Improved methods for sizing metal loss in dents for ECA

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INTRODUCTION

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.
Table 1. Case study dent data.

| 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 2. Case study pressure histogram.

| 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 3. Liftoff category assessment.

| 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        |

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 pass 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). However, the distance between the sensor carrier and the pipe surface, the integrated MFL technology. Each MFL sensor carrier typically contains 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 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. 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 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.

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.
within a dent is described below:

1. A listing containing locations for review with
   • A burst strength assessment of the metal loss feature.
   • 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
     (FE) models but less conservative than using locally
     thinned areas in finite element
     research demonstrated that these using this factor was more
     conservative than using globally thinned FE models but less conservative than using a globally
     thinned FE model [4]. The wall thickness fatigue reduction factor, $RF_{WFT}$ captures the effect that reducing the wall thickness
     will have on the nominal hoop stresses. 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
     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,
     $RF_{WFT}$ 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.

2. The sensor liftoff is <1.5 mm, and 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.

4. 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.

3. Anomalies not classified as Category I should
   be reviewed in LRC data. The location should
   remain visible while the LRC channels are displayed
   in color scan.

2. 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.

3. Anomalies not classified as Category I should
   be reviewed in LRC data. The location should
   remain visible while the LRC channels are displayed
   in color scan.

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

| Feature ID | Feature 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 5. ECA results

| Dent ID | Max Strain [%] | MELO Depth [% WT] | Category | Tolerance [% WT] | Initial Fatigue Life (Years)* | 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 6. MELO results

| Dent ID | Max Strain [%] | MELO Depth [% WT] | Category | Tolerance [% WT] | Initial Fatigue Life (Years)* | 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 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 PRCT 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 to account for the increased stresses that factors obtained from FE models that use reductions in the wall thickness to account for the uncertainties in the loading from cyclic spectra severity indicator (SSI) from the complete pressure data, SCFs obtained from finite element models, each of the features the remaining lives were calculated using Equation (2).

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 LRC on the dent depth to 30% of the dent depth. 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 dents was shallow, 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 rainfall 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 of the sensor signal, shown in the larger box, is on the perimeter of the dent and top-of-line location confirms that the sensor liftoff is such that sizing estimates are not applicable. Category II implies that the sensor liftoff associated with the reported metal loss, therefore this anomaly can be classified as Category III, meaning that detection and sizing for any metal loss associated with these 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. Using the shallow dent screening criteria [6], the feature is classified as Category II, meaning that detection and sizing for any metal loss associated with these 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. Using the shallow dent screening criteria [6], the feature is classified as Category II, meaning that detection and sizing for any metal loss associated with these features should be assessed using a suitable methodology, e.g., ASME B31G, to account for the uncertainties in the metal loss sizing. Since reduced specifications 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 specific repair recommendations. 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 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. Therefore, this anomaly is clearly below 4.5 mm; therefore the final conclusion that the features should be remediated. The case study presented in this paper used the pressure data and SCFs obtained from finite element models to determine remaining lives with an S-N approach. In the interest of brevity, the details of the analysis for dent 3 is 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 applied to the metal loss anomalies. Moreover, 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 II. 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 II 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 longer 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...
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 to note that tolerances are 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 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.

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

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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.
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