Pipeline Integrity Management: Detection of Corrosion and Cracks in Pipelines with Intelligent Pigs

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Abstract:

The international pipeline systems are growing in age and some installations have already been in operation beyond the service life they had originally been designed for. It is therefore of ever increasing importance that pipeline operators are provided with the means to accurately and reliably inspect their pipelines and obtain the information needed for decision making regarding safe operation, rehabilitation and repair.
This paper will introduce the concept of bundled services and an assessment of the latest developments in on-line testing covering all aspects of pipeline inspection as well as the advances in pigging technology. It will introduce the possibilities provided by the implementation of sophisticated NDT-technologies into intelligent on-line inspection tools as well as the type of information that can be collected by such advanced tools and consequently be used for integrity assessment and fitness for purpose analysis.
A general overview of available on-line inspection tools will be provided including details about two new tools, an ultrasonic crack detection tool and an advanced magnetic flux leakage tool.

1. Introduction

It is generally agreed that pipelines provide one of the safest means for the transportation of large quantities of liquids or gas. Today the international oil and gas-pipeline network spans several million kilometers and is growing every year.

Just like any other technical component pipelines are subject to „wear and tear" and degredation. Pipelines can fail with time if they are not properly maintained.

Considering the above and the fact that pipelines constitute a major investment, operators are well advised to establish efficient maintenance programs for their pipelines. Safety must be ensured and the asset „pipeline" must be protected.

Pipeline Integrity Management and Pipeline Inspection Programs provide the means to ensure a safe, efficient and cost-effective pipeline operation. A turnkey approach ensures that a pipeline inspection company can provide all the services required and manage all aspects of pipeline inspection and maintenance for the pipeline owner or operator.

One part of a maintenance procedure consists of a suitable monitoring program and one component of such a program should be made up of inspections using intelligent tools and utilizing the information they provide for integrity assessment and fitness-for-purpose analysis. Possible flaws and defects and their impact must be known prior to establishing and initiating repair or rehabilitation measures.

2. Some General Remarks On The Use Of On-Line Inspection Tools

In general it can be said that on-line inspection tools, sometimes also referred to as in-line inspection tools or intelligent scrapers, utilize non-destructive-testing techniques (NDT) in order to detect flaws or defects in pipelines. Ideally a feature in a pipeline should be detected by an on-line inspection tool whilst still being a flaw, i.e. corrosion, and before a defect, i.e. a leak, has developed. Unfortunately no one tool exists which can detect all possible flaws or defects that can potentially occur in pipelines. It is therefore that a whole range of tools is available today, each type of tool being specialized in specific tasks. It is of great importance and by far no trivial task that the right tool is chosen for a particular application and that the recipient of the final inspection report is fully aware of the capabilities of individual tools, their advantages, disadvantages and limitations. Especially defect specifications should be carefully examined. Choosing the most suitable tool for a given requirement is a long process and pipeline operator and on-line inspection tool vendor must work closely together

in the exchange of information and the preparation of procedures in order to ensure a successful and efficient survey.

Modern on-line inspection tools form part of a "monitoring" system to ensure the reliability of a given pipeline or pipeline system. The reliability can be understood as the sum of the following requirements put to such a system: Safety, environmental protection and economy.

Fig. 1 shows schematically the interaction between safety, protection of the environment and ensureing economic efficiency of a given line. Pipeline integrity or reliability should include all these aspects.

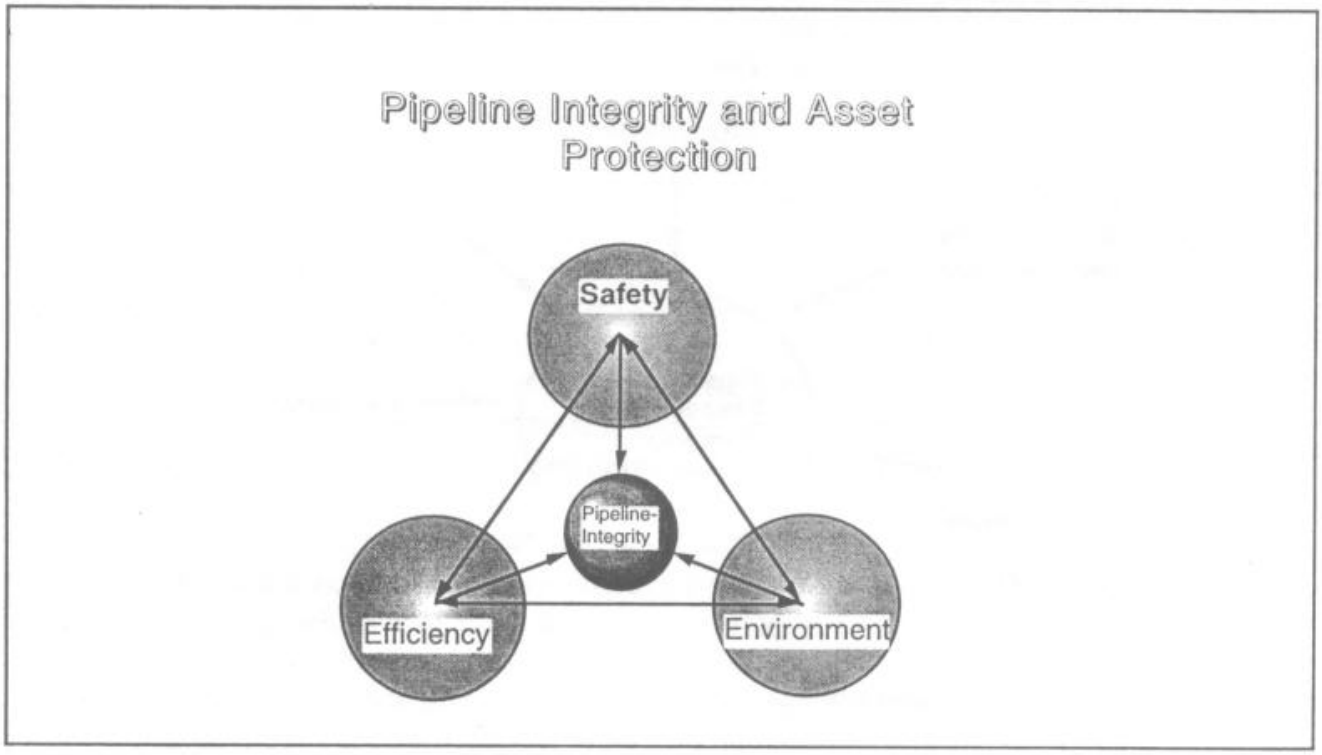

Fig. 1 Pipeline Integrity, interaction between safety, environmental protection and economic efficiency.

The latest generation of intelligent pigs have reached a level of accuracy and resolution which allows the application of integrity assessment- and fitness for purpose analysis. The information provided by intelligent tools must be seen as a critical part of the input needed for decision making regarding rehabilitation and repair.

3.0 The Turnkey Approach

A requirement which the industry will have to take note of in the future is the requirement to perform turnkey projects. What is meant by that?

More and more operators are "streamlining" departments and a trend can be noticed that pipeline maintenance including pipeline inspection and all necessarry preparatory work is being outsourced to suitable contractors.

Pipeline inspection companies will have to provide these services in order to meet future requirements.

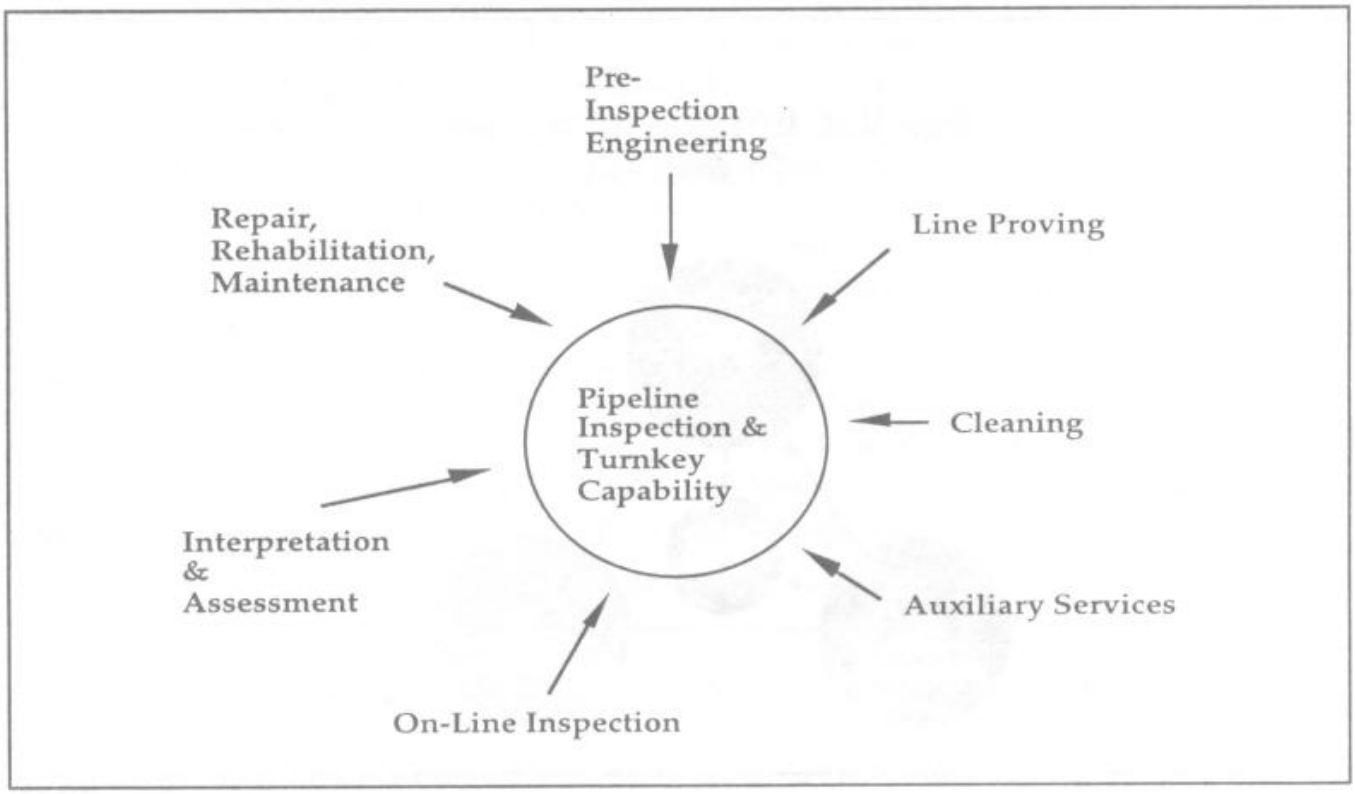

Figure 2. Turnkey capabilities by providing bundled services.

Figure. 2 shows a graphic summary of turnkey capabilities and bundled services. A pipeline operator interested in pipeline inspection will have the choice to chose any of the individual modules, such as cleaning or gauging or on-line inspection or to award a project as a turnkey project making use of the bundled service capabilities of the contractor.

3.1 Turnkey Capabilities

Full turnkey capabilities include all aspects of Pipeline Integrity Management, starting from the commissioning phase, through pipeline maintenance to rehabilitiation, repair and finally decommissioning. The range of services

required includes pressure testing, drying with air, vacuum, or nitrogen, cleaning as well as leak detection, dent detection and the calibration of measuring devices and the hiring out of equipment.

This work related to on-line inspection and integrity assessment includes pre-inspection engineering, which in turn includes site visits in order to determin whether pipelines and pipeline installations are suitable for intelligent pigging, followed by recommendations how to modify and/or actually taking care of necessarry modifications to allow intelligent pigging. It further includes review of drawings and technical data to obtain an understanding on how the line is operated including loading parameters.

A next step is to recommend and perform a suitable cleaning program. Ideally a full range of cleaning tool is available and manufactured inhouse. The range of cleaning tools covers BiDi pigs, cup pigs, spherical pigs, foam pigs and special pigs.

Cleaning is usually preceeded or followed by a gauging program and finally by the on-line inspection.

The most suitable intelligent inspection tool must be chosen according to the inspection objectives, the type or types of flaws to be detected and measured and an effective and suitable cleaning program must be established. The on-line inspection is followed by interpretation of data and integrity assessment based on that data and the loading and material parameters established previously. A final step, if needed, is to prepare procedures and recommendations regarding repair or rehabilitation either in order to operate a flaw affected pipeline at its normal operating pressure or to recommend a suitable safe operating pressure for the pipeline as it stands. Furthermore an appropriate inspection interval should be determined as to when the next inspection should be performed. Depending on the actual requirements of the pipeline operator the final step of a service contract can even include actual repair and subsequent testing.

3.2 Inspection Services

Inspection Services from part of the turnkey capabilities. Details will be covered in section 4 of this paper. It is important that the inspection company chosen can provide the right kind of tool for the type of flaw or defect that is to be found. No one tool can detect all possible flaws! It is therefore advisable that operator and inspection company cooperate closely in planning an inspection, discussing and clarifying the aim of the inspection and carefully preparing the actual inspection work together with all auxiliary measures that have to be considered, such as cleaning, gauging etc..

4. How Can On-Line Inspection Tools Actually Help?

4.1 Pipeline Monitoring And Inspection

On-line inspection is seen by Pipetronix as part of a monitoring and inspection procedure for pipelines. In turn monitoring forms part of an overall integrity and reliability program. The latter also includes, apart from monitoring, all aspects of understanding potential failure mechanisms and their causes (e.g. corrosion due to defective coating), implementing preventive action (e.g. use of inhibitors, use of cathodic protection) and planning and preparing suitable and adequate procedures for remedial action (e.g. pipeline repair or rehabilitation).

Fig. 3 shows on-line inspection as part of a monitoring and inspection program for pipelines.

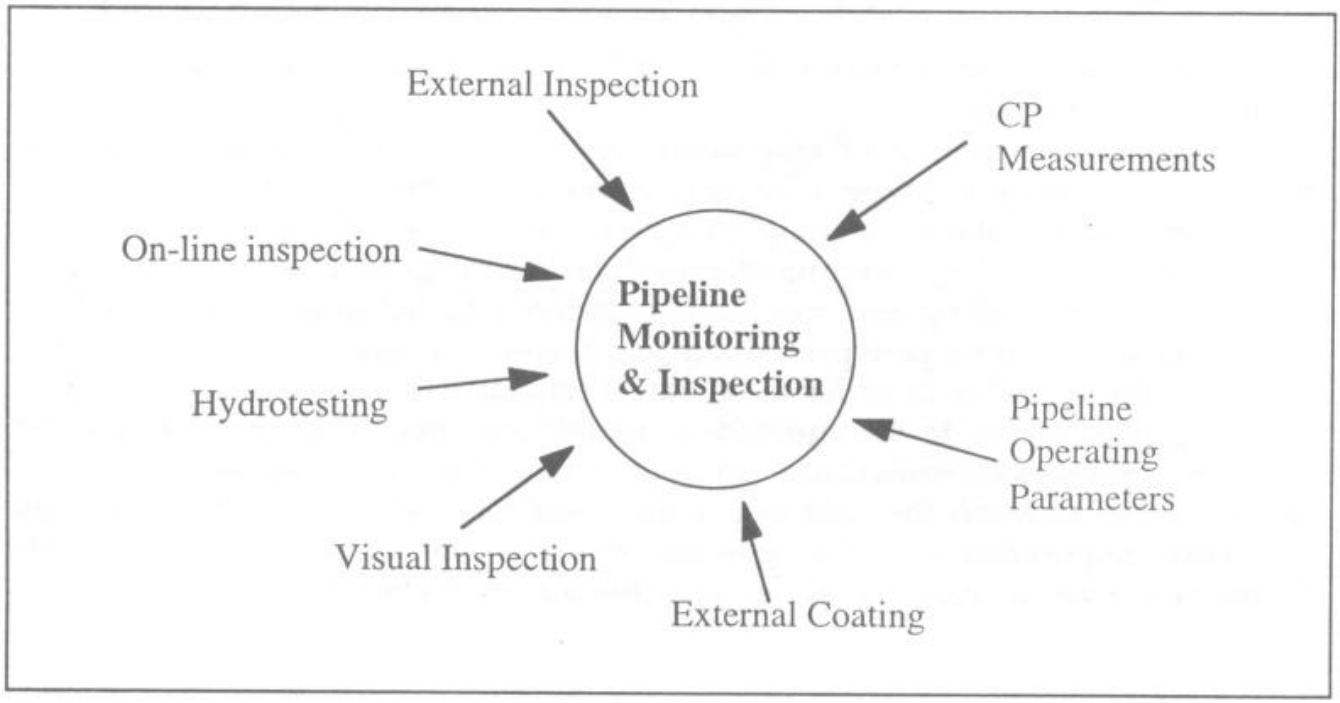

Fig. 3 On-Line Inspection: Part Of An Overall Monitoring System

4.2 What Kind Of Information Do Intelligent On-Line Inspections Tools Provide

On-line inspection tools are free swimming devices utilizing a variety of non-destructive-testing (NDT) techniques to inspect the wall of the pipe they are travelling in. They are usually pumped through the line within the medium transported in that line, thus the name used: on-line or in-line inspection tools.

The information provided by intelligent inspection tools consists of geometric data for any given flaw found. Usually the length, width, depth, location and orientation of a flaw will be reported. In addition certain tools, such as the inertia

tools, can report pipeline displacements, again geometric information or caliper tools which will report any changes to the actual internal diameter of a pipeline.

The information obtained by on-line inspection tools is essential to assess the state of a line.

In general the data obtained by an intelligent pig will be interpreted by the inspection company and the results will be handed to the pipeline operator as a written Final Report.

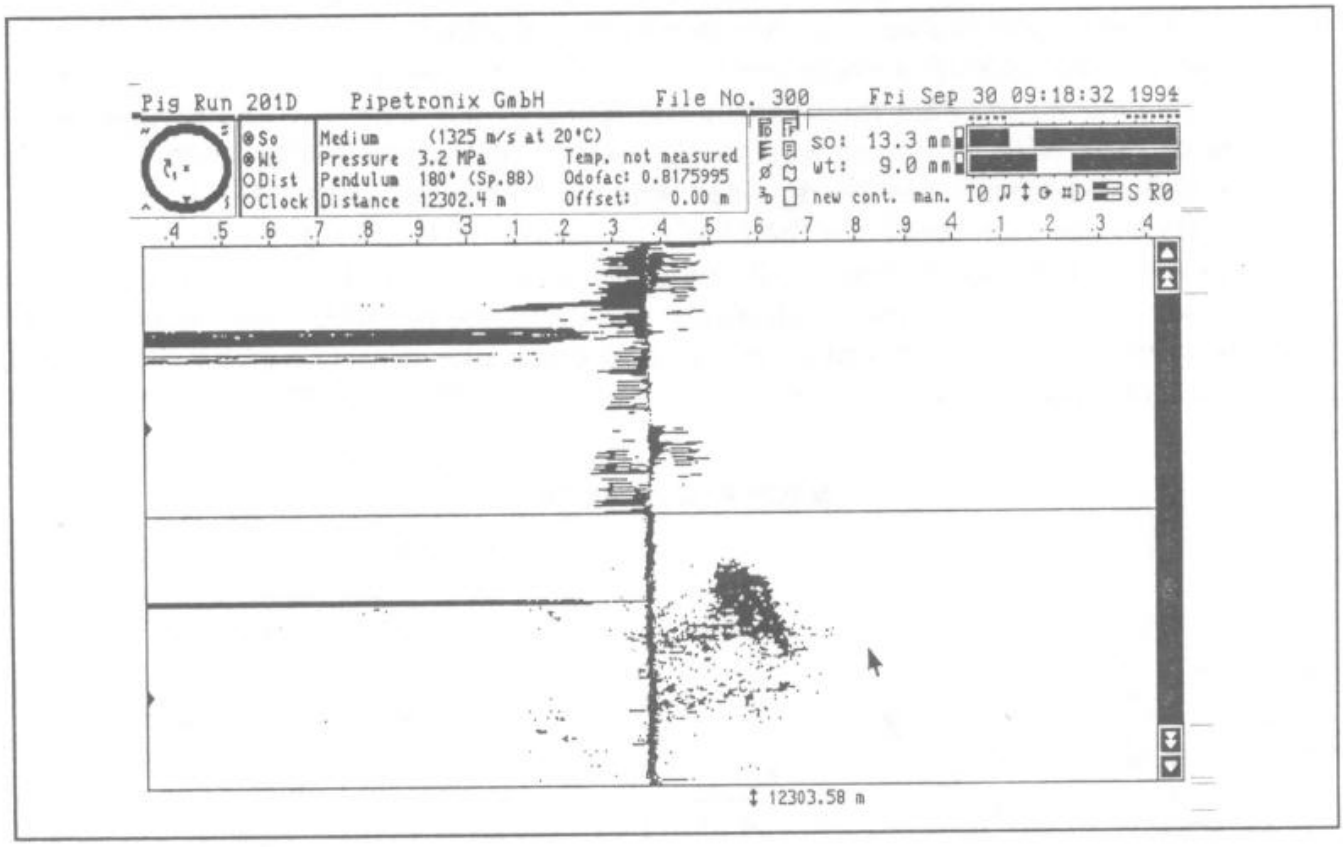

Fig. 4 Visualization of data from an on-line inspection. C-Scan shows plan view of pipe inspected. Flaws are shown through colour codeing* (colours not reproduced here)

Recently reporting is also provided in an electronic format, be it as input for a spreadsheet or data bank system or as a stand alone program which allows viewing of results or even viewing of features. A further step is the provision of visualization software which allows viewing of the entire inspection data.

Advanced visualization software allows an actual display of the flaw found on the computer screen. The pipe is opened up, flaws are shown through colours. Fig.4 shows an example taken from an ultrasonic inspection.

4.3 How Can The Information Be Used

Modern on-line inspection tools will provide a huge amount of data measured in the pipeline being inspected. More and more pipeline operators are requesting an assessment of the measured data in addition to the interpretation already provided. Such additional assessment can consist of ranking of flaws found either according to depth or any other geometric criteria. Furthermore assessment codes, such as ASME B31G, can be applied to provide maximum allowable pressure values. Usually this information can then be provided in easy to read curves or plots rather than written tables, see fig.5.

Fig. 5 shows an MAOP assessment of a section of line inspected. The MAOP acceptance plot shows data taken from the features list. The two lines represent sections of pipe with different wall thicknesses. Entries above the lines indicate serious flaws which should be repaired, entries below the respective lines show that the flaws are safe, based on the MAOP criterion used.

The codes used to date, be they B31G or other inhouse regulations that opertors might use, are limited to the evaluation of corrosion or metal loss features. A next step will be the assessment of cracks and crack like defects based on fracture mechanics or other suitable means.

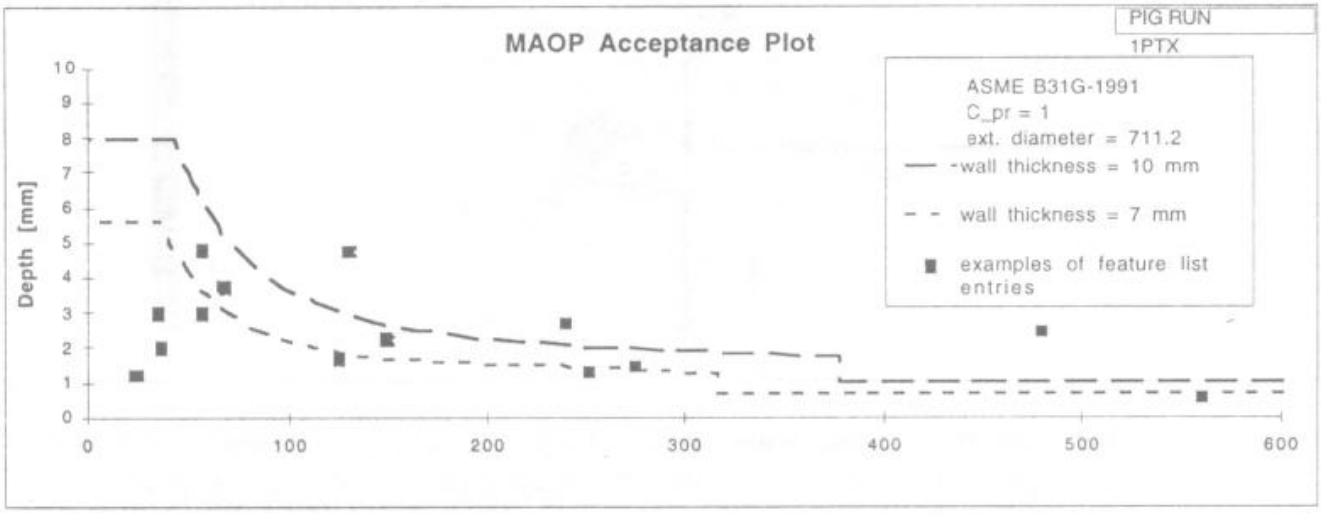

Fig. 5 MAOP Acceptance plot

5. Potential Flaws And Defects In Pipelines

In order to understand how on-line inspection tools can be used to monitor the integrity of a pipeline or pipeline-system one must develop an understanding for the types of flaws and defects that might be experienced. With regard to intelligent pigs, the types of flaws and defects that can be detected are either directly related to the pipe wall or the internal or external coating.

The following distinction can generally be made:

- Direct Flaws and Defects
- In-direct Flaws and Defects

Direct flaws and defects relate directly to the state of the pipe wall. Such flaws and defects have a direct effect on the integrity of a line or line-section. Typical examples would be corrosion, cracks or gouges. In-direct flaws and defects relate to possible damage or malfunction of a material or system related to the continued integrity of a pipeline and the failure of which, with time, can or will lead to a direct flaw or defect. Typical examples are a cathodic protection system or the internal or external coating of a line.

Basically direct flaws and defects in pipelines can be distinguished into one of the following categories:

- geometric anomalies
- metal loss
- cracks or crack like defects
- leaks

Geometric anomalies relate to any change in the geometry of a pipe such as dents, ovalities or wrinkles etc.. These geometric anomalies have to be detected for a variety of reasons. Two of these reasons are a critical reduction in free internal diameter and the formation of locally acting stress concentrations.

Considering the former, pipelines are usually regularly cleaned using metal body or other types of pigs or special pigs are introduced to seperate different types of product in a multi-product line. The type of pig used for the latter is often a metal body bidi tool. These devices only have a limited flexibility. Any geometric anomaly must therefore be known in order to ensure that these tools do not get stuck in the line. The type of intelligent tool used for inspection purposes therefore incorporates a much larger flexibility of up to 25% reduction in internal bore.

Regarding the latter let us consider dents for example. Dents cause a local re-directioning of the force flow induced into the pipe wall by the acting hoop stresses and act as notches giving rise to local stress concentrations which in the case of cyclic loading can lead to the formation of cracks /1/. Burst tests have shown that dents, depending on their geometry have a marked effect on the integrity and safety of a line /2/. Any change in a pipe from the cylindrical geometry either due to external mechanical force or residual stresses after a welding operation and resulting in an ovality will also lead to the formation of local stress peaks with an effect on the actual integrity of a line. Another type of anomaly are wrinkles often experienced in field bends. Intelligent scraper surveys have shown that wrinkles form preferential sites for internal corrosion defects.

Ideally any metal loss feature should be detected by an intelligent scraper before a leak can occur. However a large number of pipelines are still not inspected regularly or not inspected at all. Should a leak therefore occur special tools are available to detect and exactly locate any leakage.

Metal loss features usually relate to internal or external corrosion. Intelligent corrosion detection tools must therefore be able to reliably detect and measure corrosion flaws and to accurately locate them. The same can be said for cracks and crack like defects. The following types of cracks can be found in pipelines /3/:

- fatigue cracks
- stress corrosion cracks
- hydrogen induced cracks
- sulfide stress corrosion cracks

A lamination can be treated as a crack like defect.

The above can only be seen as a very brief and incomplete introduction into the types of flaws and defects that can potentially arise in a pipeline wall.

The types of potential defects for onshore and offshore installations are similar, although the frequencies with which they occur are different. Whilst most failures of onshore pipelines are attributed to third party mechanical interference, most defects in offshore lines are caused by internal corrosion.

6. Why Look At Different NDT-Techniques?

Assessing the available NDT technologies depends of course on an understanding of which anomalies have to be detected. Which features to be detected are critical and which are not. How reliable or reproduceable are the NDT measurements made? Is the signal recorded really a flaw or defect? Can the chosen NDT technology actually be applied in an internal inspection tool?

Information on potential defects is readily available in the literature (for instance /4,5,6,7,8,9/) and the main flaws or anomalies causing concern are metal loss, material defects and external mechanical damage, such as corrosion, cracks, laminations, dents and gouges.

Detection of all of these features is at present not possible by using one single tool. A variety of tools is needed, such as caliper-, metal loss- and crack detection tools. Caliper- and metal loss on-line inspection tools are already commercially available which can reliably and accurately measure geometric anomalies, internal and external corrosion and other metal loss features. The latter tools can with limitations also detect certain types of cracks, but should not be understood as crack detection tools. True crack detection tools have only been introduced into the market during the last couple of years.

7. Which Type Of On-Line Inspection Tools Are Available?

A general overview into the types of tools, be they traditional or intelligent, can be found in /4/. A summary is shown in table 1.

Inspections based on the use of intelligent on-line inspection tools usually require a cleaning program prior to the actual survey.

Type of Intelligent Pig	Physical Principle	Function of Tool
Caliper*	Mechanical, Induction.	Geometric Inspection: Dents, Ovalities etc.
Inertia Pig*	Gyroscope.	Route Surveying, Route Profile and Bends.
Leak-Detection Pig*	Pressure Difference or Ultrasound.	Detection and Location of Leaks.
Burial & Coating Pig	Radiation (Neutrons).	Loss of coating, cover and detection of free spanning.
Crack Detection Pig*	Eddy Current, Pulsed Eddy Current, Ultrasound.	Detection and sizing of internal, external and mid-wall cracks and crack-like defects.
Metal Loss Pig*	Magnetic Flux Leakage, Ultrasound.	Detection and sizing of internal and external metal loss and mid wall defects (inclusions, laminations).

Table 1: Intelligent On-line inspection tools. (*tools Pipetronix can provide)

7.1 Caliper Tools

The purpose of Caliper tools is to detect, measure and locate geometric anomalies in a line, in general any change of the free available internal diameter.

Some Caliper tools make use of mechanical sensing devices, such as spiders fitted with mechanical fingers. Other types of tools use magnetic induction principles using the fact that a change in the pipe geometry (i.e. due to a dent or ovality etc.) will cause a change in the magnetic field induced which can be detected and evaluated.

These types of tools will report dents, ovalities, general changes in internal diameter, wrinkles in field bends and other geometric anomalies affecting the available internal diameter.

7.2 Inertia Tools

Inertia Tools are used for pipeline profiling and route surveys. Gyroscopes, as implemented in the navigational systems of aircraft for instance, are used to record x-, y-, z-coordinates of the tools as it travels through a given pipeline. Special software is used to translate the information obtained to be respresented in a Gauß-Krüger or other coordinate system which can in turn be printed into a map, thus enabling route surveying and checking of the alignment of pipes to be performed. Modern sophisticated inertia tools provide information with an accuracy which allows minimal pipe movements to be recorded, data which can further be used for induced stress calculations. Together with accurate marker transmitter systems incorporating GPS they provide excellent pipeline monitoring devices in areas of subsidance, permafrost areas etc..

7.3 Leak Detection

A variety of leak detection tools are available on the market today. Again, before applying a certain type of tool pipeline operator and service company must take care to evaluate the exact need in order to chose the proper tool for a given task. For instance some types of leak detection tools can detect minute leaks, but require a pipeline to be taken out of operation during the survey, other tools can be used on-line but require a certain leakage rate to exceed their threshhold.

Two systems available from Pipetronix are based on the pressure difference method and on the principle of accoustic emmission. The former consists of a tool fitted with a pressure measureing device. The pipeline or pipeline section inspected is taken off-line and filled with a suitable liquid. The leak constitutes an area of lowest pressure in the line which the leak detection tool can locate. The latter method is based on sonic leak detection. The pipeline inspected can remain on-line. The tool utilizes the fact that leaks in pipelines generate a characteristic sound in the range of 20-40kHz. This characteristic sound is picked up by hydrophones fitted with suitable frequency selective electronics. The tools allow detection and location of leaks (minimum leakage rate 5l/h) by additional use of odometer wheels and marker systems.

7.4 Burial & Coating Tool

This type of tool was especially developed to determin burial and coating conditions of offshore pipelines. The tool utilizes a radioactive source which emits a constant stream of neutrons. These penetrate the thick pipe steel,

somastic corrosion coating, and concrete weight coating, finally emerging into the surrounding seabed material. During this process the neutrons interact with each material in turn, and produce secondary radiation which is characteristic of the material encountered.

7.5 Detection of Cracks

The reliable detection of cracks constitutes a further challenge for the pipeline inspection industry. Again potential flaws and defects have to be defined. Depending on the type of pipeline, type of pipeline material and the operating conditions different types of cracks or crack like anomalies could occur.

Much research has been carried out worldwide into the understanding of how these material defects are initiated, how they propagate and how they can be avoided. Fracture research has been carried out extensively for the nuclear and for the aviation and space industries.

Cyclic loading, for instance possible in liquid lines, can lead to the formation of pure fatigue cracks or corrosion fatigue. Strictly speaking all cracks incorporate a corrosion component unless they are placed in an inert environment. This class of cracks is most likely to be initiated at local stress concentrations. These could be due to macroscopic features such as dents or microscopic such as material voids, inclusions or local brittle zones. Stress corrosion cracks can initate at any point where the local stress intensity surpasses the actual resistance of the material. Research has and is being carried out into dynamic crack growth in pipeline steels /10/ and this is of paramount importance considering safety, especially of high pressure gas transmision lines. However some attention should also be paid to investigating sub-critical crack growth in pipeline steels.

Tools which can detect cracks are already available. Pipetronix has introduced and is operating two types of crack detection tools using eddy current and ultrasonic techniques.

Pipetronix believe that in general the most suitable available technology for the detection of cracks is ultrasound, the eddy current tool having been developed for special applications. A second generation crack tool using ultrasound sensors has been developed and introduced in 1994. Field experience and a track record of nearly 1000km of inspection runs has proven the high standard of this tool and its superb capabilities regarding inline crack detection /11/. It is well known that radial cracks are potentially the most dangerous in pressure vessels and the new tool is specifically designed to detect these, irrespective of their position, e.g. internal or external surface of the pipe-wall or mid-wall.

range	appr. 100 km
optimum Speed	1 m/s
circumferential sensor spacing	8 mm
longitudinal resolution	3 mm
minimum defect length for detection	20 mm
minimum defect depth for detection	1 mm
location accuracy (with reference to next girth weld	± 0.2m
bend capability	3D
pressure	up to 120 bar

Table 2: Technical data UltraScan CD, crack detection tool.

Table 2 includes technical information on the tool, which is currently available in sizes 24", 26" and all sizes from 40" through to 56".

7.6 Detection of Corrosion

Three NDT methods are commercially available and implemented in intelligent tools for the purpose of corrosion surveys. Detection and measurement of internal and external corrosion is possible by using the magnetic flux leakage principle, ultrasound or eddy current techniques. Which method should be used really depends on circumstances. Basically the questions would be: which kind of line is being inspected and how much information is needed and how detailed should this information be. All methods have advantages and disadvantages. Being able to provide alternatives makes is possible to chose, in agreement with the operator, the best solution for a specific inspection requirement. High resolution magnetic flux tools provide very much improved accuracies, data handling and interpretation facilities compared to the first generation magnetic flux tools. A problem which is becoming appearent is that the definition of high resolution is not clear. It would be desirable if the vendors of on-line inspection tools could come together and define what they imply by offering their tools as "high resolution". High resolution in the opinion of Pipetronix does not only relate to the number of sensors used on a given tool, but should imply that the magnetization section is optimized ensureing full saturation of the pipe wall inspected, that the sensors used allow low threshhold values in order to detect corrosion at an early stage, that the tools are equipped with suitable electronics to allow the required sampling rates, data handling and recording and finally that the data processing, interpretation and evaluation is of a high standard. True high resolution magnetic flux leakage tools, such as the MagneScan HR, provide excellent information regarding the assesment of lines.

A newly developed inspection tool based on the magnetic flux leakage principle, the MagneScan XHR has only very recently been introduced into the market. This addition to the range of corrosion detection tools has been especially designed for the inspection of very long distance, thick walled gas pipelines, where the use of a liquid batch is not feasible, and with the requirement to detect the onset of corrosion or low level corrosion.

The principle used is identical to the principle described above. Major additional research and development work centers in the optimization of the magnetic circuit in order to saturate thick walled offshore pipelines and to obtain further enhanced defect specifications. Further details of the tool will be made available shortly.

Item	MagneScan HR	MagneScan XHR	UltraScan WM
Physicle Principle used:	Magnetic Flux Leakage	Magnetic Flux Leakage	Ultrasonic wall thickness measurement
Range of tool sizes available	6" to 56"	20", 30", 40"	6" to 60"
Detection Threshhold for General Corrosion	diameter ≥ 3WT depth ≥ 10%WT	diameter ≥3WT depth ≥ 5%WT	diameter ≥ 20mm depth ≥ 1mm
Detection Threshold for Pitting Corrosion	diameter ≥ 2WT depth≥20% (diameter < 2WT is detected but not measured)	Internal diameter ≥ 0.25WT External diameter ≥ 1WT	diameter ≥ 20mm depth ≥ 1mm (diameter (d): 10≤d≤20mm, detection only)
Accuracies	General Corrosion: ±10% WT Pittings: ±20% WT	General Corrosion: ±5% WT Pittings: ±10%WT	General Corrosion ±0.5mm Pittings: ±0.5mm
Internal/External discrimination	yes	yes	yes

WT denotes Wallthickness.

Table 3: Defect Specifications

It should be noted however that only tools using ultrasound, like the UltraScan WM, allow direct quantitative measurement of wall thickness. As a company we therefore believe that both services should be provided in order to give a choice.

With regard to offshore installations it can in general be said that offshore pipelines are designed with larger wall thickness specifications than onshore lines of the same diameter. The wall thicknesses implemented depend on the design pressure and the resulting acting hoop stresses, an anticipated potential corrosion rate and a chosen or required safety factor determined by regulations.

The advantage of using an ultrasonic tool is its capability to measure wall thicknesses of up to 50mm.

Eddy current tools have been developed in order to allow thick walled small diameter offshore gas-pipelines to be inspected, where a magnetic flux leakage tool can not be used because full saturation cannot be achieved or where an ultrasonic tool cannot be used because batches are not feasible.

Tables 3 provides an overview of the defect specifications for the tools introduced above. All three tools are used for the detection and measurement of corrosion and metal loss. However each tool has areas of speciality depending on the given inspection requirements.

- High Resolution Corrosion and Metal Loss Inspection
- Low Level Corrosion and Metal Loss Inspection of long distance and/or thick walled (gas) pipelines
- Quantitative Corrosion and Metal Loss Inspection with direct measurement of remaining wall thickness.

8. Conclusions

The international pipeline systems are growing in age and some installations have already been in operation beyond the service life they had originally been designed for. It is therefore of ever increasing importance that pipeline operators are provided with the means to accurately and reliably inspect their pipelines and obtain the information needed for decision making regarding safe operation, rehabilitation and repair.

A reliable „Pipeline Integrity and Asset Protection Plan" requires input from a great variety of services and inspection techniques.

Due to the variety of possible flaws and defects, different inspection techniques have to be applied.

For economical and technical reasons it is advisable to work with inspection companies that have turnkey capabilities by providing bundled services.

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