NACE Publication 35100
Item Number 24211
ISBN 1-57590-368-7
Approved 4-11-17

NACE Publication 35100

In-Line Inspection of Pipelines

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Foreword

NACE technical committee reports are intended to convey technical information or state-of-the-art knowledge regarding corrosion. In many cases, they discuss specific applications of corrosion mitigation technology, whether considered successful or not. Statements used to convey this information are factual and are provided to the reader as input and guidance for consideration when applying this technology in the future. However, these statements are not intended to be recommendations for general application of this technology, and must not be construed as such.

In-line inspection (ILI) is an important tool in the investigation of the condition of a pipeline. It is a significant part of pipeline integrity management and, as such, complements a quality integrity management program and promotes safe, efficient, and cost-effective pipeline operation. In-line inspection tools, popularly called "intelligent" or "smart" pigs, are devices designed to survey and gather information about different aspects of the condition of the pipeline without disrupting its operation. ILI tools are inserted into the pipeline and travel through it, driven by the transported product. Their operation is based on technologies of nondestructive testing (NDT).

The purpose of this technical committee report is to analyze available and emerging technologies in the field of in-line inspection tools and review their status with respect to characteristics, performance, range of application, and limitations. It is intended as a practical reference for both new and experienced users of ILI technology. This is a support document for the API[(1)] 1163[1] standard where it is referenced.

The document pertains to free swimming tools, as used predominantly in transmission pipelines, but the technologies are sometimes applicable in tethered tools and in other types of pipelines, such as gathering and distribution lines.

This report is aimed at assisting in providing an understanding of the practical aspects of using the tools, highlighting the implications, and helping assess the benefits.

The section titled "Types of In-Line Inspection Tools" provides a brief explanation of currently available technologies and tools. The procedures and rationale behind decisions leading to the use of in-line inspection tools and the associated cost and benefits are discussed in the sections titled "Decision Making Process" and "Cost/Benefit." The procedures related to inspections are discussed in "Operational Issues," and finally, the sections titled "Results of ILI" and "Data Management" deal with the outcome and use of results of in-line inspection. A glossary of terms commonly used in the in-line nondestructive inspection of pipelines is included in Appendix A. Appendixes B, C, and D provide generic specifications of tools and lists of activities connected to performing in-line inspections. Appendix E provides information on assessing ILI data.

Scope

This NACE technical committee report was prepared by Task Group (TG) 039, (formerly T-10E-6) on In-Line Nondestructive Inspection of Pipelines, which is administered by Specific Technology Group (STG) 35, Pipelines, Tanks, and Well Casings. This report is issued by NACE International under the auspices of STG 35.

[(1)] American Petroleum Institute (API), 1220 L St. NW, Washington, DC 20001.

Introduction

Since introduction in the late 1960s, ILI tools have mainly been used to inspect the wall of the pipe for corrosion (metal loss). ILI tools have also become available for performing other tasks, such as the following:
- Crack Detection.
- Geometry Measurement.
- Leak Detection.
- Temperature and Pressure Recording.
- Bend Measurement.
- Product Sampling.
- Wax Deposition Measurement.
- Pipeline GIS—Mapping.
- Visual Inspection.
- Pipe properties identification.
- Cathodic protection current inspection.

The increased use of ILI technology reflects the improvement of the technology. Pipeline defect detection has improved in terms of the variety of anomalies detected, increased accuracy of detection, and reliable characterization of anomalies. The increased reliability of ILI, the introduction of pipeline integrity management programs by many pipeline operators, and increased regulatory involvement pushed the technological development and use of ILI tools still further.

In addition, tools have become available that utilize more than just one type of detection technology enabling multipurpose inspections looking for a wider range of anomalies.

Besides the development of technologies addressing different types of defects, operational challenges have led to the development of multi-diameter ILI tools (collapsible pigs), i.e., tools that pass through and even inspect pipelines with changing diameters. Another addition to ILI tools that has become available is speed control, the ability to bypass flow and establish inspection speeds at much lower speeds than the flow of product. In addition, some of the tools are available as tethered tools, typically for inspecting shorter pipeline sections and sections without flow. Tethered tools also preclude the necessity of launchers and receivers.

None of the above-mentioned tools and applied NDT technologies are universally applicable. The pipeline operator and the ILI service company jointly choose the proper ILI technology, and match the performance of the tool to the requested defect specifications.

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Types of In-Line Inspection Tools

Generally, ILI tools are described by:
- Principle of operation—Type of NDT technology used.
- Types of detectable features.
- General performance characteristics.

For each of the ILI types listed in this chapter corresponding typical defect and tool specifications are given in Appendix B. The performance of the ILI tool technologies is laid out in accordance with the Pipeline Operators Forum (POF)[(2)] guidelines contained in the "Specifications and requirements for intelligent pig inspection of pipelines.[2] The POF document among other things, introduces the concepts of:
- POD: Probability of Detection.
- POI: Probability of Identification.
- Sizing accuracy.

Metal Loss Detection Tools

There are two principal methods for detection of metal loss in pipe walls: the magnetic flux leakage (MFL) method and the ultrasonic testing (UT) method. MFL was the first method developed and has been the most widely used. Another method, eddy current, has been used only to detect defects on the inside of the pipe wall and EMAT (electromagnetic acoustic transducers) has not been widely used for metal loss detection. Each method has its own particular strengths and limitations.

Magnetic Flux Leakage (MFL) Tools

The basic principles of magnetic flux leakage are straightforward. MFL tools induce an axially oriented magnetic flux into the pipe wall between two poles of a magnet. A homogeneous steel wall without defects allows for an undisturbed and uniform distribution of magnetic flux to be created. Metal loss or gain associated with the steel wall causes a change in the distribution of the flux which, in a magnetically saturated pipe wall, "leaks" out of the pipe wall. Sensors detect and measure this leakage field and hence detect the metal loss. The magnitude and shape of the measured leakage field is used to characterize the size and shape of the region of metal loss. The leakage signals are recorded and the resulting data are stored for detailed analysis, i.e. interpretation, and subsequent reporting.

Types of MFL Tools

The biggest distinction between MFL tools is the orientation of magnetizing the pipe wall. The technology started with axial magnetization which is still the most widely used, with circumferential introduced in the nineties and, recently, also helical. Orientation of magnetization affects the build of the tool and its performance, as flux leakage, and with that the sensitivity and accuracy of MFL tools, depends on the shape and orientation of planar and volumetric defects. Improvements in sensitivity and sizing accuracy have been achieved by a choice or combination of these.
- Axial: tools with magnetization of the pipe wall parallel to the axis of the pipe with sensors detecting flux leakage oriented in axial, radial or circumferential direction, recently in two or all three of them.
- Circumferential (transverse) magnetization, perpendicular to the axis of the pipe, improves performance on axially oriented narrow defects.
- Oblique (spiral): magnetization demonstrates sensitivity to both axially and circumferentially oriented defects.
- Multiple direction field tool configurations are available with combination of axial and circumferential magnetizing sections in order to improve the sensitivity, reliability and sizing capabilities.
- Dual field, low field and residual field: tools with magnetic fields well below saturation run in combination with axial MFL provides information about changes in magnetic properties of steel and reveal gouges, hard spots and cold worked areas.

General Performance Characteristics
- Inferential method, indirect measurement, which allows limited quantification using complex interpretation techniques
- With additional sensors, discriminates between internal and external defects
- Maximum wall thickness is limited as a result of magnetic saturation requirement
- Signal depends on length-to-width ratio of defects; limited ability on narrow axial anomalies for axially magnetizing tools
- Results are affected by pipe steel characteristics and history
- Results are affected by stress in pipe wall
- Performance is not affected by the medium present in the pipeline—suitable for both gas and liquid pipelines

[(2)] Pipeline Operators Forum, http://www.pipelineoperators.org/

- Moderate pipeline cleaning required (compared to ultrasonic tools).
- Robust.

Types of Detectable Features: The list of detectable features illustrates what the technology is capable of in principle, but each of the feature types sometimes have additional characteristics that make it more or less suitable for detection, along with a threshold.
- External metal loss.
- Internal metal loss.
- Welds: Girth welds, longitudinal welds, spiral welds, coil welds, and thermite welds (if ferromagnetic material present in the weld).
- Hard spots.
- Cold working.
- Dents.
- Bends.
- Tee piece.
- Flange.
- Valves.
- Casings.
- Location magnets.
- Steel sleeves.
- Clamps.
- Patches.
- Spalling (if metal loss associated).
- Composite materials (e.g. repairs, sleeves) with ferromagnetic materials.
- Near-wall excess metal.
- Distinguishing pipe joints with different material properties.

MFL ILI tools differ in the number, size, and orientation of MFL sensors, magnetic circuit design and magnetization levels, as well as the type of analysis that is applied to recorded data. Virtually all tools use permanent magnets to induce a magnetic field into the pipe wall, and use solid-state (Hall-effect) sensors, increasingly replacing inductive coils, to detect flux leakage. Miniaturization and increasing the number of sensors increases circumferential resolution as each of the sensors is able to examine a smaller area of the pipe wall and reveal more detailed information. Tools with higher resolution provide a better characterization of anomalies in the pipeline. Accordingly, the amount of data are greater and the data processing procedures more sophisticated. Table B1 of Appendix B provides more detailed information about the specifications of axially magnetizing MFL ILI tools.

Ultrasonic Testing (UT) Tools

UT inspection tools for metal loss directly measure the wall thickness of the pipe as the ILI tool travels through the pipeline. They are equipped with transducers that emit ultrasonic pulses perpendicular to the surface of the pipe. An echo is received from both the internal and external surfaces of the pipe, and by timing these return signals, the wall thickness is calculated knowing the speed of sound in steel. Transducers are deployed in a carrier to uniformly cover the full circumference of the pipe wall. Typical specifications for ultrasonic inspection tools are given in Table B2 of Appendix B.

For efficient transmission of ultrasound from the ultrasonic transducers into the pipe wall and back, a suitable liquid is needed. Many liquids usually transported through pipelines provide sufficiently good coupling for UT. In gases, however, because of a mismatch in acoustic properties of steel and gas that lead to difficulties in delivering enough acoustic energy into the pipe wall, ultrasonic inspections are not possible without an additional couplant. Gas pipeline inspections are performed by utilizing UT tools in a slug (batch) of liquid, e.g., water or diesel oil, between batching pigs.

Recently, EMAT (electromagnetic acoustic transducers) have been developed for measuring wall thickness of a pipe without a need for liquid coupling.

General Performance Characteristics
- Direct and linear wall thickness measurement method¾allows reliable depth sizing.
- Is able to discriminate among internal, mid-wall, and external defects.
- No upper limits to inspectable pipe-wall thickness.
- Has a minimum wall thickness limit.
- Does not depend on changes in material properties.
- Only runs in homogeneous liquids (in a batch of such liquid in gas pipelines—see “Operational Issues” for further details).
- Generally, UT tools require a higher degree of cleanliness of the pipeline than the MFL tools.

- The accuracy of the data, especially the defect depth and length, allows for the accurate calculation of remaining strength.
- Interpretation of results is easily comprehensible because it deals with directly measured wall thickness.

Types of Detectable Features
- The list of detectable features illustrates what the technology is capable of in principle, but each of the feature types might have additional characteristics that make it more or less suitable for detection.
- External metal loss.
- Internal metal loss.
- Welds: girth weld, longitudinal weld, spiral weld, and coil weld.
- Dents, deformations.
- Bends.
- Welded attachments and sleeves if the sleeve is welded to the pipeline (features under a sleeve are also detected).
- Tee pieces.
- Flanges.
- Valves.
- Laminations.
- Sloping laminations.
- Hydrogen-induced cracking (HIC) and induced laminations.
- Blisters.
- Inclusions.
- Longitudinal channeling.
- Wall thickness variations (e.g., of seamless pipe).

Eddy Current Tools

Coils on the tool generate eddy currents in the pipe wall which are sensitive to changes in the geometry of the internal pipe surface. Eddy current sensors can be used as "proximity sensors", e.g. measuring distance to the internal wall surface and changes in the geometry detecting internal metal loss. Generally, penetration of Eddy currents into the steel wall cannot be achieved without additional magnetization and the method has, therefore, been applied for inspection of internal corrosion only.

Crack Detection Tools

Crack detection has become an increasingly important issue in the pipeline industry because of occurrences of crack-like defects (e.g., stress corrosion cracking [SCC], fatigue cracks, longitudinal seam weld imperfections, etc.) that cause leaks and ruptures on operating pipelines. Generally, the NDE technique that allows for the most reliable detection of crack-like defects is ultrasonic testing using shear waves. Because most crack-like defects (fatigue cracks as well as SCC) are axially oriented, i.e., perpendicular to the main stress component (i.e., the hoop stress in a pipe), the ultrasonic pulses are injected in a circumferential direction to obtain maximum acoustic response.

Liquid-Coupled Tools

Liquid-coupled tools utilize shear waves generated in the pipe wall by angular transmission of the ultrasonic pulses through a liquid coupling medium (oil, water, etc.). The angle of incidence is adjusted such that a propagation angle of 45° is obtained in pipeline steel, using different sensor carrier configurations depending on crack orientations, e.g., axial vs. circumferential. This technique is appropriate for crack inspection, and is established as one of the standard techniques in ultrasonic testing. Typical specifications for liquid-coupled tools are given in Table B3 of Appendix B.

General Performance Characteristics
- Can only be operated in liquid environments.
- Gas pipelines can be inspected by running the tool in a slug (batch) of liquid.
- Full pipe body coverage—no exclusion zones.
- Capable of defect-type discrimination.
- Capable of discriminating among internal, mid-wall, and external defects.
- Actual wall thickness measured.
- The technology is used mostly for detection of axial cracks, but is applied to detection of circumferential and spiral cracks by changing the orientation of transducers.

Types of Detectable Features

Longitudinally oriented cracks and crack-like defects:

Cracks:
- Stress corrosion cracks (SCC).
- Fatigue cracks.
- Toe cracks.

Crack-like defects:
- Notches.
- Grooves.
- Scratches.
- Lack of fusion.
- Longitudinal weld irregularities.

Geometry-related features:
- Welds.
- Dents.

Installations:
- Valves.
- Tee pieces.
- Welded attachments.

Mid-wall defects:
- Inclusions.
- Laminations.

Electromagnetic Acoustic Transducer (EMAT) Tools

An electromagnetic acoustic transducer consists of a coil in a magnetic field at the internal surface of the pipe wall. Alternating current (AC) placed through the coil induces a current in the pipe wall using, either Lorentz forces (force acting on moving charges in magnetic fields), or magnetostriction, depending on configuration, which in turn generate ultrasound. The type and the configuration of the transducer used define the types and modes of generated ultrasound and the characteristics of its propagation through the pipe wall.

General Performance Characteristics
- EMATs do not need a coupling medium—readily applicable in gas pipelines.
- Geared towards detecting axially oriented cracks and crack-like features.
- Potential for detecting coating disbondment, as UT wave propagation is affected by the presence and type of coating.

Typical specifications for EMAT crack detection tools are provided in Table B4 in Appendix B.

Other Methods

Eddy Current Tools

This method is used to inspect internal cracks only because of limited through-wall penetration of eddy currents.

Geometry Tools

Geometry tools (also referred to as deformation or caliper tools) use mechanical arms, electromagnetic methods, or a combination of the two to measure the bore of the pipe, look for dents, other ovality changes, deformations, and detect girth welds and bore changes as a result of changing wall thickness. Each sensing arm has to be recorded individually (multichannel tools) to reveal circumferential defect position). In some configurations, they can also measure bends in pipelines.

The applications for which the geometry tools are usually used include:
- In acceptance stages of new pipelines to detect anomalies like denting or ovalities induced during backfill.
- Monitoring the bore of pipelines to detect mechanical or third-party damage.
- Checking to see that there are no restrictions in the pipeline prior to running heavier and more sophisticated ILI tools.
- If equipped, for pipeline bend measurement verification.

General Performance Characteristics:
- Operate readily in both gas and liquid pipelines.
- Low drag, low flow and robust.
- Typically have the biggest collapsibility (tolerance to decrease of internal bore) of all ILI tools.

Mapping Tools

The operation of mapping tools is based on inertial navigation using built-in gyroscopes and accelerometers. The data acquired are X, Y, Z angular change and X, Y, Z velocity change.

The tool is used for:
- Creating pipeline log books.
- Verification of existing pipeline log books.
- Determination of local ground movement or any changes in pipeline geometry, bending strain calculation.
- Bend measurements.
- Direct feed into geographic information system (GIS)-based databases for data layering.
- Locating dig sites when correlated to inspection data.

General Characteristics:
- Establish absolute (computed) coordinates.
- Accuracy of the computed absolute coordinates depends on the accuracy of the reference point positions and the coordinate spacing.
- Superimposing inspection results with geographical data and aerial (satellite) images.
- Base for combining data with results of other ILI and pipeline data into databases.
- Absolute coordinates given as longitude, latitude, and altitude, or easting, northing, and elevation.
- Typical specifications are given in Appendix B.

Tools with Combined Technologies

With developments in electronic, mechanical and computer engineering, tool components are getting significantly smaller, enabling different ILI technologies to be combined in one single tool. The advantages of that is not only is more data gathered, but also that the data from different types of inspections are tied together and correlation is more easily done.

The most common combinations are; geometry, mapping, and metal loss, or geometry and mapping. Also, combinations of multiple magnetization directions (axial, circumferential, and spiral) and magnetization levels (high and low) are being increasingly used.

Other Developments

Leak detection Tools

Tools used for leak detection are typically based on acoustic systems that "listen" to the sounds generated at the leaks. They are shaped as one-body pigs with cups, or more recently, as balls enclosed in foam pigs. Minimum detectable leaks are in the order of 0.5 gpm (gallons per minute, or ~100 l/h)

Cathodic Protection Inspection: Induced AC Detection

This technique measures the voltage drop created in the pipe wall as CP current accumulates and flows along the pipe back to its source. The voltage drop measurements are converted to current values by applying Ohm's Law. The data plotted against measured distance along the pipeline show a graphic map of current magnitude and direction, revealing if there is a net gain of current over the entire pipeline length thereby satisfying the basic theory of cathodic protection. The tool requires an internally clean pipe as direct contact is required for measurements. They also measure AC voltage drops in the pipe.