Feasibility Study of Pinhole Inspection via Magnetic Flux Leakage and Hydrostatic Testing in Oil & Gas Pipelines

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Abstract. Oil & Gas pipeline pinhole leaks are more likely to lead to serious consequences than larger leaks because they are difficult to discover through conventional monitoring and patrolling. An undetected pinhole leak can lead to significant soil and groundwater pollution over time. The effectiveness and applicability of magnetic flux leakage (MFL) in characterizing and sizing pinhole defects is studied by pull test in a 10-inch pipe string with manufactured defects. MFL technologies from five vendors were tested in blind scenarios. In addition, the feasibility of using hydrostatic testing to detect pinhole defects is investigated. The results show that the MFL signal may be affected by pinhole diameter, depth, position, and so on. An optimal practice was developed by comparing the gap between MFL tracks, sampling frequency, intensity of magnetic field, etc. And there was no significant reduction in pressure capacity within the test pipe segment with pinhole. So it is speculated that hydrostatic testing can only identify pinholes that have fully penetrated the pipe wall.

1. Introduction

1.1. Significance of pinholes

Pinhole leaks have been reported as a significant cause of oil & gas pipeline failures in recent years. From 2010 to 2015, at least 131 significant incidents involving oil and gas pipelines in the United States (101 and 30, respectively) were attributed to pinhole leaks[¹]. Pinholes may result from normal pipeline corrosion during routine operations, such as microbiologically induced corrosion, or can be created by third-party activities, such as illegal tapping. An European Gas Pipeline Incident Data Group (EGIG) report[²] from year 2007 to 2016 identified...
“Pinhole Corrosion” & “Hot Taps” made by error” as significant causes of pipeline failure. See Figure 1. Pinhole leaks, while smaller in initial volume, can grow to become higher consequence events due to its tiny leakage that can’t be detected through pressure monitoring or patrolling if the leaked products not over flow above ground[3,4]. Figure 2 shows a pinhole leaking in a gasoline pipeline.

![Figure 1. Chart from EGIG report, relationship primary failure frequency (2007-2016)](image1)

![Figure 2. Pinhole leaking(left) and its profile (right).](image2)

1.2. Pinhole Specifications

Pinhole metal loss is defined by the Pipeline Operators’ Forum (POF) as having length (L) less than 1A and width (W) less than 1A, where A is equal to the smaller of 10 mm or wall thickness. The POF metal loss diagram for defect shape and orientation (Figure 3) forms the basis of detection and discrimination performance for the evaluated ILI technologies. In this diagram, W is the circumferential width of a feature, L is the axial length, and A is a normalizing parameter based on the wall thickness of the pipe[5]. However, the standard for pinhole classification shown in Figure 3 may be a bit conservative. In the sample defects discovered in some failure cases, the defect diameter was typically much smaller than the wall thickness, or even 4 mm or less.

Generally, it is difficult to detect pinhole corrosion using magnetic flux leakage (MFL) because the small surface dimensions and limited volume of metal loss results in very small MFL response[6]. Currently, few ILI vendors claim to meet pinhole detection specifications.
2 Magnetic Flux Leakage (MFL) Pull Through Test.

2.1. Brief of magnetic flux leakage (MFL)

The magnetic flux leakage (MFL) technology is one of the earliest technologies to be studied and introduced into oil and gas pipeline inspection[7], Figure 4 shows a typical magnetic flux leakage (MFL) tool. The detection principle of MFL is to magnetize the steel pipe wall with a strong magnet module installed in on the inspection tool[8-10]. A magnetic loop is created at the full section of the pipe wall covered by the magnet module, defects are detected and quantified by changes in the magnetic field at the defects (see Figure 5). Obviously, MFL is using indirect method to identify defects. The best situation is to magnetize the pipe wall to the near saturation state, as the magnetic flux leakage can well reflect the variation of the pipe wall thickness. MFL inspection does not need pre-processing and it’s easy to analysis the signal. Also, MFL is the most widely used and most mature in line inspection technology at present due to its advantages such as low requirements on the internal conditions of the pipeline, no need for coupling, can detect many types of defects, low price and so on.

Magnetic flux leakage (MFL) technology is sensitive to defects with volumetric type, and can well detect metal loss features such as corrosion, grooving, etc, and well sizing accuracy can be achieved[11]. But it can hardly detect small metal loss such as pinhole, and plane defects[12,13]. So, there is some research need to be done to improve the application of MFL.
2.2. Test Design
Prior to any testing, typical pinhole defects were reviewed by examining sections of pipeline recently removed from operation due to leaks caused by corrosion. The sizes and shapes of the observed pinhole defects were used as a reference for design of artificial defects used in the pull through tests.

Figure 6 portray real-world pinhole leaks detected by hydrostatic testing. Following a leak investigation, the damaged pipe spool shown in Figure 6 was removed and replaced. It was determined that the pinhole leaks in this pipe were the result of internal corrosion. Table 1 summarizes the observed defects, along with measurements and relative locations. Most of these leaks were located at the bottom of the pipe and are classified as isolated flaws. Diameters of the observed pinholes in this pipe range from two mm to eight mm.
Figure 6. Pipe spool with multiple pinhole leaks.

Table 1. Identified defects in first pipe spool.

| Defect No. | Defect Location               | Defect Morphology     |
|------------|-------------------------------|-----------------------|
| 1          | 255 mm upstream of D1         | 6 mm circular metal loss |
| 2          | 240 mm upstream of D1         | 3 mm circular metal loss |
| 3          | 140 mm upstream of D1         | 8 mm circular metal loss |
| 4          | D1 leaking point              | 8 mm circular metal loss |
| 5          | D2 leaking point              | 4 mm circular metal loss |
| 6          | 5 mm downstream of D2         | 7 mm circular metal loss |
| 7          | 59 mm downstream of D2        | 6 mm circular metal loss |
| 8          | 205 mm downstream of D2       | 6 mm circular metal loss |
| 9          | 567 mm downstream of D2       | 5 mm circular metal loss |
| 10         | 867 mm downstream of D2       | 9 mm circular metal loss |
| 11         | 910 mm downstream of D2       | 11 mm circular metal loss |
| 12         | 1130 mm downstream of D2      | 3 mm circular metal loss |
| 13         | 1517 mm downstream of D2      | 2 mm circular metal loss |

2.3. Testing

Testing was conducted on a 10-in pipe string that had been removed from an in-service pipeline. Five in-line inspection (ILI) vendors participated and tested in blind scenarios. Note that pinhole detection lies outside the MFL-ILI specifications for most of the participating vendors. Additionally, the purpose of this report is not to compare the capabilities among these vendors, but to evaluate the overall applicability of existing MFL techniques to the pinhole detection. Thus, each vendor is referred to within this report simply as Vendor A, Vendor B, etc. Figure 7 shows the test string at the test facility. The test string measured approximately 96 m in length and was comprised of three parts: the lead-in spool, the test spools, and the lead-out spools. The lead-in spools measured approximately 32 m in length; the test spools, which contained the machine-made artificial defects, measured approximately 40 m in length; and the lead-out spools measured approximately 24 m in length.
Figure 7. Pull test facility and schematic of test string.

The nominal wall thickness (NWT) of the pull test spools is 5.6mm. The artificial pinholes were machined by different drills and the feature have slightly round bottoms. The depth of all features has been checked by depth gauge. Table 2 summarizes the 47 artificial pinholes created in the test spools, and Fig.8 contains photographs of representative pinhole defects.

Figure 8. Typical artificial defects.

Five ILI vendors participated in the project. Table 3 summarizes the number of tests and speeds for each test run by vendor. Generally, due to its small area of metal loss, the amplitude and spread of MFL signal is lower for pinholes compared with pitting or general metal loss, the flux remains concentrated on the pipe surface. Increasing the number of sensors & axial sampling rate beyond may improve the detection of pinholes.

Table 2. Summary of artificial defects for pull through testing.

| Types      | Quantities |
|------------|------------|
| Pinhole    |            |
| internal   | 18         |
| external   | 24         |
| penetration| 5          |
Table 3. Summary of test runs by vendor

| Vendor ID | Total No. of Runs | No. of Runs × Speed of Run | No. of Signal Channels |
|-----------|-------------------|-----------------------------|------------------------|
| A         | 12                | 2 × 0.5 m/s 4 × 1 m/s       | 120                    |
|           |                   | 2 × 2 m/s 2 × 3 m/s         |                        |
|           |                   | 1 × 4 m/s 1 × 5 m/s         |                        |
| B         | 10                | 2 × 0.5 m/s 2 × 1 m/s       | 90                     |
|           |                   | 2 × 1.5 m/s 2 × 2 m/s       |                        |
|           |                   | 2 × 2.5 m/s                 |                        |
| C         | 11                | 5 × 0.25 m/s 4 × 1 m/s      | 120                    |
|           |                   | 1 × 2 m/s 1 × 3 m/s         |                        |
| D         | 5                 | 1 × 0.5 m/s 1 × 1 m/s       | 72                     |
|           |                   | 1 × 1.5 m/s 1 × 2 m/s       |                        |
|           |                   | 1 × 2.5 m/s                 |                        |
| E         | 2                 | 1 × 0.5 m/s 1 × 1 m/s       | 120                    |

2.4. Results

Tables 4 presents the overall results for the detection of pinholes by MFL-ILI vendors. At least 70% of the 47 total pinholes were detected by four vendors, excluding only Vendor B. The majority of the pinholes that remained undetected had a diameter of less than two mm or a diameter of less than four mm and depth of less than 40% NWT. The detection ratios for pinholes indicates that the circumferential coverage of signal channels maybe more significant influence. There is a positive correlation between a higher number of channels (see Table 3) and a higher detection of pinholes.

Table 4. Summary of test results for pinholes.

| Type of defect | No. of defects | No. of defects detected |
|----------------|----------------|-------------------------|
| Internal       | 18             | A: 15  B: 13  C: 14  D: 12  E: 15 |
| External       | 24             | A: 17  B: 13  C: 16  D: 17  E: 14 |
| Penetration    | 5              | A: 5  B: 3  C: 5  D: 5  E: 5 |
| Total          | 47             | 78.7  61.7  74.5  72.3  72.3 |

Error in reported depths $\Delta d = d_{\text{reported}} - d_{\text{machined}}$

$\pm 10\% \text{wt}$
- 12
- 5
- 11
- 5
- 7

$\pm 15\% \text{wt}$
- 15
- 5
- 16
- 10
- 9

Error in reported lengths $\Delta l = l_{\text{reported}} - l_{\text{machined}}$

$\pm 5$ mm
- 33
- 7
- 34
- 0
- 6

$\pm 10$ mm
- 36
- 24
- 35
- 21
- 24

$d =$ depth
$l =$ length
$\%\text{wt} =$ percent wall thickness
As evident in Figure 9, the vendor-reported depths for most of the pinhole defects were less than true machined depths ("low level call and scattered"). This may indicate that the conventional metal loss sizing model or algorithm used by the MFL vendors is unsuitable for pinhole defects.

Figure 10 illustrates axial MFL signals for artificial defects no. 4, 8, 13, and 18, which correspond to pinholes with a depth of 80% wt and diameters of one, two, four, and seven mm, respectively. These signals indicate that even at a depth as great as 80% wt, a feature with a one-mm diameter is unlikely to register in the magnetic response. This diagram also illustrates that the smaller the surface dimensions and volume of metal loss for a given defect, the less impact there is to the magnetic flux leakage.

It will be necessary to improve existing metal loss sizing models or develop a new model focused on pinhole defects to improve the correlation between reported results and true measurements. If such a model were applied to larger diameter pitting defects, however, the reported depths would likely be overstated.

The deviation between reported and true lengths among vendors varies significantly. Vendors A and C reported results within ± 5 mm of true values in more than 80% of pinholes, and within ± 10 mm of true values in more than 90%. 
Figure 9. Unit plots of pinholes with reported depth vs real depth.
Figure 10. Magnetic response for varying diameters with constant depth.

Figure 11 summarizes depth errors for pitting defects and pinholes for all five vendors. It is noted that vendors did not meet claimed specifications even for pitting defects. Nonetheless, the sizing algorithm of isolated small metal loss may not as applicative as expected. Depths reported by Vendors A and C are relatively consistent with true depths for all defects greater than 10 mm in diameter, with an error range of -20%wt to +10%wt and -30%wt to 0, respectively. The error range for reported depths is -40%wt to +10%wt for Vendor E, -80%wt to +10%wt for Vendor B, and -60%wt to 0 for Vendor D. Yellow dashed boxes indicate features with diameters greater than 10 mm.

Figure 11. Reported depth vs machined depth.

3 Hydrostatic Testing

3.1. Testing procedure

This study outlines tests conducted to investigate the feasibility of using hydrostatic technology to detect pinholes. The design of the hydrostatic tests referred to the actual state of pinhole defects taken from replaced pipe segments. Hydrostatic testing was conducted on six pipe spools with a 5.6 mm wall thickness. Each spool measured 5 m in length and had been removed from an in-service pipeline. Spools were comprised of 10-in(273mm) electrical resistance
welded steel with a minimum yield strength of 245MPa and an ultimate tensile strength of 415MPa. Artificial defects were created in one spool for hydrostatic testing purposes. Real defects in the second spool were a result of corrosion associated with pipeline operations. All metal loss defects were measured prior to testing using non-destructive evaluation techniques. The test facility included pipe supports, a pressure pump, a water filling tube, a vent valve, a monitoring camera, and other testing appurtenances. Figure 13 illustrates the pressurizing process for each testing. During the hydrostatic test, water is injected into the sealed pipe spool at increasing pressures, causing the spool to deform until either the pipe ruptures or a target pressure (beyond 17MPa that the spool maybe overall yield) is reached and the test is concluded.

![Figure 12. Hydrostatic test spools.](image)

![Figure 13. Schematic of pressurizing process.](image)

3.2. Results of Hydrostatic Testing
Six hydrostatic tests were completed. Five of the tests were conducted with manufactured (artificial) defects; the sixth test was conducted on a pipe with existing defects resulting from corrosion. The size of real defect is randomized and its range is from two mm to ten mm. Table 5 summarizes the defects associated with each test. It shows that no spool rupture in pinhole positions, even when pinhole depth is close to full penetration (e.g., pinhole loss depth equals 80% of the wall thickness), there is no significant reduction in pressure capacity of the test pipe segment. Therefore, it is speculated that hydrostatic testing can only identify defects that have penetrated the pipe wall. If the pinhole has not yet fully penetrated the wall, hydrostatic testing will fail to detect the defect.
### Table 5. Summary of hydrostatic tests.

| Test no. | Defect type | Defect position | No. of defects | Depth (% wt) | Diameter (mm) | Results |
|----------|-------------|-----------------|----------------|--------------|--------------|---------|
| 1        | artificial  | external         | 3              | 60/70/80     | 5            | target pressure is reached |
| 2        | artificial  | external         | 3              | 60/70/80     | 10           | target pressure is reached |
| 3        | artificial  | internal         | 3              | 60/70/80     | 5            | target pressure is reached |
| 5        | artificial  | external         | 3              | 90           | 5            | rupture in seam weld |
| 6        | real        | internal         | 41             | ≤ 45         | 2 ~ 10       | rupture in seam weld |

### 4 Conclusions

#### 4.1. Pinhole Detection via Magnetic Flux Leakage

Prior to testing, the team observed pinhole defects in pipes removed from an operating pipeline. Artificial pinholes for test scenarios were designed to mimic real world defects. Pull through testing was conducted to evaluate whether MFL technology can detect such defects, and to evaluate whether the conventional sizing algorithm or model is applicable to such defects. Most of the defects evaluated in this study are outside the claimed vendor performance specifications. Therefore, summary statistical analysis of the test results is intended to evaluate overall technology status, not to distinguish among specific vendor capabilities.

Results are summarized as follows:

1. Hardware configuration varied by vendor. Equipment from Vendors A, C, and E had 120 signal channels, whereas equipment from Vendor B included 90 channels, and Vendor D’s equipment included only 72 channels. A positive correlation was observed between the ability of a vendor’s equipment to detect small defects and a higher number of signal channels.

   Defects greater than 4 mm in diameter were detected by almost all vendors. Defects 2 mm or more in diameter and with at least 60% NWT metal loss were also detected in most instances. Vendors A and C show a high POD for defects with a diameter between 2 and 4 mm and depth of 40% NWT or greater. Vendors D and E show a high POD for features with a diameter of at least 2 mm and depth of 60% NWT or greater. Vendor B detected features with diameter of at least 7.0 mm. The maximum difference of detected metal loss features is about 10%. The main difference between different vendors is apparently the ability to detect pinhole defects.

2. Results among vendors are scattered with respect to reported vs true depth of pinholes. Overall, reported depths are much lower than true depths, indicating that the conventional metal loss sizing model may not be suitable for pinhole defects. It will be necessary to improve existing metal loss sizing models or develop a new model focused on pinhole defects to improve the correlation between reported results and true measurements. If such a model were applied to larger diameter pitting defects, however, the reported depths would likely be overstated.

3. Although axial sampling intervals varied by vendor, results for pinholes indicate that, within a certain range, the axial sampling interval has no significant impact on the probability of detection. In contrast, the number of signal channels is critical to detection of small defects.

#### 4.2. Pinhole Detection via Hydrostatic Testing

None of the six hydrostatic tests results in leaking or rupturing of the pinhole-type defects, even when the depth of the pinhole was close to penetration (e.g., 90% of the pipe wall thickness).

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This indicates that there was no significant reduction in pressure capacity within the test pipe segment. It is speculated that hydrostatic testing can only identify defects that have fully penetrated the pipe wall. If the defect is not yet penetrating, hydrostatic testing will fail to detect the defect.

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