

Risk Assessment of Hydrogen and Natural Gas Pipelines

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1 ABSTRACT

Decarbonisation of the energy supply has become a priority to help address climate change concerns. One method of decarbonisation is the use of hydrogen in place of or supplementing natural gas. The predominant method of natural gas transmission in the world is by pipeline. Many pipeline operators wish to re-use existing infrastructure that was not originally designed for hydrogen service. Such a re-purposing is a significant change to the operation of the asset that must be assessed.

The conveyance of natural gas by pipeline has a long history and is demonstrably safer, cheaper, and more efficient than alternative methods. That said, pipelines still pose a risk to their environment, which must be managed and demonstrated to be acceptable. A common method employed to demonstrate this is Quantitative Risk Assessment (QRA), which is based on mathematical modelling of consequence effects, historical statistical data, experience, and expert judgement. The methodology for natural gas has been validated through comparison with actual failures.

QRA is complex and it is not readily apparent that existing methodologies for natural gas pipelines are fit for purpose to assess the risk of pipelines conveying alternative fluids. This paper reviews the existing QRA methodology utilised for pipelines conveying natural gas to assess its suitability for use on pipelines conveying hydrogen and hydrogen natural gas mixtures. The outcome of the review highlights where knowledge gaps are present, potential resolutions to such gaps and proposed modifications to the existing methodology based on theoretical considerations and published literature, where appropriate, for use on pipelines conveying such fluids. To demonstrate the impact that conveyance of alternative fluids has on the risk posed, a comparative case study is presented. Furthermore, sensitivity studies are considered to highlight the effect that current knowledge gaps may have on the results.

2 INTRODUCTION

Over the last two centuries there has been an increase in the global surface temperature of the Earth of 1.1°C between 2011–2020 and 1850–1900 ^[1]. It is believed that the warming of Earth's climate has led, and will continue to lead to if not abated, to several adverse effects, such as rising sea levels, more frequent extreme weather events, damage to ecosystems and reduced food security. There is scientific consensus that the observed climate change is due, in part, to anthropogenic greenhouse gas emissions ^[2]. Consequently, one mitigation method being pursued to limit the temperature increase is to balance the emission and removal of greenhouse gases to/from the atmosphere, more commonly known as reaching the state of "net-zero".

In the United Kingdom of Great Britain and Northern Ireland (the UK), legislation is in place via the Climate Change Act of 2008 ^[3] that sets a legal requirement for the government to reduce greenhouse gas emissions by 100% by 2050 of the 1990 levels; this defines the UK's net-zero target. To achieve this, plans are in place to decarbonise the UK power system by 2035 ^[4], with low-carbon hydrogen identified in the UK Hydrogen Strategy as being critical to achieving net-zero in the UK ^[5]. For instance, presently the majority of buildings in the UK use fossil fuels for heating; the use of low-carbon hydrogen to replace the fossil fuels, in part or in whole, would lead to a reduction in greenhouse gas emissions.

Presently, in the UK, natural gas is supplied to residential and industrial customers via a complex network of high-pressure transport pipelines that supply local distribution grids and power stations.

The system consists of around 7,600 km of steel line pipe ^[6]. The system was originally constructed between the 1960s and 1970s to provide domestic supply of natural gas from large deposits that were discovered in the North Sea in 1965¹.

The pipelines within the UK's natural gas transmission system were generally designed in accordance with IGEM/TD/1 ^[7], which traces its roots back to IGE Communication 674 that was first published in 1965. The scope of this document is limited to the design, operation and maintenance of pipelines conveying dry natural gas. The control of the risk posed by the pipelines is managed by the code in numerous ways, for example:

- The design of the pipeline is a function of the population density surrounding the pipeline. In rural areas, thin-walled pipe can be used and be utilised at a hoop stress level of 72% of the minimum specified yield strength, whereas in suburban areas thicker walled “proximity” pipe must be used that is designed to have hoop stress utilisation of 30% of the minimum specified yield strength^{2,3}. The later design case ensures with a high certainty that the pipeline will fail by leakage rather than rupture ^[8].
- Normally occupied buildings cannot be constructed within a stipulated “building proximity distance” from the pipeline, limiting the exposure of persons to the effects of a pipeline failure should one occur. The distances are based on phenomenological models.
- Audits are performed at a maximum frequency of once every four years to verify, among other things, any developments in proximity to the pipeline and the population density. Where non-conformances with the original design intent are identified, consideration is given to the performance of a safety evaluation⁴ to assess the risk posed by the pipeline on the population and determine if mitigation measures are required to be implemented.

The safety evaluation allowed for by IGEM/TD/1 is commonly a QRA, and the proximity distances noted above are based on models developed for natural gas. The audits that are performed occur often enough, and changes along the pipeline route occur often enough that the performance of QRA is commonplace in the UK for managing the risk posed by the high-pressure natural gas pipelines, so much so that the methodology is formally documented in IGEM/TD/2 ^[9]. In addition to performing QRAs during the operational life of the pipeline, QRAs also find use during the design stage to justify and optimise pipeline routing and to justify that the risk posed by the pipeline is acceptable.

It is now envisioned that the existing natural gas pipeline network can be repurposed to support the UK's net-zero goal by blending natural gas with hydrogen such that its composition has up to 20% hydrogen on a volumetric basis. However, the pipelines were not originally designed for such service.

¹ Prior to this, gas was produced locally by coal gasification resulting in a fuel containing hydrogen, carbon monoxide and methane as majority components amongst others.

² Note that if the wall thickness is in equal to or greater than 19.1 mm, the pipeline can have a hoop stress utilisation of 50% of the specified minimum yield strength.

³ Note that there are also additional requirements for more heavily populated areas such as towns.

⁴ The safety evaluations based on the authors experience are most commonly in the form of a QRA to justify the presence of new buildings that have been built along the route of the pipeline since commissioning.

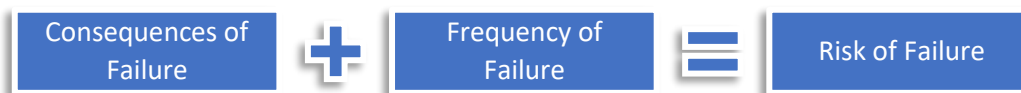
A change in the fluid being conveyed through a pipeline is a significant change that must be assessed. This is recognised in the recently developed supplement to IGEM/TD/1 “Supplement 2” for high-pressure hydrogen pipelines that requires that an “assessment of the risks posed on the surrounding population” be undertaken ^[10].

Presently, there is no documented standard guidance in the UK that documents how a QRA should be performed for a repurposed natural gas pipeline conveying hydrogen. There is a need for such a document if the UK continues to pursue the use of hydrogen as a replacement or supplement for natural gas in the pipeline network. This paper aims to review the existing QRA methodology utilised in the UK for pipelines conveying natural gas with a view to assessing its suitability for use on pipelines conveying hydrogen.

3 WHAT IS QUANTITATIVE RISK ASSESSMENT?

A QRA is a formal assessment of the risk associated with, in the current context, the operation of a pipeline. It differs from a qualitative risk assessment as the final risk value is expressed quantitatively as an absolute value⁵, such as 5 deaths per thousand years, rather than a qualitative value such as “medium risk of death”. The calculation of the risk value requires numerical estimation of the frequency of an event and the consequences associated with that event, which are combined to derive a risk value, as shown in Figure 3-1.

Figure 3-1: The Definition of Risk Used in a Quantitative Risk Assessment



Two forms of risk are considered in a pipeline QRA. The first is the individual risk, which is the risk of fatality or of receiving a dangerous dose to a hypothetical person who is exposed to the pipeline for 100% of the time at a particular location. The nature of pipelines means that if a failure were to occur, it is most likely that many persons would be affected by the failure, rather than a single person. As such, the second type of risk considered is the societal risk, which is the risk of a pipeline failure causing multiple fatalities⁶.

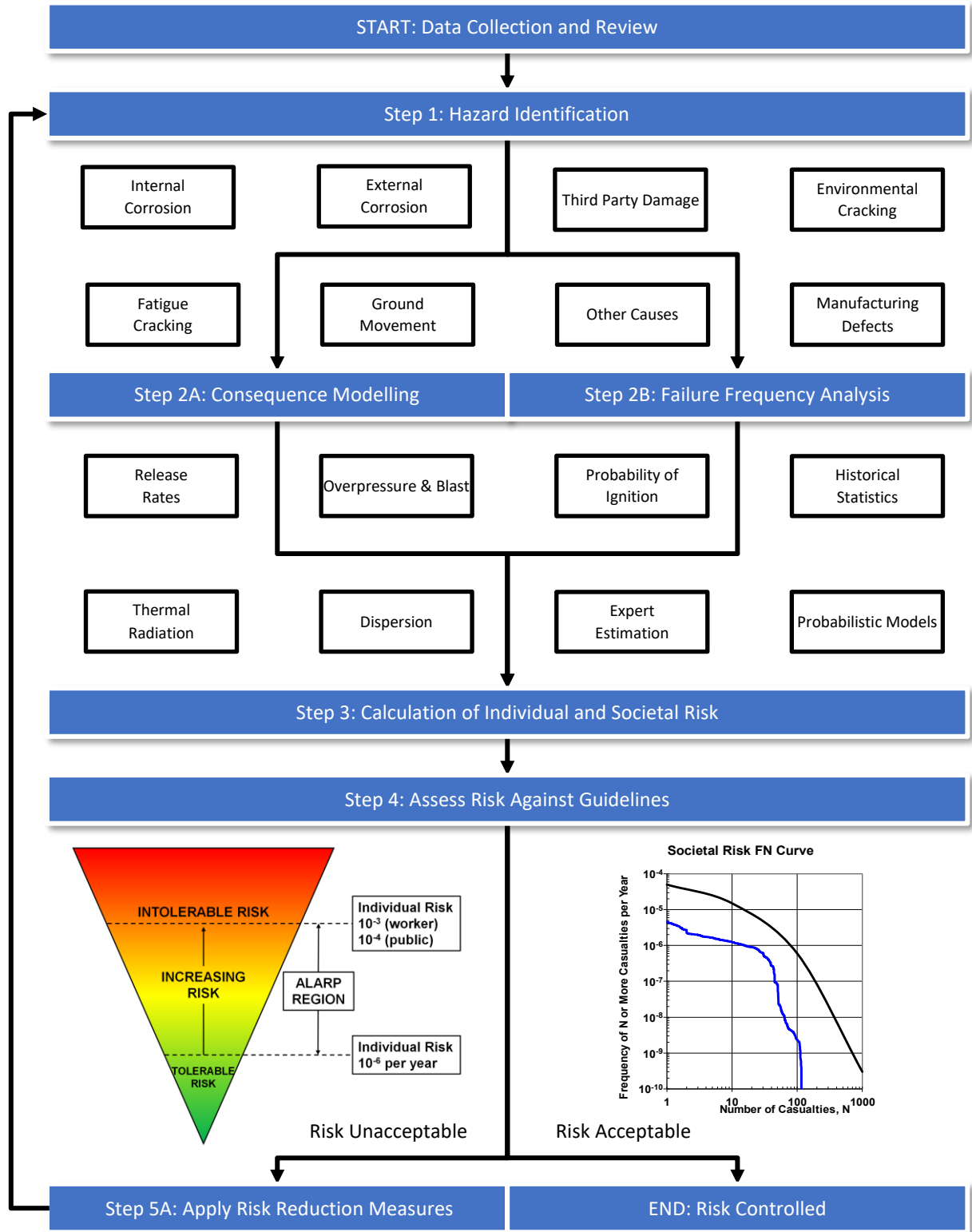
⁵ Note that due to the uncertainties associated with the plethora of variables required to perform a QRA, some schools of thought regard that the risk is not “absolute”. However, provided that a consistent method is used for all assessments, with the risk being compared against a guideline generated using the same assumptions, the relative risk can be compared meaningfully.

⁶ Some societal risk acceptability criteria argue that societal risk is applicable for ten or more fatalities although societal risk curves are often presented on a logarithmic axis starting at one fatality.

3.1 THE STEPS UNDERLYING A PIPELINE QUANTITATIVE RISK ASSESSMENT

The steps required to undertake a pipeline QRA are well established and documented [7]; these steps are shown graphically in Figure 3-2. These steps form the framework for the current methodology used in the UK.

Figure 3-2: The Steps Underlying a Pipeline Quantitative Risk Assessment



4 REVIEW OF THE APPLICABILITY OF THE QRA PROCESS TO HYDROGEN PIPELINES

4.1 STEP 1 – HAZARD IDENTIFICATION

This step is likely to require additional considerations when performing a QRA of a hydrogen pipeline, especially if the pipeline is being repurposed and has not been originally designed specifically for hydrogen service.

The hazards that affect pipelines are well documented and demonstrated through many years of historical operation. There are integrity management standards for liquid ^[11] and gas ^[12] pipelines that document the typical hazards these pipelines are subjected to, and there are organisations of pipeline operators that document and record failures that have occurred with their underlying cause ^[13,14,15].

Even so, the QRA process currently used has been developed for natural gas pipelines, and therefore the hazards included in the methodology are those that are credible for natural gas pipelines. The methodology does not forbid the inclusion of additional hazards, and as such the barrier to the inclusion of additional hazards in the assessments is low, however, guidance should be provided on what hazards are likely to require further consideration for hydrogen pipelines, such as in-service cracking and hydrogen embrittlement leading to altered material properties.

4.2 STEP 2A – CONSEQUENCE MODELLING

As shown graphically in Figure 3-2, there are multiple considerations that are had when modelling the consequences of a pipeline failure.

RELEASE RATES

The first step in modelling a consequence scenario is determining how much fluid will be released from the pipeline in the event of failure, typically, leaks and full-bore ruptures are the minimum set of release scenarios considered when performing a pipeline QRA. To calculate the release rate of fluid through a hole in a leak scenario, or from a pipeline that has been cleaved in the case of a full-bore rupture release case, an understanding of the underlying physics of release and of the thermodynamic properties of the fluid being released is required.

The release of natural gas, hydrogen, or its mixtures is comparatively simple in terms of physical effects occurring versus, for example, liquefied petroleum gas or dense phase carbon dioxide, which may undergo a single or multiple phase changes during the release such as flashing or solidification.

A complex part of the release rate modelling is associated with the rupture release case where there can be a blowdown of the entire pipeline contents. In such a release, a shock wave propagates through the pipeline from the point of rupture. The modelling of such a phenomenon is computationally intensive as a rigorous model of the release requires the numerical solution of coupled partial differential equations.

To overcome this, typically either a simplified form of the full set of equations is used or a phenomenological model is used, both methods are useful and find common use in QRAs due to their simplicity and quick solution time. The former model is more likely to be easily adapted to hydrogen releases as the model is based on first principles, the latter is less clearly applicable to

hydrogen due to the semi-empirical nature of the models; however, the models used have been developed for gas pipeline releases, and the differences between a hydrogen gas release and a natural gas release are likely to be captured by modelling the thermodynamic properties of the fluids rigorously rather than requiring a different model/set of equations.

Natural gas and hydrogen are markedly different molecules with different properties that effect the release rate calculations; the molecular weight of natural gas (16 g.mol^{-1}) is 8x that of molecular hydrogen (2 g.mol^{-1}), hydrogen has a negative Joule-Thomson coefficient at ambient conditions whereas natural gas has a positive coefficient, they have different isentropic ratios and hydrogen behaves more ideally than natural gas over the range of temperatures and pressures commonly encountered in the pipeline industry. No release rate model will provide reasonable approximations if the variation in the fluid properties is not considered. This is not a difficult task and is not expected to pose a barrier to the modification of the current methods used.

For pipeline repurposing, it will generally not be possible to increase the design pressure of pipeline to maintain a constant energy supply through the pipeline (i.e. in terms of joules of potential chemical energy delivered from point A to point B) as the magnitude of the pressure increase would be too large. Consequently, at best, the operating pressure will remain the same when repurposed natural gas pipelines are conveying either natural gas or hydrogen.

In the event of a significant leak, a choked flow release will occur and in such an event, to the first order, the square root of the ratio of the density of natural gas to the density of hydrogen represents the ratio of the volumetric flow, the inverse is the ratio of the mass flow. Considering pressures of 10 to 100 barg at a temperature of 25 °C, the ratio of the volumetric flow is calculated to be between 2.9 and 3.3 accounting for non-ideality. This results in a more voluminous release with less mass for hydrogen, which may influence the dispersion of the released gas and the dimensions of any fire that results.

THERMAL RADIATION

For a natural gas pipeline, the predominant risk posed by a failure is fatality due to exposure to thermal radiation caused by the resulting jet-fire and/or fireball. Hydrogen, and mixtures of natural gas and hydrogen are both flammable substances, hence, thermal radiation will continue to be a consideration in the QRA of hydrogen pipelines. That said, the different properties of the fluid are expected to have a marked impact on the relative levels of risk posed between pipelines conveying natural gas and of those conveying hydrogen.

Generally, for pipeline QRAs, two types of fires are considered. These are jet-fires and fireballs. A jet-fire occurs when a high-pressure leak is ignited leading to a jet of flame that can extend a significant distance from the leak location. A fireball results when there is a significantly large release of gas that ignites before it has had time to disperse, the result is a large mass of fire lasting a relatively short duration (up to 0 to 30 seconds typically).

To model the effects that these fires have on humans and structures, it is required that the thermal radiation received remote from the fire can be calculated. This requires the determination of two key parameters, these being the dimensions of the fire and the surface emissive power of the fire. This allows for the fire to be modelled as a radiation emitter of a given power. View factor algebra can then be used to determine how much radiation emitted from the fire is incident on a person or structure remote from the fire.

There is little concern with the applicability of the view-factor method in the QRA methodology as it has a rigorous fundamental basis. However, the same cannot be said for the methods used to determine the dimensions of the fire. The models used to determine the dimensions of the fires are most commonly semi-empirical equations that approximate the actual phenomenon occurring.

As an example, the diameter of a fireball is often characterized in literature by an equation of the form $D = Am_f^n$, where D is the fireball diameter, m_f is the mass of fuel in the fireball and A and n are derived constants. General, n takes the value of $1/3$, and the value of A is derived from stoichiometric combustion equations with assumptions made on the flame temperature (typically adiabatic), air entrainment and fire shape. Alternative fireball models are available in literature that are more complex, model different shapes of flame and that consider the fireball dynamics.

In literature there is a dearth of A -values available that are documented as being applicable to hydrogen, however, suitable values could be derived using similar assumptions to what has been performed for natural gas. There are also generic values available that have been derived from experiments for typical fuels such as liquefied petroleum gas and such generic values are used in QRAs for hydrogen today.

With regards to jet-fires, the models are more complex. The models attempt to model the length of the jet-fire and the diameter of the jet-fire. The shape assumed is typically that of a frustrum, and as such the variation in the diameter of the jet-fire with length is also considered in the models. Jet-fires also exhibit a phenomenon termed "lift-off", which is where the flame of an ignited jet-fire does not extend back to the leakage point, but hovers above it. There are models used in the QRA of natural gas pipelines for jet-fires that have been specifically developed for natural gas and validated on natural gas fires. Research has been performed into hydrogen jet-fires and the models arising from the research may be useful in hydrogen QRA.

The dimensions of the flame are only one aspect in the consideration of thermal radiation. The second consideration is the surface emissive power of the flame (how much radiation is emitted per unit surface area of flame). A theoretical basis for deriving this value assumes that a fraction of the heat released by combustion of the released gas is emitted as radiation. The measure of the fraction is termed the emissivity. Hydrogen flames are noted to have a lower emissivity than hydrocarbon flames.

Additionally, the type of radiation that is being emitted is important as the physiological effect is not the same for different types of radiation. Flames of different substances produce different radiation spectra. The radiation emission of a hydrogen-air flame has 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^[16]. 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^[17].

The methods for converting the amount of radiation a person receives to a harm criterion is generally consistent in the published methodologies for QRA, however, it is not clear if the criteria used are applicable for hydrogen due to the emitted radiation having a larger ultraviolet component rather than being predominantly infrared. Research has been performed to address this concern^[18] with recommendations being given as to what is an appropriate criterion to be used for hydrogen QRA.

OVERPRESSURE, BLAST & DISPERSION

When conducting natural gas pipeline QRAs, it is not commonplace to consider the effects of overpressure & blast. The reasons behind this are elucidated in a review of the event tree structure by the Health and Safety Executive of the UK ^[19], with the reasons being the low congestion surrounding rural pipelines and the lack of strong ignition sources in the vicinity of rural pipelines.

Hydrogen has a significantly lower minimum ignition energy compared to natural gas and it has a larger flammable envelope, which are factors that may make it more likely that an explosive atmosphere will form. Furthermore, the laminar flame speed of hydrogen is larger than of natural gas meaning that if ignition were to occur a larger over pressure may be created.

On the other hand, hydrogen is more buoyant than natural gas, which will affect the time it takes for a release of hydrogen to disperse to levels below the lower flammability limit (LFL). The LFL of hydrogen and natural gas are both around 4% on a volumetric basis, considering this along with the increased buoyancy of hydrogen, hydrogen may therefore disperse to a concentration below the LFL more rapidly than natural gas would. That said, the lower minimum ignition energy may prohibit a large cloud of hydrogen from forming and hence dispersing. This is presently a knowledge gap in the QRA process as it is not currently known if such a scenario is required to be considered. Full scale testing supplemented by computation fluid dynamic simulations would likely be the best way to confirm if this is a credible scenario for inclusion in a QRA of a hydrogen pipeline.

4.3 STEP 2B – FAILURE FREQUENCY ANALYSIS

The current methodology for assessing the failure frequency of natural gas pipelines in the UK is supported by an extensive analysis of the operating history of the pipelines being assessed and failures that have occurred on them. This provides a statistical measure of the occurrence of failures due to various causes.

At present, due to their being a limited amount of operational experience with hydrogen pipelines, especially of pipelines that have been repurposed for hydrogen use. Due to this, there is uncertainty as to what appropriate estimates of the failure rates for hydrogen pipelines should be for use in QRAs. It is not immediately clear that the failure rates for natural gas pipelines will apply to hydrogen pipelines, this may be more likely for some causes, such as internal corrosion and less likely for other causes such as fatigue cracking.

4.4 STEP 3 – CALCULATION OF INDIVIDUAL AND SOCIETAL RISK

It is considered unlikely that the calculation of the individual and societal risk based on the outcome of the consequence modelling and failure frequency analysis is likely to be affected significantly; commercial QRA software exists that automates this step in the analysis nowadays and the addition of additional scenarios to the risk analysis, while increasing the workload ultimately does not affect the methods employed.

4.5 STEP 4 – ASSESS RISK AGAINST GUIDELINES

It is not expected that the currently used criteria for risk tolerability and societal risk criteria will change because of the change of pipeline service.

4.6 STEP 5 – APPLY RISK REDUCTION MEASURES

It is not expected that the assessment of risk mitigation measures to pipelines in QRA will change. Even if it does, their affect is captured within Steps 2A and 2B as mitigation measures either reduce the magnitude of consequences, for example, rerouting the pipeline to a less densely populated area, or reduced the likelihood of failure, for example, applying concrete protection slabs to the pipeline to make it more difficult for mechanical equipment to damage or puncture the pipeline.

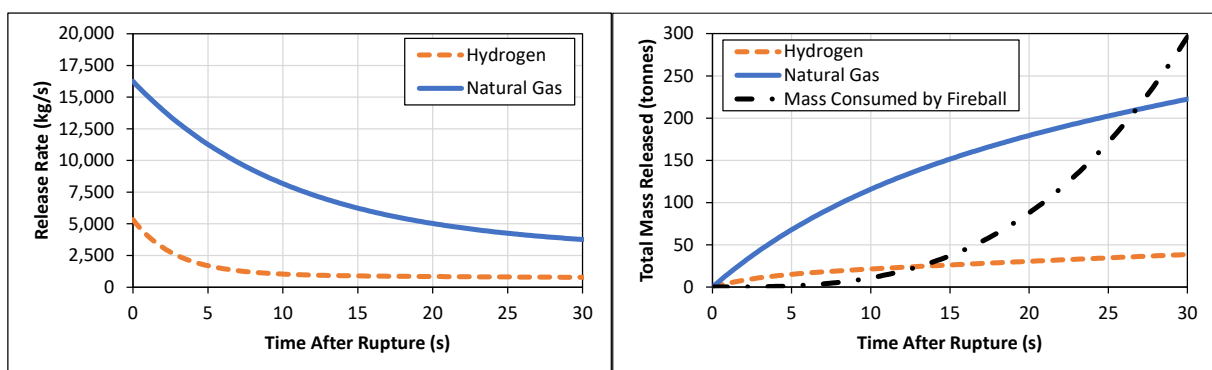
5 CASE STUDY

For the purposes of this case study, the potential consequences posed by the failure of an 18 km 36-inch pipeline operating at a pressure of 70 barg is considered for both hydrogen service and natural gas service. For brevity, only the consequence of a potential fireball is considered.

Figure 5-1 shows two plots, the left plot shows the variation in the release rate with time if the pipeline that has suffered a full-bore rupture, the right plot shows the cumulative mass released from the pipeline over time. The figure shows that for the same diameter and pressure, the hydrogen pipeline rupture results in less mass being released from the pipeline. The release rate has been calculated using standard models for gas pipeline rupture releases. The figure only utilises a single curve for both substances. The mass consumption curves may be different for natural gas versus hydrogen and the curves can also differ depending on it the fireball is momentum or buoyancy driven. For this case study, the same curve is used irrespective of the fluid.

Also shown on the right plot of Figure 5-1 is the curve of mass consumed by a fireball against time. Where the intersection of that curve with the curve of cumulative mass released from the pipeline indicates the size of the fireball. Based on this, it is clear from the figure that both the duration and size of the fireball will be small for hydrogen then natural gas. Detailed calculations show this, with the hydrogen fireball being predicted to last 13 seconds and reach a maximum diameter of 170 metres, whereas the natural gas fireball is predicted to last 27 seconds and reach a maximum diameter of 350 metres.

Figure 5-1: Plot of Release Rate (Left) and Cumulative Mass Released (Right) Versus Time After Pipeline Rupture

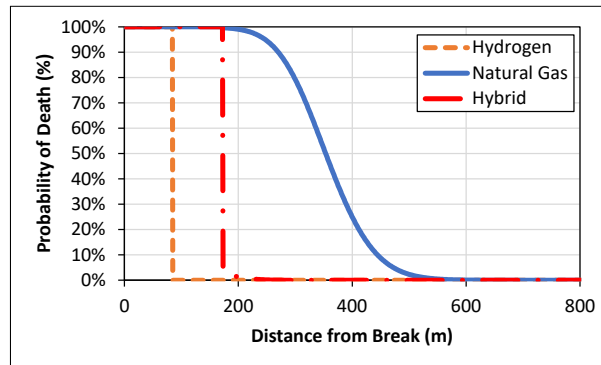


Once the size and duration of the fireball has been determined; an assumption can be made of its surface emissive power. Commonly, for hydrogen a surface emissive power of 70 kW/m² is used and for natural gas a surface emissive power of 270 kW/m² is used. Combining this with an assumed hemispherical shape of the fireball, the radiation received by a person can be determined at various distances away from the fireball. This radiation is assumed to be received for the duration of the fireball. Using a probit relationship, many of which are available in literature for exposure to thermal

radiation, the probability of death for the exposure received can be calculated. When this process is performed, the results shown in Figure 5-2 are obtained.

The curves shown in Figure 5-2 can be used to calculate the number of fatalities expected if an event were to occur (a rupture leading to a fireball of the pipeline). Assuming a uniform population density and calculating the number of fatalities results in a ratio of 18 fatalities for the natural gas pipeline to 1 fatality for the hydrogen pipeline should a fireball occur. The main reason for the difference being that the hydrogen fireball is predicted to be smaller, with a shorter duration and to emit less harmful infrared radiation than the natural gas fireball. As a sensitivity, if the hydrogen fireball had a diameter and duration equal to the natural gas fireball but using the lower surface emissive power of the hydrogen flame, the ratio of fatalities would be 4 to 1 versus 18 to 1 above. This is shown in Figure 5-2 as the “hybrid” case. This demonstrates the potential effect that fireball duration and size have on the results. The steep vertical drop in probability is due to the low surface emissive power modelled of the hydrogen flame, in effect, direct contact with the flame is required for a fatality. Note that this case study has only considered the consequences due to fireballs. In a complete study, the risk due to other hazards such as jet fires would be considered.

Figure 5-2: Probability of Death Versus Distance from Pipeline Break.



6 CONCLUSIONS

QRA can be used to calculate and compare the risks posed by pipelines to the populations that are exposed to them. The methodology has been developed over many years and is well developed for natural gas pipelines. The methodology can be applied to hydrogen pipelines, as briefly demonstrated in this paper; however, for the results to be useful there must be confidence in the values used in the process. There are two main gaps in knowledge that should be addressed for the QRA of hydrogen pipelines at present, the first is failure frequencies for threats that may be more likely to occur for hydrogen pipelines such as cracking, the second is the potential for vapour cloud explosions due to the wide flammability limit of hydrogen and its increased potential to generate overpressures compared to natural gas.

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