Combined In-Line Inspection of Pipelines for Metal Loss and Cracks

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Abstract - As pipelines grow in age it is of ever growing importance to provide operators with precise and reliable inspection data in order to perform advanced integrity assessment calculation and optimize maintenance processes. Until recently the inspection of a pipeline regarding metal loss and cracks not only constituted the need for two separate inspection runs but also the use of two separate tools. This paper will introduce a range of advanced in-line inspection tools that incorporate the ability to be used for quantitative metal loss and wall thickness- as well as crack inspections. These tools, utilizing ultrasound technology, make use of a new generation of electronics and an entirely new design of sensor carrier to enable metal loss- and crack inspection surveys to be performed with a single tool in a single run. The paper will explain the physical principle used, introduce the tool technology, introduce a case study and present the operational advantages to the operator.

Introduction

A pipeline network of over four million kilometers spans the world and is growing every year, used for the transportation of oil, oil products and natural gas. It is of greatest importance to ensure the safety, efficiency, environmental integrity and regulatory compliance of the worldwide pipeline infrastructure. Achieving this objective entails the need for effective inspection technologies, incorporating the accuracy and reliability required for optimized maintenance strategies. Figure 1 shows key requirements with regard to operators needs and operational issues.

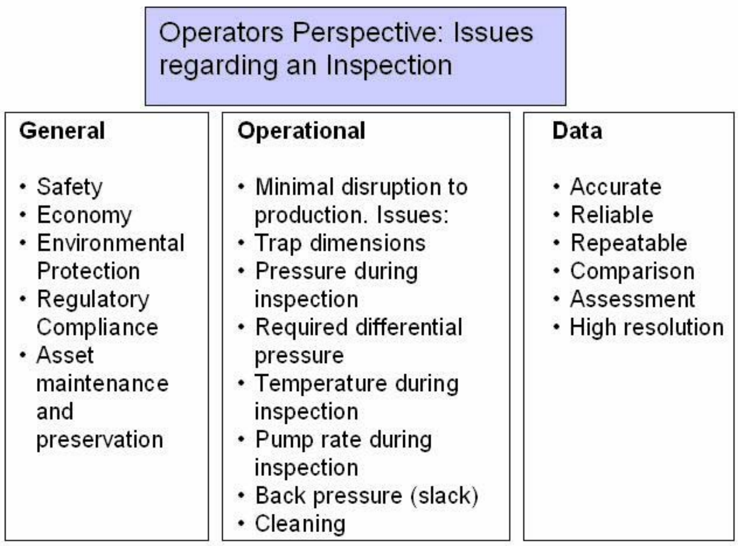

Figure 1: Issues regarding inspection

Modern in-line inspection tools provide the means to inspect pipelines for all major anomalies and flaws which can appear in the pipe wall. Two critical categories regarding the integrity of the ferrous pipe wall are metal loss, i.e. wall thinning due to corrosion or gouging, and cracks. Metal loss and cracks can appear in a large variety of flaw geometries and at any time during the lifecycle of a pipeline, for instance during production of the steel plate, manufacture of the pipe, construction and operation of the pipeline. In-line inspection tools can detect, size and locate a large variety of features in the steel wall of a pipe and provide exact geometric data regarding the shape, orientation and position of such anomalies. Table 1 includes an overview of typical flaws and defects which can generally be found during an in-line inspection project.

Category	**Type (typical examples)**
Geometric Anomaly	Dent, Ovality etc.
Metal Loss	General Corrosion, localized corrosion, pittings, gauging, narrow axially extended corrosion (NAEC) etc.
Cracks	Fatigue cracks, laminations, weld cracks, SCC, HIC etc.
Leaks	-

Table 1: Typical pipeline anomalies

In-Line Inspection Technologies

A variety of non-destructive-testing technologies are being applied in in-line inspection tools, often also referred to as intelligent pigs[1,2,3,4]. Magnetic flux leakage, eddy current and ultrasound principles can all be applied for metal loss detection and sizing [5,6]. Ultrasound has proven to be the most suitable and reliable technology for crack detection in pipelines [7]. The first in-line inspection tools utilizing ultrasound technology for metal loss surveys have been introduced into the market in the middle 1980´s, followed by crack inspection tools in the 1990´s [8]. A new generation of ultrasonic tools was introduced in 2002 [9]. These tools are based on an entirely new design, incorporating advances made in mechanical and electronics design, including a unique modular design philosophy enabling the same tool to be used for metal loss and crack inspection. Originally this referred to using the same basic tool assembly and electronic module for either configuration. Only the sensor carrier had to be changed. Whilst saving considerably on mob and demob costs, as one tool could be used for both inspection tasks, two physically separate runs were still necessary. This paper introduces a development based on the same tool technology, however using a newly designed and optimized sensor carrier design which enables quantitative metal loss and crack inspection to be performed in a single run. This ability of the tool offers a range of advantages for the pipeline operator, which will be introduced and discussed.

Tool Design

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 45º 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 can not be accessed and therefore the inspection process has to be fully automatic and cannot be supervised.

Hardware

Figure 2 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.

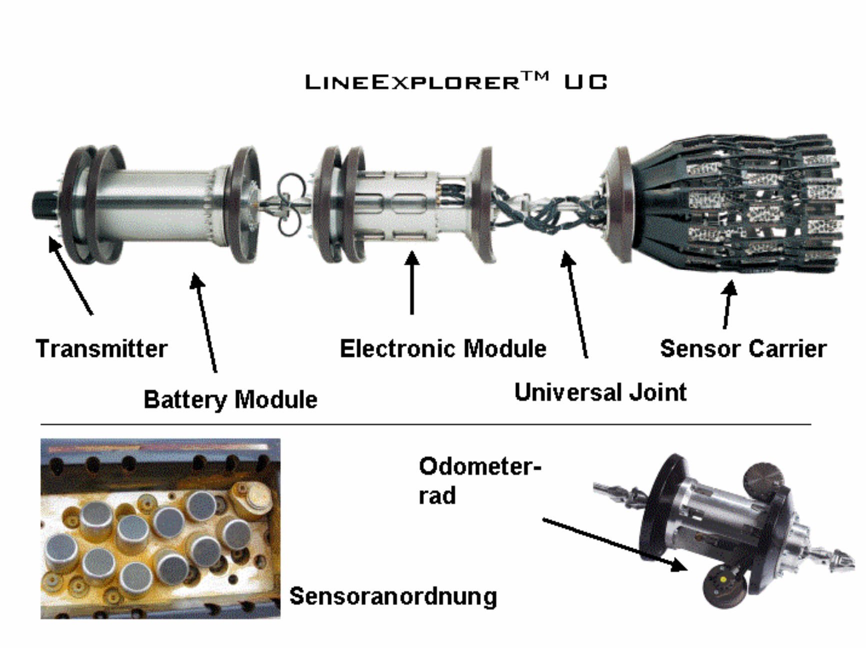

Figure 2: Ultrasonic crack detection tool

Figure 3 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.

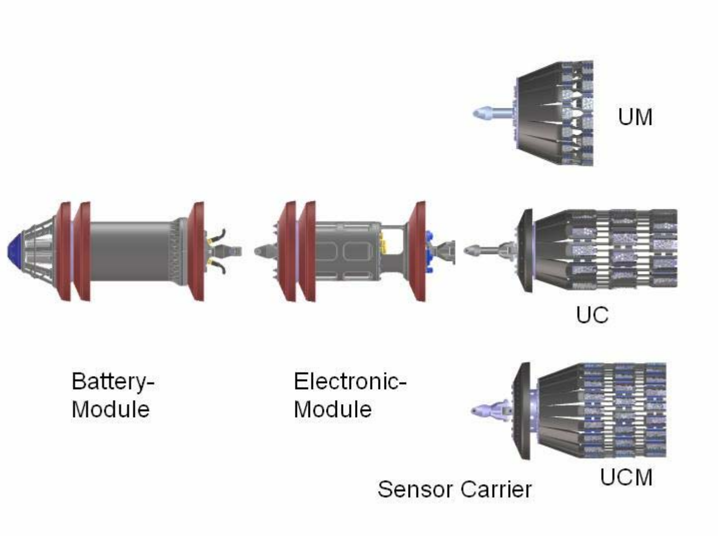

Figure 3: Modular Tool Design*

**the sensor carriers shown here are not to scale and only used to schematically show the modular design.*

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 4a shows the assembly of wall thickness sensors and figure 4b 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.

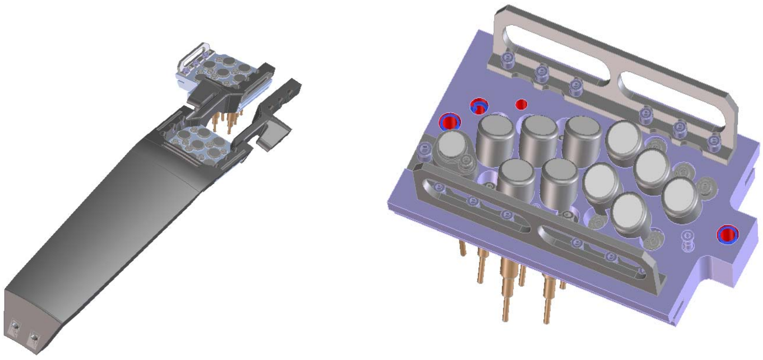

Figure 4: (a)The Assembly of the sensors for wall thickness measurement, (b) assembly for crack detection.

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. The maximum speed is constrained by the requirement to sample at least every 3 mm.

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 [10]. 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.

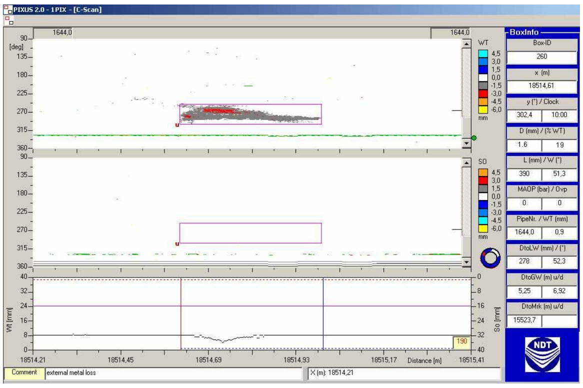

Figure 5: Screenshot of a typical external metal loss

The screenshots shown in figure 5 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.

In a further step the information provided by the in-line inspection tool can be used for a fitness-for-purpose analysis. Defect assessment aims to describe the severity that a certain flaw represents for the safe operation of the pipeline. Generally speaking, a pressure is calculated that would still allow a safe operation of the line taking into account the reduced strength of the flawed material. The assessment of corrosion-like defects detected by wall thickness tools is rather straight forward. Pipeline specific methods have been employed for several years now [11,12]. Procedures for the assessment of cracks found in a pipeline are also becoming available [13,14].

Combined Inspection

In recent years pipeline operators have increasingly requested combined inspection technologies. A typical example would be the combination of a caliper inspection with a mapping survey or a metal loss inspection with an added mapping capability. The two major advantages are related to operational issues and also data assessment and correlation. In the case study reported here the requirement was to combine a metal loss inspection with a crack detection. The pipeline operator had already previously used ultrasonic in-line inspection in his network. Wall thickness measurement and crack inspection tools were run separately in the past.

The requirement regarding a tool combining both inspection tasks was that it must provide the same quality of data and achieve the same defect specifications, based on its higher resolution as the single tools [15]. The tool used for this project was a special configuration of the ultrasonic tool provided by the inspection company. Based on the modular concept of the tool a 40"

Tool Size / Configuration	40" / UCM
Velocity range	0 - 1.4 m/s
Temperature range	-10 to +50ºC
Maximum pressure	120 bar
Tool length	approx. 7950 mm
Tool weight	approx. 3150 kg
Number of bodies incl. sensor carrier	4
Distance range	approx. 230 km
No. of crack detection sensors	600
No. of wall thickness sensors	420
Axial sampling distance	approx. 3 mm for crack detection, 1,5 mm for wall thickness measurement
Circumferential sensor spacing	approx. 8 mm (wall thickness) approx. 10 mm (crack detection)

Table 2: Key technical specifications for the configuration of the in-line inspection tool used.

configuration was used. The electronic unit used carried a sufficient number of channels to cater for all the wall thickness sensors and crack detection sensors needed to ensure full coverage of the pipe circumference. Table 2 provides an overview of the key technical specifications of this configuration used during the survey.

Case Study: Inspection of the 465 km x 40" TAL pipeline from Italy to Germany

The pipeline inspected is used for the transportation of crude oil from the port of Triest in Italy via the Alps, through Austria, to a refinery near Ingolstadt in Germany. Key specifications of the line are shown in table 3.

Length	465 km
Diameter	40"
Material	X 52
Wall thickness range	8.74 - 14.27 mm
Operating temperature range	+ 8º to appr. 20º C
Maximum experienced pressure	49 bar
Profile	line runs through alpine region including slack line sections
No. of pump stations	7
Max. (authorized) transportation rate	6400 m^3/h
Capacity	42 Mt/a

Table 3: Key specifications of pipeline inspected.

Figure 6 shows a schematic of the pipeline´s elevation profile.

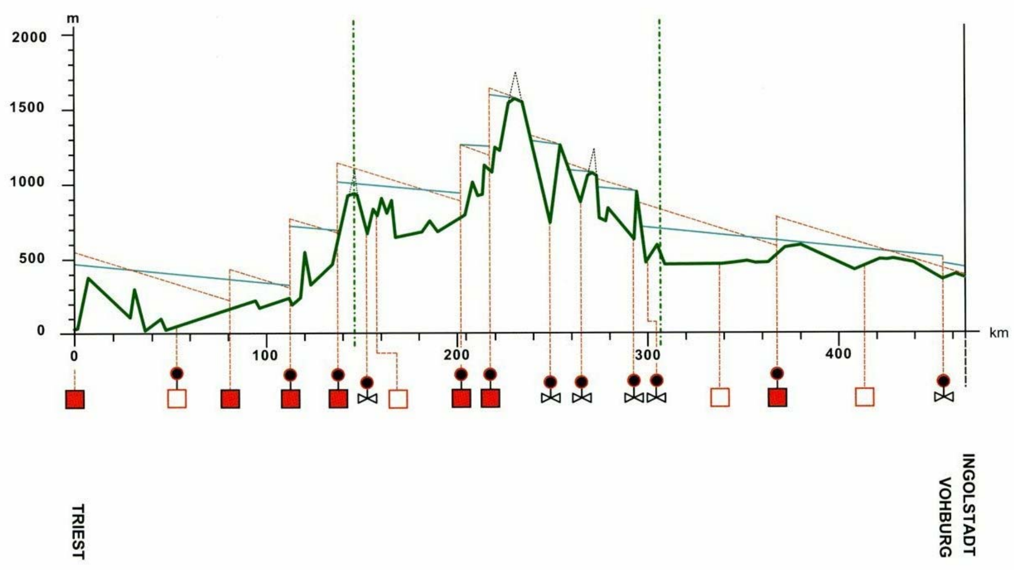

Figure 6: Elevation profile of the 40" pipeline.

Inspection Goals and Integrity Philosophy

The operator of the pipeline follows a philosophy of high quality inspections. It is the aim to have a highly accurate picture of the pipeline status regarding its integrity and fitness-for-purpose at any given time. This philosophy forms part of the strategic approach of the company towards quality and safety. Ensuring safety, environmental protection, effective and efficient operations whilst technically exceeding regulatory requirements are key elements of the approach used by the operating company.

Different approaches regarding integrity and inspection can be followed. One option is to inspect a pipeline for the purpose of detecting flaws and anomalies before they can reach a certain critical size. In a simplified view this can be seen as a screening exercise, obtaining a "picture" or "screenshot" of the pipeline condition for a specific moment in time and then agreeing on any action regarding possible maintenance or repair. Another approach would be a constant monitoring strategy including repeated inspections, including internal and external techniques, and using this information to build up a complete picture of the integrity of a line. In-line inspection needs to be seen as an integral part of such an approach. The requirements placed upon any technology used would include high levels of accuracy and resolution in order to detect and size also small changes in wall thickness or growth of any anomalies present. Major goals of such an inspection strategy are to monitor the effectiveness of integrity measures, e.g. cathodic protection or inhibition programs, optimize maintenance procedures and define suitable inspection intervals. Suitable in this context implies increasing the time between inspections whilst minimizing any risk. Optimizing inspection procedures also implies following a risk based approach and focusing attention, and therefore expenditure, on sections of higher risk.

The inspection philosophy of the operator incorporates the use of high resolution in-line inspection tools for metal loss and crack detection, geometry inspections utilizing caliper tools as well as regular leak inspections utilizing specialized acoustic leak detection tools.

Special requirements regarding the inspection goals for this particular survey were to compare the results with measurements taken during a cathodic protection survey and to compare results with measurements taken during earlier in-line inspections. A particular area of interest were the girth weld zones in the sloping sections of the pipe, in order to either find or rule out any metal loss.

Operational Considerations

The inspection of a pipeline, especially an internal inspection, always constitutes a non-regular operation. Although modern in-line inspection tools can mostly be used on-line, i.e. the pipeline does not need to be taken out of operation, their application can hardly be seen as a routine application. The processes regarding an inspection need to be planned with greatest care, especially concerning the logistics involved and provisions for possible contingencies. The following paragraph will address some of the major issues involved.

Pumping stations:

Preparation of the inspection must include procedures regarding the pumping operation for the in-line inspection tool and incorporating the by-pass of the tool around the pumping stations.

Dispatching:

A suitable amount of oil of a given quality must be available for the period of the inspection. Requirements are that the tool can travel within its operational capabilities and achieve full defect specifications. The quality of the oil, i.e. liquid medium, during and prior to inspection must be suitable regarding the cleaning operation of the internal surface of the pipe and its acoustic characteristics, which influence the performance of the tool. At the same time it must be ensured that the operator can fulfill all delivery commitments to its clients, irrespective of the inspection or possible contingencies that might occur.

Valve Operations

This issue relates to the operation of the pipeline during the inspection. The flow within the line must be regulated in such a manner that the tool travels within its optimum operational parameters with regard to defect specifications. This includes all aspects of pressure, differential pressure and back pressure requirements. The pipeline inspected crosses the alps, including differences in elevation of approximately 1680 meters. Due to this elevation profile the pipeline includes slack line sections, where special procedures must be in place in order to avoid that the tool is subject to critical accelerations or shock loading.

The procedures regarding valve operations must also include knowledge of the tools position at any time in order to avoid mechanically damaging the tool, due to valve contact. The valve and general operations of the pipeline during a survey are highly complex, especially considering the fact, that more than one device can be in the line at any given time.

Tool location

The pipeline operator always performs a tool tracking operation, not only as part of the markering operation usually undertaken regarding the location accuracy of features, but also as a tool locating exercise during the survey. The information obtained during tool tracking, i.e. confirmed tool detection at pre-defined locations, together with the information provided by the SCADA system is used to calculate the tool position at any time during the inspection run.

Tool Selection

As stated, the inspection philosophy followed by the operating company requires use of in-line inspection tools which offer a high sensitivity, i.e. low threshold, high resolution, high confidence levels regarding detection and sizing as well as high levels of accuracy regarding the sizing and locating of flaws. The information obtained through in-line inspection is used for integrity assessment, growth assessment of flaws as well as the definition of inspection intervals and optimization of maintenance strategies. These requirements are, in our opinion best met by using in-line inspection tools based on ultrasound technology, a technology which offers quantitative measurement capabilities and is also suitable for metal loss as well as crack inspection. The selection of the specific tool used during the inspection reported here was based on its capability to combine metal loss and crack inspection in a single run. This not only limited the actual inspection runs needed, but also dramatically reduced the total number of cleaning runs as well as simplifying operational procedures.

The tool chosen offers two major advantages compared to other equipment available on the market.

Higher inspection speed: The normal pump rate of the pipeline inspected is in the order of 2 m/s. The tool chosen can easily handle this speed in its wall thickness configuration and can also inspect for cracks at an inspection speed some 50% higher than competing tools. This limits production loss due to throttling the flow during inspection.

Higher resolution: The tool used offers an axial sampling rate of one measurement every 1.5 mm (wall thickness mode) and an improved maximum possible depth resolution of 0.06 mm. The practical results regarding integrity assessment are an exact measurement of the depth contour of any anomalies which can be used in advanced MAOP algorithms and a more precise length measurement of any flaw. As length is one critical parameter in maximum allowable pressure calculations any improvement in its sizing will lead to a less conservative determination regarding remaining strength.

Procedures

Normal procedures associated with an in-line inspection can be summarized as stated in table 4.

Step	Operational Procedures: In-Line inspection
1	Is pipeline suitable for in-line inspection: e.g. checking trap dimensions, free passage, pressures, differential pressures, temperatures, pump rate, bend geometries, installations etc.
2	Geometry inspection: determining free available cross section of the line. Usually inspected for by applying a caliper tool or a suitable gauging pig.
3	The operator performs regular cleaning operations as part of the overall maintenance of the line. The cleaning referred to here, addresses a specialized cleaning operation as preparation for the in-line inspection. Good cleaning is an essential part of the process of obtaining good quality data and a suitable cleaning procedure is highly recommended. Exact cleaning procedure depends on the line being cleaned. In this case a total of six bi-directional metal body cleaning scrapers with polyurethane disks were used, including final runs with metal brushes.
4	Application of the in-line inspection tool. Launching. Dispatching of the tool must include provision of a suitable oil batch in which the tool can travel, must take into consideration delivery commitments to clients (e.g. refineries etc.). 24 hour tool tracking operation using 2 men crews. Exact position of tool must always be known. Receiving the tool. Precautions during launching and receiving in order to avoid any risk during opening of traps (tool intrinsically safe, liquid nitrogen).
5	Download of data. Data check to see if run was successful and entire line has been inspected. If needed, data for specific section of the line can be viewed straight after the inspection run.
6	Preliminary reporting by inspection company, i.e. receiving information for sections/areas of high interest in the pipeline.
7	Receipt of Final Report from inspection company. Verification.

Table 4: General procedures for the in-line inspection project

Results

The operator has a policy of regularly inspecting his pipeline system. Inspection data from internal and external inspections, data regarding pipeline operations and material is correlated and used to assess the status and integrity of the line at any given time. This particular survey was performed with the intention to compare the data obtained with earlier in-line inspections and information obtained through the cathodic protection system. The high data quality and resolution of the tool, in this case especially the axial resolution, was very helpful in assessing the features found in previous inspections of the line. An improved resolution has an immediate effect regarding the integrity assessment, by enabling a less conservative approach, i.e. margin of safety, to be used. In general it can be stated that the data provided by the tool was of a very high quality, especially with regard to enhanced resolution and accuracy. The capability of the tool to combine metal loss and crack inspection proved to be a major advantage regarding the preparatory and operational procedures prior to and during the inspection run. It must also be seen as an advantage to correlate the data obtained through the wall thickness and the crack sensors. Figure 7 shows an example displaying the data recorded in the vicinity of an offtake. Fig.7a shows the data from the wall thickness sensors and Fig.7b from the crack detection sensors. The horizontal line shows the typical display of a sound longitudinal weld.

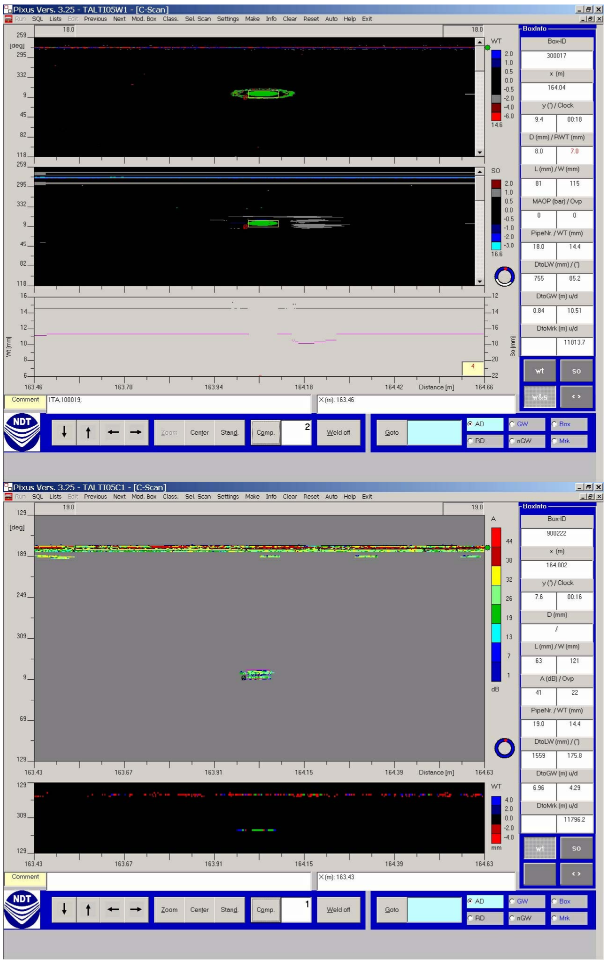

Figure 7: (a) Display of data regarding an offtake recorded by the wall thickness sensors, (b) same offtake as seen by the crack detection sensor (horizontal line shows typical display of a longitudinal weld)

Conclusions and Outlook

Higher inspection speeds, enhanced resolutions and accuracies are major improvements regarding the use of in-line inspection data for advanced integrity assessment and fitness-for-purpose studies. The combination of inspection tasks, such as metal loss and crack detection proves a major advantage from an operational perspective. From an operators point of view it would be beneficial if further combination were achievable, for instance combining metal loss and crack inspection capabilities with mapping or combining crack inspection capabilities for axial as well as circumferential features.

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