA ignition probabilities are higher than those for HyRAM modelling for any releases larger than 0.125kg/s, this has potential to affect risk modelling outcomes.

For Hydrogen projects it is worth using most conservative values for QRA, FERA, however, comparative assessments on data used should be encouraged and sensitivities carried out to ensure the conclusions drawn for such assessment remain robust and continue to support the goal to reducing risks to As Low As Reasonably Practicable (ALARP).

Given the growth in global hydrogen demand over the last decade and the increase in Hydrogen related projects, it is important that Hydrogen data for assessments becomes consistent to ensure reliability and to aid design decisions for Hydrogen projects.

5.0 REFERENCES

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