INTERNAL AXIAL CORROSION IN OFFSHORE PIPELINES: INSPECTION AND ASSESSMENT

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Abstract

Internal long axial corrosion is the most common corrosion type in offshore crude oil and water injection pipelines. It has frequently a complex shape that ranges from a smooth uniform wall thickness reduction to a rugged surface with varying depths. Long axial corrosion anomalies can be reliably detected and sized by means of ultrasonic in-line inspection (UT ILI). The rough surface of the corrosion can lead to outliers in the gathered ILI data. Accordingly, an elaborated filtering and re-processing of the inspection data is crucial for a reliable data assessment. The inspection report usually provides maximum anomaly dimensions (total length, peak depth, etc.) and does not sufficiently describe the complex shape of corrosion anomalies. Therefore, methods based on corrosion depth profile (river-bottom profile, RBP) have to be applied for pressure capacity assessment. In addition, corrosion growth rates are ideally obtained by comparing RBPs of consecutive inspections.

This paper outlines the main results of a recent joint industry project that provides guidance to the assessment of long axial corrosion based on UT ILI results. It involves the determination of RBPs, the calculation of the safe operating pressure, the determination of corrosion growth rates and the extrapolation of the future pressure capacity. Compared to other assessment methods which are also based on RBP, the presented assessment approach accounts for a higher probability of failure associated with a higher number of corroded sections in a pipeline.

1 Introduction

Many crude oil and water injection pipelines are affected by internal corrosion along the six o'clock position. Often, a coherent corrosion area extends over several kilometers length. Common synonyms for this type of corrosion are long axial corrosion, bottom-line corrosion, six o'clock corrosion or channeling corrosion.

The shape of long axial corrosion anomalies can vary significantly, depending e.g. on the corrosion mechanism and the flow regime. On the one hand, pipes can show a very smooth and uniform reduction in wall thickness along the six o'clock position as is typical e.g. for a combined corrosion/erosion process (example in Figure 1).

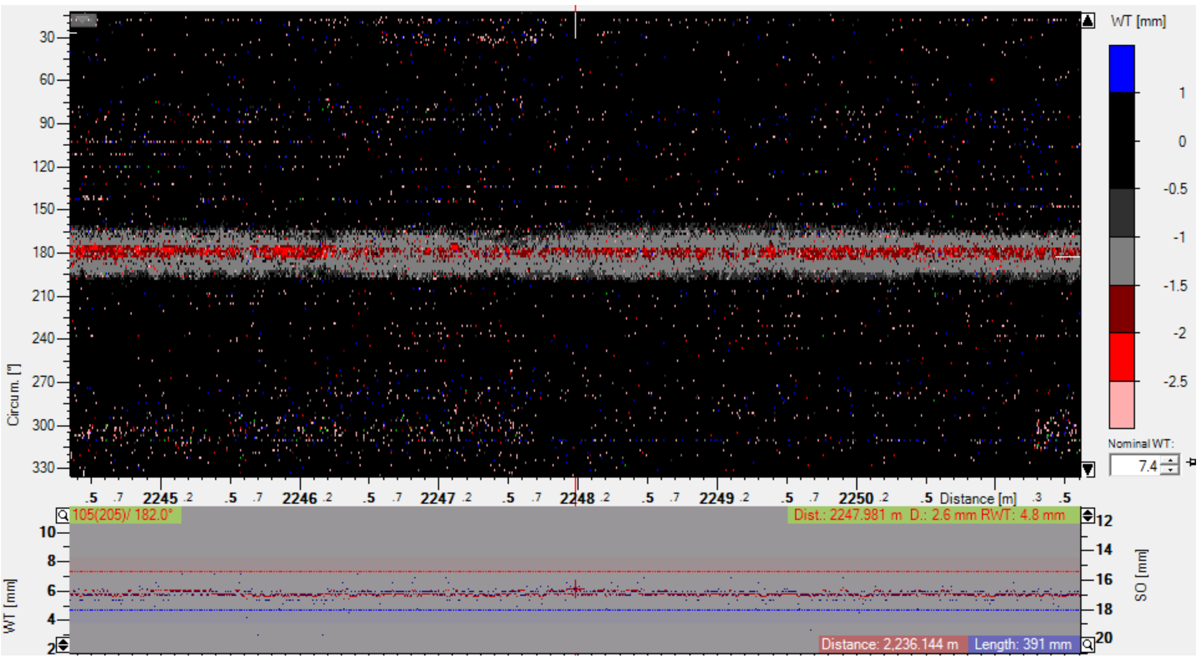

Figure 1: Long axial corrosion with a smooth and even shape

On the other hand, corrosion features can have an irregular and complex shaped geometry, often combined with a rough internal pipe surface. This is typical for microbiologically induced corrosion (MIC). An example for channeling corrosion with a complex shape is shown in Figure 2.

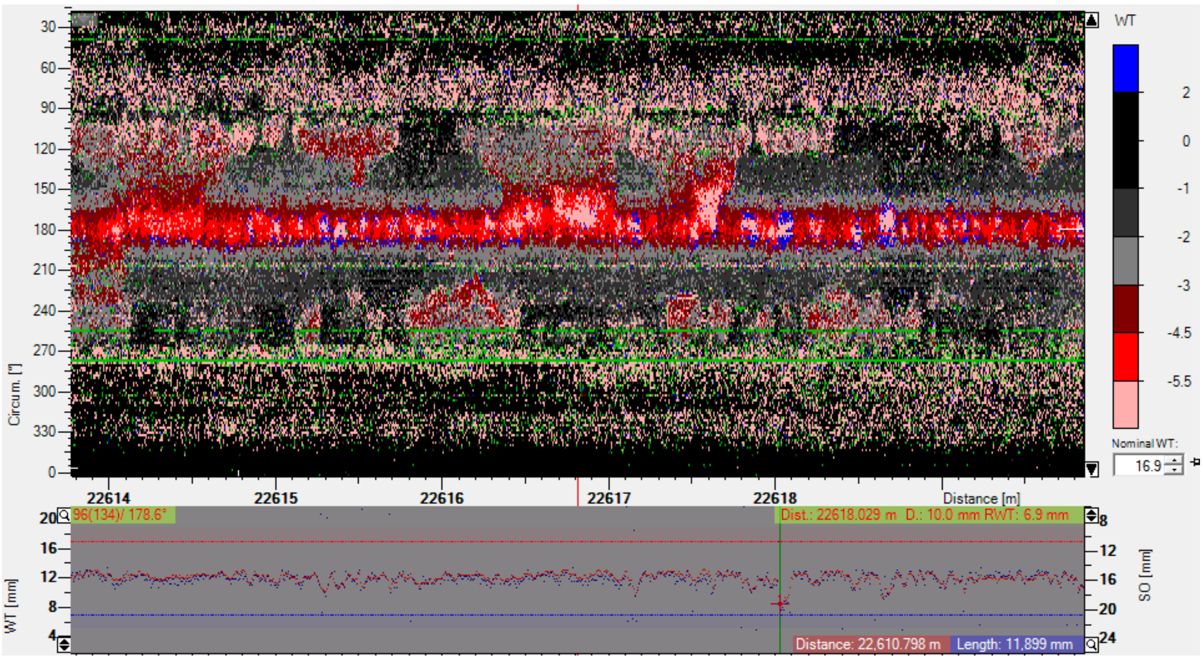

Figure 2: Long axial corrosion with a complex and rugged shape

Figure 3 shows pit-like corrosion spots lining up along the 6 o'clock position of a pipe. Often, this is an early stage of continuous channeling corrosion.

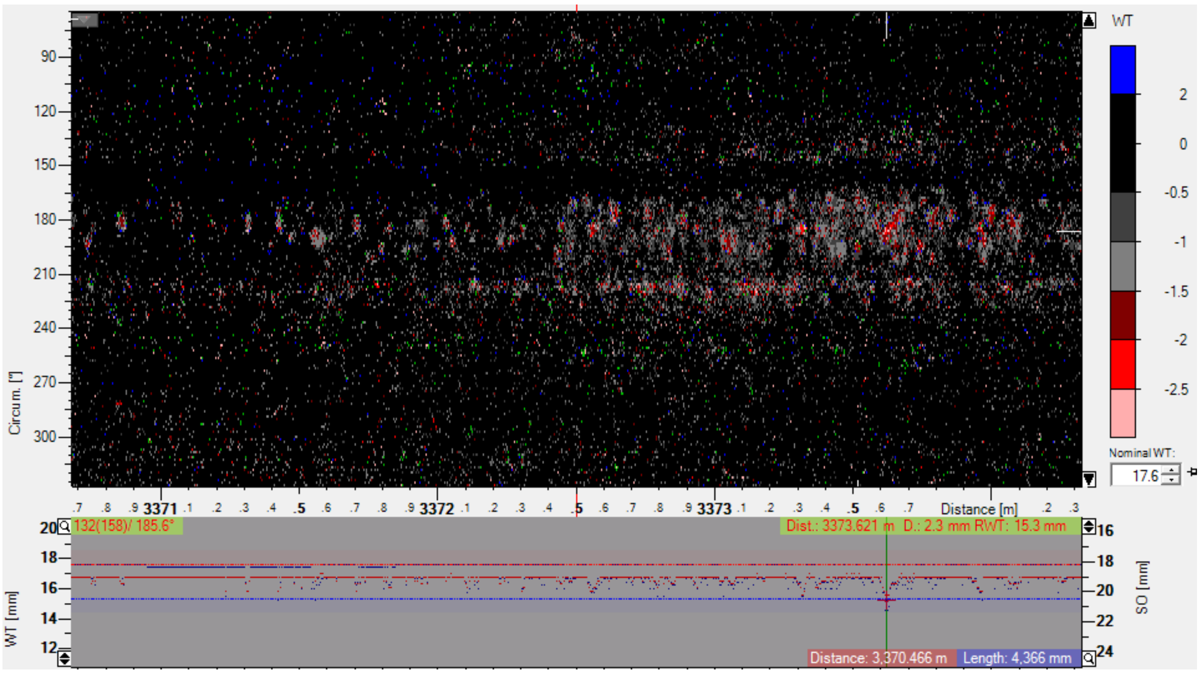

Figure 3: Chain of pit-like corrosion spots along the 6 o'clock position

Long axial corrosion has impact on several aspects of ILI and subsequent fitness for purpose (FFP) assessment. These are addressed in the following chapter. A comprehensive procedure for the assessment of pipelines affected by long axial corrosion is outlined in chapter 3

2 Impacts of Long Axial Corrosion on ILI and FFP

2.1 Inspection Technology

Channeling corrosion can be reliably detected and sized by means of ultrasonic wall thickness inspection tools. Apart from the basic anomaly dimensions (total length and width, peak depth or minimum remaining wall thickness), ultrasonic ILI data displays accurately the contour of the metal loss feature. Conventional MFL tools using axial magnetization are not well suited to detect long axially oriented anomalies and cannot reliably size them. Other generations of MFL tools (TFI, Spiral MFL) were developed for the detection of axial corrosion. However, their depth sizing capabilities are still limited in comparison to UT tools and they are not able to accurately reproduce the depth profile.

2.2 Cleaning

As residual dirt and scale poses a challenge for UT ILI, cleaning of the internal pipe surface prior to inspection is essential. Depending on the shape of the long axial corrosion, the adjustment of 'standard' cleaning procedures can considerably improve the effectiveness of the cleaning. As an example, cleaning results inside deep and relatively narrow corrosion channels can be improved by equipping cleaning pigs with longer and/or stiffer brushes around the six o'clock position.

2.3 Data Processing

The rugged shape of the corrosion surface, a rough internal pipe surface and residual dirt due to non-optimum cleaning can lead to outliers and echo loss (missing data) in the gathered ILI data. Therefore, an elaborated filtering and re-processing of the acquired inspection data is crucial for data analysis (detection and sizing of anomalies) and integrity assessment based on ILI results.

2.4 Reporting Procedure

Long axial corrosion can occur in coherent sections of several kilometers length. In ILI reports the corrosion then is usually reported as one metal loss anomaly per each pipe joint. These corrosion anomalies are characterized by

- an anomaly length equal to the pipe joint length and
- an anomaly depth equal to the peak depth in the pipe.

This feature list information however does not provide a sufficiently meaningful description of metal loss anomalies with a complex geometry as can be seen from Figure 4. The illustration shows two anomalies with the same reported dimensions (maximum depth D and total length L) but with significantly different remaining wall thickness profiles (depicted as blue and red curves).

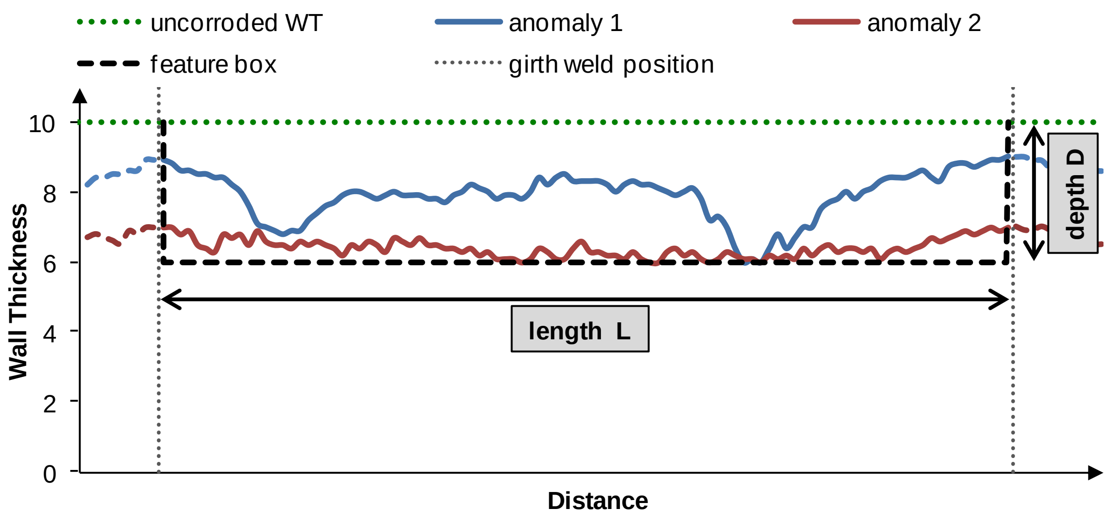

Figure 4: Sketch of two anomalies with same maximum depth and length but significantly different remaining wall thickness profiles.

2.5 Pressure Assessment

List-based vs. Data-based Methods

The assessment methods used for the calculation of the safe operating pressure P_{safe} can be subdivided into two groups:

1. *List-based* methods such as B31.G [1] or the DNV-RP-F101 Single Defect method [2] use the maximum depth and total length of a metal loss area as anomaly parameters. These list-based methods therefore yield identical P_{safe} results for anomaly 1 and anomaly 2 of Figure 4.
2. *Data-based* methods such as RSTRENG (Effective Area) [3] or DNV-RP-F101 Complex Shape [2] account for the actual remaining wall thickness profile of the anomaly (river-bottom profile, RBP).

As the feature list information does not reflect the characteristic anomaly dimensions, advanced data-based assessment methods have to be used for the P_{safe} calculation of long axial corrosion anomalies in order to yield meaningful results. Since the acquired inspection data might be affected by outliers and echo loss filtering of the wall thickness data might be required before extracting the RBPs.

Probability of Failure

'Conventional' (list-based as well as data-based) assessment methods determine the pipeline safe operating pressure from the pressure capacity of the worst anomaly. This approach is reasonable when only few pipe joints are affected by significant corrosion (left P_{safe} histogram in Figure 5). However, bottom-line corrosion over several kilometres can result in many pipe joints with reduced pressure capacity. A pressure histogram corresponding to such a situation is depicted on the right-hand side in Figure 5. Although the minimum pressure capacity is the same in both scenarios of Figure 5, it is obvious that a pipeline characterized by the histogram on the right-hand side is in a worse condition, associated with a higher probability of failure (PoF). An assessment method based on the PoF concept is outlined in chapter 3.

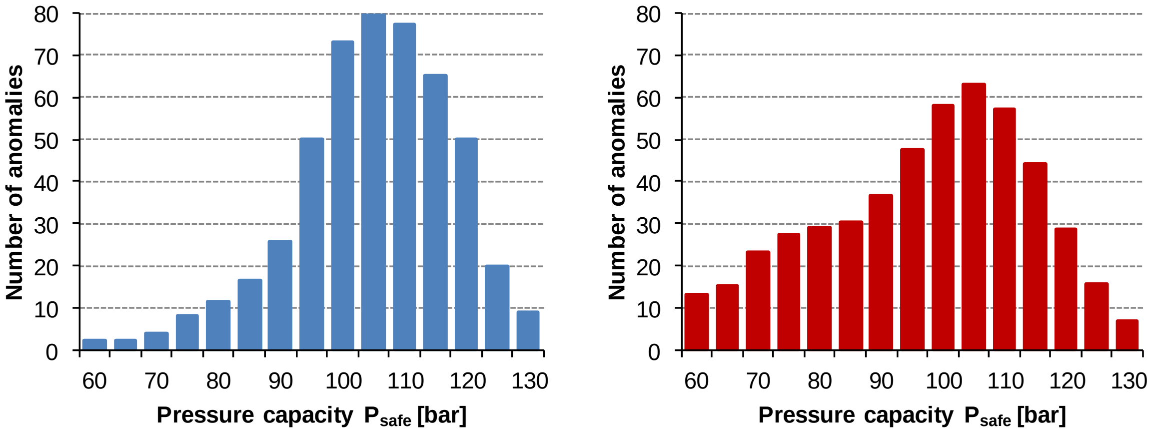

Figure 5: Two histograms of anomaly pressure capacity with same minimum P_{safe} (60 bar): left: few anomalies with low P_{safe}; right: many anomalies with low P_{safe}

Pressure Capacity and Risk of Leakage

The minimum remaining wall thickness of a channeling corrosion anomaly often occurs in a small localized spot. If the axial length of such a deep spot is sufficiently short, it does not result in a reduced (burst) pressure capacity of the affected pipe. However, deep pit-like corrosion spots which are less relevant with respect to the pressure assessment might nevertheless be associated with a risk of leakage.

2.6 Corrosion Growth Analysis

Corrosion growth rates are commonly determined from the change in depth or remaining wall thickness of metal loss anomalies measured by repeated ILIs. Corrosion growth rates calculated from the feature list information (i.e. maximum anomaly depth) might however not reflect the corrosion development in a long axial corrosion as corrosion growth occurring outside the deepest point is not taken into account. Also the location of the deepest point in the affected area could change from one ILI run to the next. Therefore, the peak depth comparison could be misleading.

As example, assume that anomalies 1 and 2 in Figure 4 show the same corrosion feature measured in two subsequent ILIs. As its maximum depth did not change between the inspections, a corrosion growth rate of 0 mm/year would be calculated although the anomaly was subject to significant active corrosion. While a corrosion growth analysis based on feature list information is reasonable e.g. for pitting type corrosion, corrosion growth of long complex shaped anomalies has to be assessed using a data-based comparison of RBPs.

3 DNV Method: Assessment of Long Axial Corrosion Defects

3.1 Overview

Within the scope of joint industry project with Statoil and DONG Energy, DNV has developed a methodology for the assessment of pipelines affected by long axial corrosion. NDT Global was involved in reviewing and testing of the developed procedure which is based on the results of ultrasonic inline-inspections. The methodology will be integrated into an updated version of the recommended practice DNV-RP-F101 and gives guidance on:

- Extraction of river-bottom profiles (RBPs), making use of appropriate filters that allow identification and proper treatment of outliers in the acquired wall thickness data.
- Calculation of the pipeline pressure capacity, accounting for a potential higher probability of failure resulting from channeling corrosion over a substantial pipeline length.
- Determination of corrosion growth rates based on RBPs of consecutive ILI runs and extrapolation of the pipeline pressure capacity into the future.

In sections 3.2 to 3.4 the main ideas of the DNV methodology are presented and illustrated by means of real data examples. More technical details about the method are given in [4].

3.2 Filtering of WT Data and Construction of RBPs

Channeling corrosion is often combined with a rough internal surface which can lead to echo loss (i.e. missing data) and/or outliers in the UT wall thickness (WT) data. Erroneous WT values have to be identified and replaced before reliable RBPs can be calculated. In addition to the WT measurement, UT ILI also records the so-called stand-off (SO). The SO is the distance between the sensor and the internal pipe wall and provides additional information on the internal contour of metal loss anomalies (Figure 6). Because the SO is determined from the strongest UT reflection (entry echo) it is usually not affected by echo loss or outliers.

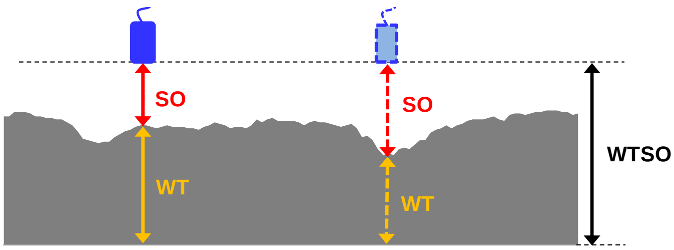

Figure 6: Illustration of WTSO = WT + SO

Level 2 of the DNV specification describes a method to detect and replace erroneous WT values making use of the sum of WT and SO, WTSO. As shown in Figure 6, WTSO corresponds to the distance from the sensor to the outer wall of the pipe. In case of no external metal loss, WTSO should ideally be constant for each sensor. Variations in WTSO are due to WT variations on the outside of the pipe, measurement uncertainty, radial movement of the tool/sensor and erroneous or missing data points. For locations (x,y) where WT(x,y) is unreliable or missing, WT(x,y) is recalculated as $WTSO_{median}(x,y) - SO(x,y)$. In this way, the reliable SO data is used to describe the local internal surface topography. The median value $WTSO_{median}$, determined in the neighborhood of (x,y), acts as reference and accounts for the fact that the sensor carrier can adapt to the internal pipe surface.

An example for the application of the above described method is presented in Figure 7, showing the inspection data for a pipe joint with severe channeling corrosion. The original WT data (a) is affected by outliers (black speckles), mainly at the sides of the corrosion channel and around the deepest area of the corrosion. Taking into account the SO information (b), the unreliable WT readings could be detected and replaced as can be seen from the filtered WT data (c). Figure 7d shows the RBP extracted from the filtered WT data.

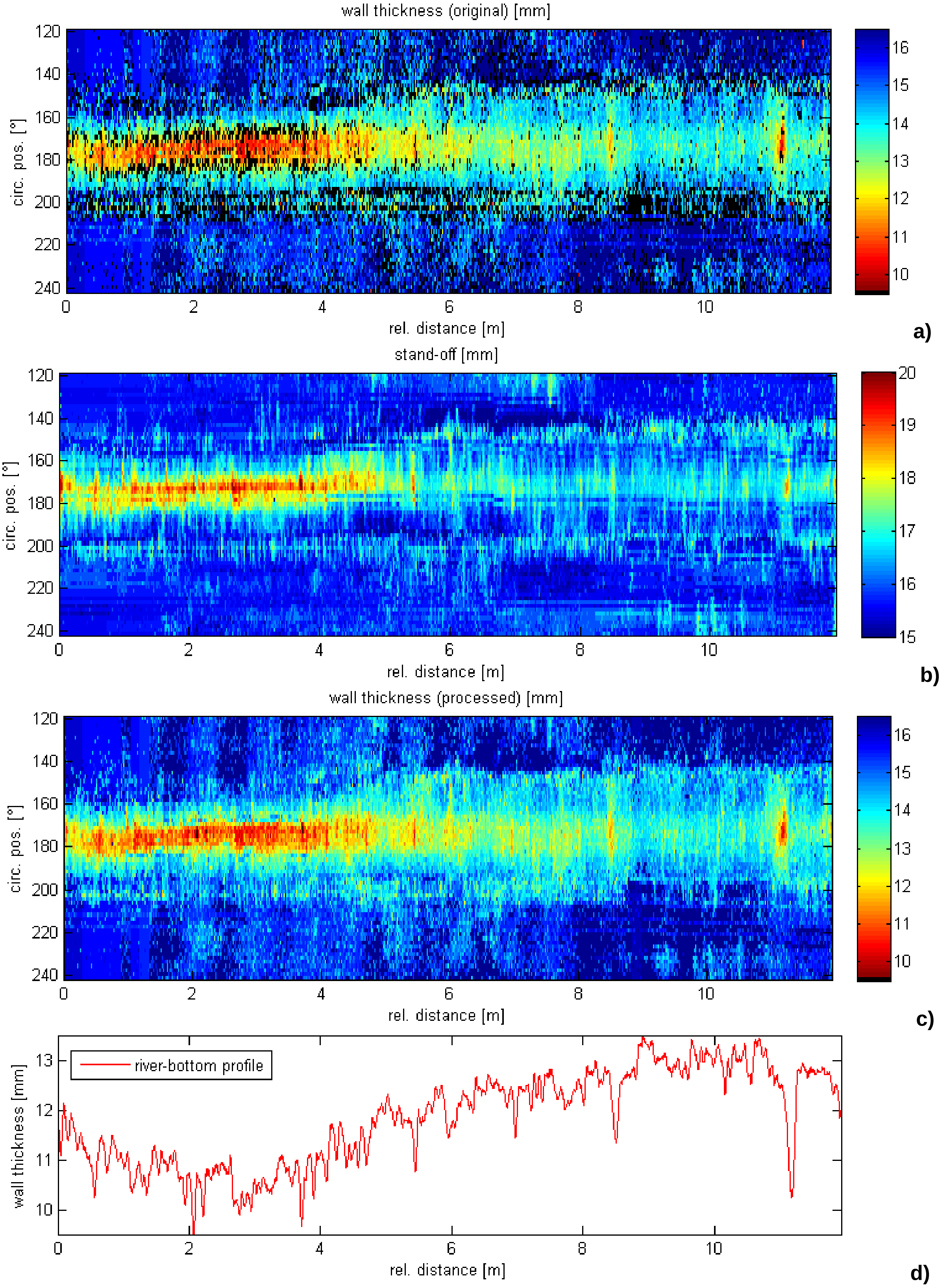

Figure 7: Filtering of WT data as basis for construction of RBPs: a) original WT data, b) stand-off data, c) filtered WT data, d) RBP extracted from filtered WT

3.3 Calculation of Pipeline Pressure Capacity

Level 3 of the DNV method describes the calculation of the pressure capacity of a pipeline affected by long axial corrosion. The methodology is based on the Complex Shaped Defect method of DNV-RP-F101 Part A. In contrast to list-based assessment methods like B31.G or the DNV Single Defect method, which only consider peak depth and total length of a corrosion anomaly, the DNV Complex Shape assessment makes use of the detailed river-bottom profile (RBP) of the metal loss features yielding more precise and usually less conservative estimates for the safe operating pressure.

The safety factors in DNV-RP-F101 Part A were calibrated assuming a single metal loss anomaly dominating the burst capacity and the probability of failure (PoF) of the pipeline. However, for pipelines with channeling corrosion of a significant length the PoF associated with the whole pipeline system PoF_{system} might be higher than the PoF of the worst pipe joint (system effect). To satisfy the safety philosophy of the Offshore Standard DNV-OS-F101 [5], PoF_{system} must not exceed the acceptable PoF of the relevant safety class (low, normal or high). As a consequence, the maximum allowable operating pressure of a pipeline affected by long axial corrosion might be lower than the safe operating pressure calculated for the worst anomaly.

According to Level 3 of the DNV specification on the assessment of long axial corrosion defects, the maximum safe working pressure of a pipeline is determined as follows:

1. RBPs are calculated for all selected pipe joints based on the filtered WT data according to Level 2 of the DNV specification (see section 3.2).
2. The safe working pressure P_{safe} is calculated for all selected pipe joints using the complex shape method of DNV-RP-F101 Part A. P_{safe} values are determined for overlapping profile subsections of length $20\sqrt{(D \cdot t)}$ where D denotes the pipe diameter and t is the nominal wall thickness.
3. Every P_{safe} value is converted to the associated PoF of the respective pipe section for the considered assessment pressure.
4. PoF_{system} is calculated from the individual PoF values of all pipe sections using statistical methods.
5. PoF_{system} is compared to the target PoF of the relevant safety class and a pressure adjustment factor is calculated. The safe working pressure of the pipeline is then given by the considered assessment pressure times the calculated pressure adjustment factor.

Below, the pressure capacity calculation according to the above described method is illustrated for a water injection pipeline affected by channeling corrosion:

- For the assessment 189 pipe joints affected by long axial corrosion with a remaining wall thickness below a certain threshold.
- For the worst pipe joint a safe working pressure of 268 bar was calculated using the DNV-RPF-F101 Complex Shape method. This value is below the original pipeline design pressure of 280 bar.
- For the considered 189 pipe joints, the safe working pressure P_{safe} was calculated for sections of approx. 1.7 m length (step 2 of the above assessment procedure). The results are shown in the histogram of Figure 8. For 20 sections (in three pipe joints) the pressure capacity is below the design pressure of 280 bar.
- The safe operating pressure of the whole pipeline system was calculated to be 260 bar.
- For this specific pipeline, the pipeline pressure capacity is eight bar (3 %) below the safe working pressure of the worst pipe joint. When a higher number of pipe joints have a pressure capacity close to the capacity of the worst joint, the pressure capacity of the pipeline system will be stronger reduced compared to the worst joint.

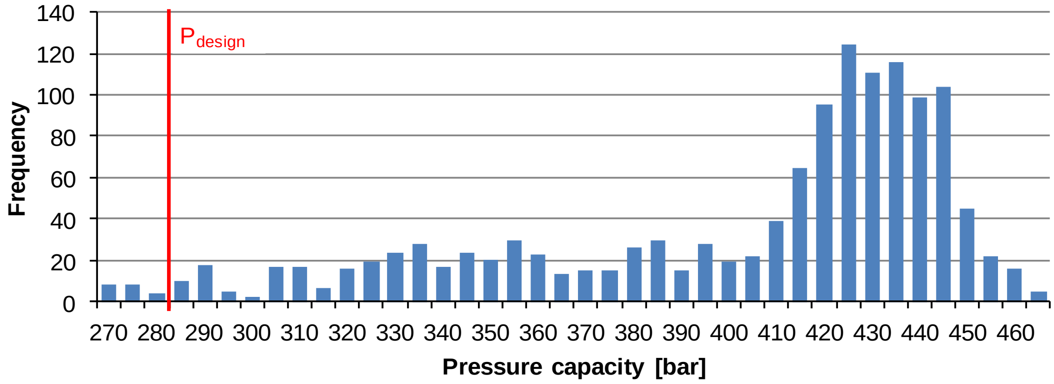

Figure 8: Histogram of pressure capacity for pipe sections of 1.6m length

3.4 Corrosion Growth Analysis and Extrapolation of Pressure Capacity

Level 4 of the DNV specification gives guidance on the determination of corrosion growth rates and on the extrapolation of the future pipeline pressure capacity. Basis for the corrosion growth analysis are RBPs of repeated ILIs, determined according to Level 2 of the DNV specification. From these RBPs, so-called characteristic wall thickness (CWT) profiles are calculated by averaging the wall thickness in sections of length $20\sqrt{(D \cdot t)}$. Subtracting the CWT profiles of one inspection from the corresponding CWT profiles of a previous inspection and dividing the obtained difference in (characteristic) wall thickness by the respective inspection interval yields the yearly corrosion growth rates for the individual sections.

As an example, Figure 9 shows RBPs and CWT profiles of one pipe joint extracted from the inspection data of three consecutive ILIs performed in 2010 (green), 2011 (blue) and 2014 (red). The corrosion growth rates calculated from the CWT profiles of Figure 9 are depicted in Figure 10. Corrosion growth rates between the first two inspections are plotted in blue, growth rates between inspection 2 and 3 are depicted in red. The solid lines show the corrosion growth rates of the individual sections of 1.7 m length, the average growth rate of the pipe joint is depicted by the dashed lines.

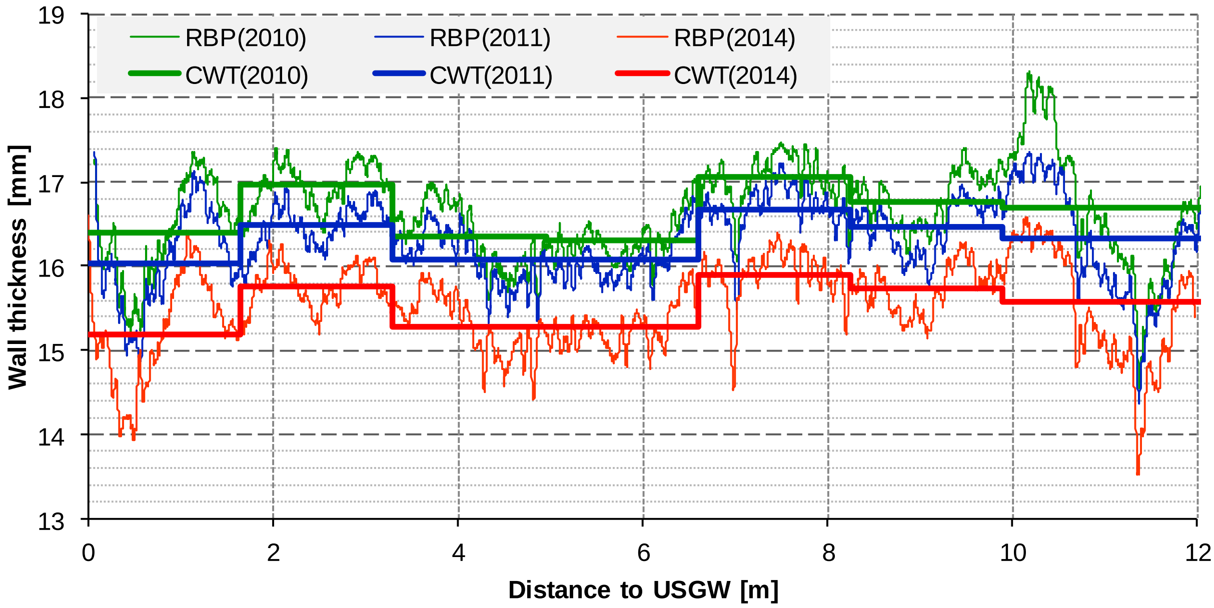

Figure 9: RBPs of three consecutive ILIs and associated CWT profiles for one pipe joint

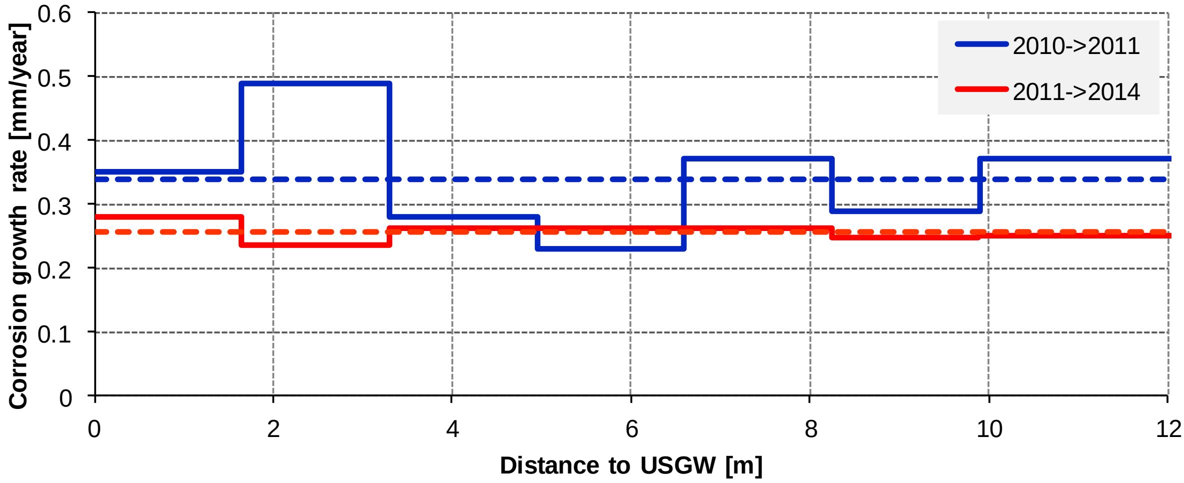

Figure 10: Corrosion growth rates calculated from CWT profiles of Figure 9

In Figure 11, the corrosion growth rates between the ILIs of 2011 and 2014, determined as described above, are plotted versus the distance along the pipeline. The red dots show the average pipe joint corrosion growth rates and the blue symbols indicate the growth rates of the single sections of 1.7 m length. If a sufficient number of pipe joints are analyzed, such a graph allows the detection and quantification of distance-dependent variations in the corrosion growth behavior.

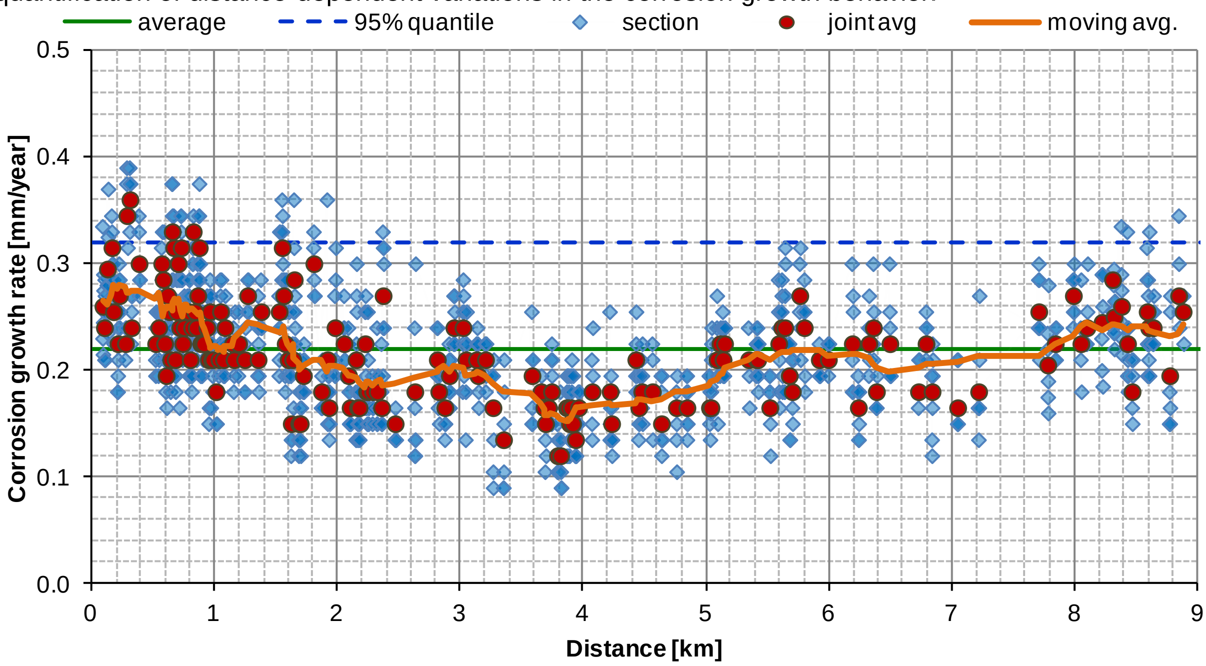

Figure 11: Corrosion growth rates versus distance along the pipeline

After the corrosion growth analysis is performed, the future development of the pipeline safe operating pressure can be extrapolated. This is achieved by reducing the remaining wall thickness of the RBPs according to the considered corrosion growth rates and by repeating the capacity assessment as described in section 3.3.

Figure 12 shows the extrapolated safe working pressure of the assessed pipeline considering three scenarios for the corrosion growth rate:

1. average corrosion growth rate of 0.22 mm/year
2. upper 95 % quantile corrosion growth rate of 0.32 mm/year
3. individual average corrosion growth rate for each anomaly (red dots in Figure 11)

In the most conservative scenario, the pipeline safe working pressure reaches the current MAOP of 215 bar 5.25 years after the last inspection.

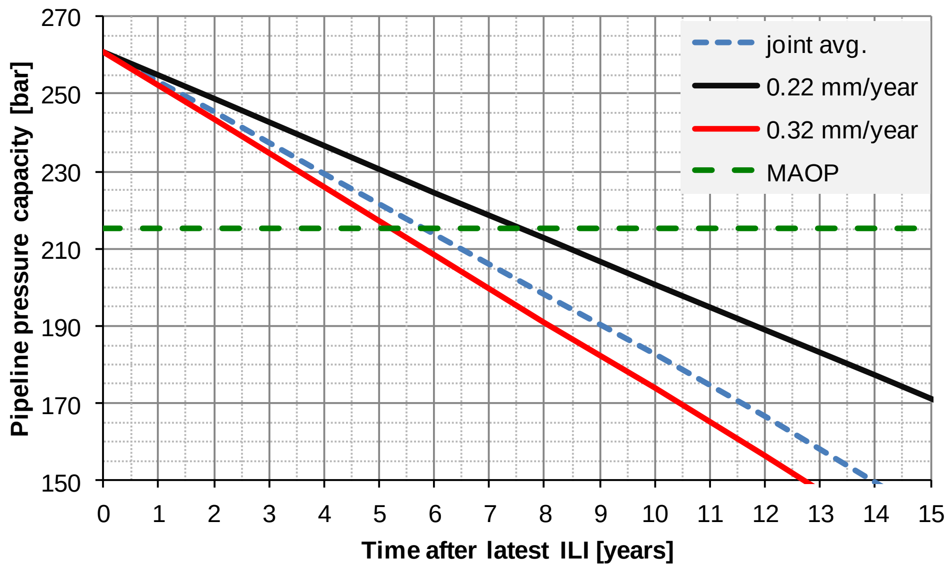

Figure 12: Extrapolation of pipeline safe working pressure

4 Conclusions

The presence of long axial corrosion can significantly affect several aspects of inline inspection and the subsequent pipeline integrity assessment. Channeling corrosion can be reliably detected and sized by ultrasonic ILI tools. The feature list information provides only maximum anomaly dimensions (total length, peak depth) and does not sufficiently describe the complex shape of corrosion anomalies. Therefore, methods based on remaining wall thickness profiles have to be applied for the assessment of long axial anomalies.

A specific methodology for the assessment of pipelines subject to long axial corrosion has been recently developed by DNV. This method is based on ultrasonic ILI data and gives guidance on the filtering of the UT data, the extraction of river-bottom profiles, the calculation of the pipeline pressure capacity, the determination of corrosion growth rates and the extrapolation of the future pressure capacity. Compared to other advanced assessment methods like DNV Complex Shape or RSTRENG (Effective Area), the presented assessment approach accounts for a higher probability of failure which is likely to occur when many pipe joints are affected by severe corrosion.

The experience gained by using the DNV methodology for the assessment of several crude oil and water injection pipelines, affected by different stages of channeling corrosion, has shown a good applicability of the different elements of the method.

Reference

[1] "ASME B31G-2012 Manual for Determining the Remaining Strength of Corroded Pipelines", American Society of Mechanical Engineers, October 2012

[2] "Recommended Practice DNV-RP-F101 Corroded Pipelines", Det Norske Veritas, October 2010

[3] "Project PR3-805: A Modified Criterion for Evaluating the Remaining Strength of Corroded Pipe", Kiefner, J.F. and Vieth, P.H., December 1989, AGA Catalog No. L51609

[4] "Assessment of Long Axial Corrosion Defects", Vigsnes, M., Eldevik, S., Etterdal, B., Verley, R., and Krogh, M., Proc. of the ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering, June 6–11, 2010, Shanghai, China

[5] "Offshore Standard DNV-OS-F101 Submarine Pipeline Systems", Det Norske Veritas, October 2007