Understanding the Impact of Corrosion Morphology on ILI Detection and Sizing Capability

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Abstract

In-line inspection (ILI) is the primary technique used for detecting and sizing corrosion metal loss in pipelines. The Pipeline Operators Forum (POF) requirements state that ILI vendors should provide Probability of Detection (POD) and sizing specifications for metal loss anomalies of different sizes (classified by the detected anomaly length and width). However, these sizing classifications do not represent the often complex morphology of corrosion. For example, deep pits within shallower general corrosion may be simplistically categorised within the general dimension classification.

This paper explores the impact of corrosion morphology on ILI tool detection and sizing capabilities, using examples of NDE field measurements and two ILI technologies. The review considers corrosion validation data for anonymised pipelines, using ILI data from Ultrasonic Wall Thickness Measurements (UTWM) and axial Magnetic Flux Leakage (MFL). Methodologies given in API 1163 (2021) have been used for the analysis of ILI tool performance and examples of validated corrosion and associated ILI sizing are discussed. The potential impacts on integrity assessment are also considered.

The review presented in this paper provides insight on the performance of both MFL and UTWM ILI detection and sizing capabilities for complex (and often typical) corrosion anomalies, such as deep pits within shallow general corrosion. The potential for fitness for service (FFS) of pipelines with this type of corrosion morphology to be non-conservative due to treatment of ILI sizing tolerance is also discussed, considering both through-wall leak and pressure-driven burst failures. The findings of this paper further support previous research stressing the importance of validating more than just the deepest ILI reported anomalies, (1) to understand the corrosion morphology, (2) the actual sizing uncertainty of the ILI, and (3) the impact on integrity assessment.

Background

Corrosion is a major source of onshore pipeline failure incidents, accounting for >20% of identified loss of containment events [1]. Onshore pipelines commonly pass through aggressive environments where protection from external corrosion is challenging. They are also more likely to be used for transport of refined products such that failures due to external degradation mechanisms occur more frequently than those due to internal degradation [2], on both oil [3] and natural gas [4] pipelines. Preventing such failures relies on corrosion barriers, such as coatings and cathodic protection (CP) [2]. However, as pipelines age and barriers degrade [5] accurate detection and sizing of active external corrosion is required to maintain good integrity management [6]. In-line inspection (ILI) is the primary and often only technique used for detecting and sizing external corrosion metal loss in pipelines [7]. Therefore, using NDE field measurements to understand an ILI tool's performance following an inspection run is critical to ensuring integrity [8].

Metal loss are typically classified according to the verified/detected anomaly length and width according to the POF specifications [9], considering the maximum measured corrosion area, see Figure 1. ILI performance specifications often provide detection capability and measurement sizing tolerances based on these anomaly dimension classifications [10].

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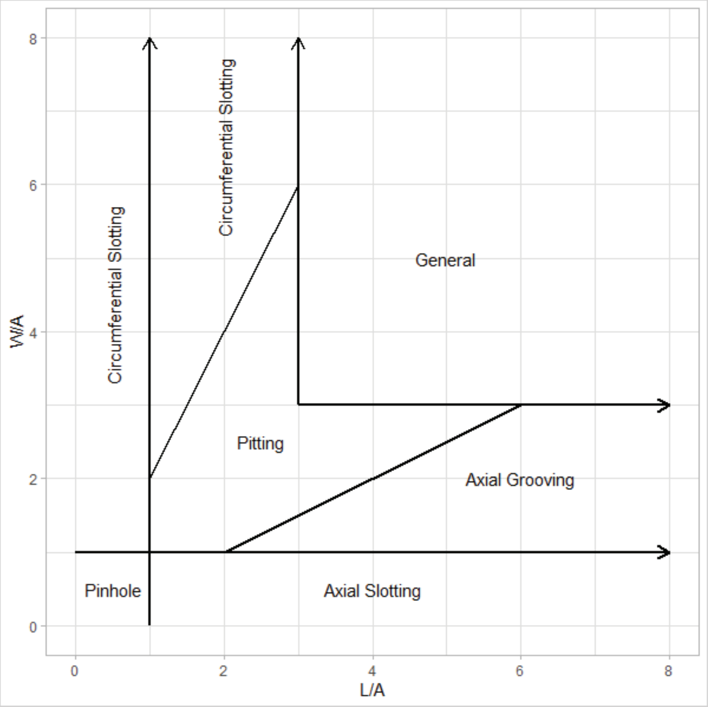

$t < 10$ mm then $A = 10$ mm
$t \geq 10$ mm then $A = t$

Figure 1. POF sizing classifications [9].

Corrosion occurs when the line pipe steel is oxidised and metal is lost from the pipe surface, and there are many possible causes of external corrosion. Environment (e.g. soil properties), steel properties/composition and physical properties (e.g. coating type) are all factors contributing to the type of corrosion that can initiate on a pipeline [11]. Depending on the source of external corrosion the metal loss morphology will typically take on one of three distinct shapes; uniform, pitting or crevice corrosion [12]. These are illustrated in Figure 2 to Figure 4 and correspond well with the POF sizing classifications (Figure 1).

Pipeline corrosion can also often result in complex morphologies, where combinations of these external corrosion forms can and do occur. This is more likely at locations where the pipe wall is subject to different electrochemical corrosion mechanisms (for example due to microbial induced corrosion) [13] or at locations where localised and progressive coating breakdown has occurred [14]. Often in these cases deep, aggressive pitting will be present within shallower uniform corrosion, see the example in Figure 5. Such anomalies may be classified as general metal loss based on their overall dimensions, despite the presence of local pitting. The assigned ILI measurement tolerances in these cases may then be under called (i.e. the tolerance for general rather than pinhole/pitting metal loss would be assumed) and further analysis of signal data would be required to improve sizing accuracy [15]. Note that for clustered metal loss the inclusion of cluster member or box data within ILI listings, followed by appropriate application of tolerances within FFS will reduce the frequency and impact of undercalled tolerances[1].

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[1] Although this is only the case when box dimensions approach that of the deepest component.

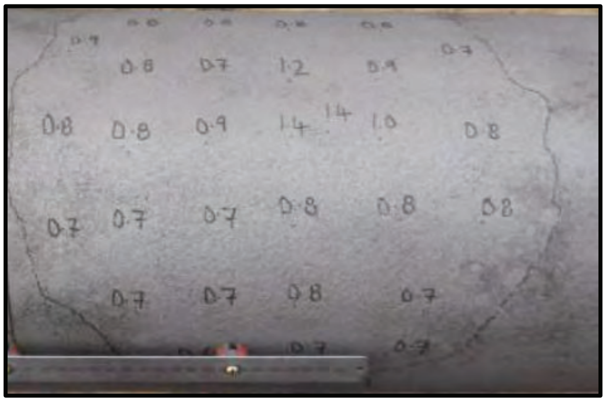

Figure 2. Typical external corrosion example: uniform wall loss.

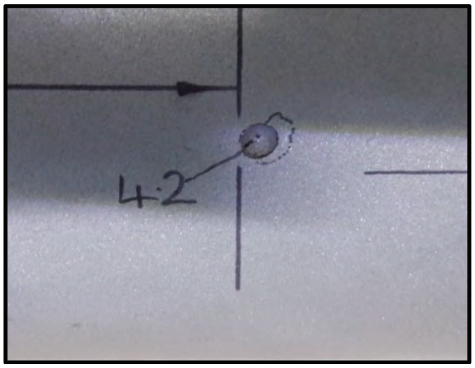

Figure 3. Typical external corrosion example: pitting corrosion.

Figure 4. Typical external corrosion example: crevice corrosion.

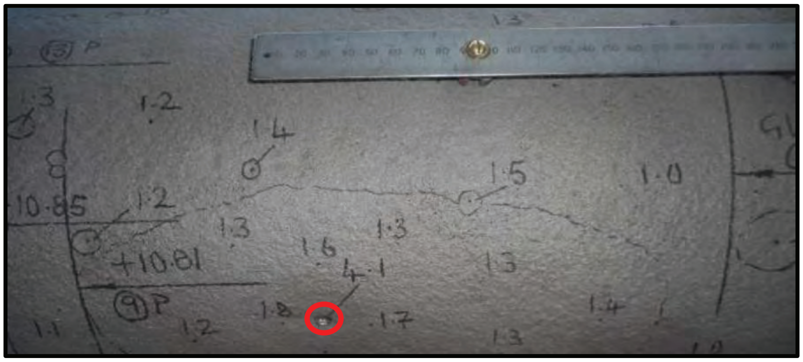

Figure 5. Example of a pit within general wall loss.

Published work discussing ILI depth sizing validation does not always link findings back to the actual corrosion morphologies found in the field (e.g. [16]), and deeper anomalies are also notably under represented (e.g. [10]). This paper aims to further explore the relationship between corrosion morphology and ILI detection/sizing capabilities using NDE field measurements. Corrosion morphology is qualitatively described based on its deepest component, as; isolated pitting, pitting within general and general[2] corrosion (see Figure 9). The review presented in this paper considers corrosion validation data for anonymised pipelines, with ILI data from two different tool technologies, Ultrasonic Wall Thickness Measurements (UTWM) and axial Magnetic Flux Leakage (MFL). The paper then discusses the potential impact of the findings on integrity management and assessment.

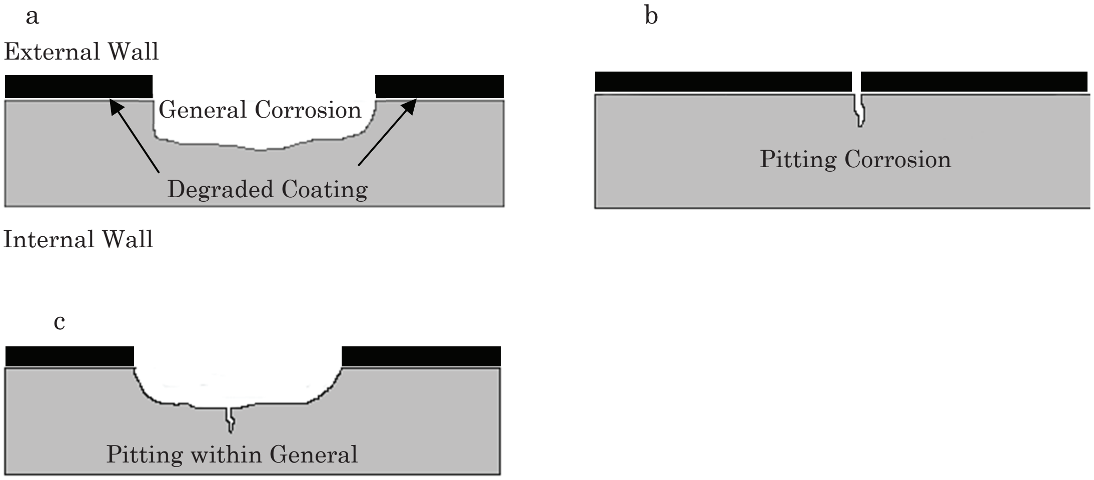

Figure 6. Typical external corrosion examples: a) general, b) pitting corrosion and c) pitting within general corrosion.

Review of validation data

All of the verified anomalies considered in this paper were measured using a consistent, standardised approach. Measurements were performed using a depth micrometer (better than 0.05 mm resolution) and bridging bar (selected length dependent on anomaly dimensions). It is acknowledged that there is measurement uncertainty associated with field verification [8]. However, given the use of depth micrometers and competence of NDE personnel, this is expected to be minimal and does not affect the finding of the analysis presented within the scope of this paper. Local uncorroded wall thickness measurements were taken using a UT probe. Verified depth measurements were converted to percentage wall thickness for comparison with the MFL ILIs. Note that following verification, anomalies were typically repaired using composite sleeves. Figure 7 summarises the verification data.

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[2] For general corrosion, the overall metal loss anomalies may be uniform or may have associated local deeper areas. However, the dimensions of the deepest component are within the general sizing classification and are not classified as pits.

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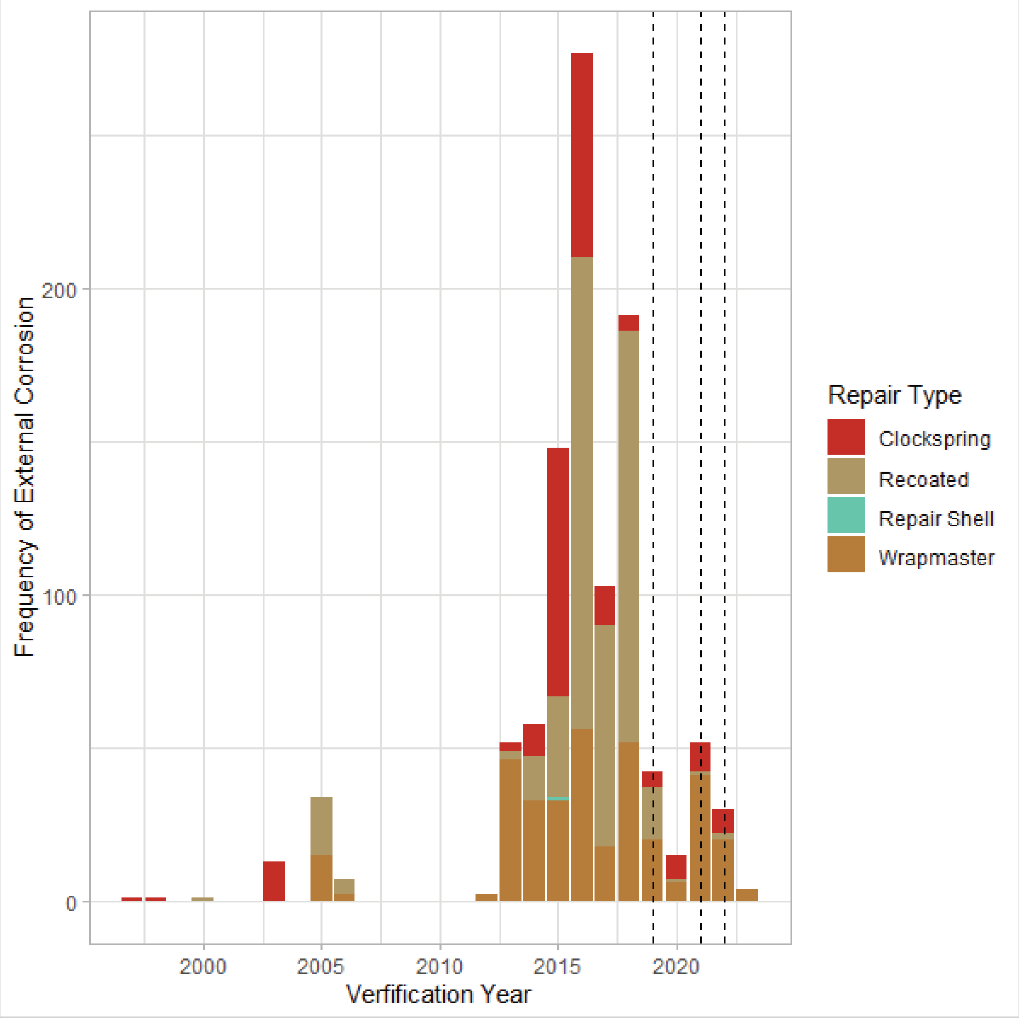

Figure 7. Summary of external corrosion verifications completed by year and subsequent repair type (black dashed line are the years of ILIs considered in this review).

A total of 1031 verified external corrosion anomalies in seamless pipelines have been reviewed. Verified metal loss depths range from 5 to 77%t, with the majority of verified depths below 50%t. Table 1 summarises the verified corrosion details and Figure 8 presents histograms and boxplots of the verified corrosion depths.

Figure 9 compares the overall anomaly dimensions[3] and the size of the deepest component against the POF sizing classifications, with verified corrosion morphology used to classify the anomalies. When the dimensions of the deepest component are considered, there is a trend for the sizing classification to move along the scale, shifting from 'General' to 'Pitting' or 'Pinhole'.

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[3] The overall dimensions of either single, continuous metal loss or clustered metal loss, as applicable.

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Table 1. Summary of verified anomalies.

Pipeline Details		Morphology Frequency					Verified Depth (%t)		
Diameter (in)	Nom Wall Thickness (mm)	All	General	Pitting within General	Isolated Pitting	N/A (no data)	Min	Median	Max
All		1031	339	554	82	56	5	47	77
6	5.60	250	7	197	4	42	12	33	76
10	6.35	681	326	284	59	12	5	21	77
12	6.41	65	4	43	16	2	9	29	68
6	7.11	20	1	16	3	0	14	25	48
12	7.80	5	0	5	0	0	38	42	73
6	11.13	7	1	6	0	0	15	44	57
12	12.70	3	0	3	0	0	17	47	51

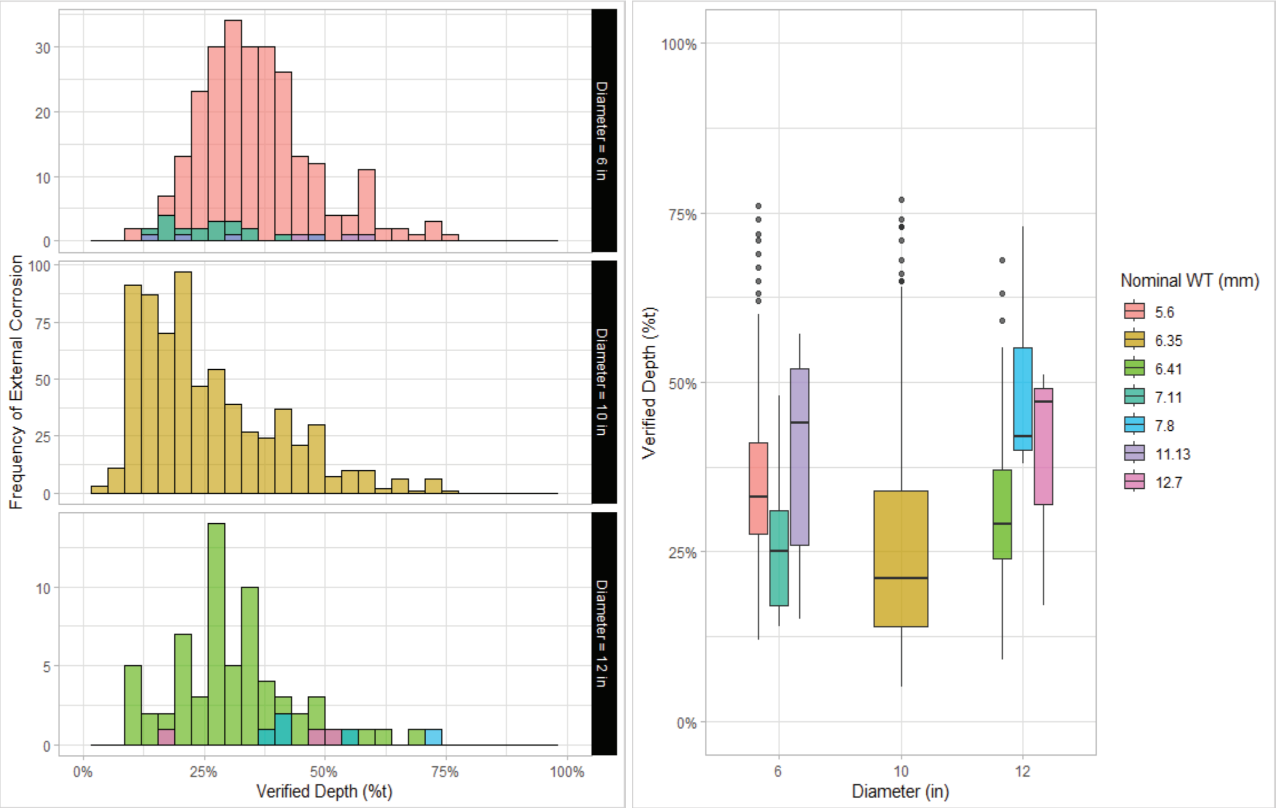

Figure 8. Histogram (left) and boxplot (right) of 1031 verified external corrosion depths.

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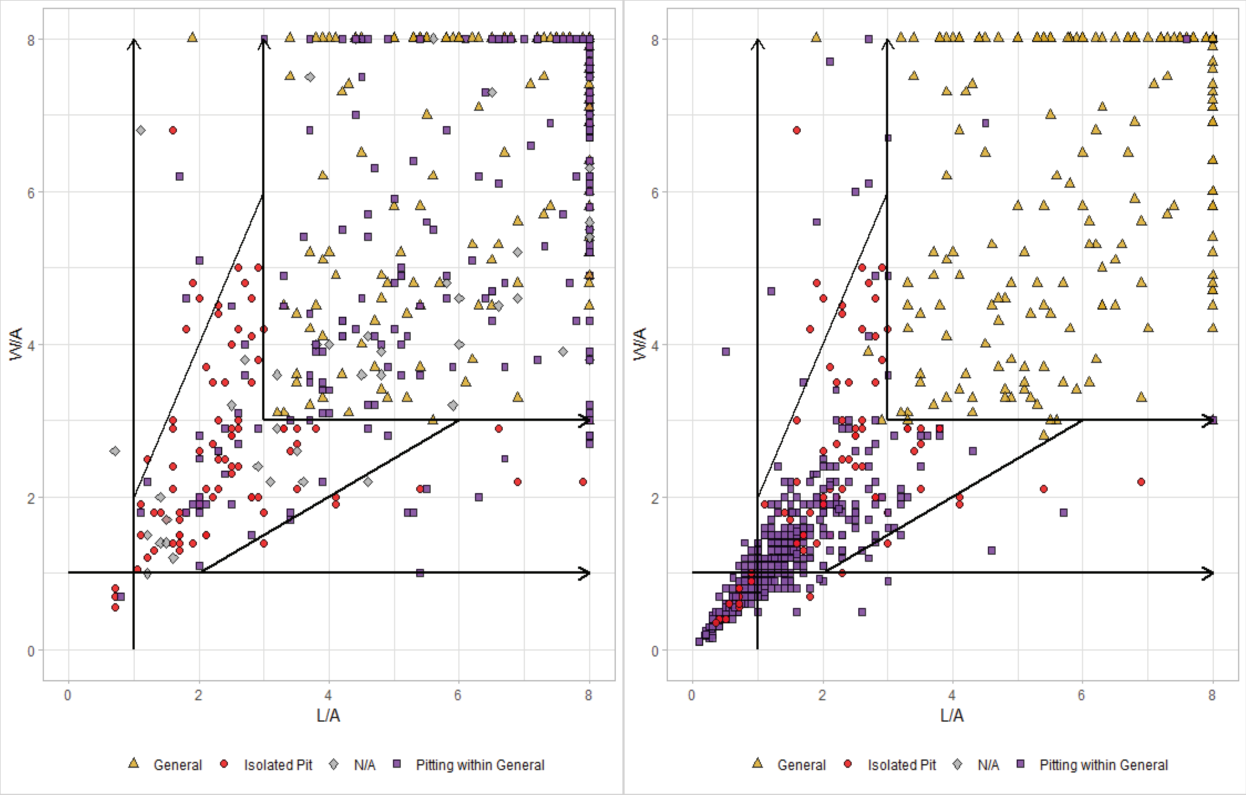

Figure 9. Verified corrosion anomaly dimensions plotted against POF sizing classifications. Overall dimensions (left) and dimensions of deepest component (right).

Results: ILI validation review

The verification data has been analysed in line with the API 1163 Level 3 frequentist approach [17]. Linear models have been fitted using R version 4.2.1 [18] and plotted using ggplot [19], slopes are allowed to be variable [20]. The linear fits and associated estimated tolerances at 90% certainty are shown as orange dashed lines on the validation plots. The grey shaded areas represent the confidence bands (i.e. uncertainty) about the fit, influenced both by the variability of the data and by the sample size. Series labelled "N/A" refer to anomalies which did not have enough available data to assign a qualitative description. The analyses consider all the matched anomaly data, although it is acknowledged that MFL depth sizing may be affected by some sleeve types[4]. Note that this analysis matches verified anomalies against the standard ILI listings, more detailed analysis could be completed considering ILI signal data.

The following sections present the results for the MFL and UTWM ILIs, and then briefly compare the two. Following this, the results of the analyses are further discussed as a whole. Note that this paper aims to analyse the validation data and review ILI performance to inform understanding and use of the data for pipeline integrity management. The analyses presented are not intended to comment on whether stated ILI detection or sizing specifications have been met.

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[4] Reviews indicated that the fitted models were similar whether these sleeves were included or excluded from the analysis.

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MFL ILI validation review

A total of 903 (88%) of the 1031 verified anomalies were reported by the MFL ILIs. Figure 10 and Figure 11, present a comparison of the MFL reported depths against the verified depths. Results are shown for each combination of diameter and nominal wall thickness (Figure 10) and for each of the described morphologies (Figure 11). For the spools with 5.6 to 6.41 mm nominal wall, the fits are above the one-to-one line, showing a trend of MFL undersizing the metal loss anomalies.

Figure 12, compares the error (i.e. NDE verified depth – ILI reported depth) against the minimum dimension of the deepest verified component. Results above zero indicate that the anomaly has been undersized by the ILI. The most significant undersizing (and widest tolerances) were found for pitting within general corrosion. Isolated pits had the smallest associated sizing uncertainty and were sized most consistently by the technology.

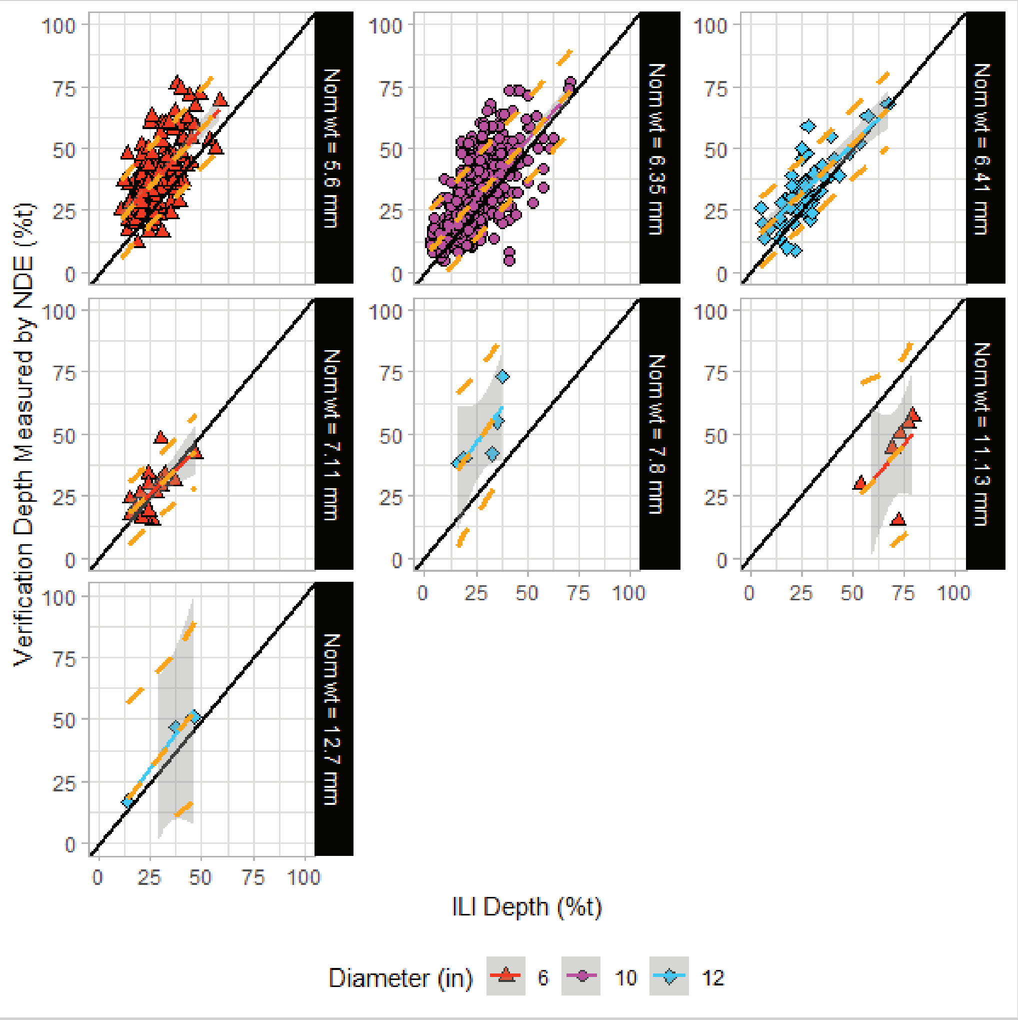

Figure 10. API 1163 Level 3 validation analysis of MFL ILI, presented for each combination of pipeline nominal wall thickness and diameter.

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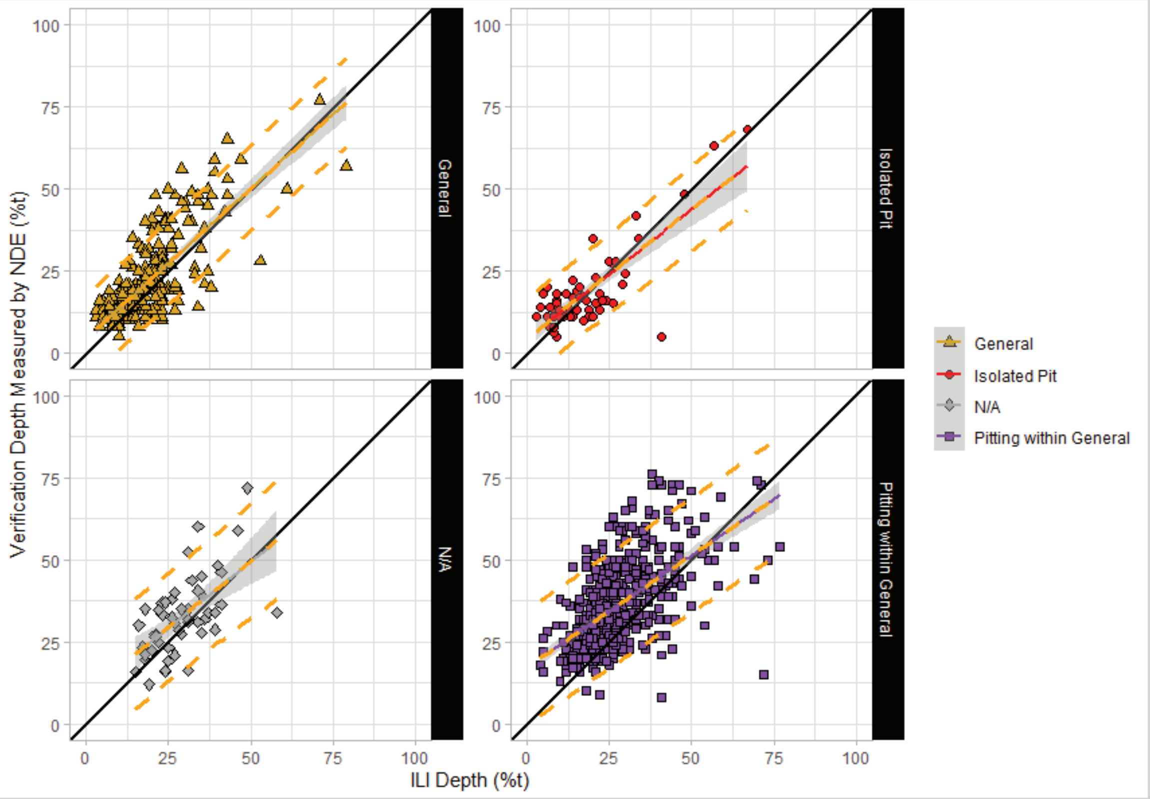

Figure 11. API 1163 Level 3 validation analysis of MFL ILI, presented by corrosion morphology.

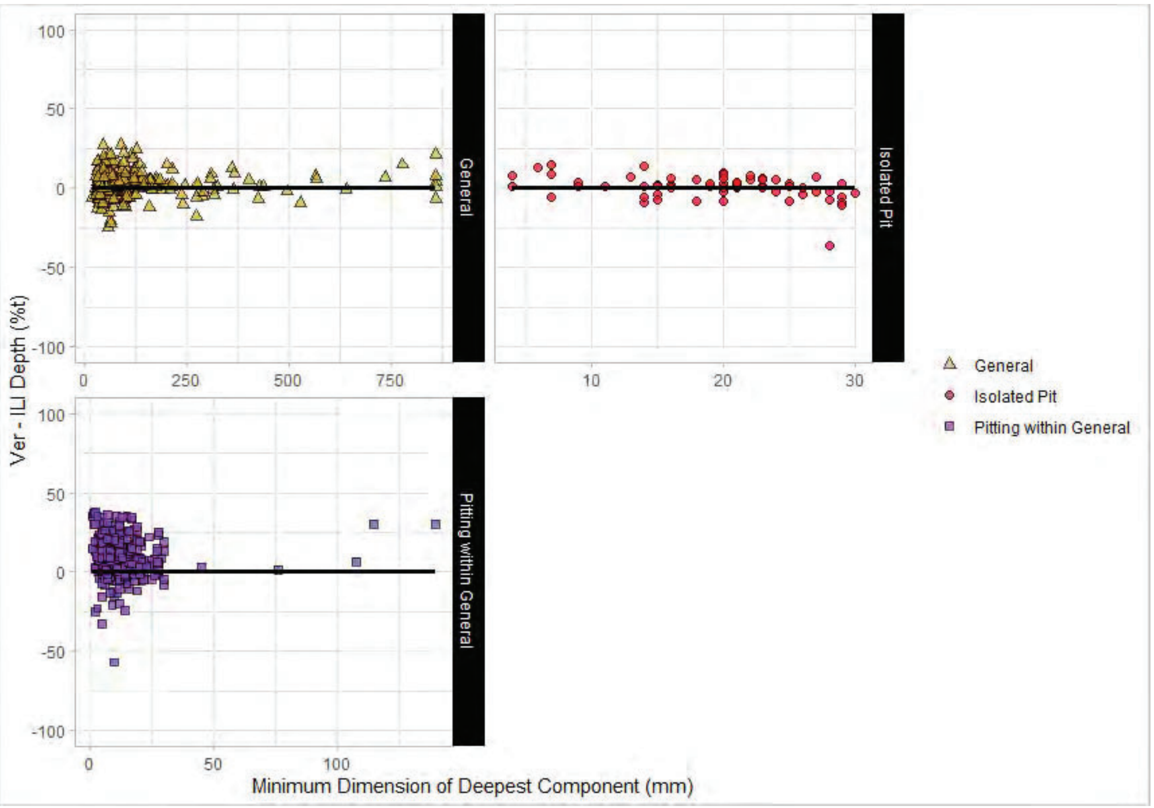

Figure 12. Comparison of MFL ILI sizing error and dimensions of deepest verified corrosion component.

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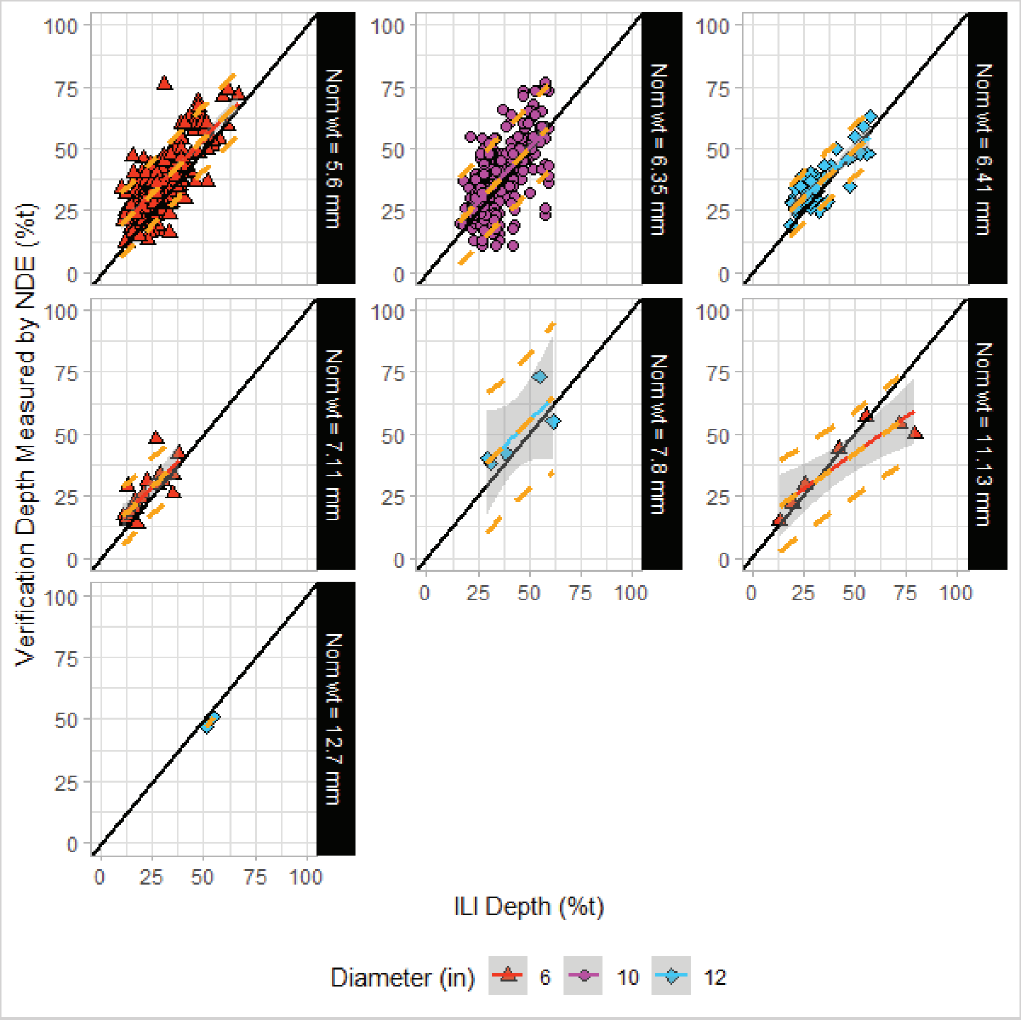
UTWM ILI validation review

A total of 612 (60%) of the 1031 verified anomalies were reported by the UTWM ILIs. Figure 13 and Figure 14, present a comparison of the UTWM reported depth[5] against the verified depth. Results are shown for each combination of diameter and nominal wall thickness (Figure 13) and for each of the described morphologies (Figure 14). For the spools with 5.6 mm nominal wall, the fits are above the one-to-one line, showing a trend of UTWM undersizing the metal loss anomalies. For 6.35 mm nominal wall, the anomalies are more evenly scattered around the one-to-one, but result in a similar sizing uncertainty to the 5.6 mm case.

Figure 15, compares the error (i.e. verified depth – ILI reported depth) against the minimum dimension of the deepest verified component. Results above zero indicate that the anomaly has been undersized by the ILI. The most significant undersizing (and widest tolerances) were found for isolated pitting, although sample size may impact this analysis. Pitting within general corrosion affects the sizing more significantly than general corrosion.



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[5] Depth measurements have been converted to percentage wall thickness for comparison with MFL data, reference wall thickness was used for the conversion.

Figure 13. API 1163 Level 3 validation analysis of UTWM ILI, presented for each combination of pipeline nominal wall thickness and diameter.

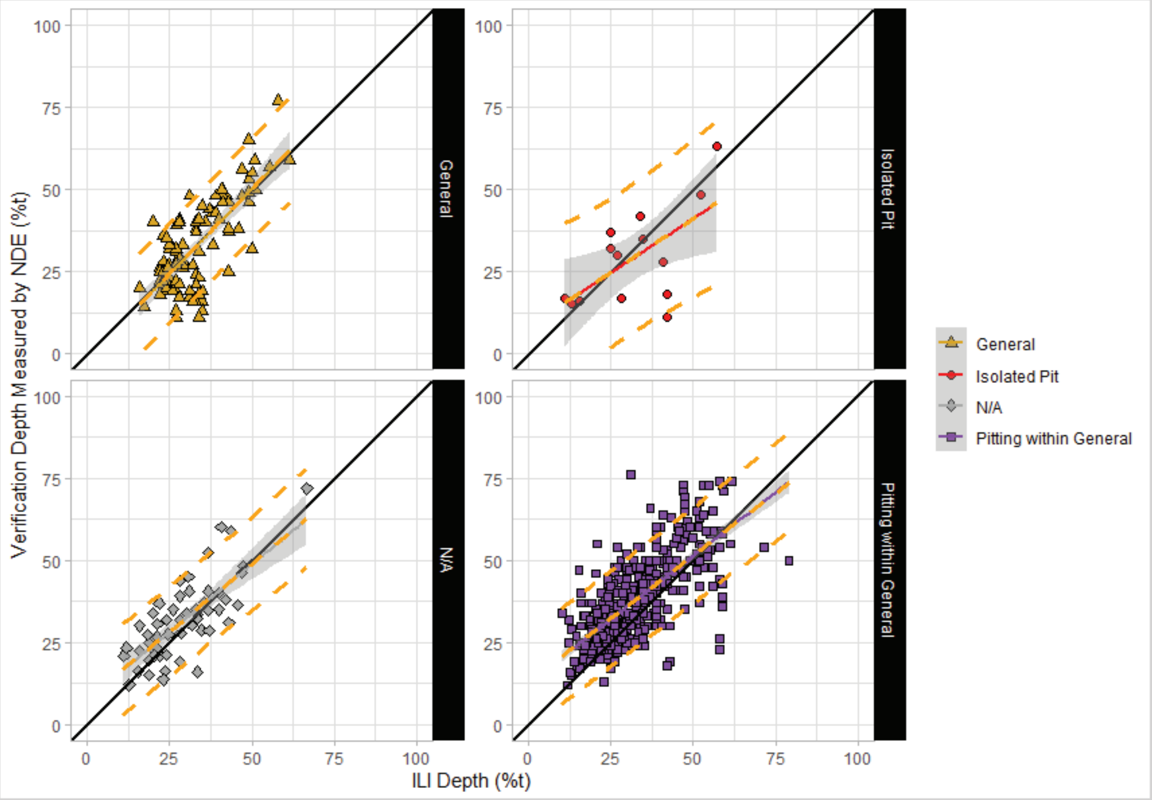

Figure 14. API 1163 Level 3 validation analysis of UTWM ILI, presented by corrosion morphology.

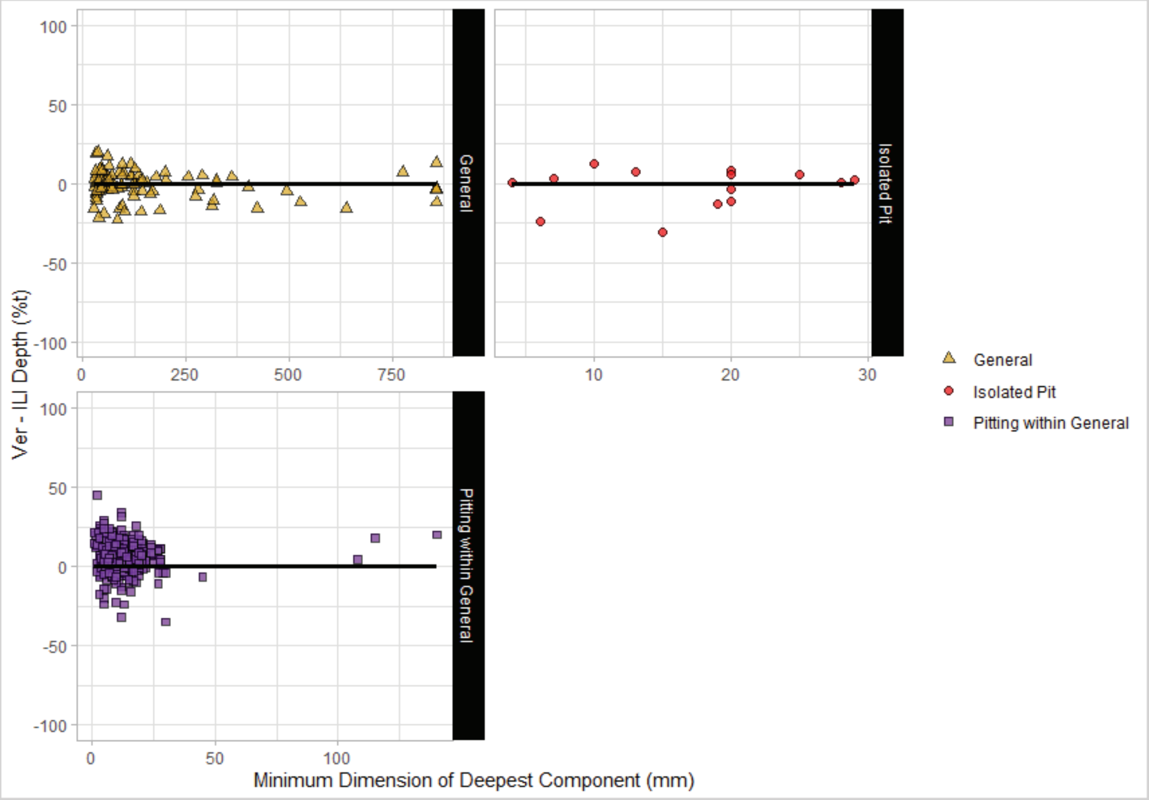

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Figure 15. Comparison of UTWM ILI sizing error and dimensions of deepest verified corrosion component.

Comparison of UTWM and MFL sizing

Figure 16 compares the calculated sizing error associated with UTWM and MFL reported validation anomalies. A value in the top right corner indicates that both the ILIs have undersized the corrosion anomaly. A value in the bottom left corner indicates that both ILIs have oversized the corrosion anomaly. Results are presented by corrosion morphology.

As shown, error in both tools is greatest for pitting within general corrosion and this is notable in comparison with the sizing error for general corrosion. The wider scatter around the one-to-one for the pitting within general corrosion suggests that the technologies have an increased disparity in their depth calls for these anomalies. The majority of pitting within general corrosion has been undersized by both tools, with the MFL error slightly greater than that of the UTWM.

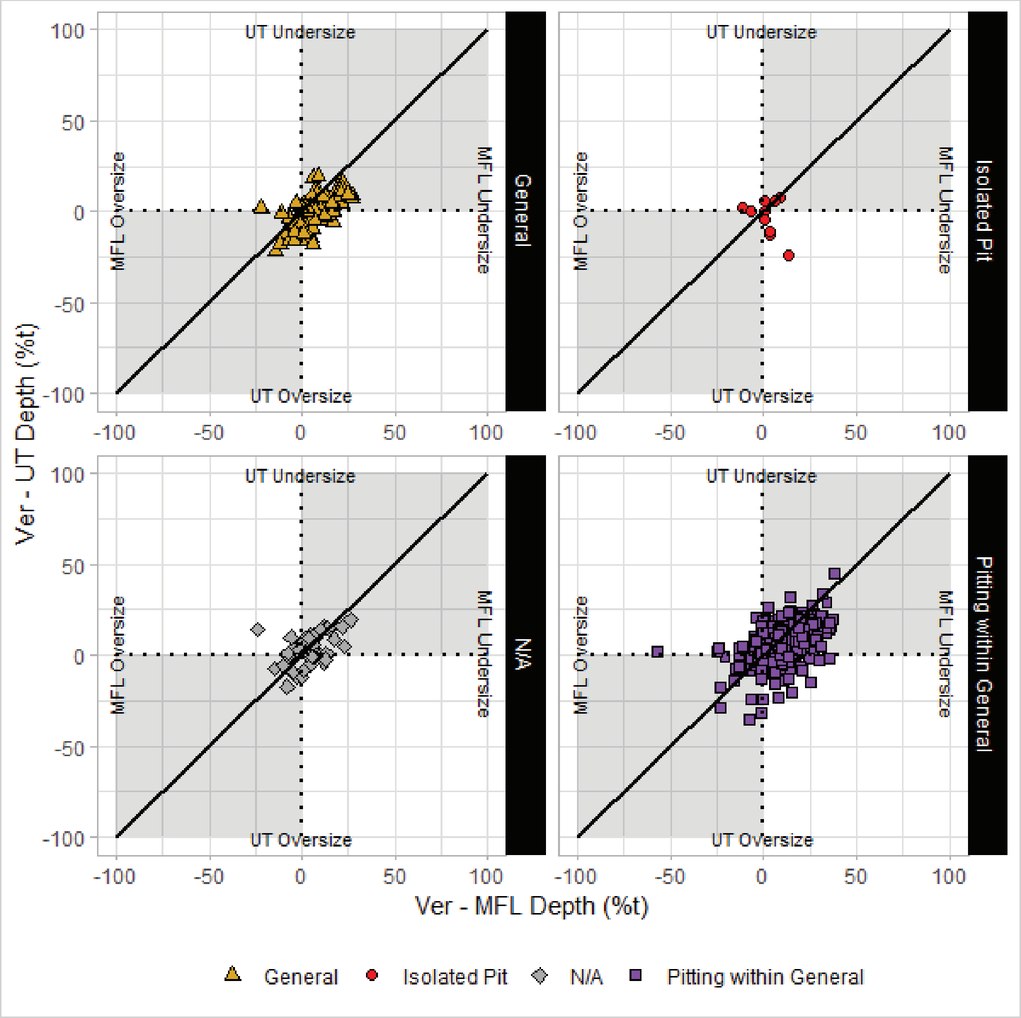

Figure 16. Comparison of UTWM and MFL ILI calculated sizing error for verified anomalies.

Discussion

Anomalies in 5.6 to 6.41 mm Nominal Wall

Both the MFL (Figure 10) and UTWM ILI (Figure 13) validations, identified that anomalies were more likely to be undersized by the tools. This effect is most significant for the MFL ILI. Both types of ILI tool appear to share similar upper bound sizing accuracies. The gradient of the fit for the MFL ILI is slightly more negative in the 6.35 and 6.41 mm pipe spools. Suggesting that deeper verified corrosion is subject to a higher sizing uncertainty. However, when the ILI reports a deeper anomaly, this is more likely to correspond to an actual deeper anomaly in the pipe wall.

In general, the UTWM tools appear to have a narrower band of scatter around the one-to-one line, suggesting more consistent sizing. However, the MFL ILIs have identified and reported significantly more of the corrosion anomalies.

Anomalies in 7.11 to 12.7 mm Nominal Wall

Both the MFL and UTWM ILI validations showed a narrower sizing tolerance for the anomalies reported in the 7.11 mm nominal wall thickness, with relatively uniform scatter around the one-to-one line. The remaining three nominal wall thickness had relatively small sample sizes, limiting the conclusions that can be taken from the analysis. However, it is notable that anomalies in 11.13 mm pipe spools appear to have been oversized by the MFL tools, with a similar trend occurring in the UTWM for deeper anomalies. These spools are older vintage seamless pipe.

Sizing Validation Considering Corrosion Morphology

The verified corrosion morphologies have been qualitatively classified as isolated pitting, pitting within general corrosion and general[6] corrosion. N/A is assigned where data on the corrosion morphology was unavailable.

For isolated pitting, the MFL ILI (Figure 11 and Figure 12) validation identified a consistent sizing accuracy across all of the verified depths and pit dimensions. The sizing accuracy for these anomalies is notably narrower than for pits within general corrosion. The pits within general corrosion have a greater level of scatter around the one-to-one, with relatively high associated sizing tolerances. This is particularly observed for shallower ILI reported corrosion which may correspond to comparatively deeper pits. The most significant sizing uncertainty is present when the minimum dimension of the deepest component is less than 25 mm. The data suggests that sizing accuracies tend to improve as the diameter of the deepest component increases. The identified greater sizing uncertainty associated with deeper and more complex corrosion supports that of previous papers **[15]**, **[16]**.

A similar pattern is present on the UTWM validation (Figure 14 and Figure 15). However, sizing accuracies appear to be narrower (Figure 16) and the gradients more closely follow the one-to-one line. The exception is for isolated pitting, which has a greater associated sizing uncertainty than the MFL. Given that the UT ILIs have reported fewer anomalies than the MFL, it is likely that the tools

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[6] For general corrosion, the overall metal loss anomalies may be uniform or may have associated local deeper areas. However, the dimensions of the deepest component are within the general sizing classification and are not classified as pits.

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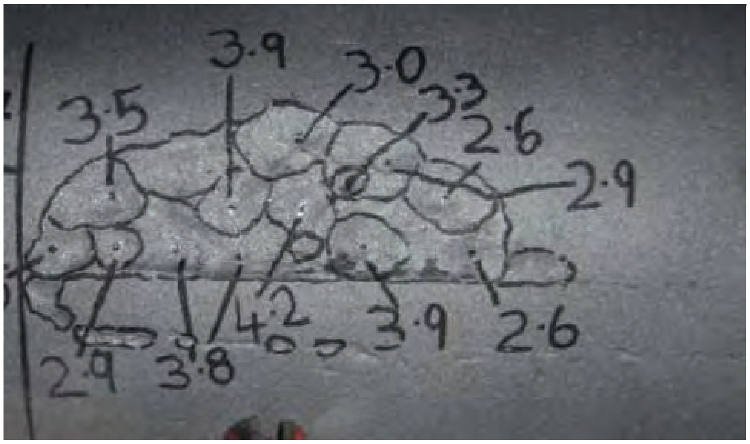
are not detecting the presence of small pits/pinholes within the areas of complex corrosion, leading to an apparent increase in sizing uncertainty.

Figure 17 to Figure 20, present examples of the validated external corrosion, as well as the associated verified, MFL and UTWM sizing. These examples demonstrate that, in general, the complexity of the corrosion positively correlates with tool sizing uncertainty.

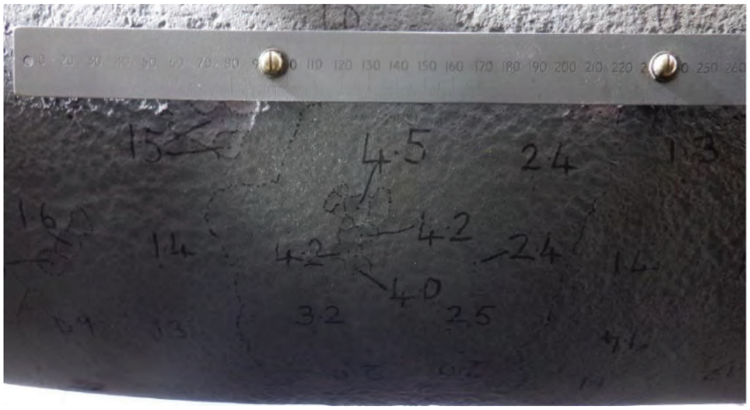


Depth	Verified	74%t
	MFL	40%t
	UTWM	62%t

Figure 17. Validated corrosion example 1 (pitting within general corrosion).

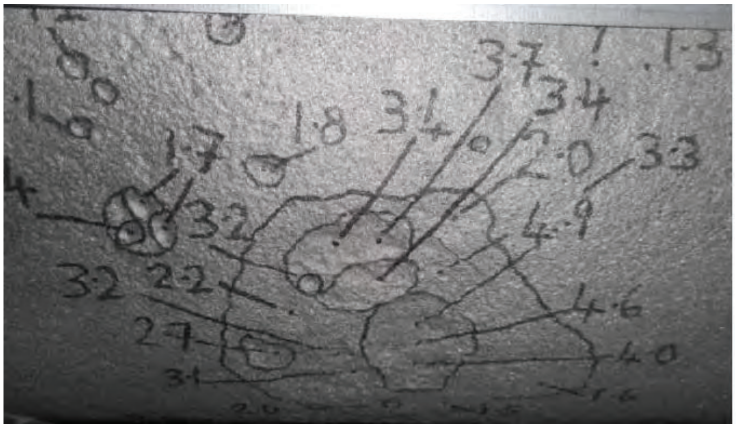
Depth	Verified	73%t
	MFL	71%t
	UTWM	47%t

Figure 18. Validated corrosion example 2 (pitting within general corrosion).



Depth	Verified	55%t
	MFL	35%t
	UTWM	61%t

Figure 19. Validated corrosion example 3 (pitting within general corrosion).



Depth	Verified	77%t
	MFL	71%t
	UTWM	58%t

Figure 20. Validated corrosion example 4 (deepest component is general corrosion).

Implications for integrity assessment

The validation results demonstrate that tool sizing uncertainty can be significant for complex corrosion. There is a trend for deeper pits within shallower corrosion to be undersized by both MFL and UTWM ILIs. Generally, the deepest component has significantly smaller dimensions than for the overall metal loss component. FFS considers both burst and leak criteria. The consequences of a burst are more likely to be realised for larger areas of general corrosion. However, for the small, deep components present within the reviewed complex corrosion, the most likely failure mode would be as a through wall leak. The analysis presented in this paper confirms that applying sizing tolerances based on the overall corrosion dimensions may therefore be underconservative for the through wall leak failure mode. However, applying validated tolerances for overall dimensions of complex corrosion may be overconservative when considering burst criteria. For clustered metal loss the inclusion of cluster member or box data within ILI listings, may allow a more appropriate application of tolerances to the burst and through wall criteria. Although this is only the case if the box dimensions consistently approach that of the deepest component and the depth sizing tolerances are within specifications.

Therefore, ILI validation should be included as standard practice for FFS assessments. The potential for complex corrosion should also be considered, reviewing likely corrosion mechanisms and the associated resulting morphology. Where pits within shallower corrosion are suspected and the ILI has not been validated, more detailed analysis of ILI data could be performed (see e.g. **[15]**) and the application of increased tolerances to a through wall failure condition should be considered.

In addition, the analysis presented in this paper suggests that POF specifications are too not appropriate for interacting corrosion morphologies and more guidance may be required in future updates of the POF specifications. ILI vendors could also consider providing additional data within listings, based on additional review of signal data to indicate the potential for the presence of pits/pinholes within larger regions of general corrosion. Note that for clustered anomalies the box/cluster member data does provide some of this information, although further clarification on, for example, whether the boxes represent single or multiple interacting anomalies would aid in identification of complex morphologies.

It is critical to investigate the most significant ILI reported anomalies, to contribute to effective pipeline integrity management. However, when the verified anomaly data from these investigations is used to validate an ILI, a bias can be introduced into the analysis. This is because the deeper ILI reported anomalies generally corresponded well with in the field measurements. Investigations carried out to validate ILI performance should cover a range of ILI reported depths, different potential corrosion mechanisms and associated morphological complexity.

Conclusions

This paper has reviewed 1031 verified external corrosion anomalies available for various pipelines, and has validated both MFL and UTWM ILIs. The review focused on the impact of corrosion morphology on ILI sizing, comparing isolated pits, general corrosion and pitting within general corrosion. The following are the key findings:

- Both MFL and UTWM ILIs appeared to generally undersize deeper pits within shallower general corrosion.
    - Sizing uncertainty increased as the diameter of the deepest component decreased. The sizing uncertainty also appeared to increase as pit depth increased.
    - POF sizing classifications may be too simplistic for the interacting morphologies.
- In comparing the sizing performance of the two technologies it was identified that the UTWM ILI tended to have a better sizing accuracy than MFL for most corrosion morphologies. However, the MFL tended to size isolated pits more accurately.
- The MFL had a greater likelihood of detecting the external corrosion anomalies than the UTWM.
- In this analysis, the deepest ILI reported anomalies tended to correspond well with NDE field measurements. The most significant sizing uncertainty was seen when the ILIs undersized the corrosion.
    - FFS will typically target investigation of anomalies that are approaching burst or through wall limiting criteria. Depending on metal loss area, the deepest ILI reported anomalies will therefore be more likely to be targeted.
    - Given this, anomalies which have been significantly undersized by the ILI tool may not necessarily be targeted for investigation based on FFS.
    - Therefore, investigating anomalies based solely on integrity assessment results may introduce bias into the validation analysis, with the potential to result in non-conservative interpretation of measurement tolerances.

Based on the findings from analysis presented in this paper, we propose the following future considerations:

- During future updates of the POF specifications, consideration could be given to reviewing and updating the guidance on interacting corrosion morphologies.
- FFS should consider the potential for complex corrosion, potentially applying a higher sizing uncertainty to the through wall failure mode.

  - To aid in this ILI vendors could consider providing additional data within listings, based on additional review of signal data, to indicate the potential for the presence of pits within larger regions of general corrosion[7].

- ILI validation should be included as standard practice with FFS assessments. Verifications for ILI validation should aim to focus on a range of ILI reported anomalies, different potential corrosion mechanisms and associated morphological complexity.
- Operators should consider running dual ILI technologies. This will give the most complete picture of corrosion that may be affecting the pipeline. When integrated with an understanding of their relative performance for detection and sizing different corrosion morphologies (i.e. a wide range of validations), this allows for better interpretation for integrity assessment and management.

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[7] Note that for clustered anomalies the box/cluster member data does provide some of this information, although further clarification on, for example, whether the boxes represent single or multiple interacting anomalies would aid in identification of complex morphologies.

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