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Application of Quantitative Risk Methodologies to Hydrogen Infrastructure for the Energy Transition

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Why Hydrogen

Hydrogen is being pursued by the energy industry in the UK and abroad at present as a means to replace or reduce the amount of carbon dioxide emitted through the burning of natural gas.

When hydrogen is burned, it produces only water, whereas the burning of natural gas produces carbon dioxide and water. It is this property that makes it desirable for combating climate change as the total emissions of greenhouse gases can be reduced.

Most hydrogen produced today is produced using steam reforming of natural gas – however, this method of hydrogen production produces significant amounts of greenhouse gases and is not green. For hydrogen to reduce the amount of carbon dioxide released into the atmosphere hydrogen must produced in a green manner, for instance via electrolysis powered by renewable energy.

To pursue this method of combating climate change, numerous countries have begun trials and preliminary studies investigating the feasibility of injecting hydrogen into their existing natural gas supply networks.

In the first instance, blending of natural gas with small amounts of hydrogen, up to 20% v/v is being pursued.

Management of Change

The conversion of natural gas transmission networks from pure natural gas to a mixture of natural gas and hydrogen constitutes a change in the way these assets are operated, as such, the change must be managed.

One of the considerations in managing the change is safety related. In the UK, high pressure natural gas pipelines are classified as major accident hazard pipelines under the pipeline safety regulations due to the catastrophic consequences that a loss of containment event could have on people.

The addition of hydrogen to the conveyed fluid does not change this, however, one question to be asked is how does it affect the overall level of risk? This is partly due to the legislative requirements in the UK for risk to be managed and assessed.

As such, a large amount of research has been performed to determine if the current methods applied are applicable, determine the physics of hydrogen releases, characterise the dispersion of hydrogen, characterize the radiative properties of hydrogen flames and to determine the ignition probabilities of hydrogen releases.

This article aims to discuss the application of Quantitative Risk Assessment (QRA) to hydrogen and to discuss the salient points that should be considered when undertaking a QRA on hydrogen assets.

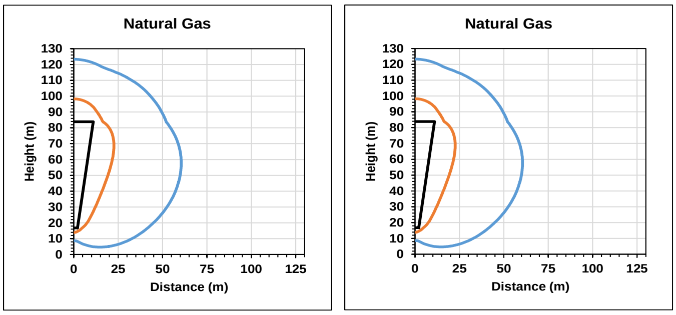

Figure 1: Comparison of the Jet Fire Flame Region (Black) and Associated Critical Heat Flux Levels, 6.3 kW/m2 (Blue) and 37.5 kW/m2 (Orange) for a Vertical Grade Release through a 110 mm Rough Edged Hole at 70 barg and 25 °C. Hydrogen Surface Emissive Power of 70 kW/m2 and Natural Gas Surface Emissive Power of 113 kW/m2.

Quantitative Risk Assessment

There are multiple methods available to assess the risk associated with a hazard, ranging from the ranking of risk by experts qualitatively on a risk matrix, to quantitative studies such as a QRA, which seeks to calculate the level of risk using physical models and past experience.

In the pipeline industry in the UK, it is common practice to perform a QRA on pipeline assets to quantify the risk associated with the pipeline. As such, the overall methodology is well defined. Figure 2 shows the elements required to perform a pipeline QRA.

The effect of adding hydrogen to natural gas, or in transporting pure hydrogen will have an impact on these elements.

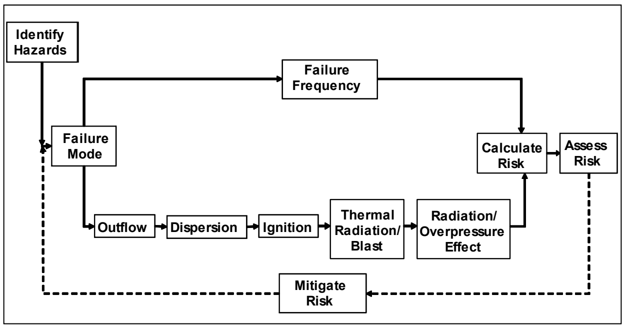

Figure 2: Elements of Quantitative Risk Assessment

Review of the Elements of Quantitative Risk Assessment[1].

Identify Hazards

The input of the application hazards to a QRA should come from a hazard identification study (HAZID), which will systematically identify all potential hazards and qualitatively assess their potential risk.

Failure Mode

For pipelines, the two common failure modes are leaks through holes and full-bore ruptures. One additional failure mode that may be more likely with hydrogen is leakage through flange, gaskets, and valve stems. This is due to its smaller molecular size compared to the typical components contained in natural gas.

Failure Frequency

The main hazard affecting pipelines in the UK is third-party interference, with other hazards such as corrosion, manufacturing and material damage and ground movement all having a reduced effect.

On new build assets, that have been designed in accordance with a design code specifically for hydrogen, such as ASME B31.12, it is not foreseen that there will be a large increase in the failure frequencies. However, there is an issue when hydrogen or hydrogen natural gas mixtures are fed into assets that are being repurposed for hydrogen as the effect of hydrogen could make failure more likely to occur.

At present, there is little operating experience of pipelines subjected to pure hydrogen and its mixtures, when compared to the large exposure recorded for natural gas pipelines. With time, as exposure increases, it is expected that more data will be available to ascertain the impact that change from natural gas to hydrogen has on pipeline failure frequencies.

Outflow

In a QRA, the consequences of a loss of containment event have to be determined, as such, it is required to determine the amount of gas released should a leak or rupture occur.

It is not expected that hydrogen or mixtures of natural gas and hydrogen will drastically affect the calculation methods currently employed for pure natural gas pipelines.

That said, hydrogen does have some interesting properties that should be considered.

The Joule-Thomson effect explains the phenomenon of the temperature change observed when a real gas undergoes a change in pressure at constant enthalpy.

Hydrogen is one of a few elements, the others being helium and neon, that has a negative Joule-Thomson coefficient at ambient conditions. This means that the gas temperature will increase when expanded at constant enthalpy. This contrasts with natural gas, which will cool when expanded. This contrasts with natural gas, which will cool when expanded. The heating of the gas will affect dispersion calculations. This represents a departure from ideal behaviour.

To quantify how ideal a substance is, it is common to use the compressibility factor to measure the deviation from ideality, where a compressibility factor (Z) of 1 is representative of an ideal gas.

Figure 3 shows the variation of the compressibility factor with pressure at 25°C for pure methane and pure hydrogen. It can be seen that hydrogen is much closer to being ideal over the range of typical transmission pipeline pressures compared to methane.

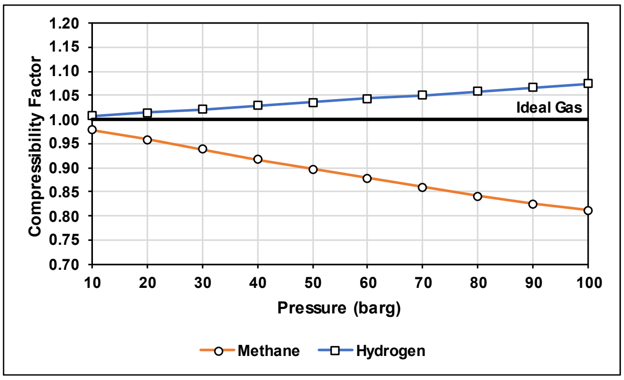

Figure 3: Comparison of Compressibility Factor of Hydrogen and Methane at 25°C using the Van Der Waals Equation of State, Solid Black Line Z=1 Representative of Ideal Gas Behaviour

Another parameter that differs drastically between natural gas and hydrogen is the differences in the atomic mass of the substances. The atomic mass of hydrogen is much lower than that of methane and is also greater than that of a typical natural gas sample, as can be seen in Table 1. Consequently, when combined with the consideration of non-ideality shown in Figure 3, the density of hydrogen is much lower than the density of methane, or natural gas, at the same temperature and pressure. This has a marked effect on the outflow.

Substance	Atomic Mass (g/mol)	Density @ 70 barg, 25°C (kg/m^3)
Hydrogen	2.016	5.5
Methane	16.04	52.4

Table 1: Atomic Mass and Density of Substances

Ultimately, the result is that when calculating the mass release rate through an orifice for hydrogen and for methane from a reservoir at the same thermodynamic conditions, a lesser mass of hydrogen is released compared to methane. As an example, see table 2.

Substance	Release Rate (kg/s)
Hydrogen	25.4
Methane	75.9

Table 2: Release Rate for Substances through a 110 mm Rough-Edged Hole from an Infinite Reservoir at 70 barg and 25 °C

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[1] Note that the overpressure and blast effects is not covered in this article for brevity.

Dispersion

Dispersion relates to how the gas travels once it is released. It is commonly stated that as hydrogen is lighter than air and buoyant that it will disperse rapidly, and a cloud of ignitable gas will not be likely to accumulate. This is, however, not always true.

There are two general types of jets, a fully buoyancy-dominated jet, and a fully momentum-dominated jet. Jets can also exhibit both behaviours with the initial part of the jet being momentum controlled and then transitioning to being buoyancy controlled.

For the pressures encountered in transmission pipelines systems, releases are almost always sonic under-expanded jets. Such jets possess a very high momentum at the point of release. In the momentum-dominated part of the dispersion, buoyancy has little effect leading to the dispersion of gas at grade level.

The HSE assume for natural gas pipelines that a vapour cloud explosion is not a credible threat based on dispersion analysis. However, for high-reactivity substances they do consider vapour cloud explosions to be a threat.

For above ground releases from pipework, dispersion and vapour cloud explosions are credible for hydrogen releases, and these have occurred.

Ignition

In the event of a loss of containment of a flammable gas, there are three possible outcomes:

- Immediate Ignition
- Delated Ignition
- No Ignition

The time of ignition, if ignition occurs at all, determines what consequences are likely to occur.

For a large diameter high pressure pipeline rupture, if ignition occurs immediately, the outflow of gas occurs at a higher rate than the gas can be consumed by the fire, and a fireball occurs. Once the fireball has consumed the large amount of initial released mass, the flame transitions from a fireball to a jet fire that is fed from the mass escaping the pipeline.

In the event of delayed ignition, the large amount of released mass disperses prior to ignition occurring. In this case, the consequences are heavily dependent on the fluid released, and on the type of release.

For natural gas, it is assumed that a release from an underground pipeline will result in a gas release that occurs vertically with high momentum. It is therefore assumed that the gas will disperse vertically rapidly. When the delayed ignition occurs, a jet fire will result.

For gases that are heavier than air, for example propane, there is a potential for the negative buoyancy of the release to form a cloud of flammable gas that can travel close to the ground. Eventually this cloud may reach an ignition source and ignite.

If the cloud occurs in the open, is not confined, and there is no congestion, a flash fire will occur where the flame travels sub-sonically through the gas cloud. However, if the gas cloud is confined, or meets an area of congestion such as a collection of process vessels, or even a forest, a vapour cloud explosion may occur where the flame speed is supersonic.

In this case, in addition to the fire, a significant overpressure can be generated. In the very worst case, a flame front that is initially a deflagration can transition to a detonation. Such an event is thought to have happened in 1970 at Port Hudson where a propane pipeline ruptured leading to a significant vapour cloud explosion [1].

To assess the risk associated with a pipeline, it is required to determine the probability of an ignition occurring, and if it does occur, is it an immediate ignition or delated ignition.

Hydrogen is classified as a high-reactivity substance due to its low minimum ignition energy, whereas natural gas is less reactive.

The probability of ignition is generally considered to be a function of location, as some locations have more potential ignition sources that others, and of the size of the release, as with more gas being released it is more likely that some part of the release will encounter an ignition source.

There are various published models for calculating the ignition probabilities that are required, however, it is noted that these models are generally developed for what is termed “low reactivity” substances such as methane and propane. Hydrogen is a “high reactivity” substance has a much lower minimum ignition energy required for ignition when compared to traditional substances used in the oil and gas and allied industries. Consequently, a number of the published models recommend that the user be cautious when applying these models to substances such as hydrogen and recommend that the ignition probabilities be doubled, up to a maximum value of one.

The HSEs has several event trees, three of these are as follows: one for natural gas, one for low-reactivity substances and one for high-reactivity substances that provide ignition probabilities that can be assumed. These event trees make no distinction between different locations or the mass release rate.

For natural gas, alternative models are available, such as the PD^2 model [2] which states that the ignition probability is a function of the pressure of the pipeline and the diameter of the pipeline squared. This model limits the ignition probability to a maximum value of 81%. It is noted that this model was determined by analysis of incidents involving natural gas, as such, it is not directly applicable to hydrogen pipeline releases.

For hydrogen, The Methodology for Assessing the Safety of Hydrogen Systems [3] produced by Sandia National Laboratories recommends the ignition probabilities shown in Table 3 for hydrogen releases. The model assumes that if ignition occurs, 2/3 of the time it will occur immediately, and 1/3 of the time it will occur as a delayed ignition. The majority of releases of hydrogen from pipelines considered as part of a QRA are likely to have release rates in excess of 6.25 kg/s. It is notable that the total ignition probability is only 35% in the worst-case scenario.

Hydrogen Release Rate (kg/s)	Probability of	
	Immediate Ignition	Delayed Ignition
< 0.125	0.8	0.4
0.125 – 6.25	5.3	2.7
> 6.25	23	12

Table 3: Ignition Probabilities Specified by the HyRAM Model

An alternative model is recommended in Norway when performing hydrogen QRAs, the HYEX model [4]. This is a modified form of the HyRAM model, made to be continuous rather than discrete in terms of the relation of the mass release rate with the ignition probability. Furthermore, the revised model assumes that if the hydrogen mass release rate exceeds 12.7 kg/s that ignition is guaranteed.

A comparison of ignition probabilities obtained using various models is shown in Table 4. It should be noted that the HSE event trees were developed for substances that the HSE model such as natural gas, ethylene and propane, and as such may not be appropriate for hydrogen. Applying the HYEX model to hydrogen pipelines would be conservative.

Model	Probability of		
	Immediate Ignition	Delayed Ignition	Total Ignition
HSE Natural Gas	25.00	18.75	43.75
HSE Low Minimum Ignition Energy	35.00	42.12	77.12
HYEX2	67.00	33.00	100.00

Table 4: Comparison of Ignition Probabilities Calculated Using Various Models

Thermal Radiation

Typically, the predominant form of heat transfer from a process plant fire is via radiation. All normal matter emits radiation if its temperature is above absolute zero. Flames are hotter than absolute zero, and hence they emit radiation.

Radiation emission can either be continuous across a range of frequencies or discrete at certain frequencies. To determine the effects that the radiation emission from a flame will have on persons, the amount of radiation and the frequency must be determined.

The Stefan-Boltzmann law describes the power radiated from a black body[3] as being proportional to the fourth power of its absolute temperature. A hydrocarbon or hydrogen flame is not a black body. As such, a modification factor called the emissivity is used to characterise the efficiency of the flame as a radiation emitter compared to a black body. Such a non-ideal radiation emitter is a grey body.

A further consideration to be had is that both black and grey bodies are assumed to emit radiation across a continuous spectrum, whereas flame emission spectroscopy shows that flames tend to emit most of their radiation at discrete frequencies.

A hydrogen air mixture shows a spectrum with a peak in the ultraviolet part of the spectrum due to OH radicals and subsequent peaks in the infrared part of the spectrum due to water vibration, with comparably low emissions in the visible band of the spectrum [5].

A methane oxygen mixture also shows a spectrum with a peak in the ultraviolet part of the spectrum due to OH radicals but has much more significant peaks in the spectrum in the visible region due to carbon components emitting radiation [6] – this explains why a hydrogen flame is less visible compared to a hydrocarbon flame, due to stronger emissions in the visible region of the spectrum.

The adiabatic flame temperature using air as an oxidizer of hydrogen (2,254 °C) is greater than methane (1,963 °C), suggesting that hydrogen would emit more radiation than methane based on temperature alone. However, the emissivity of a hydrogen flame is noted in literature to be lower than that of a typical hydrocarbon flame with a value of around ~0.1 for hydrogen and 1.0 for hydrocarbons.

Ultimately, in terms of the intensity of the emissions, the overall surface emissive power (SEP) of hydrogen is noted to be lower when compared to natural gas flames, with a review of pool fire thermal radiation modelling performed in 1997 reporting a SEP of 70 kW/m2 for flames from liquified hydrogen and a SEP of 265 kW/m2 for flames from liquified natural gas [7].

An earlier report produced in 1982 on behalf of NASA reported values of SEP of 75 to 144 kW/m2 for liquefied hydrogen and 100 to 220 kW/m2 for liquified methane [8]. The reduced SEP of the hydrogen flame compared to the natural gas flame has pronounced effects when considering the consequence of thermal radiation on a person.

The SEP is not the only criterion that needs to be considered when determining the amount of thermal radiation, a person receives. For instance, the humidity of the atmosphere can have a significant effect, with water in the air absorbing emitted radiation reducing the intensity of the radiation that falls on a person. However, when comparing hydrogen and natural gas jet fires, it is likely to place the biggest role in the observed differences between the consequences posed by the jet fires.

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[2] Assuming a large gas release, with a mass release rate in excess of 12.7kg/s, which would be typical of full-bore rupture.

[3] A black body is an ideal radiator of thermal energy and emits the maximum amount of radiation at each frequency across a continuous spectrum.

Radiation Effects

The effects of radiation and overpressure on the human body need to be accounted for in a QRA to determine the lethality of the event. Research has been performed in this area and the radiation limits associated with a given level of damage are well defined as shown in Table 5.

Radiation Flux (kW/m²)	Description
> 37.5	Intensity at which damage is caused to process equipment. Significant chance of fatality for people exposed instantaneously.
25	Minimum intensity at which non-piloted (spontaneous) ignition of wood occurs. Likely fatality for extended exposure and significant chance of fatality for instantaneous exposure. Unprotected steel will reach thermal stress temperatures that can cause failure.
12.5	Minimum intensity at which piloted ignition of wood occurs. Significant chance of fatality for medium duration exposure. Thin steel with insulation on the side away from the fire may reach thermal stress level high enough to cause structural failure.
< 6.3	Intensity tolerable to escaping personnel.

Table 5: Thermal Radiation Flux Criteria Values

Calculate, Assess and Mitigate Risk

The final element of the QRA process is to calculate the risk, asses it against specified region-specific criterion and then determine if mitigation measures are required and to re-assess the risk with those mitigation measures in-place. In general, the process is not expected to differ if alternative substances are being risk assessed, except for alternative risk mitigation measures that may be required, accounting for substance specific behaviour. As such, no further discussion is made on these elements of the QRA process.

Example Thermal Radiation Consequences

To demonstrate how the differences between hydrogen and natural gas culminate in a difference in the consequences of a loss of containment event resulting in a jet fire, a release through a 110 mm rough edged hole at 70 barg and 25 °C has been simulated.

The results in the form of the flame envelope of the jet fire, for both cases, and the distance away from the flame for the 37.5 kW/m2 and 6.3 kW/m2 to be reached are shown in Figure 1. Calculated parameters are shown in Table 6.

The results show that the jet fire from the hydrogen release is smaller than the jet fire from the natural gas release, and the fire emits less radiation with the surface emissive power being 62% of the value for the natural gas fire.

Parameter	Hydrogen Jet Fire	Natural Gas Jet Fire
Lift Off Height (m)	13	17
Length of Flame (m)	51	67
Width of Flame at Base (m)	1.5	4
Width of Flame at Tip (m)	17	17
Surface Emissive Power (kW/m2)	70	113

Table 6: Calculated Dimensions of Jet Fires

Figure 1 also shows that the distances to the critical flux levels are reduced for the hydrogen jet fire compared to the natural gas fire. However, these values are around the jet fire at high elevations, persons are present closer to grade level. Furthermore, the heat flux levels are static values, whereas when considering the vulnerability of a person to radiation, it is often desirable to consider how much radiation they receive over a period.

It is noted that the criterion given in Table 5 only consider the effect of the time of exposure in a semi-quantitative way. To better account for the effect that the intensity of the radiation flux and the duration of exposure has on the resulting vulnerability of exposed populations, the thermal dose unit (TDU) concept is used, as shown below. This equation can be integrated over time to account for varying amounts of incident radiation received. A TDU of 1,800 is considered to be equivalent to a likelihood of fatality of 50% for normal populations.

$$\text{TDU} = (\text{Radiation Flux})^{4/3} \times \text{Time of Exposure}$$

Figure 4 presents the calculated heat load in terms of the TDU for both the natural gas and hydrogen jet fires at an elevation of 2 metres at various distances away from the release point. The hydrogen fire shows a reduced heat load being received by a person at all distances.

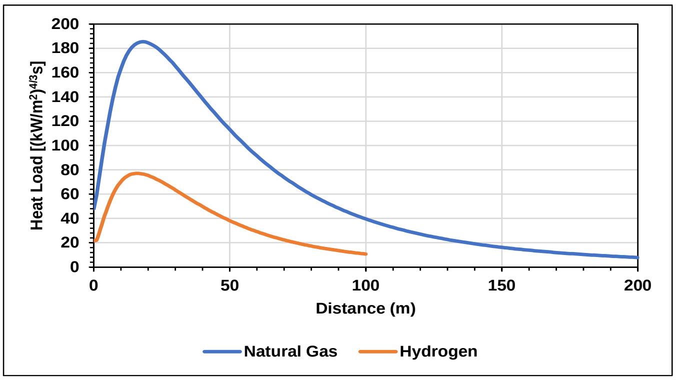

Figure 4: Heat Load (Thermal Dose Unit) Calculated at 2M Height Versus Distance from Jet Fire

Conclusions

For the cases considered, the consequences of the natural gas jet fire are worse when compared to the hydrogen jet fire.

It is noted that there are other consequences that would be considered in a full QRA, such as:

- Fireballs
- Flash Fires
- Vapour Cloud Explosions

Additionally, the following effects would be considered:

- The Effect of Wind
- Alternative Release Orientations

In this article, only the consequences have been determined, however, the risk is the product of likelihood and consequence.

Based on the likelihood of a hydrogen release and natural gas release occurring, resulting in a jet fire, being broadly similar, which is a reasonable assumption to make given that the majority of failures in the UK occur due to third party interference, the risk posed by a hydrogen jet fire is likely to be less than the risk posed by a natural gas jet fire.

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