Validation of the AC Corrosion Criteria Based on Real-World Pipeline Measurements

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Corrosion Technical Committee

Of

Pipeline Research Council International, Inc.

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Abstract

This report refers to the activities performed in the frame of PRCI project on the refinement of the AC corrosion criteria by evaluating real-world pipeline AC corrosion cases and applying an improved AC corrosion prediction model.

The diagrams of AC corrosion likelihood assessment in the standard ISO18086:2015 was used as a starting point. Correlations between field data (especially those provided through dig reports from AC corrosion anomalies) and the simulation results for different CP polarization levels, AC induced voltage, soil conditions (texture, soil resistivity and moisture) and coating defect properties (size and thickness) were investigated.

The final goal is achieving a further refinement of the proposed AC corrosion criteria in previous project (EC-6-2) based on long-term AC corrosion behavior.
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<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ACVG</td>
<td>Alternating Current Voltage Gradient</td>
</tr>
<tr>
<td>CIS</td>
<td>Close Interval Potential</td>
</tr>
<tr>
<td>CP</td>
<td>Cathodic Protection</td>
</tr>
<tr>
<td>CSE</td>
<td>Copper/Copper sulphate standard reference electrode</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DCVG</td>
<td>Direct Current Voltage Gradient</td>
</tr>
<tr>
<td>ECDA</td>
<td>External Corrosion Direct Assessment</td>
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<tr>
<td>ELF</td>
<td>Extra low frequency</td>
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<tr>
<td>ER</td>
<td>Electrical Resistance</td>
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<tr>
<td>FBE</td>
<td>Fusion Bonded Epoxy</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>2L-PE</td>
<td>Two-layer Polyethylene</td>
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<td>3L-PE</td>
<td>Three-layer Polyethylene</td>
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<tr>
<td>PSP</td>
<td>Pipe to Soil Potential</td>
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<tr>
<td>ILI</td>
<td>In-line Inspection</td>
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<tr>
<td>MFL</td>
<td>Magnetic Flux Leakage</td>
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<td>ROW</td>
<td>Right-of-Way</td>
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**List of Nomenclature**

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<tr>
<td>A</td>
<td>Ampere</td>
</tr>
<tr>
<td>A/m²</td>
<td>Ampere per square meter</td>
</tr>
<tr>
<td>cm²</td>
<td>Square centimeter</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>EIR-free</td>
<td>Pipe-to-soil IR-free potential</td>
</tr>
<tr>
<td>EON</td>
<td>Pipe-to-soil ON potential</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>Jdc</td>
<td>Direct Current density of the pipeline (A/m²)</td>
</tr>
<tr>
<td>Ksat</td>
<td>Saturation Permeability Index</td>
</tr>
<tr>
<td>kV</td>
<td>kiloVolts</td>
</tr>
<tr>
<td>mils</td>
<td>Milli inch</td>
</tr>
<tr>
<td>mm</td>
<td>Millimeter</td>
</tr>
<tr>
<td>m²/s</td>
<td>Square meter per second</td>
</tr>
<tr>
<td>μm/yr</td>
<td>Micron meter per year</td>
</tr>
<tr>
<td>Rs</td>
<td>Spread resistance</td>
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1 Executive Summary

This report refers to the activities performed in the frame of PRCI project on the refinement of the Alternating Current (AC) corrosion criteria by evaluating real-world pipeline AC corrosion cases and applying an improved AC corrosion prediction model.

Although the amount of real-world pipeline cases was rather limited, a better insight in the key parameters influencing the AC corrosion rate was obtained by combining data from dig reports and results from an improved computational model. Statistical analysis on the limited set of data underlined the importance of the soil texture, moisture content and AC and DC current density. From the study the following AC corrosion criteria is proposed:

![Graph showing corrosion criteria]

The threshold values of 30 A/m² AC current density and 1 A/m² DC current density are maintained as critical values. In principle two areas of moderate corrosion rate between 1.18 to 3.90 mils/yr (30-99μm/yr) have been added to the ISO18086:2015 diagram with the AC and DC current density on a 1 cm² coupon or coating defect surface area. They are important for the AC mitigation strategy. False negative results are expected in sand and silt when the Cathodic Protection (CP) level is lowered but considerable AC voltage is present on the pipeline and when the moderate CP is applied but the AC voltage is reduced below 30 A/m².

It must be noted that the corrosion rate decreases with the soil moisture content, surface area and (to lesser extent) the coating thickness. In any case the simulated corrosion rates were in line with the long-term field data from Electrical Resistance (ER) probes and dig hole data from real-world pipelines.
2 Introduction

Elsyca performed a PRCI sponsored research project (EC-6-2) on the development of AC+DC corrosion criteria for pipelines. Predictions from a computational model were combined with field data obtained from ER probes. Although a better understanding on the AC corrosion mechanism was obtained and a refinement of the AC corrosion criteria was proposed, it was concluded that there is need to include more real-life data on pipelines to validate the developed AC corrosion criteria for operating pipelines.

In 2014 Elsyca performed a PRCI sponsored research project on modeling DC+AC corrosion for refining existing AC corrosion criteria such as ISO18086 (or former CEN/TS 15280). The predictions of the model have been combined with field data from ER probes. From the results it could be concluded that the results from computational modeling and the ER probe technology were limited to initial corrosion rates. Also, the AC criteria found in literature are based on the short-term behavior. Therefore, long-term AC corrosion behavior could not be validated in the previous project but is very important for real life pipeline operations. With this project the aim is to extend the validation process to long term AC corrosion on real pipelines by collecting and analyzing additional real-world data and running an improved simulation model for long term calculations. This data enables to consolidate and refine the AC corrosion criteria/guidelines.

This research study aims to extend the validation process to long term AC corrosion on real pipelines by collecting and analyzing additional real-world data and running an improved simulation model for long term calculations. A more direct industry poll (such as face-to-face meetings) will be conducted for this purpose. The obtained data enables to consolidate and refine the AC corrosion criteria/guidelines allowing a better prediction of the long-term AC corrosion. Existing pipeline data consists of pipeline characteristics and historical survey data. A first prediction on AC corrosion risk is performed through modeling and consulting the existing AC criteria. A relevant set of test cases will then be defined for further investigation and refinement of the criteria. For the selected test cases additional field measurements are planned with the aim of gathering more detailed data for predicting the long-term AC corrosion behavior and to retrieve information on fluctuations over time.

The objectives of this study are therefore:

1. extend the validation process to long term AC corrosion on real-world pipelines
2. collecting and analyzing additional real-world data
3. running an improved simulation model for long term calculations
4. consolidate and refine the AC corrosion criteria/guidelines allowing a better prediction of the long-term AC corrosion

A database is created to store all relevant information obtained during the industry poll, computational simulations and field testing. A statistical analysis is then performed to deduce the importance of the various parameters and to find correlations between parameters such that a better insight in the long-term AC corrosion behavior of real-world pipelines is obtained.
As a result, the existing AC+DC corrosion criteria was validated and refined for real-world pipelines. This enables to consolidate the AC corrosion research allowing a better prediction of the long-term AC corrosion behavior on pipelines.

3 Value to Members

Increased understanding and improved quantification of the long-term AC corrosion process, resulting in a refinement of the AC corrosion criteria. In turn this allows operators to improve their efficiency and safety by better control and mitigation of AC corrosion. Pipelines are primarily mitigated against safety issues. In US and Canada, the maximum permissible touch voltage above the pipeline is 15Vac. However, AC corrosion can still occur even at lower AC induced voltage levels of the pipeline.

The assessment of AC corrosion likelihood was first proposed in the standard EN15280:2013 and later replaced by the ISO18086:2015 where the role of the AC and DC current densities in AC corrosion was evident. A DC and AC current density on a 1cm$^2$ coupon or coating defect should not exceed 1 and 30A/m$^2$ respectively. Lowering the CP level to DC current densities below 1A/m$^2$ was a second line of defense to control AC corrosion on pipelines.

However, analysis of ER probe data during the initial PRCI research study (EC6-2) has demonstrated that AC corrosion likelihood is wrongly predicted in 23% of the cases. Both false positive and false negative results were observed. Hence it is opportune to better understand which parameters control the AC corrosion process. Therefore, this project combined real-world pipeline data of AC corrosion cases, an advanced field measurement methodology for AC corrosion assessment and a time-dependent simulation software considering six electrochemical reactions and soil conditions for understanding the influencing parameters on AC corrosion.

The final goal of this project is to refine the AC corrosion criteria that are currently applied and to propose guidelines for properly assessing and controlling AC corrosion.

4 Industry poll

4.1 Survey results

PRCI members and pipeline owners outside the organization were invited to provide AC corrosion cases for this study. A list of required field data (see Appendix B) was distributed with “must have, “nice to have and “optionally” data on the field case. There are approximately 47 PRCI members and it was assumed that each member will have multiple cases of AC interference on their pipelines resulting in an estimated amount of more than hundred cases. Table 1 lists the result of the industry poll. Most pipeline operators (42 out of 47 members) have been contacted per email. In total 24 operators responded, and a follow-up call was organized but only 15 companies committed to deliver data. Finally, a total of 9 companies did provide field data for a total of 82 cases. Details of the response is given in Appendix B and summarized in Table 1. For some of field cases ILI and dig reports were available, which made the assessment of AC interference much easier. Note that some cases occurred in the same collocation but at different locations along the pipeline/power line corridor.
Table 1 – results of industry poll

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<tr>
<td>Companies envisaged</td>
<td>42</td>
</tr>
<tr>
<td>Successful contacted</td>
<td>24</td>
</tr>
<tr>
<td>Participation committed</td>
<td>15</td>
</tr>
<tr>
<td>Participation executed</td>
<td>9</td>
</tr>
<tr>
<td>Amount of cases</td>
<td>82</td>
</tr>
<tr>
<td>Amount of ILI reports</td>
<td>72</td>
</tr>
<tr>
<td>Amount of dig reports</td>
<td>42</td>
</tr>
<tr>
<td>Amount of AC corrosion cases</td>
<td>32</td>
</tr>
</tbody>
</table>

After reviewing the data, it was concluded that a total of 32 cases could be associated with AC interference. This was based on the presence of significant levels of AC interference, reduction in wall thickness, morphology of the corrosion attack or a combination thereof.

4.2 Data of selected cases

Some provided cases have been visually inspected by digging a bell hole at the location of the ILI feature. For other cases only, electrical parameters or in-line inspection (ILI) data were made available. Unfortunately, only a few operators measured the AC current density on a coupon or ER probe.

In case the location was known, the presence of overhead power lines could be verified in Google Earth. Changing the timescale of the imagery data set, allowed to verify when power lines were present in the corridor. This could be traced back till year 1993 in the best case. The rating of the power lines was available in public databases. The power line rating ranges between 138-765kV with the majority having 345kV power line circuit involved. Appendix C summarizes the pipeline and high voltage power line properties. All different coating types such as bitumen, coal tar enamel, Fusion Bonded Epoxy (FBE), extruded PP and three-layer polyethylene (3L-PE) and vintage coatings were involved. Some anomalies occurred on the same pipeline but at different locations within the corridor which results in a somewhat different soil type in some cases.

The soil properties were extracted from public databases or provided by the operator. An overview of the parameters is given in Appendix D. It must be noted that all soils belong to the loam texture class classified as being rather medium to highly corrosive and having a percentage of clay between 8.5 and 39%. At some locations the soils were classified as being peat or muck having typically a high moisture and organic matter content.
Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements

4.2.1 **Cases with dig hole reports**

Appendix E provides details on the different cases of which dig reports have been shared. A total of 26 anomalies out of 32 cases can be associated with AC corrosion as became clear after visual examination by the asset owners.

All anomalies were detected during an ILI inspection by magnetic flux leakage (MFL) technology. The wall loss reduction ranged between 12 and 67% with metal loss between 26 mils (0.67mm) and 87.8 mils (2.23 mm). In some cases, two consecutive runs have been performed but not in all cases there was an increase in wall thickness reduction over time. In addition, the orientation was not always the same which is inherent to accuracy of analyzing MFL signals. When compared with gauge measurements (after the pipe surface has been blasted), it was concluded that the wall thickness reduction was underestimated by MFL in most of the cases.

The surface area of the anomalies was measured with a ruler. Based on the measured height and width the surface area was calculated which ranged between 0.28 and 18 cm². As can be seen in Figure 1, the highest corrosion rates do not per se occur at 1 cm² surface. However, it should be noted that the coating defect could initially be smaller since the corrosion and calcareous deposits developed during the corrosion process accumulates and may further disbond the coating.

![Figure 1 - calculated anomaly surface versus corrosion rate](image)

The corrosion penetration depth measured with the gauge meter was used for calculating the corrosion rate. It was assumed that the coating defect existed since installation of the pipe line. Considering the vintage of the power lines (see Appendix C) most of the pipelines must be affected for a period of 20 years or more. Therefore, the calculated corrosion rate was based on the total time span from the installation of the pipeline till the year of AC corrosion detection, unless data from consecutive ILI runs were available. The obtained corrosion rates varied from 72 to 400 μm/year. The average ON potential was more electro-negative than -1200mV_{cse} in all cases. There is no direct correlation between the ON potential and the corrosion rate as shown in Figure 2. The AC and DC current density are important parameters for assessing AC corrosion. The average...
induced voltage was reported and ranged between 0.32 to 30 V\textsubscript{ac}. In some cases, the AC current density was measured on a temporary coupon.

![Graph 1](image1.png)

**Figure 2** - calculated corrosion rate from penetration depth versus the averaged pipe-to-soil ON potential

![Graph 2](image2.png)

**Figure 3** - calculated corrosion rate from penetration depth versus the averaged AC induced voltage

Some pipeline operators provided more details on the electrical parameters. Those were taken during the dig hole investigation, from survey reports or from nearby monitoring devices. As demonstrated in Table 2 the average AC current density is more than 20-30 A/m\textsuperscript{2} in most cases while the average induced voltage is below 6V. In the case of cases 13-19 the CP current density was measured resulting in a value exceeding 1 A/m\textsuperscript{2}.
### Table 2 - electrical signature of AC corrosion cases

<table>
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<tr>
<th>Case</th>
<th>Eon [A/m²]</th>
<th>Vac [A/m²]</th>
<th>Jdc [A/m²]</th>
<th>Jac [A/m²]</th>
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<tr>
<td>1</td>
<td>-1376</td>
<td>2.5</td>
<td>-</td>
<td>180</td>
</tr>
<tr>
<td>3 &amp; 4</td>
<td>-1496</td>
<td>1.9</td>
<td>-</td>
<td>10</td>
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<tr>
<td>2</td>
<td>-1518</td>
<td>1.9</td>
<td>-</td>
<td>24</td>
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<tr>
<td>5</td>
<td>-1373</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>-1453</td>
<td>0.3</td>
<td>-</td>
<td>126</td>
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<td>7 &amp; 8</td>
<td>-1207</td>
<td>2.3</td>
<td>-</td>
<td>-</td>
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<tr>
<td>9</td>
<td>-1084</td>
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<td>-</td>
<td>68</td>
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<tr>
<td>10</td>
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In most cases the presence of CaCO₃ and magnetite (Fe₃O₄, magnetic corrosion product) was observed to a certain extent. The calcareous deposit was in the form of a hard crust which appeared sometimes as a tubercle or as mixture with the corrosion products. According to the soil data base in Appendix D high values of CaCO₃ (weight % of carbonate in the fraction of the soil less than 2 millimeters in size) are expected for cases 13 – 23 and case 36 which was confirmed. However, some other anomalies also experienced the presence of CaCO₃ deposits such as for case 1, 4 and 7 & 8). On the other hand, at some locations (case 15 and 16) the Questar pipeline was buried in sand bedding instead of the native clay. The corrosion products looked more rusty. The corrosion rate was 3.62 and 2.87 mils/yr (92 and 73 µm/yr). The pH at the anomaly metal/soil interface was measured by some operators with litmus paper strips and resulted in values exceeding pH of 11 except for case 35 and 36 where a pH of 8.5 was measured under the hard CaCO₃ as shown in Figure 4.

![Figure 4 - corrosion morphology with CaCO₃ deposits](image-url)
Figure 4 shows the pH and specific resistivity of the bulk soil versus the calculated corrosion rate from the penetration depth. The soil resistivity varies between 0.5 (case 37) and 74 Ωm (case 12) with the majority of the cases having a value higher than 10 Ωm. There is no direct correlation with the corrosion rate as shown in Figure 5. Similar conclusion can be made for the pH ranging between 4.5 and 9.5 as shown in Figure 6.

![Figure 5 - calculated corrosion rate from penetration depth versus soil resistivity](image1)

![Figure 6 - calculated corrosion rate from penetration depth versus soil pH](image2)
4.2.2 Cases without dig hole reports

A gas pipeline operator performed extensively survey and monitoring on a 2L-PE (‘Yellow Jacket’) coated pipeline (cases 39 to 42) close to the shore line under interference by 345kV power lines (see Appendix C). The pipeline was installed in year 1996 and the presence of the power lines dated before year 2003 according to Google Earth Imagery. A Close Interval Potential Survey (CIPS) was performed in year 2013 indicating the presence of coating defects based on the ON/OFF potential readings. The monitoring data on 1 cm² coupon was measured between 2011 and 2015 on a weekly interval. The data at four test station locations is plotted in Appendix F for evaluating the AC corrosion likelihood according to the diagrams provided in ISO18086. At two locations the soil corrosivity was high and contained wet clay. Close to one location the apparent soil resistivity was 10-13 Ωm. Figure 7 shows the AC and DC current density over time. High AC current peaks up to the detection limit of the monitoring device (1000 A/m²) were recorded. Interesting to note is that the DC current density is also peaking during these events. As the coating is new the pipeline CP system could be maintained to a DC current density below 1 A/m² for controlling the AC corrosion.

![Figure 7 - monitoring of AC (squares) and DC (line) current density in wet clay](image)

According to the ISO18086 assessment criteria, AC corrosion is likely to occur at all locations except one. Some evidence of corrosion attack was reported thus far but no excavation data was shared at either of the locations.

In 2015 a set-up for AC CIPS was proposed by contractor company by connecting a trailing wire to the closest test post for measuring AC voltage with a reference electrode and the AC current with a 1 cm² pin probe inserted to 11.81” (300 mm) depth. An attenuation of AC current was observed during survey measurements resulting in an underestimation of the calculated current.
density. A correction factor was calculated to compensate for the impedance due to this set-up. A voltage drop exists in the trailing wire due to the internal impedance of the wire and the fact of spooling the wire on a reel. The impedance was calculated as 1500 and 2500 ohms for a 3218 m long coaxial and copper cable respectively. The linear impedance was larger than the inductive effect of the spool. Best results were obtained when a coaxial cable (40% reduction compared to standard copper cable) was used and the accuracy of 10% deviation was obtained after mathematical correction for the cable impedance as function of the developed length. According to the contractor the cable did not influence the voltage reading since the impedance of the wire was much lower than the input impedance of the meter. However, the voltage drop inside the pipe wall caused by the induced AC current flow cannot be neglected and should in fact be compensated through calculations. The induced AC current flowing in the pipe wall must then be simulated for calculating the attenuation in the pipe wall.

A second monitoring application was provided by second European operator for case 43 (3L-PE coated pipe) and case 44 (bitumen coated pipe) in Appendix C. Both are vintage pipelines subjected to AC interference since their installation. Coupons of 1 cm² surface area were measured with an interval of 15 seconds for 4 weeks. The results are shown in Appendix H. At both locations a clay soil of moderate resistivity (15 and 45 Ωm) was applicable. For both cases the AC corrosion is to be expected, however no corrosion attack was reported till date.

A US operator provided corrosion growth rate data of some anomalies on some FBE coated pipelines that have been measured during consecutive runs which allows calculating a corrosion growth rate assuming the ILI analysis was well performed.

Table 3 - corrosion growth by ILI

<table>
<thead>
<tr>
<th>Case</th>
<th>Location</th>
<th>CR [mils/yr]</th>
<th>CR [μm/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td></td>
<td>15.6</td>
<td>396</td>
</tr>
<tr>
<td>25</td>
<td>1</td>
<td>16.1</td>
<td>409</td>
</tr>
<tr>
<td>26</td>
<td>2</td>
<td>12.2</td>
<td>310</td>
</tr>
<tr>
<td>27</td>
<td>1</td>
<td>14.5</td>
<td>368</td>
</tr>
<tr>
<td>28</td>
<td>1</td>
<td>18.6</td>
<td>472</td>
</tr>
<tr>
<td>29</td>
<td>2</td>
<td>11</td>
<td>279</td>
</tr>
<tr>
<td>30</td>
<td>3</td>
<td>10.7</td>
<td>272</td>
</tr>
<tr>
<td>31</td>
<td>2</td>
<td>14.3</td>
<td>363</td>
</tr>
<tr>
<td>32</td>
<td>4</td>
<td>18.7</td>
<td>475</td>
</tr>
<tr>
<td>33</td>
<td>5</td>
<td>10.7</td>
<td>272</td>
</tr>
<tr>
<td>34</td>
<td>6</td>
<td>11.8</td>
<td>300</td>
</tr>
</tbody>
</table>

All cases (except case 33) are in a soil of high corrosivity as shown in Appendix D. The pipelines are interfered by double circuit (345/161kV) and single circuit (69 of 138kV) power lines that parallel over long distances. The exact installation of the power lines is between 2006 and 2008 except for the single circuit (138kV) line that was already existing when the pipelines were installed.
The locations with the highest corrosion growth rate (Table 3) did not show AC mitigation systems thus far but a design was on-going. Around the location of case 34 three different mitigation systems are installed; two at 1 and 2 miles upstream and one 1 mile downstream of the anomaly respectively. Based on consecutive ILI run the corrosion growth rate was calculated and resulted in 11.8 mils/yr (300 µm/yr). The induced voltage and the calculated AC current density (assuming 0.39 Ωm² spread resistance) at the three milepost locations is shown in Figure 8 and Figure 9 respectively. The highest AC current density at location closest to the anomaly (upstream 1) was 20 A/m². Lower current density values (~1 A/m²) at the other locations that are within 2 miles of the anomaly. WebSoilSurvey data indicates a muck type soil with high moisture content surrounded by silt loam with a clay content of 16% as shown in Figure 10.

![Figure 8 - induced voltage readings at mitigation locations](image)

![Figure 9 – calculated induced AC current density readings at mitigation locations](image)
4.3 Statistical analysis

4.3.1 Approach

The factors influencing the AC corrosion rate that were considered in this study can be conditionally divided into the following 3 groups:

- Pipeline characteristics;
- Soil characteristics;
- CP system and AC interference characteristics.

Information about the pipe characteristics and the data of excavations and in-line inspections were provided by the pipeline operators. Soil data was obtained from the WebSoilSurvey database as per Appendix D and is available for US sites only. The above-mentioned factors were used to predict corrosion rates and pipe wall thickness reductions based on linear and exponential regressions and to compare with the corresponding data from real-world in-line inspections.

At the first step, the role of each factor was individually evaluated using the *Pearson criterion* ($\chi^2$). This criterion is a measure of the linear correlation between two variables $x$ and $y$, giving a value between +1 and −1 inclusive, where 1 is total positive correlation, 0 is no correlation, and −1 is total negative correlation. It is calculated using Eq. (1)
\[ \chi^2 = \frac{n(\sum xy) - \sum x \sum y}{\sqrt{[n \sum x^2 - (\sum x)^2][n \sum y^2 - (\sum y)^2]}} \]  

(1)

where \( n \) is the number of (x,y) couples. Note that the Pearson criterion reflects the non-linearity and direction of a linear relationship, but not the slope of that relationship, nor many aspects of nonlinear relationships.

At the next step, a regression analysis was performed for the most relevant factors identified at the first step. Both linear and exponential regressions in the forms of Eqs. (2) and (3) were considered.

\[ y = m_1 x_1 + m_2 x_2 + \cdots + b \]  

(2)

\[ y = b \cdot m_1^{x_1} \cdot m_2^{x_2} \cdots \]  

(3)

Each factor was first evaluated individually followed by the combination of the factors. The measure of correlation between estimated and actual y-values in the regression analysis is so called coefficient of determination, \( r^2 \). It ranges in value from 0 to 1. If it is 1, there is a perfect correlation in the sample — there is no difference between the estimated y-value and the actual y-value. At the other extreme, if the coefficient of determination is 0, the regression equation is not helpful in predicting a y-value. Further, the F-statistic value was used to determine whether the observed relationship between the dependent and independent variables occurs by chance. This was done by comparing the calculated value of F-criterion with the critical value of the F-criterion for some desired false-rejection probability (e.g. 0.05) \( F(V_1,V_2) < F_{crit}(V_1,V_2,0.05) \). Here \( V_1 \) and \( V_2 \) represent the degrees of freedom.

4.3.2 Available real-world data

In total there were likely thirty-two AC corrosion cases which is rather a low number for statistical significance. To increase the number of cases ER probe data from the previous study was used. This data contains only electrical parameters (potential, AC voltage and spread resistance) but has the advantage to correlate the same parameters with the measured corrosion rate of (uncoated) probe element.

This means that finally two sets of data were available for the statistical analysis. The first set consists of 56 cases of AC corrosion provided by 9 pipeline operators that have been identified in the industry survey. The second set includes 149 cases of probe data that have been provided for different (unknown) locations around the world. The overview of the two sets is given in Table 4. Distribution of corrosion rates for each set is shown in Figure 11 and Figure 12. Corrosion rates from the pipelines (1st data set) are between 0.39 and 39 mils/yr (10 and 1000 \( \mu \)m/yr) in 98\% of the cases with the majority between 0.39 and 3.93 mils/yr (10 and 100 \( \mu \)m/yr). For the ER-probes (2nd data set) the distribution of corrosion rates is rather uniform but with corrosion rates exceeding 1000 \( \mu \)m/yr with predominance of cases having CR < 0.39 mils/yr (10 \( \mu \)m/yr).
### Table 4 - parameters considered for statistical analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th># of available data</th>
<th>ER probe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pipe data</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coating type</td>
<td>56</td>
<td>–</td>
</tr>
<tr>
<td>Vintage</td>
<td>56</td>
<td>–</td>
</tr>
<tr>
<td>Coating thickness [m]</td>
<td>23</td>
<td>–</td>
</tr>
<tr>
<td><strong>Soil data</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>55</td>
<td>–</td>
</tr>
<tr>
<td>Total Sand [%]</td>
<td>33</td>
<td>–</td>
</tr>
<tr>
<td>Total Slit [%]</td>
<td>33</td>
<td>–</td>
</tr>
<tr>
<td>Total Clay [%]</td>
<td>46</td>
<td>–</td>
</tr>
<tr>
<td>Cation exchange capacity [meq/100g]</td>
<td>47</td>
<td>–</td>
</tr>
<tr>
<td>pH</td>
<td>50</td>
<td>–</td>
</tr>
<tr>
<td>Calcium carbonate [%]</td>
<td>46</td>
<td>–</td>
</tr>
<tr>
<td>Gypsum [%]</td>
<td>46</td>
<td>–</td>
</tr>
<tr>
<td>Salinity [mmhos/cm]</td>
<td>46</td>
<td>–</td>
</tr>
<tr>
<td>Moisture bulk density [g/cc]</td>
<td>46</td>
<td>–</td>
</tr>
<tr>
<td>Available water capacity [In/In]</td>
<td>46</td>
<td>–</td>
</tr>
<tr>
<td>Ksat [µm/sec]</td>
<td>46</td>
<td>–</td>
</tr>
<tr>
<td>Linear extensibility [%]</td>
<td>46</td>
<td>–</td>
</tr>
<tr>
<td>Organic matter [%]</td>
<td>46</td>
<td>–</td>
</tr>
<tr>
<td>Resistivity [Ωm]</td>
<td>54</td>
<td>–</td>
</tr>
<tr>
<td><strong>Electrical data</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eon [V]</td>
<td>56</td>
<td>151</td>
</tr>
<tr>
<td>EIR-free [V]</td>
<td>–</td>
<td>151</td>
</tr>
<tr>
<td>Uac [V]</td>
<td>56</td>
<td>151</td>
</tr>
<tr>
<td>Jac [A/m²]</td>
<td>53*</td>
<td>151</td>
</tr>
<tr>
<td>Jac [A/m²]</td>
<td>–</td>
<td>151</td>
</tr>
<tr>
<td>Jac/Jdc</td>
<td>–</td>
<td>151*</td>
</tr>
<tr>
<td>Rs [Ωm²]</td>
<td>–</td>
<td>151</td>
</tr>
<tr>
<td><strong>ILI data</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Defect size [cm²]</td>
<td>53</td>
<td>–</td>
</tr>
<tr>
<td>Defect depth [mm]</td>
<td>51</td>
<td>–</td>
</tr>
<tr>
<td>WT reduction [%]</td>
<td>46</td>
<td>–</td>
</tr>
<tr>
<td>Corrosion rate [mm/yr]</td>
<td>56</td>
<td>151</td>
</tr>
</tbody>
</table>

*calculated

Figure 11 - distribution of corrosion rate of 1st data set from for real-world pipelines
The full list of factors considered for the analysis is presented in Table 4 with indication of the amount of available data. One can notice that this list is by far incomplete, which introduces extra noise in the regression analysis.

4.3.3 Results

4.3.3.1 Pearson correlation

The factors listed in Table 4 were individually evaluated with the Pearson criterion in order to determine the most relevant dependencies of the corrosion rates on the most relevant factor for two considered data sets as presented in Figure 13. The values of $\chi^2$ coefficient calculated for all considered factors using Eq. (1) are listed in Table 5. Among the most relevant parameters influencing the AC corrosion are soil pH, cation exchange capacity and linear extensibility on the one hand and DC current density and ON potential provided by CP system on the other hand.
Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements

Figure 13 – corrosion rates as functions of the most relevant factors for the first (a) with $\chi^2 = 0.546$ and second (b) data sets with $\chi^2 = 0.566$

Analysis of Table 5 reveals that the highest value of the Pearson coefficient does not exceed 0.6. This is related to the fact that the corrosion rates for both data sets are rather scattered and statistically insufficient, especially for the first data set. Moreover, the Pearson criterion is meant to reflect the linearity of a function therefore it cannot be used for evaluation of more complicated, non-linear relationships.

Table 5 - values of the Pearson criterion obtained for individual factors

<table>
<thead>
<tr>
<th>Factor</th>
<th>$\chi^2$ criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1^{st}$ set</td>
</tr>
<tr>
<td>Total Clay</td>
<td>-0.332</td>
</tr>
<tr>
<td>Soil cation exchange capacity</td>
<td><strong>-0.438</strong></td>
</tr>
<tr>
<td>Soil pH</td>
<td><strong>0.546</strong></td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>0.184</td>
</tr>
<tr>
<td>Salinity</td>
<td>0.083</td>
</tr>
<tr>
<td>Moisture bulk density</td>
<td>0.382</td>
</tr>
<tr>
<td>Available water capacity</td>
<td>0.241</td>
</tr>
</tbody>
</table>
4.3.3.2 Regression analysis

Linear and exponential regression analyses were performed for the two sets of corrosion data in order to describe the measured AC corrosion rate as a function of different factors. First each factor was evaluated individually. The quality of the linear or exponential fit was estimated based on the value of the determination coefficients $r^2$ listed in Table 6. The examples of linear and exponential fits of corrosion rates are shown in Figure 14.

Performed regression analysis confirmed that the most relevant factors determining the AC corrosion rate among the soil characteristics are pH, cation exchange capacity, and linear extensibility. Other important parameters include ON potential and both $J_{dc}$ and $J_{ac}$ (Table 6).

<table>
<thead>
<tr>
<th>Factor</th>
<th>$r^2$ (1st set)</th>
<th>$r^2$ (2nd set)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Clay</td>
<td>0.1104</td>
<td>-</td>
</tr>
<tr>
<td>Soil cation exchange</td>
<td>0.1915</td>
<td>-</td>
</tr>
<tr>
<td>capacity</td>
<td>0.2986</td>
<td>-</td>
</tr>
<tr>
<td>Soil pH</td>
<td>0.1158</td>
<td>-</td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>0.0441</td>
<td>-</td>
</tr>
<tr>
<td>Salinity</td>
<td>0.0235</td>
<td>-</td>
</tr>
<tr>
<td>Moisture bulk density</td>
<td>0.1190</td>
<td>-</td>
</tr>
<tr>
<td>Available water capacity</td>
<td>0.1041</td>
<td>-</td>
</tr>
<tr>
<td>$K_{sat}$</td>
<td>0.0146</td>
<td>-</td>
</tr>
<tr>
<td>Linear extensibility</td>
<td>0.1906</td>
<td>-</td>
</tr>
<tr>
<td>Organic matter</td>
<td>0.0088</td>
<td>-</td>
</tr>
<tr>
<td>Soil Resistivity</td>
<td>0.0100</td>
<td>-</td>
</tr>
<tr>
<td>$E_{on}$</td>
<td>0.0220</td>
<td>0.0491</td>
</tr>
<tr>
<td>$E_{IR}$-free</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$U_{ac}$</td>
<td>0.1166</td>
<td>0.0361</td>
</tr>
<tr>
<td>$J_{ac}$</td>
<td>0.0929</td>
<td>0.0361</td>
</tr>
<tr>
<td>$J_{dc}$</td>
<td>0.3205</td>
<td>0.3868</td>
</tr>
<tr>
<td>$J_{ac}/J_{dc}$</td>
<td>0.0070</td>
<td>0.0119</td>
</tr>
<tr>
<td>$R_s$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements

Figure 14 - Corrosion rates as linear and exponential functions of the most relevant factors for the first (a) and second (b) data sets.

Note that the determination coefficients for all individual factors are smaller than 0.4 indicating that the corrosion rate is the function of more than one parameter. Therefore, different combinations of factors from Table 4 were evaluated in order to find a function that gives the best fit with the measured corrosion rate.

For the real-world pipeline data, the best fit is found in the case of a function of 5 parameters: soil pH ($x_1$), total clay content ($x_2$), linear extensibility ($x_3$), cation exchange capacity ($x_4$), and moisture bulk density ($x_5$):
\[ CR \left[ \frac{\mu m}{yr} \right] = (0.2 \pm 1.5)x_1 - (11.6 \pm 7.9)x_2 + (2.9 \pm 1.8)x_3 + \]
\[ + (30.9 \pm 10.4)x_4 + (76.1 \pm 157.6)x_5 + (184 \pm 263) \]
\[ r^2 = 0.4287 \]

For ER probe set of data the best fit is found in the case of a function of 4 parameters: \( E_{on} \) \( x_1 \), \( J_{dc} \) \( x_2 \), \( U_{ac} \) \( x_3 \), and \( J_{ac} \) \( x_4 \):

\[ CR \left[ \frac{\mu m}{yr} \right] = -(8.38 \pm 13.02)x_1 - (0.78 \pm 0.49)x_2 + (1966 \pm 171)x_3 + \]
\[ + (319 \pm 27)x_4 + (2257 \pm 267) \]
\[ r^2 = 0.6454 \]

The obtained regressions were further evaluated using the F-statistics in order to determine whether the observed relationship between the dependent and independent variables was accidental. The probability that the observed relation is accidental is less than 5% for the first data set and nearly 0 for the second data set. Therefore, the obtained regressions are likely to be relevant.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Calculated F-factor</th>
<th>dF</th>
<th>( V_1 = n-dF-1 )</th>
<th>( V_2 = dF )</th>
<th>Probability of the accidental relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.50</td>
<td>30</td>
<td>1</td>
<td>30</td>
<td>4.2e-2</td>
</tr>
<tr>
<td>2</td>
<td>66.43</td>
<td>146</td>
<td>4</td>
<td>146</td>
<td>3.3e-27</td>
</tr>
</tbody>
</table>

One can notice that despite the relevance of the found regression equations (4) and (5), the determination coefficients are still too low to accept these relationships as a good prediction for AC corrosion rate. There are at least two reasons for this: 1) insufficiency of the field data and 2) corrosion rate is more complex than linear function of different factors.

### 4.4 Computational modeling

#### 4.4.1 Introduction

Many research has been performed to quantify the corrosion rate of buried steel in laboratory set-ups and on coupons in the field. However, the challenge to extrapolate these experimental data to real-world (coated) pipeline corrosion conditions remains difficult because not all mechanisms that occur at the steel surface can be measured, nor can be differentiated from each other to reveal which reaction contributes the most to the AC corrosion rate.

A conventional way for explaining pipeline corrosion is referring to the Pourbaix diagram that describes the stable phases of iron in aqueous solutions for a given pH and polarization level. The concentrations (better activity) of the iron species is calculated by the Nernst equation. The Pourbaix diagram however does not consider changes in temperature and concentration of solvated
ions in solution nor the kinetic aspects of the reactions in which the species are involved. To understand the corrosion kinetics much more mechanisms must be considered and computed in parallel.

1. the Butler-Volmer equations that describe the relationship between the current density and the potential, the kinetic constants and the concentrations of the species;
2. the diffusion coefficient of the species towards and away of the metal surface thus their influence on the reaction rate;
3. the carbonate species with buffering effect on the pH and formation of CaCO$_3$ precipitates which in turn influences the diffusion of the species;
4. the change in resistivity (or resistance-to-earth) based on the new composition of the ionic species while the electrochemical reactions take place;
5. potential drop in the soil and inside the coating defect and over the formed passivity layers.

It is obvious that an understanding of the corrosion kinetics in a given environment and for a given cathodic protection and AC interference level at a pipeline coating defect is a complex subject.

4.4.2 **Soil as a corrosive environment**

Soils behave differently than aqueous solutions with that respect that soils have a solid matrix (grain particles) which are fully or partly filled by soil moisture. The presence of the solid matrix has several consequences on the mobility of the species involved in the electrochemical corrosion reactions. The porosity of the soil defines the free space between grain particles and can vary from 0.15 (gravels) to 0.75 (organic clays with high plasticity). The free space can be fully filled with water (saturated conditions) or partly with a (interconnecting) water film around the grain particles (rather dry or field capacity conditions). It is obvious that the diffusion coefficient of the species is largely influenced by the moisture content of the soil. In aqueous solutions such as for Pourbaix diagram and in many experimental work, the diffusion coefficient of the species is relatively high and ranges in the order of $10^{-9}$ m$^2$/s. In soils however the (apparent) diffusion coefficient of most of the species is one or two orders of magnitude smaller namely between $10^{-10}$ (saturated conditions) and $10^{-11}$ (field capacity) m$^2$/s because of the physical hindrance of the particles which is expressed as the tortuosity of the soil. Oxygen is an exception to the rule. Its apparent diffusion coefficient behaves inversely with the soil moisture content and can have a much larger variation depending on the soil conditions. If the soil is fully saturated and all pores are filled with groundwater, the apparent diffusion coefficient of oxygen is as low as $10^{-11}$ m$^2$/s. However, if the pores in the soil are partly filled with water, oxygen can easily penetrate in the air space and diffuse in the thin water film around the soil particles and wetted metal surface. Under this condition the apparent diffusion coefficient of oxygen can be as high as $10^{-5}$ - $10^{-6}$ m$^2$/s as is the case with well aerated sand with low moisture content.

4.4.3 **Modeling technology**

A computational model Elsyca ACCor is proposed for simulating the corrosion behavior of a coating defect on a buried pipeline under cathodic protection in the presence or absence of AC and DC interference.

The following input parameters can be entered in the model:
• hydrodynamic conditions
• (bulk) soil resistivity & pH
• soil particle grain size
• concentration & diff coefficient of the soil species
• soil tortuosity & porosity
• coating thickness
• defect size
• Eon (remote)
• AC voltage (remote)

The perturbation signal can be of any type such as a cathodic protection remote earth ON potential with superimposed AC voltage, or a varying ON potential as occurring during DC stray current. The computational model provides time-dependent results for the following output parameters:

• current density (6 reactions)
• corrosion rate
• IR-free potential
• thickness of passive (Fe$_3$O$_4$) and/or rust (Fe(OH)$_2$) film
• spread resistance
• pH front
• CaCO$_3$ formation
• concentration of species
• updated concentration and diffusion coefficient of the species

The chemical species considered in the computational domain are given in Table 8. Sodium and chlorides are used to maintain electro-neutrality of the solution and their concentration is determined as function of the specific resistivity of the soil electrolyte.

Table 8 - ionic species in the computational model

<table>
<thead>
<tr>
<th>Na$^+$</th>
<th>Cl$^-$</th>
<th>H$_2$</th>
<th>OH$^-$</th>
<th>H$_2$O</th>
<th>O$_2$</th>
<th>Fe$^{2+}$</th>
<th>H$_2$CO$_3$</th>
<th>HCO$_3^-$</th>
<th>CO$_3^{2-}$</th>
<th>Ca$^{2+}$</th>
</tr>
</thead>
</table>

In total 6 different electrochemical reactions as shown in Table 1 are considered in the model. The current density of each electrochemical reaction is calculated according to Butler-Volmer equation.
for each time step (milliseconds) of the induced voltage signal. As can be seen all reactions (except iron oxidation) are pH dependent.

Table 9 - electrochemical reactions considered in AC modeling

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Name</th>
<th>Stochiometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>H₂ evolution / re-oxidation</td>
<td>2H₂O + 2 e⁻ = H₂ + 2 OH⁻</td>
</tr>
<tr>
<td>1</td>
<td>O₂ reduction / formation</td>
<td>2 H₂O + O₂ + 4 e⁻ = 4 OH⁻</td>
</tr>
<tr>
<td>2</td>
<td>ferro – ferri conversion</td>
<td>3 H₂O + Fe₂O₃ + 2 e⁻ = 2 OH + 2 Fe(OH)₂</td>
</tr>
<tr>
<td>3</td>
<td>magnetite reduction to iron hydroxide</td>
<td>4 H₂O + Fe₃O₄ + 2 e⁻ = 2 OH + 3 Fe(OH)₂</td>
</tr>
<tr>
<td>4</td>
<td>iron oxidation</td>
<td>Fe = Fe²⁺ + 2 e⁻</td>
</tr>
<tr>
<td>5</td>
<td>magnetite formation</td>
<td>3 Fe + 8 OH⁻ = 4 H₂O + Fe₃O₄ + 8 e⁻</td>
</tr>
</tbody>
</table>

Furthermore, the ACCor considers the growth of the rust layer Fe(OH)₂ and passivating magnetite film Fe₃O₄ over a period of 1000 seconds. The magnetite can be reduced (reaction 4) and the redox condition of rust film can be converted (reaction 2). This ferri-ferro conversion represents the capacitive component of the AC corrosion mechanism. Both the rust and passive film layer have a voltage drop that depends on their thickness. The thickness of the layers and voltage across them is calculated as well. Reaction 4 is the corrosion reaction at moderate pH while reaction 5 only occurs when the pH is sufficiently high. Once the passive film is completely formed, reaction 4 is inhibited because of the voltage drop over the magnetite or passive film layer is too high to keep the iron oxidation active. Iron oxidation or AC corrosion can then only occur through reaction 5.

In addition, three recombination reactions in the electrolyte can take place and will partially control the pH at the metal surface.

Table 10 - chemical recombination reactions occurring in the soil

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Name</th>
<th>Stochiometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>iron hydroxide recombination</td>
<td>Fe²⁺ + 2 OH⁻ = Fe(OH)₂</td>
</tr>
<tr>
<td>7</td>
<td>carbonate equilibrium</td>
<td>H₂CO₃ + OH⁻ = HCO₃⁻ + H₂O</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>HCO₃⁻ + OH⁻ = CO₃²⁻ + H₂O</td>
</tr>
</tbody>
</table>
The computational domain consists of an axisymmetric model of a coating defect which thickness, and radius can be modified. The size of the surrounding soil has dimensions of 56 mm width and 56 mm height. The ion concentration in the computational domain is updated with the new concentrations of species that are produced or consumed by the reformation and electrochemical reactions. As such the concentration profile of the species is determined from which the evolution of the ion concentrations, pH front, the soil resistivity and spread resistance is simulated.

The soil species can diffuse into the soil and the concentration gradient can be established as function of the electrochemical and chemical processes taking place. The mobility of the species however is dependent on physico-chemical properties of the soil are defined by the tortuosity, porosity and moisture content which in turn will determine the diffusion coefficient of the chemical species. The steric hindrance of the species further increases when calcareous deposits are formed. The software adjusts the diffusion coefficient automatically. Figure 16 shows the various electrolyte conditions and their effect on the steric hindrance of the species involved in the AC corrosion reaction.

Figure 16 - representation of soil electrolyte conditions influencing the diffusion of species (a) aqueous solution or 100% saturation, (b) 100% saturated soil, (c) soil at field capacity (e.g. 50% water saturation) and (d) soil at field capacity with calcareous deposit formation.
Many data on AC corrosion obtained in laboratory are performed in aqueous solutions or in saturated sand. Measurements in other soil conditions and soil types are rarely found due to the difficulty for compensating for IR-drop errors and controlling the moisture content. On the other hand, many data exist from coupons and ER probes for monitoring purposes (Figure 18) but poor or no information is made available on the soil conditions at site.

Figure 17 - field measuring data from 5 measuring stations on an AC interfered pipe

Figure 18 - corrosion rates from ER probes around the world (courtesy Metricorr)
4.4.4 Simulation results

AC corrosion rates were simulated in the ACCor computational model for three different soil types and conditions as shown in Table 11. A defect of 1 cm$^2$ in FBE coating of 400 μm thickness and a soil water saturation ratio of 50% was assumed as a reference. The oxygen concentration was assumed to be 10 ppm and no carbonate species were present.

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>250</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>Grain size [μm]</td>
<td>5000</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.39</td>
<td>0.42</td>
<td>0.45</td>
</tr>
<tr>
<td>Tortuosity</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Saturation rate [%]</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>pH</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

The cathodic protection potential and AC interference level was imposed from remote earth according to Table 12 until an equilibrium condition was achieved. For most cases this was after 1000 seconds.

<table>
<thead>
<tr>
<th>Signal</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSP Eon [V$_{cse}$]</td>
<td>-0.900</td>
<td>-1.200</td>
<td>-1.500</td>
</tr>
<tr>
<td>AC voltage [V$_{cse}$]</td>
<td>3</td>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>

The simulated corrosion rate plotted according to the ISO18086 is shown in Figure 19 and is in good agreement with the field data in Figure 17 and Figure 18. It is expected that the AC and DC current density increases proportionally (in log-log scale) because of the autocatalytic nature of the AC corrosion process. All corrosion rates exceeding the 3.94 mils/yr (100 μm/yr) were obtained in the clay type soil. The lowest corrosion rate was simulated in sand. The results for silt were in between sand and clay with some overlap.

Some conditions lead to a higher corrosion rate than expected. For example, seven cases with a corrosion rate between 1.18 and 3.90 mils/yr (30-99 μm/yr) have a DC current density smaller than 1 A/m$^2$ but an AC current density above 30 A/m$^2$. They belong to sand or silt with a low CP.
potential of -0.900 or -1.200 V$_{\text{cse}}$ but high AC induced voltage exceeding 50V. There is only one case for clay with 3Vac and -0.900 V$_{\text{cse}}$. All cases have an average simulated IR-free potential between -0.890 and -0.910 V$_{\text{cse}}$. As such the CP level can be reduced upon condition that the induced voltage on the pipeline is decreased. There are two cases with an AC current density below 30 A/m$^2$ and a DC current density exceeding 1 A/m$^2$ but having a corrosion rate of 2.04 and 3.27 mils/yr (52 and 83 μm/yr) respectively. These higher corrosion rates are also confirmed by the measurements in Figure 18. Both cases were simulated in silt at low interference of 3Vac and moderate (-1.2 and -1.5 V$_{\text{cse}}$) CP level. On the other hand, some conditions lead to smaller corrosion rate than expected. Those cases have DC current density between 1 and 3 A/m$^2$ and AC current densities between 30 and 300 A/m$^2$. These are cases in the drier silt and clay with 25% saturation level and a AC voltage of 10 V$_{\text{cse}}$. At higher saturation level of 50% and the corrosion rate is higher.

Figure 19 - simulated corrosion rate for different soil, CP and AC interference conditions

The contribution of the partial electrochemical reactions in Table 9, is shown in Figure 20 for the different cases, ordered according increasing corrosion rate. The ferri-ferro conversion reaction has the largest contribution to the overall current density. This reaction does not cause corrosion but is responsible for the pseudo-capacitive behavior of the corrosion products Fe(OH)$_2$ and Fe$_2$O$_3$. In other words, Faraday's law to calculate corrosion rates based on the total current density, does not apply in AC corrosion. The highest thickness of the rust layer Fe(OH)$_2$ after 1000 seconds is 0.0394, 0.0397 and 0.0421 mils (1.00, 1.01 and 1.07 μm) thick in sand, silt and clay respectively. The magnetite reactions are very small and can hardly be seen on the top of the bars but exists in all cases. The simulated pH at the metal surface is plotted as well and the corrosion rate increases with pH. The oxygen concentration decreases at the metal surface. In clay the consumed oxygen cannot be refreshed due to the slow diffusion rate in this type of soil. The contribution of the oxygen reduction reaction to the overall current density is thus non-existing in clay and the pH is maintained by the electrolysis of water to hydrogen gas according reaction 0 in Table 9. On the opposite side the oxygen concentration at the surface remained sufficiently high in sand (2.81 ppm)
at lowest CP potential of -0.900 V_{cse} and explains the larger contribution of the iron oxidation reaction 4 in Table 9. Figure 21 compares the partial reactions and the thickness of the magnetite film (Fe$_3$O$_4$) with the corrosion rate. The parameter theta is a measure of the thickness of the magnetite film that provides passivation. A theta equal one (1) means that the metal surface is fully covered by a closed monolayer with a thickness in the nanometer scale.

Figure 20 - contribution of partial electrochemical reactions to the total AC current density and the corresponding pH at the metal surface.
Figure 21 - contribution of partial electrochemical reactions to the total AC current density and the corresponding Fe₃O₄ thickness on the metal surface.

The corrosion rate was plotted as function of the ratio between the simulated AC to DC current density. From Figure 22 it is seen that the corrosion rate is significant if the current density ratio is between 3 and 800. The corrosion rate decreases at higher ratio when the DC current density is at lower values reducing the conversion of the magnetite film to iron hydroxide. This is only applicable when the AC current density is moderate to low. At high AC current density, the corrosion rate will be high. As such this ratio cannot be used as a criterion and sufficiently mitigation must be foreseen to reduce the AC current density below 30 A/m².

![Graph showing corrosion rate versus ratio of AC to DC current density.](image)

Figure 22 - corrosion rate versus ratio of AC to DC current density

The influence of the coating thickness, coating defect area and degree of soil saturation was investigated. In all cases (except in clay at 25% saturation) the corrosion rate is lower if a coating is applied and/or the surface area is increased. The surface area has the largest impact on the corrosion rate which is reduced by 45-69% depending on the soil conditions. Increasing the coating thickness reduces the corrosion rate but with a lesser extent than does the surface area of the defect.
Table 13- influence of coating property and soil moisture on simulated corrosion rate

<table>
<thead>
<tr>
<th>soil type</th>
<th>saturation ratio (%)</th>
<th>surface area (cm²)</th>
<th>coating thickness (μm)</th>
<th>CR (μm/yr)</th>
<th>deviation</th>
<th>from ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>50</td>
<td>1</td>
<td>400</td>
<td>16</td>
<td>6</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1</td>
<td>400</td>
<td>16</td>
<td>4</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>2</td>
<td>400</td>
<td>16</td>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>2</td>
<td>2000</td>
<td>79</td>
<td>3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>5</td>
<td>400</td>
<td>16</td>
<td>3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>5</td>
<td>2000</td>
<td>79</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>Silt</td>
<td>50</td>
<td>1</td>
<td>400</td>
<td>16</td>
<td>51</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1</td>
<td>400</td>
<td>16</td>
<td>31</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>2</td>
<td>400</td>
<td>16</td>
<td>22</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>2</td>
<td>2000</td>
<td>79</td>
<td>14</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>5</td>
<td>400</td>
<td>16</td>
<td>16</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>5</td>
<td>2000</td>
<td>79</td>
<td>13</td>
<td>0.5</td>
</tr>
<tr>
<td>Clay</td>
<td>50</td>
<td>1</td>
<td>400</td>
<td>16</td>
<td>203</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1</td>
<td>400</td>
<td>16</td>
<td>251</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>2</td>
<td>400</td>
<td>16</td>
<td>172</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>2</td>
<td>2000</td>
<td>79</td>
<td>176</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>5</td>
<td>400</td>
<td>16</td>
<td>112</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>5</td>
<td>2000</td>
<td>79</td>
<td>104</td>
<td>4.1</td>
</tr>
</tbody>
</table>

The effect of reduced moisture content (25 instead of 50% saturation ratio) is shown in Figure 23 and Figure 24. Sand shows an opposite behavior compared with silt and clay. The pH and the thickness of magnetite film slightly increases with decreasing moisture content. For sand and silt the corrosion rate decreases with moisture content by a 31 to 53%.
4.4.5 Discussion of the simulations

Simulations have been performed for pure sand silt and clay with different CP levels (−0.9, −1.2 and −1.5 V_{cse} to remote earth) and AC interference levels (3, 10 and 50 V_{cse} to remote earth). As
Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements

a reference the soils were water saturated for 50% of the pore volume and typical soil resistivity values were used. The simulated corrosion rate was the lowest for sand, followed by silt and clay:

- Sand: 0.2 – 1.3 mils/yr (5 – 34 μm/yr)
- Silt: 1.1 – 3.3 mils/yr (28 – 84 μm/yr)
- Clay: 1.8 – 17.5 mils/yr (45 – 445 μm/yr)

Loam is a very common type of soil which consists predominantly of silt (>40%). The clay content in loam varies from 20% to 40%. The composition of the soils in their basic fractions sand, silt and clay can be found in the soil texture diagram. The soil resistivity considered in the simulations was 5 and 50 Ωm for respectively pure silt and clay. Typical values of loam type soils fall within this range depending on the clay fraction in the loam.

![Soil Texture Diagram](source: Wikipedia)

The simulations show that the corrosion rate increases with the pH at the metal surface varying from 11.7 to 14.2 and increases from sand to silt and clay. The hydroxyls are less mobile in clay than in sand (at least under sufficient moisture content), and are more easily produced in clay because of the water electrolysis (no diffusion limitation) and lower ohmic drop (low soil resistivity). The pH is proportional with the concentration of hydroxyls (OH⁻) at the metal surface. The hydroxyls are generated by the oxygen reduction reaction and the water reduction reaction. Hydroxyls are involved in all reactions except the oxidation reaction of iron according to reaction 4. As such a correct measurement of the pH could be an indicator of the corrosion rate but this is impossible to measure in practice.

Operators can only rely on the current density but should be aware that a coupon or ER probe overestimates the AC corrosion if they are not coated and the surface area is smaller than the
coating defect. Simulations have demonstrated that the surface area of the coating defect has a larger influence than the coating thickness.

An accepted strategy to mitigate AC corrosion is to reduce the CP level on the pipeline, especially in the case more extensive mitigation becomes practical impossible or too expensive. The simulations have demonstrated that the AC voltage must stay below 10 V, even if the DC current density is 1 A/m².

4.5 Field testing method

4.5.1 Procedure for AC corrosion assessment

The AC corrosion assessment method is based on an improved set-up of the intensive measurement technique for determining IR-free protection levels on real-world pipelines as described in the standard EN13509 Annex F. The improved procedure consists of performing the potential gradients in vertical position within a borehole that is made at the epicenter of the DCVG or ACVG signal. The voltage gradient is the largest when the second reference get closest to the coating defect.

The field testing was performed by the subcontractor Corrpro. First the coating defects at indicated sites have been surveyed by DCVG and ACVG method to locate the epicenter of the voltage gradient. The intensive measurement was executed in DC and AC mode. In DC mode the closest rectifiers were interrupted (3s ON - 1s OFF). In the AC mode the AC excitation signal was imposed with the signal generator of an ACVG equipment (Radio Detection) selectable for 4A-3/6/98Hz, 4A-98Hz, 2A-491Hz. The voltage response is measured with an oscilloscope.

A ¾” diameter Collins Rod (Figure 26) with defined surface area of the active tip (7.5 cm²) was inserted at different depths as shown in Figure 27. The potential of the rod was calibrated with respect to a Cu/CuSO₄ cell such that any reading on the rod could be translated to the standard reference cell. In addition, measurements were repeated with artificial defects (coupons) of three known surface areas of (7.5, 1, 100 or 417 cm² respectively) connected to the pipeline. The set-up is demonstrated in Figure 27.

![Figure 26 - Collins Rod for local soil resistivity testing and potential profiling](image)
Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements

Figure 27 - field set-up for AC corrosion assessment

The intensive measurement method allows to:

- determine the orientation and position of the defect;
- estimate the defect size (when reference coupons are used);
- calculate the AC and DC current density of the defect.

The properties of the pipelines and anomalies are summarized in Table 14.

Table 14 - cases for AC corrosion assessment field testing

<table>
<thead>
<tr>
<th>Pipeline reference</th>
<th>diam. [inch]</th>
<th>ILI data</th>
<th>Soil resistivity</th>
<th>Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Questar 1</td>
<td>12.75</td>
<td>unknown</td>
<td>unknown</td>
<td>n.a.</td>
</tr>
<tr>
<td>Shell 2</td>
<td>6</td>
<td>11:00</td>
<td>1.5</td>
<td>n.a. n.a.</td>
</tr>
<tr>
<td>Enbridge 3</td>
<td>32</td>
<td>08:45</td>
<td>27.5</td>
<td>46.91 37.43 3.75 54</td>
</tr>
<tr>
<td>Enbridge 4</td>
<td>42</td>
<td>11:10</td>
<td>7.7</td>
<td>10.15 19.53 1.25 45</td>
</tr>
</tbody>
</table>

The AC gradients obtained as function of the penetration depth of the Collin rod are shown in Appendix K. A good response signal was found on the pipe 2 with a gradient peak of ~200mV occurring at 72” depth. Adding the 1 cm² coupon did not change much the profile of the voltage gradient indicating that the anomaly should have a defect size larger than 1cm² and thus dominating the soil potential gradients. Even with the 10 cm² connected the profile didn’t change much. Note that the AC interference on the pipeline was enough to measure good gradients in the
soil because the “ambient” condition shows similar profile than those obtained with the imposed AC signal at 4/6/98Hz and 98Hz. The current density on the Collins tip and 100 cm² coupons was approximately 49 A/m². The AC induced voltage was 2.1 V. Note that the field test happened after to most severe anomalies further down the line have been repaired and mitigation was in place.

Pipe 2 has a much less interfered during testing. The induced AC voltage was 1.11 V only. The current density was measured on the Collins rod and was only 1 A/m². The soil resistivity was relatively high (~100 Ωm) because of the dry season. As a consequence, the voltage gradient under “ambient” condition was hardly measurable. When the AC signal was applied a peak of approximately 400 mV clearly appears at 36” depth. Adding a 1 cm² at 52” depth changed the profile and the peaks associated to the anomaly and coupon respectively, are of similar amplitude. Same is seen for the 10cm². So most probably the anomaly is at 36” depth and has size between 1 and 10cm².

For the 32” pipe 3 the Collins rod was inserted to higher depths. The induced voltage was 1.75 Vac and the current density was 21.6 A/m² measured on the Collins rod. The soil resistivity was 28.8 Ωm. The voltage gradient of the anomaly was moderate, but no clear peak could be distinguished, even not when an AC signal was imposed. A slight increase can be seen at 52” depth. However, the anomaly was on top of the pipeline. When inserting a coupon of 7.5 and 417 cm² a peak appears in the voltage gradient profile at insertion depth. Since the anomaly could not be detected through the gradient its surface must be less than 7.5 cm². Similar behavior is found for the 42” pipe 4. The anomaly has a moderate to low gradient, even when an AC voltage is applied. A clear peak in the profile cannot be distinguished. There seems to be an effect of multiple defects. The AC voltage of the pipeline was 0.64 only but even when imposing an AC signal there was no much improvement. The soil has a normal resistivity of approximately 20 Ωm.

4.5.2 Discussion of field testing

The intensive measurement method was used to determine the position and size of the coating defect. The ACVG signal was preferred because less is introduced than with DCVG because rectifiers do not have to switched off creating equalizing currents, and higher AC current can be imposed to create a sufficiently large gradient of a small coating defect to be detected. It is crucial to insert the Collins rod through the epicenter of the ACVG signal. Details on the epicenter were not provided but the %IRfree and dB voltage attenuation were reported and in-line with the anomaly size from the ILI inspection. Peaks in the AC voltage gradients were detected but did not allow to make correlations with the position. Introduction of coupons changed the voltage gradient, but no good correlation can be made for sizing the coating defect. This method requires further improvement and field validation.

5 Conclusions

The goal of this study was to refine the existing AC corrosion criteria with real-world pipeline data and long-term simulations. The number of AC corrosion cases was rather limited (32 in total) for an in-depth assessment but some interesting observations can be made.
Real-world corrosion cases showed that:

- Affected pipelines were buried in moderate to corrosive soils of the type peat, muck or loam with minimum 10% of clay;
- AC corrosion occurred on variety of coating types (coal tar enamel, FBE, 2L-PE and 3L-PE);
- soil resistivity was pre-dominantly larger than 10 Ωm, and thus not a priori low;
- surface area of the corrosion anomaly between 1 and 10 cm² resulted in the highest corrosion rates;
- corrosion rates calculated from the penetration depth and estimated time of exposure were between 2.83 and 15.74 mils/yr (72 and 400 μm/yr);
- pipeline operated at ON potentials more negative than -1200 mV\text{cse} with AC induced voltage between 0.3 and 30 V;
- corrosion products were dominantly black magnetite (Fe₃O₄) mixed with CaCO₃;
- hard CaCO₃ crusts coincide with scaling property according to soil maps.

The real-world pipeline data (56 cases) in conjunction with ER probe data (149 cases) were used in statistical analysis for finding correlations between pipeline conditions and the corrosion rate. The Pearson correlation and linear regression method were applied. Unlike the data population was rather small for statistical significance the following conclusions can be made with some precautions:

- ER probes shows more variance and higher values in the corrosion rate than the real-world pipeline data
- clay content, moisture content and the cation exchange capacity (ability to retain minerals) shows the best correlation with the corrosion rate while for the electrical parameters Jdc and Jac are most significant

The AC corrosion mechanism was investigated with an advanced time-dependent simulation software that considers the main electro-chemical reactions and the change in the soil properties. The remote earth ON potential was -0.9, -1.2 or -1.5 V and the AC induced voltage was 3, 10 or 50 V. Simulations were performed in sand, silt and clay respectively and the effect of water saturation ratio, size of the coating defect (1, 2 or 5 cm²) and the thickness of the coating was investigated. Typical soil resistivity values (The simulations confirmed the field data obtained on ER-probes and was well in line with the real-world pipeline cases. The following interesting conclusions can be made:

- corrosion rate is the lowest in sand followed by silt and clay; results for silt partly overlap those of sand and clay;
- corrosion rate varies between 0.2 and 17.5 mils/yr (5 and 445 μm/yr) and covers the range of the real-world pipeline data;
- pH is the highest in clay because water electrolysis is the dominant reaction producing OH⁻ and the IR drop in the soil is the lowest
- magnetite (Fe₃O₄) is formed but full coverage of the surface for maintaining passivity is not achieved under AC interference
- decreasing the moisture content from 50 to 25% saturation reduces the corrosion rate by 30-50%
- increasing the surface area from 1 to 5 cm² reduces the corrosion rate with 45-69%.
- some cases the simulated (and measured) corrosion rate deviates from the AC corrosion likelihood assessment according to ISO18086:2015:
  - corrosion rate is underestimated (false negative result) in sand and silt at low CP (-0.9 V) but high AC interference (50 V) and in clay at low AC interference (3 V).
  - corrosion rate is underestimated (false negative result) in silt under moderate CP conditions (-1.2 and -1.5 V) and low AC voltage (3 V).
  - corrosion rate is overestimated in dry silt and clay (25% saturation) and moderate AC voltage (10 V).

From the above conclusions a further refinement of the AC corrosion criteria is proposed in Figure 28 which takes into account the cases that result a false positive and false negative corrosion prediction. It must be noted that the false positive predictions have been overruled by more conservative approach since not all cases have been simulated. The decision was rather based on field data.
6 References

[1] EN15280:2013 Evaluation of a.c. corrosion likelihood of buried pipelines applicable to cathodically protected pipelines


# Appendix A – Field data questionnaire on AC cases

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## Appendix B – Results of industrial survey

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| Total amount cases     | 42                    | 24                       | 15            | 9            | 82          | 72          | 42        | 32        |
Appendix C – Retained cases with AC interference

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<td>1984</td>
</tr>
<tr>
<td>Diameter [inch]</td>
<td>6.625</td>
</tr>
<tr>
<td>Material grade</td>
<td>X52</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.219</td>
</tr>
<tr>
<td>Coating Type</td>
<td>Extruded polypropylene (55 mils)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>1.0</td>
</tr>
<tr>
<td>Soil type</td>
<td>Clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>Clay</td>
</tr>
<tr>
<td>pH</td>
<td>6.5</td>
</tr>
</tbody>
</table>

*carbonate (80mg/l) and chloride (0mg/l) content

<table>
<thead>
<tr>
<th>ILI data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative position</td>
<td>01:16 o’clock</td>
</tr>
<tr>
<td>Wall thickness reduction year 2009</td>
<td>15%</td>
</tr>
<tr>
<td>Wall thickness reduction year 2014</td>
<td>22%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dig data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomaly size</td>
<td>Year 2015</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>12.7</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>12.7</td>
</tr>
<tr>
<td>Depth [mm]</td>
<td>1.524</td>
</tr>
<tr>
<td>Calculated surface area [cm²]</td>
<td>1.61</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>7.0</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>-----</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [μm/yr]</td>
<td>175</td>
</tr>
</tbody>
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<table>
<thead>
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<th>Electrical parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PSP ON [mVcse]</td>
<td>-1376</td>
</tr>
<tr>
<td>PSP AC [Vcse]</td>
<td>2.45</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Pictures</th>
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</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.jpg" alt="Image 1" /></td>
<td><img src="image2.jpg" alt="Image 2" /></td>
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<table>
<thead>
<tr>
<th>Pictures</th>
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</thead>
<tbody>
<tr>
<td><img src="image3.jpg" alt="Image 3" /></td>
<td><img src="image4.jpg" alt="Image 4" /></td>
</tr>
</tbody>
</table>

- Hard crusty soil immediately in contact with anomaly, iron product inside of damaged coating, gray moist deposits at pipe surface; pH=12 of anomaly
- AC current density of 180A/m² as-found; 47A/m² after mitigation w/ zinc
Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements

Case 2 & 3

<table>
<thead>
<tr>
<th>Pipeline properties</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Year of construction</td>
<td>1984</td>
</tr>
<tr>
<td>Diameter [inch]</td>
<td>6.625</td>
</tr>
<tr>
<td>Material grade</td>
<td>X52</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.219</td>
</tr>
<tr>
<td>Coating Type</td>
<td>Extruded polypropylene (55 mils), wrinkled with water under coating</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>33.0</td>
</tr>
<tr>
<td>Soil type</td>
<td>Clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>Clay</td>
</tr>
<tr>
<td>pH</td>
<td>6.0</td>
</tr>
</tbody>
</table>

*high carbonate (>180mg/l) and chloride (>1600mg/l) content

<table>
<thead>
<tr>
<th>ILI data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative position</td>
<td>06:27 and 04:32 o’clock</td>
</tr>
<tr>
<td>Wall thickness reduction year 2009</td>
<td>unknown</td>
</tr>
<tr>
<td>Wall thickness reduction year 2014</td>
<td>26%</td>
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</table>

<table>
<thead>
<tr>
<th>Dig data</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Anomaly size</td>
<td>Year 2015</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>11.94</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>37.34</td>
</tr>
<tr>
<td>Depth [mm]</td>
<td>1.447</td>
</tr>
<tr>
<td>Calculated surface area [cm²]</td>
<td>4.46</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>11.4</td>
</tr>
</tbody>
</table>
### Estimated Corrosion Growth Rate [µm/yr]

<table>
<thead>
<tr>
<th>Estimated Corrosion Growth Rate [µm/yr]</th>
<th>285</th>
</tr>
</thead>
</table>

### Electrical parameters

<table>
<thead>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PSP ON [mVcse]</td>
<td>-1496</td>
</tr>
<tr>
<td>PSP AC [Vcse]</td>
<td>1.93</td>
</tr>
</tbody>
</table>

### Pictures

<table>
<thead>
<tr>
<th>Pictures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backside of coating Fe product with magnetic property pH=11 of anomaly</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AC current density of 10.4A/m² as-found;</th>
</tr>
</thead>
</table>
Case 4

<table>
<thead>
<tr>
<th>Pipeline properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of construction</td>
<td>1984</td>
</tr>
<tr>
<td>Diameter [inch]</td>
<td>6.625</td>
</tr>
<tr>
<td>Material grade</td>
<td>X52</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.219</td>
</tr>
<tr>
<td>Coating Type</td>
<td>Poly tape 80 mils (damaged w/ wrinkles)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>29.0</td>
</tr>
<tr>
<td>Soil type</td>
<td>Clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>Clay</td>
</tr>
<tr>
<td>pH</td>
<td>6.5</td>
</tr>
</tbody>
</table>

*high carbonate (>180mg/l) and chloride (>1600mg/l) content

<table>
<thead>
<tr>
<th>ILI data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative position</td>
<td>12:19 o’clock</td>
</tr>
<tr>
<td>Wall thickness reduction year 2009</td>
<td>15%</td>
</tr>
<tr>
<td>Wall thickness reduction year 2014</td>
<td>22%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dig data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomaly size</td>
<td>Year 2015</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Length [mm]</td>
<td>32.26</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>39.88</td>
</tr>
<tr>
<td>Depth [mm]</td>
<td>0.838</td>
</tr>
<tr>
<td>Calculated surface area [cm²]</td>
<td>12.9</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>3.0</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [μm/yr]</td>
<td>75</td>
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<td>----------------------------------------</td>
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<table>
<thead>
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<tbody>
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<td>PSP ON [mVcse]</td>
<td>-1518</td>
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<tr>
<td>PSP AC [Vcse]</td>
<td>1.932</td>
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<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Picture 1" /></td>
<td><img src="image2.png" alt="Picture 2" /></td>
</tr>
</tbody>
</table>

- tubercle attached to pipeline
- pH=12 at anomaly
- AC current density 23.6 A/m²
Case 5

<table>
<thead>
<tr>
<th>Pipeline properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of construction</td>
<td>1984</td>
</tr>
<tr>
<td>Diameter [inch]</td>
<td>6.625</td>
</tr>
<tr>
<td>Material grade</td>
<td>X52</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.219</td>
</tr>
<tr>
<td>Coating Type</td>
<td>Shrink sleeve 80 mils (teared and with wrinkles)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>26.0</td>
</tr>
<tr>
<td>Soil type</td>
<td>Clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>Clay</td>
</tr>
<tr>
<td>pH</td>
<td>7.5</td>
</tr>
</tbody>
</table>

*carbonate (120mg/l), chloride 0mg/l, sulphate (1200 mg/l) content

<table>
<thead>
<tr>
<th>ILI data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative position</td>
<td>08:47 o’clock</td>
</tr>
<tr>
<td>Wall thickness reduction year 2009</td>
<td>0%</td>
</tr>
<tr>
<td>Wall thickness reduction year 2014</td>
<td>17%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dig data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomaly size</td>
<td>Year 2015</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>12.7</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>12.7</td>
</tr>
<tr>
<td>Depth [mm]</td>
<td>1.016</td>
</tr>
<tr>
<td>Calculated surface area [cm²]</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>7.4</td>
</tr>
<tr>
<td>--------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>7.4</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [μm/yr]</td>
<td>185</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>-1373</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSP ON [mVcse]</td>
<td></td>
</tr>
<tr>
<td>PSP AC [Vcse]</td>
<td>1.17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>AC current density 7.2 A/m2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pictures</td>
<td></td>
</tr>
<tr>
<td>black inside pit, little to no corrosion product to sample, hard calcareous soil buildup immediately in contact with pipe, no magnetic properties pH=12 at anomaly</td>
<td></td>
</tr>
</tbody>
</table>
Case 6

<table>
<thead>
<tr>
<th>Pipeline properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of construction</td>
<td>1984</td>
</tr>
<tr>
<td>Diameter [inch]</td>
<td>6.625</td>
</tr>
<tr>
<td>Material grade</td>
<td>X52</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.219</td>
</tr>
<tr>
<td>Coating Type</td>
<td>Shrink sleeve/Xtru coat (teared damage)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>46</td>
</tr>
<tr>
<td>Soil type</td>
<td>Clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>Clay</td>
</tr>
<tr>
<td>pH</td>
<td>6.5</td>
</tr>
<tr>
<td>*high carbonate (&gt;180mg/l), chloride (0 mg/l) and sulphate (0 mg/l) content</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ILI data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative position</td>
<td>01:54 o’clock</td>
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<tr>
<td>Wall thickness reduction year 2009</td>
<td>0%</td>
</tr>
<tr>
<td>Wall thickness reduction year 2014</td>
<td>15%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dig data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomaly size</td>
<td>Year 2015</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>38.10</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>15.87</td>
</tr>
<tr>
<td>Depth [mm]</td>
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</tr>
<tr>
<td>Calculated surface area [cm²]</td>
<td>6.05</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>6.6</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [µm/yr]</td>
<td>165</td>
</tr>
</tbody>
</table>

| Electrical parameters | \(\text{PSP ON [mVcse]}\) | -1453 |
| | \(\text{PSP AC [Vcse]}\) | 0.334 |

<table>
<thead>
<tr>
<th>Pictures</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.jpg" alt="Image" /></td>
<td><img src="image2.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>

| pH=11 at anomaly | AC current density 126 A/m² (as-found), 18.1 A/m² after mitigation w/ zinc |
### Case 7 & 8

<table>
<thead>
<tr>
<th>Pipeline properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of construction</td>
<td>1984</td>
</tr>
<tr>
<td>Diameter [inch]</td>
<td>6.625</td>
</tr>
<tr>
<td>Material grade</td>
<td>X52</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.219</td>
</tr>
<tr>
<td>Coating Type</td>
<td>Xtru coat 55 mils (disbanded at anomaly)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>23</td>
</tr>
<tr>
<td>Soil type</td>
<td>Clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>Clay</td>
</tr>
<tr>
<td>pH</td>
<td>6.5</td>
</tr>
</tbody>
</table>

*high carbonate (>180 mg/l), chloride (0 mg/l) and sulphate (>1600 mg/l) content

### ILI data

| Relative position           | 12:36 o’clock             |
| Wall thickness reduction year 2009 | 0%                      |
| Wall thickness reduction year 2014 | 30%                     |

### Dig data

<table>
<thead>
<tr>
<th>Anomaly size</th>
<th>Year 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [mm]</td>
<td>11.2</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>31.2</td>
</tr>
<tr>
<td>Depth [mm]</td>
<td>1.676</td>
</tr>
<tr>
<td>Calculated surface area [cm²]</td>
<td>3.49</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>13.2</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [μm/yr]</td>
<td>330</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>-----</td>
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<table>
<thead>
<tr>
<th>Electrical parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PSP ON [mVcse]</td>
<td>-1207</td>
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<tr>
<td>PSP AC [Vcse]</td>
<td>2.291</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Pictures</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>![Image](78x386 to 276x551)</td>
<td>![Image](306x399 to 533x551)</td>
</tr>
</tbody>
</table>

- Hard crusty deposits at anomaly, black deposits in contact with anomaly on soil backside, magnetic property pH = 11
- AC current density 56.6 A/m² (as-found)
Case 9

<table>
<thead>
<tr>
<th>Pipeline properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of construction</td>
<td>1987</td>
</tr>
<tr>
<td>Diameter [inch]</td>
<td>30</td>
</tr>
<tr>
<td>Material grade</td>
<td>unknown</td>
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<tr>
<td>Wall Thickness [inch]</td>
<td>unknown</td>
</tr>
<tr>
<td>Coating Type</td>
<td>FBE</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>4.6-517</td>
</tr>
<tr>
<td>Soil type</td>
<td>Clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>Clay</td>
</tr>
<tr>
<td>pH</td>
<td>unknown</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ILI data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative position</td>
<td>12:00 o’clock</td>
</tr>
<tr>
<td>Wall thickness reduction year 1987</td>
<td>0%</td>
</tr>
<tr>
<td>Wall thickness reduction year 2013</td>
<td>30%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dig data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomaly size</td>
<td>Year 2013</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>Not reported</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>Not reported</td>
</tr>
<tr>
<td>Depth [mm]</td>
<td>Not reported</td>
</tr>
<tr>
<td>Calculated surface area [cm²]</td>
<td>Not reported</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>Unknown</td>
</tr>
</tbody>
</table>
Estimated Corrosion Growth Rate [μm/yr]  Unknown

<table>
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<th>Electrical parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PSP ON [mVcse]</td>
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<tr>
<td>PSP AC [Vcse]</td>
<td>3.2</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Pictures</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Anomaly close to concrete weight</td>
<td>AC current density 68A/m²</td>
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## Case 10

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<tbody>
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<td>Diameter [inch]</td>
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</tr>
<tr>
<td>Material grade</td>
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</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>Not reported</td>
</tr>
<tr>
<td>Coating Type</td>
<td>FBE, 14-16 mils</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>17.42</td>
</tr>
<tr>
<td>Soil type</td>
<td>extremely dry and rocky</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>idem</td>
</tr>
<tr>
<td>pH</td>
<td>Not reported</td>
</tr>
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<table>
<thead>
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</thead>
<tbody>
<tr>
<td>Relative position</td>
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</tr>
<tr>
<td>Wall thickness reduction year 1998</td>
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</tr>
<tr>
<td>Wall thickness reduction year 2005</td>
<td>22%</td>
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</tbody>
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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Anomaly size</td>
<td>Year 2008</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>6.50</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>6.50</td>
</tr>
<tr>
<td>Depth [mm]</td>
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<tr>
<td>Calculated surface area [cm²]</td>
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<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>9.18</td>
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</table>
Estimated Corrosion Growth Rate [µm/yr] | 229

<table>
<thead>
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<tbody>
<tr>
<td>PSP ON [mVcse]</td>
<td>-1870</td>
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<tr>
<td>PSP AC [Vcse]</td>
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Pictures

<table>
<thead>
<tr>
<th>Calcite, granular paste-like black product</th>
<th>AC current density 29 A/m²</th>
</tr>
</thead>
</table>

Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements
Case 11

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<tr>
<td>Wall Thickness [inch]</td>
<td>Not reported</td>
</tr>
<tr>
<td>Coating Type</td>
<td>FBE, 14-16 mils (blister due to CP disbondment)</td>
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<tr>
<td>Soil resistivity [Ωm]</td>
<td>14.36</td>
</tr>
<tr>
<td>Soil type</td>
<td>Heavy water-logged clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>idem</td>
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<td>pH</td>
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<tbody>
<tr>
<td>Relative position</td>
<td>01:00 o ‘clock</td>
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<tr>
<td>Wall thickness reduction year 2005</td>
<td>1.27 mm</td>
</tr>
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<td>Wall thickness reduction year 2008</td>
<td>Not reported</td>
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</table>

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>Anomaly size</td>
<td>Year 2008</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>17</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>17</td>
</tr>
<tr>
<td>Depth [mm]</td>
<td>1.20</td>
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<tr>
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<td>2.27</td>
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<tr>
<td>Estimated Corrosion Growth Rate [µm/yr]</td>
<td>400</td>
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<td>Electrical parameters</td>
<td></td>
</tr>
<tr>
<td>PSP ON [mVcse]</td>
<td>-1870</td>
</tr>
<tr>
<td>PSP AC [Vcse]</td>
<td>5.7</td>
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<tr>
<td>Pictures</td>
<td></td>
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<tr>
<td>Calcite, granular paste-like black product</td>
<td>AC current density 29 A/m²</td>
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Case 12

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<tr>
<td>Material grade</td>
<td>Not reported</td>
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<tr>
<td>Wall Thickness [inch]</td>
<td>Not reported</td>
</tr>
<tr>
<td>Coating Type</td>
<td>FBE, 14-16 mils (blister due to CP disbondment)</td>
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<tr>
<td>Soil resistivity [Ωm]</td>
<td>74.68</td>
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<tr>
<td>Soil type</td>
<td>extremely dry and rocky</td>
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<tr>
<td>Pipe bedding</td>
<td>extremely dry and rocky</td>
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<tr>
<td>pH</td>
<td>Not reported</td>
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<tr>
<td>Relative position</td>
<td>11:00 o’clock</td>
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<tr>
<td>Wall thickness reduction year 2005</td>
<td>0.77 and 1.19 mm</td>
</tr>
<tr>
<td>Wall thickness reduction year 2008</td>
<td>0 mm and 1.02 mm</td>
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</table>

<table>
<thead>
<tr>
<th>Dig data</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Anomaly size</td>
<td>Year 2008</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>6 and 16 mm</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>6 and 16 mm</td>
</tr>
<tr>
<td>Depth [mm]</td>
<td>0.77 and 1.19 mm</td>
</tr>
<tr>
<td>Calculated surface area [cm²]</td>
<td>0.28 and 2.01</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>10.26 and 2.26</td>
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### Estimated Corrosion Growth Rate [μm/yr]

| Estimated Corrosion Growth Rate [μm/yr] | 257 and 57 |

### Electrical parameters

<table>
<thead>
<tr>
<th>PSP ON [mVcse]</th>
<th>-2068</th>
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</thead>
<tbody>
<tr>
<td>PSP AC [Vcse]</td>
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### Pictures

- Calcite, granular paste-like black product
- pH > 12 at anomaly
- AC current density 30.2 A/m²
## Case 13

### Pipeline properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of construction</td>
<td>April 1989</td>
</tr>
<tr>
<td>Diameter [inch]</td>
<td>8.62</td>
</tr>
<tr>
<td>Material grade</td>
<td>X42</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.219</td>
</tr>
<tr>
<td>Coating Type</td>
<td>FBE (blistered)</td>
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### Soil properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>60 (as-found) and 18.25 (water added)</td>
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<tr>
<td>Soil type</td>
<td>Clay/rock</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>Sand</td>
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<tr>
<td>pH</td>
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### ILI data

<table>
<thead>
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<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Relative position</td>
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<tr>
<td>Wall thickness reduction year 2012</td>
<td>36%</td>
</tr>
<tr>
<td>Wall thickness reduction year 2014</td>
<td>39%</td>
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### Dig data

<table>
<thead>
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<th>Value</th>
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<tbody>
<tr>
<td>Anomaly size</td>
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<tr>
<td>Length [mm]</td>
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<tr>
<td>Width [mm]</td>
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<tr>
<td>Depth [mm]</td>
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<td>Calculated surface area [cm²]</td>
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<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
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Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements

<table>
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<tr>
<th>Estimated Corrosion Growth Rate [μm/yr]</th>
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<td>PSP AC [Vcse]</td>
<td>5.9</td>
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**Pictures**

CaCO₃ hard, white at holiday/disbonded edge (good CP), FeCO₃ white under disbondment (anaerobic), FeS black, smelly under disbondment, presence of NaHCO₃
Case 14

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<td>Diameter [inch]</td>
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<tr>
<td>Material grade</td>
<td>X42</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.219</td>
</tr>
<tr>
<td>Coating Type</td>
<td>FBE (blistered)</td>
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<tr>
<td>Soil resistivity [Ωm]</td>
<td>8.52 (as-found) and 3.55 (water added)</td>
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<tr>
<td>Soil type</td>
<td>clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>clay</td>
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<tr>
<td>pH</td>
<td>5.5</td>
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<tbody>
<tr>
<td>Relative position</td>
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<tr>
<td>Wall thickness reduction year 2012</td>
<td>36%</td>
</tr>
<tr>
<td>Wall thickness reduction year 2014</td>
<td>37%</td>
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<tr>
<td>Length [mm]</td>
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<td>Width [mm]</td>
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<td>Estimated Corrosion Growth Rate [mils/yr]</td>
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<tr>
<td>Estimated Corrosion Growth Rate [μm/yr]</td>
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<td>PSP ON [mVcse]</td>
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<td>PSP AC [Vcse]</td>
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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>CaCO₃ hard, white at holiday/disbonded edge (good CP), FeCO₃ white under disbondment (anaerobic), FeS black, smelly under disbondment, presence of NaHCO₃, FeO brown scaly (aerobic)</td>
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Case 18

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<tr>
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<tbody>
<tr>
<td>Year of construction</td>
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<tr>
<td>Diameter [inch]</td>
<td>12.75</td>
</tr>
<tr>
<td>Material grade</td>
<td>X42</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.25</td>
</tr>
<tr>
<td>Coating Type</td>
<td>Synergy (damaged coating)</td>
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<table>
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<th>Soil properties</th>
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<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>11.21 (as-found) and 5.31 (water added)</td>
</tr>
<tr>
<td>Soil type</td>
<td>Clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>Sand</td>
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<td>pH</td>
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<tr>
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<tr>
<td>Wall thickness reduction year 2014</td>
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<td>Length [mm]</td>
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<td>Width [mm]</td>
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<td>Depth [mm]</td>
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<td>Calculated surface area [cm²]</td>
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<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>3.69</td>
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Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements

<table>
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<tr>
<th>Estimated Corrosion Growth Rate [μm/yr]</th>
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<tr>
<td>PSP AC [Vcse]</td>
<td>3.7</td>
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<table>
<thead>
<tr>
<th>Pictures</th>
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</thead>
</table>

CaCO₃ hard, white at holiday/disbonded edge (good CP), FeCO₃ white under disbondment (anaerobic), FeS black, smelly under disbondment, presence of NaHCO₃, FeO brown scaly (aerobic)
Case 17

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<td>Diameter [inch]</td>
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<tr>
<td>Material grade</td>
<td>X42</td>
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<tr>
<td>Wall Thickness [inch]</td>
<td>0.25</td>
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<tr>
<td>Coating Type</td>
<td>Synergy (damaged coating)</td>
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<td>Soil resistivity [Ωm]</td>
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<td>Soil type</td>
<td>Clay</td>
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<td>Pipe bedding</td>
<td>Sand</td>
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<tr>
<td>pH</td>
<td>5.5</td>
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</table>

<table>
<thead>
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<th>ILI data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative position</td>
<td>10:20 o’clock</td>
</tr>
<tr>
<td>Wall thickness reduction year 2012</td>
<td>16%</td>
</tr>
<tr>
<td>Wall thickness reduction year 2014</td>
<td>19%</td>
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<table>
<thead>
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<td>Estimated Corrosion Growth Rate [μm/yr]</td>
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<tr>
<td><img src="image1.jpg" alt="Image 1" /></td>
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<tr>
<td>Black powder</td>
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Case 13

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<tbody>
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<td>Nov 1998</td>
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<tr>
<td>Diameter [inch]</td>
<td>12.75</td>
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<tr>
<td>Material grade</td>
<td>X42</td>
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<tr>
<td>Wall Thickness [inch]</td>
<td>0.25</td>
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<tr>
<td>Coating Type</td>
<td>Synergy (damaged coating)</td>
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<table>
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<th>Soil properties</th>
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<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>11.2 (as-found) and 8.27 (water added)</td>
</tr>
<tr>
<td>Soil type</td>
<td>Clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>Clay</td>
</tr>
<tr>
<td>pH</td>
<td>6.5</td>
</tr>
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<tbody>
<tr>
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<tr>
<td>Wall thickness reduction year 2012</td>
<td>30%</td>
</tr>
<tr>
<td>Wall thickness reduction year 2014</td>
<td>28%</td>
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</thead>
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<td>Anomaly size</td>
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<tr>
<td>Length [mm]</td>
<td>12.7</td>
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<tr>
<td>Width [mm]</td>
<td>12.7</td>
</tr>
<tr>
<td>Depth [mm]</td>
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<tr>
<td>Calculated surface area [cm²]</td>
<td>1.61</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>4.31</td>
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Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements

<table>
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<th>Estimated Corrosion Growth Rate [$\mu$m/yr]</th>
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**Electrical parameters**

<table>
<thead>
<tr>
<th>PSP ON [mVcse]</th>
<th>-1560</th>
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</thead>
<tbody>
<tr>
<td>PSP AC [Vcse]</td>
<td>5.04</td>
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**Pictures**

![Pipe corrosion image]

![Pipeline measurement image]
Case 15

**Pipeline properties**

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<tbody>
<tr>
<td>Year of construction</td>
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<tr>
<td>Diameter [inch]</td>
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</tr>
<tr>
<td>Material grade</td>
<td>X42</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.25</td>
</tr>
<tr>
<td>Coating Type</td>
<td>Synergy (damaged coating)</td>
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</table>

**Soil properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>28.18 (as-found) and 22.45 (water added)</td>
</tr>
<tr>
<td>Soil type</td>
<td>Clay/rock</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>sand</td>
</tr>
<tr>
<td>pH</td>
<td>6.5</td>
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**ILI data**

<table>
<thead>
<tr>
<th>Property</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>Wall thickness reduction year 2012</td>
<td>18%</td>
</tr>
<tr>
<td>Wall thickness reduction year 2014</td>
<td>19%</td>
</tr>
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**Dig data**

<table>
<thead>
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<th>Value</th>
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<td>Length [mm]</td>
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<td>Width [mm]</td>
<td>14.2875</td>
</tr>
<tr>
<td>Depth [mm]</td>
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<td>Calculated surface area [cm²]</td>
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<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>2.94</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [μm/yr]</td>
<td>73</td>
</tr>
<tr>
<td>----------------------------------------</td>
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<thead>
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<td>PSP ON [mVcse]</td>
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<td>PSP AC [Vcse]</td>
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<table>
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<tr>
<td><img src="brown-scaly-FeO-product-with-CO3-pH-6.5.png" alt="Picture" /></td>
<td>brown scaly FeO product with CO3, pH 6.5</td>
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</table>
Case 19

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<tbody>
<tr>
<td>Year of construction</td>
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</tr>
<tr>
<td>Diameter [inch]</td>
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</tr>
<tr>
<td>Material grade</td>
<td>X60</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.281</td>
</tr>
<tr>
<td>Coating Type</td>
<td>FBE</td>
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</tbody>
</table>

<table>
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<th>Soil properties</th>
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<tr>
<td>Soil resistivity [Ωm]</td>
<td>10.55 (as-found) 10.55 (water added)</td>
</tr>
<tr>
<td>Soil type</td>
<td>wet clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>Wet sand</td>
</tr>
<tr>
<td>pH</td>
<td>9.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ILI data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative position</td>
<td>4:32 o’clock</td>
</tr>
<tr>
<td>Wall thickness reduction year 2007</td>
<td>0</td>
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<tr>
<td>Wall thickness reduction year 2012</td>
<td>40%</td>
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<table>
<thead>
<tr>
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</thead>
<tbody>
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<td>Anomaly size</td>
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</tr>
<tr>
<td>Length [mm]</td>
<td>19.05</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>19.05</td>
</tr>
<tr>
<td>Depth [mm]</td>
<td>1.499</td>
</tr>
<tr>
<td>Calculated surface area [cm²]</td>
<td>3.63</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>7.375</td>
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Estimated Corrosion Growth Rate [μm/yr] | 184

<table>
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</thead>
<tbody>
<tr>
<td>PSP ON [mVcse]</td>
<td>-1545</td>
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<td>PSP AC [Vcse]</td>
<td>12.96</td>
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Pictures

- dark black scaly granular product with slight magnetism
- FES test indicates black smelly under coating
Case 21

<table>
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<tr>
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</thead>
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<tr>
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<tr>
<td>Diameter [inch]</td>
<td>20</td>
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<tr>
<td>Material grade</td>
<td>X60</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.281</td>
</tr>
<tr>
<td>Coating Type</td>
<td>FBE</td>
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<table>
<thead>
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</thead>
<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>18.94 (as-found) 18.94 (water added)</td>
</tr>
<tr>
<td>Soil type</td>
<td>clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>sand</td>
</tr>
<tr>
<td>pH</td>
<td>7.5</td>
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</tbody>
</table>

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</thead>
<tbody>
<tr>
<td>Relative position</td>
<td>11:43 o’clock</td>
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<tr>
<td>Wall thickness reduction year 2007</td>
<td>0</td>
</tr>
<tr>
<td>Wall thickness reduction year 2012</td>
<td>40%</td>
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</table>

<table>
<thead>
<tr>
<th>Dig data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomaly size</td>
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<tr>
<td>Length [mm]</td>
<td>25.4</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>25.4</td>
</tr>
<tr>
<td>Depth [mm]</td>
<td>2.972</td>
</tr>
<tr>
<td>Calculated surface area [cm²]</td>
<td>6.45</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>14.63</td>
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</table>
### Estimated Corrosion Growth Rate [μm/yr]

<table>
<thead>
<tr>
<th>Estimated Corrosion Growth Rate [μm/yr]</th>
<th>366</th>
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### Electrical parameters

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</thead>
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<td>PSP ON [mVcse]</td>
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<td>PSP AC [Vcse]</td>
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### Pictures

<table>
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<tbody>
<tr>
<td><img src="image1.jpg" alt="Picture 1" /></td>
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- dark black scaly granular product with slight magnetism
- FES test indicates black smelly under coating
Case 22

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</thead>
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<tr>
<td>Diameter [inch]</td>
<td>20</td>
</tr>
<tr>
<td>Material grade</td>
<td>X60</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.281</td>
</tr>
<tr>
<td>Coating Type</td>
<td>FBE</td>
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<table>
<thead>
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</thead>
<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>19.73 (as-found) 19.73 (water added)</td>
</tr>
<tr>
<td>Soil type</td>
<td>clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>sand</td>
</tr>
<tr>
<td>pH</td>
<td>7.5</td>
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</table>

<table>
<thead>
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<tbody>
<tr>
<td>Relative position</td>
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<tr>
<td>Wall thickness reduction year 2007</td>
<td>0</td>
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<tr>
<td>Wall thickness reduction year 2012</td>
<td>22%</td>
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<td>Year 2015</td>
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<td></td>
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<td>Length [mm]</td>
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<tr>
<td>Width [mm]</td>
<td>25.4</td>
</tr>
<tr>
<td>Depth [mm]</td>
<td>2.972</td>
</tr>
<tr>
<td>Calculated surface area [cm²]</td>
<td>6.45</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
<td>14.63</td>
</tr>
<tr>
<td>Estimated Corrosion Growth Rate [μm/yr]</td>
<td>366</td>
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<tbody>
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</tr>
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<td>PSP AC [Vcse]</td>
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### Case 23

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<td>Diameter [inch]</td>
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<tr>
<td>Material grade</td>
<td>X60</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.281</td>
</tr>
<tr>
<td>Coating Type</td>
<td>FBE</td>
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<table>
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<tbody>
<tr>
<td>Soil resistivity [$\Omega$m]</td>
<td>10.53 (as-found) 10.53 (water added)</td>
</tr>
<tr>
<td>Soil type</td>
<td>clay</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>sand</td>
</tr>
<tr>
<td>pH</td>
<td>-</td>
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<tbody>
<tr>
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<tr>
<td>Wall thickness reduction year 2007</td>
<td>0</td>
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<tr>
<td>Wall thickness reduction year 2012</td>
<td>24%</td>
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<table>
<thead>
<tr>
<th>Dig data</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Anomaly size</td>
<td>Year 2015</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>19.05</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>19.05</td>
</tr>
<tr>
<td>Depth [mm]</td>
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<tr>
<td>Calculated surface area [cm$^2$]</td>
<td>3.63</td>
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<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
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</table>
Estimated Corrosion Growth Rate [μm/yr] | 175

<table>
<thead>
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</thead>
<tbody>
<tr>
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<td>PSP AC [Vcse]</td>
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<thead>
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</tr>
</thead>
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<tr>
<td></td>
<td></td>
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<tr>
<td></td>
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</tr>
</tbody>
</table>

- dark black scaly granular product with slight magnetism
- FES test indicates black smelly under coating
**Case 35**

<table>
<thead>
<tr>
<th>Pipeline properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of construction</td>
<td>1953</td>
</tr>
<tr>
<td>Diameter [inch]</td>
<td>20</td>
</tr>
<tr>
<td>Material grade</td>
<td>X52</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.344</td>
</tr>
<tr>
<td>Coating Type</td>
<td>Coal Tar Enamel</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil properties</th>
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</thead>
<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>10.0</td>
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<tr>
<td>Soil type</td>
<td>loam/marsh wetlands</td>
</tr>
<tr>
<td>Pipe bedding</td>
<td>native soil, loose back fill</td>
</tr>
<tr>
<td>pH</td>
<td>5.5</td>
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</tbody>
</table>

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative position</td>
<td>06:10 o’clock</td>
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<tr>
<td>Wall thickness reduction year 2014</td>
<td>67%</td>
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</table>

<table>
<thead>
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<th>Dig data</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Anomaly size</td>
<td>Year 2015</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Length [mm]</td>
<td>82.30</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>21.84</td>
</tr>
<tr>
<td>Depth [mm]</td>
<td>0.233</td>
</tr>
<tr>
<td>Calculated surface area [cm²]</td>
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</tr>
<tr>
<td>Estimated Corrosion Growth Rate [mils/yr]</td>
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</tr>
<tr>
<td>Estimated Corrosion Growth Rate [μm/yr]</td>
<td>90</td>
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</table>

*total surface area of two anomalies*
## Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements

### Electrical parameters

<table>
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<th>Parameter</th>
<th>Value</th>
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<tbody>
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</tr>
<tr>
<td>PSP AC [Vcse]</td>
<td>1.5</td>
</tr>
</tbody>
</table>

### Pictures

- **hard CaCO$_3$ crust**

![Image of hard CaCO$_3$ crust](image-url)
**Case 36**

<table>
<thead>
<tr>
<th>Pipeline properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of construction</td>
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<tr>
<td>Diameter [inch]</td>
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</tr>
<tr>
<td>Material grade</td>
<td>X52</td>
</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.344</td>
</tr>
<tr>
<td>Coating Type</td>
<td>Coal Tar Enamel</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Soil properties</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>17.0</td>
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<tr>
<td>Soil type</td>
<td>loam, marsh, wetlands, swampy</td>
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<tr>
<td>Pipe bedding</td>
<td>native soil, loose back fill</td>
</tr>
<tr>
<td>pH</td>
<td>4.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>ILI data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative position</td>
<td>07:10 o’clock</td>
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<tr>
<td>Wall thickness reduction year 2014</td>
<td>52%</td>
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</table>

<table>
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<tr>
<td>Depth [mm]</td>
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<tr>
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<td>72</td>
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*total surface area of two anomalies
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<td>PSP ON [mVcse]</td>
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<tr>
<td>PSP AC [Vcse]</td>
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<table>
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<tbody>
<tr>
<td>[Image of hard CaCO3 crust]</td>
<td>[Image of something with times 7:00, 7:15, and 6:45]</td>
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</table>

hard CaCO3 crust
Case 37

<table>
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<th>Pipeline properties</th>
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</thead>
<tbody>
<tr>
<td>Year of construction</td>
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</tr>
<tr>
<td>Diameter [inch]</td>
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</tr>
<tr>
<td>Material grade</td>
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</tr>
<tr>
<td>Wall Thickness [inch]</td>
<td>0.51</td>
</tr>
<tr>
<td>Coating Type</td>
<td>3L-PE (3-4mm thick)</td>
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</table>

<table>
<thead>
<tr>
<th>Soil properties</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Soil resistivity [Ωm]</td>
<td>0.5 (as-found) 0.57 (water added)</td>
</tr>
<tr>
<td>Soil type</td>
<td>Not reported</td>
</tr>
<tr>
<td>Pipe bedding</td>
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<tr>
<td>pH</td>
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<table>
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<tbody>
<tr>
<td>Relative position</td>
<td>Not reported</td>
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<td>Wall thickness reduction year 2014</td>
<td>29%</td>
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<table>
<thead>
<tr>
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</tr>
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<td>Length [mm]</td>
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<td>Width [mm]</td>
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Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements

<table>
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<tbody>
<tr>
<td>PSP ON [mVcse]</td>
<td>-1250</td>
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<td>PSP AC [Vcse]</td>
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*effective AC mitigation in place since 1999

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<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
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some grey or greyish to black soil parts with oily black substance, hard stone soil formation
pH = 8.5 at anomaly

Case 38

<table>
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<tbody>
<tr>
<td>Year of construction</td>
<td>1993</td>
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<td>Diameter [inch]</td>
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<td>Material grade</td>
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</tr>
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<td>8.6 (as-found)</td>
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<td>Pipe bedding</td>
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<td>pH</td>
<td>7.88</td>
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<table>
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<tr>
<td>Relative position</td>
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<tr>
<td>Wall thickness reduction year 2012</td>
<td>12%</td>
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<table>
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</tr>
</thead>
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<td>Length [mm]</td>
<td>13</td>
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<tr>
<td>Width [mm]</td>
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</thead>
<tbody>
<tr>
<td>PSP ON [mVcse]</td>
<td>-1300</td>
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<tr>
<td>Pictures</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
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<tr>
<td><img src="image1.png" alt="Picture 1" /></td>
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</table>

some grey or greyish to black soil parts with oily black substance, hard stone soil formation
Appendix F – AC corrosion likelihood assessment (ISO18086 Annex F)

Key
1  less negative cathodic protection level
2  more negative cathodic protection level
3  AC corrosion
x  DC current density (A/m²)
y  AC current density (A/m²)

Key
1  less negative cathodic protection level
2  more negative cathodic protection level
3  AC corrosion
x  $E_{cd}$ (V against CSE)
y  $U_{ac}$ (V)
NOTE  Axis limits for x are given for information. In practice, it is possible to have higher axis ranges.
Appendix G - Monitoring data from case 39 till 42

![Graph 1: TP050](image1.png)

![Graph 2: TP050](image2.png)
Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements
Appendix H - Monitoring data from case 43 and 44
Appendix I - Monitoring data from case 24 to 34

Upstream AC grounding 1

Upstream AC grounding 2

Downstream AC grounding
Appendix J – Field procedure for AC corrosion risk assessment

Summary

The objective of this document is to describe a field procedure for better qualification of the AC corrosion risk on buried pipelines in collocation with high voltage power lines. The procedure was elaborated based on Elsyca’s experience and the additional knowledge gained during the PRCI research project. The procedure is still subjected to changes. Improvements and/or modifications are still to be expected.

AC corrosion assessment procedure

The procedure shall be executed in chronological order as given below. Elsyca realizes that some testing methods may not be feasible to perform due to constraints in the field. In some cases, alternative set-ups and test methods are provided.

Pipe properties:

General properties of the pipe section under investigation are required for obtaining a good interpretation of the field data. They are the following:

1. Year of installation
2. Pipe grade
3. Diameter
4. Soil coverage or burial depth
5. Coating type and thickness
6. Amount of pipelines paralleling in same ROW

Location

The objective is to identify the field conditions (presence of power lines, environment, etc) through Google Earth image and to retrieve additional soil information from available geotechnical databases (e.g. WebSoilSurvey for US operators). Please provide:

1. Lat/Long coordinates where the readings will be taken
2. Specify location of interest (detected anomalies by ILI or ECDA methods, high AC voltage, …)
Soil resistivity measurements

Perform soil resistivity measurement nearby the pipe through 4-pin Wenner method. Pin spacing should be 2.5, 5, 10, 15 and 20 ft respectively. Execute for parallel and perpendicular alignment with respect to the pipe. Calculate the apparent soil resistivity of the different soil strata, if possible.

Alternative methods like soil box or Collin rods are allowed in case of e.g. space restrictions. Both methods require soil augering which should be done preferentially as close as possible to the pipe. Readings should be taken at various depths at 0.5m intervals until the depth of the bottom of the pipe is reached. These techniques can also be applied during the interpolation method (see below).

Coating defect survey

The objective is to detect and qualify coating holidays for a better estimation of the AC corrosion risk. Conventional methods like DCVG or ACVG (A-frame) can be used for this purpose.

- Determine epicenter of the DCVG/ACVG signal.
- Note the position of the epicenter with respect to the pipe centerline (e.g by GPS coordinates if accurate positioning system is used)
- Notify if other epicenters are present within 50 meters distance

Interpolation method

The objective is to obtain more accurate data on the CP level and the AC voltage near the pipe surface, and to determine the conditions that rules at the coating defects. More background on the interpolation method is given in Appendix A. The procedure is as follows:

DC measurement:

1. Perform a boring by manual augering through the epicenter as determined in previous step until 0.5m (of 1.6 ft) depth.
2. Place one reference electrode just below grade near the boring by removing the top layer. Connect to the negative (COM) of multimeter. Connect the positive pole to the pipe at closest test station.
3. Place a second reference electrode at the bottom of the borehole. Connect to the positive pole of a second multimeter. Connect the negative (COM) to the negative (COM) of the first multimeter.
4. Put the multimeters in AC measuring mode. Take induced AC voltage reading.
5. Apply an AC signal to the pipe from a temporary anode at 5m perpendicular distance from the pipe. Perform test with constant current output (e.g. 100mA). Select a low frequency output signal first (LF mode). Then repeat the same with extra low frequency signal (ELF mode). See note (3) and (4) for more details. Record at each frequency the AC voltage reads on the readers.
6. Put the multimeters in DC measuring mode.
7. Record the readings on the multimeters under normal CP operation. Then modify the CP level by interrupting the rectifiers or by decreasing the rectifier output. A minimum of 100
mV pipe-to-soil potential swift into electropositive direction should be obtained. Record the readings on both multimeters.

8. Increase the depth of the boring with increments of 0.5 m until the level of the bottom of the pipe is reached and repeat the steps 2 through 7 for every depth.

Notes:

(1) In the case that the epicenter is located above the pipe, a boring next to the pipe must be performed. Please provide position with respect to pipe centerline.

(2) Use coaxial cables that are NOT coiled. Unspool the cable from the reel if needed.

(3) AC signals can be applied by transmitter of the ACVG equipment. In general, the user can select the applied frequency (extra low frequency of e.g. 4 Hz when using the A-frame and low frequency of e.g. 640/512 kHz when performing the fault localization in ACCA mode) and current output of the generator.

(4) induced AC (50 or 60 Hz) originating from the power line load may be used as an alternative. The AC voltage readings should be logged for at least 1h such that sufficient AC fluctuations are measured. Please provide time stamped AC reads.

**AC current measurement**

The objective is to obtain an impression of the AC current density. This a snapshot in time and does not reflect the long-term process at the pipe coating defects.

- Insert a 1 cm² coupon into the bore hole
- Measure the AC current drained by the coupon

**Soil characterization**

During augering event of the interpolation method, the excavated soil is collected at grade and aligned according to the depth.

1. Take a picture of the obtained soil profile.
2. Determine the presence of high groundwater table by (borehole is gradually filling with water or sampled soil have a very water saturated appearance).
3. Describe the soil type for each soil stratum (stones/gravel, sand, silt or clay) and note the depth.
Appendix K - background IR-free interpolation method

The EN13509 standard describes intensive measurements to determine the IR-free potential at coating holidays detected by various methods. The intensive measurement technique measures simultaneously pipe-to-soil potentials and associated horizontally opposed potential gradients according to Figure K1. The technique identifies coating defects and enables calculation of IR-free potentials at the defects.

The IR-free obtained with this set-up is calculated according formula K1:

\[ E_{IRfree} = E_{off} - \frac{\Delta E_{off}}{\Delta E_{on} - \Delta E_{off}} (E_{on} - E_{off}) \]  \hspace{1cm} (K1)

Re-arranging formula K1 gives formula K2.
\[
\frac{E_{IRfree} - E_{off}}{E_{on} - E_{off}} = -\frac{\Delta E_{off}}{\Delta E_{on} - \Delta E_{off}} \quad (K2)
\]

With

- \(E_{IRfree}\)  IR free pipe-to-soil potential
- \(E_{off}\)  Instant off pipe-to-soil potential
- \(E_{on}\)  Pipe-to-soil ON potential
- \(\Delta E\)  Potential difference or voltage gradient

The graphical representation of the formula (K2) is given in Figure K2. The slope of the interpolation line is determined by the voltage gradient of pipe-to-soil-potential ratio. The IR-free is found by interpolating the line to a zero-voltage gradient.

![Graphical Representation of the IR-Free Interpolation Method](image-url)
Under DC stray current conditions, the two measurements gives two different IR-free potentials. After averaging these two IR-free potentials the correct IR-free potential is obtained.

So far it is not known to which extent the IR-free interpolation method is applicable in more complicated situations as encountered for real pipelines and how accurate the method is in practice. The sensitivity of the IR-free interpolation method was studied through simulation technology and a new set-up of the reference electrodes is proposed for improved accuracy.

Different scenarios were investigated to demonstrate the sensitivity of the IR-free interpolation method for measuring errors, position of the reference cells and DC stray current. Finally, a set-up with vertical alignment of the electrodes is preferred and will be described.

Furthermore, the same set-up is used for measuring in AC modus for the purpose of AC corrosion risk evaluation.

Below, some external influences are summarized that may make the IR-free determination erroneous.

1. Noise on the reference electrodes

Portable reference electrodes may produce a noise in the potential reading at the contact interface under certain soil conditions. This occurs mainly at grade level and less just below the top soil surface. Variations up to 7 mV per reference electrode can be experienced in some cases. This offset error will shift the IR-free interpolation curve in both vertical and horizontal direction.

2. Position of the remote reference electrode on grade level (cells 3 and 3’ in figure 1)

Increasing the distance of the remote reference cell increases the potential gradient and thus the sensitivity of the measurement. Typical perpendicular distance of the remote electrode to the pipe centerline is between 5 to 20 m. However, the measurement becomes more prone to stray current interference and potential disturbances caused by foreign objects close to the pipe.

3. Influence of stray currents

DC stray currents are dynamic (e.g. DC traction systems) or static in nature (e.g. 3rd party CP or HVDC systems). They will affect both pipe-to-soil and potential gradient readings. A typical electrical field originating from DC stray currents ranges from 0.1 to 1.0 mV/m.

The external influences may occur simultaneously leading to significant errors in the obtained results.

In order to minimize these errors an alternative set-up was elaborated based on a vertical alignment of the reference electrodes. The vertical alignment is located at the epicenter of the DCVG signal.
The improved set-up for accurate IR-free interpolation measurements is shown in Figure 3. The two reference electrodes are put in line in vertical direction at the epicenter of the potential cone. The reference cell 2 in Figure K1 is placed below reference cell 3.

![Figure K3](image)

**Figure K3** – graphical representation of improved IR-free interpolation method with vertical alignment

A minimum pipe-to-soil potential swing of 100 mV (ON/OFF) is required and it is assumed that the interruption cycle should be adjusted such that negligible depolarization occurs during the switching.

By putting the central reference cell deeper into the borehole, the potential gradient can be increased again. The gradient can thereby be significantly larger than the original setup even when the remote reference cell is located at 20 m perpendicular distance from the pipe. An example for a 36 inch pipe with a defect at respectively 9 and 6 o’clock position is given in Figure 4 and 5. In the case of the 6 o’clock position (defect at bottom of the pipe) the reference cell set-up can be aligned next to the pipe.
Figure K4 – vertical alignment of reference cells for 36” pipe with defect at 9 o’clock and 100mV potential shift

Figure K5 – vertical alignment of reference cells next to 36” pipe with defect at 6 o’clock and 100mV potential shift

It is important to note that a greater gradient can be realized by using the vertical measurement setup than in the classic measurement setup. The vertical alignment is less sensitive for stray currents, which would make single vertical measurements acceptable instead of two measurements at both sides of the pipeline.
Conclusions

The IR-free interpolation method requires an intensive measurement that is mostly only executed for an in-depth analysis such as for AC corrosion risk assessments. To increase the certainty of the IR-free value a vertical alignment of the reference cells is recommended.

The vertical set-up has the benefit to generate enough strong signals while minimizing the effect of stray currents.

In case of suspected defects at the top and side of a pipe, it can be enough to perform a single vertical measurement at the epicenter. In case of suspected defects on the underside of large pipelines due to weak signals a vertical measurement on both sides of the pipe (and averaging afterwards) is recommended, however, one single vertical measurement is highly likely to be practically sufficient. It is recommended to place the “remote” reference cell directly below ground level in order to avoid noise on the reference cells.
Appendix L – Results of AC corrosion assessment method

Pipe 1

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<th>Coupon area [cm²]</th>
<th>Current density</th>
<th>Depth [inch]</th>
<th>ρ [Ωm]</th>
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<tbody>
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<td>5.71</td>
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<tr>
<td>1</td>
<td>0.7</td>
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<td>100</td>
<td>11.5</td>
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<td>8.88</td>
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<td></td>
<td></td>
<td>72</td>
<td>7.11</td>
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Current density: Jdc [A/m²], Jac [A/m²]
Pipe 2

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<th>Coupon area [cm²]</th>
<th>Current density Jdc [A/m²]</th>
<th>Jac [A/m²]</th>
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</thead>
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<tr>
<td>7.5</td>
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<td>1</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>-</td>
<td>-</td>
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</table>

<table>
<thead>
<tr>
<th>Depth [inch]</th>
<th>ρ [Ωm]</th>
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</thead>
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<td>50</td>
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<td>65</td>
<td>177.72</td>
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Anomaly

![Anomaly graph showing different anomaly levels for various depths and frequencies.](image-url)
Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements
Pipe 3

### Current density

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<thead>
<tr>
<th>Jdc [A/m²]</th>
<th>Jac [A/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.2</td>
<td>21.6</td>
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</tbody>
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---

**Anomaly**

- ambient
- 3/6/98Hz 1000mA-8V
- 98Hz 3000mA-16V

**Anomaly+7.5cm²@26”**

- ambient
- 3/6/98Hz 1000mA-8V
- 98Hz 3000mA-16V
Pipe 4

<table>
<thead>
<tr>
<th>Current density</th>
<th>Jdc [A/m²]</th>
<th>Jac [A/m²]</th>
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<tr>
<td>-7.3</td>
<td>3.6</td>
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</tr>
<tr>
<td>34</td>
<td>16.46</td>
</tr>
</tbody>
</table>
Validation of the AC Corrosion Criteria on Real-World Pipeline Measurements

**Anomaly+7.5cm^2@26''**

- **ambient**
- 3/6/98Hz 1000mA-8V
- 98Hz 3000mA-16V

**Anomaly+417cm^2@38''**

- **ambient**
- 3/6/98Hz 1000mA-8V
- 98Hz 3000mA-16V