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Investigation of Internal Corrosion Mechanisms of a Pipeline with Specified Parameters: Application of Various Mitigation Strategies

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Abstract

Herein, the internal corrosion mechanisms of a pipeline with the given construction and operational parameters are evaluated using iFILMS® software. The initial output of the software revealed that the only corrosion mechanism for this pipeline is Microbiologically Influenced Corrosion (MIC). The unmitigated results showed that the corrosion rate of the pipeline was 0.2 mm/y, which is considered corrosive. Also, the remaining wall percentage in unmitigated condition was 84.86 %, whereas time to failure was 13 years. Using proper mitigation strategies, the corrosion rate decreased up to 0.04 mm/y, with the remaining wall percentage of 98.18 % and time to failure rate of 110 years.

1. Introduction

According to Natural Resource Canada, the pipeline inventory in Canada is approximately 825,000 km, of which about 25,000 km are gathering lines, 25,000 km are feeder lines, 100,000 km are large diameter transmission lines and 450,000 km are local distributions lines. About 10 percent of the Canada's pipelines, which are primarily large transmission pipelines, are regulated by the federal government, while the remaining are regulated provincially [1–3].

The oil and gas industry's goal is to reach "zero failure". Some of the items that contribute to this goal are as follows [4]:

- Implementation of cost-effective methods to control corrosion,
- Accurate monitoring of corrosion rates at various stages of infrastructure,
- Maintenance of corrosion control strategies for the entire duration o the infrastructure,
- Incorporation of industry best practices and standards in corrosion management.

The 5-M methodology can help industry to reach the mentioned "zero failure" goal. The 5-M methodology includes five individual elements of modeling, mitigation, monitoring, maintenance, and management. In simple words, corrosion is the "enemy" and we should all fight against it. Internal and external corrosion are the main threats to pipelines. Cathodic protection and coatings are some of the external corrosion control strategies [2]. Internal corrosion, however, is the main contributing factor to pipeline failures [4].

In this report, internal corrosion of a pipeline is investigated using iFILMS® software. The pipeline length is about 100 m with the outer diameter (OD) of 114.3 mm and the wall thickness of 3.96 mm. The operational parameters of the pipeline are summarized in Table 1.

Table 1: Operational parameters of the pipeline

Parameter	**Unit**	**Value**
Data collection date	**mm/yyyy**	06-2012
Oil flow rate	**m^3/d**	782
Water flow rate	**m^3/d**	39.108
Gas flow rate	**m^3/d**	40
Temperature	**°C**	23
Total pressure	**kPa**	984
pH_2S	**mol %**	0
pCO_2	**mol %**	0
Sulfur	**g/m^3**	0
Sulfate	**g/m^3**	0
Bicarbonate	**g/m^3**	0
Chloride	**g/m^3**	0
Acetic acid	**g/m^3**	0
Solid	**g/m^3**	0

Transmission pipelines are large lines (typically 6-48 inches in diameter) and operate at high pressures of 1380 to 10350 kPa. However, distribution lines that deliver natural gas to homes and businesses usually operate at lower pressures. The size of distribution pipelines can range from 12.7 mm to 152.4 mm [5,6]. According to the operational parameters, the pipeline in this study seems to be a distribution pipeline. Also, based on the following criteria and operational parameters, it can be said that this pipeline is multiphase (option c). [PR=production rate]

$$a)\ \left(\frac{PR_{Oil}}{PR_{Oil}+PR_{Water}+PR_{gas}}\right) > 0.95 \qquad Single-phase\ oil$$

$$b)\ \left(\frac{PR_{gas}}{PR_{Oil}+PR_{Water}}\right) > 5000 \qquad Single-phase\ gas$$

$$c)\ None\ of\ the\ above \qquad Multiphase$$

The pipeline herein was constructed in January 1994. In June 2020, our consulting company became in charge of the pipeline, and this will continue until December 2022. Dates are selected only for the matter of writing this report. It should be mentioned that the KPIs related to Measurement, Maintenance, and Management could not be evaluated due to the lack of information and data.

2. Internal Corrosion - Model

The American Petroleum Institute Specifications (API SPEC) 5L provides standards for different types of pipes, such as conveying gas, water, and oil in the natural gas and oil industries. This addresses seamless and welded steel line pipe for pipeline transportation systems in the petroleum and natural gas industries [7].

According to the data in iFILMS®, the grade X52 carbon steel that falls under API 5L was selected for the pipeline in this report, which seems to be a good choice. The chemical composition of this alloy is shown in Table 2. This data was taken from the iFILMS® software, composition tab. The X52 pipe can be manufactured seamless or welded, and it is widely used in the transportation of petroleum and natural gas. Different manufacturer websites show that this pipe can be made through hot rolling or cold drawing procedures. Two product specification levels (PSL), PSL1 and PSL2 can be explained for the X52 grade pipe. The PSL2 has better mechanical properties with small difference in the chemical composition. However, both PSL1 and PSL2 pipes are used for oil, water, and gas transportation. The PSL2 grade also has a high yield strength that can stand the high temperature and pressure conditions [8,9]. The aforementioned are confirmed by the API 5L specifications [7].

Table 2: Chemical composition of API 5L X52 carbon steel, taken from iFILMS®

Element	**Fe**	**C**	**Mn**	**P**	**S**	**Si**	**V**	**Pb**	**Ni**	**Cr**	**Cu**	**Mo**	**Al**	**Nb**	**Ti**	**W**	**Sn**	**B**	**Co**	**Zr**
Wt.%	98.31	0.20	1.0	0.012	0.007	0.28	0.010	0.010	0.020	0.016	0.007	0.030	0.043	0.010	0.011	0.020	0.0013	0.005	0.004	0.002

Fig. 1 shows the pipe length vs. water accumulation. It is known that the water accumulation areas are potential locations for corrosion [4]. According to Fig. 1, water accumulation occurs on the following distances along the pipeline length:

1- ~ 14-30 m
2- ~ 42-48 m
3- ~ 58-67 m
4- ~ 71-81 m
5- ~ 95-98 m

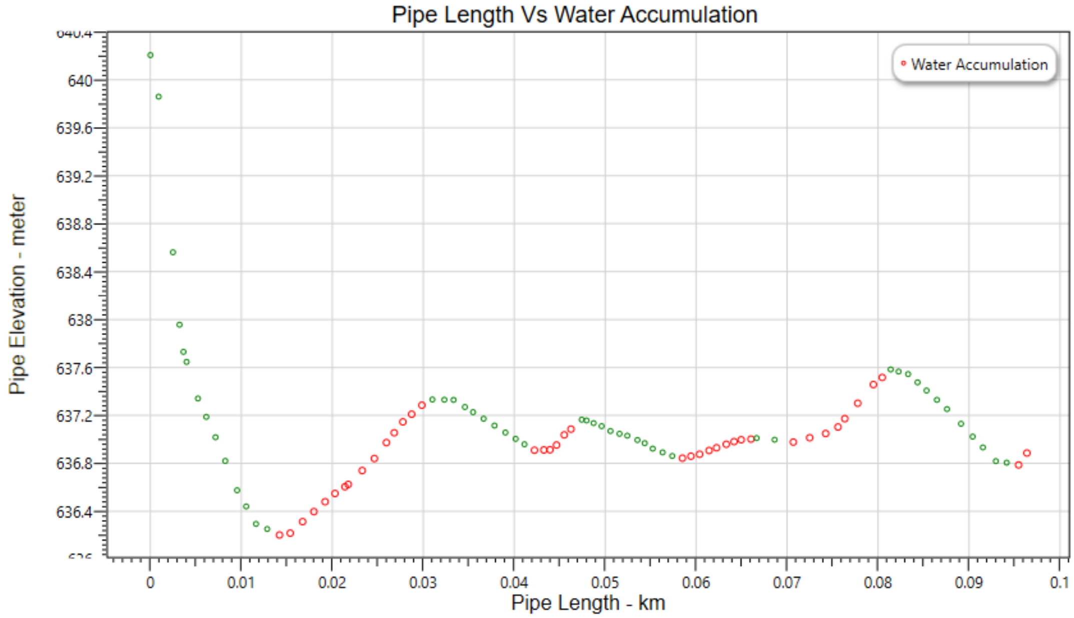

Figure 1: Pipe length (km) vs. pipe elevation (m)

It is expected to see the corrosion at water accumulated areas. Fig. 2 shows that the only corrosion damage mechanism (CDM) in this pipeline, based on the operational parameters, is Microbiologically Influenced Corrosion (MIC). As expected, this type of corrosion (MIC) occurred on the water accumulation areas.

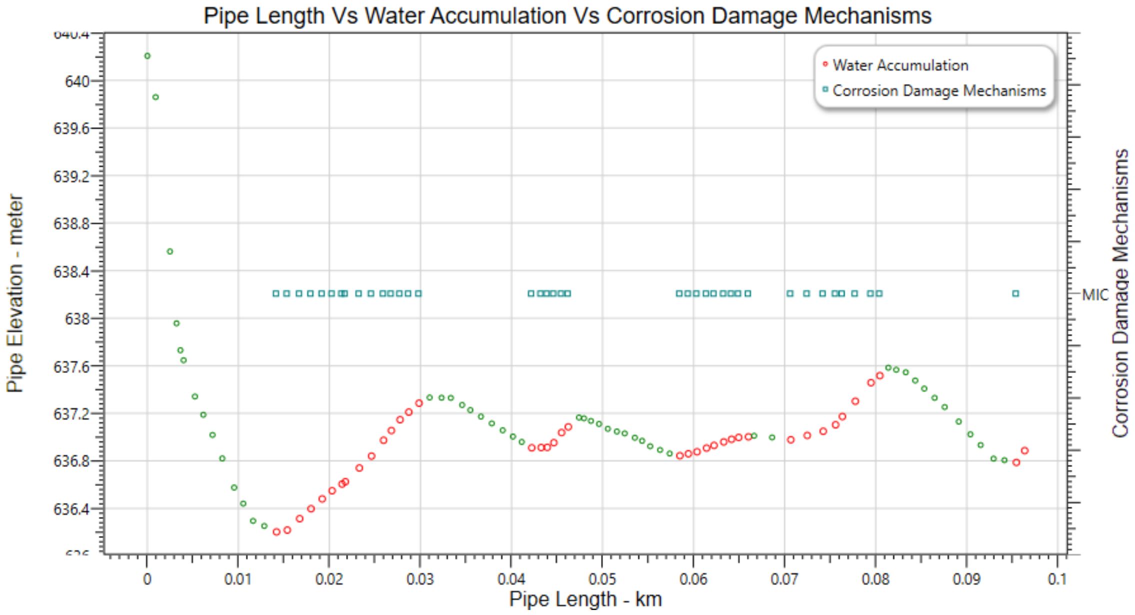

Figure 2: Pipe length (km) vs. pipe elevation (m) and CDM

As a result of water accumulation and presence of other required factors, MIC would occur and in turn, it can result in localized corrosion, which can lead to pit formation or pitting corrosion (PC). The stagnant flow inside the pipeline can exacerbate this situation. Also, pitting corrosion is one of the corrosion damage mechanisms which is normally seen in the pipelines, where water accumulates [4]. Using iFILMS® software, Pitting Corrosion Rate (PCR) of the pipeline was evaluated and are shown in Fig 3. As expected, the PC was seen at water accumulated areas. The maximum PCR was estimated to be around 0.3 mm/y. In the industry, normally the corrosion rates less than 0.1 mm/y are considered as non-corrosive conditions. Therefore, anything above the 0.1 mm/y represents the corrosive condition [4,10].

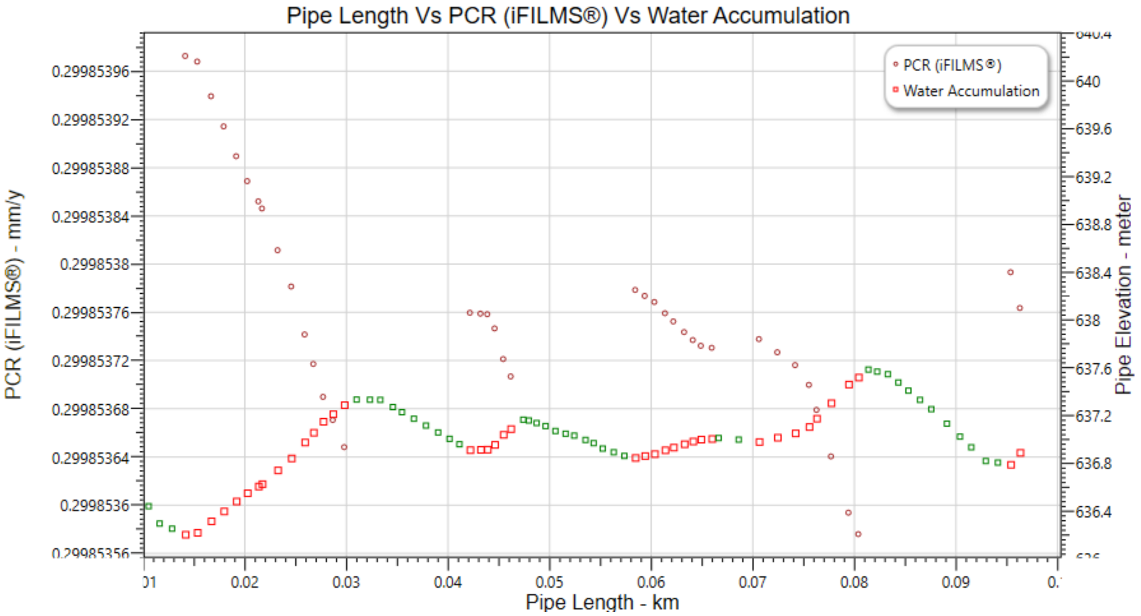

Figure 3: Pipe length (km) vs. PCR (mm/y) and pipe elevation (m)

Fig. 4 shows the PCR values and CDM (which is MIC), along the length of the pipeline. According to the extracted data from iFILMS®, MIC occurs in 40 locations, of which 15 are high priority corrosion locations. More details about these locations are provided in Appendices (section 5.2). The unmitigated remaining wall percentage (RWP) is 84.86%, whereas the time to fail (TF) for the pipeline is 13 years.

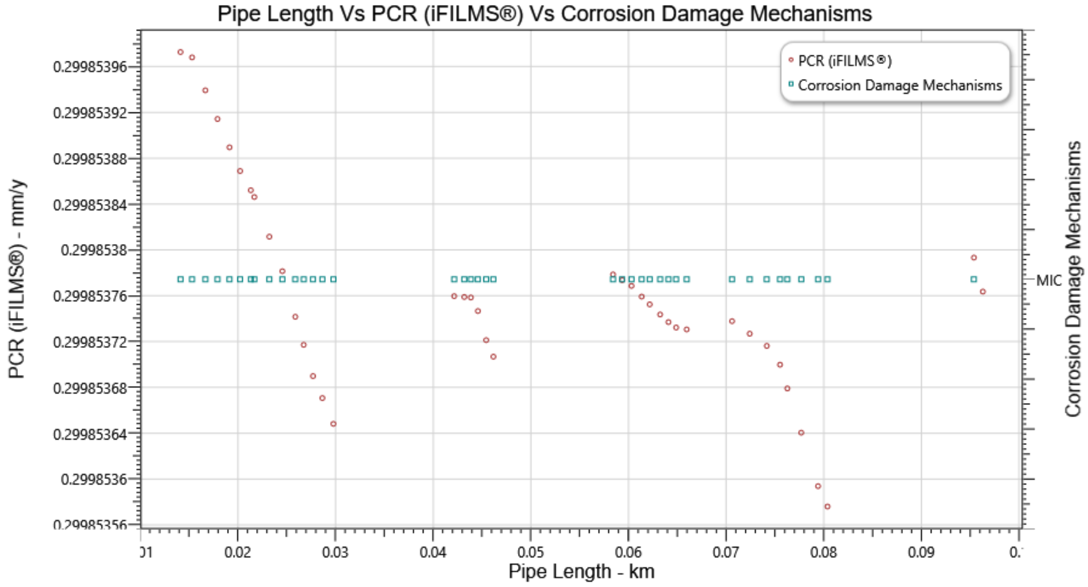

Figure 4: Pipe length (km) vs. PCR (mm/y) and CDM

Fig. 5. shows the pipe length vs. wall loss percentage and PCR. It can be seen from Fig. 5 that the pitting corrosion degrades the pipeline wall about 15% by time. The PCR higher than 0.1 mm/y, and 15% wall loss are valid reasons to consider an appropriate mitigation strategy to control the corrosion that resulted in this amount of wall loss and corrosion. Fig. 5 also shows that the wall loss occurred at the distances where the MIC happened (overlapped green and red points).

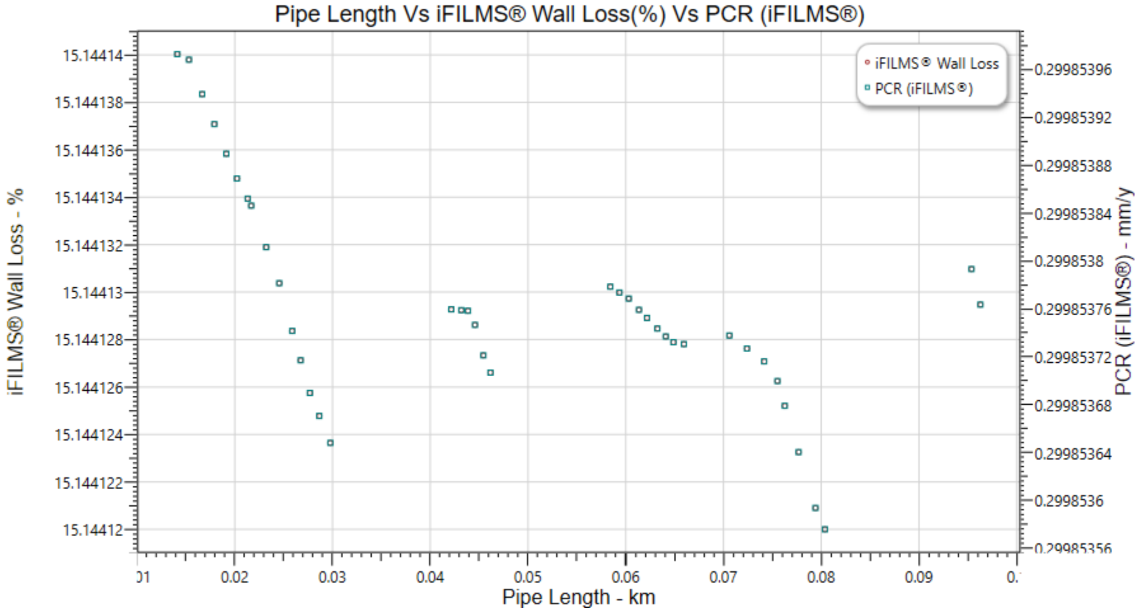

Figure 5: Pipe length (km) vs. wall loss (%) and PCR (mm/y)

Fig. 6 shows the flow regime along the length of the pipeline. According to the iFILMS® results, flow types of Slug & Bubble, Stratified, and Dispersed are seen along the various locations of the pipeline. The type of flow regime can be affected by operational parameters.

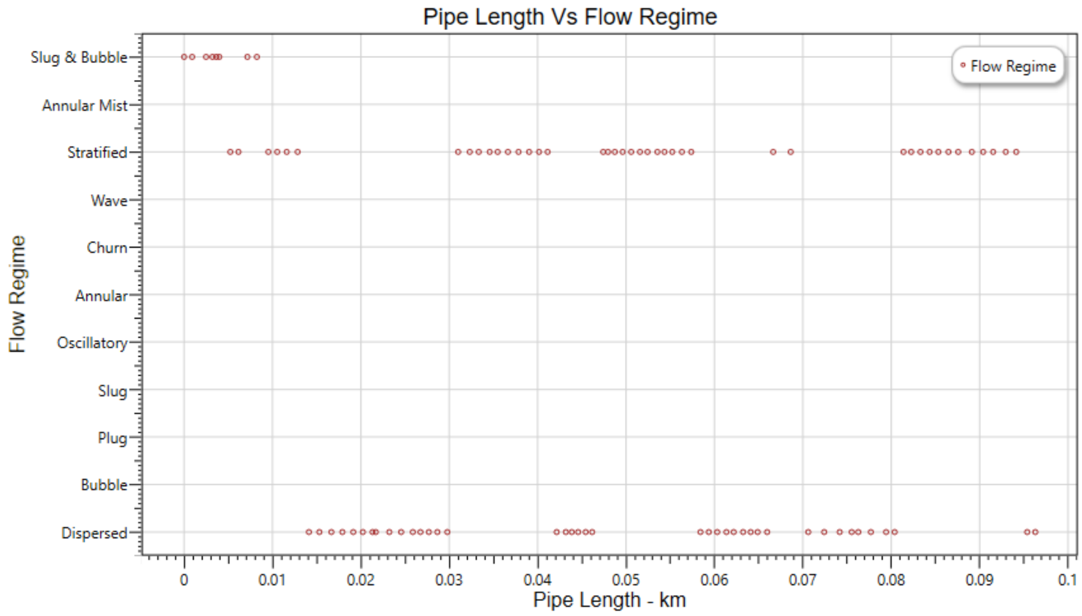

Figure 6: Pipe length (km) vs. Flow regime

3. Internal Corrosion - Mitigation

As explained in the previous section, the unmitigated corrosion rate was around 0.2 mm/y, which is considered as a corrosive condition in the industry. Therefore, suitable mitigation strategies should be applied for the corrosion prevention or improvement. Using iFILMS® software, different corrosion mitigation strategies were evaluated, solely and mixed with other, to study their effect on the corrosion rate. It should be noted that not all the frequencies for each method were tested due to financial considerations. That is, it was assumed that it might not be economically viable to use mitigation strategies frequently with a very short interval in between investigations. For the sake of consistency, figures related to this section are attached to Appendices. It should also be noted that the continues inhibitor and internal coating strategies were not considered due to the lack of data and information. Also, considering the current pipeline being in service, the internal coating mitigation strategy could not be applied for an in-service pipeline.

3.1. Pigging

Pigging (cleaning) was first studied with a frequency of more than a year. The iFILMS® output showed that the corrosion rate was decreased to around 0.15 mm/y (Fig. 7), which is still considered as corrosive (higher than 0.1 mm/y). Next, the yearly pigging option was selected and the iFILMS® output showed that the PCR decreased to about 0.12 mm/y (Fig. 8), which is closer to the threshold of the corrosive condition. After the evaluation of the pigging option with yearly frequency, monthly pigging was tested in iFILMS® and results revealed that this option would be helpful in decreasing the corrosion rate to less than 0.1 mm/y, to reach a non-corrosive condition. Considering the monthly pigging option along the whole pipeline length, the PCR would decrease to around 0.09 mm/y (Fig. 9). More details about the pigging with different time frequencies can be found in Table 3.

3.2. Batch Inhibitor

The batch inhibitor mitigation strategy was also tested to study its effect on the PCR. The batch inhibitor with the frequency of more than a year results in a PCR of around 0.15 mm/y (Fig. 7). Also, the yearly batch inhibitor shows that the PCR decreased to about 0.12 mm/y (Fig. 8). Monthly use of batch inhibitor can decrease the PCR to around 0.09 mm/y, which meets the non-corrosive conditions (Fig. 9). More details about the batch inhibitor applied in different time frequencies can be found in Table 3. It should be noted that the results for the pigging and batch inhibitor were the same, when solely evaluated at each time frequency.

Table 3: PCR (mm/y), RWP (%), and TF (years) for solely use of pigging and batch inhibitor: More thana year, yearly, and monthly

Factor / **Type and frequency**	**Pigging or Batch Inhibitor (solely)**			
	More than a year	**Yearly**	**Monthly**	**Biweekly**
PCR (mm/y)	0.15	0.12	0.09	0.06
Remaining Wall, Percentage	92.43 %	93.94 %	95.46 %	96.97 %
Time to fail (years)	26	33	44	66

3.3. Mixed effect

To study further the effect of combined mitigation strategies on the corrosion rate of the pipeline, pigging and batch inhibitor strategies were selected. The iFILMS® results showed that the yearly pigging and batch inhibitor can decrease the PCR to around 0.05 mm/y (Fig. 10), which is the least value that was obtained so far, compared to the sole use of either batch inhibitor or pigging. Moreover, yearly pigging and monthly batch inhibitor can decrease the PCR to around 0.03 mm/y (Fig. 11). Considering all the scenarios, with one and two mitigation strategies, the last scenario of yearly pigging and monthly batch inhibitor seems to be effective to decrease the corrosion rate to less than 0.1 mm/y, even with the safety factor of 0.5 [2].

It should be noted that the pigging and batch inhibitor with lower frequency of application was not studied due to the monetary considerations. Table 4 summarises the details on PCR (mm/y), RWP, and TF for each of the evaluated scenarios. Fig. 12 also shows that using the proper mixed mitigation strategy, the wall loss percentage can be decreased from 15% (RWP=85%) to around 1.81% (RWP=98.18%).

Table 4: PCR (mm/y), RWP (%), and TF (years) for mixed use of pigging and batch inhibitor: More thana year, yearly, monthly, and mixed

Type and frequency / Factor	**PCR (mm/y)**	**RWP (%)**	**TF (years)**
Pigging and batch inhibitor, more than a year	0.07	96.21 %	53
Pigging and batch inhibitor, yearly	0.05	97.58 %	83
Pigging and batch inhibitor, monthly	0.03	98.64 %	147
Yearly pigging and monthly batch inhibitor	0.04	98.18 %	110

4. Internal Corrosion – Monitoring

Corrosion monitoring techniques should be used to ensure the material and mitigation strategies continue to be effective. Industry uses inspection techniques to monitor the internal corrosion and to ensure the mitigation strategies are correctly in place. Ultrasonic, Magnetic flux leakage (MFL), and Electromagnetic-Eddy current are some of the inspection techniques. The advantage of the mentioned techniques is that they are non-intrusive, meaning that the application of these techniques would not disturb the internal flow of the pipeline because they are applied on the external surface. The other advantage is that they can measure the corrosion rate of the structure. Also, since these inspection techniques are non-destructive, they can be used repeatedly. Due to the relatively short length of the pipeline in this study, the application of at least one of the inspection methods at high priority corrosion locations would be beneficial. Also, the application of a proper monitoring strategy doesn’t seem to be expensive since the pipeline is relatively short with only 15 high priority corrosion locations. More data and information are required to plan the monitoring strategies in detail. It should also be mentioned that the "reliability of measurement" or "data confidence of monitoring data" are very critical. Therefore, important business decisions should not be made based on the limited or incorrect data.

5. Summary

The internal corrosion was studied in this report using the 5-M methodologies and iFILMS® software. It was found that the water accumulation occurred at five different distances along the 100 m pipeline. The water accumulation areas are the potential locations for corrosion. MIC was observed as the active corrosion mechanism of the pipeline. In the absence of any mitigation strategies, the PCR was around 0.2 mm/y, which is regarded as the corrosive conditions. Therefore, appropriate mitigation strategies should be applied to control the corrosion of the pipeline.

In order to control MIC, microbial community should be destroyed or biofilm formation and development on metal/non-metal surfaces should be averted. Various mitigation strategies have been mentioned in the literature to prevent and control MIC, including the use of biocides as corrosion inhibitors. A biocide inhibits the biofilm formation by changing the local environment conditions in the corrosion process. Also, the use of green biocides has gained attention, due to their non-toxic, abundant, low-cost, and eco-friendly characteristics [11]. Therefore, green biocides can be considered as potential corrosion inhibitors.

Results of the iFILMS® showed that by the monthly application of pigging, PCR would decrease to less than 0.1 mm/y, which is a threshold for corrosive conditions in the industry. The batch inhibitor strategy also showed that the monthly application results in reaching to non-corrosive conditions. The mixed effect of yearly pigging and monthly batch inhibitor confirmed that the PCR could decrease to 0.0359 mm/y, which reduces the wall loss percentage to around 1.81 and improves the time to failure to 110 years.

6. Acknowledgments

The author gratefully acknowledges Professor Edouard Asselin for his support.

7. References

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Appendix A: Figures of mitigated scenarios

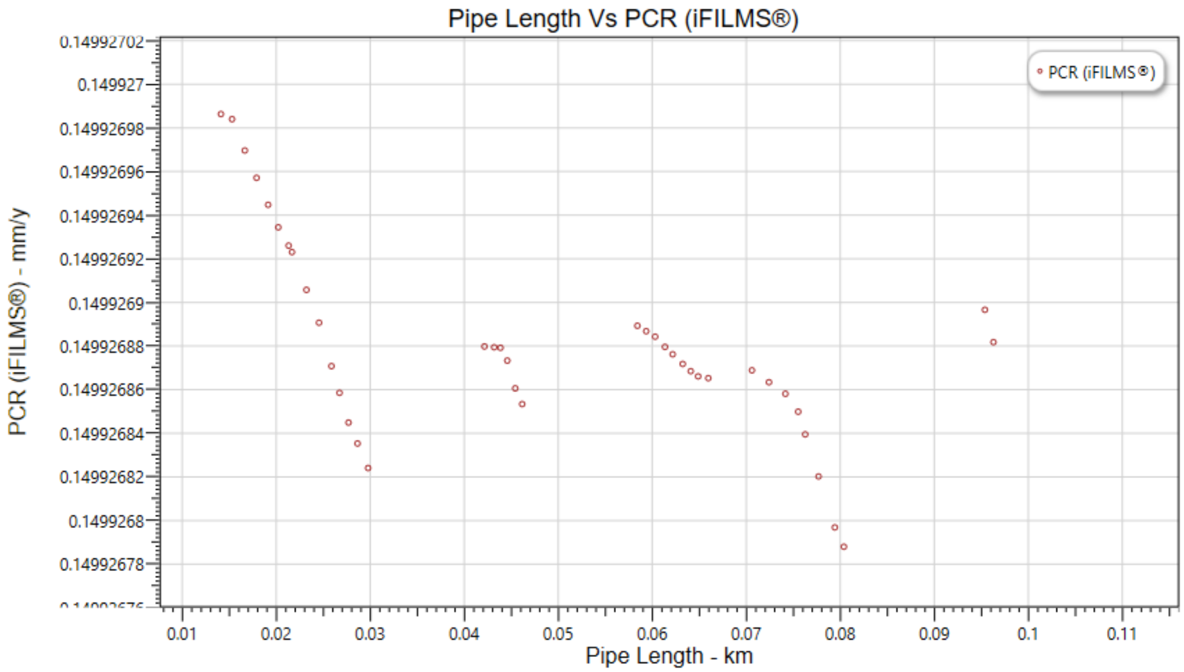

Figure 7: Pipe length (km) vs. PCR (mm/y): **Pigging or batch inhibitor, more than a year**

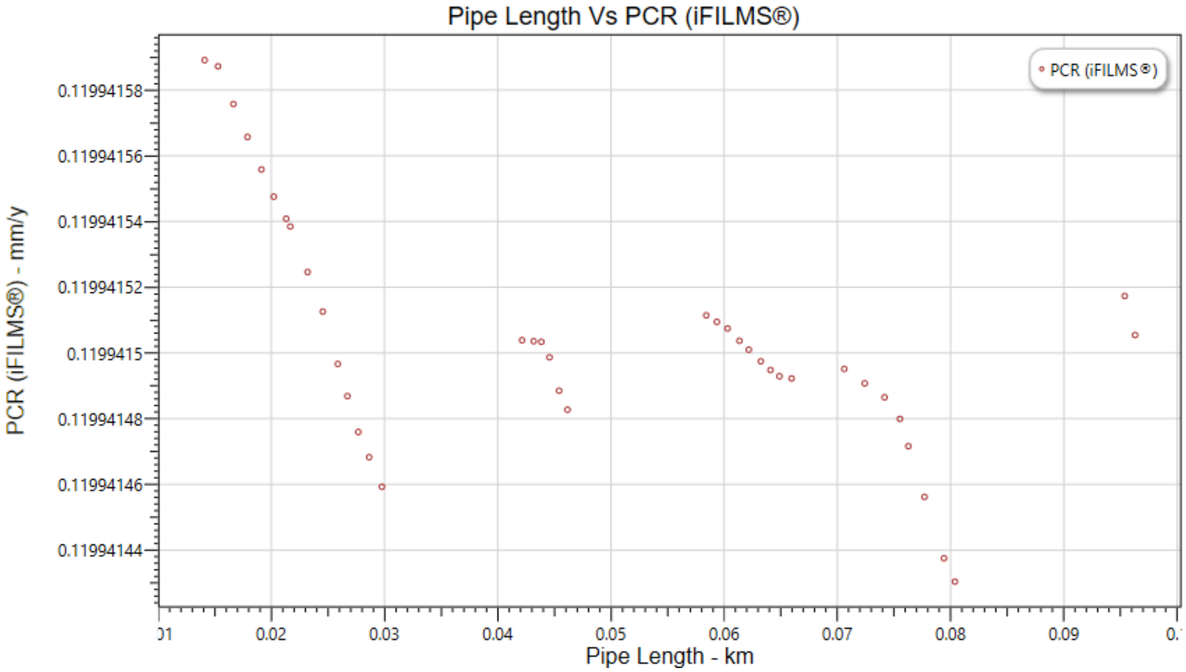

Figure 8: Pipe length (km) vs. PCR (mm/y): **Pigging or batch inhibitor, yearly**

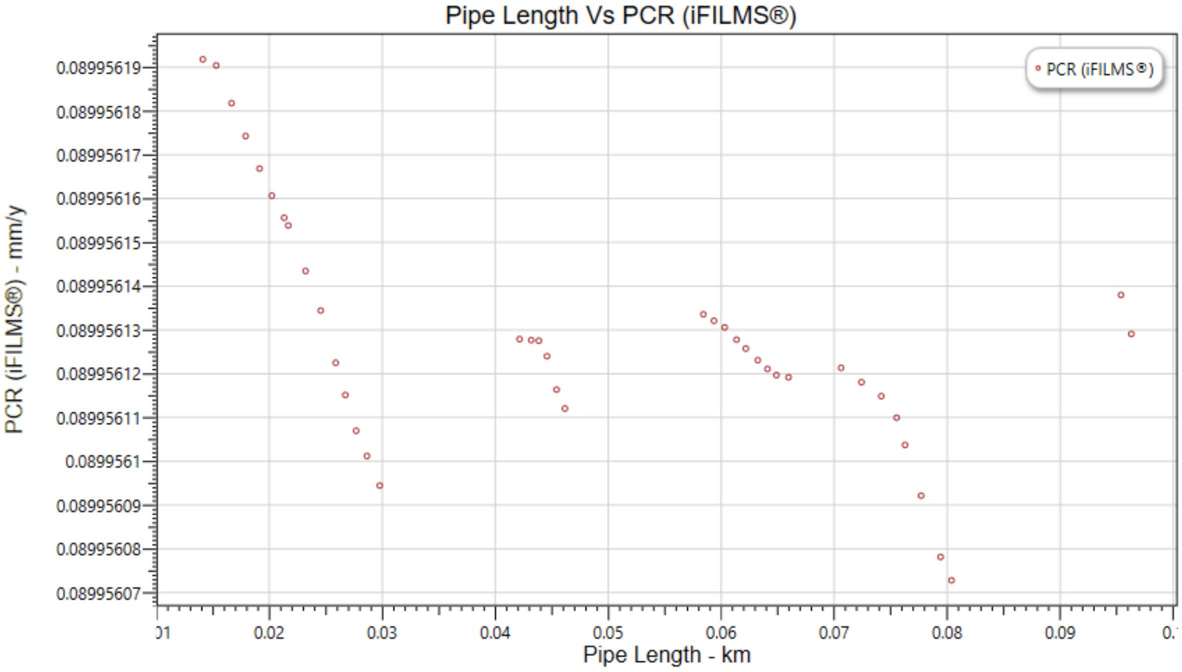

Figure 9: Pipe length (km) vs. PCR (mm/y): **Pigging or batch inhibitor, monthly**

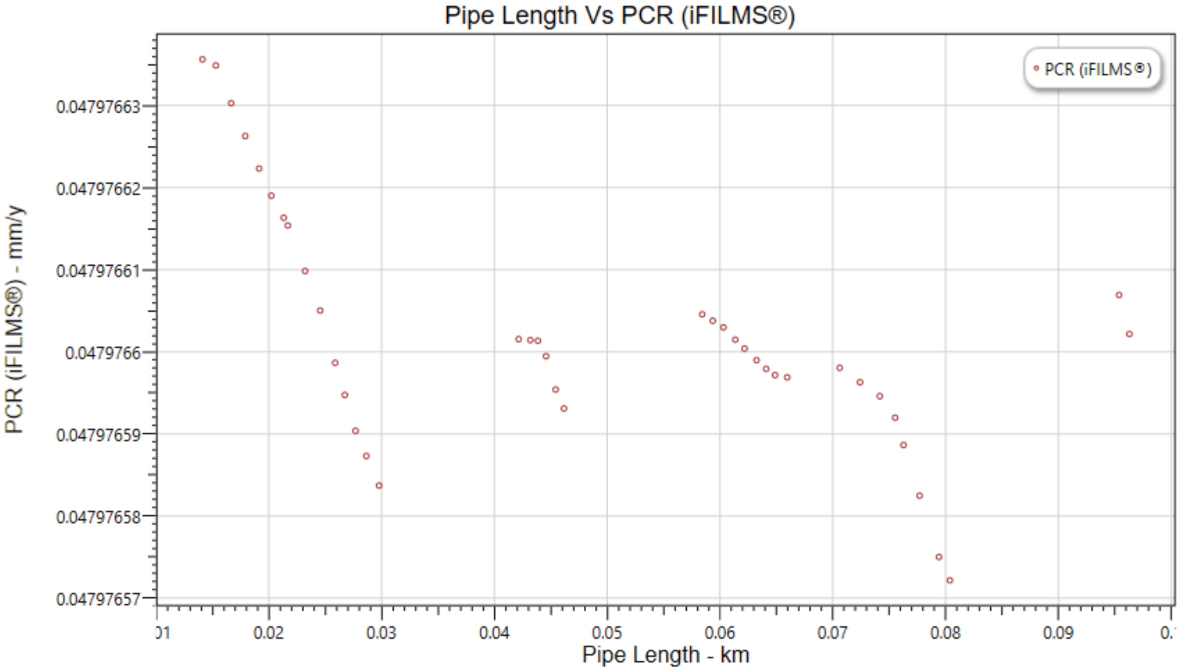

Figure 10: Pipe length (km) vs. PCR (mm/y): **Mixed yearly pigging and batch inhibitor**

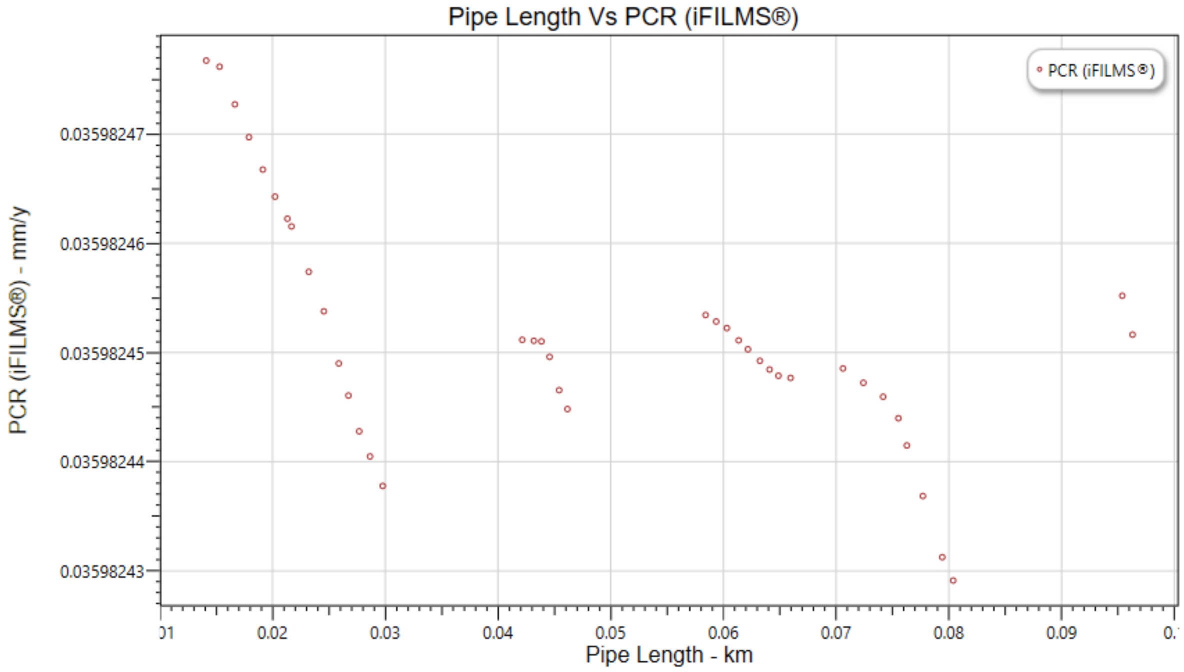

Figure 11: Pipe length (km) vs. PCR (mm/y): **Mixed yearly pigging and monthly batch inhibitor**

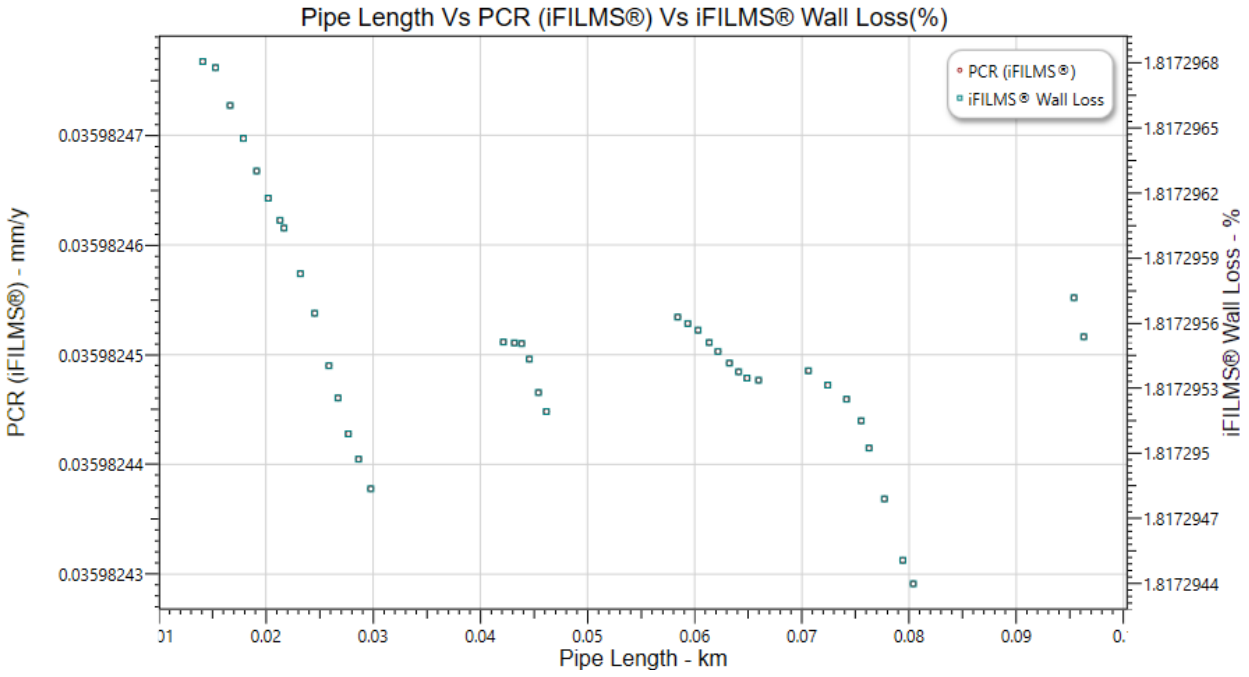

Figure 12: Pipe length (km) vs. PCR (mm/y) and wall loss (%): **Mixed yearly pigging and monthly batch inhibitor**

Appendix B: Figure and data related to unmitigated pipeline

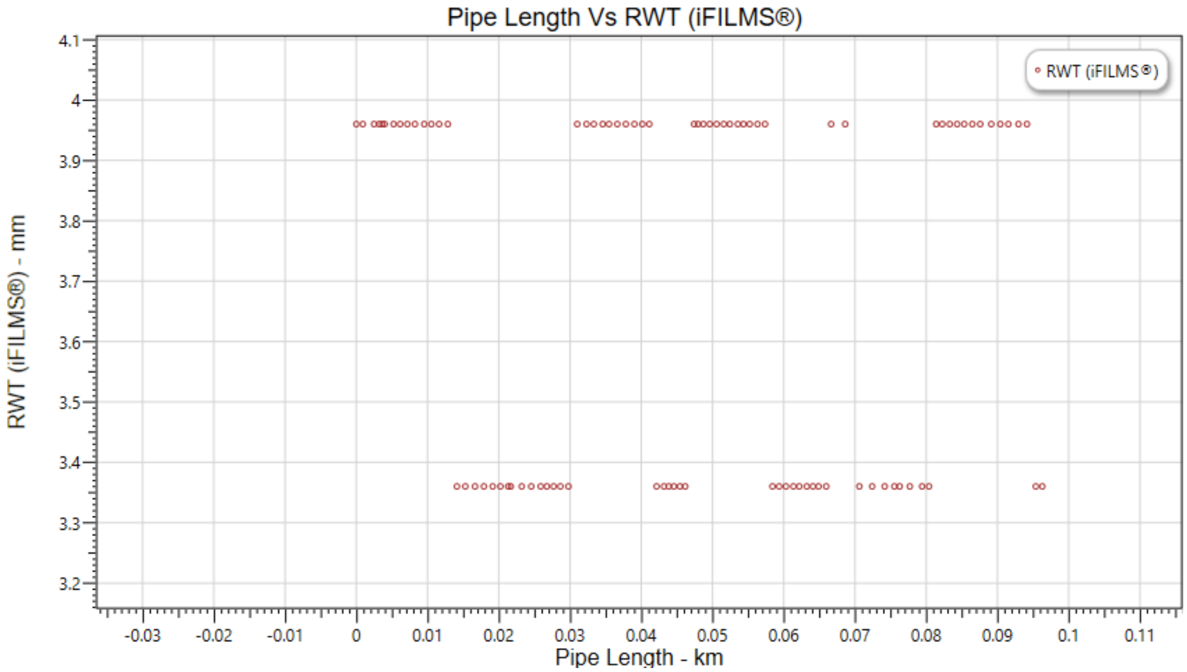

Figure 13: Pipe length (km) vs. RWT (mm): **Unmitigated pipeline**

The 15 high priority corrosion locations are summarized in the following Tables.

- Characteristics of High Priority Corrosion (HPL) Location #1:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.21 meter
Pipe length at which the feature is located	0.01412 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #2:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.22 meter
Pipe length at which the feature is located	0.0153 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #3:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.32 meter
Pipe length at which the feature is located	0.01666 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #4:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.4 meter
Pipe length at which the feature is located	0.0179 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #5:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.49 meter
Pipe length at which the feature is located	0.01913 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #6:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.55 meter
Pipe length at which the feature is located	0.02022 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #7:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.61 meter
Pipe length at which the feature is located	0.02131 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #8:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.63 meter
Pipe length at which the feature is located	0.02168 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #9:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.75 meter
Pipe length at which the feature is located	0.02321 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #10:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.79 meter
Pipe length at which the feature is located	0.09537 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #11:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.85 meter
Pipe length at which the feature is located	0.02455 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #12:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.85 meter
Pipe length at which the feature is located	0.05841 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #13:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.87 meter
Pipe length at which the feature is located	0.05935 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #14:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.88 meter
Pipe length at which the feature is located	0.0603 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		

- Characteristics of High Priority Corrosion (HPL) Location #15:

Coordinates of the location in which this corrosion feature is present	Latitude	Longitude	Elevation profile
	NA	NA	636.89 meter
Pipe length at which the feature is located	0.09629 km		
Corrosion Damage Mechanisms (CDMs)	MIC		
PCR	0.3 mm/y		
Percentage Deviation or uncertainty in PCR	0.12 mm/y		
Remaining Wall, Percentage	84.86 %		
Time to fail (from construction or operation year)	13 Years		
Remaining life	11 Years		