Integrity Management of Selective Seam Weld Corrosion in Gas Transmission Pipelines

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Abstract

A natural gas transmission pipeline network operates across approximately 2,500 km of the North Island of New Zealand. In 2022, the Operator identified crack like linear indications on the longitudinal seam of the pipeline by non-destructive testing carried out opportunistically during coating refurbishment of a length of pre-1971 pipeline. Quest Integrity were engaged to investigate these crack-like linear indications. Metallurgical analysis of coupons removed from the pipeline concluded that the linear indications observed were Selective Seam Weld Corrosion (SSWC). With knowledge of this new threat, the Operator initiated a work program to manage this risk in the pipeline.

The work program included a like-and-similar analysis of the three most recent magnetic flux leakage metal loss in-line inspection data sets collected in the pipeline and metallurgical analysis results and additional field verification using advanced ultrasonic methods to further characterize metal loss features interacting with the longitudinal seam. Corrosion growth rates determined from the like-and-similar analysis and characterisation of features detected ultrasonically and/or metallurgically verified were utilized in a Fitness-for-Service and remaining life assessment of external metal loss features, both interacting with and away from the longitudinal seam weld.

The Operator used the results obtained from the above investigation to update their integrity management plan for their pre-1971 pipelines. This paper presents the full scope of work performed by the Operator and Quest Integrity to investigate the threat posed by SSWC for the pre-1971 8-inch pipeline network and shares the learnings obtained from the process.

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Introduction

On 18 December 2021, linear indications were detected at the longitudinal seam weld during a coating refurbishment project on a Coal Tar Enamel (CTE) coated, pre-1971vintage pipeline downstream of a major gas treatment plant. The indications were identified by Magnetic Particle Inspection (MPI), which was required as part of the Operator's stress corrosion cracking (SCC) Management Plan. MPI was generally carried out at significant metal loss anomalies, girth welds, and along the seam welds. Minor corrosion was not inspected further by MPI because of the extent of general corrosion occurring under the disbonded Coal Tar Enamel (CTE coating).

Loss of adhesion and increased permeability of CTE coating has resulted in a high incidence and increasing severity of corrosion in substantial sections of the approximately 600 km of pre-1971 constructed pipeline network. Coating was particularly degraded in this section downstream of a gas treatment plant by high gas temperatures. This resulted in a relatively high corrosion incidence that was only partially mitigated by cathodic protection (CP), due to CP current being limited by interference imposed on other operators' pipelines and CP shielding under disbonded coating, and exacerbated by wetting and drying of the pipe-wall under the permeable, disbonded coating. The effect of coating degradation on CP for the pipeline section downstream of the gas treatment plant is shown in Figure 2 and Figure 3.

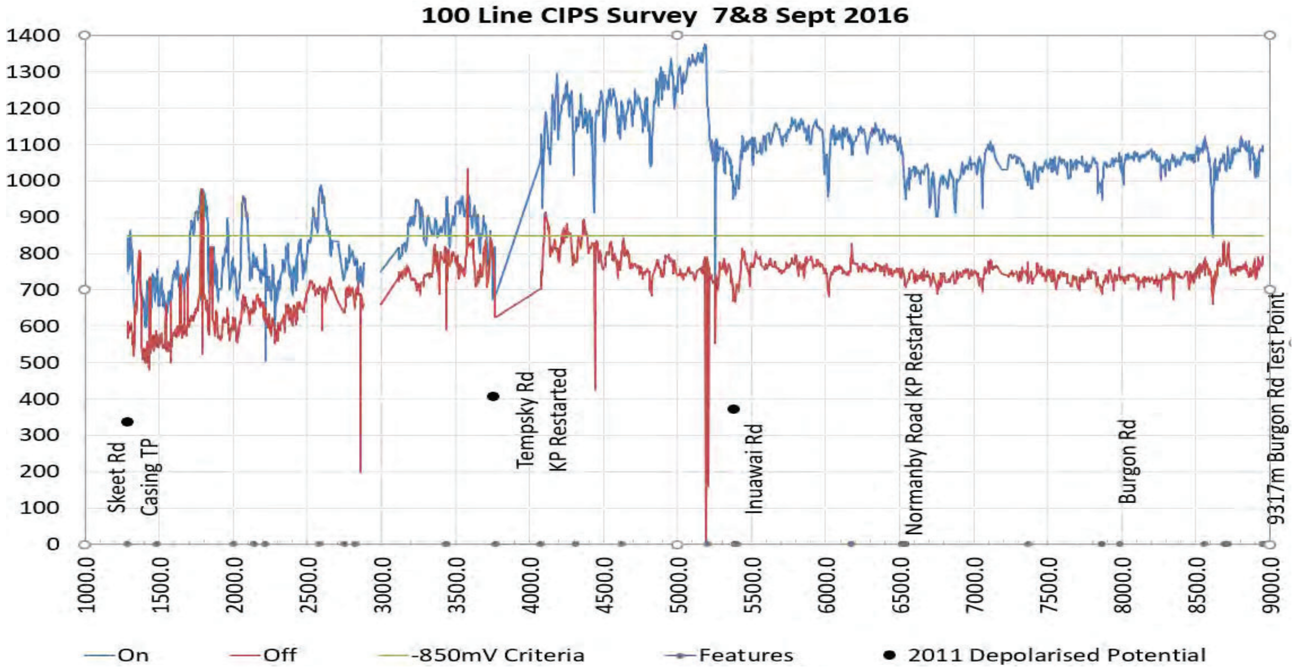

Figure 1. 2016 CP potentials from Close Interval Potential Survey (CIPS) from 1300m (Skeet Rd) to 9 km.

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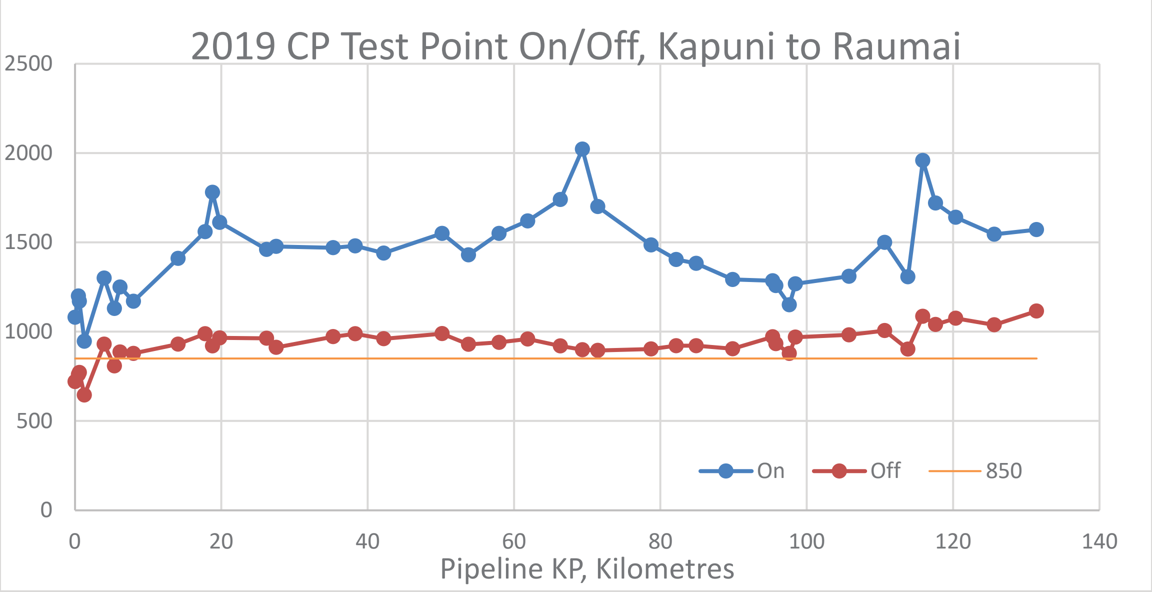

Figure 2. 2019 CP Test Point On/Off.

In addition to the observed general corrosion, there was a suggestion that the pipeline's tolerance to cracking damage may be reduced based on the inherent condition of the pipeline steel. This was based on other testing undertaken for the pre-1971 8-inch pipeline where a low impact energy was obtained for the parent pipe material. It was considered this may be attributed to a high concentration of non-metallic stringer inclusions in the parent pipe material. By inference of the impact energy results, it was implied that a smaller critical flaw/crack sizes can be tolerated by the parent pipe due to a low fracture toughness.

The consequence of a rupture or loss of containment is also high in several sections of the pre-1971 pipeline network based on proximity to suburban and industrial developments and where there are no alternative loop pipelines. The latter includes the section where the linear indications were detected. The risk of a rupture or loss of containment would also affect the security of supply to a major city in New Zealand.

Given the uncertainty with the nature of the linear indications detected at a high consequence area (HCA), Quest Integrity were engaged by the Operator to investigate the linear indications detected at the longitudinal seam weld with the objective of confirming the damage mechanism, particularly with respect to any active cracking threats. Quest Integrity was also requested to undertake an engineering assessment to determine the remaining life of the pipeline based on the threat identified.

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Engineering Assessment Approach

Metallurgical Examination

A metallurgical examination of coupons sampled from Site 6 and Site 34 along the excavated 8-inch pipeline was undertaken. Linear indications were detected by MPI within the longitudinal seam weld for the sampled coupons, see Figure 3 and Figure 4.

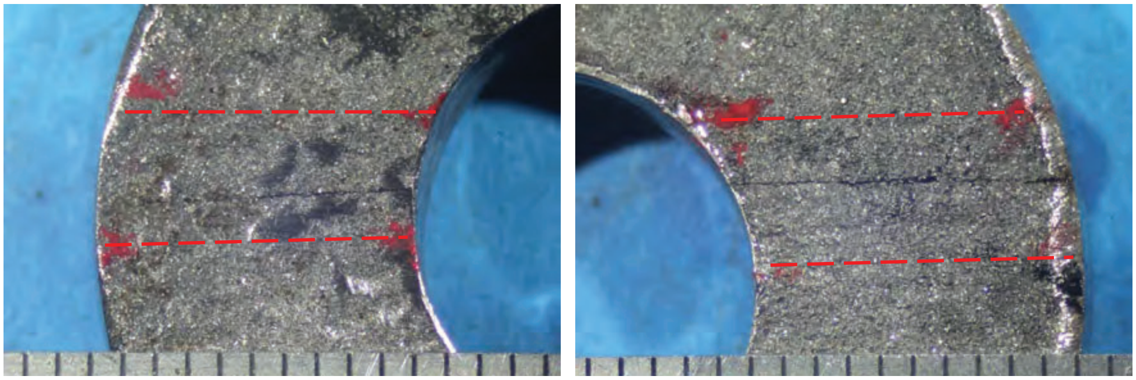

Figure 3. MPI indications detected for the Site 6 coupons. The approximate locations of the seam weld boundaries are shown by the red dashed lines. Scale bar increments = 1 mm.

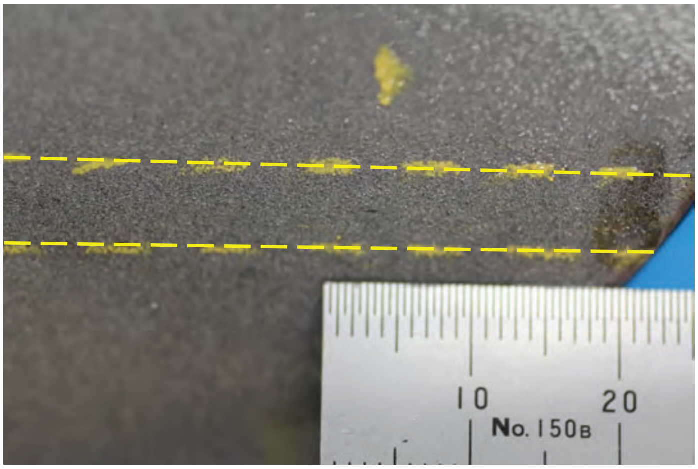

Figure 4. MPI indications detected for the Site 34 coupon. The approximate location of the seam weld boundary is shown by the yellow dashed lines. Scale bar increments = 0.5 mm.

Metallurgical cross sections of the linear indications detected by MPI for these coupons confirmed these to consist of an oxide notch at the longitudinal seam weld bondline. These were predominantly at the external surface (as detected by MPI, see Figure 5) with a localised instance of internal corrosion coincident with the bondline observed at Site 6, see Figure 6. The observed notches and internal corrosion coincident at the weld bondline were indicative of selective seam weld corrosion (SSWC), which likely occurred as a result of in-service corrosion of material known to be susceptible to SSWC given the known issues with respect to the coating condition and associated CP changes along this section of the pipeline. The appearance of the external oxide notches was sufficiently sharp and narrow for SSWC to be active. The observed metallurgy and chemical composition at the weld did not contribute to the observed SSWC damage. In particular, no evidence of significant segregation of non-metallic inclusions were observed in the microstructure.

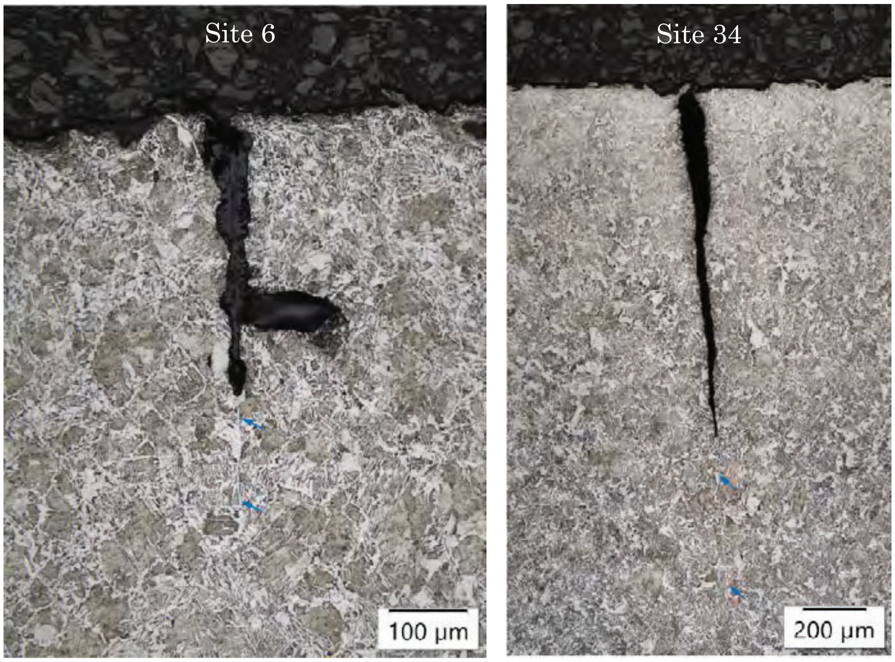

Figure 5. Representative longitudinal seam weld cross sections. Notch features were observed at the bondline. The blue arrows indicate the narrow band of ferrite grains along the bondline.

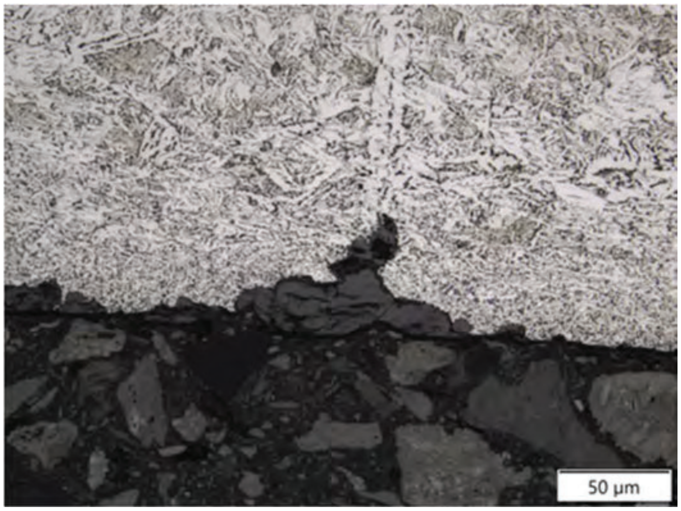

Figure 6. Localised notch at the internal surface, Site 6. The blue arrows indicate a narrow band of ferrite grains along the bondline.

The metallurgical examination also confirmed that the longitudinal seam weld was hourglass in shape, see Figure 5. This indicates that the weld was formed using a high frequency electric resistance welding (HF-ERW) process. It was noted that although HF-ERW pipe can also be susceptible to SSWC, particularly for earlier vintage HF-ERW, the threat of SSWC for these welds is not as common as that for direct current ERW (DC-ERW) or low frequency ERW (LF-ERW) [1][2]. No anomalous microstructures were observed across the longitudinal seam weld. In addition, no

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evidence of significant segregation of non-metallic inclusions were observed in the microstructure at the longitudinal seam weld.

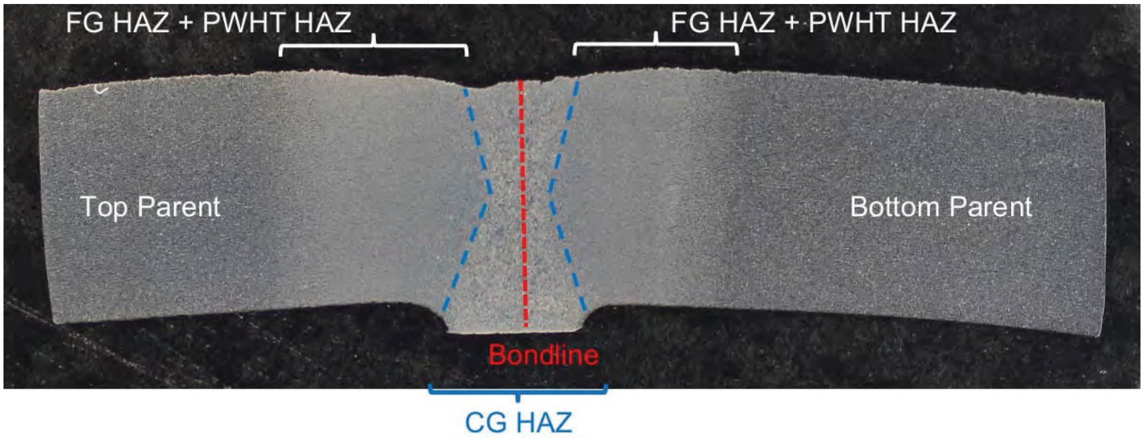

Figure 7. Representative seam weld cross section. Site 6 shown.

Material Verification

Tensile testing and Charpy V-notch (CVN) impact testing was undertaken for the hot tap coupon sampled from Site 34 to verify the material properties with the expected material specification. The material properties obtained were also used as inputs into the Fitness-for-Service assessment. The tests were carried out at the following temperatures:

- Tensile testing of parent pipe: ambient temperature.
- CVN impact testing of the parent pipe: - 75 °C to 100 °C.
- CVN impact testing of the longitudinal seam weld: 0 °C and ambient temperature.

Sub-size specimens were used for all tests and the tests were carried out in accordance with ASTM E8/8M [3] and ASTM E23 [4].

The tensile properties obtained for the parent pipe met the minimum tensile requirements specified for API 5LX X42 material.

The CVN impact testing results obtained for the parent pipe is shown in Figure 8. Given that no impact properties are specified for API 5LX X42 material, the acceptance criterion specified in API 5L for PSL2 material was used. The CVN impact energy obtained at 0 °C for the parent pipe was less than the adjusted specified absorbed energy/impact energy acceptance criterion defined in API 5L. Similarly, the CVN impact energy obtained for the seam weld at 0 °C was also less than the adjusted specified absorbed energy/impact energy acceptance criterion defined in API 5L. These results likely indicate that the impact properties for the parent pipe and seam weld are at the lower shelf of the CVN transition curve at typical operation temperatures.

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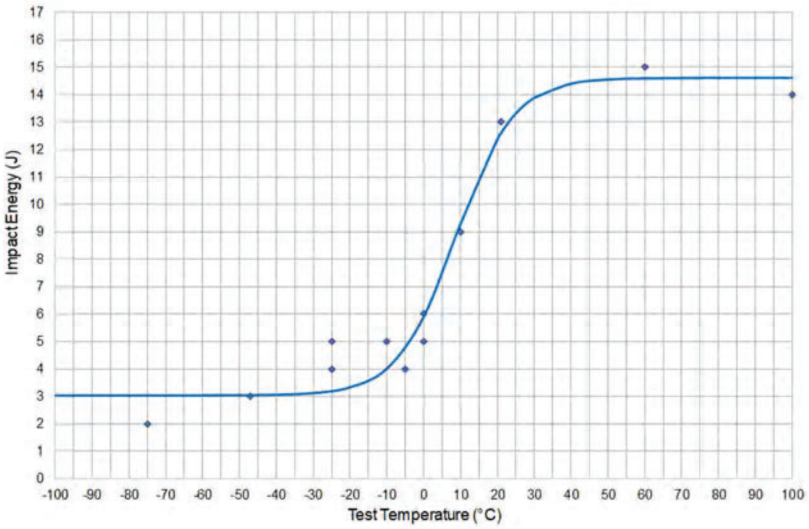

Figure 8. Charpy impact energy curve for the parent pipe material.

Advanced Non-Destructive Testing

Additional direct assessment of the excavated pipeline was done using advanced ultrasonic testing of the seam weld, primarily with phased array (PA) and Time of Flight Diffraction (ToFD) methods. Manual ultrasonic testing (MUT) was undertaken to obtain measurement of some surface defect depth. A total of 50 m of the excavated pipeline was ultrasonically inspected. The objective of the ultrasonic testing was to determine whether a more efficient method for determining seam weld features and embedded defects for direct assessment.

A possible linear feature within metal loss at the longitudinal seam weld was detected by ToFD and PA at Site 134 of the excavated pipeline. Linear indications had also been detected by MPI at this location prior to the ultrasonic inspection, see Figure 9. As a precautionary measure, this feature was removed by hot-tap repair and further metallurgical examination was undertaken for the sampled coupon.

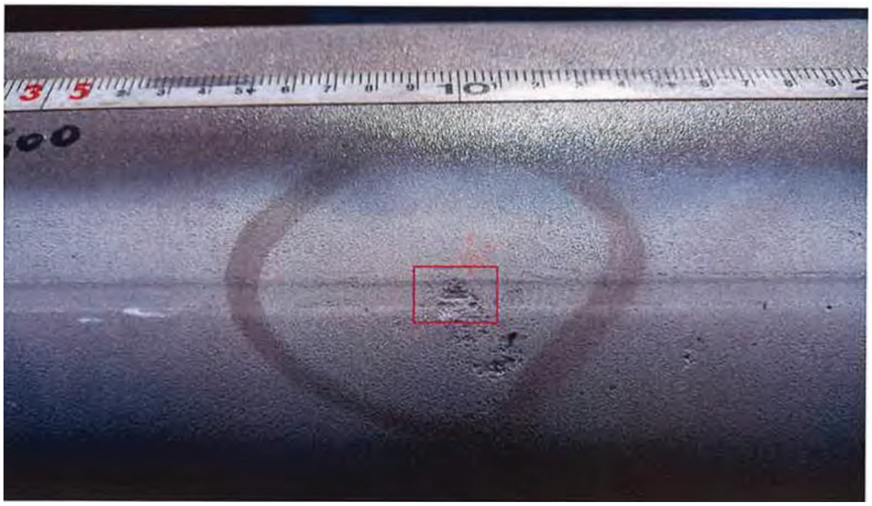

Figure 9. Metal loss and linear indicated detected at Site 134. Image after MPI shown.

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A representative cross section across the longitudinal seam weld of the coupon from Site 134 is shown in Figure 10. Further metallurgical examination confirmed that the feature detected at Site 134 was likely to be indicative of SSWC based on the grooving factor determined (i.e., comparison of the depth of the groove from corrosion at the bondline compared to the overall metal loss of the pipe material). It was noted that the appearance of SSWC at Site 134 differed from that observed at Site 6 and Site 34 and it was considered likely that the damage observed for Site 134 was representative of early stages of SSWC. This suggests that this level of SSWC damage may be at the limits of detection for the inspection methods used.

Figure 10. Representative image of the seam weld cross section at Site 134. The bondline is highlighted by the red arrows.

The inspection overall allowed for a direct measurement of at least one seam weld feature. However, it was noted that further development may enable improvement of the methodology, particularly in improving the correlation between reflectivity and manual ultrasonic measurement for broader use in a direct assessment.

Review of ILI Data

A like-and-similar analysis was carried out for in-line inspection (ILI) runs completed for the 8-inch pipeline in 2010, 2015, and 2020. The data obtained included magnetic flux leakage (MFL, all runs), deformation (GEO, all runs), and inertial mapping (IMU, 2020 run only). The analysis was completed for the first 18 km of the pipeline, including the pipe sections containing Site 6 and Site 34. Once ILI datasets were aligned, a total of 146 features on the longitudinal seam were analysed, as follows:

- 143 external metal loss features on the longitudinal seam. These were reported as "EXT ML (SW)" in the 2020 ILI.
- One external manufacturing anomaly on the longitudinal seam. This was reported as "EXT MFG (SW)" in the 2020 ILI.

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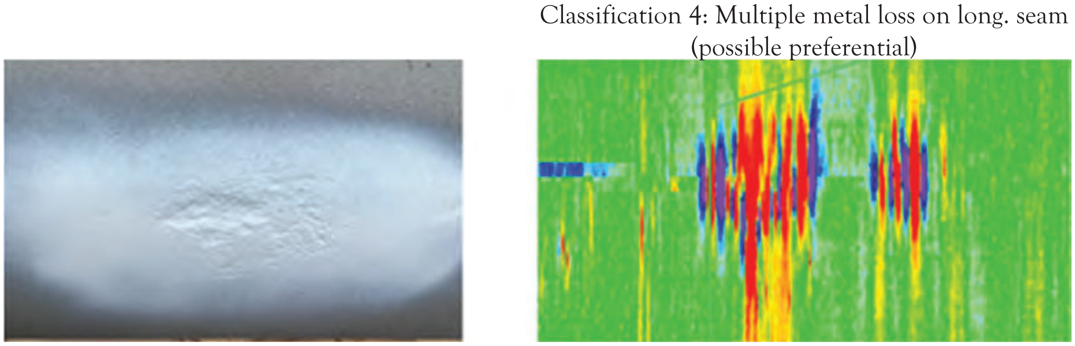
- Two axial features observed at Site 6 and Site 34 are characteristic of SSWC, as determined from the metallurgical examination.

A classification matrix was established to categorise the detected features, see Table 1. The like-and-similar analysis was performed independently by two analysts. Site 6 (approximate 2020 odometer 114.471 m) received a matrix classification of 4 from both analysts. Site 34 (2020 odometer 1157.453 m) received a matrix classification of 2 from both analysts. Features with similar characteristics to Site 6 and Site 34 were further prioritised. A comparison between in-the-ditch findings and ILI data can be seen in Figure 11.

Table 1. Matrix classification.

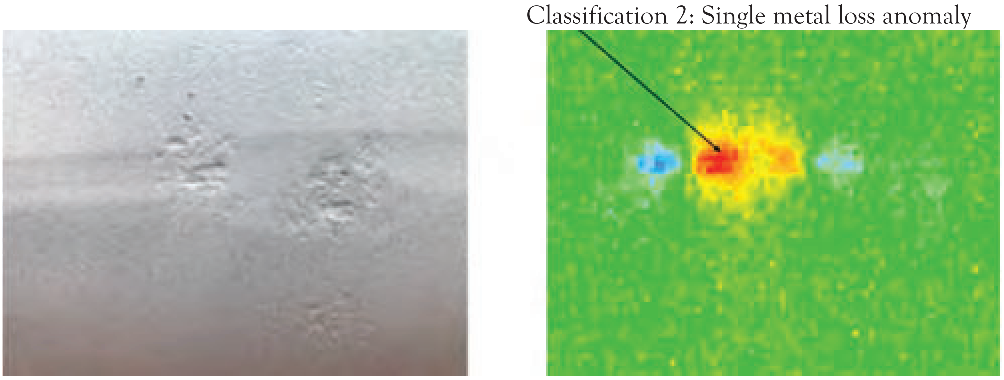
Matrix classification	Characteristics
1	The feature has characteristics of a manufacturing anomaly
2	The feature is a single pit/metal loss (ML) anomaly
3	There are multiple anomalies observed and appear to be coincidental to the longitudinal seam weld.
4	There are multiple anomalies observed and appear to be preferential to the longitudinal seam weld.



Classification 4: Multiple metal loss on long. seam (possible preferential)

Site 6

ILI Data



Classification 2: Single metal loss anomaly

Site 34

ILI Data

Figure 11. Comparison of the visual appearance and ILI data for Site 6 and Site 34.

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Determination of the Corrosion Growth Rate

A corrosion growth rate (CGR) was determined for all metal loss features reported in 2020 for the first 18 km of the 100 Line. The CGR assessment utilized both a spreadsheet run comparison and an ILI raw data review. The assumptions and factors accounted for include:

- the time between ILIs,
- a correction of tool bias calculated between the 2015 ILI reported depths and field found depths,
- spreadsheet to spreadsheet match of metal loss features and
- identification of geometric change of metal loss features during the raw data review.

For those metal loss features with geometric change, a secondary CGR was calculated to leverage raw data review results and provide a focused and more accurate CGR model. Figure 2 provides a distribution of metal loss with geometric change, and an empirical cumulative distribution function (CDF) of resulting CGRs is seen in Figure 13.

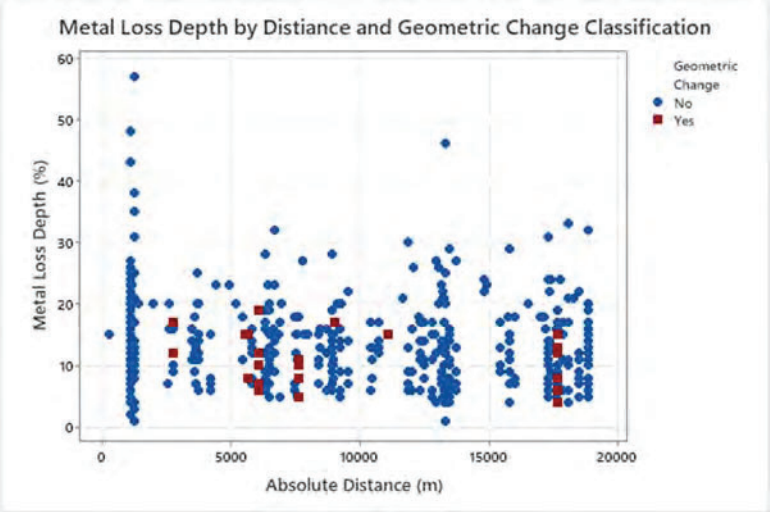

Figure 12. Distribution of metal loss geometric change classification.

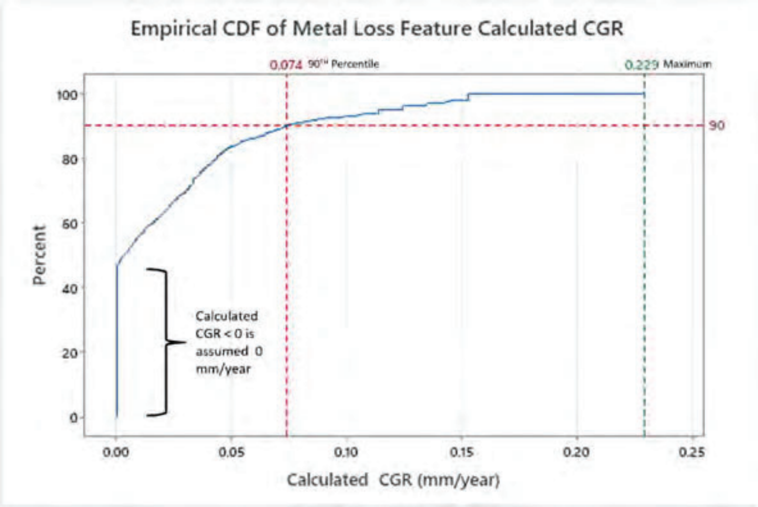

Figure 13. Empirical CDF of calculated metal loss features CGRs.

The highest CGR determined was 0.229 mm/year. Geometric change was identified in the corresponding pipe joint, with metal loss ranging from 4 % to 15 % that was not detected in the 2015 ILI. Approximately 90% of the selected CGRs are less than or equal to 0.074 mm/year, with the average selected CGR being 0.025 mm/year.

The CG assessment conservatively applied the maximum calculated metal loss feature CGR in a pipe joint to all metal loss in the pipe joint (referenced as Joint CGR). The Joint CGR was subsequently used in the fitness-for-service and remaining life assessment.

Fitness-for-Service and Remaining Life

An initial Fitness-for-Service assessment was carried out by Quest Integrity in 2007, where critical flaw size charts were determined for defects located ± 60° from the longitudinal seam and the pipe body at all other locations. Based on these charts, it was inferred that the dimensions of the observed features for the examined coupons were likely to be acceptable, with no immediate threat with respect to pipeline rupture. Despite this, the presence of SSWC creates weaknesses at points in the pipe, which in turn makes the pipe more susceptible to third-party damage and overpressure events and interacting features such as lack of fusion (i.e., SSWC does not necessarily need to cause the leak or rupture itself to increase risk) [2]. In addition, observed rates of SSWC have been documented at two to four times as fast as metal loss in base material [1][2].

The initial Fitness-for-Service assessment was refined by considering the burst pressure and remaining life of all metal loss features. The burst pressures for all reported features were calculated using the modified equation in ASME B31.G [5]. The remaining life of each reported metal feature was calculated considering the corrosion growth rates determined. For features located on the longitudinal seam, additional burst pressure and remaining life calculations were executed by idealizing the metal loss feature as a crack-like flaw, as these metal loss features on the longitudinal seam had the potential to be SSWC. The calculated CGRs were multiplied by a factor of 4.0 to model the potential future SSWC growth rate and calculate the remaining life.

The remaining life was defined as the lesser of the following:

- Time for the calculated safe operating pressure (P_{safe}) of the feature to be less than or equal to the maximum allowable operating pressure (MAOP).
- Time for the depth of the feature to be greater than or equal to 80% wall thickness.

All crack stability calculations were executed per ASME FFS-1/API 579-1 (API 579) Part 9 Level 2 [6]. The material properties used for the burst pressure and remaining life calculations are summarized in Table 2.

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Table 2. Material properties assumed for burst pressure and remaining calculations.

Nominal wall thickness (mm)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Fracture toughness
5.56	456[1]	520[1]	38,152 psi√inch[2]
8.18	289[3]	413[3]	N/A[4]

[1] Minimum measured value from destructive testing of Site 34 Coupon.

[2] Fracture toughness only required for additional API 579 Part 9 Level 2 calculations for ML features reported on the LS.

[3] Destructive testing of Site 34 Coupon only relevant for 5.56 mm wall thickness pipe; specified minimum value per API 5L was assumed.

[4] No metal loss features on the longitudinal seam were reported in 8.18 mm wall thickness pipe; API 579 Part 9 Level 2 calculations were not executed.

The fracture toughness was estimated using the CVN impact testing results obtained from the Site 34 coupon. The CVN test data indicated that the material was in the lower shelf of the ductile to brittle transition curve at the assumed minimum pipe metal temperature of 10°C. Therefore, the Sanz lower shelf correlation [7] was used to calculate a fracture toughness.

The burst pressure and remaining life calculations determined for the pipe body and at the longitudinal seam are provided in Table 3 and Table 4, respectively.

Table 3. Burst pressure and remaining life per ASME B31.G modified, 5 features with lowest remaining life.

Absolute distance (m)	WT (mm)	Location	Depth (%WT)	Length (mm)	CGR (mm/yr)	MAOP (barg)	Burst pressure (barg)	Psafe[1] (barg)	Remaining life[2, 3] (years)
1263.524	5.56	Pipe body	57	61	0.1524	86.2	192.2	138.4	<10
1263.532	5.56	Pipe body	57	53	0.1524	86.2	199.3	143.5	<10
1114.990	5.56	Pipe body	48	17	0.1524	86.2	254.7	183.4	<15
13313.365	5.56	Pipe body	46	9	0.1524	86.2	263.1	189.4	<15
1114.965	5.56	Pipe body	43	46	0.1524	86.2	226.5	163.1	<15

[1] P_{safe} = burst pressure x design factor; design factor = 0.72

[2] RL is the number of years from the 2020 inspection date of 3 December 2020.

[3] RL does not include any additional factor of safety.

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Table 4. Burst pressure and remaining life per API 579 Part 9 Level 2, 9 features with lowest remaining life.

Absolute distance (m)	WT (mm)	Location	Matrix Class[1]	Depth (%WT)	Length (mm)	CGR (mm/yr)	MAOP (barg)	Burst pressure (barg)	Psafe[2] (barg)	Remaining life[3, 4] (years)
1114.856	5.56	Seam	4*	23	45	0.1524	86.2	248.4	178.9	2.5
1115.697	5.56	Seam	4*	15	73	0.1524	86.2	249.1	179.3	2.7
1114.772	5.56	Seam	4*	16	53	0.1524	86.2	252.3	181.6	2.9
1115.046	5.56	Seam	4*	24	29	0.1524	86.2	255.7	184.1	3.9
9248.145	5.56	Seam	2	12	47	0.1049	86.2	250.4	180.3	3.9
1121.181	5.56	Seam	4*	7	31	0.1524	86.2	263.5	189.7	4.9
8349.816	5.56	Seam	2*	7	32	0.1449	86.2	263.3	189.6	4.9
1169.129	5.56	Seam	3	11	37	0.1090	86.2	260.2	187.4	5.5
15182.347	5.56	Seam	2*	9	63	0.0931	86.2	257.5	185.4	5.5

[1] See Table 1 for matrix classification description. Seven of the 10 MLOS were identified during the raw data review as having qualitative characteristics most similar to the MLOS at Site 6 Coupon and Site 34 Coupon.

[2] P_{safe} = burst pressure x design factor; design factor = 0.72

[3] RL is the number of years from the 2020 inspection date of 3 December 2020.

[4] RL does not include any additional factor of safety.

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Direct Inspection Results

Table 4 lists corrosion features, including those considered to be characteristic of SSWC, with short remaining lives. The features from 1114 m to 1169 m are all within the section recoated in the 2021 refurbishment project. The three features with the shortest remaining life, which had not been previously inspected and/or recoated, were inspected in 2023, and are presented with the direct inspection results in Table 5. General images of the features observed at each inspection location are shown in Figure 14 to Figure 16.

At all 2023 direct assessment locations, the observed damage was primarily corrosion pitting damage at or near the longitudinal seam weld; these were consistent with the matrix classifications provided in Table 4. In addition, no linear indications were observed or detected along the longitudinal seam weld, this is particularly significant at locations 8349.816 m and 15182.347 m which were identified to have similar metal loss characteristics as the Site 6 and Site 34 coupons. The direct assessment results indicate no immediate interaction of corrosion features with the longitudinal seam weld, possibly inferring no significant reduction to the estimated remaining life.

Table 5. Comparison of ILI, remaining life and direct inspection results.

Absolute Distance (m)	December 2020 ILI Features and Remaining Life Assessment					Direct Inspection - October 2023		
	WT	Depth (%WT)	Length (mm)	CGR (mm/yr)	Remaining Life (Years)	Depth (%WT)	Length (mm)	Linear Corrosion
8349.816	5.56	7	32	0.1449	4.9	8	NR	None
9248.145	5.56	12	47	0.1049	3.9	17	36	None
15182.347	5.56	9	63	0.0931	5.5	5	5	None

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Figure 14. Corrosion feature at 8349.816 m.

Figure 15. Corrosion feature at 9248.145 m.

Figure 16. Corrosion Feature at 15182.347 m. Longer length reported by ILI appears to be due to the corrosion defect being, mostly, ground out during construction.

Conclusions

From the engineering assessment, the following were determined:

- The linear indications detected at the longitudinal seam weld (HF-ERW fabrication) were identified to be indicative of SSWC. The observed notches were sufficiently sharp and narrow to be considered active.
- No evidence of active cracking damage was observed in the examined metallurgical samples.
- No evidence of significant segregation of non-metallic stringer inclusions were observed in the microstructure of the examined metallurgical samples.
- A low impact energy was obtained for the tested parent pipe and longitudinal seam weld. The results likely indicate that the impact properties for the parent pipe and seam weld are at the lower shelf of the CVN transition curve at typical operation temperatures.
- A CGR was determined based on a like-and-similar analysis of available ILI data completed in 2010, 2015 and 2020. Approximately 90% of the selected CGRs are less than or equal to 0.074 mm/year, with the average selected CGR being 0.025 mm/year.
- The remaining life estimated for 9 “worst” corrosion anomalies (isolated or observed/appearing to be coincidental or preferential to the longitudinal seam weld) ranged from 2.5 years to 5.5 years.

The assessment presented here has confirmed and assessed the threat of SSWC in 18 km out of the approximately 600 km of pre-1971 8-inch pipeline. The direct inspections completed to date have found relatively shallow SSWC. The next actions are likely to be based on the extent of effort needed to understand any remaining uncertainty and likelihood of a failure from SSWC. The risk of a rupture or loss of containment due to SSWC is being considered in combination with other threats identified for the pre-1971 8-inch pipelines, including localised regions of low toughness steel, SCC, land movement, coating degradation/failure and third-party damage.

A restricted pipeline operating pressure was temporarily implemented for the pre-1971 8-inch pipeline network based on the engineering assessment and recent direct assessments as an interim risk mitigation measure. All the potential SSWC features with a remaining life of 5.5 years or less has been inspected. Longer term, the Operator is reviewing available ILI and direct assessment methodologies and update the pipeline integrity management plan to address the various threats identified, including SSWC. There is not yet a proven ILI technology for detecting narrow, crack-like pipe-wall anomalies in 8-inch dry gas pipelines without running an ultrasonic ILI tool in a liquid. There are EMAT tools understood to be in development for small diameter gas pipelines, which the Operator will assess and integrate into its ILI programme to supplement surveys and direct assessment programmes as appropriate.

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