Independent Review

Engineering Investigation of a Residential Natural Gas Explosion

Technical Safety BC Incident #26151

Submitted to:

[redacted]

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[redacted]

Contents

1. Executive Summary

Net-Zero Engineering has prepared this report to serve as an independent engineering review of the natural gas explosion, "the incident", that occurred on February 9, 2022. Please refer to Technical Safety BC (TSBC) Incident Report #26151 for site and investigation details.

The intent of the report contained herein is to assess the following areas relating to the incident:

1. Determine whether proper installation procedures of the gas line were followed according to the BC Natural Gas and Propane Code Regulation under the Gas Safety Act. The following relevant national codes are listed under the regulation:
    a. CSA B149.1-00, the Natural Gas and Propane Installation Code, published January 2000;

    b. the National Standard of Canada CSA Z662-99, Oil and Gas Pipeline Systems, published April 1999;

    The last alteration to the gas service connection to the subject property was altered on May 30, 2000. Therefore, the active listed national codes and their publication versions at the time of the last alteration to the subject gas line are utilized.

    The "design code transition" location between CSA Z662-99 and CSA B149.1-00 is at the outlet of the customers gas meter. CSA Z662-99 applies upstream and includes the customer gas meter. CSA B149.1-00 applies downstream of the customers gas meter.

    It should be noted that CSA Z662-99 calls upon CSA B137.4-99, Polyethylene Piping Systems for Gas Services, published July 1999. CSA B137.4 applies to all types of fittings and connections used in a plastic gas pipe system, including plastic-to-metal transition fittings, plastic component fittings such as elbows, tees, end caps, valves, etc, and clamps and couplings which are of particular interest in this investigation.

2. Determine if the proper installation procedures of the gas line were followed according to [redacted] standards if they are more conservative than CSA Z662-99.

3. Review and assess the steel and polyethylene (PE) piping and material test data provided by Acuren to determine the appropriate failure theory that led to the natural gas pipeline loss of containment.

The findings of this investigative report demonstrate that all materials specified and used by [redacted] in the design and installation of the gas service line were compliant with CSA Z662-99 as required by the BC Natural Gas and Propane Code Regulation under the Gas Safety Act. Compliance was confirmed through a thorough review of the [redacted] material specifications, CSA B137.4 material property requirements, and Acuren test results which confirm the material properties of the PE pipe involved in the natural gas explosion.

The three (3) key factors being evaluated in this engineering report are all deemed acceptable.

2. Incident Background

Refer to TSBC Incident #26151 for a detailed account of the events that occurred before and after the natural explosion incident.

The following picture are provided for purposes of identifying important aspect of the site conditions to assess the failure mechanism of the severed natural gas service line.

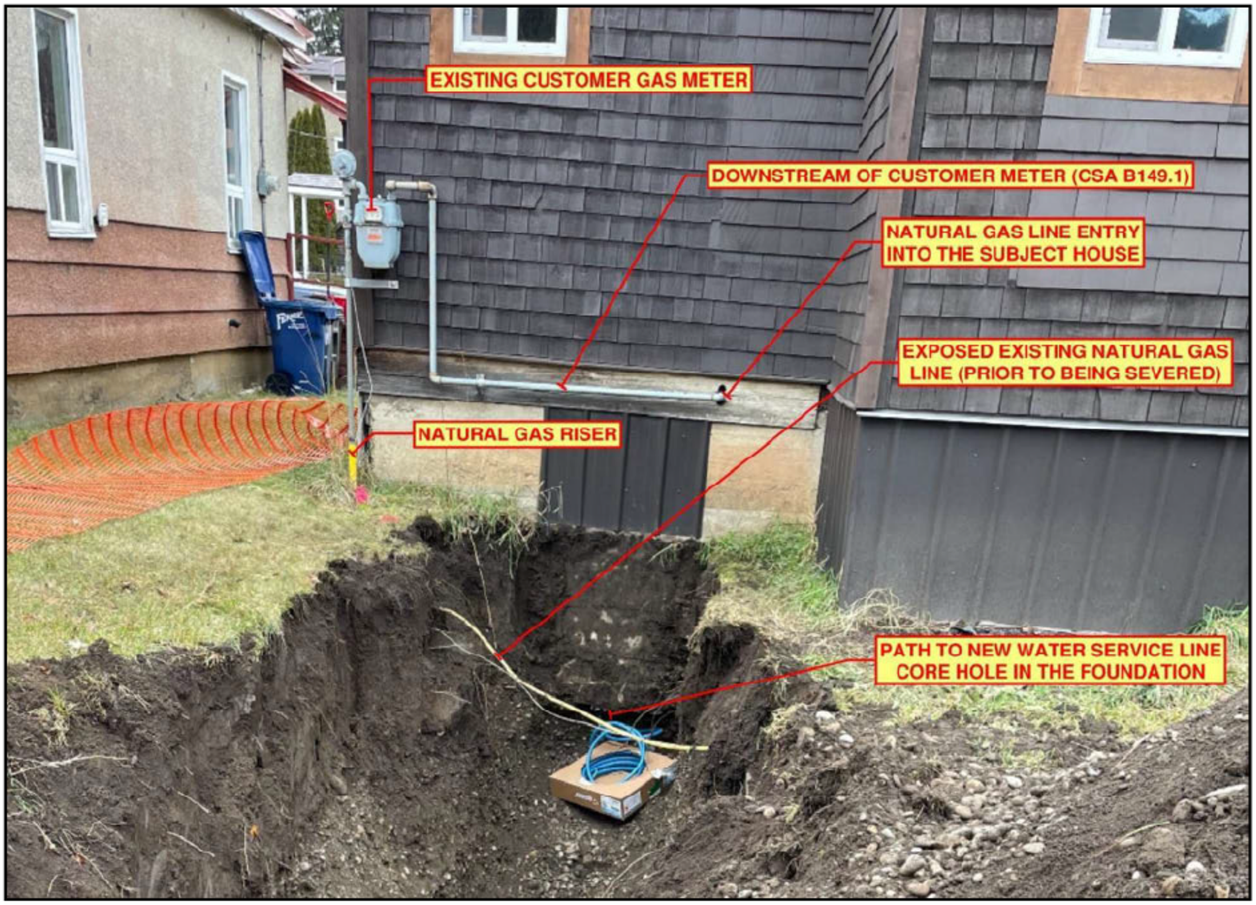

Figure 1 - New Water Service and Sanitary Line Trench (~5.0 ft deep) prior to the NG Explosion

Figure 2 - New Water Service and Sanitary Line Trench (assume ~5.0 ft deep) prior to the NG Explosion

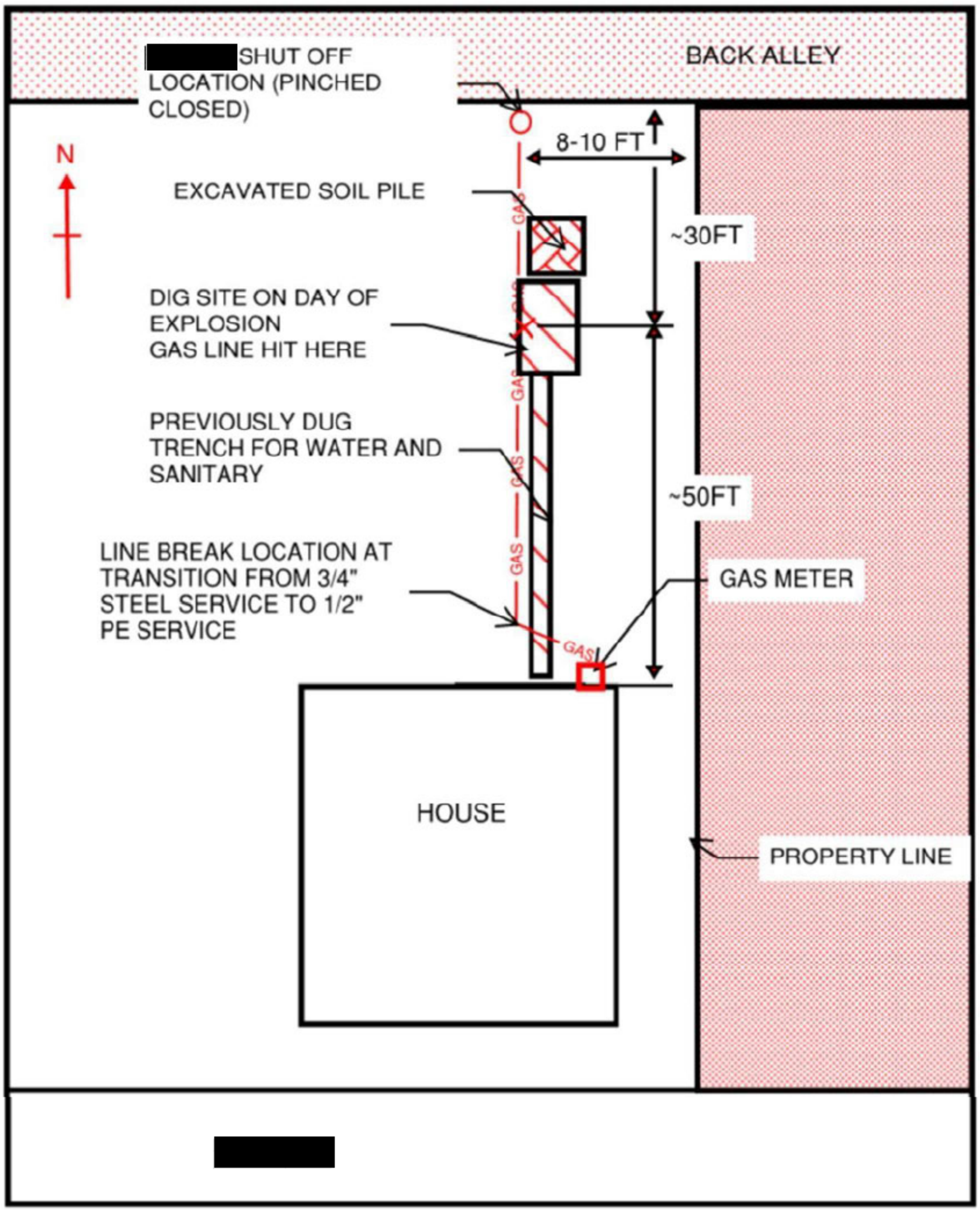

Figure 3 - Approximate Routing of the Existing Natural Gas Line Service

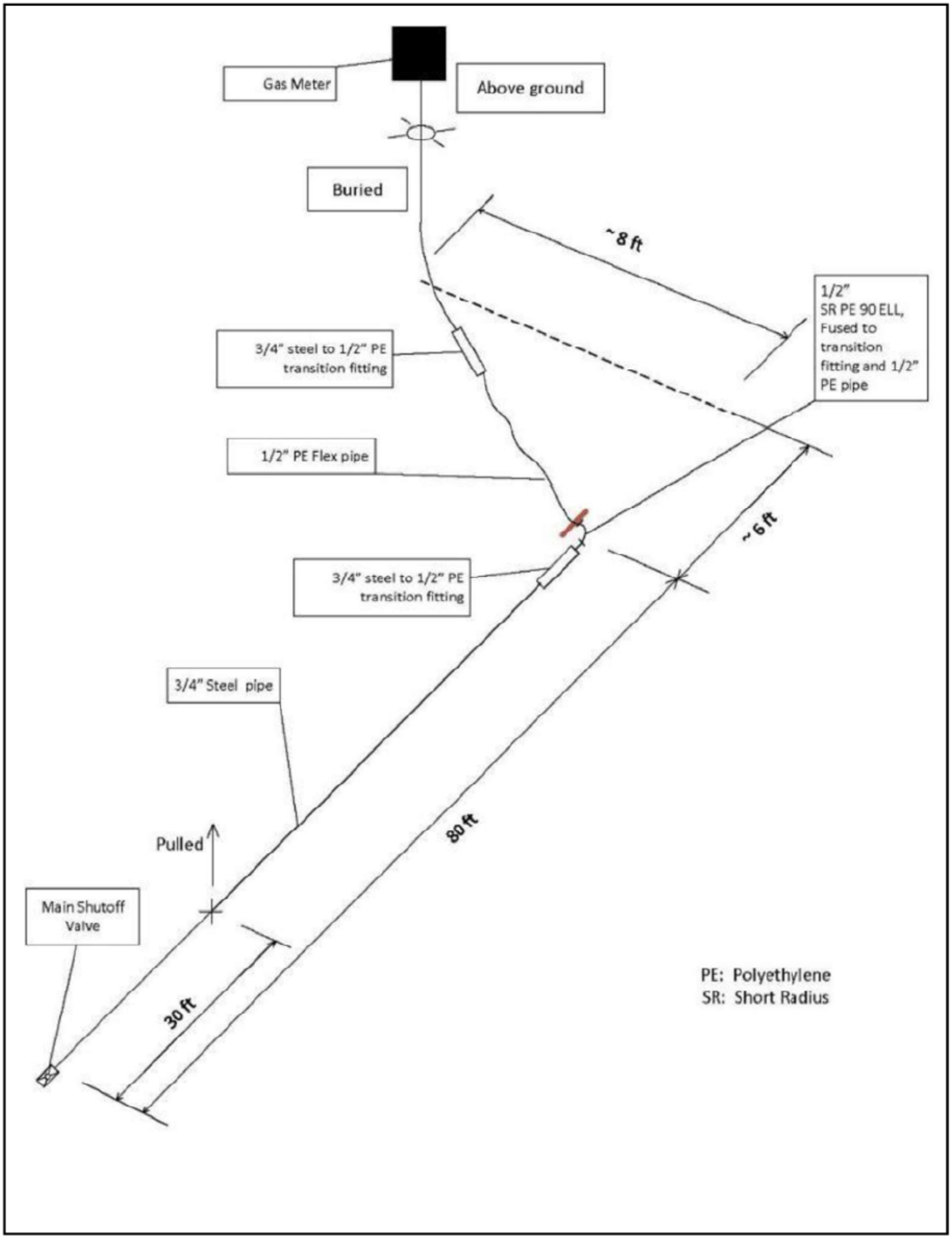

Figure 4 - Isometric Sketch of the Existing Gas Line that was Severed during Excavation

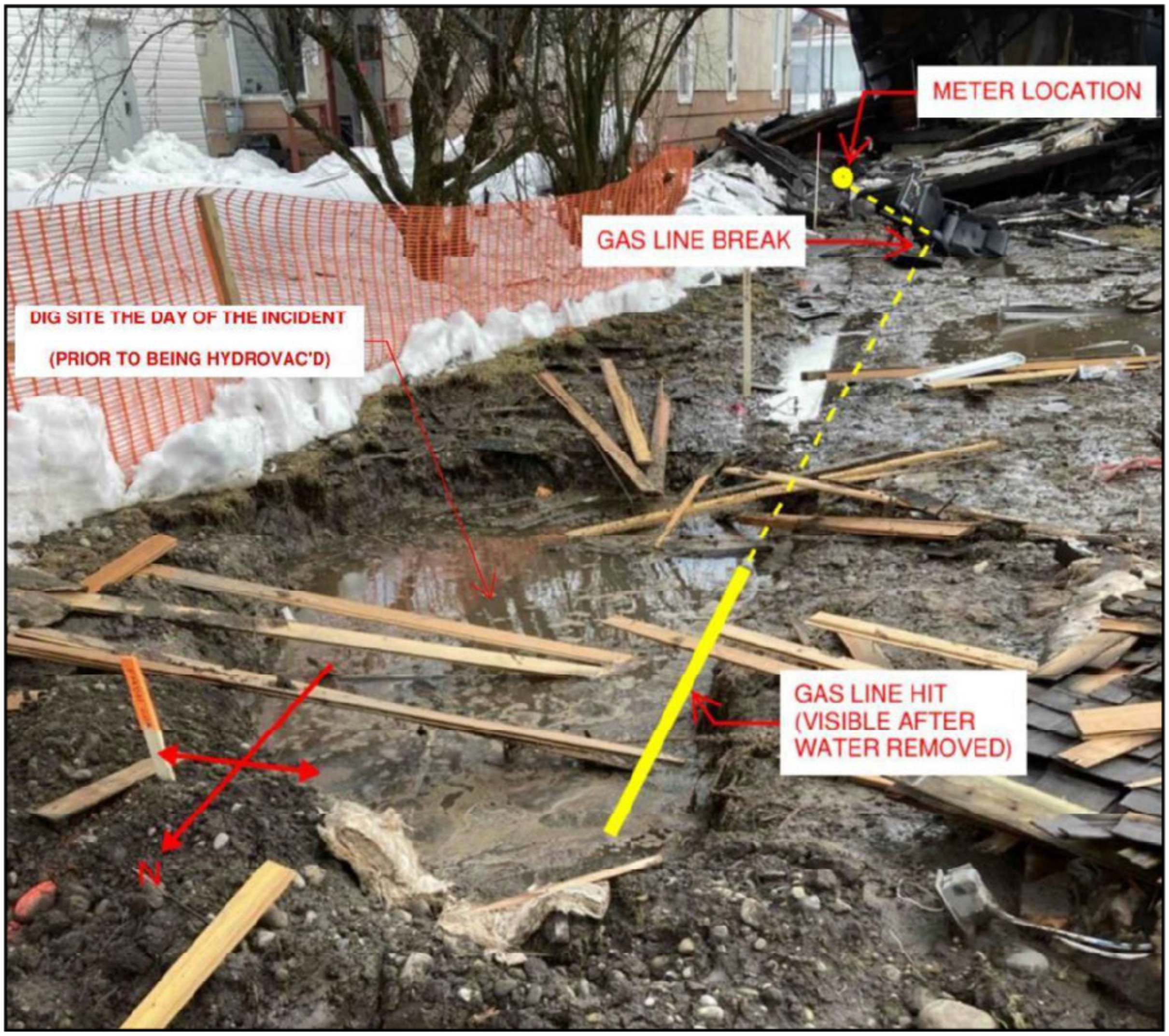

Figure 5 - Dig / Excavation Area after the NG Explosion (prior to Hydrovac)

3. Summary of [redacted] Gas Service Pipeline Design and Installation Specifications

Table 1-A outlines the relevant [redacted] specifications to this investigation and briefly details the applicable content of each specification.

Specification No.	Title	Comments
[redacted]	Locating Buried Gas Piping	Spec was missing at time of review
[redacted]	Piping Cover	Spec was missing at time of review. CSA Z662-99 requires 600mm of pipe cover which is enacted by [redacted] guidelines and referenced specifications
[redacted]	Polyethylene Pipe and Tubing	- Dimensions of PE Pipe and Tubing with associated SDR - Demonstrated compliance and references to CSA B137.4 (a requirement of CSA Z662)
[redacted]	Polyethylene Fusion and Mechanical Fittings	- specifies the requirements for the design, manufacture, testing, inspection, and supply of polyethylene (PE) fittings for [redacted] - Product manufacture and verification must meet CSA B137.4 - Maximum system design pressure of 550 kPag (8-psig) with a maximum system test pressure of 800 kPag (115 psig) - Temperature ranges between -45degC to 30degC permitted - All fittings must be certified to CSA B137.4 (requirement of CSA Z662)
[redacted]	Polyethylene Electrofusion Fittings	- specifies details the minimum requirements for the design, manufacture, testing, inspection and supply of polyethylene (PE) electrofusion fittings for [redacted] - Product manufacture and verification must meet CSA B137.4.1 *Electrofusion-Type Polyethylene Fittings for Gas Services* - maximum system design pressure is 550 kPag (80 psig) with a maximum system test pressure of 830 kPag (120 psig)

[redacted]	PE Transition Fittings	- applies to steel to polyethylene (PE) transition fittings used in the underground gas distribution system in accordance with CSA-Z662 Oil and Gas Pipeline Systems - Product manufacture and verification of PE transition fittings must meet the requirements of CSA Z662 and CSA B137.4 - Maximum system design pressure of 550 kPag (8-psig) with a maximum system test pressure of 800 kPag (115 psig) - Temperature ranges between -45degC to 30degC permitted - Fittings must comply with the product testing requirements of ASTM F1973 and ASTM D2513 - Category 1 - Steel body components of transition fittings must meet the requirements of ASTM A53, Type E or S, or approved equivalent - Steel piping components of transition fittings must meet the wall thickness requirements of Schedule 40 steel pipe - The steel end must be provided with a standard 37½° weld bevel - Steel components of transitions must be epoxy-coated over their entire length except on the specified cut back area of the weld end - Epoxy coating must be "gas meter grey" according to color specification ASA 49 - A 50 mm long copper tracer wire connection must be provided 75 mm (3") from the weld end. The connector must have an internal diameter able to fit 14 AWG wire size. - All welding must comply with CSA-Z662 or other equivalent industry standards accepted by FBC (Gas) - The supplier is responsible to ensure that transition fittings meet the requirements of CSA Z662 and CSA B137.4, the purchasing specification, and this standard. - Manufacturing test results and other quality control documentation for transition fittings are not normally requested. In situations where documentation is required and requested, supporting documentation must be forwarded for approval before shipment.
[redacted]	PE Risers	No content is applicable to this investigation

[redacted]	Polyethylene Ball and Plug Valves	No content is applicable to this investigation
[redacted]	Polyethylene Insertion	No content is applicable to this investigation
[redacted]	Installation Methods	The relevant sections to this investigation reference CRL# 1397 Excavating
[redacted]	Installing DP Steel and PE Services	No content is applicable to this investigation
[redacted]	Excavating	The below clauses reference activities <u>for locating the gas line only</u>. It does not detail procedures for after the gas line has been positively located and marked. - All buried facilities that may be impacted by the proposed excavation must first be hand-exposed prior to using power tools or mechanized equipment. - Power tools and equipment must not be used within 0.5 m from the outside surface of a gas pipe. - The following provisions will apply for [redacted] crews and for [redacted] contractors who have been granted specific approval in writing by [redacted]: 1. For [redacted] [Gas] crews working with experienced backhoe operators, power tools and equipment must not be used within 0.5m from the outside surface of a gas pipe. 2. For [redacted] contractors working on behalf of/and on [redacted] assets, the 1m plus pipe diameter mechanized digging zone will remain in effect until the [redacted] plant is hand exposed in sufficient number of locations to accurately confirm the asset location. Once exposed and confirmed, a distance of 0.5m plus pipe diameter can be applied to mechanized digging only if a written site-specific project plan or SWP (Safe Work Plan) is produced and approved in writing by a [redacted] representative (Operations or/Project Management Office (PMO).
[redacted]	Steel Pipe (detailed pipe specification)	Spec missing from [redacted] at time of review
[redacted]	Use and Installation of PE Pipe	The relevant sections to this investigation reference other specification contained on this table herein.
[redacted]	Use and Installation of Steel Pipe	The relevant sections to this investigation reference other specification contained on this table herein.
[redacted]	Excavating Safety	Spec missing from [redacted] at time of review
-	Excavation Safety Around Natural Gas (public brochure)	
-	Excavation Safety Infosheet (public)	

Table 1-A - Owner and Excavator Operator Key Notes from Interviews post Explosion

4. Assessment of [redacted] Gas Line Installation to the requirements of CSA Z662-99 and CSA B137.4

The material properties of the line pipe utilized at the subject property of the incident in addition to the installation practices of [redacted] are cross-referenced and checked against the requirements of CSA Z662-99 and CSA B137.4.

4.1. [redacted] Specified Gas Service Pipe vs the Requirements of CSA B137.4

<table>
<tr><th colspan="2">[redacted] Service PE Pipe Material Properties</th><th>[redacted] Reference Spec</th></tr>
<tr><td>PE Pipe Material</td><td>Ineos K38-20-188 resin (PE2708 resin)

Medium Density Polyethylene Yellow Gas Pipe MDPE (PE2708) in compliance w/ ASTM D2513 Standard Specification for Polyethylene (PE) Gas Pressure Pipe, Tube and Fittings</td><td>[redacted] - Polyethylene Pipe and Tubing Specification</td></tr>
<tr><td>PE Pipe Dimensions</td><td><table>
<tr><th>Nominal Size (mm OD)</th><th>Nominal Size (NPS)</th><th>SDR</th><th>OD Minimum (mm)</th><th>OD Maximum (mm)</th><th>Out-of-Round (mm)</th><th>Min. Wall Thickness (mm)</th><th>Max. Wall Thickness (mm)</th></tr>
<tr><td>15.9</td><td>½ CTS</td><td>7</td><td>15.8</td><td>16.0</td><td>-</td><td>2.28</td><td>2.50</td></tr>
</table></td><td>[redacted] - Polyethylene Pipe and Tubing Specification</td></tr>
</table>

	Values English Units	Values SI Units	ASTM Method
Resin			
Density	–	0.940 g/cc	D4883
Melt Index 190 °C/2.16 kg	–	0.20 g/10 min	D1238
Melt Index 190 °C/ 21.6 kg	–	20 g/10 min	
Compression Molded Sample			
Tensile Strength (2 in/min)			D638
@ Yield	2,800 psi	19.3 MPa	
@ Break	4,750 psi	32.7 MPa	
Elongation (2 in/min)			D638
@ Yield	11.8 %	11.8 %	
@ Break	>800%	>800%	
Flexural Modulus			D790A
2% Secant Method	90,000 psi	620 MPa	
Notched Izod Impact Strength			D256
@ 23 C	7 ft-lbf/in	37 kJ/m²	
Hardness (Shore D)	62	62	D2240
Vicat Softening Point	248 F	120 C	D1525
Brittleness Temperature	<-180 F	<-118 C	D746
Environmental Stress Crack Resistance			D1693
Condition B, 10% Igepal, F50 (hrs.)	>5,000	>5,000	
Condition C, 100% Igepal, F50 (hrs.)	>5,000	>5,000	
Hydrostatic Design Basis (HDB)			D2837
@ 23 C	1,250 psi	8.6 MPa	
@ 60 C	1,000 psi	6.9 MPa	
Notch Tensile (PENT) (hrs.)	>500	>500	F1473
Oxidation Induction Time @ 210 C, (min.)	>20	>20	D3895
Thermal Stability	>464 F	>240 C	D3350
Cell Classification	234370D 234373E[2]	234370D 234375E[2]	D3350

Figure 6 – [redacted] Specified Gas Service Pipe - Ineos K38-20-188 - PE Pipe Material Properties (Confirms Compliance with CSA B137.4)

[redacted] specifies the use of Copper Tube Size "CTS" which uses copper tubing outside diameters which is acceptable under CSA B137.4

Table 2
Wall thicknesses of PE pipe for gas services
(See Clauses 4.2.2.1, 4.2.2.3, 4.2.2.5, 4.2.2.7 to 4.2.2.9, 4.3.2.2, 4.2.3.1, and 7.1.2.)

Nominal pipe size	Wall thickness, mm									
	DR 21		DR 17		DR 13.5		DR 11		DR 8.8	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
1/2	1.58	1.75	1.58	1.75	1.58	1.75	1.93	2.16	2.43	2.71
3/4	2.29	2.57	2.29	2.57	2.29	2.57	2.41	2.69	3.03	3.38
1	2.29	2.57	2.29	2.57	2.46	2.77	3.02	3.38	3.80	4.24
1 1/4	2.29	2.57	2.49	2.80	3.12	3.51	3.84	4.30	4.79	5.36
1-1/2	2.29	2.57	2.85	3.18	3.58	4.01	4.39	4.92	5.48	6.15
2	2.87	3.23	3.56	3.99	4.47	5.00	5.49	6.15	6.86	7.68
2-1/2	3.48	3.89	4.29	4.80	5.41	6.07	6.63	7.42	8.30	9.30
3	4.24	4.75	5.23	5.87	6.58	7.37	8.08	9.04	10.10	11.32
4	5.44	6.10	6.73	7.54	8.46	9.47	10.39	11.63	12.99	14.55
6	8.03	9.00	9.91	11.10	12.47	13.96	15.29	17.12	19.15	21.44
8	10.41	11.66	12.90	14.45	16.23	18.19	19.94	22.33	24.90	27.89
10	12.98	14.53	16.06	17.98	20.24	22.68	24.84	27.81	30.98	34.69
12	15.44	17.29	19.05	21.34	24.00	26.87	29.46	32.99	36.75	41.15
14	16.93	18.97	20.92	23.43	26.34	29.50	32.33	36.21	40.41	45.26
16	19.35	21.67	23.91	26.77	30.10	33.72	36.95	41.38	46.18	51.72
18	21.77	24.38	26.89	30.12	33.87	37.93	41.56	46.55	51.95	58.19
20	24.19	27.09	29.88	33.47	37.63	42.15	46.18	51.72	57.73	64.65
22	26.61	29.80	32.87	36.82	41.39	46.36	50.80	56.90	63.50	71.12
24	29.03	32.51	35.86	40.16	45.16	50.57	55.42	62.07	69.27	77.59

Notes:
1) *Pipe intended for direct burial shall have a minimum wall thickness of 2.3 mm or greater.*
2) *Pipe intended for insertion in casing shall have a minimum wall thickness of 1.6 mm or greater.*
3) *Pipe on which saddle fusions are to be performed shall have a minimum wall thickness of 4.2 mm or greater (e.g., for NPS-1-1/4 pipe, the minimum wall thickness would be 4.22 mm, with the maximum wall thickness not exceeding 4.88 mm; the pipe would then be marked with the actual DR number of DR 10).*

Figure 7 - CSA B137.4-20 - Wall Thickness Requirements for PE Pipe

Table 9
Minimum required LTHS values for HDB-rated PE compounds
(See Clause 4.2.4.1.1)

Pipe material designation codes	Hydrostatic design basis, MPa (psi)	Minimum required LTHS, MPa (psi)
PE 2708	8.62 (1250)	8.28 (1200)
PE 4710	11.03 (1600)	10.55 (1530)

Figure 8 - CSA B137.4-20 - Minimum Hydrostatic Design Basis (HDB)

4.2.4.4 Apparent tensile strength
When pipe or tubing specimens are tested in accordance with Clause 6.4 of CSA B137.0, the apparent tensile strength at yield, *S*, shall be at least 17.4 MPa for medium density PE compounds and at least 22.3 MPa for high density compounds.

Figure 9 - CSA B137.4 - Minimum Tensile Strength of Medium Density Polyethylene (PE) Pipe

4.2. Use of Transition Fittings

CSA B137.4-20 requires transition piece pullout strength to be equivalent to the force required to deform (neck down) unsupported pipe rather than meet or exceed a specific tensile load rating as in previous versions of the standard such as CSA B137.4-99.

CSA B137.4-99 was the active CSA code at the time of the [redacted] PE pipe installation at the subject property where the incident occurred.

4.3.3.4 Pullout strength — Compression-type and transition fittings only

When compression-type and transition fittings are tested in accordance with Clause 5.4, the force required to cause any separation of the joint shall be appropriate for the specified fitting category. For all gas pipe and tubing sizes, fittings shall be Category 1.

For Category 1 fittings, the force required to cause any separation of the joint shall not less than the force required to deform (e.g., "neck down") pipe.

5.4 Pullout strength test

5.4.1

PE pipe and fittings shall be assembled using the manufacturer's recommended procedures.

5.4.2

PE pipe used in the assemblies shall comply with the dimensional and strength requirements of this Standard. For tests on fittings in sizes NPS-1 and smaller, pipe with the highest combination of yield strength and wall thickness shall be used.

5.4.3

Test conditions shall be 23 °C ± 2 °C and 50% ± 5% relative humidity.

5.4.4

The apparatus used shall be attached to the specimens in a manner that will not induce bending or shearing. When applying the separating load, the relative rate of motion of the testing machine grips shall be 50 mm/min.

Figure 10 - CSA B137.4-20 - Transition Piece Pullout Strength and Pullout Strength Test

The certification and use of compression-type transition fittings has come under scrutiny in this investigation. Lab test results from Acuren reveal there were leaks around the transition couplings / fittings after the incident.

However, scrutiny of the transition coupling / pieces does not offer evidence of poor installation practices as far as CSA B137.4 is concerned.

The main reason for this is the transition couplings / fittings are only required to resist forces that exceed those that would first cause the PE pipe to neck down or deform the pipe. Because the PE gas line was severed, the transition couplings / fittings are not required to remain intact or continue to prevent loss of containment.

4.3. Pipe Bends vs Fittings

[redacted] installation practices witnessed on the subject property of the gas explosion do contradict CSA Z662-99 *Clause 12.6.2.5 Pipe Bends* (refer to Figure 11). The ½"diameter 90-degree PE elbow installed at the subject property by [redacted] could have been avoided. There was sufficient area to rely on the allowable bend radius of the PE pipe to avoid installing a 90 deg fitting which is meant to reduce the number of possible leak points and fused joints.

However, while this installation practice was not followed by [redacted], it did not contribute to the root cause of the explosion and is therefore not a contributing factor in this engineering assessment.

> **12.6.2.5 Bends and Branches**
> It shall be permissible to make changes in direction with bends, tees, or elbows, with the following limitations:
> (a) Pipes shall not be bent to a radius smaller than the applicable minimum recommended by the manufacturer for the particular pipe used.
> (b) Bends shall be free of buckles, cracks, and other evidence of damage.
> (c) Bent portions of pipe shall not contain joints or saddle fusion lateral connections.
> (d) Where the requirements of Item (a) cannot be met, changes in direction shall be made with fittings.
> (e) Mitred bends shall not be permitted.
> (f) Branch connections shall be made with fittings specifically designed for the purpose.

Figure 11 - CSA Z662-99 - Section 12 - Gas Distribution Systems – Direct Buried PE Pipe - Clause 12.6.2.5 Bends and Branches

Figure 11 highlights an important aspect of CSA Z662 with respect to general piping stress; the preference of natural pipe bends over fittings. To correctly approximate stresses in metallic fittings, stress intensification factors (or "SIFs") are utilized.

SIFs are defined as the ratio of maximum stress in the fitting to the maximum stress in the pipe when exposed to equal loading.

The maximum bending stress in a straight pipe and fittings is calculated as follows:

$$S_b = i \cdot \frac{M}{Z}$$

where:

- S_b = Bending Stress
- i = Stress Intensification Factor (SIF) (i =1.00 for straight pipe & i >1.00 for a fitting)
- M = Bending Moment
- Z = Section Modulus (derived from pipe geometry)

The definition of SIFs is supplemented with the high-level facts below:

- A short radius elbow will have a larger SIF than a long radius elbow
- With an increase in the bend radius, the SIF decreases until it reaches 1.00 (which is equivalent to straight pipe)
- With an increase in pipe wall thickness or schedule, the SIF of a bend will keep on decreasing until it reaches 1.00

SIFs for a wide range of fittings in the ASME piping codes (B31.1/B31.3) if metallic piping systems are being evaluated.

Metallic SIF values typically do not apply to polyethylene (PE) fittings due to differences in geometries and differences in definitions of SIFs between PE and metallic fittings.

ASME NM.2 contains equations for calculating SIF's for a limited number of fittings and laminate constructions. However, to obtain appropriate SIF's for PE fittings in general, it is often necessary to generate values by testing or by using FEA.

The PE piping manufacturer should be consulted for appropriate SIF's for their fittings. Typically, the PE pipe manufacturers will only specify a minimum bend radius for design purposes, however, the SIF concept is still applicable in PE elbow fittings in comparison to equal loading on straight pipe. It is always advantageous to increase the bend radius as much as possible to reduce the SIF in the bend.

5. Polyethylene Pipe Material Test Results and Analysis

5.1. Acuren Lab Test Results

Key findings relevant to this engineering review of the incident are reproduced from the Acuren Draft Report "Fernie Natural Gas Explosion; Fractured Polyethylene Pipe Evaluation" for the readers convenience and ease of reference.

5.0 TENSILE AND HARDNESS TESTING OF 16MM YELLOW PIPE

A segment of the 16mm polyethylene yellow Pipe downstream from the fracture was cut from the pipe segment at a distance of 1m from the fracture and prepared for tensile testing. No permanent deformation had occurred to the pipe at this location. The average pipe dimensions are as follows:

- Outside diameter – 16.0 mm
- Inside diameter – 11.10 mm
- Average wall thickness – 2.45 mm

The pipe failed at a tensile load of 521 lb at a maximum stress of 3183 psi (21.95 MPa). The tensile test load - position curve is shown in Appendix B. The fracture appearance is very ductile and is much more elongated than that found with the field fracture as shown side by side in Figure 31. This is an important observation since the strain rate during

Figure 12 - Tested Polyethylene Pipe Dimensions and Tensile Failure (Break) Force[1]

The hardness of the yellow pipe was measured using a Shore D hardness tester calibrated in the range Shore D 30 – 90. The average hardness of the yellow pipe at least 1 m away from the fracture was Shore D 60. The pipe material was slightly harder near the fracture zone and averaged Shore D 62 – 65 in this cold worked area. These hardness values are in the correct range for medium density polyethylene gas pipe.

Figure 13 - Tested Polyethylene Pipe Hardness Testing Results[2]

[1] shown to be compliant with CSA B137.4 and [redacted] Specifications; refer to Figure 7
[2] shown to be compliant with CSA B137.4 and [redacted] Specifications; refer to Figure 6

The fracture contains ductile tendrils that have a shear component that indicates that the pipe was pulled in tension with a moderate bending component at the same time (Figure 32 and 33). Higher magnification views of the fracture surface show fine ductile tendrils (Figure 34and 35).

Figure 14 - Tested Polyethylene Pipe Failure Mechanism Demonstrated to be Combined Loading in Tension, Shear, and Bending

The evidence shows that the yellow 16 mm OD MDPE pipe suffered a catastrophic ductile fracture due to overload conditions introduced to the pipe. Permanent deformation in the unrestrained end of the yellow pipe indicates that the pipeline was lifted or pulled in a way that loaded the pipe both axially and in rotational shear. The shear component of the fracture features indicate that the pipe was being twisted during the failure event. For the fracture to occur with such little elongation, the pipe must have been fully restrained and/or loaded at a high strain rate at the elbow location. The lifting action allowed the pipe to rotate around the restrained elbow location while the remainder of the pipe leading to the house was relatively fixed.

Figure 15 - Acuren Summary of Findings

5.2. Discussion of Acuren Lab Test Results and Findings

The Acuren lab results discuss in detail testing and condition assessment of the transition couplings / fittings used in the gas service installation at the subject property where the incident occurred.

Figure 16 - 3/4" steel to 1/2" PE Transition Fitting from the Subject Property

Despite leaks being found at some of the couplings, the results do not serve as evidence of faulty installation. Refer to *Section 4.2 – Transition Fittings* in this report.

6. Finding as to the Incident Cause and Contributing Factors

The findings of this investigative report demonstrate that all materials specified and used by [redacted] in the design and installation of the gas service line were compliant with CSA Z662-99 as required by the [BC Natural Gas and Propane Code Regulation under the Gas Safety Act.] Compliance was confirmed through a thorough review of the [redacted] material specifications, CSA B137.4 material property requirements, and Acuren test results which confirm the material properties of the PE pipe involved in the natural gas explosion.

The Acuren test results show a PE pipe maximum tensile stress of 3183 psi (21.95 MPa) at a failure load of 521 lbs. The noted tensile strength at break for [redacted] specified pipe specifies a break tensile strength of 4750 psi (32.7 MPa). Refer to Figure 6. This variance in tensile stress is considered acceptable based on the pipe age of ~22 years and recognizing the additional load required to achieve a tensile stress 4750 psi is small based on the small cross-sectional area of the PE pipe. This assessment is quantified below for further understanding; the additional load required to reach break strength is low enough to be considered negligeable.

$$PE\ Pipe\ Cross\ Sectional\ Area = \pi\ \frac{[D^2 - d^2]}{4}$$

D = outer diameter [in]
d = inner diameter [in]
wt = wall thickness [in]

Calculate the inner diameter of the pipe:

$$d = D - 2 \cdot wt = 0.5in - 2 \cdot (0.090in) = 0.32in$$

Calculate the cross-sectional area of the pipe:

$$PE\ Pipe\ Cross\ Sectional\ Area = \pi\ \frac{[0.50in^2 - 0.32in^2]}{4} = 0.116\ in^2$$

Calculate the additional pull force required to produce 4750psi of tensile stress:

$$4{,}750\ \frac{lb}{in^2} = \frac{F_{additonal\ pull}}{A_{pipe\ cross-section}} - 521lbs$$

$$F_{additional\ pull} = 4{,}750psi \cdot 0.116in^2 - 521\ lbs = 30\ lbs$$

Acuren test results document a PE pipe elongation at break of 300%. The noted elongation at break for [redacted] specified pipe specifies an elongation of 800%. Refer to Figure 8. This noted difference in elongation would not have prevented the gas line severing and is therefore not of concern for purposes of this engineering assessment. Pipe age vs elongation is excluded from this engineering assessment.

The gas service line modifications performed to the subject property on May 30th, 2000 by [redacted] was confirmed to be acceptable overall, despite room for improvement as outlined in *Section 4.3* of this report.

The three (3) key factors being evaluated in this engineering report are all deemed acceptable.