PARSC 017

Enbridge Line 3 Abandoned Pipeline Segment Subsurface Field Study

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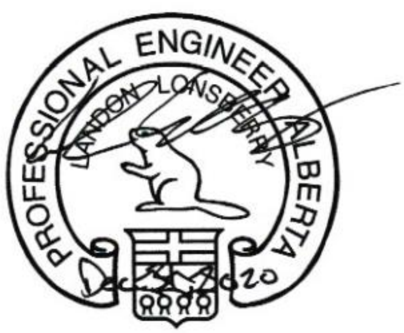

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EXECUTIVE SUMMARY

The Pipeline Abandonment Research Steering Committee (PARSC), a working body within the Petroleum Technology Alliance Canada (PTAC), initiated PARSC 017 to implement recommendations from "*Review of Previous Pipeline Abandonment Programs, Phase 3 – Abandonment on Farmland"* (PARSC 015) to perform a subsurface assessment of NPS 34 Enbridge Line 3 between Edmonton and Hardisty abandoned between 1978 and 1980. The project objectives included collecting, analyzing and comparing in-situ data against model predictions generated in PARSC 001, "*Understanding the Mechanisms of Corrosion and their Effects on Abandoned Pipelines*."

Three site locations along Enbridge Line 3 were evaluated, including MP 27.5276 and MP 29.52 in August 2020, and MP 80.4655 in November 2019. The field assessments included:

- Visual site assessment, including soil subsidence and soil conditions.
- Excavation of the pipeline (performed by Enbridge)
- Visual inspection of the pipe coating and pipe surface
- Sandblasting to expose the bare steel
- Visual inspection of the bare pipeline
- Measurements of corrosion features and wall loss.
- Documentation of activities and observations

No soil subsidence, contamination, nor through wall penetration was observed at any of the three sites. The PE tape wrap coating was found to be in good condition for its vintage, with minor holidays, damage, and disbondment. Moderate wrinkling patterns were observed along the axial and circumferential directions, as well as tenting along the pipe seam.

Pitting corrosion features were identified and measured via laser scanning and confirmed with mechanical measurement at all three sites. The remaining wall thickness ranging from 69% to 94%. The pitting was generally clustered along the sides of the pipelines, matching areas of coating disbondment. However, MP 29.52 and MP 80.4655 experienced minor corrosion despite significant coating disbondment. At MP 27.5276, corrosion features with high surface area were found clustered along the exposed girth weld. This corresponded with primarily circumferential wrinkling disbondment observed at MP 27.5276.

Penetration and mass loss rates, calculated from the corrosion feature data, suggest the PARSC 001 corrosion modelling is conservative by factors ranging from 1.5 - 2.5 times, resulting in predicted timelines for structural integrity loss on the order of hundreds to thousands of years. Based on this analysis, loss of structural integrity on the evaluated sections of abandoned Line 3 is more likely to occur through the mechanism of through-wall penetration and pit coalescence than general wall loss, and the evaluated segments have maintained structural integrity to a greater degree since abandonment than the PARSC 001 model predicts.

Additional field testing should be completed to further refine the findings of this study, specifically to evaluate the effects of disbonded area on the severity of corrosion on pipelines with a variety of coating types, including the orientation of wrinkling patterns for PE tape wrap. This would also be beneficial in determining the variables most impactful to the integrity of the pipeline. Other recommendations include the completion of soil analyses, controlled subsidence testing, and pipe ring sampling.

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ABBREVIATIONS AND ACRONYMS

API	American Petroleum Institute
API 5L	American Petroleum Institute specifications for seamless and welded steel pipe
C/S	Compressor Station
CP	Cathodic Protection
Enbridge	Enbridge Pipelines, Inc.
KM or KP	Kilometer Post
LSD	Legal Subdivision
MP	Mile Post
NEB	National Energy Board
NPS	Nominal Pipe Size
OD	Outer Diameter
PARSC	Pipeline Abandonment Research Steering Committee
PARSC 001	Understanding the Mechanisms of Corrosion and their Effects on Abandoned Pipelines (DNV)
PARSC 015	Review of Previous Pipeline Abandonment Programs, Phase 3 – Abandonment on Farmland
PE	Polyethylene Coating
Plex	Plex Projects, Inc.
PTAC	Petroleum Technology Alliance of Canada
ROW	Right-of-Way
RWT	Remaining Wall Thickness
WT	Wall Thickness

1.0 PROJECT DESCRIPTION

The Pipeline Abandonment Research Steering Committee (PARSC), a working body within the Petroleum Technology Alliance Canada (PTAC), initiated PARSC 017 to implement recommendations from *Review of Previous Pipeline Abandonment Programs, Phase 3 – Abandonment on Farmland* (PARSC 015, see Appendix A). PARSC 015 consisted of a field surface assessment of the present-day state of areas where segments of Enbridge's Line 3 (NPS 34) were abandoned between 1978 and 1980. The scope included identification of areas in which subsurface testing could be conducted to evaluate the effects of pipeline abandonment

PARSC 017 includes the subsurface assessment of the abandoned sections of Enbridge Line 3 located in the Edmonton/Hardisty region between the active Lines 2 and 4. The project objectives are to make on-site observations, collect relevant data including wall loss measurements and soil samples if required, and subsequently complete analyses and reporting.

1.1 Project Location

The abandoned Line 3 segments selected for this project are located between the Edmonton and Hardisty regions in Alberta, and were selected on the basis of the following:

(a) Susceptibility to risks associated with pipeline abandonment per PARSC 015, including soil subsidence, contamination, and erosion.

(b) Accessibility given that Enbridge was performing work in particular areas along the ROW.

The locations selected for subsurface assessment are provided in Table 1.1.

Table 1.1: Line 3 assessment locations.

Location	LSD	GPS Coordinates
MP 27.5276	06-14-49-21 W4	53.226236°N, 112.970301°W
MP 29.52	01-12-49-21 W4	53.210359°N, 112.92878°W
MP 80.4665	13-05-45-13 W4	52.854992°N, 111.861958°W

1.2 Scope

The scope of work is guided by the PARSC 015 objectives, and includes the following tasks [1]:

- **Task 1 – Field Work at Line 3 Abandoned Segments**
  - Preparation of a site inspection plan.
  - Visual inspection of abandoned pipe, coating, and soil conditions.
  - Collection of surrounding soil if evidence of soil contamination is observed.
  - Visual inspection of the pipe surface, after removal of coating and sandblasting.
  - Laser scan measurements of the exposed pipe to record corrosion data.
- **Task 2 – Laboratory Analysis**
  - Arrange for relevant analyses of the collected soil samples.
- **Task 3 – Information Analysis and Reporting**
  - Completion of a comprehensive report summarizing project background, activities, methodologies, results, analyses, and conclusions.

2.0 BACKGROUND

2.1 Record Review

Plex reviewed historical information regarding the abandoned Line 3, provided by Enbridge. The information consisted of Enbridge records, and publicly available documents filed with the NEB. Documents reviewed include the following and are attached in Appendix B:

- ‘As-built’ drawings of the abandoned section of Line 3 from MP 72 to MP 85 (NEB File No. 1793-J1-21).
- Schematic diagram of Line 3 major piping and equipment showing abandoned and removed lines from KM -0.274 to KM 139.90 (1980)
- Line 3 Abandonment Application (1980)
- Line 3 Abandonment Approval (NEB Order No. MO-14-80)

From these records, it was confirmed that two sections of the former Line 3 (NPS 34), totalling 72.315 km in length, were abandoned between KM -0.274 to KM 51.357, and KM 116.016 to KM 136.7. The application was submitted to the NEB on November 3, 1980 and approved on November 26, 1980.

The conditions of the approval were that the abandonment be performed in accordance with the Oil Pipeline Regulations SOR/78-746 (1978), and that cathodic protection be maintained on the abandoned pipeline. The abandonment application indicates an estimated completion date of December 31, 1980.

As per PARSC 015, the abandoned sections of Enbridge Line were constructed using NPS 34 (863.6mm OD) x 0.281” WT (7.14mm), API 5L X52 (359 MPa) carbon steel pipe [1].

2.2 Soil Corrosivity

The corrosion and structural integrity modelling outlined in PARSC 001 (see Appendix E) utilizes soils data generated by the National Bureau of Standards (NBS) based on the aeration or drainage capacity of various soil types. This classification is shown in Table 2.1 [2] [3].

Table 2.1: Classification of soil corrosivity based on aeration/drainage.

Soil Type	Description of Soil	Aeration / Drainage	Water Table
I – Lightly Corrosive	1. Sands or sandy loams 2. Light textured silt loams 3. Porous loams or clay loams thoroughly oxidized to great depths	Good	Very Low
II – Moderately Corrosive	1. Sandy loams 2. Silt loams 3. Clay loams	Fair	Low
III – Badly Corrosive	1. Clay loams 2. Clays	Poor	2 ft to 3 ft below surface
IV – Unusually Corrosive	1. Muck 2. Peat 3. Tidal marsh 4. Clays and inorganic soils	Very Poor	At surface, or extreme impermeability

In general, soils with poor drainage, low permeability, and high moisture content tend to have lower resistivity. These conditions are more conducive to corrosion as seen in Table 2.2, the information contained within was obtained from the PARSC 001 report [2] [4].

Table 2.2: Classification of resistivity and corrosivity for various soil types.

Soil Classification	Resistivity (Ωcm)	Corrosivity
Clay	750 – 2,000	Severe - Very Severe
Loam	3,000 – 10,000	Severe - Moderate
Gravel	10,000 – 30,000	Mild
Sand	30,000 – 50,000	Very Mild
Rock	50,000+	Very Mild

Based on this criterion, PARSC 001 used soil data from the NBS to generate corrosion models in various soil types. The models included both uniform corrosion (i.e. the mass loss model) and depth of penetration. The model in PARSC 001 used to estimate the remaining wall thickness of a pipeline after a given amount of time is given as [2]:

$$t = t_0 - k \cdot T^{0.5}$$

(Equation 1)

where:

t = Remaining Wall Thickness (mm)
t_0 = Nominal Wall Thickness (mm)
k = Mass Loss (k_{ml}) or Penetration (k_p)
T = Elapsed Time (years)

Note Equation 1 is applicable for both penetration depth (i.e. in the case of pitting corrosion), as well as for general wall loss predictions according to PARSC 001. The upper bounds for the corrosion coefficient in various soil types as found through the NBS soils and corrosion data are summarized in Table 2.3 [2].

Table 2.3: Upper bound curve fit data for the NBS soils data.

Soil Type (Internal Drainage)	Coefficient for Mass Loss, k_{ml} (mm/√yr)	Coefficient for Penetration Data, k_p (mm/√yr)	Penetration Ratio (k_p/ k_{ml})
Good	0.05	0.75	15
Fair	0.10	1.0	10
Poor	0.15	1.0	6.7
Very Poor	0.20	1.0	5
All Data	0.25	1.0	4

The penetration ratio in Table 2.3 (from PARSC 001) is used to balance the two corrosion types considered, as localized and uniform corrosion can take place simultaneously to some degree. A soil with a higher penetration ratio has a lower effective corroding area, however at the higher penetration rate rather than the mass loss rate.

To compare and corrosion patterns at Enbridge Line 3 to the PARSC 001 predictions, the field assessment is essential to obtain:

- The soil type(s) present and ground conditions to generate a baseline expected corrosivity.
- The condition of any coating present, including areas of disbondment and exposure to soil environment. This has an expected effect on the degree of localized or general corrosion. A well-coated pipeline is only expected to corrode in areas of coating disbondment, damage, or holidays, while a bare pipeline without cathodic protection is expected to experience general wall loss.
- Quantitative corrosion data (i.e. general wall loss, corrosion pitting depth, etc.) to compare with “expected” values.

3.0 RESULTS & ANALYSIS

3.1 Soil/Ground Conditions

Visual inspections of the three sites were performed to identify the soil/site properties and any evidence of subsidence or contamination. The findings are summarized in Table 3.1, and additional images can be found in Appendix C.

Table 3.1: Summary inspection of site and soil conditions for Enbridge Line 3.

Site Location	MP 27.5276	MP 29.52	MP 80.4655
Soil Type	Clay Soils	Clay Soils	Clay and Sand
Evidence of Soil Subsidence	No	No	No
Evidence of Soil Contamination	No	No	No
Site Conditions	High moisture content	High moisture content	Dry around pipeline Signs of moisture in proximity

The material at both sites MP 27.5276 and MP 29.52 was found to be primarily clay soils. This classifies the material as "badly" or "unusually corrosive" due to its high moisture content and low permeability as discussed in Section 2.2. Both excavations had standing water and required frequent dewatering. MP 27.5276 is in close proximity to the landowner's drainage trench, while MP 29.52 is near a highway ditch. This is shown in Figure 3-1 and Figure 3-2 respectively.

Figure 3-1: Standing water site conditions, MP 27.5276

Figure 3-2: Standing water site conditions, MP 29.52

The soil at MP 80.4655 was primarily a mixture of clay and sand. Based on the information provided in PARSC 001, the resistivity range of such soil is expected to be between 750 to 2000 Ω-cm, which corresponds to a 'severe' or 'very severe' corrosivity, conservatively assuming the poor drainage of clay is more significant than the drainage of sand [2]. Unlike at MP 27.5276 and MP 29.52, the soil surrounding the pipeline was dry, however there was evidence of moisture approximately 1 foot below the pipeline. The area is also low-lying and likely exposed to seasonal standing water.

There was no indication of soil subsidence nor soil contamination at any locations upon site inspection, and therefore no soil samples were extracted for laboratory testing.

3.2 Pipe Coating and Pre-Blast Surface Inspection

The coating at all three sites was identified to be polyethylene (PE) tape-wrap coating. PE tape wrap is known to cause localized corrosion and pitting related to poor coating adhesion or disbondment. Some known concerns include:

- Coating disbondment along the long seam of the pipeline, commonly referred to as tenting, which can lead to localized corrosion.
- Coating wrinkling patterns commonly found along the 3 o'clock and 9 o'clock positions of the pipeline in the axial direction. If moisture ingresses and is trapped at this location, localized pitting corrosion can occur.
- Cathodic protection (CP) shielding at disbonded locations, where the CP current is unable to penetrate the disbonded coating, leaving areas of bare steel unprotected from corrosion [5].

The findings of the visual inspection of the coating and pipe surface prior to sandblasting are summarized in Table 3.2 and discussed in detail in Sections 3.2.1 through 3.2.3.

Table 3.2: Summary inspection of coating and pipe surface for Enbridge Line 3.

Site Location	MP 27.5276	MP 29.52	MP 80.4655
Coating Type	Polyethylene Tape Wrap		
Coating Observations	• Moderate general wrinkling, circumferential direction • Very little adhesive remaining beneath coating • Minor tenting along long seam	• Moderate wrinkling, axial direction, mostly along sides of pipeline • Minor breaks/lacerations • Minor tenting along long seam	• Severe localized disbondment/laceration • Moderate wrinkling, axial direction, localized along side of pipeline
Pipe Surface Observations (Pre-sandblast)	• No through wall defects • Moisture trapped on underside of pipe beneath coating • Mud trapped on underside of pipe beneath coating	• No through wall defects • Moisture trapped on sides and underside of pipe beneath coating	• No through wall defects • Moisture trapped on underside of pipe beneath coating

Note there were no indications of past modifications made on the pipeline at any of the three sites, such as the installation of sleeves or coating repairs. It is possible that sections of the abandoned Line 3 or surrounding soil may have been disturbed during integrity or maintenance work on the other Enbridge pipelines running in close proximity.

3.2.1 MP 27.5276

At MP 27.5276, moderate circumferential wrinkling as well as tenting along the long seam were observed along the pipe section as seen in Figure 3-3 and Figure 3-4. Note that the circumferential orientation and generalized nature of the wrinkling is atypical for PE tape wrap, the cause of which is likely related to the application of the coating. Overall, the condition of the PE tape was fair considering the vintage of the line, as no major indications of damage were observed.

Figure 3-3: Minor tenting along pipe seam, MP 27.5276.

Figure 3-4: General circumferential wrinkling of coating, MP 27.5276.

The coating was easily removable with little adhesive remaining, which may be an indicator of additional disbondment not observed initially on the exterior of the tape wrap. Moisture was trapped on the underside of the pipe, including a mud-like substance as seen in Figure 3-5 and Figure 3-6.

Figure 3-5: Mud trapped beneath coating, MP 27.5276.

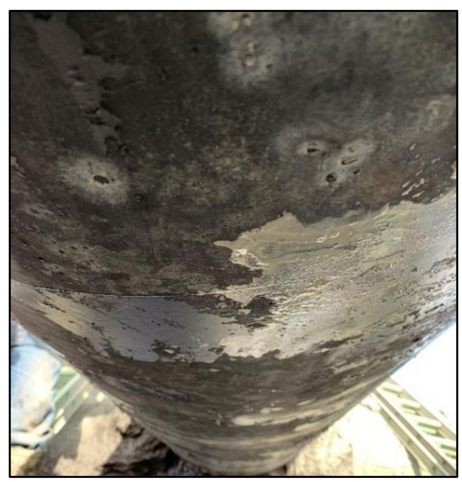

Figure 3-6: Moisture trapped on underside of pipe, MP 27.5276.

3.2.2 MP 29.52

Moderate disbondment and wrinkling was observed at MP 29.52, localized primarily on the sides of the pipe at the 3 o'clock and 9 o'clock positions as seen in Figure 3-7 and Figure 3-8. As stated in Section 3.2, this is typically attributed to the friction and weight of the soil "pulling" the coating down upon backfill of the pipeline.

Figure 3-7: Moderate coating disbondment, MP 29.52

Figure 3-8: wrinkling disbondment at 9 o'clock position, MP 29.52.

Minor lacerations were observed on the exposed section of pipeline coating, and minor tenting disbondment was noted along the long seam as seen in Figure 3-9 and Figure 3-10 respectively. Much like at MP 27.5276, moisture was trapped along the bottom of the pipe due to water ingress between the pipe steel and coating at disbondment locations.

Figure 3-9: Minor lacerations in coating, MP 29.52

Figure 3-10: Tenting along pipe seam, MP 29.52

3.2.3 MP 80.4655

Similar to MP 27.5276 and MP 29.2, the coating at MP 80.4655 was in fair condition, considering its age. However, a gash was observed at the 9 o'clock position (Figure 3-11 and Figure 3-12) and a large disbonded patch was observed at the 1 o'clock position (Figure 3-13 and Figure 3-14), both of which resulted in bare steel being exposed to the soil. Tenting was visible along the longitudinal pipe joint seam (Figure 3-13), and there was significant axial wrinkling observed at the 3 o'clock and 9 o'clock positions (Figure 3-11), typically attributed to the friction and weight of the soil upon backfill. This is commonly observed on PE wrapped pipelines of this vintage. Upon coating removal, no through wall defects were observed, and some moisture was found trapped on the underside of the pipe.

Figure 3-11: Axial wrinkling pattern along the 9 o'clock position, MP 80.4655.

Figure 3-12: Coating damage at 9 o'clock position, MP 80.4655.

Figure 3-13: Tenting disbondment along pipe seam, MP 80.4655.

Figure 3-14: Disbonded coating at 1 o'clock position, MP 80.4655.

3.3 Pipe Surface and Laser Scan

The pipe surface was sandblasted and inspected visually. No through wall defects were observed at any of the three sites. The laser scan results, including the range pit depth range and corresponding remaining wall thicknesses are summarized in Table 3.3, while the complete reports can be found in Appendix D. All site pictures taken can be found in Appendix C.

Table 3.3: Summarized laser scan data.

Site Location	# of Features	Nominal Wall Thickness (mm)	Maximum Penetration Depth (mm)			Remaining Wall Thickness (%)		
			Deepest	Shallowest	Average	Minimum	Maximum	Average
MP 27.5276	84	7.5	2.32	0.75	1.00	69.1%	90.0%	86.7%
MP 29.52	2	8.0	0.94	0.83	0.89	88.2%	89.6%	88.9%
MP 80.4665	8	7.4	0.61	0.43	0.51	91.8%	94.2%	93.1%

Wall thickness values of 7.5 mm, 8.0 mm, and 7.4 mm were measured for the three sites, all of which are greater than the expected 7.14 mm for this segment of Enbridge Line 3 per PARSC 015 [1]. These fall within acceptable wall thickness tolerances for API 5L line pipe, although given the vintage, it is difficult to ascertain the true nominal wall thickness of the segments without additional material details. For all calculations based on field data, the measured values listed above were taken as nominal wall thickness.

3.3.1 MP 27.5276

Upon visual inspection of the pipe surface, pitting corrosion was observed along the sides of the pipeline near the 3 o'clock and 9 o'clock positions (see Figure 3-14), however was not limited to those locations. The most severe corrosion was found to be along the exposed girth weld as seen in Figure 3-15, matching the location of the mud-like substance uncovered beneath the coating.

Figure 3-14: Clustered pitting corrosion and wall loss along girth weld, MP 27.5276

Figure 3-15: Wall loss near girth weld at 9 o'clock position, MP 27.5276

A total of 84 features were identified for MP 27.5276. From Table 3.3, it can be seen that the greatest maximum pit depth was found to be 2.32 mm (CLS13) near the girth weld, corresponding to 69.1% RWT. The types of features observed at MP 27.5276 ranged from clustered features with larger areas of wall loss, and 'pinole' features with higher depth-to-surface area ratios. The concentration of features of high surface area along the girth weld may be an indication of corrosion by a mechanism other than pitting alone, such as microbiologically-influenced corrosion (MIC). Figure 3-16 shows clusters of features along the girth weld, along the sides of the pipeline, and other dispersed locations on the surface.

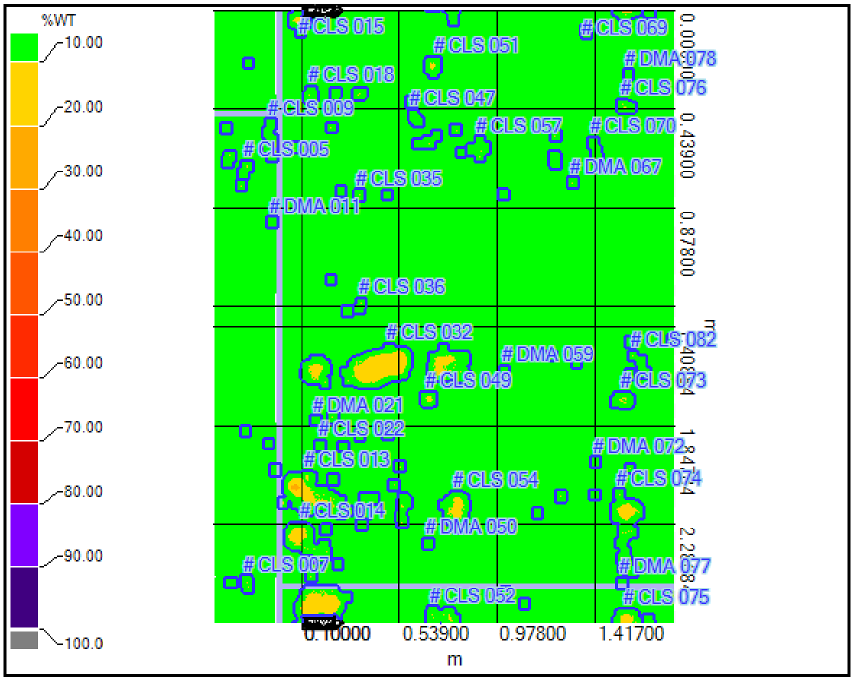

Figure 3-16: Overview of laser scan results, MP 27.5276.

3.3.2 MP 29.52

Corrosion was observed visually to a lesser degree at MP 29.52 as compared to MP 27.5276. Some pitting was dispersed along the sides of the pipeline as seen in Figure 3-17, however did not register on the laser scan as the depth at no point exceeded the critical factor threshold of 10% wall loss. Some shallow pitting corrosion was observed near the seam at the 12 o'clock position as seen in Figure 3-18.

Figure 3-17: Pipe surface, 9 o'clock position, MP 29.52.

Figure 3-18: Corrosion features at 12 o'clock position, MP 29.52

Negligible corrosion was observed along the bottom of the pipeline, despite water entrapment beneath coating on the underside of the pipe. Two features were measured near the seam at the 12 o'clock position in Figure 3-19. Negligible general wall loss was observed visually, and the nominal wall thickness was measured as 8.0 mm.

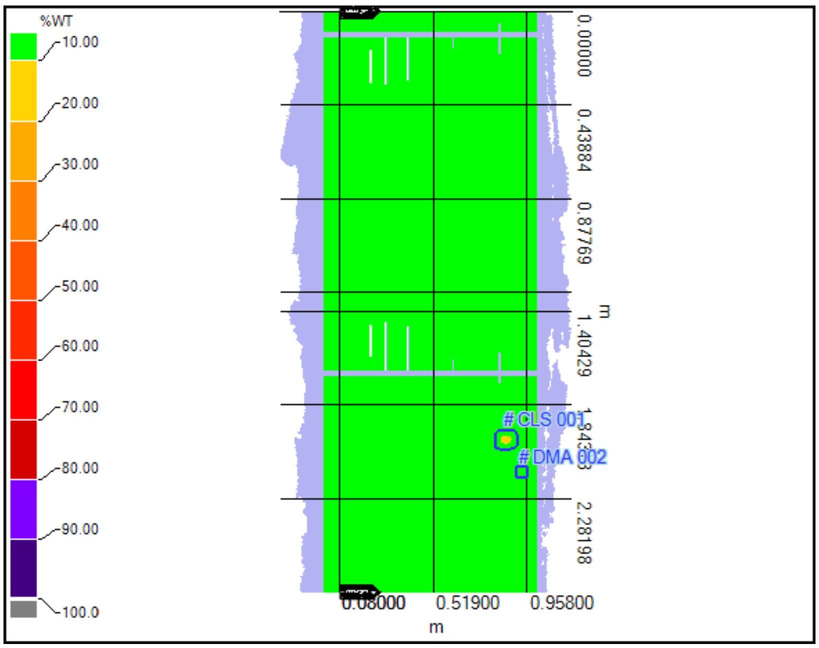

Figure 3-19: Overview of laser scan results, MP 29.52.

3.3.3 MP 80.4655

After sandblasting, little evidence of corrosion was detected visually. A minor grouping of pits were noted along the 9 o'clock position, corresponding with the coating disbondment location.

Figure 3-20: Pipe surface at 9 o'clock position, MP 80.4655.

Figure 3-21: Minor pitting at 9 o'clock position, MP 80.4655.

Figure 3-22: Pipe Surface at 3 O'clock Position

The nominal wall thickness was measured to be 7.4mm. A total of 8 features were identified for MP 80.4655. From Table 3.3, the greatest maximum pit depth was found to be 0.61 mm (Feature #5), corresponding to 91.7% RWT. Figure 3-23 confirmed the cluster of minor pitting along the 9 o'clock position.

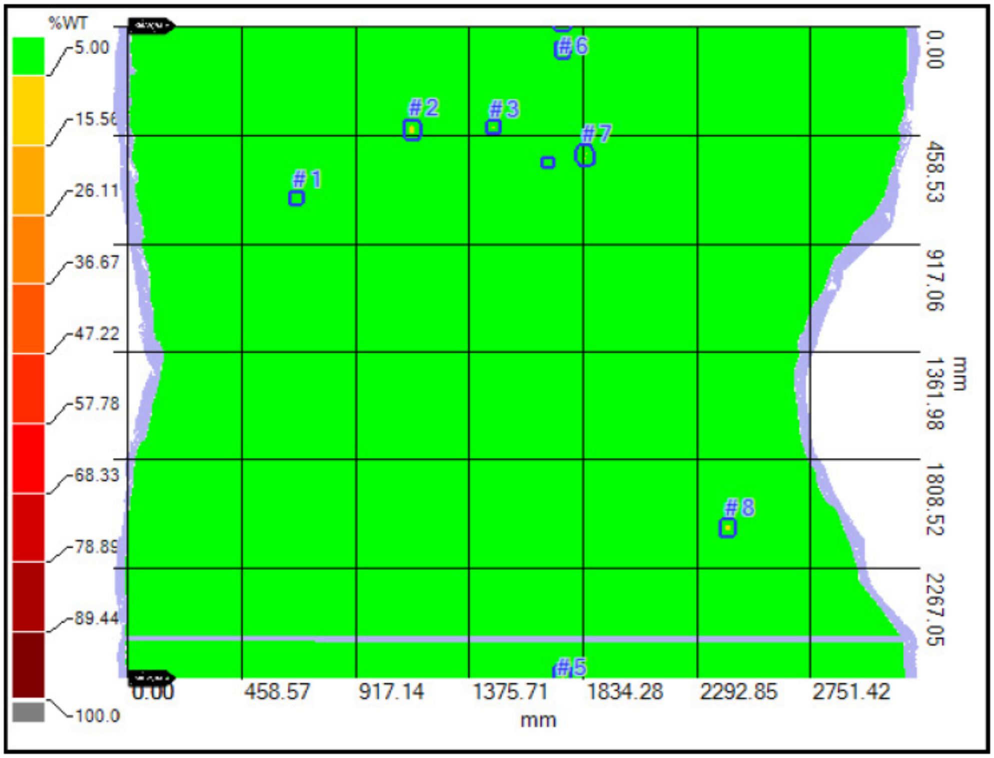

Figure 3-23: Overview of laser scan results, MP 80.4655.

There was no evidence of liquid present within the abandoned pipe section, indicating that there is no through-wall corrosion in the vicinity. The pipe was heated and hoarded for completion of the laser scanning, and no condensation or temperature discrepancy was noted across the pipe circumference. The temperature gradient between the top and bottom of the pipeline was less than 1°C.

4.0 MODEL COMPARISON

4.1 Soil Subsidence

As discussed in Section 3.1, no soil subsidence nor loss of structural integrity via through-wall penetration was observed at any of the three sites for Enbridge Line 3.

The model for soil collapse in PARSC 001 assumes 100% infill of soil into the pipeline void space. Based on this, the formula for predicting soil subsidence depth is given as [2]:

$$S = \frac{(2C+D)-\sqrt{(2C+D)^2-\pi D^2}}{2} \quad \textit{(Equation 2)}$$

where:

S = Soil Subsidence Depth (m)
C = Depth of Cover (m)
D = Pipe Diameter (m)

For the NPS 34 (864 mm OD) Enbridge Line 3, the predicted soil subsidence depth for various depths of cover is shown in Figure 4-1.

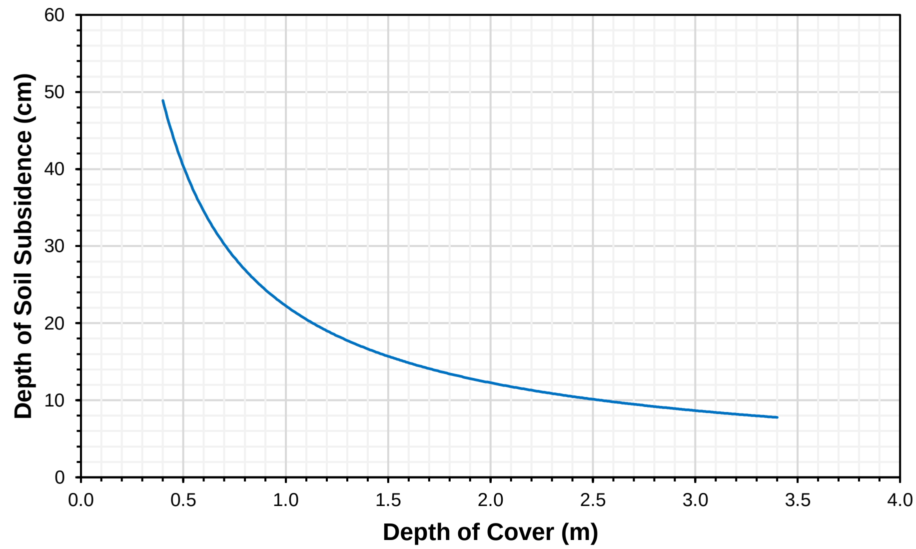

Figure 4-1: Predicted soil subsidence depth for NPS 34 pipe.

From Figure 4-1, it is shown that for a depth of cover of 1.2 m (estimated for MP 27.5276, MP 29.52, and MP 80.4655), the predicted soil subsidence is approximately 19 cm. It is unclear whether this would be differentiable form natural deviations in terrain upon visual inspection. More precise surveying techniques, such as LiDAR mapping may be required to evaluate the degree of soil subsidence in areas with typical depth of cover. Note that in areas of shallower depth of cover, the predicted soil subsidence significantly increases to greater than 40 cm for NPS 34 pipe, which would likely be evident upon visible inspection.

Soil subsidence, through wall defects nor soil infill were observed at MP 27.5276, MP 29.52, or MP 80.4655 for Enbridge Line 3. Therefore, it is difficult to validate the PARSC 001 soil collapse model from the collected observations, as the model is contingent on collapse of the pipeline and soil infill. Controlled subsidence testing is also recommended to generate some data to compare against the model predictions.

4.2 Pipe Coating

As stated in PARSC 001, it is estimated that "the area of disbonded coatings is of the order of 1% of the pipe surface," which corresponds to 1% of the pipe surface corroding. Note that this does not specify the type of coating, nor does it take into account degradation over time [2].

From visual inspection of the coating and pipe surface, it is clear at all three sites that greater than 1% of the coating experienced disbondment, wrinkling patterns, lacerations, or tenting. At MP 27.5276 specifically, it is evident that greater than 1% of the surface experienced corrosion.

To investigate this quantitatively, the area of each feature can be estimated as an ellipse, with major and minor axes corresponding to axial and circumferential length. Note that while this approximation is effective at estimating the corroded area of "regular" features, the area of "irregular" or clustered features may be overestimated using this technique as shown in Figure 4-2, and provides conservatism in the estimation.

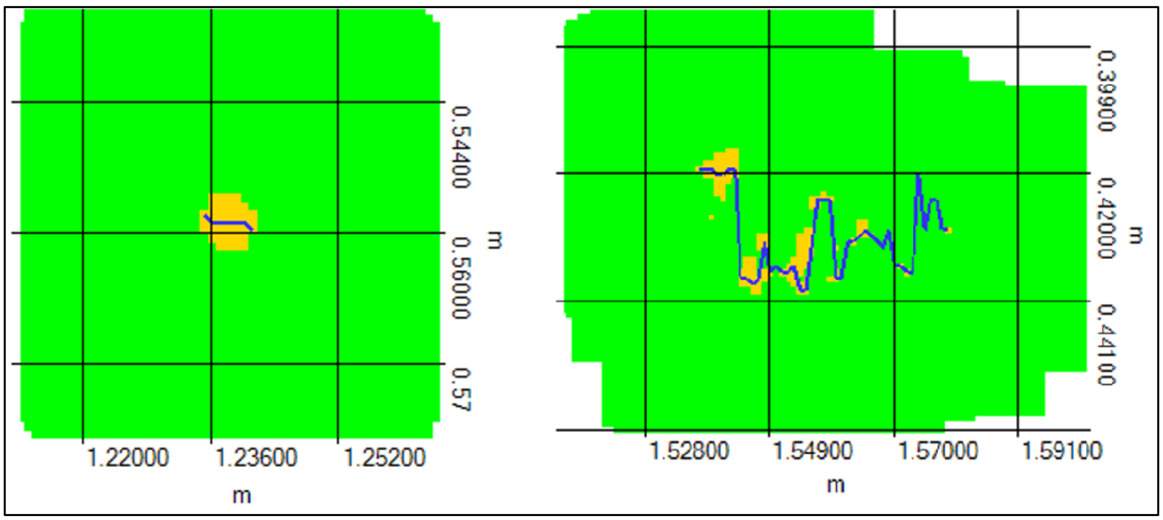

Figure 4-2: Laser scan of regular (left, DMA 65) and irregular (right, CLS 76) features.

The total area of corrosion at each location can be estimated as the sum of the total feature surface area, and represented as a percentage of the total area scanned. The results for each site are shown in Table 4.1, along with the qualitative observations of the coating condition.

Table 4.1: Estimation of corroded area and corresponding coating inspection results.

Site Location	# of Features	Condition of Coating	Total Area Scanned (cm^2)	Estimated Feature Surface Area (cm^2)	Estimated Corroded Area (%)
MP 27.5276	84	• Moderate general wrinkling, circumferential direction • Very little adhesive remaining beneath coating	56098	10773	19.20%
MP 29.52	2	• Moderate wrinkling, axial direction, mostly along sides of pipeline • Minor breaks/lacerations	27140	17	0.06%
MP 80.4665	8	• Severe localized disbondment/laceration • Moderate wrinkling, axial direction, localized along side of pipeline	54280	28	0.05%

From Table 4.1, MP 27.5276 had significantly higher corroded area than at either MP 29.52 or MP 80.4655, which matches what was observed visually. It is evident that greater than 1% of the area was disbonded at all three sites, which does not match the calculated corroded area in Table 4.1. Sites MP 80.4655 and MP 29.52, which had worse localized coating disbondment than MP 27.5276, experienced significantly less corroded area comparatively.

One potential reason for this discrepancy is that PE tape wrap commonly experiences wrinkling, which under suitable conditions can shield the pipeline from CP allowing localized corrosion. Lacerations in the coating, such as what was observed at MP 80.4655, have been known to allow penetration of CP current to the pipeline, preventing corrosion at disbonded locations. For reference, holidays as small as 2 mm in diameter have been shown to begin allowing CP to penetrate PE coating 2 mm in thickness [5].

Note that at MP 27.5276, there was less coating adhesive remaining than at MP 29.52 or MP 80.4655. This may be an indication of additional disbondment not detected upon visual inspection of the coating exterior. The cause of this would likely be related to the coating application.

The orientation of the wrinkling observed was primarily in the circumferential direction at MP 27.5276. Conversely, the wrinkling was localized along the 3 and 9 o'clock positions at MP 29.52 and MP 80.4655 in the axial direction and accompanied by lacerations. The latter is typically what is expected for PE tape wrap and attributed to the weight and friction of the soil upon backfill. It is recommended that additional subsurface assessment be completed on abandoned pipelines with other types of coating, such as fusion-bonded epoxy (FBE) and tar-asbestos wrapping, to further refine the 1% disbonded coating estimate discussed in PARSC 001.

4.3 Wall Penetration

The penetration coefficient for each feature was calculated by rearranging Equation 1, using maximum pit depth and elapsed time from a 1980 abandonment year. Table 4.1 summarizes the calculated penetration coefficients for the three sites. The deepest pit at each site was used for the calculations, as it is of interest to determine the earliest time in which water or soil may enter the pipeline due to through-wall corrosion. Refer to Appendix D for the calculated values for each feature.

Table 4.1: Maximum calculated penetration coefficients (k_p) for abandoned Enbridge Line 3.

Site Location	# of Features	Nominal Wall Thickness (mm)	Deepest Feature (I.D.)	Penetration Depth (mm)	Remaining Wall Thickness (mm)	*Time Since Abandonment (yr)*	Penetration Coefficient, k_p (mm/√yr)
MP 27.5276	84	7.50	CLS 013	2.32	5.18	40	0.37
MP 29.52	2	8.00	CLS 001	0.94	7.06	40	0.15
MP 80.4665	8	7.40	#5	0.61	6.79	40	0.013

These “upper bound” values can be re-insterted into Equation 1 to predict the time to through wall penetration, this time using a nominal wall thickness of 7.14mm to better represent a typical case for Enbridge Line 3. These are compared in Figure 4-3 to the upper bounds for the ‘good’ and ‘very poor’ soils as provided by the NBS soils data.

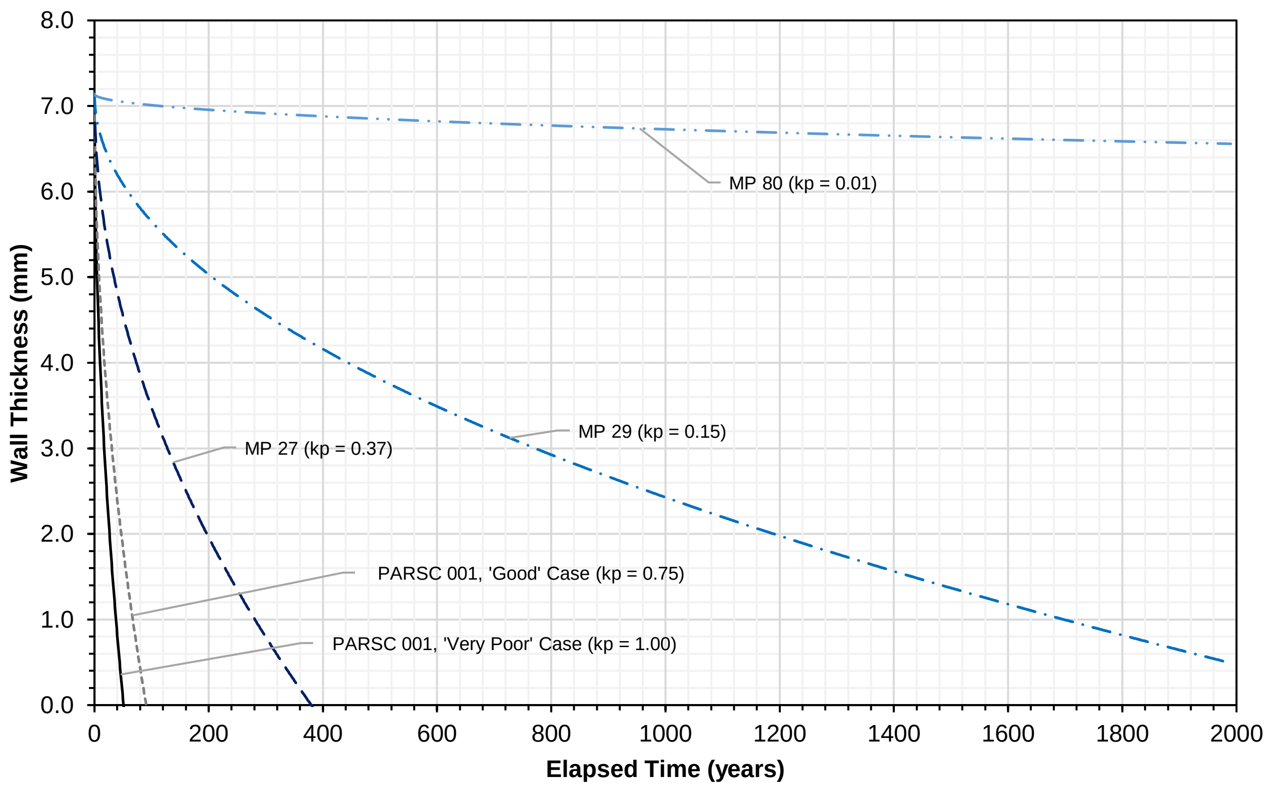

Figure 4-3: Predicted time to through-wall penetration for various penetration rates (k_p).

As seen in Figure 4-3, the NBS models from PARSC 001 indicate that through wall penetration would occur in 51 years for the soils with ‘very poor’ to ‘fair’ drainage (k_p = 1.00, see Table 2.3) and 91 years for the soils with ‘good’ drainage (k_p = 0.75). The upper bounds selected from the Enbridge Line 3 data yield much longer timelines, the shortest of which being 379 years for MP 27.5276 ($k_{p,max}$ = 0.37). Given the clay soils for Enbridge Line 3 have ‘poor,’ or ‘very poor’ drainage, this would suggest that the PARSC 001 models for through-wall penetration are conservative by a factor of 2.5, and predict that the pipeline should have experienced near through-wall penetration after the 40 years that have elapsed since abandonement. This is inconsisntent with what was observed in the field. These results are applicable only for this Enbridge Line 3 case study.

Note the PARSC models are based on the pipe at disbonded locations freely corroding, which may not be the case for Enbridge Line 3. It is known that cathodic protection was maintained on the line, but it is unclear to what degree CP inhibited corrosion on Enbridge Line 3. CP shielding is a known issue for disbonded PE tape wrap, and may be the cause for the discrepancy in corrosion observed between the sites despite similar soil conditions.

4.4 Structural Integrity

To analyze the effects of corrosion on the structural integrity of the line, PARSC 001 outlines a "Combined Corrosion Rate and Structural Integrity" model in which the load bearing capacity of the pipeline is estimated. This can be done either as a function of the wall thickness over time assuming uniform corrosion (mass loss), or at a moment in time using the "Swiss Cheese" model where areas of corrosion are assumed to be through-wall [2].

The combined corrosion and structural integrity modelling in PARSC 001 utilize Equations 3 and 4 below to estimate the load bearing capacity of the pipeline for plastic and elastic collapse respectively, with the lower calculated value being limiting [2]:

$$P_{cap,\,plastic} = \frac{2\pi C^2}{3F'} \cdot \left[\left(\frac{\sigma_{yield}}{4E} \right) \cdot \left(\frac{2R}{t} \right) \cdot \frac{(EI)_{eq} + 0.06E'R^3}{LKR^3} - P_{soil} \right] \qquad \textit{(Equation 3)}$$

$$P_{cap,\,elastic} = \frac{2\pi C^2}{3F'} \cdot \left[\frac{1}{FS} \sqrt{32 R_w B' E' \frac{(EI)_{eq}}{D^3}} - P_{soil} \right] \qquad \textit{(Equation 4)}$$

where:

$P_{cap,\ plastic}$	= Load Bearing Capacity for Plastic Collapse (N)
$P_{cap,\ elastic}$	= Load Bearing Capacity for Elastic Collapse (N)
F'	= Impact Factor due to live loads (~1.0 to 1.75)
σ_{yield}	= Yield Strength of Pipe Steel (Pa)
E	= Modulus of Pipe Steel (Pa)
R, D	= Radius of Pipe, Diameter of Pipe (m)
$(EI)_{eq}$	= Equivalent Stiffness of Pipe Wall per Unit Length (Pa·m^4/m), dependent on wall thickness.
E'	= Modulus of Soil Reaction (Pa)
L	= Lag Factor (~1.5)
K	= Bedding Constant (~0.1)
P_{soil}	= Soil Load (Pa)
R_w	= Water Buoyancy Factor (if water table is above pipeline)
B'	= Empirical Coefficient of Elastic Support
FS	= Factor of Safety (2.5 or 3.0)

Because Enbridge Line 3 is coated, and the evaluated locations have experienced negligible general wall loss since abandonment, the more suitable approach described above would be to assume full wall penetration in areas of corrosion. The baseline load bearing capacity of Enbridge Line 3 was first calculated assuming the following:

- Nominal wall thickness of 7.14mm, and no general corrosion or pitting.
- The pipeline was constructed using the trench and backfill method.
- The soil conditions were assumed to be coarse-grained clay with little or no fines, compacted to AASHTO relative 90%.
- Depths of cover of 1.2m for all sites.
- Pipe coating has negligible contributions to stiffness.
- Dry density of soil of 1818 kg/m^3 [6].

The resulting baseline load bearing capacity for 864mm Enbridge Line 3 was found to be 172.3 kPa. This then must be adjusted to account for the loss of integrity due to areas of full wall loss. Using the estimated corroded area from Table 4.1 for each site, the adjusted load bearing capacity is seen in Table 4.2.

Table 4.2: Adjusted load bearing capacity (kPa) for each Enbridge Line 3 site.

Site Location	Estimated Corroded Area (%)	Adjusted Load Bearing Capacity (kPa)
MP 27.5276	19.20%	139.2
MP 29.52	0.06%	172.2
MP 80.4665	0.05%	172.2

Note while this method conservatively estimates the instantaneous capacity of the pipeline to bear live loads, such as commercial vehicles or farm equipment, it is not beneficial in estimating this capability over time as the coating and pipeline degrade. To predict the load bearing capacity over time assuming uniform corrosion, mass loss coefficients (k_{ml}) must be utilized, as PARSC 001 assumes the pipe is freely corroding. Uniform mass loss rates can be extrapolated from the corrosion feature data using two different methods:

(a) Utilizing the estimated surface area of the pitting, and known volume lost.

(b) Utilizing the calculated penetration rates for the features, and corresponding theoretical penetration ratios listed in Table 2.3.

For Method (a), the summed volume lost for of all features was divided by the estimated surface area of the identified features from Table 4.1, which yields an "average uniform wall loss." This can be used to estimate the uniform mass loss coefficient using Equation 1, as seen in Table 4.3 for each site.

Table 4.3: Estimated mass loss rates for each Enbridge Line 3 site, Method (a).

Site Location	Estimated Feature Area (cm^2)	Volume Loss (mm^3)	Average Uniform Wall Loss (mm)	Estimated Mass Loss Coefficient, $k_{ml,max}$ (mm/√yr)
MP 27.5276	10773	74975	0.070	0.01
MP 29.52	17	1327	0.770	0.12
MP 80.4665	28	877	0.314	0.05

The predicted critical loading over time based on the estimated mass loss rate, using Equations 1, 3, and 4, for Method (a) is shown in Figure 4-4 and compared to the predictions based on the NBS soils criteria, as well as typical live loads such as a personal truck, highway traffic, and railway loads transferred to the pipe per PARSC 001 [2].

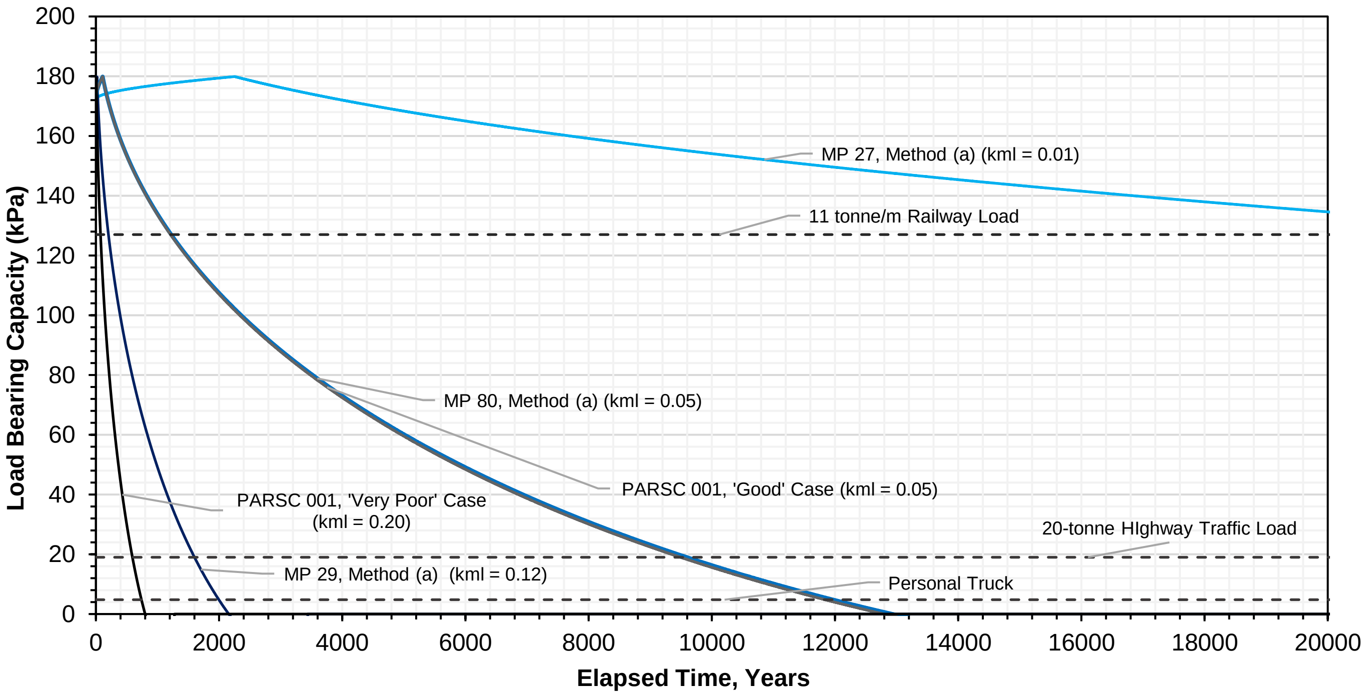

Figure 4-4: Predicted critical loading over time, Method (a).

From Figure 4-4, The PARSC 001 models predict a complete loss of load bearing capacity in approximately 1,200 years for soils with ‘very poor’ drainage (k_{ml} = 0.20), and approximately 20,000 years for soils with ‘good’ drainage (k_{ml} = 0.05). The estimated data using Method (a) yields timelines ranging from 3,200 years to beyond 20,000 years. Once again assuming the soils for the Enbridge Line 3 sites are considered to have ‘poor’ or ‘very poor’ drainage, Figure 4-4 suggests that PARSC 001 models are conservative by a factor of 1.5. Due to the experimental relationship between P_{cap} and T, this results in much longer timelines for loss of load bearing capacity. Note the timeframes estimated are only used for comparative purposes based on the theoretical models in PARSC 001. In reality, it is not expected the pipeline will sustain load on the order of hundreds to thousands of years.

Note that these estimates do not account for time for the coating to deteriorate, which would occur prior to the pipeline freely corroding in all areas at mass loss rates. Based on the results using Method (a), the timelines to pipeline collapse due to general wall loss are greater than those predicted in Section 4.3 for full wall penetration. When through wall penetration occurs, soil and/or water infill is likely, which may lead to localized or general wall loss on the inner wall of the pipe. This is not accounted for in the PARSC 001 models and would likely contribute to accelerated corrosion rates and decline in structural integrity. Further field testing is recommended to account for the change in corrosion conditions upon through wall penetration and infill of soil and water.

For Method (b), a penetration ratio of 5 was selected, as field observations indicated the soils had 'very poor' drainage. Using the upper bounds for k_p calculated in Section 4.3, values for k_{ml} were estimated and are shown in Table 4.4.

Table 4.4: Estimated mass loss rates for each Enbridge Line 3 site, Method (b).

Site Location	Calculated Penetration Coefficient, $k_{p,max}$ (mm/√yr)	Penetration Ratio	Estimated Mass Loss Coefficient, $k_{ml,max}$ (mm/√yr)
MP 27.5276	0.37	5	0.07
MP 29.52	0.15	5	0.03
MP 80.4665	0.013	5	0.003

The critical loading over time is again predicted, this time based on the estimated mass loss rate found using Method (b). These results are shown in Figure 4-5.

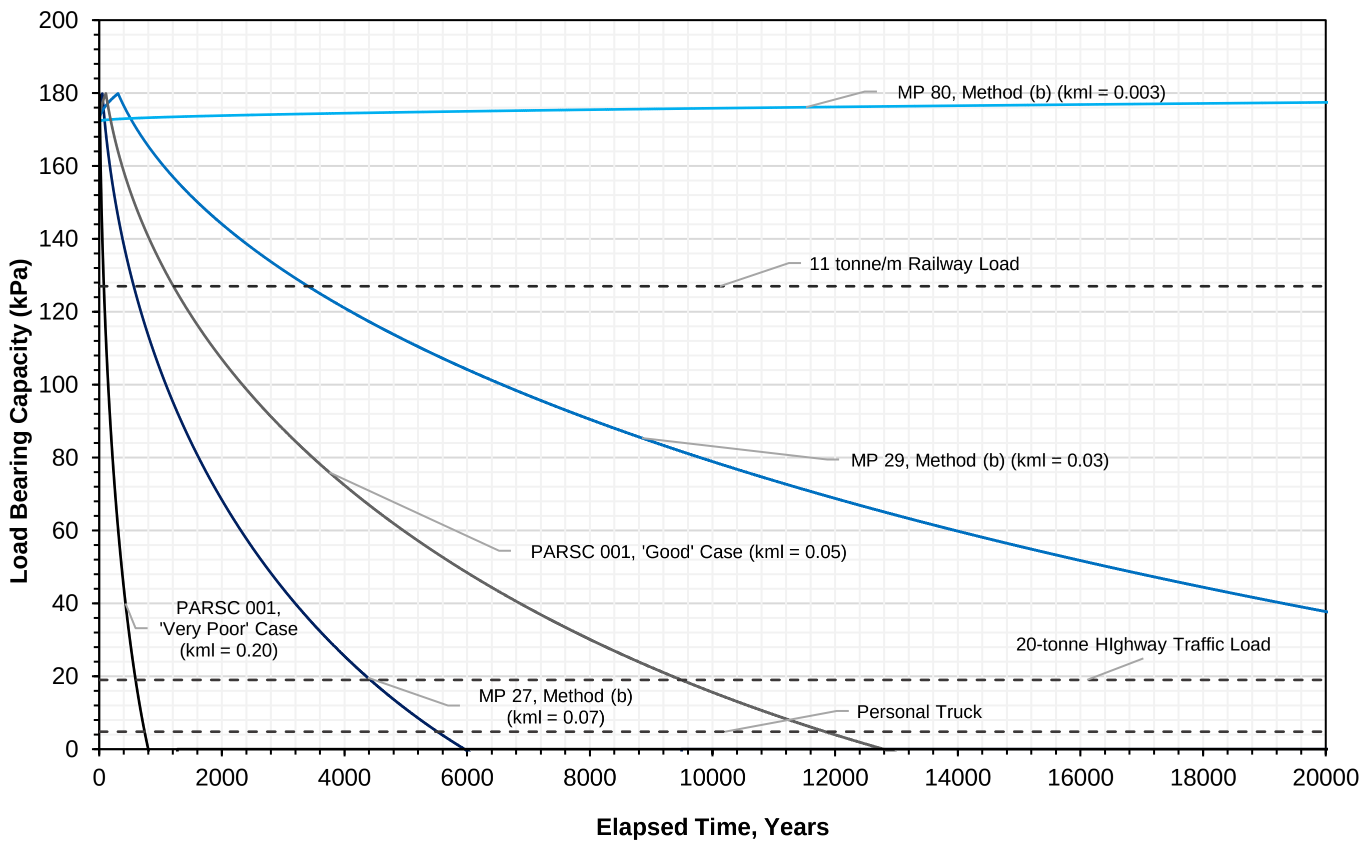

Figure 4-5: Predicted critical loading over time, Method (b).

The upper bound load bearing capacity predictions using Method (b) yield a similar result to that of Method (a), being that the timelines for the Enbridge Line 3 are significantly longer than the model predictions for comparable soil conditions. This suggests the PARSC model predictions of mass loss rates are conservative by a factor of 2.5. As was the case with Method (a), the timelines to pipeline collapse using Method (b) are far greater than those predicted in Section 4.3 for full wall penetration. Note this comparison was made assuming that areas of corrosion were fully shielded from cathodic protection. This analysis also shows that the predictions based on the field data yield much longer timelines for susceptibility to collapse from a typical load, such as a personal truck, as compared to the theoretical mass loss rates from PARSC 001. It is important to note that is not realistic to expect the pipeline to maintain its structural integrity on the order of thousands or years, and thus the results found in this analysis are used for comparative purposes only.

Note the discrepancy in timelines between the mass loss coefficients at each site using methods (a) and (b). One possible reason for this is the feature geometry, as the ellipse approximation for surface area is more effective at estimating the area of “regular” features.

As discussed in Section 4.3, it is unknown to what extent cathodic protection inhibited the corrosion at disbonded coating locations, and is likely the cause of the discrepancy in corrosion severity between the sites despite similar soil conditons. This will require further investigation, which will aide in validating the findings of this investigation in comparisons to the PARSC 001 models.

5.0 CONCLUSIONS

The scope of PARSC 017 included the evaluation of three sites along abandoned Enbridge Line 3, including visual inspection of the soil conditions, pipeline coating, pipe surface, and collection of corrosion feature measurements. Following comparison between the field-collected data and model-predicted outcomes of pipeline abandonment provided in PARSC 001 for soil subsidence, pipe coating disbondment, pipeline corrosion, and structural integrity, the following conclusions are presented for Enbridge Line 3 under PARSC 017:

1. No soil subsidence, contamination, nor through wall penetration was observed at any of the three sites, and therefore it is difficult to validate the soil collapse model in PARSC 001. There was no evidence of water present within the abandoned pipe sections, indicating that structural integrity has been maintained since abandonment.
2. The PE tape wrap coating was found to be in overall good condition for its vintage, with minor holidays, damage, and tenting. Moderate circumferential and axial wrinkling patterns were observed, causes of which are likely related to the coating application and backfill of the pipeline. From visual inspection, greater than 1% of the pipe coating was disbonded at all three sites.
3. Pitting corrosion features were identified and measured at all three sites, with remaining wall thickness ranging from 69% to 94%. The pitting was generally clustered along the sides of the pipelines, with the exception of MP 27.5276, where high-surface area corrosion features were found clustered along the exposed girth weld. This corresponded with primarily circumferential wrinkling disbondment observed at MP 27.5276. This may be an indication of a mechanism such as MIC taking place and may warrant further investigation.
4. The estimated area of corrosion does not correlate with degree of disbondment observed. MP 27.5276 experienced moderate, atypical disbondment patterns and the most severe corrosion, while MP 29.52 and MP 80.4655 experienced significantly less corrosion and typical wrinkling disbondment and lacerations seen on PE tape wrap coatings. This discrepancy is likely due to the cathodic shielding effect, and holidays of a critical size allowing penetration of the CP current.
5. Penetration and mass loss rates, calculated from the corrosion feature data, suggest the PARSC 001 corrosion modelling is conservative by factors ranging from 1.5 - 2.5 times, resulting in predicted timelines for structural integrity loss on the order of hundreds to thousands of years, and are used for comparative purposes only. Note this analysis was completed assuming that areas of corrosion were fully shielded from cathodic protection.
6. Loss of structural integrity is more likely to occur through pit coalescence than general wall loss. This is expected given the pipeline is coated (with areas of disbondment). Predicted timelines for integrity loss due to uniform corrosion are contingent on significant degradation or disbondment of the PE coating and removal of the cathodic protection system currently in place. Note that soil and water infill upon through-wall penetration would likely accelerate corrosion, and therefore negatively impact the long-term structural integrity of the pipeline.
7. Overall, the models for corrosion and structural integrity outlined in PARSC 001 are conservative. Abandoned Enbridge Line 3 has maintained its structural integrity to greater degree than the PARSC 001 models predict despite corrosive soil conditions and moderate coating damage and disbondment.

6.0 RECOMMENDATIONS

Based on the analysis and conclusions provided, the PARSC models for corrosion and structural integrity were found to be conservative. The following recommendations would further benefit the study of pipeline conditions post-abandonment:

1. **Additional Field Assessments:** Subsurface evaluation of a greater sample size of abandoned pipelines (Enbridge Line 3 or otherwise) is recommended to further evaluate the accuracy of the model predictions presented in PARSC 001. Particular items of interest include:
    a. Corrosion model comparisons for additional pipeline segments with corrosion similar to that found at MP 27.5276 along the girth weld. The high surface area features discovered indicates that corrosion mechanisms other than pitting corrosion may be present.
    b. Penetration rates for coated pipelines at disbonded and exposed areas, both with and without cathodic protection to further evaluate the effects of CP shielding.
    c. Refined estimates of disbonded coating area, including other lines coated with PE tape wrap, as well as other coatings such as FBE or tar-asbestos wrap.
    d. Trends regarding disbondment orientation (specifically for PE tape wrap), presence of holidays, and corrosion area and depth.
    e. Risk assessments for soil and water infill upon through-wall penetration, including corrosion model development or refinement to account for the changing corrosion conditions as water and soil enter the pipe.
2. **Soil Analysis:** Laboratory analysis of soils would aide in characterizing the corrosion models and corroborate the NBS data. Soil composition, resistivity, moisture content, microbial content, and electrolyte content are valuable assets.
3. **Controlled Subsidence Testing:** The predicted timelines for structural integrity loss are on the order of hundreds to thousands of years, which makes it difficult to observe gradual subsidence in the field. Simulating subsidence for various soil types and pipe sizes in a controlled environment will aide in further refinement of the soil collapse models and applied to field inspections.
4. **Materials Testing:** Pipe ring samples should be extracted and analyzed to investigate potential modes of failure and corrosion, such as stress corrosion cracking (SCC).

7.0 REFERENCES

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