CASE STUDY: QUANTITATIVE RISK ASSESSMENT OF HYDROGEN BLENDED NATURAL GAS FOR AN EXISTING DISTRIBUTION NETWORK AND END-USE EQUIPMENT IN FORT SASKATCHEWAN, ALBERTA

Wattis, Z.E.[1], Phillips, A.G.[2] and Jensen, K.[3]
[1] UK Safety and Integrity, DNV, Holywell Park, Ashby Road, Loughborough, LE11 3GR, UK, zoe.wattis@dnv.com
[2] UK Safety and Integrity, DNV, Holywell Park, Ashby Road, Loughborough, LE11 3GR, UK, andrew.phillips@dnv.com
[3] Hydrogen Projects, ATCO Gas & Pipelines Ltd., 7210 42nd Street, Edmonton, T6B-3H1, Canada, kalen.jensen@atco.com

ABSTRACT

In a first-of-its-kind project for Alberta, ATCO Gas and Pipelines Ltd. (ATCO) began delivering a 5% blend of hydrogen (H_2) in natural gas into a subsection of the existing Fort Saskatchewan natural gas distribution system (approximately 2,100 customers). The project was commissioned in October 2022 with the intention of increasing the blend to 20% H_2 in 2023. As part of project due diligence, ATCO, in partnership with DNV, undertook Quantitative Risk Assessments (QRAs) to understand any risks associated with the introduction of blended gas into its existing distribution system and to its customers. This paper describes key findings from the QRAs, through the comparison of risks associated with H_2 blended natural gas at concentrations of 5% and 20% H_2 and the current natural gas configuration. The impact of operating pressure and hydrogen blend composition formed a sensitivity study completed as part of this work. To provide context and to help interpret the results, an individual risk (IR) level of 1×10^{-6} per year was utilised as a reference threshold for the limit of the 'broadly acceptable' risk level and juxtaposed against comparable risk scenarios. Although adding hydrogen increases the IR of ignited releases from mains, services, meters, regulators and end user appliances, the ignited release IR was always well below the broadly acceptable reference criterion for all operating pressures and blend cases considered as part of the project. The IR associated with carbon monoxide poisoning dominates the overall IR and the results demonstrate that the reduction in carbon monoxide poisoning associated with the introduction of H_2 blended natural gas negates any incremental risk associated with ignited releases due to H_2 blended gas. The paper also explains how the results of the QRA were incorporated into Engineering Assessments as per the requirements of CSA Z662:19 [1] to justify the conversion of existing natural gas infrastructure to H_2 blended gas infrastructure.

1.0 INTRODUCTION

ATCO has undertaken a pilot project within the City of Fort Saskatchewan, Alberta, to introduce hydrogen blended natural gas (H_2 blended gas) containing between 5% - 20% hydrogen by volume to a portion of its existing gas distribution system. The project will initially deliver H_2 blended gas at a concentration of 5%, increasing to 20% in 2023. At the time of commissioning (October 2022), the project involved approximately 2,113 private residences, 8 light commercial properties, 1 primary school, and 1 multi-unit apartment complex. As the project is occurring in an area of Fort Saskatchewan that is under active expansion/development, new residences are being added on a continuous basis.

Prior to commissioning the project, ATCO undertook an extensive organizational change management (OCM) process to ensure ATCO was equipped with a thorough understanding of all potential challenges, and that thoughtful due diligence was completed. Part of the OCM process included ATCO partnering with DNV to complete a Quantitative Risk Assessment (QRA) to conceptualize and understand any risks associated with the introduction of H_2 blended gas into the existing distribution system and end-use appliances. It was critical for ATCO to demonstrate that H_2 blended gas can be delivered to domestic customers in a manner that is considered safe when compared to an industry established risk acceptability criterion and an equivalent natural gas network. It is noted that although site-specific assessments were performed as part of the overall QRA for non-domestic and multi-occupancy properties such as the school and apartment block, the results of these assessments are not included in this paper.

2.0 DESCRIPTION OF SCOPE

The QRA was comprised of two components: the gas distribution QRA (mains and services) from the outlet of the hydrogen blended station to the inlet of the customer meter (operating at 550 kPa/80 psi), and the end-user QRA (customer meter, internal pipework and end-use appliances) from the inlet of the customer meter to the burner tip (operating at 1.7 kPa/0.25 psi). Both QRA components considered large scale (e.g., full line break) and small scale (e.g., failed fittings or pinhole leak) releases, the impact of gas migration, the effect of a variety of housing types (bungalow, semi-detached, detached, multi-attached) and the effect of finished vs. unfinished basements. The end-user QRA also considered the impact of floor plan and the type of end-use appliance (furnace, boiler, cooking range, etc.). A summary of the approach used to model the risk to people in houses is provided in Section 3.0.

The QRA was comparative in nature as it juxtaposed the risk associated with the delivery of H_2 blended gas to the baseline risk associated with the delivery of natural gas. The QRA also compared the resultant risk associated with H_2 blended gas to that of established thresholds within industry [2]. Finally, a sensitivity analysis was conducted which considered size of distribution main, operating pressure and hydrogen content. The QRA considered the risk of a fatality both in terms of individual risk (IR) and societal risk (SR) from the perspective of fire and explosion, and carbon monoxide (CO) poisoning, however only IR results are discussed within this paper. A summary of key results for both gas distribution and end-use appliances is provided in Section 4.0 for domestic customers.

3.0 APPROACH

3.1 Introduction

The pilot study area was too large to assess in detail for every main and every customer, but not so large that abstract representations of the area need to be applied, as in the evaluation of risks for a whole network of millions of customers. Thus, the relatively uniform nature of the area was used to determine the total risk posed by mains, services and end-user appliances within domestic properties across the pilot study area.

3.2 Risk Assessment Software

The CONIFER risk assessment package [3], [4] was developed during the H21 project in the UK [5]. It was produced specifically to evaluate the risks associated with distribution mains and services, as well as releases downstream of the Emergency Control Valve (ECV). A series of linked predictive and statistical models can take the following aspects into account:

- Natural gas, blend, and pure hydrogen releases.
- Cast iron, spun iron, ductile iron, steel, open cut PE and inserted PE pipes in the distribution network.
- Spontaneous failures, such as joint failure or corrosion, and mechanical damage by equipment striking.
- Hazards associated with external fires and ignited releases within buildings, predominantly leading to explosions.
- Variety of building types, including different physical characteristics and occupancy patterns.
- Behavior of people, including ability to detect gas ingress into buildings and likelihood of reporting it.

The package covers releases from the distribution network up to at least 700 kPa/102 psi and releases downstream of the ECV that are typically regulated to around 1.7 kPa/0.25 psi for natural gas.

3.3 Failure Frequencies

The failure frequencies were derived from historical performance of ATCO's natural gas network and applied to releases of H_2 blended gas without alteration. Research available to DNV suggested that no significant changes to the failure frequencies would be expected when hydrogen is introduced, at least within the pressure range of interest to this assessment [6], [7], [8], [9], [10], [11], [12].

ATCO's specific failure data provided by ATCO for the 15-year period from 2005 to 2019 was filtered by pipe material, operating pressure and diameter and used in conjunction with the lengths of pipework in each category to determine the failure frequencies (per metre per year) for mains and services within the distribution network. Although the assessment considered the impact of changes in operating pressure, the data indicated there was no statistically significant difference in failure frequencies between operating pressure classes. The failure frequencies used in the study included both mechanical damage (such as striking by excavating equipment) and spontaneous failure modes (such as joint failure).

The overall release frequency across the pilot study area is 0.51 per year for the mains, which suggests that one release would be expected on the mains in the pilot study area around every 2 years, on average. Approximately 75% of these failures are predicted to occur due to mechanical damage. The overall release frequency for the services is 1.01 per year for all services in the pilot study area. Approximately 42% of these failures are predicted to occur due to mechanical damage. Most of these releases would be small and have no serious consequences.

A sample of ATCO's customer call out data from between January 2018 and October 2021 across their entire network was investigated by analysts within DNV and ATCO to determine how many call outs involved gas leaks, and within those cases, the specific leaking component (e.g., furnace, meter, etc.) and location. This allowed a set of failure frequencies to be developed for customer meter, regulator, internal pipework and each appliance type across the pilot area. The overall release frequency for this equipment is 11.8 per year for all appliances in the pilot study area. Approximately 46% of the leaks were from the meter and regulator; as these leaks are outdoors, well ventilated, and unlikely to be ignited, they are unlikely to pose a significant risk to members of the public.

3.4 Methodology

3.4.1 Distribution QRA

The following process was used to determine the risk posed by the mains across the pilot study area:

- The pilot study area was divided into neighborhoods and each main segment was classified by diameter, neighborhood, and land use district. Although other physical characteristics of the main can be important, in this study the pipe material (polyethylene PE) and operating pressure (550 kPa/80 psi) was the same for every main, and so no further subcategories were introduced.

- An initial representative set of specific main segments on particular streets were assessed in detail using the CONIFER risk assessment package to determine a "risk per unit length" for each type of main. These calculations were used to determine how much differentiation is needed between types of mains and land use districts.

- The risks calculated in this manner were extrapolated according to the lengths of main of each type in each neighborhood. This uses the assumption that a main of a particular diameter surrounded by a particular housing type has a societal risk level that is similar to an identical main on a different, but similar, street.

- The types of mains shown to be significant risk contributors were subjected to further analysis and further detailed assessments until sufficient resolution in the results was obtained.

A similar process was applied to services, but there are fewer combinations of service type and house type than there are main type and land use district type.

3.4.2 End User

Each house in the pilot study area was assumed to have a gas supply such that the total number of houses is equal to the total number of services within a neighborhood. Releases inside bungalows, semi-detached houses and multi-attached buildings were considered for each potential release source. The pressure was assumed to be regulated at each house, immediately upstream of the customer meter, to approximately 1.7 kPa/0.25 psi. Therefore, it was assumed that all equipment and pipework downstream of this point, including the meter, within the customer's property, was supplied at this residential pressure. A range of hole sizes were modelled to represent releases from pipework and fittings and releases from connections such as those associated with the meter unit or domestic appliances. ATCO completed a comprehensive survey of residences within the project footprint. The results of this survey indicated that the following assumptions could reasonably be made for the appliances:

- All properties were assumed to have a pressure regulator and a meter located outdoors on the external face of the building.

- All properties were assumed to have pipework between the meter and appliances within the house. Leaks from the pipework downstream of the meter were assumed to be equally likely to occur in any of the above ground rooms within the house.

- All houses were assumed to have one furnace for space heating. It was assumed that 80% of furnaces were in a finished basement and 20% were in an unfinished basement.

- It was assumed that 89% of households have one gas fired hot water heater. It was assumed that 80% of hot water heaters were in a finished basement and 20% were in an unfinished basement.

- It was assumed that 68% of households that receiving piped natural gas own a fireplace. It was assumed that 90% of fireplaces were in an open plan living room with combined kitchen, and the remaining 10% were in a separate living room or smaller second room.

- Data gathered by ATCO suggested that 24% of households used a garage heater.

- Data gathered by ATCO suggested that approximately 13% of households use a natural gas range. It was assumed that 90% of ranges were in an open plan living room with combined kitchen, and the remaining 10% were in a separate kitchen.

4.0 INDIVIDUAL RISK RESULTS

4.1 Individual Risk (IR) Criteria

When considering the impact on risk from introducing hydrogen blends into the distribution network, it is important to realize that all activities present some level of risk. Whether these risks are acceptable depends on how well the hazard is understood, the exposure of the individual to the event, the size of event and whether the risk is voluntary. Voluntary risks are those that are within the individual's control e.g. road traffic or DIY accidents, whereas involuntary risks are imposed on individuals or by naturally occurrence e.g. passive smoking or earthquakes. Additionally, public perception may consider a single large event such as a plane crash killing 100 people to be unacceptable compared with several smaller events such as 100 road traffic accidents each killing one person; despite the likelihood that a plane crash may only occur once every few years whereas multiple road traffic accidents occur each day.

The magnitude of the risk takes into consideration both the likelihood and severity of an event and the impact on the individual and/or the society at large and may range from a minor injury to permanent disability or death. Within the process industry, risk is generally quantified in terms of events with consequences that would result in fatality. Within this paper, this is quantified through the use of individual risk (IR). The individual risk is the probability (per year) that a particular person becomes a fatality and takes into account the likelihood that the person is present at the time the hazard occurs.

ATCO currently uses semi-quantitative metrics to assess the acceptability of individual risk levels for the mains and services on the distribution network as well as the meter and regulator. ATCO does not have corporate individual acceptability levels that would apply to end-users. It is important to clarify that ATCO does not own or operate any piping, fittings or end use equipment/appliances located downstream of the meter. Therefore, there is no acceptable risk threshold that ATCO is required to meet or exceed as it relates to end-users. Rather it is ATCO's responsibility to ensure that customers are not exposed to significant additional risk as a result of introducing blended gas as the end-user is not in control of the composition of gas that is delivered to their home. While the absolute risk values are meaningful from the point of interpretation, the relative change between natural gas and blended gas is of primary importance.

The quantitative criteria introduced in the proposed revisions to CSA Z662 [2] are based on the As Low As Reasonably Practicable (ALARP) principle (see Table 1). Whilst the proposed Annex B of CSA Z662 [2] is labelled as informative, it is written in a mandatory way to allow companies such as ATCO to implement it into their codes and practices. It also states that the criteria documented within the Annex applies to all pipelines within the scope of this standard; and as such includes distribution networks similar to the one assessed for this study. To provide context and in order to help interpret the results, these quantitative criteria have also been considered for the end use equipment to be consistent with the mains and services.

Table 1: IR criteria from proposed Annex B of CSA Z662 [2]

Zone	Description	IR Criteria (per year)
Upper (Unacceptable)	Any activity or practice giving rise to risks within this region should be ruled out unless the activity or practice can be modified to reduce the degree of risk so that it falls on one of the regions below	$> 1 \times 10^{-4}$
Middle (Tolerable)	Risks in this region are typical of the risks from activities people are prepared to tolerate provided the nature and level of risks have been properly assessed and the results used to determine control measures. Within this region, the residual risks should be kept as low as reasonably practicable (ALARP) and periodically reviewed to ensure they still meet the ALARP criteria.	1×10^{-6} to 1×10^{-4}
Bottom (Broadly Acceptable)	Risks falling within this region are generally regarded as adequately controlled	$< 1 \times 10^{-6}$

4.2 Individual Risk from Fire and Explosion

4.2.1 Distribution

The CONIFER model was run with all the houses along a street set to the same type (bungalow, detached, semi-detached and multi-attached) in order to consider the impact of the four house types with unfinished basements on the individual risk following a release from the distribution mains or the service to the house. The area of the basement is assumed to be equal to the building's footprint. A fifth case (detached house type with finished basement) was also run to consider the impact of the basement configuration. The services from the main are located below ground until they reach the house when they come above ground into the meter located outside of the house. A comparison of the overall IR and the increase in risk from the natural gas case for each house type is provided in Table 2.

Table 2: Mains IR for each building type and blend

Contributor	Individual Risk (per year)				
	Natural Gas	5% Blend	20% Blend	25% Blend	30% Blend
Bungalow/Unfinished basement					
Mains	7.15×10^{-9}	7.21×10^{-9}	7.67×10^{-9}	8.04×10^{-9}	8.38×10^{-9}
Services	2.02×10^{-8}	2.06×10^{-8}	2.19×10^{-8}	2.38×10^{-8}	2.51×10^{-8}
Total	**2.74×10^{-8}**	**2.78×10^{-8}**	**2.96×10^{-8}**	**3.19×10^{-8}**	**3.35×10^{-8}**
Increase from Natural Gas	-	*1.7%*	*8.1%*	*16.5%*	*22.4%*
Detached/Unfinished basement					
Mains	7.72×10^{-9}	7.89×10^{-9}	8.35×10^{-9}	8.82×10^{-9}	9.19×10^{-9}
Services	2.04×10^{-8}	2.09×10^{-8}	2.24×10^{-8}	2.43×10^{-8}	2.59×10^{-8}
Total	**2.81×10^{-8}**	**2.88×10^{-8}**	**3.07×10^{-8}**	**3.31×10^{-8}**	**3.51×10^{-8}**
Increase from Natural Gas	-	*2.6%*	*9.4%*	*17.9%*	*25.0%*
Semi-detached/Unfinished basement					
Mains	1.02×10^{-8}	1.04×10^{-8}	1.14×10^{-8}	1.21×10^{-8}	1.27×10^{-8}
Services	2.30×10^{-8}	2.37×10^{-8}	2.61×10^{-8}	2.88×10^{-8}	3.17×10^{-8}
Total	**3.31×10^{-8}**	**3.41×10^{-8}**	**3.75×10^{-8}**	**4.09×10^{-8}**	**4.45×10^{-8}**
Increase from Natural Gas	-	*2.9%*	*13.2%*	*23.5%*	*34.3%*
Multi-Attached/Unfinished basement					
Mains	1.15×10^{-8}	1.18×10^{-8}	1.29×10^{-8}	1.37×10^{-8}	1.45×10^{-8}
Services	2.58×10^{-8}	2.66×10^{-8}	2.95×10^{-8}	3.27×10^{-8}	3.63×10^{-8}
Total	**3.73×10^{-8}**	**3.84×10^{-8}**	**4.24×10^{-8}**	**4.64×10^{-8}**	**5.08×10^{-8}**
Increase from Natural Gas	-	*3.0%*	*13.8%*	*24.5%*	*36.2%*
Detached/Finished basement					
Mains	4.42×10^{-8}	4.80×10^{-8}	6.19×10^{-8}	6.90×10^{-8}	7.82×10^{-8}
Services	1.01×10^{-7}	1.08×10^{-7}	1.34×10^{-7}	1.46×10^{-7}	1.62×10^{-7}
Total	**1.45×10^{-7}**	**1.56×10^{-7}**	**1.96×10^{-7}**	**2.15×10^{-7}**	**2.40×10^{-7}**
Increase from Natural Gas	-	*7.8%*	*34.9%*	*48.6%*	*65.8%*

4.2.2 End-User

The risk for the end user was calculated for the case where the basement is unfinished with an open plan living room/kitchen (lowest risk combination) and the case where the basement is finished with a separate kitchen (highest risk combination). The risk is calculated across all variations in house type for three groups of equipment:

- Meter and regulator – These are located outdoors and are considered to be well ventilated.
- Furnace and pipework – This is considered to be the minimal level of gas equipment. This may be located in an open, unfinished basement or within a utility room in a finished basement.
- All other appliances – This includes a fireplace, a garage heater, a kitchen range and a hot water heater. The locations of these appliances have been assumed based on the options listed in Section 3.4.2.

Table 3 summarizes the individual risk predictions for properties with an unfinished basement and open plan living room/kitchen. A similar set of risk predictions are provided in Table 4 for properties with a finished basement and separate kitchen.

Table 3: Individual risk to the end user from ignited releases for different types of houses (unfinished basement; open plan living/kitchen)

Contributor	Individual Risk (per year)				
	Natural Gas	5% Blend	20% Blend	25% Blend	30% Blend
Bungalow					
Meter and regulator	2.24×10^{-9}	2.35×10^{-9}	2.69×10^{-9}	2.80×10^{-9}	2.91×10^{-9}
Furnace and pipework	4.06×10^{-8}	4.22×10^{-8}	5.06×10^{-8}	5.49×10^{-8}	6.07×10^{-8}
Other Appliances	4.16×10^{-8}	4.28×10^{-8}	5.01×10^{-8}	5.22×10^{-8}	5.62×10^{-8}
Total	**8.45×10^{-8}**	**8.73×10^{-8}**	**1.03×10^{-7}**	**1.10×10^{-7}**	**1.20×10^{-7}**
Increase from Natural Gas	-	*3.4%*	*22.4%*	*30.1%*	*41.8%*
Detached					
Meter and regulator	2.24×10^{-9}	2.35×10^{-9}	2.69×10^{-9}	2.80×10^{-9}	2.91×10^{-9}
Furnace and pipework	3.04×10^{-8}	3.19×10^{-8}	3.77×10^{-8}	4.11×10^{-8}	4.50×10^{-8}
Other Appliances	3.09×10^{-8}	3.16×10^{-8}	3.67×10^{-8}	3.81×10^{-8}	4.05×10^{-8}
Total	**6.36×10^{-8}**	**6.59×10^{-8}**	**7.71×10^{-8}**	**8.20×10^{-8}**	**8.84×10^{-8}**
Increase from Natural Gas	-	*3.7%*	*21.4%*	*29.0%*	*39.1%*
Semi-Detached					
Meter and regulator	2.24×10^{-9}	2.35×10^{-9}	2.69×10^{-9}	2.80×10^{-9}	2.91×10^{-9}
Furnace and pipework	3.28×10^{-8}	3.42×10^{-8}	4.10×10^{-8}	4.43×10^{-8}	4.84×10^{-8}
Other Appliances	3.89×10^{-8}	4.06×10^{-8}	4.91×10^{-8}	5.22×10^{-8}	5.59×10^{-8}
Total	**7.39×10^{-8}**	**7.71×10^{-8}**	**9.28×10^{-8}**	**9.93×10^{-8}**	**1.07×10^{-7}**
Increase from Natural Gas	-	*4.3%*	*25.4%*	*34.3%*	*45.0%*
Multi-Attached					
Meter and regulator	2.24×10^{-9}	2.35×10^{-9}	2.69×10^{-9}	2.80×10^{-9}	2.91×10^{-9}
Furnace and pipework	3.45×10^{-8}	3.61×10^{-8}	4.40×10^{-8}	4.75×10^{-8}	5.25×10^{-8}
Other Appliances	4.16×10^{-8}	4.35×10^{-8}	5.34×10^{-8}	5.72×10^{-8}	6.12×10^{-8}
Total	**7.83×10^{-8}**	**8.19×10^{-8}**	**1.00×10^{-7}**	**1.08×10^{-7}**	**1.17×10^{-7}**
Increase from Natural Gas	-	*4.5%*	*27.7%*	*37.2%*	*48.8%*

Table 4: Individual risk from ignited releases for different types of houses and end-use appliances (finished basement; separate kitchen)

Contributor	Individual Risk (per year)				
	Natural Gas	5% Blend	20% Blend	25% Blend	30% Blend
Bungalow					
Meter and regulator	2.24×10^{-9}	2.35×10^{-9}	2.69×10^{-9}	2.80×10^{-9}	2.91×10^{-9}
Furnace and pipework	8.35×10^{-8}	8.67×10^{-8}	1.03×10^{-7}	1.13×10^{-7}	1.26×10^{-7}
Other Appliances	9.12×10^{-8}	9.57×10^{-8}	1.13×10^{-7}	1.23×10^{-7}	1.36×10^{-7}
Total	**1.77×10^{-7}**	**1.85×10^{-7}**	**2.19×10^{-7}**	**2.38×10^{-7}**	**2.64×10^{-7}**
Increase from Natural Gas	-	*4.4%*	*23.0%*	*34.6%*	*49.3%*
Detached					
Meter and regulator	2.24×10^{-9}	2.35×10^{-9}	2.69×10^{-9}	2.80×10^{-9}	2.91×10^{-9}
Furnace and pipework	6.98×10^{-8}	7.42×10^{-8}	8.64×10^{-8}	9.49×10^{-8}	1.05×10^{-7}
Other Appliances	7.25×10^{-8}	7.69×10^{-8}	9.04×10^{-8}	9.78×10^{-8}	1.07×10^{-7}
Total	**1.44×10^{-7}**	**1.54×10^{-7}**	**1.79×10^{-7}**	**1.95×10^{-7}**	**2.15×10^{-7}**
Increase from Natural Gas	-	*6.2%*	*24.2%*	*35.3%*	*48.7%*

Contributor	Individual Risk (per year)				
	Natural Gas	5% Blend	20% Blend	25% Blend	30% Blend
Semi-Detached					
Meter and regulator	2.24×10^{-9}	2.35×10^{-9}	2.69×10^{-9}	2.80×10^{-9}	2.91×10^{-9}
Furnace and pipework	7.44×10^{-8}	7.99×10^{-8}	9.45×10^{-8}	1.05×10^{-7}	1.17×10^{-7}
Other Appliances	8.23×10^{-8}	9.17×10^{-8}	1.07×10^{-7}	1.18×10^{-7}	1.32×10^{-7}
Total	$\mathbf{1.59 \times 10^{-7}}$	$\mathbf{1.74 \times 10^{-7}}$	$\mathbf{2.04 \times 10^{-7}}$	$\mathbf{2.26 \times 10^{-7}}$	$\mathbf{2.51 \times 10^{-7}}$
Increase from Natural Gas	-	*9.4%*	*28.5%*	*42.1%*	*58.0%*
Multi-Attached					
Meter and regulator	2.24×10^{-9}	2.35×10^{-9}	2.69×10^{-9}	2.80×10^{-9}	2.91×10^{-9}
Furnace and pipework	7.93×10^{-8}	8.59×10^{-8}	1.03×10^{-7}	1.16×10^{-7}	1.30×10^{-7}
Other Appliances	8.76×10^{-8}	9.54×10^{-8}	1.17×10^{-7}	1.32×10^{-7}	1.48×10^{-7}
Total	$\mathbf{1.69 \times 10^{-7}}$	$\mathbf{1.84 \times 10^{-7}}$	$\mathbf{2.23 \times 10^{-7}}$	$\mathbf{2.50 \times 10^{-7}}$	$\mathbf{2.80 \times 10^{-7}}$
Increase from Natural Gas	-	*8.5%*	*31.8%*	*47.8%*	*65.7%*

4.2.3 Discussion of Results

The fire IR is the same for all house types for releases from mains, and from services, because the internal layout of the house does not affect the prediction of how likely the building is to be ignited by an external fire (one of the contributions in Table 2). Thus, the change in IR relative to natural gas is due to changes in the explosion IR, as different room and basement sizes affect the predictions for gas accumulation for a given ingress rate. Gas ingress into a building with a basement is assumed to occur in the basement, as the gas moves below ground, so the arrangement of above ground rooms does not influence the results. The total IR increases as the footprint of the building decreases because accumulation of gas to a flammable concentration is more likely in a smaller volume, resulting in an increase in the explosion IR. This means that the bungalow has the lowest risk. Although the semi-detached or multi-attached buildings have the same building footprint, the total IR for multi-attached buildings is higher due to the proximity of the additional adjoined buildings, and the possibility of an explosion in one dwelling harming people in adjoined dwellings. The small section of service to the meter that is above ground is located outside the house and as such is not considered to enable gas ingress into the house or basement at a rate that could lead to an explosion.

As well as highlighting the change in IR for different building and basement types, Table 2 allows comparison of a range of blends for mains and services. As the proportion of hydrogen in the blend increases, the rise in IR becomes more significant, with some dependence on the house type and basement configuration. In all cases the IR remains well below the broadly acceptable criterion for individual risk (1 x 10^{-6} per year). The difference between unfinished and finished basements is due to the smaller room sizes within the finished basement, which makes gas accumulation to a flammable concentration more likely, combined with higher ignition probabilities when people are present.

The individual risk in Table 3 and Table 4 due to ignited internal releases in a particular house is dependent on the type and number of appliances present, as well as the configuration of the basement, and the living room/kitchen.

As the proportion of hydrogen in the blend increases, the rise in IR becomes more significant, with some dependence on the house type and basement and the living room/kitchen configuration. There is less variation for the houses with unfinished basements and open plan living rooms / kitchens because a large room is less likely to fill to a flammable concentration regardless of the gas composition, and if it does happen then there is less differentiation between the possible explosion severities associated with each blend case. Generally, a small release will not form a flammable gas/air mixture in a large room for any of the gas compositions, so any differences in the risk predictions are associated mainly with the less frequent, larger releases. Hence, the differentiation between releases in unfurnished cellar and open plan above ground rooms is limited.

For the finished basement, and the separate living room and kitchen, the division into smaller volumes results in faster gas accumulation, and potentially accumulation to a greater gas concentration. Therefore, flammable conditions are more likely, and more severe explosions can occur. In these smaller rooms, a greater proportion of leaks form a flammable gas/air mixture as the hydrogen content of the gas increases, primarily because the volumetric outflow rate increases, but also because the flammable range of concentrations is widened. Under these conditions, the more common, smaller leaks have a greater influence over the proportion of releases that can potentially lead to explosions. The high occupancy of finished basements also introduces additional ignition sources, which increases the overall risk. Hence, the differences in the risk predictions between natural gas and the four blend cases becomes more noticeable when there are smaller rooms and when people are more regularly present. However, in all instances, the IR remains well below the broadly acceptable criterion for individual risk (1 x 10^{-6} per year).

4.3 Individual Risk from CO Poisoning

There is the potential for end users to become fatalities as a result of carbon monoxide poisoning from malfunctioning natural gas appliances. Adding hydrogen to natural gas may alter the carbon monoxide production rate of the appliances and therefore the potential for end users to become fatalities. This has been the subject of a number of research projects [13], , [14], [15], [16], [17]. The results of this work indicated that there is no clear consensus on the relationship between the %H_2 and the amount of carbon monoxide produced.

Based on information published by the Canadian Gas Association [18], and census data from 2016 [19], around 18,125,000 people are at risk of being poisoned by carbon monoxide from malfunctioning natural gas appliances across Canada. Also, the University of the Fraser Valley published a report [20] concerning carbon monoxide poisoning incidents between 2000 and 2013 and concluded that, on average, there are 267 fatalities per year in homes from carbon monoxide poisoning across the whole of Canada. There is some uncertainty over the proportion of cases where these fatalities are as a result of malfunctioning natural gas appliance, as opposed to another fuel source (wood, oil, etc.). Therefore, although there is some variation in fuel gas and appliance types, based on available data from the USA [21] and the UK [22] (which are broadly comparable), it is assumed that on average 10% of carbon monoxide fatalities are associated with natural gas appliances, as opposed to another fuel source. For simplicity this QRA has assumed that the risk posed to users of the appliances associated with carbon monoxide poisoning decreases linearly as the hydrogen content increases (from the current natural gas level to no risk for pure hydrogen). This is considered conservative as the HyDeploy project demonstrated that the 20% blend may halve the current natural gas risk [23]. This approach gives the average individual risk predictions associated with carbon monoxide poisoning for the pilot study area (Table 5). There is no acceptable risk threshold that ATCO is required to meet or exceed as it relates to end users. However, to provide context and in order to help interpret the results, the quantitative criteria introduced in the proposed revisions to CSA Z662 [2] and discussed in Section 4.1 have been considered, to be consistent with the distribution system and ignited releases due to end-use appliances.

Table 5: Individual risk values for carbon monoxide poisoning to people living in the pilot study area

Gas	Average Individual Risk (per year)
Natural Gas	1.48×10^{-6}
5% Blend	1.40×10^{-6}
20% Blend	1.18×10^{-6}
25% Blend	1.11×10^{-6}
30% Blend	1.03×10^{-6}

5.0 APPLICATION OF RESULTS TO PILOT STUDY AREA

5.1 Distribution

An Engineering Assessment (EA) to justify the conversion of existing distribution assets from natural gas to H_2 blended gas service was conducted by ATCO as per the requirements of CSA Z662:19 [1], with consideration of the quantitative criteria introduced in the proposed revisions to CSA Z662 [2] . The results of the risk assessment detailed above for 5% and 20% H_2 blends were considered by the EA, and compared against the reference criterion (1 x 10^{-6} per year); see Figure 1 below.

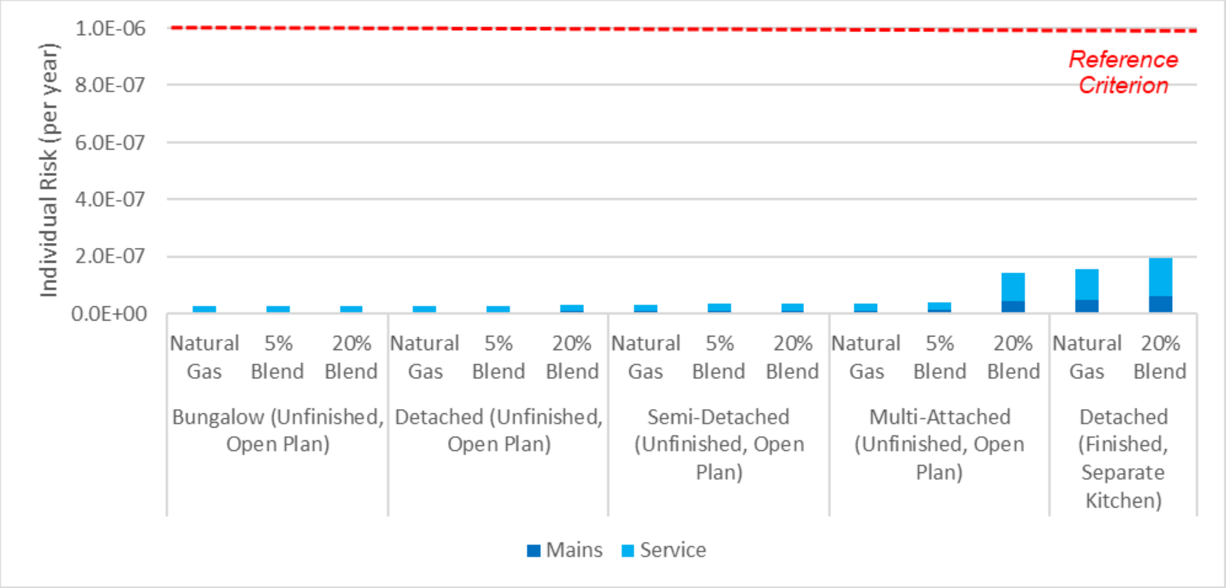

Figure 1: Individual Risk from ignited releases only for different types of houses within the project footprint

Adding 5% or 20% hydrogen to the natural gas distribution system results in an increase in the absolute individual risk relative to natural gas. However, even for the 20% blend, the combined IR for the mains and services is still significantly below the reference criterion (around 4% for properties with an unfinished basement and around 20% for properties with a finished basement). Therefore, no risk reduction measures were warranted to convert the existing natural gas distribution system to H_2 blended gas service.

Additionally, the EA provided several risk comparators associated with analogous involuntary risks, to help frame the results of the QRA and provide perspective. For example, a property with a finished basement supplied with a 20% blend, results in the highest IR from ignited releases from the distribution network within the project footprint. This individual is still 47 times more likely to become a fatality as a result of an electrical fire [24], and 291 times more likely to become a fatality due to a motor vehicle incident [25].

5.2 End-user

ATCO also prepared a safety case examining the suitability of converting end-users from natural gas to H_2 blended gas leveraging the results of the QRA for end-users discussed above. As shown in Figure 2, adding 5% or 20% hydrogen increases the IR due to ignited releases from the customer meter, internal pipework and appliances (green bars) relative to natural gas. However, the total IR for the end-user is comprised of the risk from both CO poisoning (grey bars) and ignited gas. This results in an overall decrease in IR for end-users. The total IR for the 20% blend is between 10% and 15% lower than the IR for the natural gas case, depending on the property configuration considered. The IR for the end-user is dominated by the risk associated with CO poisoning (between 70% and 89% of the total IR, depending on the scenario considered); therefore, the increase in IR due to ignited releases as a result of introducing hydrogen is relatively inconsequential.

Comparison of the IR for the end-user with the reference criterion (1 x 10^{-6} per year) introduced in the proposed revisions to CSA Z662 [2] indicates the existing natural gas system is 1.9 times the reference level. Although introducing 20% hydrogen into the system will also result in an IR above the reference criterion, it is lower than the natural gas case (up to 1.7 times the reference level). In other words, the total IR for end-users from natural gas and hydrogen blended gas is greater than the reference threshold (1 x 10^{-6} per year). However, the total IR associated with blended gas is less than that for natural gas. Therefore, no risk reduction measures were warranted to convert end-users from natural gas to H_2 blended gas service. For context, an individual is approximately 5 times more likely to become a fatality in a fire caused by an electrical fire [24] and approximately 33 times more likely to become a fatality as a result of a motor vehicle incident [25]. Additionally, as mentioned previously, it is important to consider that the risk acceptance thresholds within the proposed revisions to CSA Z662 [2] are not necessarily applicable to end-users. There is no broadly acceptable risk threshold for the consumption of energy by an end-user within Canada.

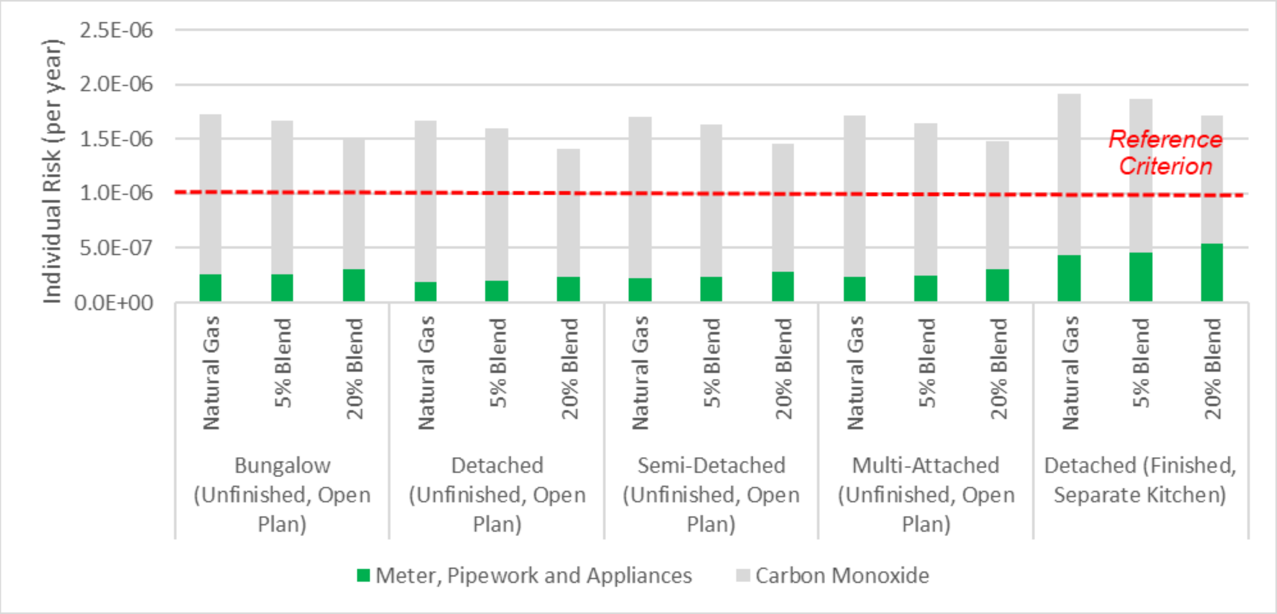

Figure 2: Combined Individual Risk from carbon monoxide and ignited releases for different types of houses within the project footprint

6.0 REFERENCES

1. CSA Z662:19 Oil and Gas Pipeline Systems, CSA Group, 8th Edition, April 2020.
2. CSA Z662:23, Oil and Gas Pipeline Systems', CSA Group, DRAFT Issued for Public Review, January 2022
3. Acton, M.R., Halford, A.R., Phillips, A.G., Oxley, R. and Evans, D., Quantification of the Risks Associated with a Hydrogen Gas Distribution Network, Hazards 31 Conference, 16-18 November 2021.
4. Phillips, A., Halford, A. and Oxley, R., Comparison of the Risks Associated with Natural Gas and Hydrogen Distribution Networks, Hazards 32 Conference, 18-20 October 2022.
5. H21 Project, https://h21.green/

6. Blending hydrogen into Natural Gas Pipeline Networks: a Review of Key Issues, National Renewable Energy Laboratory, NREL/TP-5600-51995, March 2013.
7. Hermkens, R., van der Stok, E., de Bruin, J., and Weller, J., Can PE and PVC Gas Distribution Pipes Withstand the Impact of Sustainable Gases?, Proceedings of the 18th Plastic Pipes Conference, 12-14 September 2016.
8. Hydrogen in the Gas Distribution Networks, GPA Engineering, 205215, November 2019.
9. Work Package 7, Safety Assessment: Experimental Testing – Domestic Pipework Leakage, Steer Energy for Hy4Heat, May 2020.
10. De Invloed van Waterstof op de Zachte Materialen in RNB Gasdrukregelinstallaties, Kiwa, GT-200237, January 2021.
11. Appliance and Equipment Performance with Hydrogen-Enriched Natural Gases, CSA Group, May 2021.
12. Garrison, A.J., and Gant, S., An Investigation into the Change in Leakage when Switching from Natural Gas to Hydrogen in the UK Gas Distribution Network, 9th International Conference on Hydrogen Safety, 21-24 September 2021.
13. Gersen, S., van Essen, M., and Pysyk, L., Impact on Canadian Residential End Use Appliances with the Introduction of Hydrogen into the Natural Gas System – An Application, 10th International Conference on Hydrogen Safety, 19-21 September 2023.
14. Zhao, Y., McDonell, V., and Samuelsen, S., Influence on Hydrogen Addition to Pipeline Natural Gas on the Combustion Performance of a Cooktop Burner, International Journal of Hydrogen Energy, **44**, 2019, pp. 12239 to 122553.
15. Pursell, M.R., Wagstaff, D., McLaughlin, P., Langer, D., and Isaac, T., Mitigation of CO Poisoning Hazard in Malfunctioning Gas Appliances through Use of Hydrogen Blended Gas, 9th International Conference on Hydrogen Safety, 21-24 September 2021.
16. Sun, M., Huang, X., Hu, Y., and Lyu, S., Effects on the Performance of Domestic Gas Appliances Operated on Natural Gas Mixed with Hydrogen, Energy, **244**, November 2021.
17. Glanville, P., Fridlyand, A., Sutherland, B., Liszka, M., Zhao, Y., Bingham, L., and Jorgensen, K., Impact on Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NO_x Emission and Operational Performance, Energies, **15**, February 2022.
18. ‘Natural Gas Facts, Canadian Gas Association, website accessed 20th May 2022, https://www.cga.ca/natural-gas-statistics/natural-gas-facts/.
19. Census Profile - 2016 Census, Statistics Canada, website accessed 20th May 2022, https://www12.statcan.gc.ca/.
20. Carbon Monoxide Poisoning, Hospitalizations and Deaths in Canada, University of the Fraser Valley, October 2017.
21. Carbon Monoxide, American Gas Association, website accessed 20th May 2022, https://www.aga.org/research/policy/carbon-monoxide/.
22. CO-Gas Safety’s Summary of Statistics on Deaths and Injuries, The Carbon Monoxide and Gas Safety Society, website accessed 20th May 2022, https://www.co-gassafety.co.uk/data/.
23. Isaac, T., Mahmood, S., Madgett, A., Hooker, P., Torrado, D., Pursell, M., Gant, S., Kelsey, A., and Lander, D., Evidence Base Utilised to Justify a Hydrogen Blend Gas Network Safety Case, 9th International Conference on Hydrogen Safety, 21-24 September 2021.
24. Statistics Canada, website accessed 20th May 2022, https://www150.statcan.gc.ca/n1/pub/71-607-x/71-607-x2021032-eng.htm
25. Statistics Canada, website accessed 20th May 2022, https://www150.statcan.gc.ca/n1/daily-quotidien/220616/dq220616b-eng.htm