Pipeline In-line Inspection – Challenges to NDT

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Abstract. A vast network of pipelines transports large volumes of energy products over long distances from production wells to processing and consumption sites. The pipeline industry relies on nondestructive testing (NDT) methods to detect and characterize the degradation and damage. To quickly and economically survey the large portions of the infrastructure, autonomous in-line inspection tools, commonly referred to as pigs, examine the pipe from the inside as they are propelled by the product flow. Thousands of kilometres of pipelines are examined using various implementations of electromagnetic and ultrasonic modalities. Inspection tool developers are challenged to implement sensitive measurement technology on a platform that must survive the pipeline environment. This paper will review fundamental challenges that restrict the implementation of NDT technologies that are applied in other industries. The anomaly types that affect pipeline operation will also be reviewed to frame the gaps between inspection capability of existing tools and inspection needs of the pipeline industry.

Introduction

A vast network of pipelines transports large volumes of energy products over long distances from production wells to processing and consumption sites. Historically, pipelines have proven to be a relatively safe transportation mode. As with any infrastructure, the integrity can be affected by time dependent degradation and abrupt damage from outside forces. The pipeline industry relies on nondestructive testing (NDT) methods to detect and characterize the degradation and damage. To quickly and economically survey the large portions of the infrastructure, autonomous in-line inspection tools, commonly referred to as pigs, examine the pipe from the inside as they are propelled by the product flow. Inspection tool developers are challenged to implement sensitive measurement technology on a platform that must survive the pipeline environment. Inspection tools must meet measurement specifications for long distances at high speeds, while negotiating tight bends that induce substantial forces, obstructions that protrude into the pipe, debris that forces the sensors from the pipe and other inspection dilemmas. Furthermore, the reliability of the inspection system must be high since the pipeline anomalies are typically localized events, not general degradation. One inspection technology, magnetic flux leakage, can be implemented to overcome the physical barriers while adequately detecting and characterizing corrosion anomalies. Other technologies address other classes of anomalies such stress corrosion cracking, mechanical damage, seam weld anomalies and more precise corrosion assessment. Some pipelines, referred to as unpigable, have excessive physical or operational barriers that prevent the use of available pigs. Crawler technologies are being implemented that overcome these barriers, sometimes with alternative inspection methods. After internal inspection, the details of the anomalies are commonly quantified after excavation using more classical NDT methods. In-the-ditch sizing methods for corrosion and cracking are used to quantify pigging results. This paper will review the fundamental challenges that restrict the implementation of NDT technologies that are applied in other industries. The anomaly types that affect pipeline operation will also be reviewed to frame the gaps between inspection capability of existing tools and inspection needs of the pipeline industry.

Application of Inspection Methods to Pipelines

In-line inspection equipment is commonly used to examine a large portion of the long distance transmission pipeline system that transports energy products from well gathering points to local distribution companies. A piece of equipment that is inserted into a pipeline and driven by product flow is called a 'pig'. Using this term as a base, a set of terms have evolved. Pigs that are equipped with sensors and data recording devises are called 'intelligent pigs'. Pipelines that cannot be inspected using intelligent pigs are deemed 'unpigable'. But many factors affect the passage of a pig through a pipeline, or the 'pigability'. The concept of pigability pipeline extends well beyond the basic need for a long round hole with a means to enter and exit. An accurate assessment of pigability includes consideration of pipeline length, attributes, pressure, flow rate, deformation, cleanliness, and other factors as well as the availability of inspection technology. All factors must be considered when assessing the appropriateness of in-line inspection (ILI) to assess specific pipeline threats. The process is illustrated in Figure 1.

In terms of implementing an integrity management plan (IMP), the first step is the evaluation of potential threats that exist in the pipeline or segment being considered and their credibility. Once the credible threats are established, the appropriate integrity assessment method(s) are then selected. Where instrumented non-destructive ILI tools are deemed appropriate, several preliminary aspects must then be considered. Otherwise, alternative integrity assessment methods that may include pressure testing and direct assessment will be required.

The first decision point shown in Figure 1 concerns the availability of inspection technology. Each inspection technology implementation must be examined to determine suitability of both assessment of threats and passage of pipeline attributes.

Some pipelines may constitute a single source of supply to a locale that cannot be easily interrupted even for scheduled ILI or other maintenance operations. If an interruption does occur, alternative (and often very expensive) supply sources such as truck is required to maintain service. Even where suitable permanent launchers/receivers (or some temporary configurations) are available, pipeline operating characteristics may need to be modified to conduct a successful ILI integrity assessment. Such operating parameter modifications can impact gas delivery and may not be acceptable. Also, more detailed piggability assessment should be performed to ensure free passage of ILI tools.

The length of the pipeline or segment to be assessed is also an important initial consideration. It is rarely practical to run product driven ILI tools in short segments of pipeline that might include a short high consequence area (HCA), crossovers between pipelines, and short length laterals. Equipping such pipelines or segments for periodic ILI tool operation would be expensive unless the equipment was also used for other pipeline operational purposes such as liquid removal. Furthermore, the required flow conditions for proper ILI operation may be difficult to achieve in short segments. Costs for gas driven ILI tools are typically compared on an approximate cost/mile basis that includes the ILI vendor's fixed mobilization charge. A typical cost/mile analysis shows that gas driven ILI run lengths should exceed about 50 kilometres (30 miles) to approach the least unit cost.

Other types of instrumented ILI tools (i.e., wireline ILI tools) are more appropriate for shorter lengths of pipe.

Another initial consideration is the particular instrumented ILI technology that is capable of assessing the established threats and the suitability of that technology in pipelines. Each of the available ILI technologies has its strengths and limitations for anomaly detection. A description of anomaly types that occur in pipelines is included later in this paper. Inspection technologies for each of these conditions are at various stages of development. Many of the inspection technologies are product specific and may not applicable in gas or liquid pipelines in all cases.

Pipeline operating pressure and flow conditions can dictate if it is feasible to satisfactorily operate an ILI tool. For gas natural pipelines, low pressure (25-40 bar, 400-600 psi) and flow conditions may not be sufficient to efficiently drive a pig. A minimum gas pressure is needed to assure stable ILI operation since higher pressures create a higher density fluid column behind and in front of the pig thus minimizing speed variations and surges. The effects of low pressures can be more extreme in hilly terrain since the gas column would not effectively restrain the tool thus permitting velocity variations. Instrumented ILI tools should be operated within their recommended velocity ranges to achieve optimum inspection results. For example, magnetic flux leakage (MFL) tools speeds are typically 1-3 m/s and inspection results can degrade when an ILI tool when operated out of the recommended range, especially where excessive velocities occur.

Typical pipeline operating parameters may require modification to control flow rates and product pressures thereby optimizing ILI inspection results. In some pipelines, the pressure increases needed to assure satisfactory ILI operations may be precluded by pressure limiting restrictions. This may include pressure regulator adjustments, compressor station operation modifications, and flow throttling with valves. ILI tools equipped with gas bypass technology are now being applied to provide improved inspection velocities in a wider range of flow conditions.

Other operating conditions that can affect ILI operations include gas corrosivity that may damage ILI tool components and high temperatures (> ~60 C) that can damage on-board electronic components

Some pipelines contain identified threats that can potentially affect ILI passage such as deformation and mechanical damage such as dents. Deformation may result from the action of outside forces such as slides or floods. ILI passage can be limited by more localized pipe deformation such as dents resulting from rocks in the right of way and impacts on the pipe which is a leading cause of pipeline incidents. Deformation may reduce the pipe internal cross section to the point that ILI tool passage may be impaired and repair would be required prior to attempting an ILI tool run.

Other construction related threats such as wrinkle bends can have sufficient associated pipe deformation that will impede pig passage. Mechanically coupled pipelines can be another issue affecting ILI tool applications although some coupled pipelines have been successfully assessed. ILI passage is not restricted by mechanical couplings but they present a potential safety issue due to the lateral deformation that may be result when the tool passes a coupling that is not sufficiently supported by the backfill.

Pipelines can contain dirt, debris, debris, and deposited solids such as salt. Solid deposits (i.e., salt) can form an adherent, solid barrier that affects pig passage and adversely impacts ILI data quality, and can be very difficult to remove. Depending on conditions, pre-ILI cleaning can be an essential element in obtaining good quality integrity data. Such foreign materials can interfere with the sensors on instrumented ILI tools and also affect the accuracy of geometry tools that may be run prior to the ILI. Cleaning can be accomplished by various methods including chemical and dry (scrapers, brushes, magnets). Although an ILI tool could be run in a dirty pipeline, the resulting data would be questionable thereby implying a "pigability" issue.

Pipeline attributes are one of the most frequently quoted criteria that impact pipeline pigability. This includes physical attributes such as reduced port or plug valves, short radius or mitre bends, back-to-back bends, and branches or tees (side or inverted positions) without bars. Pipelines containing any of these attributes must be modified prior running an instrumented ILI tool. Other common features such as pipe diameter changes (> 2 inches) can also prevent a continuous ILI run but can usually be assessed in separate segments. Another similar issue is the presence of pipeline drips for fluid collection. In some cases, a larger diameter pipe section (expansion chamber) is installed in the pipeline above the drip to reduce the gas velocity and promote liquid drop-out into the off line drip barrel. Some check valves can have internal dimensions larger than the pipeline. Depending on the magnitude of such internal diameter increases, the ILI tool driving force imparted by the flowing gas may be reduced to the point the tool stops.

Heavy wall pipe sections, such as those at road crossings and required by construction codes, are another pipeline attribute that can affect pig passage. Line pipe is purchased based on outside diameter tolerances so the internal cross section is reduced as the wall thickness increases. This reduced internal cross section diameter of heavy wall pipe can encroach on the minimum required diameter for ILI passage. Although some ovality is present in most line pipe, its effect is more critical when considering ILI passage in heavy wall pipe through further reduction of the internal bore. Pipeline components such as induction bends and ells are often formed from heavy wall pipe to allow for thinning that occurs during the forming process. The combination of heavy pipe walls and ovality in induction bends have caused ILI tools to become stuck in a pipeline.

Other less frequently cited attributes can also exist that can also impact pigability. One such feature is a suspended, aerial pipeline crossing. The additional dynamic stress created by the moving ILI tool should be considered. Also, the configuration of the pipeline entering and exiting such a crossing may preclude ILI passage. This type of feature would impede the continuous pigability of a pipeline or segment but the adjacent pipeline could be evaluated separately.

The tiered definition of pigability described above includes the presence of launcher/ receiver equipment. Several typical launcher/receiver configurations are:

1. Permanent launcher/receiver equipment installed.
2. Pipeline is equipped with permanent piping transitions to the mainline that include full opening valves and flanges that permit attachment of launcher/ receivers and associated piping while the line is in operation. ILI tools can then be run without removing the pipeline from service.
3. The pipeline or segment is removed from service, cut, and temporary launcher/receiver equipment is attached at the open ends to run the ILI tool. The

temporary equipment is then removed and the segment is re-inserted into the line following completion of the ILI tool run.

The first two launcher/receiver configurations facilitate ILI tool runs since the pipeline does not have to be removed from service. These would be acceptable options for pipelines that serve areas without redundant gas supply. The third option requires service interruption and access to two locations for launcher/receiver installation and removal. In locations where access to the pipeline is an issue and continuous supply is required, this option would significantly impair pigability even though the pipeline attributes are suitable for ILI tool passage. Another related issue concerns some pipelines that are equipped with permanent launcher/receiver equipment that are too short to accommodate instrumented ILI tools.

Some pipes are not suitable for in-line inspection. For example, pipelines constructed of seamless pipe can present unique log interpretation problems especially for MFL ILI tools. Welded pipe produced from plate or skelp typically has a uniform wall thickness with good surface quality. Seamless pipe, however, is often eccentric with a systematic wall thickness variation around the pipe circumference. Also, the piercing process used in seamless pipe production tends to introduce deformation at the pipe ID surface which is detected by ILI tools. Compared to welded pipe, the inherent surface roughness of seamless pipe is another issue. These features combine to produce higher ILI signal "noise levels" (high signal/noise ratio) that are difficult to separate from defect signals when interpreting the log. This reduces the accuracy of the integrity assessment made from the ILI log. For ultrasonic ILI tools, the inclusion content is an important factor. The inclusion content can vary significantly from joint to joint, with one joint permitting a high quality inspection and the next being not inspectable.

Classes of Pipeline Anomalies

Inspection systems must provide information on anomalies that are likely to cause failures. The United States Department of Transportation keeps a data base available via the internet of failures on interstate pipeline failures. In these data, four general categories of failure mechanisms are used:

<u>Outside force and third party damage</u>. These incidents involve an external force acting on an otherwise sound pipe that damages or overloads the pipe to the point where failure occurs. The force may be naturally occurring, such as in a landslide, or it may result from construction equipment accidentally digging into or hitting the pipeline. Included here are dents, gouges, dents with gouges, wrinkles, ripples, buckles, and over-stressed areas.

<u>Environmentally induced failures</u>. These incidents involve anomalies that were created by the action or attack of an environment on the pipe. Included here are internal and external corrosion, stress corrosion cracking, chemical attacks, weld seam corrosion, and internal erosion.

<u>Material, construction and fabrication failures</u>. These failures are due to anomalies that were created during material processing, fabrication, and construction. Included here are seam and girth weld anomalies, laminations, hard spots, and weld pinholes.

<u>Operational error and miscellaneous causes</u>. Failures in this category are generally the result of operational or operator errors. An example of an operational error is cutting into a

pipe line while it is under pressure. Incident data in this category were not considered as candidates for inspection.

Anomaly Prioritization

Excluding operational causes of failures, the major cause of incidents is third-party damage and outside force. Most of the failures due to third-party damage occur very soon after the damage. Therefore, prevention of mechanical damage is key. Systems that monitor the pipeline right of way of excavation equipment would prevent many failures; however there is not a widely accepted practical approach to preventing third-party damage along thousands of kilometres of right-of-way. Opportunities for a mechanical-damage detection tool to detect the presence of mechanical damage are present because the impact to the industry is high.

The next largest cause of pipeline failures is environmental anomalies. Environmental failures were subdivided into a variety of categories, such as pitting, general corrosion, erosion, and stress-corrosion cracking. Of these, the largest cause of failures is pitting corrosion; general corrosion causes a significant, but smaller, number of incidents. These two categories account for nearly 80 percent of the environmental incidents, and so, they were given high priority. There are few incidents caused by stress-corrosion cracking. Nonetheless, stress-corrosion cracking is a significant problem because it is expensive to control, and, so it was given medium priority.

Material and construction anomalies cause the smallest number of incidents. While small, the number attributed to each is comparable to that due to general corrosion and delayed mechanical-damage failures. However, many material and construction anomalies can be uncovered or proved to be inconsequential using hydrotests. So, they were given low priority.

High Priority Anomalies

<u>Pitting</u>. Individual pits, by themselves, rarely cause ruptures. Instead, they generally lead to leaks when not detected or sized properly. Pits are most important for liquid pipelines where the cost of environmental remediation of leak defect can be significant. The most important inspection parameter for individual pits that NDT systems should measure is depth.

Patches of pits can interact to produce a combined defect whose length exceeds the critical (unstable fracture) length of the pipeline. When this happens, a rupture can occur. Consequently, separation of pits and the presence of corrosion between pits are important. Analysis methodologies and prior test data suggest that pit interaction is small if the separation is greater than, for example, six times the wall thickness or one inch. Consequently, the most important inspection parameters for groups of pits that NDT systems should measure are the separation distances, individual pit depths, overall (group) length, and the presence of corrosion between pits.

<u>General Corrosion</u>. General corrosion, wall thinning, and other forms of general wall loss can cause ruptures when the length of these anomalies is larger than the critical length for a pipeline. Errors in reported length are generally not important. As a result, the most important geometry parameters for general corrosion that NDT systems should measure are depth and axial length.

Medium Priority Anomalies

Gouges in Dents. For excavation damage that remains in the pipe, test and field data have shown that cracking can occur at gouges in dents with significant rerounding. Gouging creates a stress concentration and damages the microstructure under the indenter. Rerounding locally strains the damaged zone, leading to micro or macro cracks. Subsequent pressure cycles extend the cracks by stable tearing or low cycle fatigue. As a result, the most important parameter for dents with gouges and rerounding that NDT systems should measure is the presence of cracks. This has proven to be an elusive goal. A secondary, parameter that may be more practical is the presence of dents with gouges and rerounding, from which the cracking can be inferred.

Stress Corrosion Cracks. Stress corrosion cracks in pipelines typically start at many locations. Stress corrosion cracking can lead to ruptures when multiple cracks coalesce to form a single long defect. Crack coalescence is the subject of ongoing research and development. Results suggest that coalescence is most likely in areas of sparsely populated cracking when the cracks are nearly aligned axially. Coalesced cracks can grow in a stable fashion until they are nearly through wall in high-toughness materials. So, the most important defect parameters for stress corrosion cracks that NDT systems should measure are depth and alignment of individual and coalesced cracks, especially in areas where the cracking is relatively sparse.

Gouges without dents. The most important defect parameters for gouges without dents are the width, depth, and length of microstructural damage.

Seam Weld Corrosion. Seam corrosion, when it occurs, often causes deep and long anomalies, which can lead to ruptures. So, the maximum depth and length over which the corrosion occurs are the most important defect parameters.

A Differential Inspection Pig

Magnetic flux leakage (MFL) is and will remain the most commonly used in-line inspection method for pipelines[1]. MFL technology can successfully overcome the physical and practical inspection challenges presented by transmission pipelines. Ultrasonic systems are also useful in liquid pipelines for both corrosion and cracks [2-3]. However, many anomalies can affect the serviceability of a pipeline. Current in-line inspection tools are limited in the variety of anomalies they can detect, and no comprehensive method is available for finding all defect types.

Engineering decisions often require a broad range of information on all anomalies, as opposed to detailed information on a limited number of defect types. A broad range of information is better for overall risk assessment, while detailed information is better for defect assessment and maintenance prioritization. Hydrotests can provide go/no go information on most anomalies that can threaten pipeline integrity at the time of the test. However, they are expensive, difficult, provide no information on subcritical (but possibly active) anomalies, and not always practical. So, an alternative is needed that provides an overall assessment of a line by determining whether any potentially threatening defect is present. Such an assessment would be done as a replacement for hydrotesting.

In-line inspection pigs have historically been used to detect and size corrosion defects. More recently, tools have been built to detect and size other defects, such as mechanical damage and cracks. But all tools have limitations, and no tool can accurately size all defects. This is not a problem with one type of tool or another: regardless of the technology used, all smart pigs have inherent limitations with regard to defect sizing. While these limitations can be reduced through developments, pipeline operators will always be forced to make potentially decisions for many years: leaving known anomalies in pipelines where smart pigs indicate seemingly insignificant anomalies.

Pipelines can and do operate safely with corrosion, mechanical damage, and other defects. Static defects rarely cause problems. Instead, new, spreading, or growing defects cause problems. This new smart pig *process* that overcomes inherent limitations in current pigging by:

- Providing a smaller, easier to use, and cheaper to run tool whose primary purpose is to detect changes
- Detecting and prioritizing changes that could lead to integrity problems, including those due to corrosion, mechanical damage, and coating disbond.

The pig would be designed to be run on a regular basis and use automated analysis techniques.

Because the pig would be built for detecting changes only, its sensor packages could be simpler and smaller. The pig could be designed to pass through difficult obstructions (e.g., very tight bends and some reduced-port valves). In addition, it could be made to run with little outside support and without the need for changes in operating conditions as the inspection was performed. To apply the process, a pipeline company would purchase, lease, or contract for a set of inspections using a difference-detection pig. Normally, the same pig would be run each time, making data alignment and interpretation easier. Software would quickly identify potential problems, directing maintenance and repair to areas where they are most needed.

Conclusion

The pipeline industry relies on non-destructive inspection to ensure the serviceability of this energy transportation infrastructure. The inspection is primarily performed by service companies dedicated to providing implementations that overcome the physical constraints of the pipeline system. However, not all pipelines can be inspected with current equipment and not all potentially service limiting anomalies can be detected. Developments in new or improved inspection technologies and novel deployment methods will help keep this historically safe transportation mode functional for many more decades.

References

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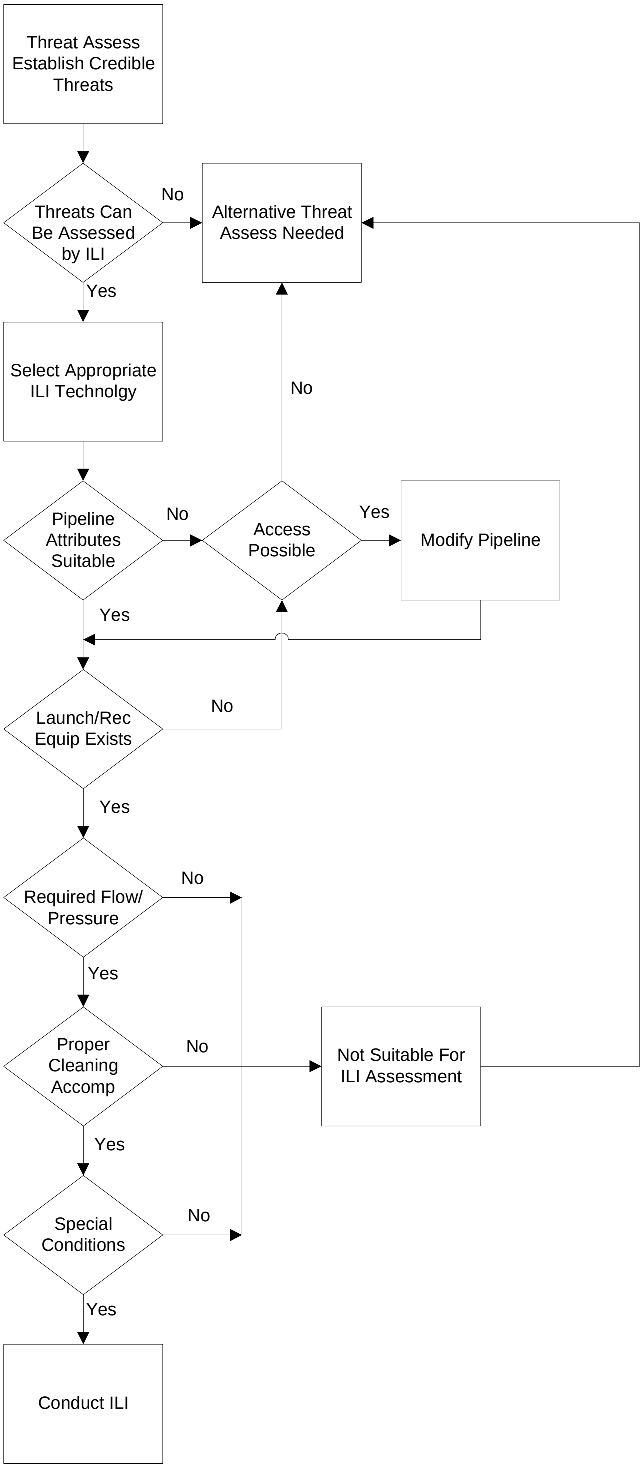

Figure 1. Pigability of Pipelines.