Project report

Flame Visibility Risk Assessment 10172283-1

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A report prepared for SGN by DNV GL

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Your gas. Our network.

Document control

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Contents

1. Introduction

1.1. Executive Summary

This report contains information on the relative risks of natural gas and hydrogen fires, particularly regarding their visibility. The fires considered are those that could occur on the H100 Fife trial network. The H100 Fife project will connect a number of residential houses to 100% hydrogen gas supply. The project includes hydrogen production, storage and a new distribution network.

From a review of large and small-scale tests and incidents, it is concluded that hydrogen flames are likely to be clearly visible for releases above 2 bar, particularly for larger release rates. At lower pressures, hydrogen flame visibility will be affected by ambient lighting, background colour and release orientation, although this is also the case for natural gas.

Potential safety implications from lack of flame visibility are that SGN workers, other utility workers, or members of the public could inadvertently come into contact with an ignited release. However, some releases would be detected through noise, thrown soil or interaction with objects. From a workshop and review of risk reduction measures and analysis of historical interference damage incidents, it is concluded that flames with the potential for reduced visibility are adequately controlled. This is due to the likelihood of such scenarios occurring being low and that the consequences of coming into contact with such a flame are unlikely to be severe.

These conclusions are supported by cost-benefit analysis that shows that no additional risk mitigation measures are justified for the H100 project. It is recommended that the cost-benefit analysis is revisited before applying the approach to a network wider than the H100 project.

It was observed that the addition of odorant at relevant concentrations did not have an effect on the visibility of hydrogen flames.

1.2. Project Background

SGN is introducing hydrogen, rather than natural gas, as a fuel to a new purpose-built part of their network. The hydrogen network includes:

- Secure and remote hydrogen production facility and high-pressure storage.
- Vessels that store hydrogen at pressures up to 30 bar.
- Supply to low rise buildings at low pressure up to 75 mbar, and downstream of the customer Emergency Control Valve (ECV) at a pressure of 21 mbar.

This report reviews the relative risks of natural gas and hydrogen, particularly regarding their flame visibility. The study includes fires that could occur on the H100 Fife network, which comprises hydrogen production, storage and distribution.

The work included a workshop to review the hazards and risks associated with the flame visibility of hydrogen releases, a review of literature and small-scale tests, and a review of historical interference damage data.

It is assumed that the new PE network is being built to current natural gas standards and that these are suitable for hydrogen and that the hydrogen is odorised as it leaves the production and storage facility.

1.3. Project Objectives

The study identifies where hydrogen fires could occur on the H100 Fife network covering hydrogen production, storage and distribution. It considers the risk to the public and workers on the network from identified loss of containment events. Additional risk reduction measures related to the potential lack of visibility of an ignited hydrogen release are discussed. A literature review and small-scale tests supplement the discussion of the relative risk of natural gas and hydrogen regarding flame visibility.

2. Project Delivery

2.1. Scope

This report reviews the relative risks of natural gas and hydrogen, particularly regarding their flame visibility. The study includes fires that could occur on the H100 Fife network, which comprises hydrogen production, storage and distribution.

The work included a workshop to review the hazards and risks associated with the flame visibility of hydrogen releases, a review of literature and small-scale tests, and a quantification of the likelihood of flame visibility leading to harm to people.

2.2. Workshop

2.2.1. Approach

A workshop was held to identify the range of scenarios where an ignited hydrogen release might occur and to identify potential risk reduction measures should the hydrogen fire be less visible than the equivalent natural gas fire.

The workshop was held at SGN's premises in Edinburgh on 11th December 2019.

2.2.2. Guidewords

The guidewords set out in Table 1 below were used in the workshop to cover the potential leak scenarios and stimulate discussion. The objective of the workshop was to review the hazards and risks from ignited releases on the H100 Fife network due to lack of visibility. It also identified whether further applicable risk reduction measures could be introduced to reduce the risks due to the lack of visibility of the hydrogen flames.

Table 1 Flame visibility workshop guidewords

Primary	Secondary
Equipment location	Inside controlled area, outside controlled area, inside building, outside building
	Equipment buried/above ground
Equipment type	Bullet, pipeline, other components
Pressure	More than 7 bar, less than 7 bar, less than 2 bar
Failure cause	Interference damage, spontaneous failure
Safeguards	Procedures, training, PPE, knowledge of equipment location, fire extinguishers, maintenance
	Flame detection measures if non-visible
	Emergency Control Valve (ECV)
	Release noise, odour
	Other
Additional risks if flame non-visible	Escalation, injury
Other	Other

For the purposes of the risk reduction discussion, the assumption was made that the hydrogen flame is less visible than the equivalent natural gas flame.

2.2.3. Output

The following points provide a brief summary of the workshop:

- The H100 Fife network includes a controlled site that contains production and storage equipment, operating and pressures up to 30 bar. Some aspects of the site operation were discussed and the potential for experience from elsewhere to be used was investigated.
- Some potential mitigation measures and procedures for dealing with fires on distribution networks were discussed.
- Carrying out a small experimental programme at field scale to compare the visibility of the hydrogen and natural gas fires was considered. This would provide further evidence to support the operation of a large hydrogen distribution network but is not necessary to complete the H100 Fife project.

2.3. Information Review

2.3.1. Range of Potential Releases

From the workshop discussions, the range of fires that could occur on the H100 network include:

- Pressures from 19 mbar to 75 mbar on the distribution network and up to 30 bar on the production and storage facility.
- Small and large diameter releases.
- Locations on SGN production/storage site and in public areas.

The following sections contain a review of the visibility of large and small releases consisting of hydrogen and natural gas fires. Information from literature on hydrogen flame visibility is also considered.

2.3.2. Large Scale Tests

A range of studies of gas pipeline fires have been published with pressures ranging from 350 mbar to 60 bar.

Low pressure releases have been considered in the current H21 tests. H21 [1] is a suite of gas industry projects designed to support conversion of the UK gas networks to carry 100% hydrogen. These H21 tests cover releases in open trenches at pressures from 30 mbar up to 7 bar. Some data has been published [2] and is reproduced below showing 20 mm diameter puncture releases at pressures of 350 mbar, 2 bar and 7 bar. The tests represent a vertical release from a puncture at the top of a PE distribution pipe, e.g. simulating damage during trench construction.

Figure 1 Large scale hydrogen releases performed as part of the H21 test programme

LR051
20mm, 350mbar

LR053
20mm 2 bar

LR055
20mm 7 bar

These fires are clearly visible, although it is noted that the background of these tests is dark (due to the trees) and this may aid the flame visibility. This is discussed further in Sections 2.3.3 and 2.3.4.

Previous hydrogen tests at higher pressures, including a buried pipeline rupture fire [3], can be used to provide information about flame visibility. This release was from a buried 6” pipeline operating at a pressure of 60 bar. The fire is shown below and is clearly visible in this instance, with the test performed at night-time. The release is also impacting with the ground and this is also likely to increase its visibility.

Figure 2 Rupture test of a buried 6" pipeline operating at 60 bar

Comparisons with natural gas are appropriate, including with a programme of natural gas fires from PE distribution pipelines [4]. Comparisons of the earlier natural gas tests with the H21 hydrogen tests are shown below.

Figure 3 shows a natural gas fire from a 25 mm diameter puncture at the top of a distribution pipeline at 2 bar pressure. This is compared to the H21 test shown previously shown in Figure 1.

Figure 3 Comparison of large-scale natural gas and hydrogen tests at 2 bar

Test 3, natural gas (2 bar, 25 mm, up) LR053, 100% hydrogen (2 bar, 20 mm, up)

It is concluded that fires from releases of at least 2 bar are likely to be visible for natural gas and hydrogen. Entrainment of soil or interaction with the ground or objects makes the fires more visible.

2.3.3. Small Scale Tests

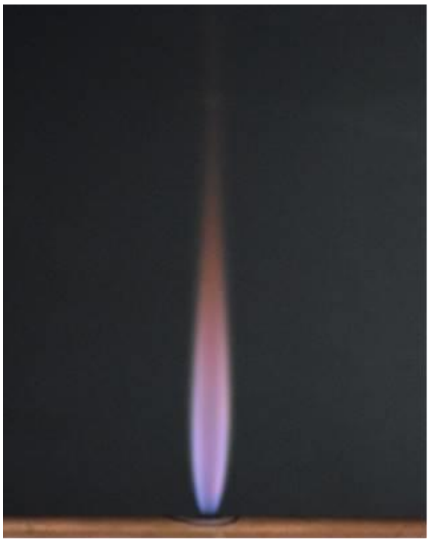
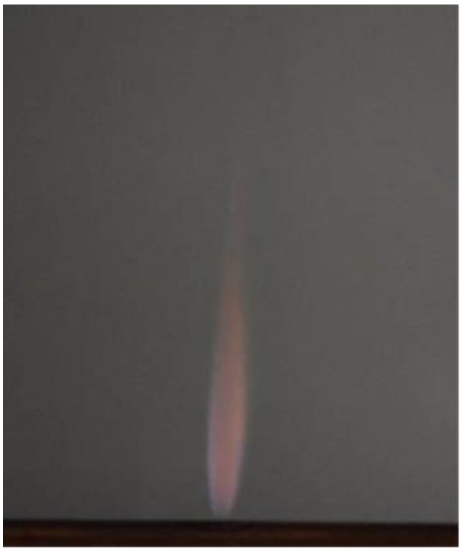
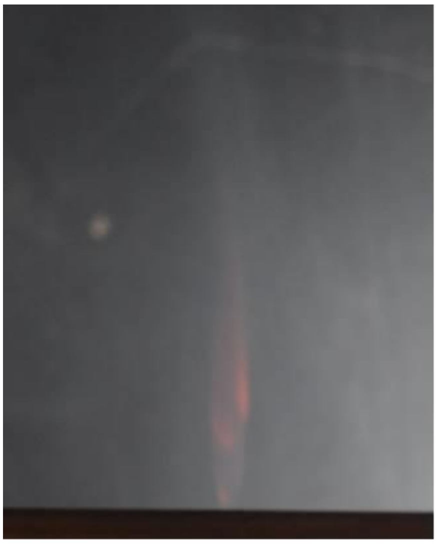
Small lab-scale tests have been performed by DNV GL with a 0.5 mm diameter hole in a 15 mm copper pipe at pressures of 21 mbar and 60 mbar. The pressures are representative of the hydrogen distribution system (60 mbar) and downstream of the ECV (21 mbar). These releases are 100% hydrogen with no odorant or colour added. Note that the release diameter considered is the largest that could be used for these release pressures in the laboratory setting. The pipe material for these tests is copper and the flame colour may be different for PE pipes or when originating from contaminated existing distribution networks. In particular, the presence of dirt and debris, either from inside the pipe or when picked up by the gas jet from the surroundings, makes the flame more visible.

The photographs from these tests are shown in Figure 4 for the 60 mbar tests and in Figure 5 for the 21 mbar tests.

Figure 4 Small scale ignited hydrogen releases at 60 mbar

60 mbar ignited hydrogen release with no illumination and black background 	60 mbar ignited hydrogen release with no illumination and white background 
60 mbar ignited hydrogen release with bright illumination and black background 	60 mbar ignited hydrogen release with bright illumination and white background 

Figure 5 Small scale ignited hydrogen releases at 21 mbar

21 mbar ignited hydrogen release with no illumination and black background 	21 mbar ignited hydrogen release with no illumination and white background 
21 mbar ignited hydrogen release with bright illumination and black background 	21 mbar ignited hydrogen release with bright illumination and white background 

A direct comparison of the luminosity of methane and hydrogen is shown below. It is noted that methane is the dominant component of natural gas (approximately 93% by volume) and it is considered that any difference in flame visibility due to the other components such as ethane and propane will be small. It was very difficult to get the methane flame to stabilise at the pressures of 60 mbar and 21 mbar above and a methane flame could not be sustained. A lower pressure of 1 mbar was therefore used, which allowed a stable flame to be studied.

Releases at 1 mbar are shown in Figure 6 for the methane tests and in Figure 7 for the hydrogen tests.

Figure 6 Small scale ignited methane release at 1 mbar

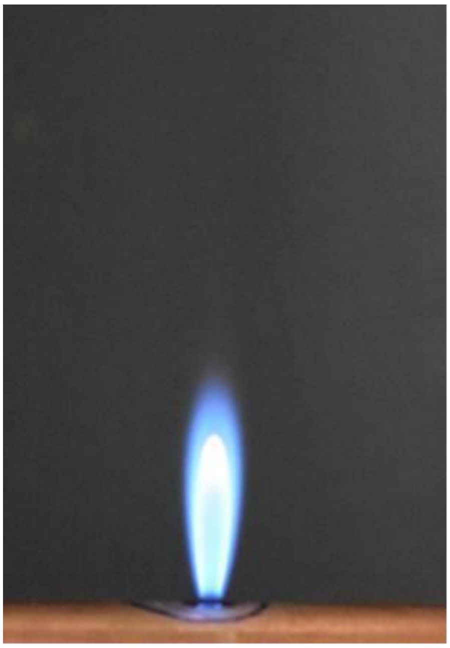
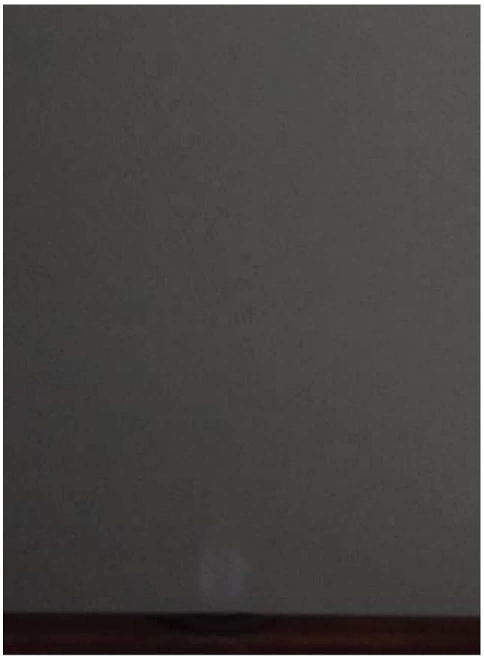
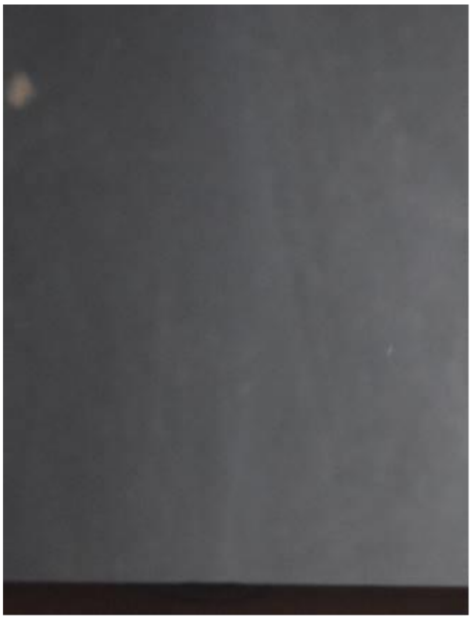
1 mbar ignited methane release with no illumination and black background 	1 mbar ignited methane release with no illumination and white background 
1 mbar ignited methane release with bright illumination and black background 	1 mbar ignited methane release with bright illumination and white background 

Figure 7 Small scale ignited hydrogen release at 1 mbar

1 mbar ignited hydrogen release with no illumination and black background 	1 mbar ignited hydrogen release with no illumination and white background 
1 mbar ignited hydrogen release with bright illumination and black background 	1 mbar ignited hydrogen release with bright illumination and white background 

These tests confirm that small hydrogen flames can be visible, but that the visibility depends on the background colour and ambient lighting. In particular, the hydrogen flame is most visible when the ambient lighting is low and the background is dark, and least visible when the ambient lighting is high and the background is light.

A direct comparison of the visibility of small hydrogen and methane flames suggests that methane is more luminous than hydrogen. However, methane flame visibility is also affected by the background colour and ambient lighting. The tests considered only unimpacted vertical releases and it is also likely that if the release interacts with a surface or object then it will be more visible.

In other, similar, laboratory tests, it was observed that the addition of odorant at relevant concentrations did not have an effect on the visibility of hydrogen flames.

2.3.4. Literature Review

The hydrogen tools website gives advice on detecting hydrogen flames [5]:

“Hydrogen burns with a pale blue flame that is nearly invisible in daylight. The flame may appear yellow if there are impurities in the air like dust or sodium. A pure hydrogen flame will not produce smoke. Hydrogen flames have low radiant heat. Unlike a hydrocarbon fires, you may not feel any heat until you are very close to the flame. Because of these properties, use a portable flame detector, such as a thermal imaging camera, when possible. If flame detection equipment is not available, listen for venting hydrogen and watch for thermal waves… Flame detectors may be installed in storage facilities and fuelling stations. Listen and watch for audible or visual alarms.”

It is noted that this advice is more relevant to hydrogen releases on sites, rather than on a distribution network. It refers to potential problems with detecting releases, but notes that it is still possible to notice hydrogen fires through visual indicator or sound. Note that the possibility of using thermal imaging equipment or detectors across a distribution network is not justified based on the cost-benefit analysis that is given in Section 2.7.

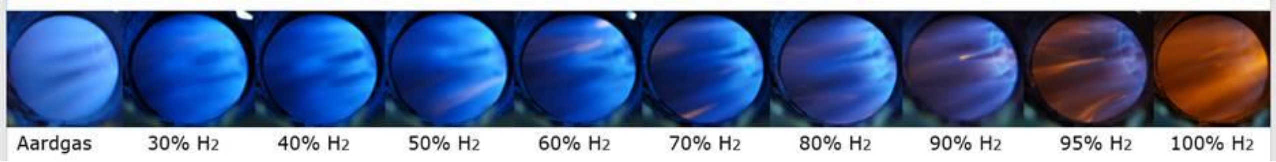
This site also demonstrates that low pressure hydrogen fires can be invisible in daylight conditions by comparing equivalent propane and hydrogen flames in day and night ambient light. During daylight, the hydrogen flame is not visible but it can be clearly seen at night, as shown in Figure 8, reproduced from [5] and also on the corresponding YouTube video [6].

Figure 8 Comparison of propane and hydrogen flames at night (from [5])

An experimental study [7] suggests that hydrogen flames are visible although considerably weaker than comparable natural gas flames; however, they are generally visible at reduced light levels. It also concludes that the blue flame colour is due to chemistry involving hydrogen and oxygen, rather than due to any contaminants.

DNV GL has performed tests on a forced draft burner set up with mixtures of natural gas/hydrogen. This shows the flame colour changing from blue to red as the proportion of hydrogen to natural gas increases, illustrated in Figure 9. This is thought to be caused by the radiation from the water vapour. Although the visibility decreases substantially, hydrogen diffusion flames are still visible.

Figure 9 Flames in burner set up showing effect on flame colour of mixtures of natural gas and hydrogen



A further review and experimental study [8] considered the flame characteristics of cooker top burners operating with various mixtures of natural gas and hydrogen. A reddish flame is observed in burners as the proportion of hydrogen increased. The study concluded that the red flame is mainly due to fine particles in the gas flow from the hydrogen storage cylinder (although it did accept that some of the red colour will be due to excited water molecules). The particles are produced by reaction of hydrogen with metal or metal oxide particles in the flow, due to hydrogen embrittlement which is worst in high pressure systems.

At much higher pressures, a release [9] from the pressure relief system on a hydrogen fuelled car also shows that the flame is visible. This is attributed to the presence of naturally occurring particulate matter containing sodium which is entrained into the flame.

Figure 10 Ignited release from pressure relief system on a hydrogen fuelled car [9]

A review of incidents [9], [10], [12], [13], [14], [15], [16], [17] involving hydrogen as a fuel did not give any new information on flame visibility. These incidents are major accidents involving high pressure releases resulting in fires or explosions. One of the incidents reviewed comprised an ignited leak from a 6” diameter 80-90 bar hydrogen pipeline during trenching operations [10]. The flame is clearly visible in the report film as seen in Figure 11 and this could be due to the high pressure of the release and the presence of debris from the ground being entrained into the fire.

Figure 11 Pipeline fire involving hydrogen release during trenching [10]

2.4. Discussion

2.4.1. Factors affecting Visibility of Flames

It is concluded that hydrogen flame visibility may be less than the equivalent natural gas flame in some situations. From the experimental studies and incidents reviewed above, it appears that the factors affecting the visibility of hydrogen flames are:

- Release pressure: 2 bar and higher pressure releases have a higher visibility.
- Release orientation: impacting releases are more likely to be visible, particularly where contact with the ground results in entrainment of dust particles or soil.
- Ambient light levels: releases at low light levels (e.g. at night) are more likely to be visible.
- Background colour: releases against darker backgrounds more likely to be visible.

It is noted that these factors also apply to the visibility of natural gas fires.

2.4.2. Safety Implications

The potential safety implication from lack of flame visibility is that SGN workers/contractors, other utility workers or members of the public may inadvertently come into contact with an ignited release. It is considered that the reduced hydrogen flame visibility of these low pressure releases would not significantly affect the risk of a fatality occurring. The relevant failure modes are discussed further in Section 2.5.

The bowtie diagram shown in Appendix A indicates the causes and hazards associated with a failure on a buried PE distribution pipeline containing hydrogen at pressures up to 75 mbar. The bowtie includes the prevention and mitigation measures discussed in the workshop that are already in place or have been agreed for implementation. It is concluded from this bowtie that the likelihood of a member of the public being injured by an ignited hydrogen release is low due to the limited flame length and small probability of being in the vicinity of the release. The risk is quantified in Section 2.7.

2.5. Possible Failure Modes

2.5.1. Approach

The following sections discuss the possible failure modes that could occur on a distribution network. Each is considered in terms of the type of release that would likely occur, and the associated hazards. The likelihood of detection of those hazards is also discussed, based upon the information presented in previous sections.

2.5.2. Above Ground Equipment

The majority of a gas distribution network consists of buried pipework. However, the possibility of a leak from above ground pipework and equipment is considered here.

If a release occurs above ground and in the open, but does not interact with any nearby structures or equipment, and an ignition source is present, then it is possible for a low visibility fire to occur. On a restricted gas industry site this is unlikely to pose a risk to the public, but an unsuspecting worker on the site could potentially walk into an established fire. However, the probability of a particular release being ignited without interacting with equipment is low. It is more likely that a worker would accidentally walk into a previously unignited flammable hydrogen-air cloud, and ignite it through their actions. However, as equipment and activities on sites are controlled, this is also unlikely. In addition, detection equipment can be used effectively on sites to warn workers of a release. Also, many releases on sites would be high enough pressure to be audible, and possibly noticed through changes to process conditions. It would certainly be the case that releases at 30 bar on the Fife site would be audible, even for small hole sizes.

It is difficult to quantify the differences between natural gas and hydrogen releases because many factors are involved. For example, in quantitative risk assessments a hydrogen release is often considered to have a higher ignition probability than the equivalent natural gas release in terms of the mass outflow rate. This is partly because the corresponding volumetric outflow rate is greater for hydrogen, but also because hydrogen has a lower minimum ignition energy, and a slightly lower concentration at which the gas-air mixture becomes flammable. If the immediate ignition probability is higher for hydrogen, this means that the probability of an unignited cloud forming could be lower than the equivalent natural gas release. In turn, this means that the likelihood of someone entering that cloud by accident is higher for natural gas. However, the probability of that person’s actions subsequently causing ignition of the cloud could be higher for hydrogen than natural gas. Overall, it is difficult to determine which case has the higher risk as it depends on many characteristics of the specific release in question.

A similar situation could potentially occur on a pressure reduction station or at a governor, for example, where members of the public could be nearby. However, most of the potential releases on these types of sites would occur inside enclosures, or would interact with fences, walls or other equipment or objects. This would make fires more visible and unlikely to be entered by people who happen to pass by. Again, at least medium and intermediate pressure releases would be audible, and most members of the public would be wary of the hissing sound.

It should be noted that the pressure reduction station for the H100 Fife trial will be located within a restricted site and therefore not will not be accessible to the public.

It is therefore concluded that above ground releases would either be detected or pose a very low risk to workers and the public, and hence only below ground releases need to be considered further.

2.5.3. Interference Damage

Interference damage, such as striking pipes with excavating equipment, is most commonly a result of accidental impact during work on the gas networks or other utilities. These workers should be aware of the presence of gas pipes and be wearing Personal Protective Equipment (PPE). Even if this is not the case, releases from interference damage would tend to be larger and more obvious than spontaneous failures, projecting dirt and debris, and hence are likely to be visible. For medium and intermediate pressure mains at least, the release would likely be audible too.

In the event of interference damage leading to a release, it would be expected that the operator of the equipment would make the area safe and not allow people to approach the leaking gas, which is likely to be the case with professional utility workers. It is also likely that the area would have been cordoned off before beginning an excavation. Any kind of agricultural or construction work that strikes a pipeline is likely to be in an area where the public are not present, either because it is remote or because it is not a publicly accessible site, so this will naturally limit the possibility of accidentally being exposed to the fire. These treats might be discounted completely for the H100 Fife trial network.

Interference damage to below ground pipes, even if uncovered, would almost always involve interaction of the released gas with the surrounding soil, and whatever equipment caused the failure. If the release were to ignite, it would therefore be visible, based on the test results that are discussed in Section 2.3.2.

Even if releases were not visible or cordoned off, there is a possibility of detection through the smell of the odorant or the noise associated with the release, at least at medium pressures and above.

For these reasons, it is unlikely that people would walk into an established fire on a gas pipe that was caused by interference damage, without being aware of the fire first. This applies to natural gas or hydrogen releases. Nevertheless, some example hazard distance calculations are given in 2.6 and quantification of the risk associated with this case is presented in Section 2.7.

2.5.4. Spontaneous Failures

Definition

'Spontaneous' failures include any loss of containment event that is not associated with interference. This includes joint failures and corrosion, depending on the material. Spontaneous failures tend to produce relatively small holes or areas through which gas can escape from the pipe into the ground surrounding the pipe.

Low Pressure Mains and Services

Full scale experiments carried out at the Spadeadam research and testing facility by DNV GL's predecessors [18], [19] have shown that:

- The majority of spontaneous failures of buried low pressure mains and services would not be expected to have sufficient energy to break the ground and form a route to the atmosphere. From DNV GL's experience with full scale tests, it is estimated that fewer than 1% of failures on pipes operating at less than 75 mbar would be able to form a permanent route through the soil to the surface.
- The outflow rate from a small hole at low pressure would be low. It is highly dependent on the ground conditions and the failure type, but the outflow rate would be expected to be less than 10 m^3/hour, and less than 1 m^3/hour for most releases underground.

For both natural gas and hydrogen, releases of gas at up to 75 mbar would be expected to result in migration through the surrounding soil. In these cases, the gas could disperse through the surface of the ground, but over a wide area or through multiple cracks or fissures in the soil. This would lead to a very low gas flux through the ground.

This type of release would be difficult to ignite because any flammable gas-air mixtures are close to the ground, if they are present at all. Any ignited releases would result in diffuse fires with small flames of less than 0.5 metres in length, as predicted using DNV GL's models, with the size of fire depending on the outflow rate from the pipe and the ground conditions. It is possible that someone could be injured by such a fire, but fatalities are extremely unlikely, as quantified in Section 2.7.7. It is not expected that hydrogen fires would be significantly less visible than natural gas fires in this situation, and historically these types of fires have not been a significant safety concern on natural gas networks. Lab scale test data shows that the visibility of natural gas and hydrogen flames are both affected by the lighting conditions and background, rather than the nature of the flame, as noted in Section 2.3.3.

It is therefore concluded that the visibility of flames is not a significant issue for spontaneous failures of low pressure buried pipes, and that people would not be seriously injured by walking into any subsequent fire without being aware of its presence. Therefore, spontaneous failures on low pressure pipes are not considered in the risk calculations within Section 2.7.

Medium and Intermediate Pressure Mains

It is noted that there are no medium or intermediate pressure pipes within the H100 Fife network, but mains of this type are considered for completeness. This would be relevant if distributing hydrogen over a larger area.

Full scale experiments at Spadeadam by DNV GL's predecessors have shown that many below ground failures of medium pressure and intermediate pressure mains could have sufficient energy to break the ground and form a route to atmosphere [19]. The possibility of breaking the ground is dependent on the soil state and failure size as well as the operating pressure of the main. If releases on medium and intermediate mains are small and do not break the ground then they are unlikely to pose a significant fire risk, as discussed for low pressure mains above. This discussion is therefore concerned only with the larger holes of around 10 mm diameter or greater, not small leaks.

Note that larger releases from medium and intermediate pressure mains would likely be audible. For the same operating pressure and hole size in a given pipe, a release of hydrogen would occur at a greater volumetric flow rate, and at a greater exit velocity, than the equivalent natural gas release. The hydrogen release would be at least as audible as an equivalent natural gas release, and would likely produce more debris throw and physical disturbance, and so is more likely to be noticed.

However, supposing that a release could occur but not be noticed, a passing person could cause the ignition and hence be injured by the subsequent fire. In this case the visibility of the unignited release is likely to be similar for natural gas and hydrogen, as discussed in Section 2.3.2. Noting that this situation is not currently a significant concern for existing natural gas networks, and that the risk is expected to be no greater for hydrogen networks than natural gas networks, this case is not considered further.

Possible cases of concern are therefore limited to spontaneous failures of medium or intermediate pressure mains that are large enough to break the ground, and where the release is ignited but without anyone initially noticing and preventing others from approaching.

Incident data and full scale tests for large releases show that natural gas and hydrogen fires from buried pipes are both clearly visible, as discussed in Section 2.3.2. It is not likely that fires originating on medium and intermediate pressure mains that have sufficient energy to break the ground would not be noticed, due to the dirt and debris that is entrained in the flame, and interaction with the surrounding ground. In addition, an established fire in an urban or suburban environment, where most gas mains operate, could also be noticed through its effects on nearby structures, street furniture, vegetation, parked vehicles or other objects.

It is noted that hydrogen and natural gas fires at night or against a dark background are more noticeable than fires in good light against a light background. More surface types where buried pipelines are present, such as asphalt, tarmac, soil or grass, would provide darker backgrounds.

It is therefore concluded that the visibility of flames is not an issue for spontaneous failures of medium and intermediate pressure buried pipes as they are likely to entrain sufficient soil to be noticeable, even if a pure gas flame is less visible. It is also noted that the H100 Fife trial network does not include any medium or intermediate pressure mains. Therefore, spontaneous failures on medium and intermediate pressure pipes are not considered in the risk calculations within Section 2.7.

2.6. Example Fire Hazard Calculations

Some example hazard distances have been calculated using the hydrogen fire models from the CONIFER risk assessment package that was developed as part of the H21 project. Not all of the operating pressures are relevant to the H100 Fire network, but the results are included for information. The results are summarised in Table 2 below. Note that the flame length is measured along the trajectory of the flame, but the hazard distances to specified thermal fluxes are in the horizontal downwind direction. These results represent releases as a result of interference damage to uncovered pipes, as discussed in Section 2.5.3.

As discussed in Section 2.5.4, below ground releases would give relatively low fluxes over a wider area, and hence smaller flames. Below ground failures are therefore not considered in these examples.

Table 2 Example hazard distances for hydrogen fires from distribution mains

Type of Release	Pressure (mbar)	Release Diameter (mm)	Wind Speed (m/s)	Flame Length (metres)	Hazard Distance (metres)	
					4.73 k/m^2	1.58 kW/m^2
Vertically upwards, in free air	60	10	2	0.9	0.1	1.7
	60	20	2	1.8	1.7	3.5
	60	20	5	0.8	2.2	3.5
Downwards, impacted	60	20	2	2.5	2.7	4.7
Vertically upwards, in free air	500	10	2	2.0	0.2	2.2
	500	20	2	4.0	2.2	4.5
	500	20	5	1.8	2.7	5.0
Downwards, impacted	500	20	2	4.2	4.2	8.2
Vertically upwards, in free air	2000	10	2	2.9	1.5	2.5
	2000	20	2	5.6	3.0	6.0
	2000	20	5	3.2	3.7	7.0
Downwards, impacted	2000	20	2	5.8	6.2	11.0

These thermal fluxes are defined as follows in API 521 for on-site personnel [20]:

- At 1.58 kW/m^2, personnel with appropriate clothing can be continuously exposed without harm.
- Personnel can be exposed to 4.73 kW/m^2 for 2 to 3 minutes, without shielding but with appropriate clothing, in order to carry out emergency actions.

It is therefore reasonable to expect members of the public to be able to escape from at least the 4.73 kW/m^2 distance if exposed to a fire. In the examples shown above, people would become aware of the thermal radiation 1.5 to 5 metres before reaching the 4.73 kW/m^2 level, depending on the nature of the fire. This is between 2 and 7 steps for a typical person walking and is likely to be enough time to stop before being injured.

If travelling in a vehicle, cycling or even running, the person would pass through the entire affected area quickly and would not likely receive a thermal dose that would lead to serious harm.

One possibility for harm involves someone passing through the fire itself without seeing it in time. Direct contact with the flame could cause burns around the feet and legs and could potentially ignite clothing. This case would not be expected to result in fatal injuries.

The largest distance to 1.58 kW/m^2 given in Table 2 is 11 metres. Escape speeds of 2.5 m/s and 1 m/s could be applied to 'typical' members of the public and 'vulnerable' people respectively [21]. These vulnerable populations include children, elderly people and disabled people, who might find it more difficult to move away from a fire. Even at a speed of 1 m/s, a person could move from the source of the fire to beyond its area of effect in 11 seconds. The flux levels given in API 521 above suggest that this would not cause serious injuries.

Also note that slow-moving people would move into the area affected by thermal radiation from an established fire more slowly than a 'typical' person, and hence have more time to react and not enter the higher flux region closer to the flame. They are arguably less likely to come into contact with the fire itself because a slow escape speed also implies a longer time between first feeling the radiation effects and reaching the fire itself. There is no history of this being a significant safety concern for natural gas networks.

This suggests that people are unlikely to suffer serious harm from these types of fires, even if they approach them without realising that they are present. The majority of fires would have smaller hazard distances and the effects are directional, so the hazard distance is not necessarily as great as Table 2 suggests in all directions.

2.7. Quantification of Risk to People

2.7.1. Events Considered

The discussion in the above sections shows that the risk associated with releases from spontaneous failures is not significantly affected by the visibility of fires. Therefore, as natural gas leaks on buried pipes have not historically been a significant source of risk to people, it is expected that hydrogen leaks on buried pipes would not be either.

This report concludes that there is only one scenario where the visibility of a hydrogen fire could pose an additional level of risk beyond that posed by a natural gas fire. This scenario is as follows:

- Interference damage leads to failure of a live gas pipe.
- The release is ignited.
- The fire occurs in unfavourable light conditions.
- People are able to approach the fire.

The risk associated with this sequence of events is quantified in the sections below for mains and services. Some elements are based on the historical performance of SGN's distribution network, but the risks are calculated for the H100 Fife project trial network.

2.7.2. Frequency of Interference Damage on Mains

SGN has supplied historical failure data on the natural gas distribution network from April 2014 to March 2020, which is a period of 6 years. During this time, the number of interference damage cases that occurred in the South of England and Scotland were 2,138 and 1,014 respectively. This is a total of 3,152 cases, or an average of around 525 damage incidents per year. It is assumed that all these failures led to a release of gas.

Based on SGN's Safety Case [22], the approximate length of distribution mains in service is 48,205 km in the South of England and 23,694 km in Scotland, which is 71,899 km in total. These lengths include low, medium and intermediate pressure mains for consistency with the failure data, which is not broken down by pressure tier. For the purposes of this calculation, this mains population is assumed to apply over the same period as the failure data, from April 2014 to March 2020. It is assumed that these lengths do not include the Independent Gas Transporter (IGT) networks.

Combining these values gives a failure frequency due to interference damage of

3,152 / (6 × 71,899) = 7.31×10^{-3} per km per year

2.7.3. Frequency of a Fire Occurring on a Main

Within the same period, from April 2014 to March 2020, only 6 natural gas releases were ignited and resulted in a fire, across all pressure tiers. This includes 2 releases associated with Independent Gas Transporters. A conservative approach is taken in this example calculation, where the IGT failures are included, but Section 2.7.8 examines the effect of removing these incidents from the data set.

Using the mains population from Section 2.7.2, the frequency of a natural gas fire occurring is therefore

6 / (6 × 71,899) = 1.39×10^{-5} per km per year

It is recognised that hydrogen has a greater flammable concentration range than natural gas, and a lower minimum ignition energy. In addition, a hydrogen release from a pipe produces approximately 3 times the volumetric outflow rate than the equivalent natural gas release, and therefore the resulting flammable cloud is larger. It is therefore reasonable to take into account the increased likelihood of a hydrogen release igniting.

For the purposes of this assessment it is assumed that hydrogen is 3 times more likely to ignite than the equivalent natural gas release. This is a slightly conservative interpretation of some confidential information that is available to DNV GL. It is broadly consistent with approaches suggested in the open literature. For example, the International Association of Oil & Gas Producers [23] recommends doubling the ignition probability for hydrogen releases, based on the mass outflow rate.

Applying this factor of 3, the frequency of a hydrogen fire is estimated to be 4.17×10^{-5} per km per year.

2.7.4. Adjustment for Main Material

SGN's Safety Case [22] gives the proportion of SGN's distribution network that is composed of different materials. For low pressure mains, the South of England part of the network is 71.7% PE and the Scotland part of the network is 78.9% PE, by length. Using the lengths of low pressure mains in operation [22] this gives 74.1% of low pressure distribution mains overall being PE.

Based on confidential information that is available to DNV GL from another project, PE mains have interference failure frequencies approximately 1.5 times greater than metallic mains. The H100 Fife project trial network will consist of entirely PE pipework, so the historical failure frequency from SGN's historical data is adjusted accordingly. Based on the lengths of pipework in operation on SGN's network, the overall failure frequency is increased by a factor of 1.11 if all the metallic pipework is replaced by PE mains.

Based on the results from Section 2.7.3, this gives an approximate hydrogen fire frequency on a network of PE mains of

$(4.17 \times 10^{-5}) \times 1.11 = 4.63 \times 10^{-5}$ per km per year

2.7.5. Risk from Low Visibility Fires on Mains

The risk associated with low visibility hydrogen fires on the H100 Fife project trial network is based on 8.5 km of PE mains operating for 4 years. This gives the expected number of fires in that period as

$(4.63 \times 10^{-5}) \times 8.5 \times 4 = 1.57 \times 10^{-3}$

It is assumed that half of all failures occur in unfavourable light conditions and against a pale background. This is likely to be cautious as there is bright light outdoors less than half the time, if weather and daylight are taken into account, combined with the likelihood of the background being pale.

It is assumed that there is a 10% chance of the fire being accessible. This is likely to be conservative as most releases would be cordoned off, as discussed in Section 2.5.3.

Combining these elements gives the expected number of accessible, low visibility fires over the 4-year operating period as

$(1.57 \times 10^{-3}) \times 0.5 \times 0.1 = 7.87 \times 10^{-5}$

For each accessible, low visibility fire that occurs, it is conservatively assumed that someone eventually walks into it. This is unlikely to be the case, even if the situation allows it to potentially occur.

This is approximately equivalent to a 1 in 12,700 chance of there being a low visibility fire where someone comes into contact with it, for a 4-year period of operation of the H100 Fife network.

2.7.6. Risk from Low Visibility Fires on Services

The risk of low visibility fires on services is estimated in a similar manner to that applied to mains, as described in Sections 2.7.2 to 2.7.5 above. The following steps are used:

- The frequency of interference damage is based on 46 fires over 6 years across approximately 5,800,000 services. This gives a frequency of 1.32×10^{-6} per service per year. This includes IGT failures, but Section 2.7.8 examines the effect of removing these incidents from the data set.
- Applying a factor of 3 to represent the increased ignition probability of hydrogen, relative to natural gas, gives a hydrogen fire frequency of 3.97×10^{-6} per service per year.
- Based on confidential information that is available to DNV GL from another project, PE services have interference failure frequencies approximately 3 times greater than metallic services. It is assumed that PE services exist in the same proportion as mains within the current SGN network. This is likely to be slightly conservative. Taking these factors into account, adjusting to a purely PE network gives a hydrogen fire frequency of 4.79×10^{-6} per service per year.
- Assuming that 300 services are included in Phase 1 of the H100 Fife project trial network, this gives 5.75×10^{-3} expected fires on services in a 4-year operation period.
- As with mains, it is assumed that 50% of fires occur in unfavourable light conditions, and 10% occur in a location that can be accessed and is occupied. In this case it is assumed that nobody enters the area around the fire 90% of the time, either because they are warned or because the garden is simply not in use. This gives 2.88×10^{-4} accessible, low visibility fires on services over the 4-year period.
- For services it is assumed that someone comes into contact with 25% of fires. This represents the likelihood of these fires being on private land, rather than in the road or footpath. This gives a probability of 7.19×10^{-5} that someone comes into contact with a service fire, over 4 years.

This is approximately equivalent to a 1 in 13,900 chance of there being a low visibility fire where someone comes into contact with it, for a 4-year period of operation of the H100 Fife network.

2.7.7. Cost-Benefit Calculations

The section includes cost-benefit calculations for the 4-year operation of the H100 Fife project trial network.

From Section 2.7.5, the probability of someone walking into an accessible, low visibility fire on a main is estimated to be 7.87×10^{-5}. From Section 2.7.6, the probability of contact with such as fire on a service is 7.19×10^{-5}. This gives an overall probability of fire contact of 1.51×10^{-4}.

It is assumed that each person who walks into a fire on a main or service suffers at least a 'serious injury' as defined by the HSE cost-benefit analysis guidance [24], and that fatalities could potentially occur. This approach is conservative because at least some incidents would involve minor injuries or no harm at all, and it is unlikely that fatalities could occur. This conservatism is deliberate in order to ensure that all possibilities are covered.

The statistical value of a life saved is taken to be £2,000,000 for the purposes of this analysis. The financial values associated with different levels of harm are based on the HSE's cost-benefit guidance [24] but scaled up such that a fatality is valued at £2,000,000. The distribution of injury severities is by judgement and is likely to be conservative, as there is little data for injuries from natural gas fires in the street causing harm to members of the public. It is assumed that there are approximately order of magnitude variations between the severity categories, which is a common assumption in risk assessments. This gives the following:

- 1% of people suffer fatal injuries with a value of £2,000,000.
- 9% of people suffer 'permanently incapacitating injuries' with a value of £309,994.
- 90% of people suffer a 'serious injury' with a value of £30,670.

This gives an average cost of each fire contact incident of £75,503.

A gross disproportion factor of 10 is applied in the calculation. This gives a justifiable spend to avoid low visibility fire issues of

$(1.51 \times 10^{-4}) \times 75{,}503 \times 10 = £114$

Of this total, around 54% is associated with fires on mains and around 46% is associated with fires on services.

If the H100 Fife trial network is expanded to include 1,000 services with the same length of distribution mains then the total justifiable spend increases from £114 to £240.

It is clear that no credible risk mitigation measures can be put in place and maintained for four years for this cost. Varying the inputs significantly, such that the justifiable spend is increased by one to two orders of magnitude, would not alter this conclusion.

2.7.8. Effect of Removing IGT Data

The calculations can be repeated with the exclusion of fires that are associated with Independent Gas Transporters, but that appear in SGN data because SGN First Call Operatives are involved. This leaves 4 fires (rather than 6) on mains and 38 fires (rather than 46) on services in the period from April 2014 to March 2020. Following the same approach as described in Sections 2.7.2 to 2.7.7 gives a justifiable spend of £84, rather than £114, to remove all risk from low visibility fires on the H100 Fife trial network.

This reduction in risk makes any proposed risk mitigation measures even less viable, but doesn't change the conclusions of the study.

2.7.9. Application to Great Britain's Distribution Network

The same approach can be applied to a distribution network the size of that currently in use in Great Britain. Assuming a total of 284,000 km of mains and 21,950,000 services [25] gives the following results based on the analysis from Section 2.7.7:

- An average of 0.6 low visibility accessibly fires per year on mains, and 5.3 per year on services.
- An average of 0.6 fire contact incidents per year on mains, and 1.3 per year on services.
- A justifiable spend to avoid these incidents of around £496,800 for mains and £993,200 for services.

This gives a total justifiable spend of around £1,490,000 per year to avoid harm from low visibility hydrogen fires. This is unlikely to be high enough to justify the inclusion of mitigation measures across the whole of Great Britain, but this should be confirmed. Note that this result features some conservatism that is deliberately included in the cost-benefit analysis of the H100 Fife trial network. If some of the conservatism is removed, the following inputs could arguably be applied:

- 0.1% of people suffer fatal injuries with a value of £2,000,000.
- 0.9% of people suffer 'permanently incapacitating injuries' with a value of £309,994.
- 9% of people suffer a 'serious injury' with a value of £30,670.
- 90% of people suffer a 'slight injury' with a value of £449.
- People come into contact with fires on mains 20% of the time, and fires on services 10% of the time.

This reduces the justifiable spend to prevent low visibility hydrogen fires to £10,500 per year for mains and £41,900 per year for services, which is a total of £52,400 per year. The justifiable spend is reduced further to £41,600 per year if the IGT incidents are removed from the historical data set. This is a much lower sum of money than £1,490,000 per year, and no risk mitigation measures could be put in place and maintained every year, across a network of this size, for a cost lower than this value.

It is recommended that these calculations are reviewed before they are applied to a wider network. It is appropriate to use conservative assumptions for the analysis of the H100 Fire trial network, but once further information is available some of this conservatism could be removed in order to refine the justifiable cost that is calculated for the wider network.

This conclusion also applies to intermediately sized networks. The justifiable cost to prevent low visibility fires on the network scales with the length of mains and number of services is use. Applying conservative assumptions to the H100 Fire trial network is possible because the network is small, but following the same approach for the whole of SGN's network, for example, would likely give a high justifiable cost value.

3. Conclusions

From a review of large and small-scale tests and incidents, it is concluded that hydrogen flames are likely to be clearly visible for releases above 2 bar, particularly for larger release rates. At lower pressures, hydrogen flame visibility can be affected by ambient lighting, background colour and release orientation, which is also the case for natural gas.

Potential safety implications from lack of flame visibility are that SGN workers, other utility workers, or members of the public could inadvertently come into contact with an ignited release. However, some releases would be detected through noise, thrown soil or interaction with objects. From a workshop and review of risk reduction measures, it is concluded that flames with the potential for reduced visibility are adequately controlled. This is due to the likelihood of such scenarios occurring being low and that the consequences of coming into contact with such a flame are unlikely to be severe. This is supported by cost-benefit analysis that shows that no additional risk mitigation measures are justified for the H100 project.

It was observed that the addition of odorant at relevant concentrations did not have an effect on the visibility of hydrogen flames.

4. Recommendations

A small programme of fire tests could be performed at field scale to directly compare the visibility of hydrogen and natural gas flames, to provide further evidence to support introducing hydrogen throughout a large network. However, the information presented in this report suggests that there are only certain situations in which hydrogen fire visibility could be an issue, and these tests are not necessary for the H100 Fife network.

It is recommended that the cost-benefit analysis is reviewed if it is applied to a large network, beyond the H100 project.

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APPENDIX A BOWTIE FOR HYDROGEN RELEASES FROM DISTRIBUTION PIPELINES

As discussed in Section 2.4.2, the bowtie diagram below illustrates releases for hydrogen from a distribution pipeline.