RESEARCH PAPER

Improved methods for sizing metal loss in dents for ECA

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ABSTRACT

Dents interacting with metal loss remain as a significant challenge to operators. Existing regulations require that dents with metal loss within high consequence areas be treated as immediate repairs or 60-day conditions, resulting in costly excavations for many operators. At the time when these regulations were written, it was not clear whether inline inspection technologies could discriminate the nature of the metal loss (i.e. corrosion or mechanical damage) or provide accurate sizing. Furthermore, advanced analysis techniques such as finite element analysis were limited, and fitness- for-service evaluations were not common. While the technological hurdles involved with evaluating interacting dent and metal loss features have been overcome, sensor lift-off remains a challenging issue for magnetic flux leakage (MFL) inspection tools, as sizing accuracy degrades at larger lift-off distances. Until recently, the sensor lift-off issue limited the ability to perform fitness-for-service evaluations because the metal loss in dent features could not be confidently sized. This study demonstrates how integrated lift-off sensors can be used to quantify the lift-off as the MFL sensors pass over a dent. This technology integration has allowed the confident application of sizing specifications for many dents with metal loss, thereby permitting robust fitness-for-service evaluations. Several case studies are examined in this paper, demonstrating how the integrated MFL and lift-off technology can serve to reduce excavations while still ensuring safe pipeline operations..

Key words: Pipeline anomalies, metal loss, dent inspection, magnetic flux leakage inspection, fitness-for-service evaluation.

INTRODUCTION

Current regulations, as of late 2019, require that pipeline operators respond to all dents with metal loss within HCAs. In the case of regulated natural gas pipelines operating inside of HCAs, any dent with metal loss was classified as an immediate condition [1]. In the case of regulated liquid pipelines, these dents would be considered as either immediate or 60-day conditions, depending on the circumferential location of the dent [2]. The implicit assumption in the regulations is that any dent associated with metal loss is a result of mechanical damage, and therefore, the metal loss may be associated with gouging. At the time the regulations were written, it was not clear whether magnetic flux leakage (MFL) inline inspection (ILI) tools were capable of discriminating generalized metal loss such as corrosion or manufacturing features from the more severe metal loss associated with gouging. Consequently, the regulations conservatively required all dent with metal loss features be removed from the pipeline.

Unfortunately, these regulations result in a significant number of unnecessary excavations while only successfully removing a few injurious dents. Many bottom side dents are associated with minor corrosion as shown in Fig. 1. In this particular instance a 1.5% OD bottom side dent was identified as interacting with an 11% WT metal loss anomaly in the final report. The field excavation confirmed the dent and found a 5.1% WT metal loss feature. However, this situation is clearly not injurious to the pipeline and in almost all cases would not require an immediate excavation.

In many cases, the severity of the regulations has influenced analysts and operators to be "conservative" when identifying interacting dent and metal loss features for fear of being out of compliance. In some cases, this has resulted in ILI analysts identifying interacting dents even when the depth

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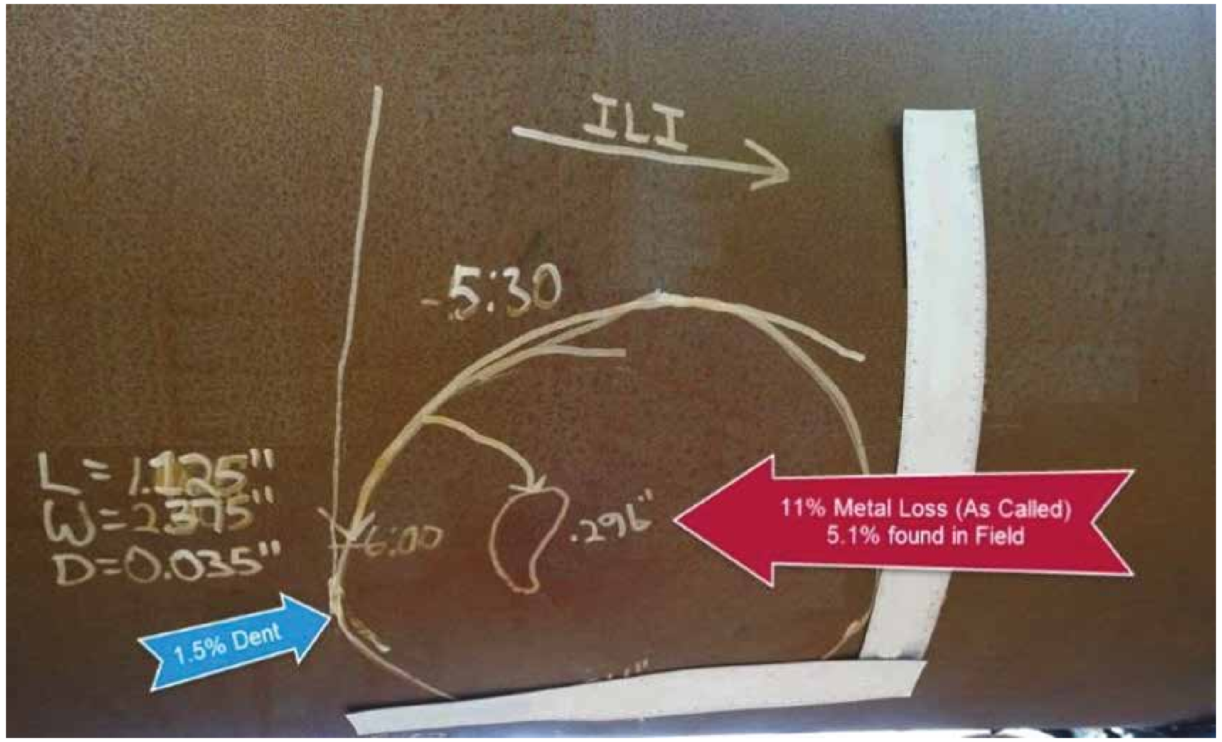

Figure 1. *Example dent with minor metal loss.*

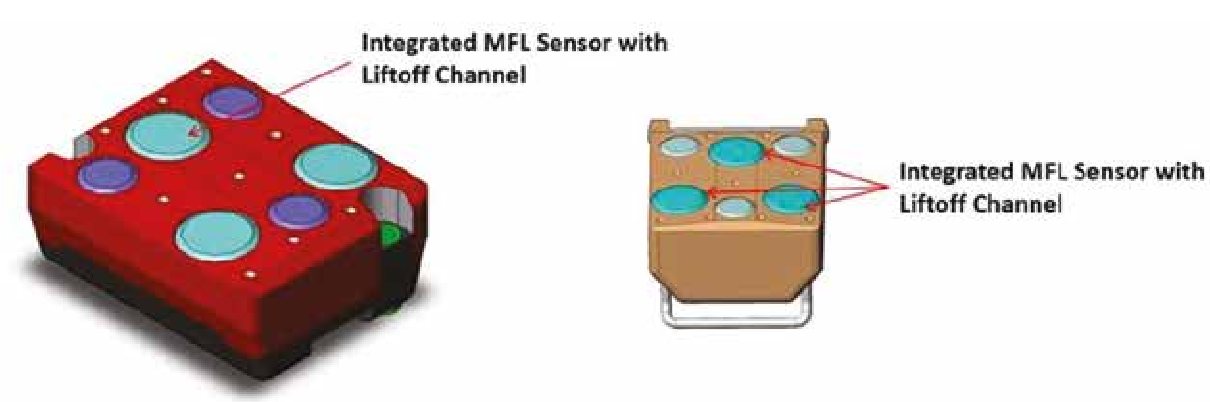

Figure 2. *MFL sensor carrier with liftoff coil noted.*

of the dents is below the caliper reporting threshold or the metal loss is below the MFL reporting threshold. In almost all cases, these types of interacting dents with shallow metal loss features are not injurious to the pipeline and can be addressed through engineering critical assessments (ECAs) or fitness for service (FFS) assessments.

Unfortunately, another challenge has hindered the application of ECAs to address these dents. MFL performance specifications have not been made available for metal loss features interacting with dents. The lack of a specification is a result of uncertainty in the MFL performance in areas where the pipe wall is distorted. It is understood that MFL sizing performance may suffer in these areas as the distance between the sensors and the pipe wall increases. In smooth dents, the sensors may traverse the dent well with no impacts to the sizing capabilities of the tool. On the other hand, when an MFL tool encounters a sharp dent, it is possible that the distance between the sensors and the pipe wall becomes so large that metal loss sizing or even identification may be impacted.

Reliable sizing accuracy is critical to performing a robust ECA for dents with metal loss. Most assessments require the engineer to perform the assessment accounting for the sizing tolerance on the metal loss feature or using a "conservative" estimate. However, if no sizing estimate for the metal loss is available, then the engineer has no means of accounting for

Dent ID	Pipe Diameter	Anomaly Type	Metal Loss Peak Depth [%wt]	Dent Depth [%OD]	Orientation [hh:mm]
1	12.75	Dent w/ ML	6	1	1:13
2	12.75	Dent w/ ML	4	1	12:24
3	12.75	Dent w/ ML	17	2.3	3:04
4	12.75	Dent w/ ML	6	1.9	3:06
5	12.75	Dent w/ ML	2	1.2	3:03
6	12.75	Dent w/ ML	10	2.3	5:51
7	12.75	Dent w/ ML	57	1	6:19
8	12.75	Dent w/ ML	29	1.1	11:33
9	12.75	Dent w/ ML	6	1.3	8:18
10	12.75	Dent w/ ML	6	2.6	5:39
11	12.75	Dent w/ ML	27	1.3	5:39
12	12.75	Dent w/ ML	6	1.6	5:25
13	30.00	Dent w/ ML	2	1.2	6:25

Table 1. *Case study dent data.*

the potential error. This information gap places the operator in the unfortunate circumstance of having the tools to deal with the issue but not enough information to deal with the potential measurement errors.

ILI technology capabilities

Until recently, there was no reliable way to determine how well MFL sensors passed over a dent thereby preventing any statement on tool performance from being provided. However, the distance between the sensor carrier and the pipe wall can be quantified by incorporating a liftoff sensor (i.e. Liftoff Radial Coil, LRC) onto the primary sensor carrier. This integration has been achieved in the current generation of MFL technology. Each MFL sensor carrier typically contains a liftoff sensor in addition to IRC coils and primary metal loss channels (PHH), as shown in Fig. 2. In perfectly straight and smooth pipe the LRC sensors measure no liftoff (i.e. 0 mm). If a disruption in the internal surface of the pipeline causes the carrier to lose contact with the pipe surface, the integrated LRC sensor would record a liftoff measurement. Examples that would result in sensor liftoff include debris, pipe wall deformations, and appurtenances.

Historically, the measurements from the LRC sensor have

Pressure Range (psi)	# Cycles Per Year
175	1
250	5
300	7
325	4
350	7
375	6
450	5
550	38
575	1
596	1

Table 2. *Case study pressure histogram.*

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Dent ID	Anomaly Type	Metal Loss Peak Depth [%wt]	Dent Depth [%OD]	Orientation [hh:mm]	Category
1	Dent w/ ML	6	1	1:13	3
2	Dent w/ ML	4	1	12:24	3
3	Dent w/ ML	17	2.3	3:04	2
4	Dent w/ ML	6	1.9	3:06	2
5	Dent w/ ML	2	1.2	3:03	2
6	Dent w/ ML	10	2.3	5:51	3
7	Dent w/ ML	57	1	6:19	4
8	Dent w/ ML	29	1.1	11:33	3
9	Dent w/ ML	6	1.3	8:18	4
10	Dent w/ ML	6	2.6	5:39	4
11	Dent w/ ML	27	1.3	5:39	3
12	Dent w/ ML	6	1.6	5:25	4
13	Dent w/ ML	2	1.2	6:25	1

Table 3. *Liftoff category assessment.*

been used to confirm if the presence of pipeline debris would compromise the quality of the metal loss data. If the LRC measurement from a carrier exceeded 4.5 mm at any location, the carrier was considered to be “blind” at that location. In general, the LRC measurements have to be less than 1.5 mm at a given location in order for the standard pipe body specification to apply. For LRC measurements between 1.5 and 4.5 mm, degraded specifications may be offered. The information recorded from the LRC channels is often used to determine if an ILI run can be considered acceptable or if additional cleaning and/or a re-run is required.

The same LRC sensor data can be used to quantify sensor liftoff resulting from the tool navigating through a pipe deformation/dent. The following guidelines have been developed when evaluating metal loss data in deformations:

- **In deformations where sensor liftoff is less than 1.5 mm:** standard metal loss sizing specifications apply and liftoff does not adversely affect metal loss sizing.
- **In deformations where sensor liftoff is greater than 1.5 mm but less than 4.5 mm:** data degradation occurs in this range of liftoff. Metal loss anomalies in this liftoff range can be detected; however, a degraded sizing specification would be applied.
- **In deformations where sensor liftoff is greater than 4.5 mm:** metal loss data is not considered to be reliable above this threshold. Detection and sizing specifications cannot be provided.

Currently, the reduced specifications are not available for dents as more data is typically required to develop reduced sizing specifications in the case of debris and this is done on a case by case basis. However, the threshold is identified in anticipation of future developments providing specifications for this range.

Analysis methodology

After a final report has been issued, an engineer and data analyst review any dents with associated metal loss. The goals of the review are twofold. First, they ensure that the metal loss is interacting with the dent by examining the location of the deformation and metal loss features and/or the extents of the feature boxes. Second, they review the LRC measurements for each of the dents. After completing this review, any dent with metal loss may fall into one of the following four categories. This categorization is the first step in assessing dents with metal loss.

Feature ID	Dent Category	MAOP [psi]	Failure Pressure, PF [psi]	Safe Pressure, PSafe [psi]	Acceptable?
1	III	500	1428	1028	Yes
2	III	500	1441	1038	Yes
6	III	500	1784	1285	Yes
8	III	500	1736	1250	Yes
11	III	500	1720	1239	Yes
7	IV	500	1683	1212	Yes
9	IV	500	1792	1290	Yes
10	IV	500	1799	1295	Yes
12	IV	500	1789	1288	Yes

Table 4. *Category III and IV features modified B31G burst pressure.*

- **Category I:** The dent and metal loss are associated, but not necessarily interacting and may be analysed independently.
- **Category II:** The sensor liftoff is beyond the capabilities of the tool (>4.5 mm) and sizing estimates are not recommended.
- **Category III:** The liftoff is between 1.5 mm and 4.5 mm, and sizing estimates may be provided with reduced specifications.
- **Category IV:** The sensor liftoff is <1.5 mm, and the standard pipe body specifications may be provided.

In practice, the procedure for quantifying the liftoff within a dent is described below:

1. A listing containing locations for review with relevant information is provided. This should contain the odometer distance, length/width and orientation of the dent, and depth of the metal loss feature.
2. The anomaly is confirmed in both the Caliper and MFL ILI data with the feature boxes plotted over the data. The engineer confirms that the metal loss and dent are interacting using MFL internal discrimination channels (e.g. IRC). If the metal loss is determined to be near the dent rather than interacting, the engineer may recommend classifying this anomaly as **Category I**. Particular attention is paid to the nature of the metal loss and orientation with respect to the dent peak.
3. Anomalies not classified as **Category I** should be reviewed in LRC data. The location should be reviewed in a snapshot that allows sufficient resolution, such as a 1:5 aspect ratio covering 1/3 of the pipe. The dent and metal loss boxes should remain visible while the LRC channels are displayed in color scan.
4. The initial LRC measurement scale should be set to a maximum value of 1.5 mm to determine if the liftoff within the dent exceeds the initial limit of 1.5 mm. In the color scan plot, blue typically indicates the sensor is in contact with the pipe wall and red would indicate that the upper limit has been exceeded. If no red is present near the metal loss anomaly, the feature is classified as **Category IV**.
5. If the outcome of step 4 determines that the threshold of 1.5 mm has been exceeded, the plot scale is adjusted to a maximum value of 4.5 mm, and the location is re-analyzed. If no red is present near the metal loss anomaly, the feature is classified as **Category III**. If red is present, the threshold of 4.5 mm is exceeded and the anomaly is classified as **Category II**.

It is possible to begin an Engineering Critical Analysis (ECA) for dents with metal loss once categories have been assigned to the liftoff associated with each dent. An ECA for geometric features will assess the static strength and fatigue life of each interacting anomaly. These assessments will determine the fitness for service and remaining life of each feature. A typical engineering critical analysis of a dent with metal loss will entail the following:

Applied MELO							
Dent ID	Max Strain [%]	MELO Depth [% WT]	Category	Tolerance [% WT]	Initial Fatigue Life (Years)†	RFSF x RFWT	Remaining Life [years]
1	2.4	6	III	20	702.2	0.19	132.4
2	2.1	4	III	20	356.5	0.21	73.8
3	n/a	17	II	n/a	n/a	n/a	n/a
4	n/a	6	II	n/a	n/a	n/a	n/a
5	n/a	2	II	n/a	n/a	n/a	n/a
6	2.5	10	III	20	265.1	0.16	41.1
7	0.7	57	IV	10	1046.3	0.01	11.7
8	3.9	29	III	20	2971.8	0.05	152.2
9	1.3	6	IV	10	1673.4	0.29	491.6
10	2.9	6	IV	10	1743.9	0.29	512.3
11	2.1	27	III	20	1269.3	0.06	74.4
12	1.9	6	IV	10	1620.4	0.29	476.0
13	1.2	2	I	-	754	n/a	n/a

†The initial fatigue life is the calculated fatigue life not accounting for the influence of the wall thickness reduction or surface finish effect

Table 5. *ECA results.*

- A static strain assessment of the dent to determine the potential for cracking associated with dent formation.
- A remaining life assessment that estimates how long the dent can remain in service before a fatigue failure occurs.
- A burst strength assessment of the metal loss feature. This entails assessing the metal loss associated with the dent separately using a suitable methodology; typically Modified B31G. This assessment is limited to dent features with a depth less than 6% OD consistent with ASME B31.8-2018 [3].

In order to assess a dent with metal loss a few considerations must be made. The effect of decreased wall thickness and surface finish associated with the metal loss corrosion must be accounted for in the remaining life assessment. The reduction in wall thickness and surface finish can be taken into account by using multiplicative factors. Guidance on the surface finish and wall thickness reduction factors can be found in the PRCI MD-4-9 Documentation [4]. The metal loss interaction is not considered in the strain assessment as the corrosion is assumed to occur after the dent has formed. It should also be noted that the strains will be higher if the original wall thickness is used in the calculations.

The wall thickness reduction can be accounted for by using the ratio between nominal and corroded remaining wall thicknesses. The wall thickness ratio fatigue reduction factor, RF_{WT}, captures the effect that reducing the wall thickness will have on the nominal hoop stresses. The PRCI MD 4-9 research demonstrated that these using this factor was more conservative than using locally thinned areas in finite element (FE) models but less conservative than using a globally thinned FE model [4]. The wall thickness fatigue reduction is calculated using Equation 1.

$$RF_{WT} = \left(\frac{t_{nom}}{t_{corr}}\right)^n \quad (1)$$

This fatigue life reduction factor can be used when evaluating the fatigue life of features and is well suited to methods similar to the level 1 and 2 shape parameter methods presented in the PRCI MD 4-9 research.

Alternatively, one could use stress concentration factors obtained from FE models that use reductions in the wall thickness to account for the increased stresses that are experienced as a result of the wall loss associated with corrosion. Using a global reduction in the wall thickness will typically result in the greatest reduction in fatigue life and is typically the most conservative approach. Using locally thinned areas (LTAs) in FE models should reduce conservativism in fatigue life estimation. The other effect that metal loss will have on the fatigue life of a dent is related to the surface finish effect. Here, it is possible to use a fatigue life reduction factor based on the expected surface finish. The PRCI MD 4-9 research provides guidance on the surface finish factors to use and requires knowledge of the ultimate tensile strength of the pipe [4]. The surface finish fatigue life reduction factor can be calculated using Equation 2.

$$RF_{SF} = \left(K_{SF}\right)^n \quad (2)$$

The wall thickness reduction factor and surface finish factor can be combined together when calculating the remaining life to form a single factor that can be applied to the remaining life. The inverse of this combined factor can be multiplied by the initial fatigue life (i.e., the fatigue life calculated for a plain dent) to account for the influence of both surface finish and wall thickness reduction. This combined factor is provided in the case studies presented in this paper.

A safety factor is applied to the remaining life calculations to account for the uncertainties in the loading from cyclic pressures and geometry inputs. The depth tolerances are applied to the metal loss features in the assessments and are used to account for the uncertainties in the metal loss sizing. The category for each feature is used to select the appropriate tolerances to apply to metal loss features. It is noted that features considered Category III would require reduced specifications for sizing estimates, and currently, reduced specifications are not available. Category II implies that the sensor liftoff is such that sizing estimates are not applicable for interacting metal loss features.

In addition to performing a dent strain and remaining life assessment, the burst strength of the metal loss features should be assessed using a suitable methodology, e.g., ASME Modified B31G for dent depths up to 6% OD, consistent with ASME B31.8 [4]. The burst capacity for dents with metal loss that have a dent depth greater than 6% OD typically entails a level III assessment, which is beyond the scope of this publication.

Case study data

Twelve dents were selected for review in this study, and the particulars of each dent are summarized in Table 1. All of the dents were identified as dents with metal loss. The majority of the dents were taken from a pipeline with a 12-inch nominal OD, and one dent was selected from a pipe with a nominal diameter of 30-inches. The 12-inch material was Grade B with a nominal wall thickness of 0.25 inches. The 30-inch dent was Grade X42 with a nominal wall thickness of 0.360 inches. The orientation of the dents varies around the pipe with a combination of top-of-line and bottom-of-line dents. The majority of the dent depths are fairly shallow with reported depths less than 2% OD. The metal loss associated with most of the dents is also fairly shallow with most of the reported metal loss being less than 10% WT, and only 3 metal loss anomalies having depths greater than 20% WT.

A condensed histogram of the pressure cycle data is shown in Table 2. This condensed histogram was calculated from an actual pressure spectrum using a rainflow analysis. The spectrum severity indicator (SSI) from the complete pressure history is 63.3. If the data is compared to the benchmark profiles produced by Kiefner in [5] using an equivalent number of annual cycles (or SSI), the profile is slightly more severe than a "lightly cycled" liquid line. It should be noted that this is more conservative than a typical natural gas line.

Liftoff assessment

The process for quantifying the liftoff is described for one dent in each of the categories while the classification for each dent is summarized in Table 3. In each case, the anomaly location is reviewed in both caliper and MFL data. The images for the liftoff assessments can be found in Appendix 1. The first liftoff assessment is provided for Dent 9. The initial review is performed on the caliper data shown in Fig. 3. The signal is confirmed to be consistent with a dent feature. Next, the feature box for the dent is projected onto the MFL data and reviewed in Fig. 4 to confirm the interaction between the dent and the reported metal loss. The dent, shown in the larger, greyed box, is confirmed to be interacting with multiple metal loss anomalies denoted by the red boxes. In this example, the metal loss call boxes are clearly within the bounds of the dent, so the dent and metal loss are considered to be interacting and therefore not Category I.

The next step is to overlay the data from the LRC sensors with the metal loss and dent calls as shown in Fig. 5. As shown in Fig. 5, the color scan scale is set to a maximum value of 1.5 mm initially. The red colors indicate higher liftoff values, but none of them exceed the maximum value of 1.5 mm. This example shows that the maximum liftoff associated with this anomaly is just below 1.5 mm. Therefore, the resulting classification is Category IV, and standard MFL specifications may be applied to the metal loss.

The second example liftoff assessment is shown for dent 11. The signal is confirmed to be consistent with a dent feature as shown in Fig. 6. The combination of the geometry data and the MFL data shown in Fig. 7 demonstrates that the reported metal loss signals are clearly interacting with the dent, and therefore it is suitable to conduct a liftoff review. The default color scan scale for the LRC shown in Fig. 8 indicates that the MFL sensors have a liftoff exceeding 1.5mm; therefore the scale is readjusted to a maximum value of 4.5 mm in Fig. 9. This image confirms that the sensor liftoff associated with this anomaly is clearly below 4.5 mm; therefore the final classification for this interaction is Category III. It is also important to note that the liftoff is directly adjacent to the identified metal loss locations.

The next example addresses dents 3, 4, and 5 together as the three features were adjacent to each other. The caliper data is shown in Fig. 10. The initial geometry review notes that these features are complex and would likely require a detailed level 3 FEA assessment if a metal loss evaluation is possible. Fig. 11 confirms that the dents and metal loss features are interacting, and therefore it is suitable to conduct a liftoff review. Similar to example 2, the initial LRC measurement range in Fig. 12 shows that the dents have clearly exceeded the upper threshold of 1.5 mm and the scale must be readjusted to determine if the location is Category III or II. As observed in Fig. 13, there is clear indication that these 3 dents result in sensor liftoff beyond 4.5 mm; therefore, the 3 are classified as Category II, meaning that detection and sizing for any metal loss associated with those dents is beyond the current capability of the tool. It is also noted that the complex geometry associated with the dents and top-of-line location on the pipe tend to support remediation of these features.

The last example is shown for dent 13. After confirming a typical dent signature, Fig. 14 shows the MFL data with the extents of the geometric deformation noted. This example shows that the reported metal loss, denoted by the smaller box on the top-right corner, is on the outer perimeter of the dent box, so a more detailed review of the metal loss interaction is considered appropriate. The internal discrimination channels are useful in determining the area affected by the deformation using a sensor that is mounted on the same MFL carrier as the primary metal loss sensors. This data, in Fig. 15, overlaid as a color scan behind the primary metal loss data, confirms that the affected area noted by the dashed line is not interacting with the reported metal loss, therefore this anomaly can be classified as Category I. The dent with metal loss is considered a conservative classification made by the analyst upon observing that the boxes are interacting; however a detailed review demonstrates that the dent and the metal loss can be assessed separately in this case.

ECA results

An ECA was performed after the categorization was completed. The ECA entailed a dent strain assessment, a remaining life calculation, and a Modified B31G burst pressure calculation for the associated metal loss features. The assessments were performed using geometry and MFL data obtained from the inspection. Methods that may be used to calculate remaining lives include the shape factor as described by the PRCI MD 4-9 documentation [4], the shallow restrained dent fatigue life tables [6, 7], or SCFs coupled with S-N curves [8].

The case study presented in this paper used the pressure data and SCF's calculated from finite element models to determine remaining lives with an S-N approach. In the interest of brevity, the details of the assessment are not presented in this paper, but can be found in previous publications [8]. Sizing tolerances for the MFL features that are appropriate to the feature's respective liftoff categories were used in the assessments. A design fatigue factor of 3 was used when determining the remaining life. The results of the remaining life assessments are summarized in Table 5.

Only one feature (dent 13) was identified as Category I meaning that the metal loss and the dent were not interacting. In this case, the dent is treated as a plain dent. Given that the dent depth is below 2% OD, the feature would typically be considered shallow and not addressed by most integrity management programs but is included in this study. The calculated surface strains are 1.2% which is below the lower bound limit of 6% OD for plain dents in ASME B31.8-2018. Using the shallow dent screening criteria [6], the feature is shown to have a remaining life of 754 years, which is also acceptable. The burst pressure of the plain dent is not a concern as plain dents up to a depth of 6% OD have been demonstrated to not impact burst capacity [9].

There were three features that were marked as Category II (dents 3, 4, and 5). The sensor liftoff in these cases is beyond the current capabilities of the tool and sizing estimates are not recommended for the metal loss. Absent a hydrotest or previous in-field verification, these features would likely need to be remediated because an ECA does not have the necessary information to provide sizing specifications for the metal loss anomalies. Furthermore, the complex shape of these anomalies and the close interaction of multiple features as noted in the review of the liftoff assessment tends to support the conclusion that the features should be remediated.

There were five features that were marked as Category III. These features would require reduced specifications for sizing estimates. Since reduced specifications are not available at this time, an additional 20% WT depth was added to all Category III features for demonstration purposes. For each of the features the remaining lives were calculated using pressure data, SCFs obtained from finite element models, S-N curves and appropriate wall thickness and surface finish fatigue factors. The calculated fatigue surface finish factor is 1.192 for each of the features.

The results for the Category III are summarized in Table 5. None of these features exhibited lives that would have been deemed as immediate threats. It is noted that the ECA performed should result in a conservative remaining life because the increase in peak stresses that is estimated to occur as a result of reduced wall thickness is applied for the entire life of the feature. In reality, the corrosion likely started

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after the feature had already experienced some cycling. In addition, the assessment methods have some conservatism built into the wall reduction factor.

The burst pressure for each of the Category III features is presented in Table 4. The relatively shallow nature of the metal loss features, even when accounting for amplified tool tolerances, still produces an acceptable pressure containing capacity for each of the Category III features. While the results for the Category III dents are presented for demonstration purposes, the plausibility of this approach demonstrates the need for identifying tool tolerances for Category III features that have sensor liftoff between 1.5 and 4.5 mm.

There were 4 features that assigned as Category IV. These features were analyzed by applying standard tolerances for metal loss sizing. For each of the features the remaining lives were calculated using pressure data, SCFs obtained from finite element models, S-N curves and appropriate wall thickness and surface finish fatigue factors. The calculated fatigue surface finish factor is 1.192 for each of the features.

Of these Category IV features, one feature exhibited a fatigue life less than 100 years, and this was primarily on the basis of the significant metal loss depth of 67% WT (inclusive of the tolerance of 10%). The shorter remaining life reflects the significance of the corrosion rather than the interaction between the metal loss and the dent. A more detailed remaining life assessment is likely to yield an improved fatigue life. The other remaining features have significant remaining lives in excess of several hundred years. The calculated burst pressure for each of the Category IV features is shown in Table 4. All metal loss features exhibited satisfactory burst strength capacity.

Findings

Current regulations, which are anticipated to change, currently consider any dents with metal loss within HCAs to be significant anomalies requiring either immediate or 60-day response times. This study has shown that the inspection and analysis tools exist to address dents with metal loss. However, it is important that tool tolerances be considered in the remaining life analysis. Unfortunately, tool tolerances are often not provided for metal loss features interacting in dents due to uncertainties with MFL sensor passage over deformations.

This study demonstrated how the integration of liftoff sensors onto the MFL sensor carriers can address the issue of quantifying sensor passage. The LRC sensors can quantify the liftoff across a deformation which then determines whether specifications can be provided for a given feature. If specifications can be provided, then an ECA process is possible which can prevent costly and unnecessary excavations. The current review process presented in this study also includes a method for improving the evaluation of interactions with dent and metal loss features.

In the study presented in this paper, approximately 1/3 of the features were shown to not be immediate conditions. Another 1/3 of the features can be assessed using an ECA but would require the development of reduced specifications. While these reduced specifications are not currently available, the study demonstrates the considerable industry value such specifications would have.

Competing interests

The authors declare that there is no competing interest regarding the publication of this paper.

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[9] Bood, R, Gali, M, Marewski, U, Steiner, M, Zarea, M, "EPRG Methods for Assessing the Tolerance of and Resistance of Pipelines to External Damage (Parts 1 + 2)", European Pipeline Research Group (EPRG), 10-11/1999 Pg 739-744, 12/1999 Pg 806-811.

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Appendix 1

Evaluation images for liftoff assessment

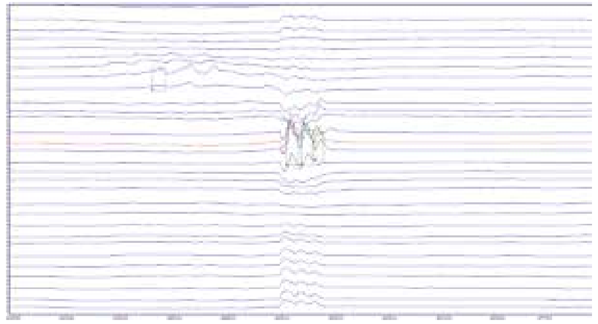

Figure 3. *Caliper data for Dent 9.*

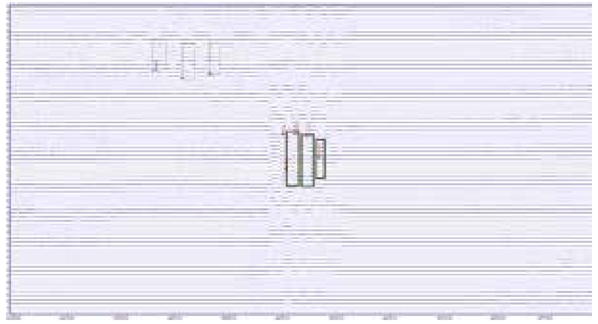

Figure 4. *MFL data confirming metal loss interaction for Dent 9.*

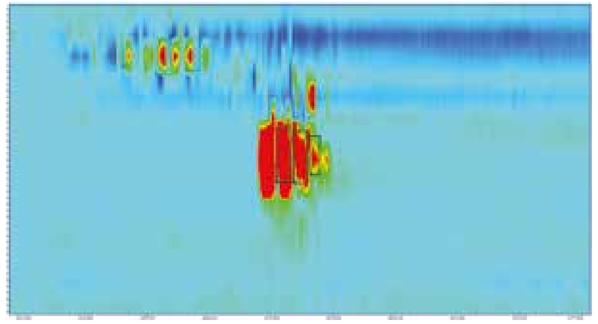

Figure 5. *Liftoff data (LRC) confirming category iv classification for Dent 9.*

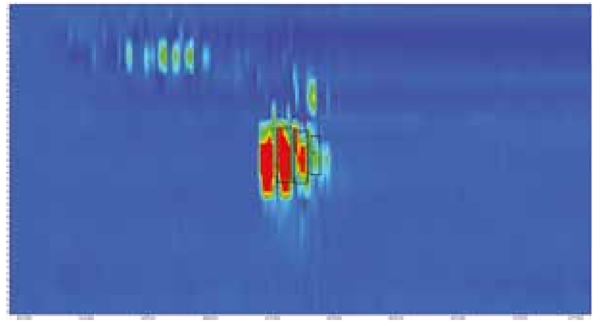

Figure 6. *Caliper data for Dent 11.*

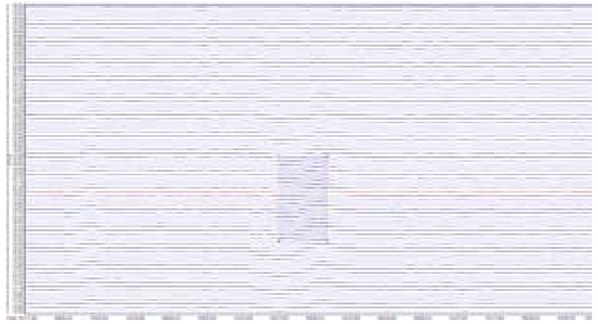

Figure 7. *MFL data confirming metal loss interaction for Dent 11.*

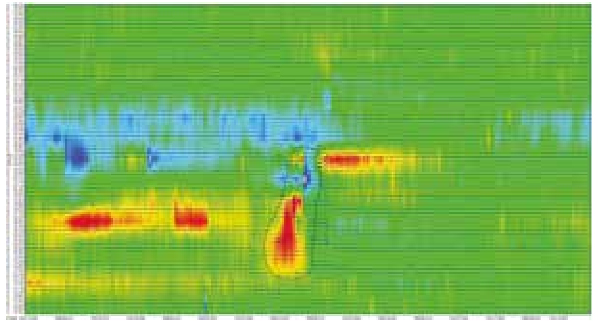

Figure 8. *Liftoff data (LRC) showing sensor liftoff > 1.5mm for Dent 11.*

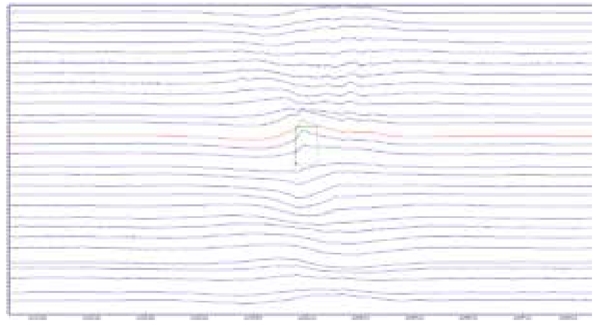

Figure 9. *Liftoff data (LRC) with adjusted scale showing liftoff < 4.5 mm for Dent 11.*

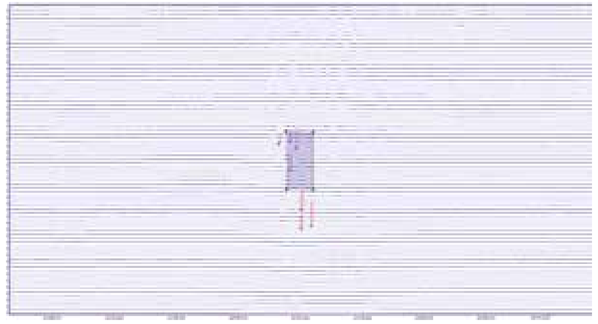

Figure 10. *Caliper data showing 3 dents under review for Dents 3 to 5.*

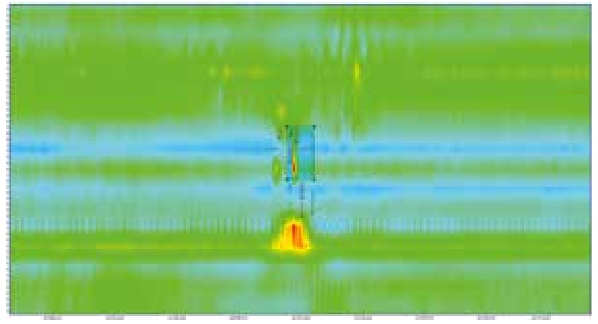

Figure 11. *MFL data confirming metal loss interaction for Dents 3 to 5.*

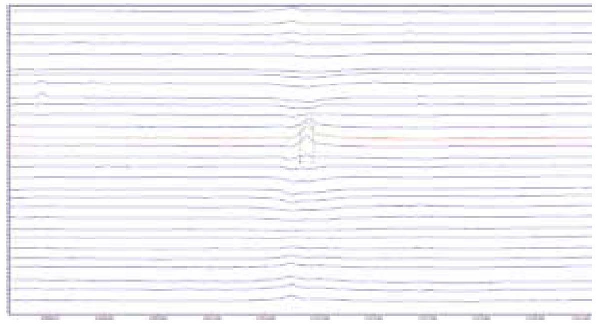

Figure 12. *Liftoff Data (LRC) showing sensor liftoff > 1.5mm for Dents 3-5.*

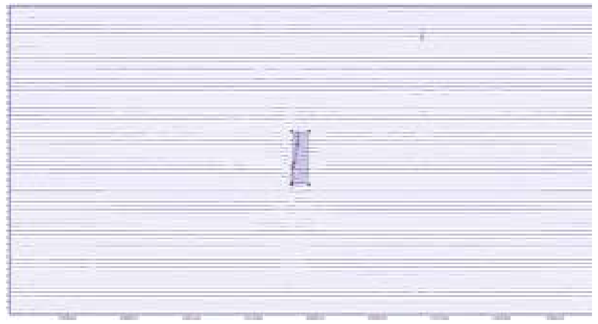

Figure 13. *Liftoff data (LRC) with adjusted scale showing liftoff > 4.5 mm for Dents 3-5.*

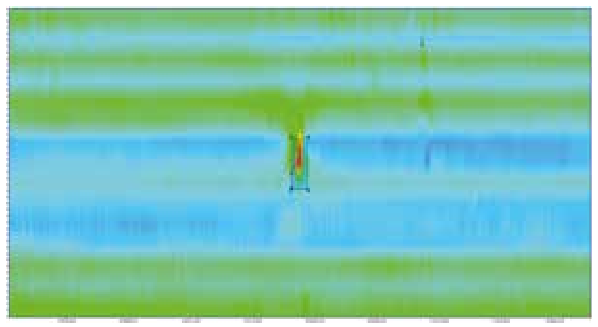

Figure 14. *MFL metal loss data showing interaction between dent and metal loss call boxes for Dent 13.*

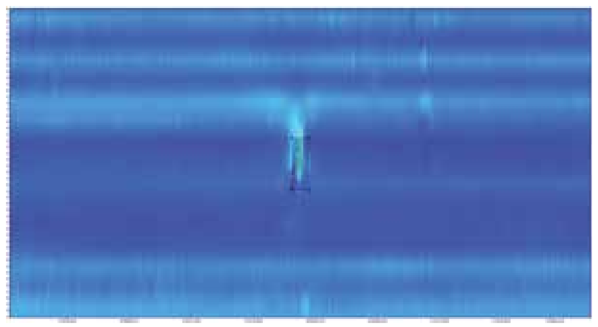

Figure 15. *MFL metal loss data with internal discrimination channels in background color scan for Dent 13.*

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Image courtesy of Nord Stream 2 and Axel Schmidt.