In-Line Inspection of High Pressure Transmission Pipelines: State-of-the-Art and Future Trends

Alfred BARBIAN, Michael BELLER
NDT Systems & Services, 76297 Stutensee, Germany; Phone: +49 7244 7415 0, Fax: +49 7244 7415 97, alfred.barbian@ndt-global.com, michael.beller@ndt-global.com

Abstract
Today in-line inspection through the use of in-line inspection tools is a standard procedure. These inspection tools collect highly precise data regarding the geometry of flaws and defects in the pipe wall. In turn this data is used for fitness-for-purpose investigations, the final goal of the operator being an understanding of the true state of integrity for a given pipeline.

Different physical principles are applied during the non-destructive testing of pipelines, each with its own set of advantages and disadvantages. Choosing the most suitable non-destructive testing technology and therefore in-line inspection tool for a given inspection task requires an understanding of these different techniques and their system-specific measurement thresholds, accuracies and resolutions.

This paper will provide an overview of the most widely used in-line inspection technologies of today, with a special focus on the use of ultrasound technology for the detection and sizing of metal loss, quantitative wall thickness measurement and crack inspection. Case examples will be used to illustrate the information that these tools can provide and the influence of accuracy, resolution and confidence levels on integrity assessment and fitness-for-purpose procedures.

The paper will also discuss current trends in the industry: the development and application of specialized inspection tools for offshore pipelines in a deep water environment, the combination of different inspection tasks into a single tool or utilizing a multi-technology approach to optimize inspection performance.

The advantages of the multi-technology approach will be illustrated through its use in a new inspection tool combining ultrasound, magnetic flux leakage and eddy-current technologies in order to provide true quantitative wall thickness measurement and metal loss inspection capabilities for gas pipelines.

Finally, the paper will provide an outlook on the future technical trends in the pipeline inspection industry.

Keywords: Pipeline inspection, inline inspection, integrity assessment, ultrasound, magnetic flux leakage, EMAT, combo tools, metal loss, crack inspection

1 Introduction

With a worldwide aging pipeline infrastructure and increasing economical and regulatory constraints for pipeline operators, pipeline integrity issues are an area of increasing relevance. In many countries of the world pipeline regulations not only demand inspections or monitoring of structural integrity at certain intervals, but a continuous process of verification of pipeline integrity and fitness-for-purpose. In-line inspections complemented by other inspection techniques applied externally are today the method of choice for these inspection requirements. Many regulations recommend or even demand the use of intelligent in-line inspection (ILI) tools [1, 2]. The use of these tools provides an effective and efficient way to inspect large lengths of pipelines within reasonably short time spans.

The purpose of an in-line inspection is the detection, sizing and location of flaws and defects within the pipe wall. In other words, the determination of geometric dimensions, which in turn are used as input for the codes applied for integrity assessment.

There is a huge choice of ILI tools on the market today. Useful information can be found in the literature [3, 4] and is regularly published in the industry journals.

The following three diagrams provide a short overview regarding the in-line inspection technologies currently commercially available and the inspection missions that can be covered.
The most widely performed inspections relate to geometry inspection, metal loss and lately also crack inspections.

A trend in the industry, mainly driven by developments in electronics and increase in the number of individual channels that these units can record is the combination of technologies. Two terms widely used today are "Combo-Tools" and "Multi-Technology Tools":

The information provided by ILI tools basically consists of geometric data regarding a flaw or anomaly found, namely:

- length (how long is a flaw from beginning to end, extent in the direction of the pipe?)
- depth (how deep is a flaw, deepest point?)
- width (how wide is a flaw, circumferential extent?)
- circumferential position (orientation, o’clock position of a flaw?)
- longitudinal position (where along the line is the flaw?)
- pipeline route (where is the pipeline and was there any change in position?)

This data is then used to analyze the integrity of a line. Integrity assessment and fitness-for-purpose investigations in turn play an important role in defining and optimizing maintenance and possible rehabilitation procedures. Two extremely important issues within this context are the defect specifications (probability of detection, probability of identification) achieved and the question of measurement accuracy (confidence level).
The Rationale For In-Line Inspection

Pipelines are the primary means to safely transport large quantities of oil or gas at high pressures and over large distances. Their safety and availability are of greatest importance. From the integrity side pipelines can be treated as pressure vessels. Any anomaly or flaw must be detected and identified before it has a detrimental effect on the integrity of a given line or pipeline system. The internal pressure of a pipeline will induce a state of mechanical stress in the pipe wall. Pipelines are designed or rather the wall thickness of the pipeline is chosen such that a given operational pressure can safely be endured. In high pressure pipelines the hoop and axial stresses are usually of greatest relevance. As stress analysis tells us, a reduction in load bearing area will increase local stresses. This is the reason why corrosion in particular or metal loss in general have a negative effect on the integrity of a line. The load bearing cross sectional area of the pipe wall is reduced and the acting stress subsequently increased. A scenario whereby the local stresses at any point in the line exceed the yield strength is to be avoided. The same line of thought also relates to cracks. Cracks must be found and ideally sized, before they reach a certain material specific critical size. In fracture mechanics this critical size is the boundary between having a subcritical crack which will stop, if external load is reduced or eliminated and rapid crack growth driven by the energy stored in front of the crack tip and independent of external load. If either metal loss or cracks are not identified in time plastic instability or fracture can occur. Modern integrity assessment follows a fitness-for-purpose approach. An important input required in the process is the geometry of any flaw or anomaly present. It is the mission of in-line inspection to detect, size and locate features, thus providing the required geometric input. As a consequence, this is also the rationale for using them. Only in-line inspection can inspect a pipeline, offering full coverage of the pipe surface, or actually the full volume of the wall.

Defects in Pipelines

Anomalies, flaws or defects are usually associated with the operation of a pipeline. However, it is also important to understand that anomalies can be present in the pipe wall, long before the pipeline starts its operational life. Table 1: Milestones in the Life of a Pipeline shows the usual milestones in the life of a linepipe (i.e. the actual pipe or pipes that make up a pipeline). The example shown here relates to a longitudinally welded pipe.

Table 1: Milestones in the Life of a Pipeline

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Possible Flaws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Production</td>
<td>Impurities, cavities, segregation etc.</td>
</tr>
<tr>
<td>Plate Production in Steel Mill</td>
<td>Laminations, blisters, scabs, cracks and other rolling defects such as slivers etc.</td>
</tr>
<tr>
<td>(Line)Pipe Production in Pipe Mill</td>
<td>Out of roundness, roofing, any flaws/cracks related to the welding technique (ERW or SAW) etc.</td>
</tr>
<tr>
<td>Pipeline Construction and Commissioning</td>
<td>Dents, plastic deformation, flaws/cracks related to the girth weld etc.</td>
</tr>
<tr>
<td>Pipeline Operations</td>
<td>Geometric Flaws, Metal Loss and Cracks, Pipeline Movement etc.</td>
</tr>
<tr>
<td>Pipeline Rehab and Repair</td>
<td>Flaws introduced during a rehab or repair operation</td>
</tr>
</tbody>
</table>
In-line inspection therefore not only need to detect and size features found, usually during an inspection performed during the operational life of the pipeline, but they need to characterize the feature. Manufacture related and operational features must be distinguished. The better this can be done, and the better the accuracies of the inspection technology applied are, the better will be the quality and usefulness of the fitness-for-purpose analysis.

3 Technologies Applied for Metal Loss and Corrosion Inspection

This paper will not address geometric inspection and mapping, but will focus mainly on metal loss and corrosion inspection, the most widely performed inspection type.

The well proven technologies applied for metal loss and corrosion inspections today are magnetic flux leakage (MFL) and ultrasound (UT). Both technologies are based on different physical principles, both with their individual characteristics.

Some publications refer to three non-destructive testing technologies being applied for metal loss and crack inspection, namely magnetic flux leakage, piezo-electric ultrasound and ultrasound using EMAT (where EMAT actually stands for electro-magnetic acoustic transducers).

![Figure 1: Ultrasound principle for wall thickness measurement](image)

Figure 1 depicts the ultrasound principle most widely used for metal loss inspection and quantitative wall thickness measurement. A sufficient number of ultrasound probes must be used to ensure full circumferential coverage of the pipe. Here, one piezo-electric transducer is sketched at two locations. The transducer sends out a short pulse of ultrasonic energy which is initially reflected from the internal surface of the pipe wall. The ultrasonic signal is not an individual arrow, but a wave front of acoustic energy. Part of this signal will be reflected; the remainder will enter the wall and be reflected from the outer surface of the pipe, the back wall. The electronics of the tool will precisely measure the time of flight. As the speed of sound of the medium in the pipe and also the pipe wall are known and constant, the time of flight will provide quantitative values for the stand-off distance between sensor and internal wall, as well as the wall thickness. Any changes in stand-off and wall thickness readings will
clearly identify internal metal loss; any changes in wall thickness only will identify external metal loss. In addition, ultrasound can detect and size mid wall features such as laminations and inclusions.

The drawback is that piezo-electric transducers require a liquid medium. This liquid is present in oil or products lines, but not in gas pipelines for instance. The liquid is needed to ensure that a sufficiently strong ultrasonic signal enters the wall. In a gas environment too much energy is lost and a meaningful measurement cannot be achieved. However, this predicament can be overcome by using a methodology to induce the ultrasonic signal directly in the wall to be inspected, EMAT. Figure 2 shows one simplified principle.

![EMAT working principle](attachment:image.png)

**Figure 2: EMAT-working principle**

Here the ultrasound is induced at the surface of the pipe to be inspected. Electromagnetic principles are used to excite ultrasonic vibrations at the surface of the test piece. Different approaches, the magneto-restrictive principle or the principle based on Lorentz forces are today applied in the industry.

Another flaw type which can significantly affect the integrity of a line is a crack or material separation. Due to the loading conditions present in pipelines - from a stress analysis perspective they are actually pressure vessels with a cylindrical geometry - they are in most cases orientated in a longitudinal direction - along the axis of the pipe - and grow in a radial direction, parallel to the ultrasonic beam depicted in figure 1. As they are parallel, they would not cause a reflection and therefore would be "invisible". For this reason it is necessary to search for cracks with an ultrasonic beam travelling under an angle, as shown in figure 3. A crack will now reflect the signal and can be detected reliably.
4 Tool Design: Ultrasonic Tools

Exemplary the design of an ultrasonic tool will be provided here. Ultrasonic in-line inspection tools are in general fitted with a sufficient number of ultrasonic transducers to ensure full circumferential coverage of the pipe. They work in a pulse-echo mode with a rather high repetition frequency. Straight incidence of the ultrasonic pulses is used to measure the wall thickness and 45° incidence is used for the detection of cracks.

In terms of data processing, ultrasonic tools represent one of the most challenging tasks in ultrasonic non-destructive testing. Depending on the pipe diameter to be inspected up to several hundred sensors have to be controlled, their echoes recorded, on-line data processing applied in order to reduce the total amount of data and the resulting data stored. The speed of the tool during a survey depends on the medium pumped in the line. It may therefore vary within a certain range and should be able to cope with the usual pumping rates in liquid lines, in order to limit any need for reducing the flow and therefore creating a potential production loss. Pressure and temperature range as well as mechanical parameters such as vibration and shock loading during tool movement have to be considered. A further requirement is that in-line inspection tools should be designed intrinsically safe in order to avoid any safety issues during launching and receiving. After launching the tools cannot be accessed and therefore the inspection process has to be fully automatic and cannot be supervised.

Today ultrasonic in-line inspection tools are available for all typical pipeline diameters, starting from 6".

4.1 Hardware

Figure 4 shows a picture of an ultrasonic in-line inspection tool. Here the 24" crack detection configuration is shown. The major difference compared to other inspection tools utilizing ultrasound technology is the modular design philosophy applied. It was the goal to develop a single tool type, which can be configured for a variety of inspection tasks. This resulted in a family of tools equipped with electronics which can be used for tasks including wall thickness measurement as well as crack detection. The number of channels is thereby sufficient to always ensure full circumferential coverage for any chosen inspection task, including special
applications such as a pitting corrosion survey. The mechanical layout is such that the tool components can be scaled up or down. The advantage of this approach is that a minimum of different components need to be built in order to cover a wide range of pipeline diameters as well as inspection tasks.

Figure 4: Ultrasonic crack detection tool

Figure 5 shows schematics illustrating the modular design approach. The figure shows the individual sensor carriers configured for wall thickness, crack inspection as well as combined inspection. As shown in Figure 2 the 24" tool, for instance, is made up of two pressure vessels housing the power supply, electronics as well as a trailing sensor carrier housing the ultrasonic transducers.

The data obtained during an inspection are stored on solid state memories that are the safest and most reliable means of storing data in such a hostile environment. The distance traveled in the line, needed for locating the features detected, is measured using several odometer wheels. The front of the tool is covered by a protecting unit (nose), covering the transmitter housing shown here. The individual pressure vessels are connected through universal joints which allow the tool to negotiate either 3D- or 1.5D-bends, depending on the tool configuration. The first body is fitted with batteries ensuring a safe supply of power to the tool for up to several days. The electronic and recording unit of the tool is housed in the second vessel and incorporates enough channels to cover pipeline diameters from 20" to 56" for wall thickness and 20" to 42" for crack detection application. The sensor carrier is made of polyurethane and houses the ultrasonic transducers. To adapt the tool to a different pipe diameter the polyurethane cups are exchanged, which can be done quickly.
There are a variety of different sensor carrier designs depending on the inspection requirement. Configurations are available for wall thickness measurement, crack detection (axial, circumferential and spirally welded), combined inspection (wall thickness and cracks) and special tasks (e.g. pitting, bi-directional etc.).

The wall thickness version houses sensors aligned at right angles to the wall inspected, whilst the crack detection version contains sensors orientated at a predetermined angle to the pipe wall which ensures that ultrasonic shear waves will travel under a 45º-angle within the metal. Figure 6a shows the assembly of wall thickness sensors and figure 6b the one for crack detection. All sensors are mounted on metal plates. The polyurethane sled will ensure a constant stand-off. The design will also have to ascertain that wax cannot clog the exposed parts of the sensor carrier.

The tool is configured for individual pipeline sizes through adaptation kits and corresponding sensor carriers, which will be available for all intermediate sizes. With the advancement of data processing power, shorter processing times became feasible. This has a direct influence on the possible inspection speeds. The inspection speed, however, affects the production loss of the pipeline operator. It is often desirable that the pumping speed of the product should not be reduced due to pigging issues.
Using the latest processor technology an inspection speed of at least 1.5 m/s for crack detection and up to 2.4 m/s for wall thickness measurement is possible whilst achieving full defect specifications.

4.2 Data Analysis and Reporting

Several data processing steps are carried out on the tool. The analog A-Scan is AD-converted and processed according to the ALOK algorithm [5]. In a next step, there is a crack detection algorithm that will determine which signals result from potential crack candidates and select them for storage. In addition, the position of the long seam weld is evaluated. The data is stored in a more suitable format such that no time consuming data translation process is required. This means that the data retrieved from the tool can be directly loaded into a desktop or laptop PC for visualization or analysis. With the data quickly ready to analyze there is still a lot of work to be done. An artificial intelligent network selects defect candidates and reduces the number of indications to be manually checked. The display of the data, using proprietary software, allows the analyst to quickly access the relevant portions of the data and enter conclusions. The actual compiling of the report is partly automated using reporting tools that work on a centralized database.

![Figure 7: Screenshot of a typical external metal loss](image)

The screenshots shown in figure 7 shows a typical display of an external corrosion found with an in-line inspection tool. The identification of cracks is mainly done by looking at several B-Scans at the same time. The viewing software will display the B-Scan of sensors that are circumferentially aligned. Defect signals show up in all B-Scans at a specified time-of-flight difference between the corresponding sensors.

5 Typical Thresholds

Table 2 shows typical thresholds regarding the depth sizing of metal loss for different in-line inspection tools. This means any feature or flaw in the pipe wall must have a minimum depth in order to be picked up by the inspection tool utilized. Typical values regarding the minimum defect diameters a feature must have in order to be detected and sized by a magnetic flux leakage tool are between 1 and 3 x t (MFL-tools usually relate defect specifications to the wall thickness (t) of the line being inspected). For a 10 mm wall thickness this would mean 30 mm. A typical industry specification for high resolution ultrasound tools is a minimum depth of 0.5 mm, with a minimum surface diameter of 20 mm. Detection only can usually be
achieved for smaller surface diameters. Some magnetic flux leakage tools state 1 x t, and ultrasonic tools 10 mm.

**Table 2: Typical minimum defect specification for different tool types**

<table>
<thead>
<tr>
<th>Tool Type</th>
<th>MFL high resolution</th>
<th>MFL extra high resolution</th>
<th>UT high resolution</th>
<th>UT pitting configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General Metal Loss</strong></td>
<td>&gt; 10 % t</td>
<td>&gt; 5 % t usually valid for internal metal loss.</td>
<td>0.5 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Minimum depth of feature to ensure detection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pitting Corrosion</strong></td>
<td>&gt; 20 % t</td>
<td>&gt; 10 % t usually valid for internal metal loss.</td>
<td>1.5 mm for minimum feature diameter of 10 mm</td>
<td>1.5 mm for minimum feature diameter of 5 mm</td>
</tr>
<tr>
<td>Minimum depth of feature to ensure detection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where t = wall thickness.

Only recently have ultrasonic tools entered the market which offer full depth sizing capabilities starting from a depth of 0.4 mm with a surface diameter of 10 mm, and detection without depth sizing starting from a surface diameter of 5 mm.

### 6 The Three Dimensions of Resolution

The term resolution is most widely used in relation to depth measurement in the context of metal loss surveys, i.e. relating to the question of how precisely a given tool can resolve the depth of a flaw. Another critical issue is the ability of a tool to reliably detect the actual deepest point of a metal loss feature.

However, it has to be noted that resolution is an issue of all three dimensions, e.g. depth, axial size (length of feature along the pipe) and width (circumferential extent of feature).

- **Axial Resolution and Circumferential Resolution**

  Measurements taken by an in-line inspection tool basically supply a grid of measurement points taken. The actual area that a sensor covers will ensure that there is overlap from sensor to sensor, thus ensuring full coverage of the pipe wall.

  A standard value in the industry regarding axial resolution is approximately 3 mm, i.e. taking a reading every 3 mm along the axial direction of the pipe. For an average speed of 1 m/s during the inspection this value relates to a pulse repetition frequency of 300 Hz. The term “pulse repetition frequency” relates to the number of times the ultrasound transducer switches from emitting to receiving a signal per second.

  The number of samples taken can be raised, for example by increasing the pulse repetition frequency, whilst retaining the same inspection speed (e.g. 600 Hz at a speed of 1 m/s would result in an axial sampling of 1.67 mm or 3.3 mm at 2 m/s). Latest generation ultrasonic tools are available which can offer a 0.75 mm sampling (i.e. one measurement taken every 0.75 mm). Advanced electronics also allow for survey speeds to be increased to approximately 2.5 m/s.
Most ultrasonic tools on the market relate to the resolution 3 mm in the axial direction and approximately 8 mm in the circumferential direction. This configuration is often referred to as “high resolution”, making use of the same term also used for magnetic flux leakage tools.

- **Depth Resolution vs. Accuracy**
The depth resolution of an inspection tool indicates which precision the depth measurement can achieve. It is not to be mistaken with the depth sizing accuracy, which is a value defined by the operator of the tool and which is usually stated in the defect specification sheet. An important aspect in depth sizing accuracy is to consider whether a measurement technique provides quantitative depth measurement characteristics or qualitative ones. Ultrasound is an example of a quantitative wall thickness measurement technique. Wall thickness, and in the case of metal loss, remaining wall thickness, can be measured directly in mm. The accuracy is determined by the hardware capabilities of the tool, e.g. sensor design, electronics. Resolution relates to the quality of the measurement. The better the resolution an inspection tool can achieve the greater its ability to precisely measure the depth contour of a given flaw or defect.

The issue of resolution and its effect on integrity assessment is discussed in more detail in [6].

7 **A Word on Localized Metal Loss and Pitting Corrosion**

Regarding the depth sizing accuracy of ultrasound tools, it is also important to understand that an average value of wall thickness is determined regarding the time of flight (i.e. time taken until an emitted ultrasonic signal returns to the transducer) for all reflections received for a given sensor covering a specific area. A transducer with an emitting diameter of 10 mm will cover a greater area than, say, a 6 mm sensor. The true actual area covered will further depend on whether the transducers used are focused or not, see figure 8.

![Figure 8: Unfocused vs. focused ultrasonic transducer](image)

The upper figure shows how the cylindrical beam of acoustic energy covers a much wider area of the pipe wall than the focused probe in the lower figure.

The geometries and specifications of the ultrasonic transducers used in the industry determine the minimum defect specifications attainable. Typical industry values for the detection of
metal loss features start from a feature diameter of 10 mm and depth sizing capabilities starting from feature diameters of 20 mm. These values were the reason why ultrasonic tools were considered less suitable for pitting inspection compared to magnetic flux leakage tools for a long time.

Today, modern configurations of ultrasonic in-line inspection tools are available which can achieve detection thresholds for metal loss starting from a surface diameter of 5 mm, with full depth sizing capabilities starting from 10 mm surface diameter. The advantage over magnetic flux leakage is that these new configurations of tools provide quantitative sizing for the depth of pitting corrosion and the remaining wall.

These configurations make use of a closer sensor spacing in the circumferential direction of the pipe and higher pulse repetition frequencies enhancing the axial resolution, resulting in a more highly resolving grid.

Due to the optimized sensor carrier design used for pitting inspection, the circumferential spacing of the sensors was decreased to 3.7 mm for the tool considered here. The axial sampling can be increased from 3 mm to 1.5 mm (i.e. one reading taken every 1.5 mm along the pipe axis) or even to 0.75 mm.

Figure 9 shows as an example the various UT sensor plate layouts for standard high resolution, enhanced resolution and pitting resolution.

![Sensor Plate Layout](image)

<table>
<thead>
<tr>
<th>8 Sensors per plate</th>
<th>12 Sensors per plate</th>
<th>16 Sensors per plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Resolution</td>
<td>Enhanced Resolution</td>
<td>Pitting Resolution</td>
</tr>
<tr>
<td>8 mm</td>
<td>5.5 mm</td>
<td>3.7 mm</td>
</tr>
</tbody>
</table>

**Figure 9: Sensor Plate Layout**

In general it can be said that the more readings a tool can take for a given area inspected, the better. If only a relatively small number of readings (i.e. samples) can be taken for a given area, the effect of any spurious signal will be much larger than if a higher number of readings can be obtained.

Increasing the resolution will of course result in a higher total number of sensors used and therefore number of electronic channels the in-line inspection tool needs to provide, in order to secure full circumferential coverage of the pipe surface. The great advantage is that such a "pitting"-resolution tool provides reliable detection and sizing of local metal loss, such as pitting corrosion, with the precision and confidence level of an ultrasound tool.

Table 3 provides a rough guide regarding the capabilities of different tool types available regarding the detection and sizing of localized metal loss and pitting corrosion.
According to the POF Standard [7], the geometrical parameters of anomalies are length "L", width "W", depth "d" and reference wall thickness “t”. The parameter A is used for the geometrical classification of the anomalies detected by a tool. This parameter is needed for pipes with t<10 mm. The geometrical parameter A is linked to the NDE methods in the following manner:

- If t < 10 mm then A = 10 mm
- If t ≥ 10 mm then A = t

Table 3: Detection and sizing capabilities regarding localized metal loss (pitting) for different in-line inspection tool types.

<table>
<thead>
<tr>
<th>Feature surface dimension: 10 mm by 10 mm; wall thickness (t): 10 mm</th>
<th>High Resolution MFL&lt;sup&gt;1&lt;/sup&gt;</th>
<th>MFL &amp; UT combination tools&lt;sup&gt;2&lt;/sup&gt;</th>
<th>High Resolution UT&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Pitting Configuration UT&lt;sup&gt;4&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>detection only</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>depth sizing</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>quantitative wall thickness measurement</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Feature surface dimension: 10 mm by 10 mm, wall thickness (t): 20 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>detection only</td>
<td>x</td>
<td>x</td>
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<tr>
<td>depth sizing</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>quantitative wall thickness measurement</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

* definition according to POF.

Pitting is defined in said document as a feature having a surface area of less than 2A x 2A. A feature as small as 0.5A x 0.5A is termed as a "pin hole" type feature. Applying these defect specifications means that the new generation of ultrasound tools with pitting configuration can offer detection and sizing capabilities for pitting and pin hole type features.

8 Special Configurations

8.1 Combining Metal Loss and Crack Inspection

In the past, metal loss and crack inspections had to be performed completely separate of each other. Mainly due to developments in electronics and the ability to incorporate more and more recording channels, it is now possible to combine both these inspection tasks. The major advantages are that both inspections missions can be carried out in a single tool run, with considerable savings regarding all operational aspects of an in-line inspection, e.g. only one

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1 Typical minimum defect specification reported in industry for magnetic flux tools is t x t, detection only; depth sizing starting from 2t x 2t.
2 combines high resolution MFL and UT.
3 Typical minimum defect specification reported in industry for ultrasonic high resolution is 20 mm x 20 mm for depth sizing and 10 x 10 mm for detection only.
4 Typical minimum defect specification reported in industry for ultrasonic pitting corrosion tools is 10 mm x 10 mm for depth sizing and 5 mm x 5 mm for detection only.
cleaning program instead of two, one run of the inspection tool, metal loss and crack data can be correlated with high precision.

Figure 10a shows one of the sensor plates used by such a tool combining transducers arranged at right angles at the wall to be inspected as well transducers fixed at an angle to the wall, resulting in the ultrasonic signal travelling under a 45° angle within the pipe wall. Figure 10b shows the launch of a 40" tool combining metal loss and crack inspection. Further information can be found in [8,9].

Figure 10: a. sensor plate, b. 40" tool prior to launching

8.2 Multi-Technology Tool for the Quantitative Wall Thickness Measurement in Gas Pipelines

Gas pipelines are traditionally inspected with MFL tools. The major advantages of ultrasonic tools, namely the ability to perform precise quantitative wall thickness inspections, recording the true river bottom profile - contour of an anomaly - being able to detect and size mid-wall anomalies in addition to internal and external ones and the ability to detect hydrogen induced cracking could only be made use of, if the tool is run in a suitable liquid batch. For operational reasons, as well as cost reasons, this is often not feasible.

The need for a liquid batch can however be overcome by using an alternative method to induce the ultrasonic signal into the pipe wall. As shown earlier in this paper, this can be achieved by utilizing electro-magnetic acoustic transducers (EMAT). Figure 11 shows a multi-technology tool utilizing EMAT as well as magnetic flux leakage and eddy current technologies to provide the precision and accuracy of ultrasound for gas pipelines.

The reason for utilizing additional non destructive technologies is a limitation of EMAT based on its working principle. As the ultrasound wave is generated at the surface of the pipe wall to be inspected, the distance between the transducer and the internal surface cannot be measured. This implies that internal corrosion cannot be sized. This is overcome by using eddy current technology which is very sensitive for detecting and sizing internal flaws, or rather near bound flaws.
The runs performed so far have proven the concept of the tool and delivered good quality data. The use of different non-destructive testing technologies, each enhancing and extending the detection and sizing capabilities of the tool, have led to increased values regarding probability of detection and confidence levels for sizing and feature identification, as opposed to magnetic flux leakage tools commonly used for the inspection of gas pipelines. Figure 12 shows one example of a feature found in the vicinity of a girth weld.

8.3 Special Tool Configuration for Liquid Lines with High Wax Content
Offshore crude oil lines often have high contents of wax being present, deposited on the pipe wall or transported with the flow. The presence of this wax can seriously affect the performance of a chosen in-line inspection tool and lead to a dramatic deterioration of the quality of the inspection data, thus endangering the purpose of the inspection and leading to waste of time and money. Significant amounts of wax or paraffin deposits can still be in a line, even after lengthy and careful cleaning. Issues such as the pour point can lead to wax falling out of the oil, immediately after a cleaning run, making it next to impossible to achieve a completely clean wall prior to launching an intelligent inspection tool.
Based on the analysis of available data regarding previous tool performance, operational parameters and procedures, a tool modification program was initiated by a large offshore operator to design a special ultrasonic tool configuration, optimized for the inspection in a heavy wax environment.

![Figure 13: Wax built up on sensor carrier](image1)

The major issues which had to be addressed from the tool design side were the sensor carrier and the odometer wheels. Fig. 13 shows a sensor carrier being clogged up by wax. Here the ultrasonic signal would disperse resulting in echo loss. Fig. 14 shows the modified sensor carrier after the run in a heavy wax line. As can be seen the modifications led to the tool coming out in a much "cleaner" state, ensuring that the sensors were able to pick up good quality signals.

![Figure 14: Modified sensor carrier; clean after run in high wax content line](image2)

The odometer information is of critical importance in order to locate and length size any anomaly found. In a heavy wax environment the odometer can slip, leading to erroneous information. Again after special modifications to the wheel, slippage could be reduced to a tolerable amount. Further information can be found in [10].

8.4 Detection and Sizing of Localized Corrosion and Pitting

8.4.1 Local Corrosion: Detecting and Identifying the Deepest Point

Figure 15a shows a screenshot of a localized corrosion feature (surface diameter less than 20 mm) detected with a specially configured ultrasonic tool using a 5.5 mm circumferential sensor spacing. The metal loss was clearly detected and sized. The B-Scan of the ultrasonic
data shows a corrosion feature with a maximum depth of 9 mm. Figure 15b shows the same feature detected and sized with a tool using a standard industry configuration. The depth sizing delivered a value of 4.6 mm. Both configurations have performed to within their specifications, but show the effect of sensor spacing with regard to the detection and sizing of small area metal loss. Even smaller features will be detected and sized reliably with a tool using a pitting configuration and a 3.7 mm circumferential spacing.

**Figure 15a,b: Improved depth sizing capability for localized metal loss and pitting corrosion with a surface area of less than 20 mm by 20 mm**

This screenshot nicely shows the importance of resolution with the regard to the sizing of localized metal loss, such as pitting corrosion.

**8.4.2 Localized Corrosion in Girth Weld**

Figures 16a shows the screenshot of the data obtained for a 12" product pipeline with a wall thickness range from approximately 6 to 8 mm. The inspection identified a localized metal loss feature within the girth weld zone. The detection and sizing of this type of flaw requires a pitting resolution or at least an enhanced resolution above the normal industry standard. For this inspection the axial resolution of the tool was set to 1.5 mm (i.e. 1 reading taken by each sensor every 1.5 mm in the axial direction) and approximately 4 mm for the circumferential resolution. Figure 16b shows a photograph of the feature, after the feature had been verified and the pipe had been excavated. The dimensions of the feature found were 15 x 56 mm.
9 Effect on Integrity Assessment

As more refined integrity assessment codes are being used, the resolution and accuracy of tools play an ever increasing role. High resolution magnetic flux leakage tools usually report metal loss features found with an accuracy of ± 10% of wall thickness and a confidence level of 80%. The industry standard for ultrasound tools is approximately ± 0.5 mm with a confidence level of 90%, and latest generation ultrasonic pitting detection tools offer the same accuracy and confidence level for localized metal loss.

Accuracies also strongly influence the results obtained regarding the estimation of corrosion growth based on consecutive in-line inspection runs. Anticipated corrosion growth and the
definition of safe inspection intervals will be influenced by the accuracy of the inspection measurements. It can be stated that a larger error in measurement will result in a more conservative assessment of a given metal loss feature and its associated maximum allowable operating pressure (MAOP). More features will be identified to be outside the safe region of the failure assessment curve. Resulting verification costs, e.g. potential costs for excavating the line and performing external inspections may be significantly higher.

Larger measurement errors will also lead to the need for more inspections and shorter inspection intervals. The additional costs that this conservatism may cause should be taken into account when the direct inspection costs of different tool technologies are evaluated. Figure 17 shows the effect the error band (accuracy) has on integrity assessment investigations.

![Figure 17: Effect of accuracy on integrity assessment](image)

The figure gives an indication of how long a pipeline can be operated in the presence of a corrosion flaw that is growing. The anticipated corrosion rate is calculated based on consecutive in-line inspection measurement assumed to be taken in 2005 and 2010 in this example. The y-axis shows the measured depth of the metal loss, the time axis being shown in the x-direction. In 2005 this depth was 3 mm.

A second measurement in 2010 in this example provides a depth reading by the tool used of 4 mm. In order to use these results for a corrosion growth assessment, the error bands of the tool technologies used have to be taken into account, and a worst case scenario has to be considered. This means the greatest likely corrosion growth must be assumed. This scenario would imply that the corrosion depth measured first takes on a least value, i.e. the depth is oversized by the tool. The second depth measurement taken after 5 years however underestimates the real corrosion depth.

An ultrasonic tool has a measurement error (or reporting accuracy) of ± 0.5 mm, a MFL tool of 10% of wall thickness, i.e. ± 1 mm for the 10 mm wall considered here. Taking these accuracies and applying the worst case scenario provides the blue and magenta lines. These show how the calculated corrosion growth can be projected into the future. The
blue line - representing the MFL tool - intercepts the 80% wall loss failure criterion of B31G in the year 2015, the magenta line - representing the UT tool - roughly 4 years later in 2019. This schematically shows the conservatism in the MFL results, due to the higher error band. Re-inspection intervals based on this assessment would therefore have to be shorter for MFL tools than for UT tools. The green line shows the "life" of the pipeline based on the B31G failure criterion (metal loss must not exceed 80% of wall thickness) if no measurement errors are taken into account.

10 Conclusions and Outlook

In-line inspection tools provide important data regarding the flaws and anomalies detected in a pipeline wall. This data, comprising of geometric information regarding the length, width, depth and location of flaws and anomalies are critical input for integrity assessment and subsequent effective planning of repair and rehabilitation measures. Modern integrity assessment codes benefit from higher levels of inspection data quality, especially with regard to accuracy and resolution. Ultrasonic in-line inspection tools provide these accuracies and confidence levels as well as quantitative measurement capabilities, allowing for a less conservative assessment.

Latest generation ultrasonic tools with special pitting configurations widen the scope of inspection of ultrasonic tools and provide detection and accurate sizing capabilities for these small metal loss and corrosion features and are ideally suited for the future requirements regarding integrity assessment, fitness-for-purpose and corrosion growth studies.

A large variety of special tool configurations is available, each specifically optimized to meet the inspection requirements of the pipeline industry.

In the future we will see a trend of combining inspection tasks. At this moment in time there are two types of combined tools: firstly so called Combo tools which make use of different technologies in order to perform different tasks at the same time. Secondly, so called Multi-Technology tools. Here different technologies are utilized in order to enhance and optimize one specific inspection task. An example for the former would be a tool combining geometry and metal loss inspection, an example for the latter is the combination of different technologies, as described in paragraph 7.2. in order to optimize corrosion inspection and wall thickness measurement capabilities. As electronics become more and more powerful, one trend we will see is combo-tools and multi-technology tools will grow together forming a new generation of tools which will offer combined inspection missions with optimized tool performance and defect specification.

References

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