

## Integrity Management & Inline Inspection

Advances in In-Field ILI Indication and Material Verification

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Long Distance Inline Inspection of an Unpiggable Natural Gas Pipeline with Robotic Technology

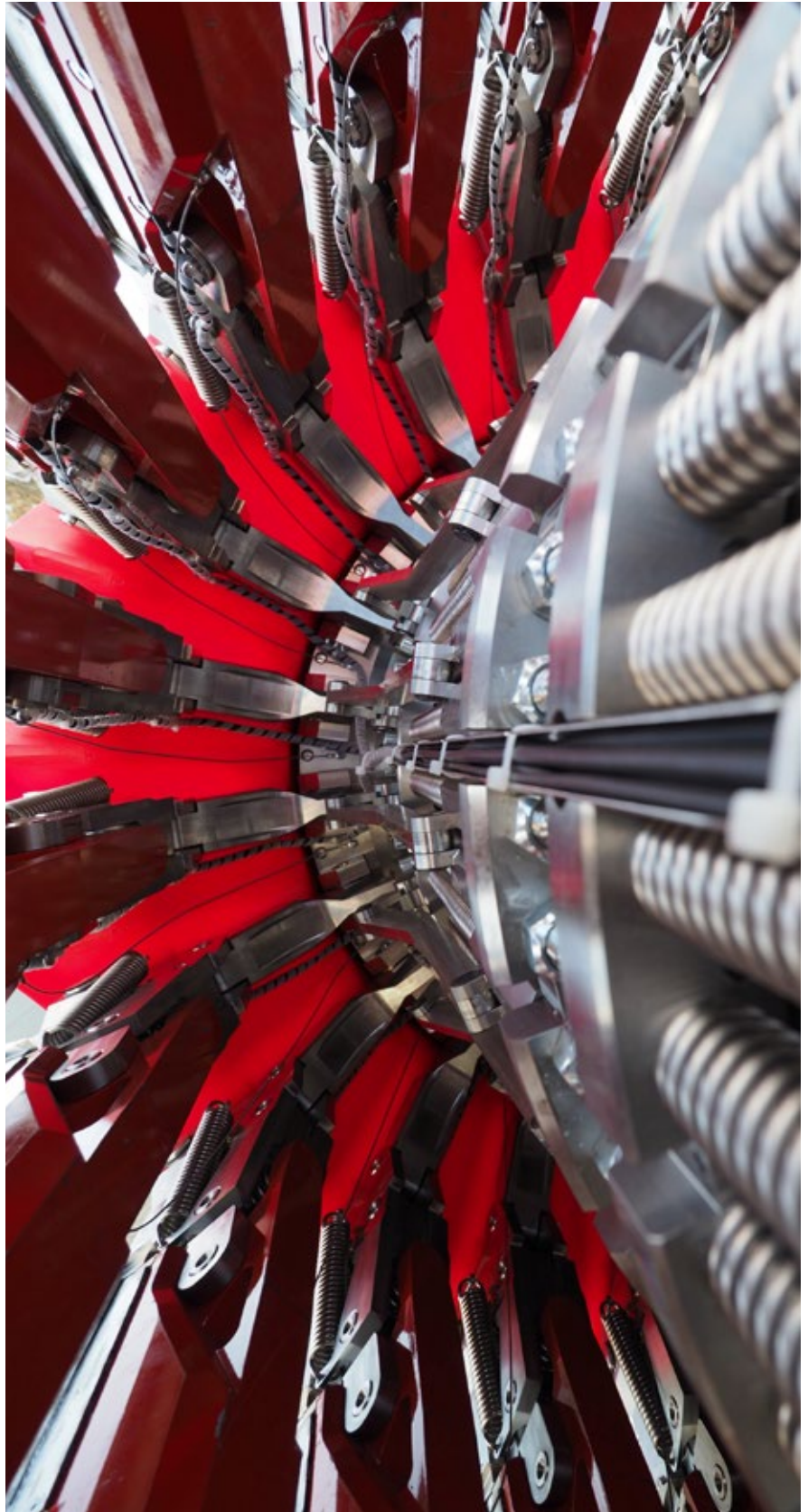
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A New Phased Array Sensor for Pipeline Inspection – Optimization and Quantitative Performance Evaluation

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# Dear Readers,

**W**ith this issue you are holding a redesigned Pipeline Technology Journal in your hands. We have been developing this design for some time, so that the presentation of the journal conveys its content more effectively. As in all aspects of our business, the founder of the EITEP Institute and publisher of ptj, Dr. Klaus Ritter, was involved in every step of this development.

To our regret, Dr. Klaus Ritter passed away on 19 December 2021. What you hold in your hands is part of his legacy. From the very beginning when we launched the Pipeline Technology Journal back in 2013, we decided to provide all the technical articles on an open access basis. Today, the journal with its ptj newsletter reach more than 20,000 pipeline professionals worldwide.

As a former association leader, it was always important to Dr. Klaus Ritter to create a community. The ptj and the ptj News, launched in 2015, have always been an important channel for this group, which meets annually at #ptcBerlin - you might just be reading it there: the 17th Pipeline Technology Conference will take place from 7 - 10 March 2022.

The handover of the management to us was planned for the turn of the year 2021/2022 and it is a great honor for us that Dr. Ritter has entrusted us with the management of his EITEP Institute as one of his last acts. We will do our best to continue his mission together with the team.

We are looking forward to the exchange with you in Berlin.

Best regards,  
Dennis Fandrich & Marian Ritter



Dennis Fandrich  
Managing Director  
EITEP Institute



Marian Ritter  
Managing Director  
EITEP Institute

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[www.pipeline-journal.net](http://www.pipeline-journal.net)  
[ptj@eitep.de](mailto:ptj@eitep.de)

### PUBLISHER

Euro Institute for Information  
and Technology Transfer GmbH  
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Dennis Fandrich & Marian Ritter

Register Court: Amtsgericht Hannover  
Company Registration Number: HRB 56648  
Value Added Tax Identification Number  
DE 182833034

### EDITOR IN CHIEF

Dennis Fandrich  
E-Mail: [d.fandrich@eitep.de](mailto:d.fandrich@eitep.de)  
Tel: +49 511 90992-22

### EDITORIAL BOARD

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### EDITORIAL MANAGEMENT

Marian Ritter  
E-Mail: [m.ritter@eitep.de](mailto:m.ritter@eitep.de)  
Tel: +49 511 90992-15  
Constantin Schreiber  
E-Mail: [c.schreiber@eitep.de](mailto:c.schreiber@eitep.de)  
Tel: +49 511 90992-20

### ADVERTISING

Rana Alnasir-Boulos  
E-Mail: [r.alnasir-boulos@eitep.de](mailto:r.alnasir-boulos@eitep.de)  
Tel: +49 511 90992-19

### EDITORIAL STAFF

Mark Iden: [m.iden@eitep.de](mailto:m.iden@eitep.de)  
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**PERFORATOR GmbH**  
Bei dem Gerichte  
37445 Walkenried, Germany  
Tel.: +49 5525 201-0  
[info@perforator.de](mailto:info@perforator.de)



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# European Hydrogen Backbone Initiative Adds 6 Pipeline Operators As Members

On Tuesday, January 18 2022, European Hydrogen Backbone initiative announced receiving six new members expanding its membership base to 29 operators from 27 European countries. The new members include Bulgartransgaz (Bulgaria), Amber Grid (Lithuania), Conexus Baltic Grid (Latvia), Plinacro (Croatia), Gassco (Norway), and REN (Portugal).

All members of the initiative are united in working towards a shared goal of making Europe climate-neutral by investing in the low carbon and renewable hydrogen market. Since its creation in 2020, the EHB has significantly contributed to the European hydrogen market development through its highly publicized flagship EHB maps, promoting a vision of creating a pan-European hydrogen transport network.

Both the network's studies and corresponding maps demonstrate how the vision is economically viable and technically feasible. With the EHB's initiatives widely accepted by key players in the Hydrogen market and policymakers, the initiative's technical inputs got referenced multiple times in the European Commission's hydrogen and decarbonized gas package published in December 2021.

In 2022, the initiative will focus on techno-economic assessment efforts of hydrogen supply corridors. The initiative will also focus on regional cooperation by the infrastructure operators in meeting the goals. At the same time, the group will be engaged in updates, expansion, and digitization of the published maps while revamping the initiative's website to provide effortless access to critical insights.

The European Hydrogen Backbone initiative aims to speed up Europe's decarbonization journey by defining the vital role of hydrogen infrastructure based on new and existing pipelines to enable a liquid and competitive pan-European low carbon and renewable hydrogen market. Moreover, the initiative promotes market competition, demand and supply security, and more cross-border collaborations within and outside the European Union.



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## Advances in In-Field ILI Indication and Material Verification

P. ROBSON, D. BAGLIN, T. OLDFIELD AND N. GALLON > ROSEN

### Abstract

Post in-line inspection (ILI) digs are essential tools in the integrity arsenal to validate and verify ILI tool performance and provide data for use in post-ILI integrity assessments. In addition, dig verification can be utilized to validate material properties, increase confidence in feature characterization or even replace previously lost records vital for assessing the integrity of features identified by ILI.

Historically, to fully characterize ILI features and/or verify line pipe material properties, the only viable option was to remove sections for destructive testing/examination. This has obvious disadvantages, but as technology has developed, more advanced non-destructive methods have become available; these can provide accurate data without the need for removal.

A number of new technologies have become available for non-destructive testing (NDT), sizing, and characterization of features and unknown line pipe material properties. An unfortunate consequence of this proliferation of new technologies is that they often require the expertise of numerous third parties, which can lead to organizational challenges and even multiple dig campaigns.

This paper reviews a number of established, new and emerging technologies for in-field, non-destructive characterization. In addition, it looks at current ROSEN in-field processes, which allow for full ILI indication verification and material property verification to be performed at the same time, by the same team of technicians.

## 1. Introduction

The European pipeline infrastructure is aging, with transmission pipelines still in operation today that often were constructed more than 50 years ago and have operated well beyond their original design life. Time has taken its toll, and managing the various integrity threats is becoming ever more challenging in the pipeline industry.

There are various tools and assessment methods available to assist in ensuring continued safe operation. Of particular note are the various fitness-for-purpose assessment methods available (e.g. BS 7910 [1] and API 579 [2]). While these methods may differ in application, they all have one thing in common: Every assessment method is completely reliant on accurate input data. For all the assessment codes, this data includes details of the threat assessed (e.g. dimensions of a crack-like feature) and the material properties (strength and toughness, principally) of the associated section.

Advancements in ILI are providing operators with ever more accurate inspection data, with technologies such as ROSEN's EMAT for crack detection or the RoMat suite for the identification of materials properties, offering unprecedented accuracy and information relating to the asset in question. Inspection conditions in pipeline can vary significantly, which can lead to uncertainty in some measurements. With this in mind, the emphasis on data obtained from in-field campaigns becomes even more important. Therefore, only by engaging with competent engineers and inspection technologies and techniques can we gain additional confidence regarding safe operation. A benchmark can also be established against which future ILI data can be assessed. The philosophy of the paramount importance of accurate in-field data can also be adopted when undertaking a direct assessment approach for un-piggable pipelines. Therefore, whatever the motivation behind in-field work, the requirement for accurate data is absolute.

Historically, to obtain accurate data (either sizing of potential defects or material properties), pipeline sections would have to be removed and subjected to destructive testing methods. This is intrusive and has obvious disadvantages (e.g. downtime, cost, safety,

etc.). However, recent advancements in technology have made it possible for the majority of the required data to be obtained in-field, non-destructively. This makes in-field verification an attractive proposition; however, an unintended consequence of the proliferation of new in-field technologies can be the requirement for multiple independent technicians or third parties to apply all the different techniques. At best, this can lead to severe logistical challenges. At worst, it can result in either multiple digs at the same location being required, or the correct data not being collected due to availability issues. Therefore, a comprehensive approach to each scenario is needed – ahead of mobilization.

While NDT and material property acquisition technologies have improved, and there are increased technology options, it is very easy to forget the overriding factor of WHY. Before considering mobilization, a comprehensive understanding of the target must be gained to ensure the best-possible preparations are in place. If mistakes happen at this stage, the consequences could ultimately include inferior data, which could result in failure.

## 2. ILI Indication and In-Field Feature Verification

Advances in technologies assist technicians with sizing and the characterization of certain feature types, but these technologies have not eliminated the need for highly skilled technicians to follow comprehensive procedures. Among other things, there is still a need for reference blocks, an understanding of pipeline networks and an appreciation of defect assessments in order to collect the most relevant information in the field. The increasing complexities of the available technologies have made trained, skilled and competent technicians even more critical. Only with a complete service package can the data assist engineers in making informed decisions about maintaining throughput of product while operating safely.

### 2.1 Metal Loss and Geometric Features

Metal loss and geometric features have traditionally been measured with the likes of micrometers, pit gauges, brass rubbings, bridging bars, etc. These still prove to be a valuable part of in-field validation, but their use can be time-consuming on large and/or



complex features and rely heavily on inspector competence and an understanding of what data is required.

The past decade has seen the widespread use of laser-scan data for sizing of metal loss and geometric features in pipelines (see Figure 1). The detailed data can be interrogated to create finite-element (FE) models. Indeed, some more-modern equipment offers the capability to perform these metal loss assessments in-ditch to the more complex ASME B31G [3] Level 2 metal loss assessments. The data can also be used to remove unnecessary conservatism from empirical models, and in some cases, it can help to explain why certain features have formed where typically we would not expect to see them.



Figure 1: In-field laser scan

## 2.2 Crack-Like Defects

Sizing of cracks in-field is not a one-solution-fits-all operation: there are various types of cracking morphologies that may cause challenges to size for certain types of technologies or that may have limitations that need to be understood before the inspection. A thorough understanding of the different expected crack morphologies and types is necessary in order to identify the best technology/technique and develop procedures that can guarantee a certain level of sizing accuracy.

### 2.2.1 Ultrasonics

Ultrasonic testing (UT) and phased-array ultrasonic testing (PAUT) are generally accepted in the industry as the “go-to” techniques for sizing crack-like indications. Identifying and sizing cracks as part of a colony with UT can be complex and challenging (see Figure 2). Even with the latest technologies, these techniques

require a high level of skill and experience to operate with high accuracy, particularly on thin-wall pipes.



Figure 2: In-field PAUT inspection of a girth weld

Interpretation of PAUT data is generally considered to produce higher-accuracy results than UT due to a wider fixed field of view of a feature with the PAUT probe than can be achieved with manual manipulation of a UT probe. However, it is still possible for an experienced UT technician using conventional probes to effect better quality results than a less-skilled operator with PAUT.

Another UT technique, time-of-flight diffraction (TOFD), is also often used to improve feature sizing of crack-like indications. Instead of measuring the reflected UT signal from a probe, TOFD uses a pitch-and-catch technique and identifies the diffracted signals from the crack tips, which can be interpreted to size the features. This is generally a higher-accuracy technique at certain through-wall positions; however, limitations of the technology must be understood by the operator, including detection of small flaws in the dead-zone areas of the near-surface and back-wall signals.

### 2.2.2 EC

The eddy current (EC) inspection technique uses alternating magnetic fields to generate eddy currents in a material to identify features through changes in the material impedance. Features can be sized against known reference defects for specific materials and a known impedance response. The use of magnetism as an inspection technique means that there is no need for direct contact with the test piece, and EC can operate through coatings, if necessary.

EC can be an improvement over UT for surface-breaking features where potential cracking is associated with surface corrosion because lift-off compensation can be applied to the measurements to compensate for corrosion or coating. A range of depth measurements can be taken depending on the probe properties and setup. Crack sizing near welds or areas where material properties are non-homogenous can cause challenges with sizing because the datum for impedance measurements can change.

### 2.2.3 ACPD

Alternating current potential drop (ACPD) is one of the few techniques to be named by [4] as suitable for sizing cracks. ACPD measures the change in electrical potential as an AC current pass around a crack tip using the skin effect; this change in potential can be calibrated to material curves, and a prediction of depth can be given.

### 2.3 Emerging and Future Technologies

In-field X-ray computed tomography (XCT) is a three-dimensional X-ray technology currently used mostly in laboratory conditions as a high-accuracy technique for feature validation. That said, a few contractors offer XCT as a “mobile” service. It has been reported that the accuracy that can be achieved by XCT can be comparable to destructive testing [5].

The total focus method (TFM) and full matrix capture (FMC) are competing advancements in PAUT methods that can offer sizing and characterization improvements over PAUT by collecting higher quantities of data from a bigger send-receive location, allowing the UT beam to focus at all depths.

## 3. In-Field Material Verification

In general, the main datasets required from material verification are related to strength (yield stress [YS], ultimate tensile stress [UTS] and fracture toughness). Obtaining other material properties (hardness, chemical composition and metallography) also gives valuable insights into the material and helps supplement the main datasets to provide a complete understanding of the material properties.

Historically, to obtain material property data, cut-outs were required. From an in-field point of view, a number of established “non-destructive” tests were (and

still are) available (chemistry, metallography and hardness) that yield qualitative material data. This data can be used to estimate material properties, but it provides nothing quantitative in terms of strength and toughness. These traditional activities are cheaper and less intrusive options than cut-outs, even though some form of surface preparation is required, the quality of which is key for competent data collection.

In recent years, ILI (ROSEN’s RoMat pipe-grade sensor [PGS]) and portable site technologies have emerged that report YS and UTS values non-destructively. In addition, there is technology currently in validation trials looking into the non-destructive measurement of toughness.

### 3.1 Hardness

Hand-held technologies are available that can be used on a prepared pipe surface to provide hardness results. These technologies can provide outputs in a number of hardness scales (HRB, HV, HBW; etc.), but it is important to differentiate the testing standard from the reported value. The two main technologies currently in use are based on ultrasonic compact impedance (UCI) and portable Rockwell hardness testing. Both leave small indents on the pipe surface. In general terms, UCI is easier to use in cases of restricted access or where exact indent positioning is required; portable Rockwell testers are more robust.

### 3.2 Chemical Composition

Chemical composition can be measured either by means of scraping analysis (where scrapings are removed from the pipe surface and sent to a laboratory for analysis [see Figure 3]) or portable OES.



Figure 3: Collection of scraping samples

Accuracy and repeatability of scraping analysis results are very high, it can be used in limited-access areas, and equipment cost and complexity of use are considered low compared to other techniques. However, results are not instantaneous and, due to safety implications, the technique can be limited to pipes above a minimum wall thickness (typically 5 mm).

Portable OES is less intrusive than scraping samples, and results are instantaneous. However, it has been observed through operational experience that the equipment is overly sensitive to atmospheric conditions (i.e. wind and rain), which affects the argon shield and thus accuracy and repeatability. The equipment is the most complex and expensive of the types reviewed and relatively large, making it unsuitable for some field applications.

### 3.3 Microstructure

Microstructure can be assessed either using surface replicas (where the microstructure is recorded on an acetate strip and assessed later in a laboratory) or directly using a portable microscope. For both of these techniques, there are COSHH implications in transporting the required acids/etchants to the site.

Surface replication is relatively low cost and can provide adequate images to fully characterize microstructure. However, results are not instantaneous, and there is no way of knowing whether the level of etch (and therefore the image quality) is of sufficient quality until the replication is observed in the lab.

Portable microscopy is instantaneous, and there is an ability to periodically check the level of etch, thus obtaining the optimum image quality (example given in Figure 4). However, the equipment cost and complexity is higher than replication, and additional training is required for use and interpretation.

### 3.4 Strength

The non-destructive measurement of strength (both YS and UTS) is a hot topic in the industry at the moment. Various technologies are available, most of which were summarized in a recent PRCI report [6]. The details vary, but all technologies rely on access to the exposed outside surface of the pipe. This surface is then prepared to a suitable finish, and small areas are plastically deformed (either through indentation or by

means of scratching a stylus across the surface). The response of the indenter or stylus and the shape of the resultant deformation are analyzed, and the estimated yield and tensile strengths of the material are reported.

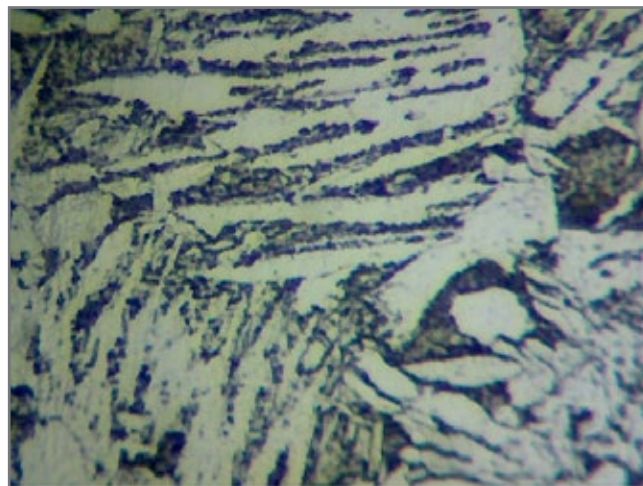


Figure 4: In-field portable microscope microphotograph of a bend neutral axis parent material (outlier found by RoMat PGS), 500x original magnification

The PRCI report shows that some of these technologies (notably based on instrumented indentation testing [IIT] or the hardness, strength, ductility [HSD] tester of MMT) yielded reasonable agreement with destructive tensile testing. This finding notwithstanding, it is important to recognize that the surface plastic deformation (whether indent or a scratch) is shallow, so any properties measured will be surface properties. Bulk properties – for example if the mid-thickness pipe wall has a different strength than the surface – are not measured. Expert knowledge is therefore advised both when collecting this data in the field and when interpreting and using the results.

### 3.5 Emerging Technologies

A number of technologies are currently in development across various stages of readiness, but none can yet be considered ready for commercial in-field use, although there are various ongoing programs looking to address this.

MMT is in the process of performing method validation trials of a non-destructive toughness tester (NDTT), which is reported to provide the Charpy upper shelf and Jc values. There is also distinct work being performed looking at various options to improve IIT. For example, Plastometrex, a company associated with Cambridge University, has developed a type of IIT known as indentation plastometry.



#### 4. The ROSEN Approach

Excavating a pipeline can be an expensive and high-risk activity, so maximizing the value of the data collected from each dig should be considered a top priority. Therefore, the preferred approach is to determine the exact data needed prior to excavation.

Once the data critical to the assessment has been determined, it is vital that the quality of the data being received is of a known high quality. This can be done by understanding the strengths and limitations of various technologies and selecting the most appropriate tools for the job. There are a large number of alternative technologies for field verifications now available, all with their own economics and characteristics.

The starting point for any in-field verification scope, therefore, is to hold a comprehensive understanding of the target location. This can be achieved by a thorough interrogation of ILI data and a review of historic construction and/or material data records.

Adopted by ROSEN, this approach takes as its starting point an understanding of why a dig is necessary. Because this cannot be achieved in isolation, ROSEN collaborates closely with clients to gain a comprehensive understanding of the situation at hand. From this, it is possible to identify any operational issues, identify gaps in current data and pinpoint the steps necessary to ensure that quality data is captured. This required data is dependent on the specific client requirements, type of assessment being performed and the ILI technology used (i.e. MFLA, EMAT, RoMat PGS/DMG). Once the desired data has been identified, arrangements can be made to ensure that it can be collected. Often-overlooked aspects in this regard are the logistics surrounding any excavation: ensuring that the appropriate areas of pipeline are safely accessible and that all necessary arrangements are in place.

A vital element of any dig campaign is procuring the right personnel and equipment. The basis any quality in-field work relies upon – and the most important aspects in any verification effort – still is made up of human factors. These factors include the robustness of procedures and an understanding of the data requirement, together with comprehensive knowledge of the equipment being used. This human influence

on inspection is a significant factor, for example with respect to sizing tolerance on defects, particularly with more complex features such as cracks. While technology is helping to improve accuracy, there still needs to be clear and robust operating procedures for technicians to follow, bolstered by investment and adequate training on real samples. It is never quite as easy as it seems; only through experience, comprehensive training, procedures and knowledge of the verification requirements in question can technicians adapt to perform in adverse conditions.

Once complete in-field reports are issued and normal operations resume, does the work stop there? Utilizing the information received in-ditch relating to the morphology of the anomalies being assessed and coupling it with a thorough understanding of the material properties, this data can feed back into the initial ILI and direct assessment process. This key forensic information can help to improve ILI technology and interpretation as well as the evaluation techniques used when assessing pipeline integrity data.

ROSEN believes that this approach is key for verification of ILI indications in pipelines and that such practices should be adopted for pipelines without ILI data. After all, having more quality data and information available allows for a more comprehensive understanding of the asset in question, which in turn assists the process of making integrity-based decisions – a key contributor to successful and safe operating practices.

#### 5. Concluding Remarks

Verification of ILI features and material properties is an essential component in the ILI validation process. Field data can be used to boost confidence in ILI data, enabling integrity engineers to make clear decisions regarding the current and future safe operation of the pipeline. The higher-quality verification data being fed back to ROSEN can also be used to refine the sizing and classification models used on ILI data, ensuring safer future operation for the pipeline industry. Future verification activities can also potentially be reduced by a higher level of confidence in the ILI data. The use of existing, new and emerging in-field non-destructive technologies by trained and competent technicians makes it possible to obtain more consistently accurate data.

ROSEN's approach of integrity-led field data collection deploying existing and proven technologies alongside highly skilled technicians ensures that the required data is collected efficiently and to a high standard. Using appropriate integrity decisions, this process

can be performed efficiently without the need for additional digs and/or multiple unnecessary contractors on-site, alleviating potential logistical challenges and cost implications while ultimately facilitating the safe operation of the pipeline.

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## AUTHORS



**Phill Robson**  
ROSEN

Work Group Lead - Materials and Corrosion  
[probson@rosen-group.com](mailto:probson@rosen-group.com)



**Neil Gallon**  
ROSEN

Principal Materials and Welding Engineer  
[ngallon@rosen-group.com](mailto:ngallon@rosen-group.com)



**Tom Oldfield**  
ROSEN

Senior Field Verification Services Engineer  
[toldfield@rosen-group.com](mailto:toldfield@rosen-group.com)



**Dave Baglin**  
ROSEN

Work Group Lead – Field Verification Services  
[dbaglin@rosen-group.com](mailto:dbaglin@rosen-group.com)

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## Long Distance Inline Inspection of an Unpiggable Natural Gas Pipeline with Robotic Technology

R. LEE, D. GIAN > INTERO INTEGRITY

### Abstract

In-line inspection (ILI) is a pipeline assessment method used by operators to receive a comprehensive integrity assessment of their pipeline. However, ILI may become unfeasible due to factors such as insufficient flow/pressure parameters for propulsion, pipeline features such as valves, back-to-back elbows and unbarred tees, as well as the lack of infrastructure such as launcher and receiver for tool entry and exit. These pipelines are deemed as difficult to inspect, or “unpiggable,” and are often limited to other integrity assessment methods such as Direct Assessment or hydrostatic testing.

The Pipe Explorer MFL robot fleet originally developed by Pipetel Technologies and merged in January 2021 with Intero Integrity Services, is powered by rechargeable batteries and can travel up to 750 meters under live gas conditions before returning to the size-on-size hot-tap fitting or point to point with the use of an exit hot-tap fitting. The inspection distance may also be extended by cascading in-line-charge (ILC) stations until the desired inspection length is obtained. With Intero’s in-line charge system, The Pipe Explorer is charged in-line and subsequently may continue the inspection up to another 750 meters (point-to-point) to the next ILC station or receiver hot tap fitting.

This paper reviews the process, execution, and data from the use of The Pipe Explorer MFL robot for long distance inspections that are several kilometres in length by examining a 3.5 km, two day inspection. This inspection utilized two hot tap fittings for Pipe Explorer entry and exit, as well as three charge points. The comprehensive MFL, deformation, and video data provided the operator with the integrity information required for continual undisrupted operation.

## 1. Introduction

Over the summer of 2019, a natural gas and electricity supplier in Winnipeg, Manitoba worked with Intero Integrity to plan and execute the robotic inspection of the Brandon lateral; approximately 8.3 km of 10 inch, otherwise “unpiggable” pipeline north of Brandon, Manitoba.

Across the globe, there are pipelines that prove difficult to inspect using traditional methods. Whether the infrastructure has challenging features, impassable components, or little to no flow; launching and receiving inline inspection pigs may be impractical or impossible.

Since 2011, Intero Integrity, merged in January 2021 with Intero Integrity, has been working to mitigate the challenges of traditional pigging by utilizing their fleet of tetherless robotic crawlers known as Pipe Explorer MFL robots. Ranging from 6 to 36 inch in diameter, Intero’s Pipe Explorer robots are able to perform Magnetic Flux Leakage (MFL) sensing, Laser Deformation Sensing (LDS), and video inspection on pipelines that are in or out of service. The ILC system operates as illustrated in Figure 1.

## 2. The Pipeline Inspection Challenge for A Natural Gas Operator

The Brandon lateral stretches between the city of Brandon and the hamlet of Forrest; 8.25 km of pipe that had never previously been inspected. The limits of the

segment to be inspected were defined by a plug valve and a valve station; both unsuitable for launching and receiving traditional pigging equipment. Additionally, as the pipeline had been built in the 1950s, pipeline geometry, fittings, wall thickness, and cleanliness were all unknown factors. Furthermore, there was a possibility of different pipeline diameters within the segment and a feasible location to add a permanent pig launcher was not available. These were all reasons to look for an alternative inspection method.

The inspection of the Brandon lateral posed numerous challenges for inspection such as the unknown geometry of the pipeline, the number of fittings and excavations required, the trajectory of the pipeline through farmland, as well as potential weather delays. Given the uncertainties of the pipeline composition, the decision was made to inspect the pipeline out of service

Intero’s Pipe Explorer MFL robots are tetherless and battery operated, which means they have a finite distance they are able to inspect before they must be recharged. In lieu of numerous size-on-size hot tap fittings, recharging stations were added to the pipeline thereby reducing the number of times the Pipe Explorer robot would be removed from the line. Working together, the pipeline operator and Intero determined 13 sites were required along the pipeline length. The pipeline operator worked with the land owners and their farmland to determine the optimal locations. Special consideration was given to how far equipment would need to travel over farmland, as rain and mud could make excavations inaccessible.

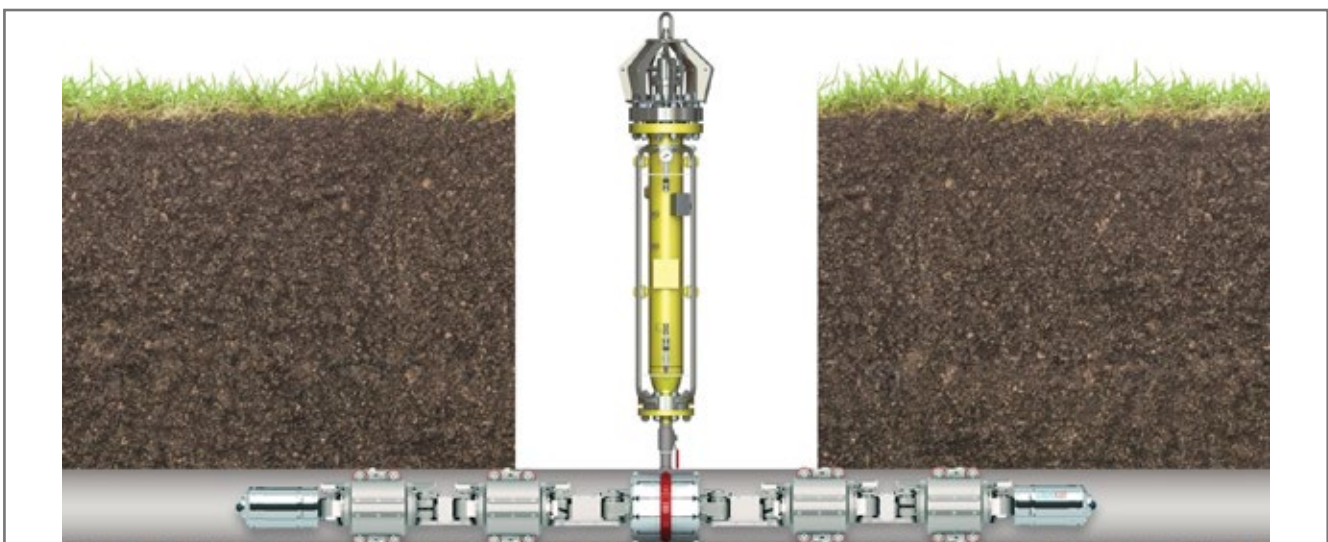


Figure 1: Pipe Explorer MFL robot with In-line Charger

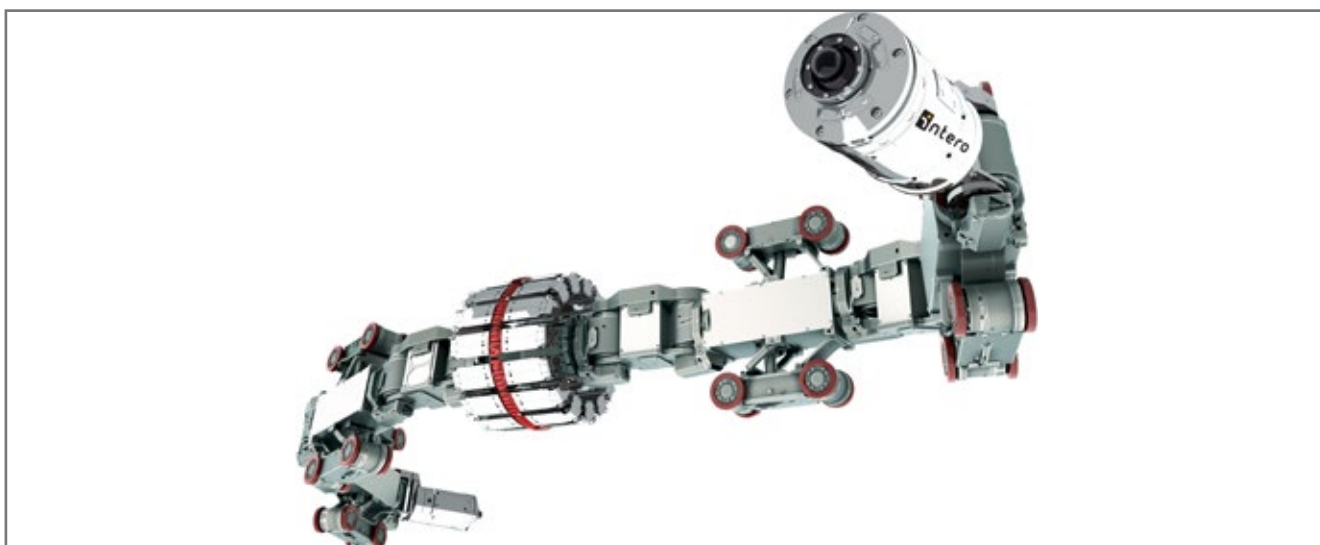


Figure 2: Explorer 10/14

### 3. Robotic Pipeline Inspection

Given the 10 inch pipe to be inspected, the Pipe Explorer 10/14 was used for the inspection of the pipeline. Pipe Explorer 10/14, shown in Figure 2, is capable of inspecting 10 to 14 inch diameter pipe both in and out of service.

Unlike a traditional pig, Pipe Explorer robots are driven remotely by an Intero operator. The operator is able to control where the robot travels and how quickly it moves. Should the operator come across any previously unknown feature, it can be documented in real time and the decision to continue or turn back can be made. A view from the inside of one of the hot tap fittings is illustrated in Figure 3.

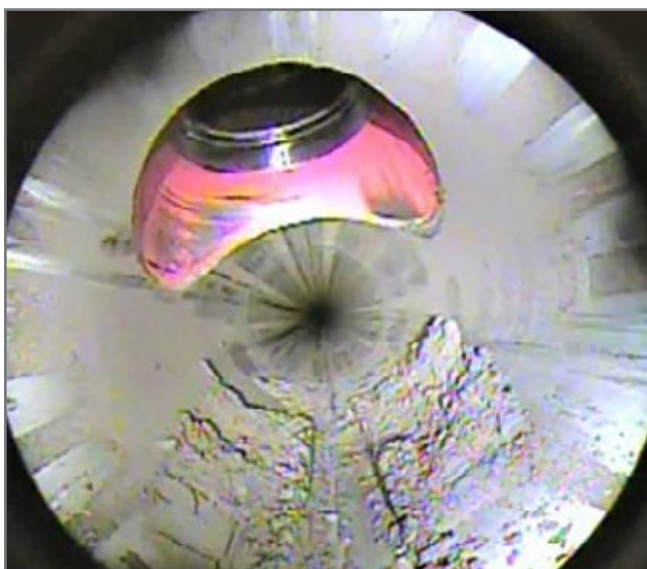


Figure 3: 254 mm (10 inch) hot tap Fitting

Pipe Explorer MFL robots does not require permanent launchers and receivers to be installed on the pipeline. Instead, the robots are able to launch through size-on-size hot tap fittings. The pipeline operator set up four of these launch and receive sites along the 8.3 km. During an Pipe Explorer MFL robotic inspection, operators have the ability to either launch and receive from a single fitting or launch at one site and receive at another. Given the fittings on the pipeline, both methods would be utilized on the project. As outlined in Figure 4, Pipe Explorer 10/14 was launched and received at the same location one time and completed the remainder of the inspection by travelling from launch site to launch site.

As Pipe Explorer MFL robots are battery powered, their inspection range is limited by battery capacity. In an effort to extend the range of the Pipe Explorer fleet, Intero implements a proprietary in-line charging (ILC) system. In effect, by adding “refueling” stations along the pipeline, the number of more costly entry and exit fittings can be reduced. Each charging location is much smaller than a launch site and proves less impactful on the pipeline surroundings. In total, nine charging sites were utilized during the inspection. An example of an In-line Charge site is shown in Figure 5.

By utilizing in-line charging technology, pipeline operators are able to execute longer robotic inspection than would otherwise be possible. The pipeline operator was able to leverage Intero’s ILC such that the launch system, outlined in Figure 6, would only be utilized four times. Reducing the quantity of launch sites





Figure 4: Schematic of Brandon Lateral



Figure 5: In-line Charge Site on 10 inch Pipeline

reduced capital expenditure and the time required for inspection. Since the Pipe Explorer robot did not need to come out of line as frequently, the inspection was completed in nine days.

#### 4. Interro's Performance and Data

Whenever launching into a pipeline that has not been inspected before, the conditions of the pipeline are unknown. Be it pipe cleanliness, geometry, or inspection equipment malfunction; collecting high quality data can be challenging in these situations. For Pipe Explorer MFL robots, many of these challenges are

mitigated by being able to control the robot in real time. While executing an inspection, real time video, MFL data, and deformation data are transmitted to the operator so that they are able to make informed decisions about tool passage and data quality.

Once the inspections began, the line was found to be quite clean, with minimal debris inhibiting Pipe Explorer's travel. Through the 8.3 km of inspection, Our Pipe Explorer MFL robot averaged over 99% for MFL and LDS data coverage respectively. Over the 8.3 km, previously unknown taps and bottom out fittings were discovered.



Figure 6: Intero's Launch System for Explorer 10/14

In order to provide added confidence to stakeholders, the pipeline operator produced a validation spool for Intero. By scanning the spool with Intero's Pipe Explorer, the pipeline operator and Intero were able to use this as a reference for interpreting the data from the full inspection. The pipeline operator sourced a 10 inch diameter pipe, added defects to their own specification, and had The Pipe Explorer detect and size what it found.

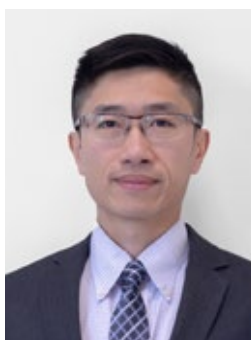
## 5. Summary

When inspecting the Brandon lateral, many of pipeline operator's challenges and costs came from adding the multiple fittings required by the Pipe Explorer MFL

robot and charging equipment. As Intero looks to the future, in order to reduce the required number of fittings on the pipeline, the range of The Pipe Explorer must be extended. Multiple initiatives are underway to both reduce the energy demands of The Pipe Explorer as well as optimize charging to prove less impactful on the inspection's surroundings.

The pipeline operator was successful in inspecting the 8.35-km Brandon lateral using Intero's Pipe Explorer MFL robot and Intero was able to collect high quality MFL, Laser Deformation, and video data with over 99% coverage. By utilizing Intero's launcher and in-line charging, the long length of unpiggable gas line was inspected in only nine days.

## AUTHORS



**Roderick Lee**  
Intero Integrity  
Global Business Development Manager MFL Robotics  
[Rod.lee@intero-integrity.com](mailto:Rod.lee@intero-integrity.com)



**David Gian**  
Intero Integrity  
Business Development Manager – Eastern Hemisphere  
[David.gian@intero-integrity.com](mailto:David.gian@intero-integrity.com)



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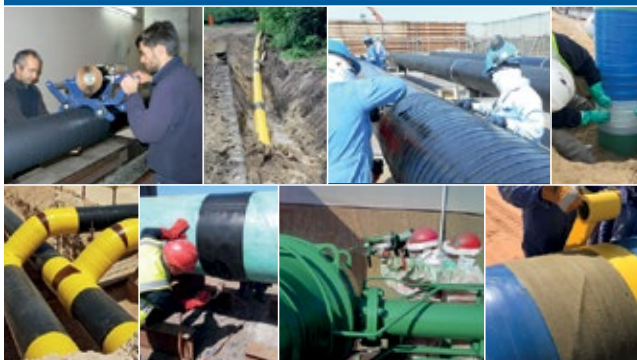
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# A New Phased Array Sensor for Pipeline Inspection – Optimization and Quantitative Performance Evaluation

M. SPIES, O. MÜLLER, I. LACHTCHOUK, M. TSCHUCH > BAKER HUGHES

## Abstract

The phased array technique allows for a flexible adaption of the ultrasonic inspection techniques for a large range of applications. By using it in the area of pipeline inspection various inspection modes can be performed simultaneously. That was the reason for Baker Hughes (previously PII Pipeline Solutions) to develop an inspection tool based on the phased array technique which is successfully operated since more than a decade. In order to make optimal use of the various testing modalities supplied by the phased array technique, especially in view of the identification of different defect morphologies, a new generation of phased array transducers has been designed in the course of simulation-based investigations.

In this contribution, we report on the different optimization objectives, which served as input for the simulations and which have been accounted for accordingly. The performed simulations aimed at the optimization of the beam fields generated by different virtual apertures. We describe the iterative procedure used for the optimization and we present selected results of the simulation calculations and of the experiments performed for validation. Special focus of the experimental investigations was on the validation of the beam field simulation results. For various operating modes (beam field steering and/or focusing) beam profiles have been recorded in water using a hydrophone and compared against the simulation results. For quantitative evaluation an acceptance criterion has been defined via a 'performance number' which has been determined for the various examined cases.

We present an overview of the various steps of this study and show representative results which prove the performance capabilities of the new phased array sensor.



## 1. Introduction

New developments in the area of ultrasonic inspection are mainly based on the phased array technology which allows to steer and focus the ultrasonic beam fields. Thus, it bears a tremendous potential for a flexible adaptation of ultrasonic inspection to a wide spectrum of applications and constitutes an efficient alternative to inspection techniques using various conventional single-element transducers. By using it in the area of pipeline inspection various inspection modes aiming at crack detection and the detection of metal loss can be performed simultaneously. In account of these advantages, Baker Hughes (formerly PII Pipeline Solutions) have developed a pipeline inspection tool based on the phased array technique. Meanwhile, the UltraScan™ DUO tool ([1], Figure 1) is successfully operated since more than a decade.

Figure 2 schematically illustrates the various inspection modes which can be executed by correspondingly applying adapted delay laws when exciting the respective active array elements. The inspection for metal loss due to corrosion is performed using longitudinal waves at perpendicular incidence, while the detection of external and internal cracks in the pipe wall is performed using transverse waves at an angle of incidence of, e.g., 45°.

Moving from this schematic to a realistic view, it gets apparent that threats to pipelines are becoming more complex and interactive. Cracks can exist in pipelines and can often remain stable until acted upon by an external force, hence the crack will grow in service. Mechanisms that stimulate crack growth are mechanical forces (e.g. fatigue, strain) or environmental effects or a combination of both (e.g. stress corrosion cracking, Figure 3). Certain cracks are difficult to detect and to distinguish

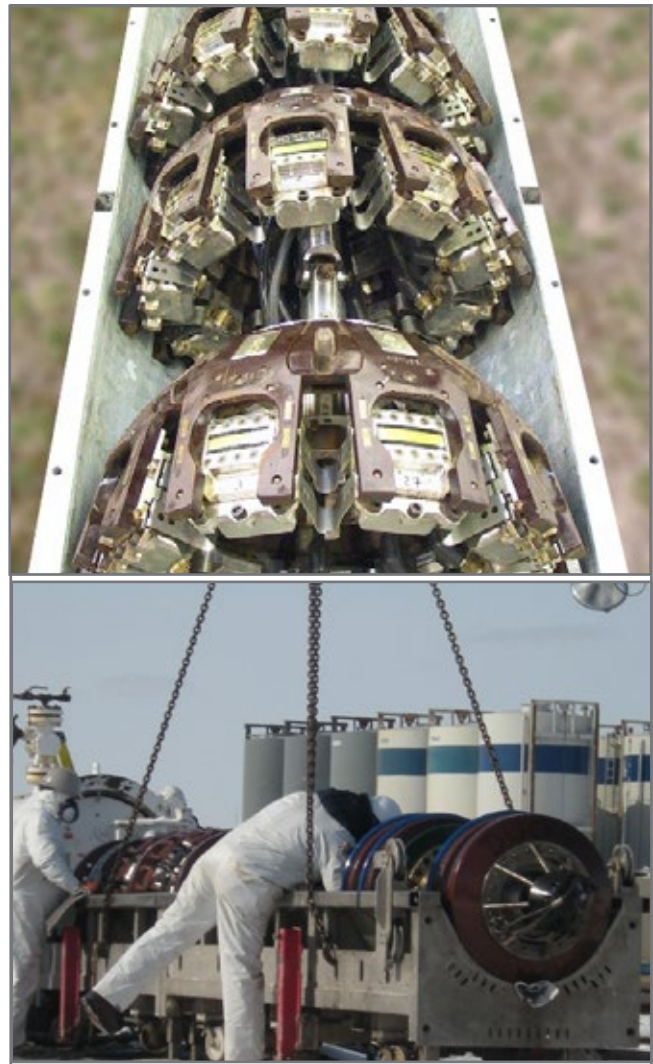


Figure 1: View of the phased array sensors and carriers of the UltraScan™ DUO (top) and tool receive after an inspection run (bottom).

from non-crack anomalies (e.g. geometric features), crack sizing being an even more difficult challenge.

It is obvious that inspection techniques utilizing one or two parameters to describe simpler features can match the Probability of Detection (POD), Identification (POI)

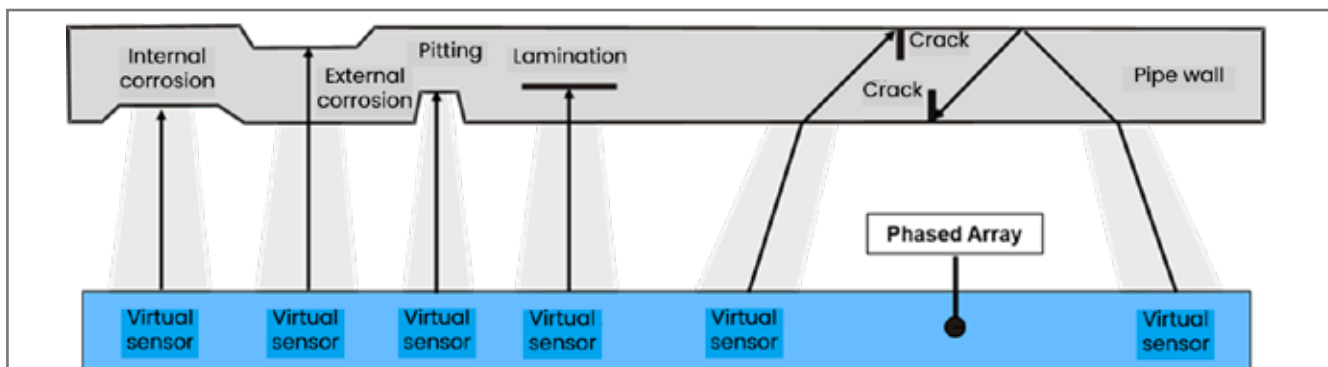


Figure 2: Schematic representation of the beam field configurations applied for the detection of the different defects. For wall thickness measurement (left), operation in focused mode can be beneficial, while for crack detection (right) the beam field can be steered to one or several angles of incidence.

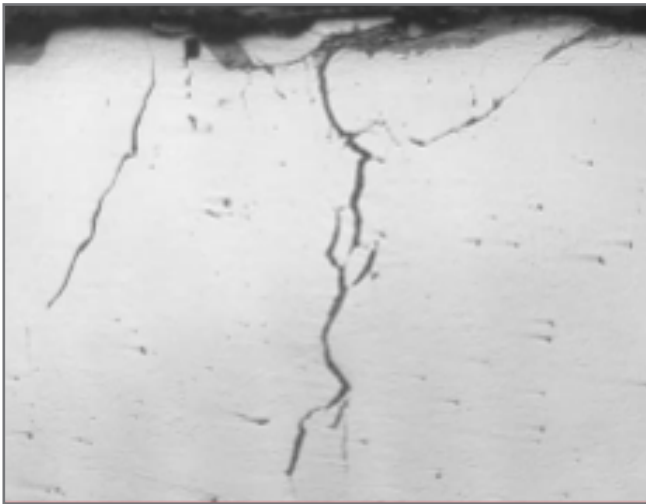


Figure 3: Micrograph of a typical stress corrosion crack [2].

and Sizing (POS) requirements. However, cracks can have significantly different morphologies, requiring much more sophisticated inspection techniques to push the boundaries to include these defect types in ILI tool performance specifications (Figure 4).

To optimally tailor such sophisticated ultrasonic inspection techniques with enhanced performance capabilities the phased array principle can be applied. Accordingly, a new generation of phased array sensors has been developed in the course of simulation-based investigations. In this contribution, we report on the optimization targets which have been considered as input for the simulations performed using the Generalized Point Source Superposition technique (GPSS [3]). We show representative results including a selection of experiments performed for validation.

## 2. Sensor Optimization – Targets and Applied Approach

The new generation of phased array sensors has been optimized for inline inspection, covering a wide range of pipe diameters and wall thicknesses. The optimization has been performed with respect to crack detection using transverse waves at various angles of incidence aiming at the further enhancement of the defect signal amplitudes. For wall thickness measurement using longitudinal waves at perpendicular incidence beam field focusing to different depths has been considered. The optimization approach has addressed different aspects which have been worked off step-wise, as briefly described in the following.

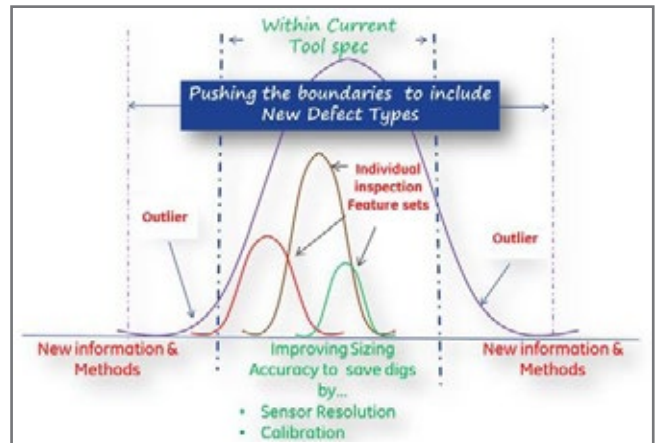


Figure 4: Schematic illustration of tool performance enhancement by extracting the maximum information from ILI data made available by single sophisticated techniques or their combination.

### 2.1 Suppression of Grating Lobes

A well-known problem in configuring phased array sensors is the generation of side lobes of higher order, the so-called grating lobes. These are due to interference effects when steering and focusing is applied by time-delayed excitation of the single array elements using the corresponding delay laws. A disadvantageous configuration can result in grating lobe formation with an amplitude which is even higher than the one of the main lobe. This can lead to misinterpretation of the inspection data.

### 2.2 Beam Field Homogenization

A second problem concerns the formation of the beam field in the component in dependence of the water path (stand-off). If the pipe surface is located, e.g., in the extreme near-field of the virtual aperture, the beam field in the steel pipe exhibits the well-known interference structure which has to be avoided for efficient detection and sizing of defects. For adaptation of the near-field length the variation of the frequency/wavelength as well as the reduction of number and length of the active elements are suited, the latter accordingly leading to a smaller effective aperture and thus to a decrease of the near-field length.

### 2.3 Beam Field Optimization Accounting for the Inspection Specification

If the first two optimization steps have been successfully performed to avoid grating lobe formation and to enhance the beam field characteristics, a further aspect has to be considered. In order to ensure optimal coverage of the inspection area, minimum requirements are specified for the width and height of the

amplitude dynamic curves for external and internal notches of different depths. Further important aspects refer to the sensitivity of the beam field to tilting, e.g. when the sensor carrier passes over excess weld metal. The optimization process is thus performed step by step, potentially requiring several iterations. Based on this approach, the new sensor has been optimized, its efficiency is illustrated in the following via representative results for the beam fields and the amplitude dynamic curves.

### 3. Beam Field Simulation and Validation

#### 3.1 Simulated and Measured Beam Fields in Water

Since simulations were the basis for the new sensor design, beam field measurements were carried out for validation. Two-dimensional scans were performed in water at various distances from the sensor. For the 2D scans a commercially available measurement system was used. It consists of a water basin, an x-y-z drive and gear, a hydrophone, an oscilloscope and an ultrasonic measurement device. The measurements were carried out for a variety of phased array steering and focusing modes as presented in the following. We compared and quantitatively assessed the beam profiles determined by simulation and by measurement. For this comparison, line profiles were extracted from the 2D beam field data. Due to the experimental set-up, the recorded datasets are slightly shifted as compared to the simulated ones. Therefore, the simulated and the measured profiles were fitted by overlapping and were aligned by 0.2 mm steps (measurement resolution) until the mean error of the sum of the square errors of each individual data point was minimal. This minimum error was then the overall performance of the simulation, scaled in [dB]. Considering  $N$  data points of the  $i^{\text{th}}$  overlap fit, the error for each fit was calculated according to:

$$e_i = \sum_{n=1}^N (A_n - \bar{A}_n)^2 / N$$

Where

$e_i$  : average error for each measured and simulated line profile,

$A_n$  : amplitude of the measured data point,

$A_n$  : amplitude of the simulated data point.

We then calculated the performance number 's' in [dB] according to  $s = \sqrt{\min e_i}$ .

#### Results

From the experimental validation results acquired we show two representative cases addressing beam field steering and focusing. For each case, the results are illustrated via a two-dimensional plot of the simulated beam field in water (x-z-plane), the two-dimensional image (x-y-plane) of the simulation and the measurement at the specific distances from the sensor and the comparison of the specified lateral line profiles.

##### Case 1 – Insonification 19°, unfocused, profile at z = 28 mm

The 2D images are plotted in logarithmic scaling and qualitatively exhibit common features. Since the simulations were performed for monochromatic excitation, the features are higher resolved. Contrary to that the measurements were performed using pulsed ultrasonic excitation which leads to a smoothening of the beam field. For the quantitative comparison, line profiles have been selected from the 2D plots. The y-position of the selected line profiles are indicated by the black lines in the measured images. This applies to Case 2 as well. The simulated and the measured beam pattern shown in Figure 8 exhibit common features.

For the quantitative comparison, only data points with amplitudes above -9 dB were considered for the comparison as for lower values the measurement was impacted by noise. The simulation of the beam field in the x-z-plane (Figure 5) shows the generation of a grating lobe, however, in our evaluation we concentrate on the main lobe. The lateral profiles at the y-positions 9.2 mm and 11.2 mm were used (Figure 6) for comparison, the calculated performance numbers 's' are 1.87 dB and 1.50 dB, respectively.

##### Case 2 – Insonification 0°, focus at z = 60 mm, profile at z = 60 mm

As in the previous case, the simulated and the measured 2D images quantitatively agree well (Figure 7). For the quantitative comparison, the profile at the position y = 12 mm of the measured beam field was evaluated (Figure 8). Using data points with amplitudes above -12 dB, the calculated performance number 's' is 0.98 dB.



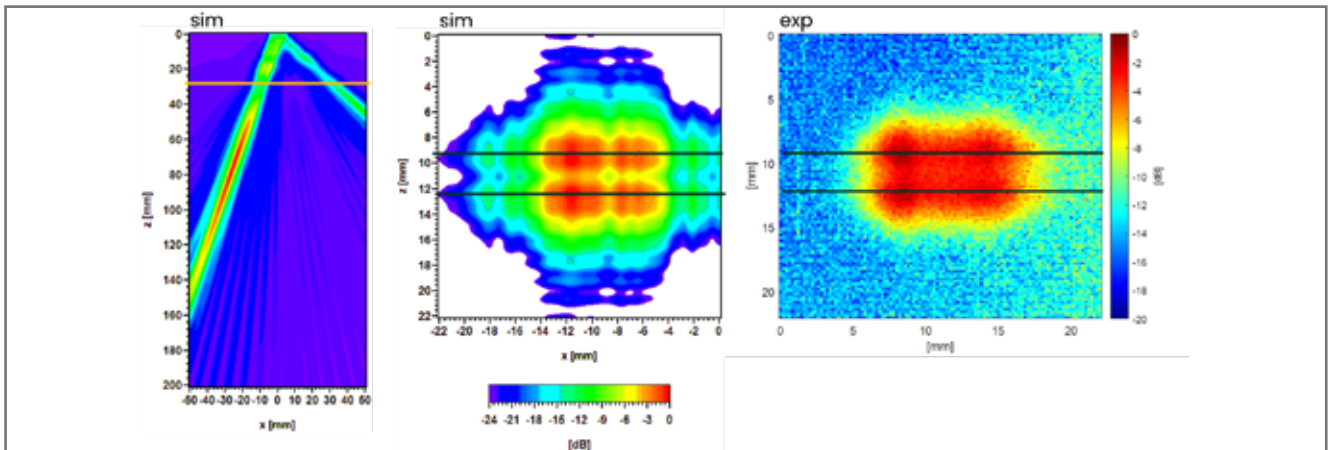


Figure 5: Case 1: Simulated beam field in water in the x-z-plane (linear scale, left). The simulated (middle) and measured (right) beam fields in the x-y-plane are shown in logarithmic scaling. The line profiles selected for the quantitative comparison are indicated by the black lines in the right image.

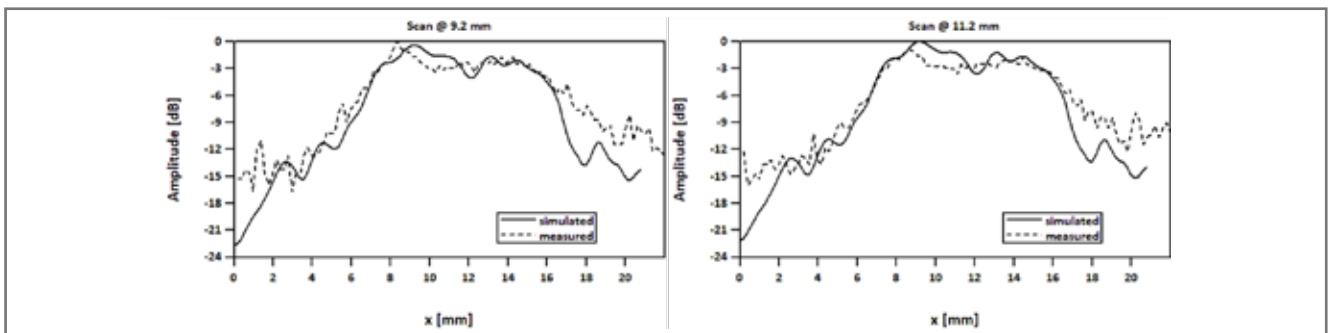


Figure 6: Case 1: Simulated and measured line profiles at  $y = 9.2$  mm and  $y = 11.2$  mm selected for the quantitative comparison.

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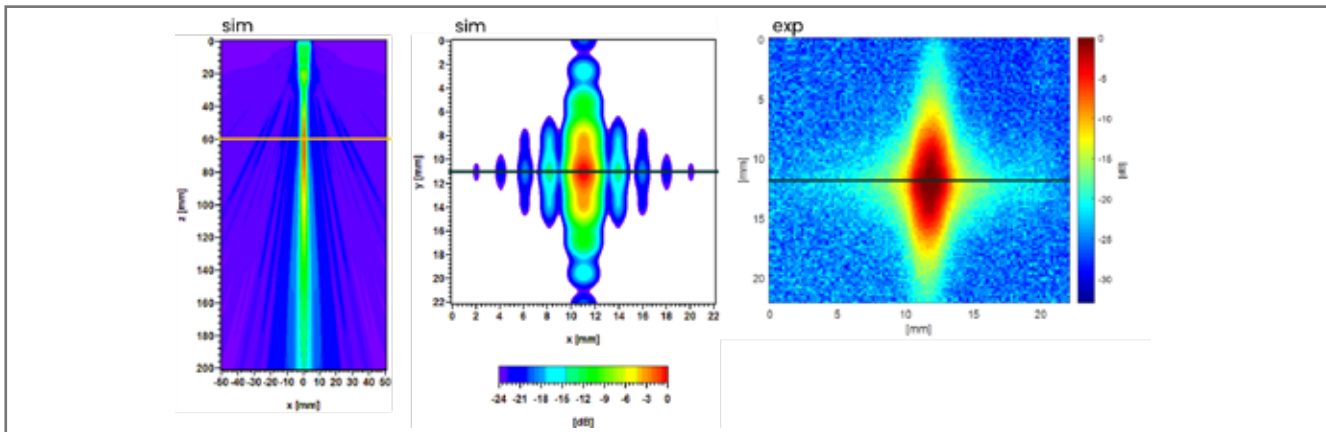


Figure 7: Case 2: Simulated beam field in water in the x-z-plane (linear scale, left). The simulated (middle) and measured (right) beam fields in the x-y-plane are shown in logarithmic scaling. The line profile selected for the quantitative comparison is indicated by the black line in the right image.

### Conclusion

Usually, the repeatability of ultrasonic measurements is within 1 to 2 dB, also from many comparisons performed in the past, the same agreement can be expected between simulated and experimental results. All compared profiles are showing a performance number 's' of less than 2 dB. Therefore, this is considered to be an acceptable result to prove the accordance of measurement and simulation and to prove the efficiency of the new transducer design in terms of its steering and focusing capabilities.

### 3.2 Simulated Beam Fields in Steel

An important part of the optimization process after each iteration was the revision of the sensor characteristics in terms of the inspection specification. The operation range of the new sensor covers a wide range of pipe diameters and wall thicknesses. Out of the large number of calculations, we have selected simulation results for a representative pipe diameter. Figure 9 shows the beam fields for transverse waves, which are generated in the pipe wall by steering to angles of incidence from 30° to 70°. Here, the array

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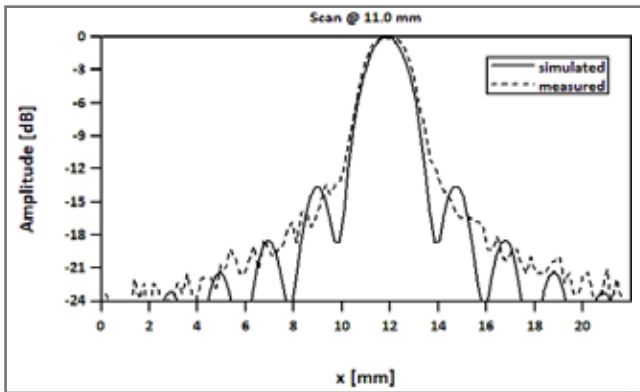


Figure 8: Case 5: Simulated and measured line profiles at  $y = 12.0$  mm selected for the quantitative comparison.

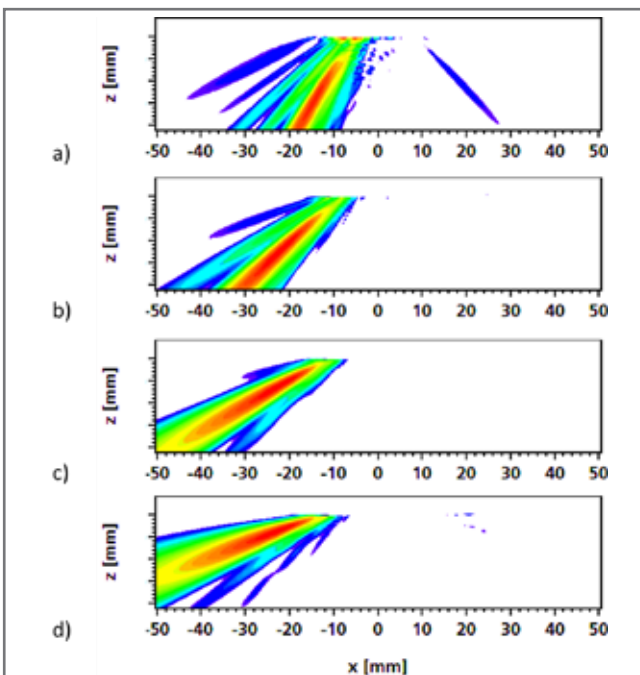


Figure 9: Beam field simulations for transverse waves with angles of incidence from a)  $30^\circ$ , b)  $45^\circ$ , c)  $60^\circ$  to d)  $70^\circ$ . The amplitudes are plotted in logarithmic scale

elements in the center of the array probe are used as a virtual sensor. In the presented depth range, the beam fields display a homogeneous appearance with only slight differences in the maximum amplitudes when compared to each other. Furthermore, no grating lobes are generated, only in the  $30^\circ$  case a weak lobe can be recognized which, however, far below the maximum amplitude of the main lobe. A further criterion for the effectiveness of the sensor is the beam field homogeneity when the virtual sensor is shifted along the complete array aperture. In Figure 10, the beam fields are plotted for an angle of incidence of  $45^\circ$  for the cases where the virtual aperture is located at the center, at the outmost left and the outmost right position. It can be seen that by shifting the virtual sensor

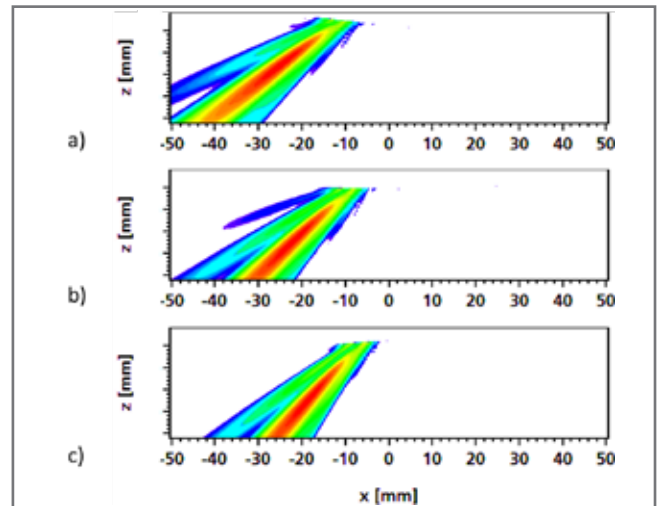


Figure 10: Simulated transverse wave beam field for different positions of the virtual sensor: position a) outmost left, b) centered and c) outmost right, the angle of incidence is  $45^\circ$ .

an electronic scanning in circumferential direction can be performed.

#### 4. Calculation of Amplitude Dynamic Curves for Notches as Model Defects

For the calculation of amplitude dynamic curves (ADCs) for notches of different depths, positioned internally and externally at the pipe wall, the GPSS simulation code has been accordingly modified. External notches are detected using the half skip reflection, while for internal notches the full skip reflection is considered. Thus, for the latter the reflection of the insonified transverse wave at the outer pipe wall has to be accounted for. Moreover, the implementation also considers the scan along the circumferential pipe direction. In Figure 11, the simulated amplitude dynamics for two representative pipe diameters are shown for the inspection with  $45^\circ$  transverse waves, the pipe wall thickness is 8 mm. Due to the optimized sensor characteristics, the maximum amplitudes and the shape of the ADCs are very similar for both the two pipe diameters and the external as well as internal notches.

#### 5. Experimental Validation of the ADC Simulations

The validation measurements were performed in the laboratory using a test rig which allows to scan test specimens of various diameters in circumferential direction using immersion technique. The test rig is shown in Figure 12 including the measurement set-up where the sensor insonifies onto the inner surface of



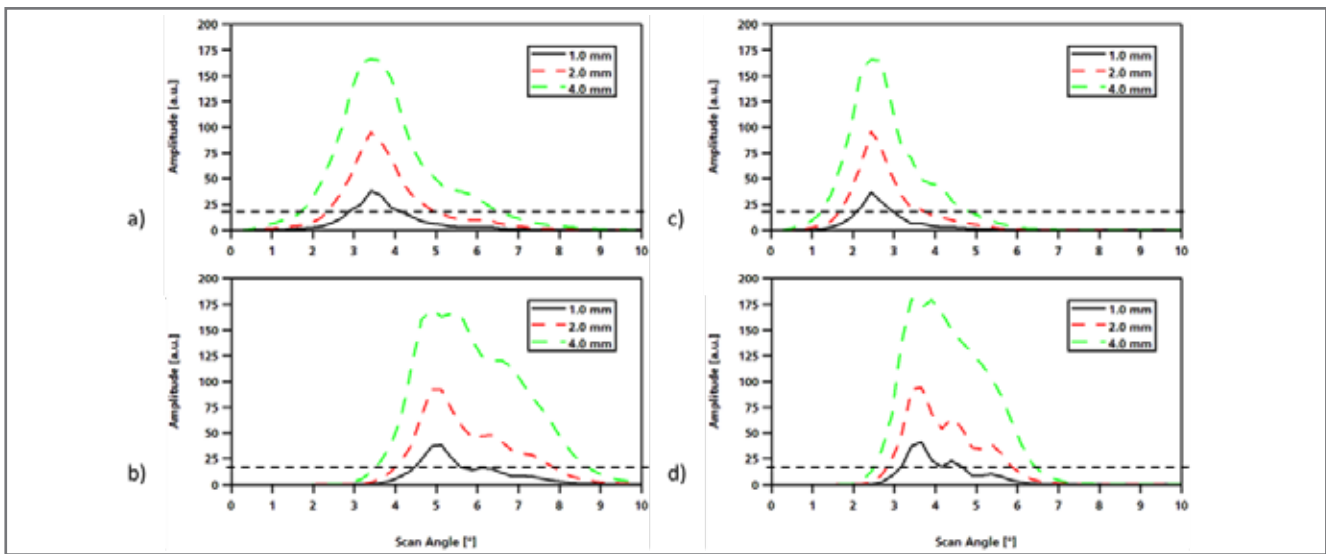


Figure 11: Simulated ADCs for two different pipe diameters (left and right), the detected defect amplitudes are plotted against the scan angle. The diagrams display the respective curves for external notches (a) and c)) as well as for the internal notches (b) and d)).

a pipe segment. For the validation of the simulated ADCs and defect amplitudes, a series of test specimens of different diameters and wall thicknesses were fabricated with notches of 1 mm, 2 mm and 4 mm depth.

For two different diameters, the diagrams in Figure 13 show the maximum amplitudes of the simulated ADCs as a function of notch depth in comparison with the experimentally determined values. For the internal notches, the values agree well, also for the external notches, except for the 1 mm deep notch where the experimental values exceed the simulated ones by approximately 4 units. This larger difference could be due to the influence of the notch width in relation to the low notch depth or to the quality of the notch preparation.

## 6. Summary

In this contribution, we report on the optimization of a phased array sensor for pipeline inspection. The

specification of the target parameters in terms of a further enhancement of the sensor currently used on the UltraScan™ DUO ILI tool was the basis for the optimization process. The simulation results for the beam fields and the amplitude dynamic curves have been validated in comparison with experimental results.

The new generation of phased array sensor is the basis for the implementation and application of sophisticated inspection techniques with enhanced performance as compared to standard techniques. Using several of these simultaneously during an inspection run allows to extract even more information from the acquired data. This is essential to achieve enhanced tool performance in terms of POD, POI and POS of complex defect morphologies. The steady progress in computer performance allows to even consider the application of sophisticated phased array imaging techniques, such as Plane Wave Imaging. Respective studies and implementations



Figure 12: Lab set-up for the validation measurements consisting of the water basin, sensor holder, manipulator and mounting element for the positioning of test specimens of various diameters. In the image on the right, the prototype of the new sensor can be seen, which has been fabricated by Waygate Technologies, a Baker Hughes business (Hürth, Germany).

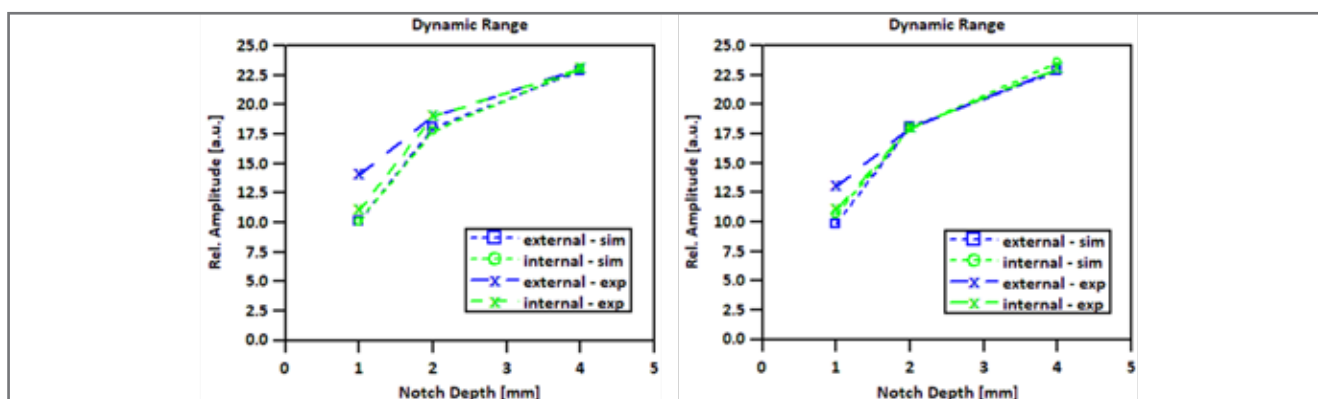


Figure 13: Maximum amplitudes as a function of notch depth for two different pipe diameters. The values are normalized to the maximum amplitude of a 1 mm external notch in a 42" pipe of 8 mm wall thickness.

have already been performed [4] and will further be addressed in due course.

The presented work is part of our ongoing efforts to support the technically and economically efficient

integrity programs of our customers. Enhanced accuracy and reliability of our ILI data help to reduce the potential threat due to certain critical defect types and to reduce the amount of unnecessary dig and repair costs.

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## AUTHORS



**Martin Spies**

Baker Hughes

Head of ILI Research

[martin.spies@bakerhughes.com](mailto:martin.spies@bakerhughes.com)



**Olaf Müller**

Baker Hughes

Specialist – Analytics

[olaf1.mueller@BakerHughes.com](mailto:olaf1.mueller@BakerHughes.com)



**Irina Lachtchouk**

Baker Hughes

German Regional Leader Data Science

[Iryna.lachtchouk@BakerHughes.com](mailto:Iryna.lachtchouk@BakerHughes.com)



**Martin Tschuch**

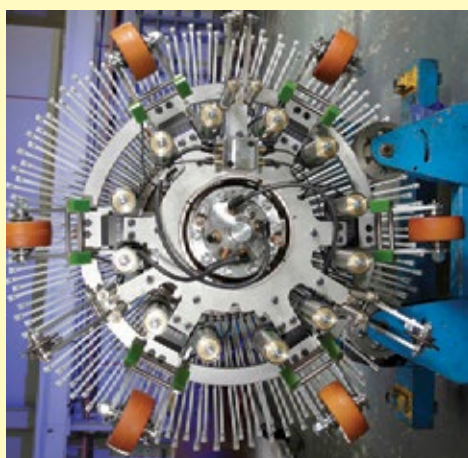
Baker Hughes

Consulting Engineer

[martin.tschuch@bakerhughes.com](mailto:martin.tschuch@bakerhughes.com)



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*An international trade association serving the pipeline industry*



# Pipeline Integrity Management: Nonmetallic Technology Perspective

R. P. DE SOUZA > SAUDI ARABIAN OIL COMPANY

## Abstract

Seawater Injection is a well-known technique which helps in supporting oil recovery cost effectively by injecting treated seawater at high pressure in the reservoir. This injected water is delivered through water injection wells placed along the periphery of the entire oilfield reservoir. The water is transported to the wells by a vast high pressure pipeline network which needs to be operated without unplanned downtime and cost effective internal/External corrosion control.

Ageing(40yrs) Pipeline network which is internally and externally coated with Fusion Bonded Epoxy (FBE) and have numerous challenges (constructed telescopically, branched, Non-piggable, underground, high pressure) that prevents the use of conventional inspection technologies in order to cost effectively know the condition of the network.

Internal pipe corrosion control is not very effective by controlling Seawater injection parameters, chemical injection (Biocides, Oxygen scavengers), Coupons, On-stream Inspection Programs (Aboveground), maintenance pigging.

In order to cost effectively prevent internal corrosion Nonmetallic technology (HDPE, RTP, Roto-lining, specialized coupling) for up to 3000psig was used first time in the world to replace and rehabilitate ageing pipelines. Extending the Asset Economic life by preventing corrosion by application of Nonmetallic material technology aided in maintaining the integrity of the vast pipeline network. Moreover, this strategic shift contributed to the local economy and also helped in the reduction of carbon footprint that contributed in reducing the environmental impact.

Evaluating the value of each improvement action to the individual pipeline asset by analyzing the relative asset value of the pipeline portfolio into strategic groups ensured robust capital budgeting process to deliver cost effective Pipeline integrity program and positively contributed to environmental and social dimension.

Lifecycle costing together with environmental impact assessment helped in assessing the contribution of the products, processes to deliver sustainable value and needs to be incorporated during the early stages of the project.

## 1. Introduction

The seawater treatment plant and injection network are the largest in the world with a treatment capacity of 14 Million barrels/ day (MMBD). The plant treats the injected seawater and transports it via a vast network of over 2000 kilometers of pipelines ranging from 60" to 8 inches. The treated seawater supported by water injection pumping stations is injected at high pressure to the reservoir via over 630 injection wells that are distributed between 250 to 350 kilometers from the seawater Treatment plant. This maintains the reservoir pressure by peripheral water flooding and helps in oil recovery over the producing life of the oilfield. Below is the overview of the seawater injection network.

As seen in Figure-1 Water is taken from the Arabian sea and gets treated at the seawater treatment plant (STP). The injected water needs to have certain quality to meet the below injection specification

- pH-7.2
- Dissolved Oxygen-less than 10ppb
- Total suspended solids (TSS)-less than 0.2mg/l
- Particle size distribution  $\leq 200$  count/0.5ml (Coulter counts).

The water quality specification is delivered by twenty-eight (28) identical treatment modules at the seawater treatment plant that are designed to deliver the

water quality. Each module has four horizontal pressure filters and a deaerator column and is designed to treat 0.5MMBPD of water. The suspended solids are trapped by the media inside the filters and is removed by backwashing at regular intervals. Ninety-five (95) percent of the dissolved oxygen in the filtered water is removed inside the deaerator by stripping with nitrogen and remaining five (5) percent is removed by treating with Sulphurous acid solution. The oxygen removed by Nitrogen stripping is vented to the atmosphere and the remaining oxygen is removed by sulphurous ( $\text{H}_2\text{SO}_3$ ) acid solution which also reduces the pH of the water from 8 to 7.2 and forms a sulfite residual compound (8-12mg/l) that remains in the water and helps to further scavenge the residual oxygen. Below figure-2 details the seawater treatment process.

## 2. EXPERIMENTAL PROCEDURE

To keep the quality of water to desired specification and safeguard the equipment including downstream pipelines against corrosion proper addition of below chemicals is undertaken at locations shown in Figure 2

- Polyelectrolyte (Filtration Aid Coagulant)
- $\text{SO}_2$  Solution (Dilute Sulphurous acid, 0.5%)
- Nitrogen
- Bactericide (Biocide)
- Hypochlorite solution

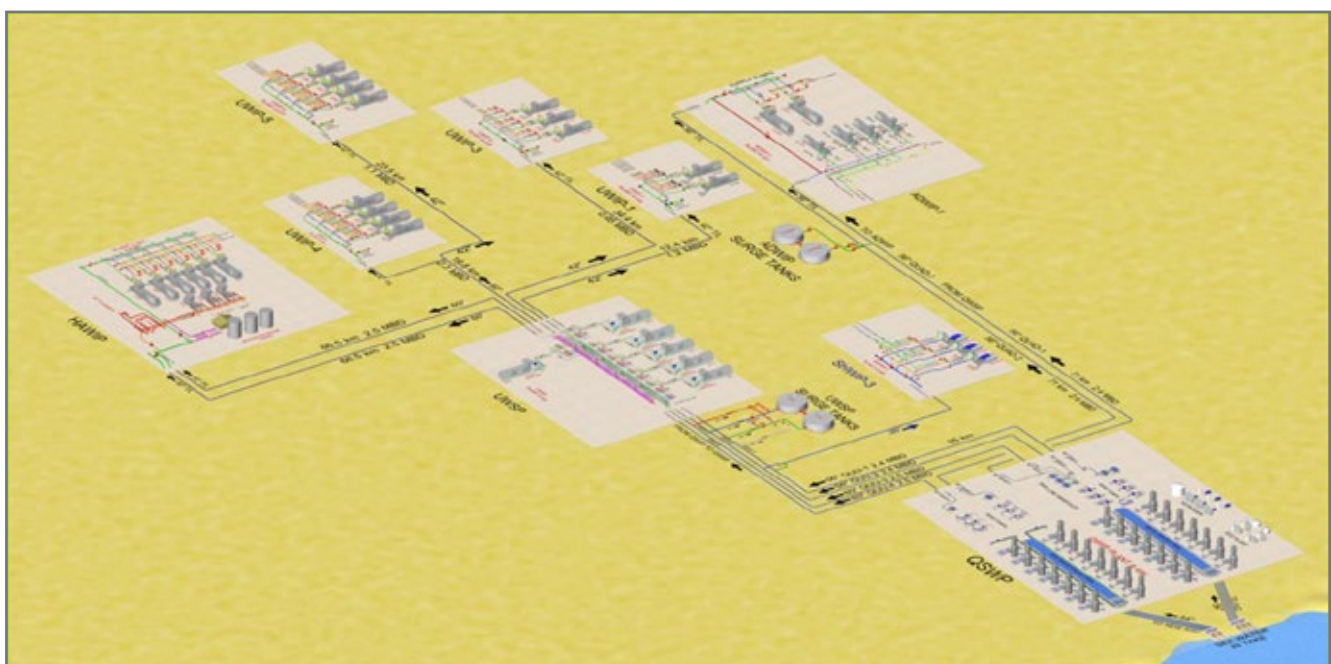


Figure 1: Overview of the seawater Injection Network

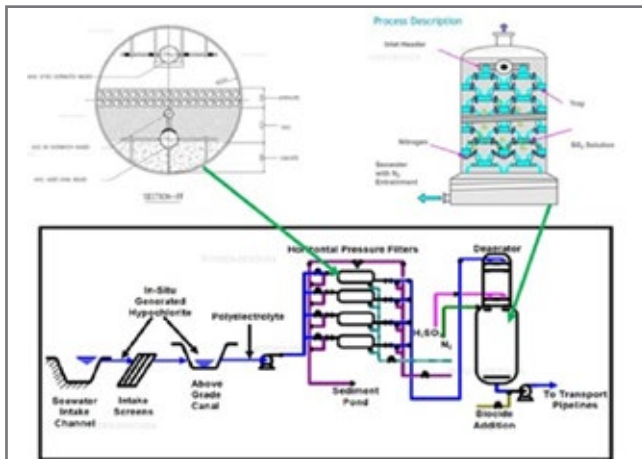


Figure 2: Schematic of Seawater treatment Process<sup>[1]</sup>

The treated water is monitored to manage corrosion and assure quality. The parameters that are monitored are residual chlorine, hypochlorite concentration, microbial level, residual oxygen, residual sulphurous acid, pH, biocide Injection rate, Planktonic aerobic and SRB bacteria population, corrosion rate, coulter counts, total suspended solids (TSS), and oxygen.

The plant is designed with a treatment capacity of 14MMBD/day but operates below its capacity due to the built-in redundancy and changing(increase/decrease) demand for treated seawater from production Engineering. As a result, there is no production impact in delivering treated seawater water if there is unplanned shutdown in one of the treatment modules.

The treated seawater is delivered to the wells by large diameter (60/56") six (6) shipper pipelines that transport the water to the Water Supply Plant (WSP). The water is then transported through six (6) transfer lines to the Water injection plants where the pressure is raised to 3000psig by turbine driven water injection pumps. The high-pressure water is delivered the wells by twenty-four telescopic injection headers that are connected with the laterals that deliver water to the reservoir through more than five hundred and sixty (560) injection wells. The wells lie between 250-350km of the Seawater Treatment plant as shown in figure-3.

Below is the overview of the pipeline network. The reliability of the system takes a priority starting with shipper lines and following a clock- wise decreasing priority as per Figure 3. This priority is established based on the volume of treated seawater production loss measured from the individual well tagerts due to unplanned downtime cause by the individual Pipeline Asset.

All the pipeline network is internally coated and not piggable by design due to the absence of launcher and receiver facilities. The twenty-four (24) headers are designed telescopically with up to six (6) diameter changes in order to have a cost-effective pumping system.

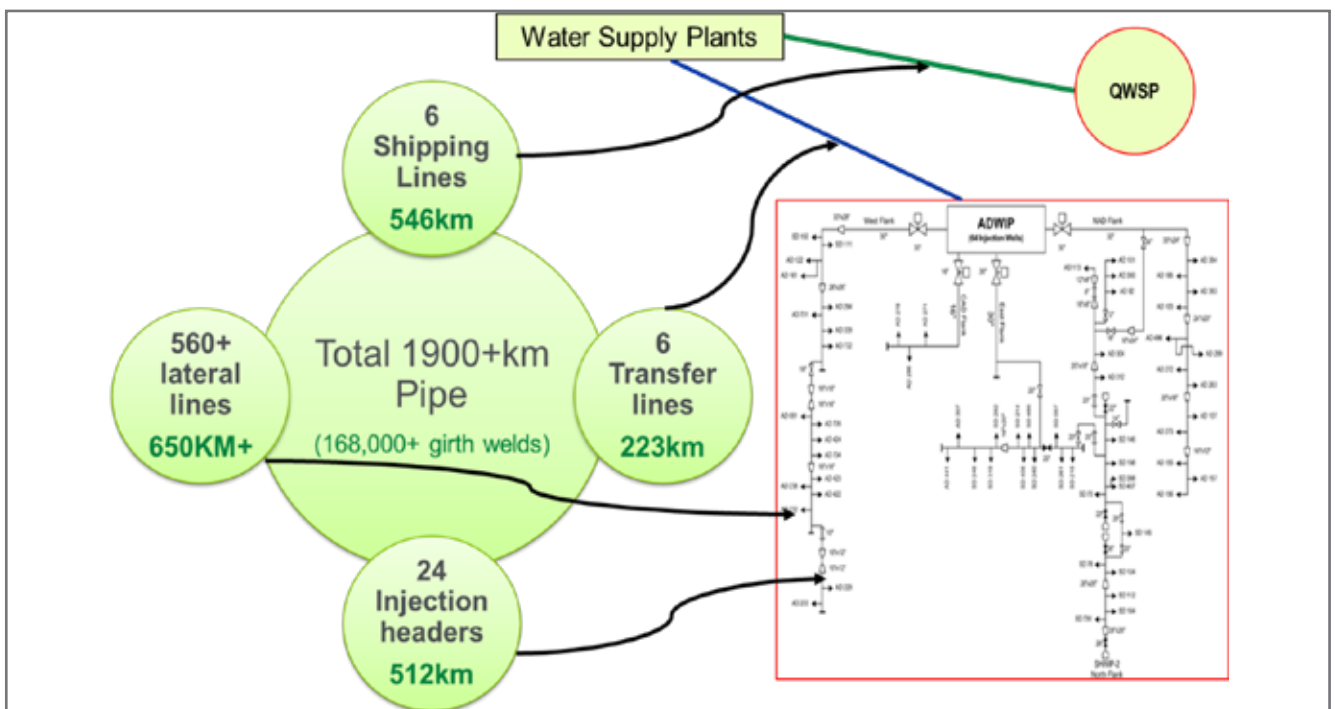


Figure 3: SWID Pipeline Network Overview



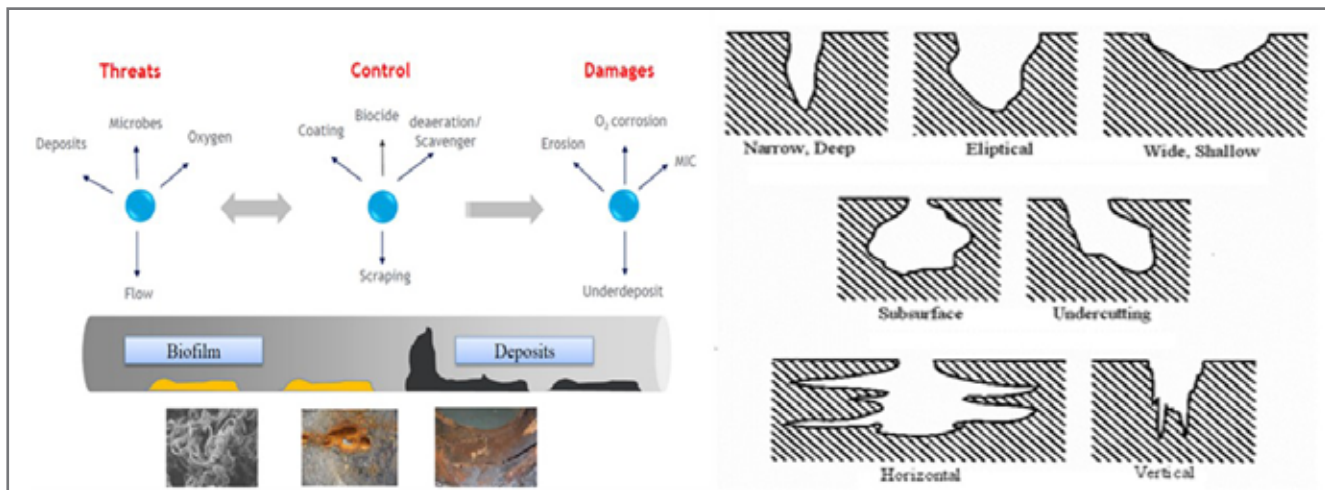
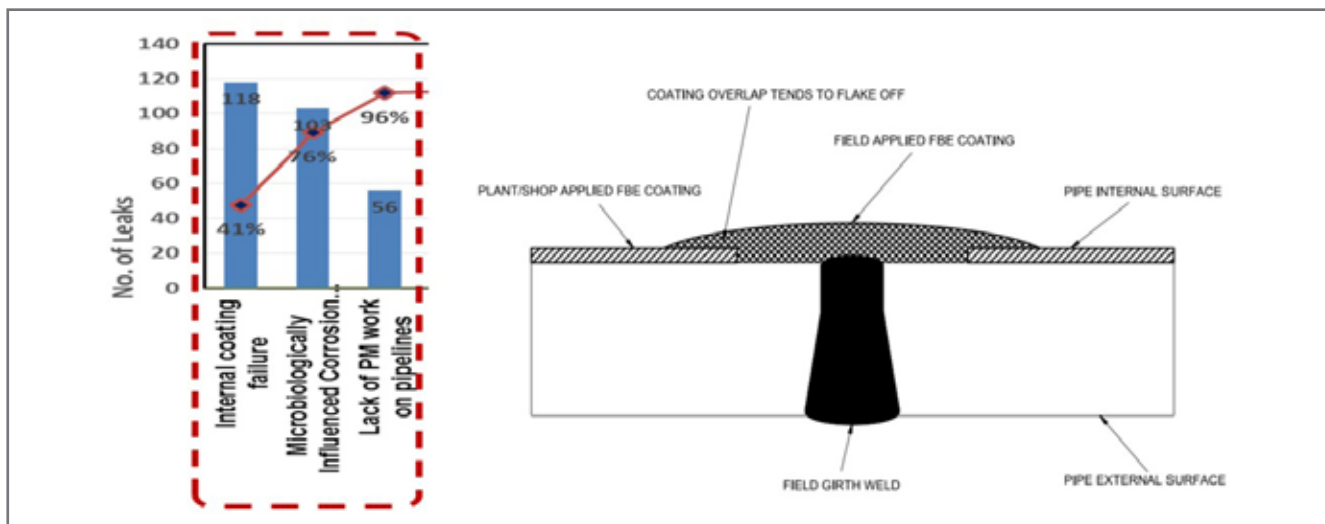
Figure 4: Internal Corrosion Model and Cross-sectional shape of Pits <sup>[2][3]</sup>

Figure 5: Pareto Root Cause Analysis and coating failure at Girth welds.

The failure of the internal Fusion bonded epoxy coating due to ageing, and application related defects has resulted in leaks. The injected biocides are not effective in controlling sessile bacteria population due to the presence of sand filtration media that has migrated over the years and has accumulated in the piping system. The accumulated deposits cannot be removed due to the absence of maintenance pigging due to system design.

The internal coating failure has resulted in localized pitting corrosion especially at the girth welds and the sludge together with biofilms has accumulated inside the pipe making the biocide treatment ineffective due to the absence of the chemical contact with the pipe surface leading to highly localized corrosive environment due under deposit corrosion. Below is a typical graphical representation of the internal corrosion

model and type of microbial pitting corrosion damages that occur in the network. (Figures 4,5)

Root cause leak analysis was undertaken, and it was concluded by pareto analysis that the majority of the leaks were caused by internal coating failure, microbially induced corrosion that couldn't be controlled effectively due to the lack of maintenance pigging. The system was not designed for maintenance cleaning and couldn't be undertaken cost effectively due to the absence of launchers/receivers, telescopic internally coated pipelines, and moreover, the cleaning in present circumstances required operational downtime of the pipelines (Figure 5).

Inspection pigging technology was deployed on various diameter pipelines, but it failed to give satisfactory results and this failure was attributed to the

unsatisfactory cleaning due to the use of Non-metallic cleaning pigs as well as failure of the UT based technology to meet the expected performance specifications.

The potential sedimentation of sand and deposit accumulation in the off-plot piping due to filter sand media migration has increased the likelihood of under deposit corrosion. The flow modeling also confirmed low velocities as the production was expected to fall in the future due to revised injection forecast which would result in low flow velocities leading to solids deposit accumulation.

### 3. HIGH PRESSURE NON-METALLIC TECHNOLOGY PERSPECTIVE

In order to cost effectively solve the internal corrosion problem it was decided to Pilot Non-metallic material technology for the pipelines. New technologies were identified to be suitable for the high-pressure application but would need to be piloted as the system was operating outside the current available Non-metallic technology envelope as shown in Figure 6.

To solve the challenge cost effectively Non-metallic materials were identified that could be deployed for High pressure water injection service and corresponding diameters as the non-metallic materials had limitation of use with increasing pressure and diameter. Below technologies were identified and successfully deployed to add long term economic value than existing methods and also have a reduced operational carbon footprint.

- Steel Reinforced Thermoplastic pipe(S-RTP).
- High density Polyethylene Pipe (HDPE).
- Rotational Lining technology using HDPE
- High pressure Non-metallic coupling

Upon successful implementation of the above technologies corporate company standards were changed to deploy Non-metallic materials in high pressure Seawater injection service as a material of choice.

#### Steel Reinforced Thermoplastic Pipe(S-RTP) Technology Application

8" S-RTP Pipe rated at 3000psig,65C/150F was deployed first time in the world for a well lateral that was one (1) km in length. The installation was completed and successfully hydrotested tested at 4500psig in two days.

6" Pipe rated at 3000psig,65C/150F was also deployed first time in the company for a well lateral that was one (1) km in length. The installation was completed and successfully hydrotested at 4500psig in two days.

The S-RTP pipe can be installed and commissioned much faster when compared to carbon steel pipe that has to be welded on site with approximately eighty-four (84) joints per kilometer. Moreover, the RTP pipe could be rolled-up and reused in the future at another location if required.

The lifecycle cost savings that could be realized with the above technology is between 40-60 percent when compared to existing processes of using carbon steel

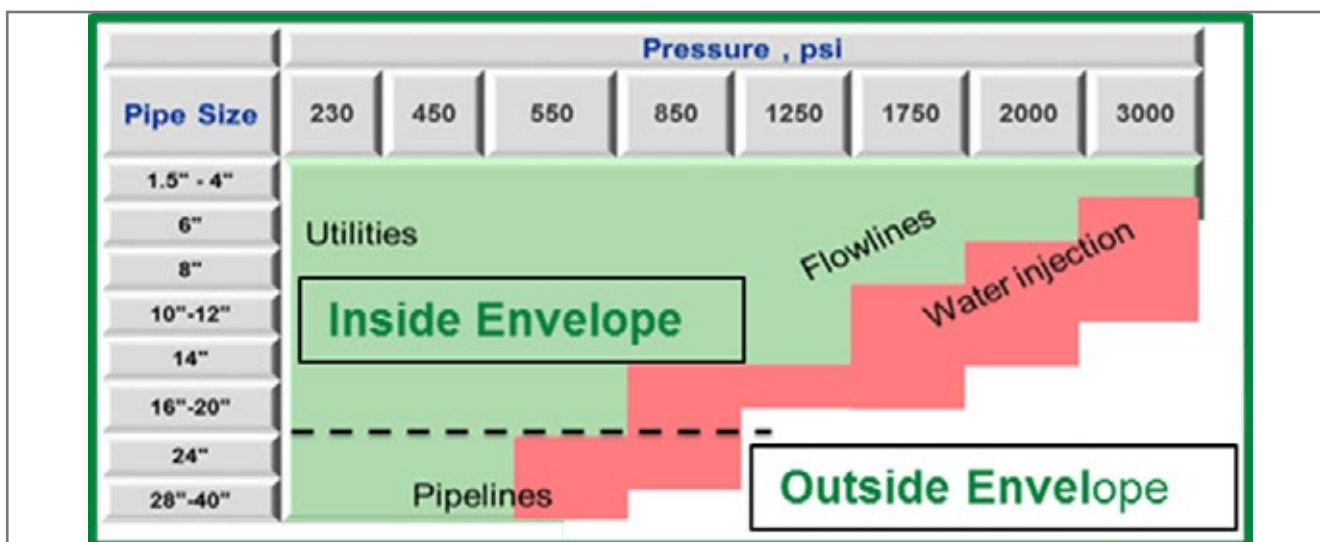


Figure 6: Pressure Envelope for seawater Injection Pipeline system



Figure 7: High Pressure RTP pipe installation

with internal Fusion Bonded Epoxy (FBE) coating. Moreover, the entire process has a much lower lifecycle carbon footprint when compared to traditional metallic technologies and the base material used to manufacture this pipe is from Oil.

As a result of the successful pilot internal market was developed and the vendors invited to set up their factories in Saudi Arabia. This technological investment would strengthen the lifecycle environmental sustainability and deliver low carbon footprint supply chain, creating jobs within the kingdom, and help to extract additional value from the crude.

#### High Density Polyethylene (HDPE) Technology Application

The technology was used to rehabilitate ageing laterals lines rated at 3000psig, 70C/150F. The technology was piloted on an ageing 10" injection lateral with active internal corrosion and having over fifteen (15) sleeves with a length of around one (1) kilometer. The tight fit HDPE liner technology was successfully deployed to rehabilitate the 10" injection lateral. Rotational lining technology along with the HDPE line coupling was also successfully used for the lining of piping fittings and for replacing heavy schedule flange joints

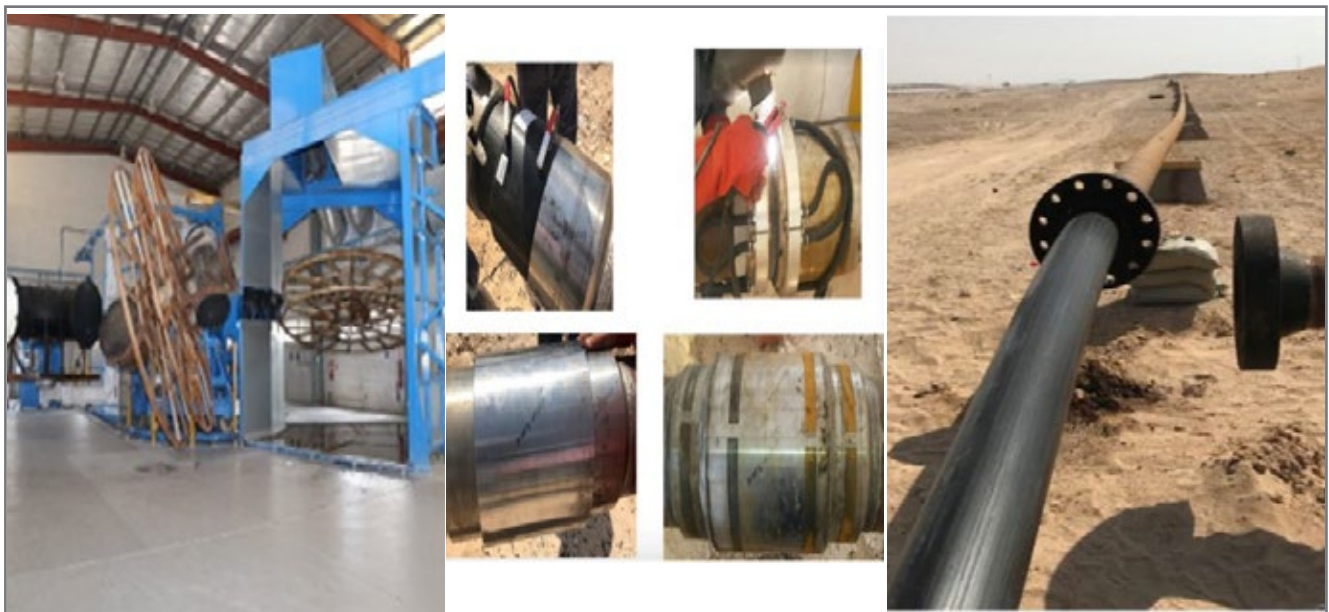


Figure 8: HDPE Lateral Rehabilitation with Coupling and Rotational Lining Process



A cost saving of 25 to 35 percent was realized using HDPE technology rehabilitation concept when compared to using carbon steel with internal Fusion bonded Epoxy (FBE) coating moreover as result of this effort a biggest regional Rotational lining facility was installed by the vendor in the kingdom. When HDPE technology is used in new construction a lifecycle cost benefit of 20 to 30percent could be accomplished.

It is to be appreciated that cost is dependent on many factors (Type of Markets, Project location etc.) and it is recommended to undertake a detailed cost benefit analysis prior to implementing the concept.

Two New pipeline(42inch) construction projects using the tight fit HDPE technology are currently ongoing. The cumulative pipeline length for the pipeline projects is thirty-five kilometers(35km). Once completed these projects will be the largest in the Middle east where Tight fit HDPE technology was used.

This initiative further strengthened the sustainable low carbon supply chain in the country and created industrial jobs, moreover HDPE material is manufactured from Oil in the kingdom.

Reinforced Thermosetting Resin (RTR) piping rated at 3000psig, 65C/150F was piloted first time on a lateral line but the pilot was not successful due to the failure at the piping joint. The learning experience was captured, and the joint is currently being re-engineered.

#### 4. LIFECYCLE COSTING ANALYSIS

Profit improvement opportunities were identified that would deliver holistic business value. Lifecycle methodologies were used to assure highest possible sustainable value and process improvement in the long term. The company has integrated lifecycle costing concepts across the entire lifecycle of the asset (Explore,

Approve, select, define, execute, operate Abandon). An opportunity was identified to cost effectively extend the life of the ageing assets by leveraging Non-metallic material technologies.

The aim was to determine the most cost- effective option between alternative competing options that would satisfy technical, operational, safety, environmental and regulatory requirements. Moreover, the options were assessed following industry approved methodologies in order to assure quality and comparability of studies.

Below diagram shows the lifecycle phases of a field development project with processes and decisions at each phase.

The scope of the application of Non-metallic materials is to be assessed in field development and subsequent changes made to the design. The select and define phases of the project have the greatest impact on the lifecycle of the Asset since subsequent changes increases the cost significantly due to additional investments required for life extension due to ageing of equipment due to internal corrosion.

The close collaboration with vendors is required to develop products cost effectively that are currently not available in the market to meet the pressure and temperature requirements.

Lifecycle costing is concerned with optimizing CAPEX, OPEX and revenue or cost and this strategy should be closely aligned with vendors goals for product sales and development cost so that all opportunities could be realized to create collaborative value as going forward profitable sustainability of the industry will depend on harnessing every improvement opportunity as shown in Figure-10

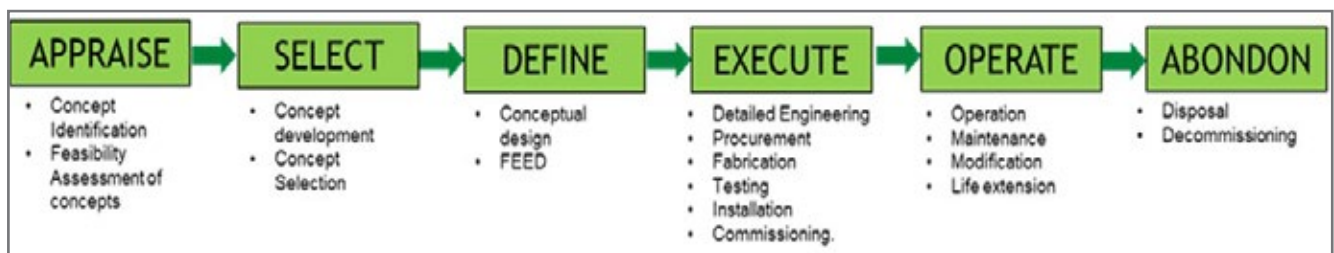
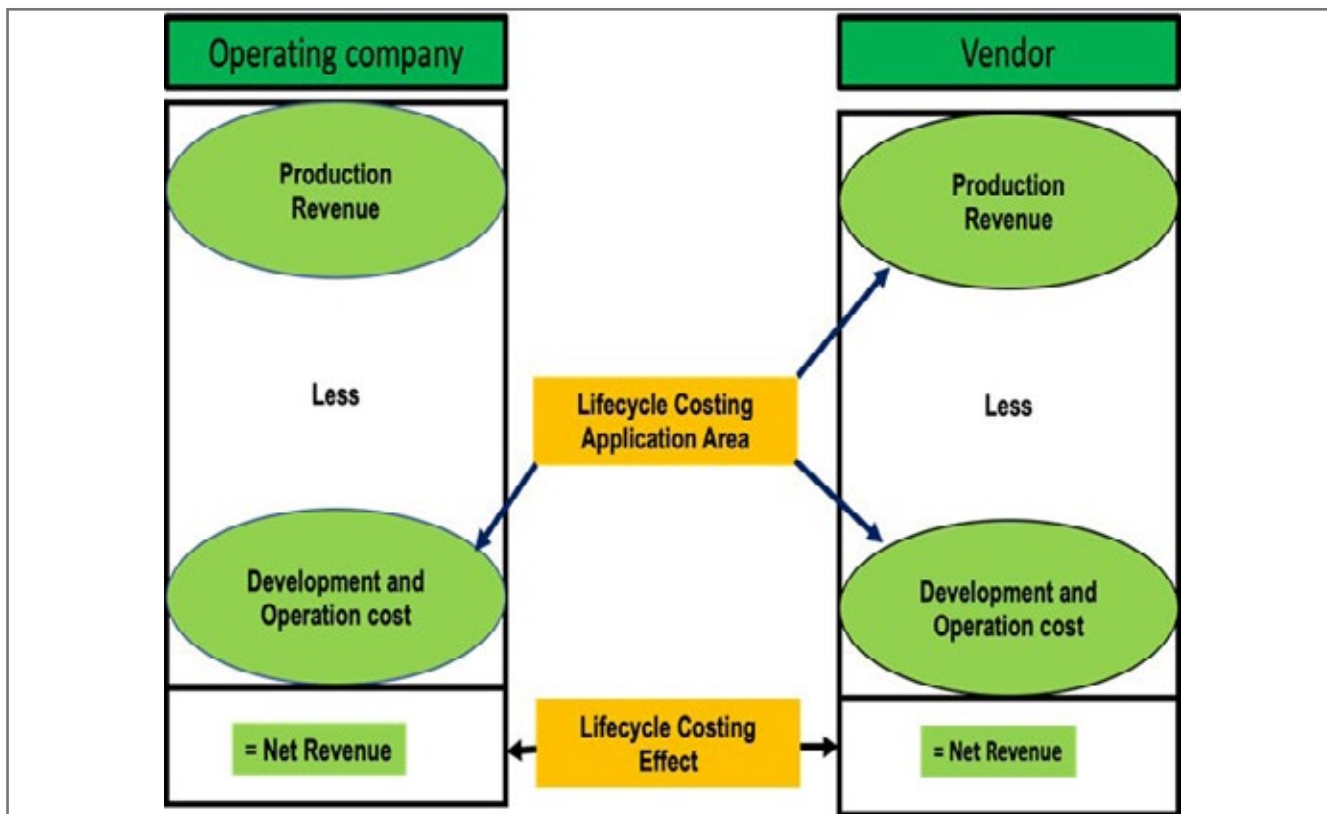


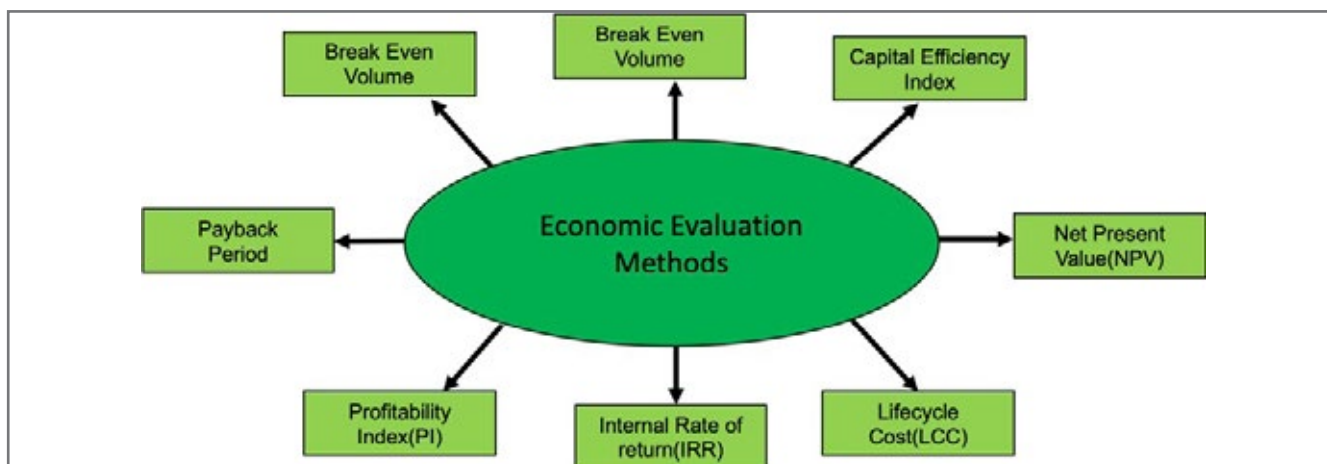
Figure 9: Typical Lifecycle phases of Project

Figure 10: Lifecycle Costing Opportunities <sup>[7]</sup>

The company has initiated the In-kingdom Total value Add(IKTVA) program where international suppliers including Non-metallic suppliers are encouraged to localize their supply chain by setting up manufacturing Units in the Kingdom and this is also more cost effective to the vendors of non-metallic materials since the oil derived raw materials are easily available in the kingdom including qualified workforce, this creates a favorable condition since the products manufactured in Saudi Arabia can be supplied to the domestic and also the regional market moreover this also helps to reduce the environmental impact due to low carbon

foot print when compared to the transportation of the products from the industrialized countries as well as delivers greater integration and agility that will ensure kingdoms long term prosperity in addition to being a win for the suppliers, manufacturers and service providers by delivering a sustainable industrial ecosystem.

The economic evaluation measures that were used are as given below. These measures were used individually and in combination to deliver a robust framework for economic feasibility analysis.

Figure 11: Economic Evaluation Methods <sup>[3]</sup>

## 5. CARBON FOOTPRINT REDUCTION STRATEGY

“Carbon dioxide footprint is a measure of the exclusive carbon dioxide emission that is directly and indirectly caused by an activity” [4].

Carbon Intensity is a measure of producing crude oil from the well to the refinery gate. The company has the lowest carbon intensity of any major producer to extract process and transport its crude oil to the refining gate. With a carbon intensity of 4.6grams of carbon dioxide (CO<sub>2</sub>) equivalent per each megajoule, which is approximately 27kg of CO<sub>2</sub> equivalent per barrel of crude oil. Oil needs to be sourced in the most carbon responsible manner and the company is further making a shift into implementing Non-metallic material technology deployments to further aid reduction in the carbon footprint and also reduce emissions in supply chain.

Most common greenhouse gasses (GHG) are Carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous Oxide(N<sub>2</sub>O). Carbon dioxide is the responsible for the greatest amount of environmental impact.

Production processes of steel pipes is far the largest emitter of carbon dioxide in the footprint of pipeline projects as significant amount of energy is required to convert raw material into steel pipes.

The company is investing in new technologies and innovation to produce new Non-metallic materials that would significantly reduce the carbon footprint.

Below are the typical carbon emission activities on a typical pipeline project.

The use of Non-metallic materials has a considerably less carbon footprint from a materials manufacturing, construction, operation, maintenance and decommission phases of the project. Moreover, the raw material is derived from oil and manufactured in the kingdom eliminating the long transportation journeys from overseas.

The material is much lighter and comes in reels in case of Reinforced thermoplastic pipe (RTP) thus eliminating extensive welding, coating and other corrosion protection processes. The construction timescale is less and involves fewer personnel and heavy equipment.

The operation and maintenance were cheaper due to the absence of corrosion monitoring and control activities. This also reduces the need for site travel and the associated Risk.

Decommission and disposal is much cost effective as the pipe can be rolled back on reels and taken to another site in case of Reinforced Thermoplastic pipe.

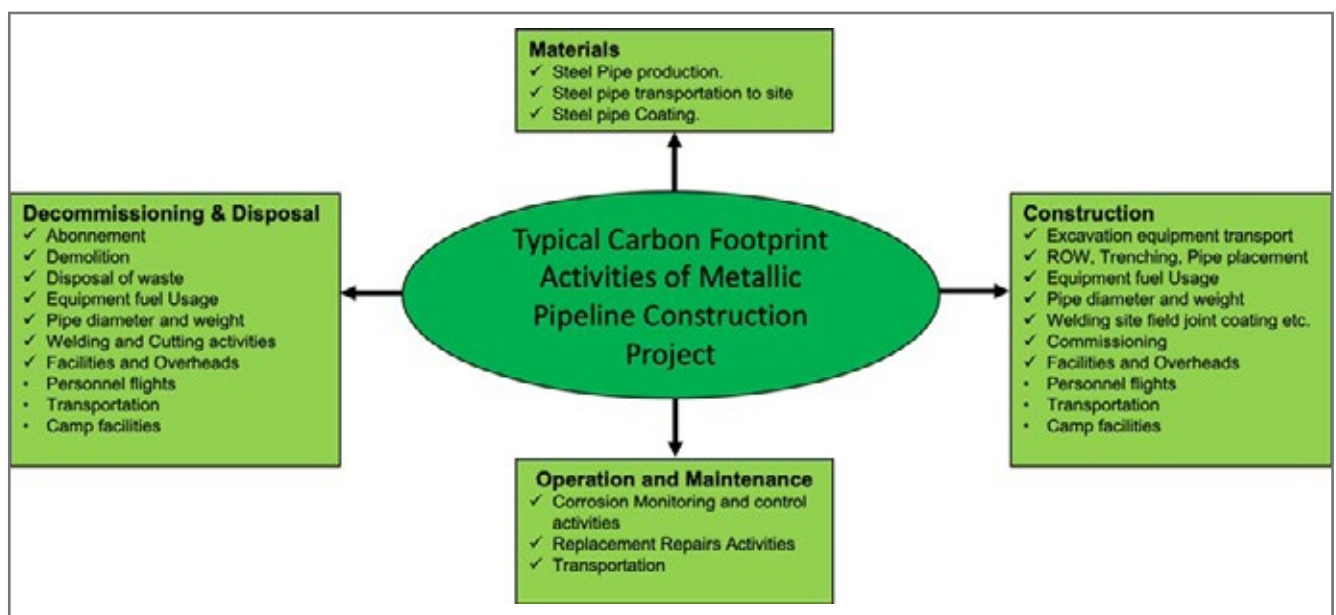


Figure 12: Typical Carbon Footprint for Metallic Pipeline Construction Project.



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Detailed Environmental Lifecycle Assessments were carried out using International Standard framework (ISO 14040,14044) which ensured the quality and comparability of the studies to existing options.

## 6. CONCLUSION

The use of Non-metallic technology has a clear technical, economic and environmental benefits. The material used in construction of the Non-metallic pipelines are derived from oil and the project commissioned using such materials have a less carbon footprint when compared to metallic materials. The first step in reducing emissions is to know where you stand by conducting lifecycle environmental impact Assessment and then assess how the products and processes compare to the existing Non-circular alternatives.

### Future Work

There is further need to promote the use of advanced polymeric materials and conduct research that addresses the challenges in developing products and technologies that accelerate their deployment. Industry standards need to be further developed and cost of Non-metallic products to be driven down by conducting further research. Overall the oil and gas industry need to move to a cost-effective path by meeting the environmental and economic goals for a sustainable future and further development of Non-metallic materials and its application throws at us a challenging opportunity.

## AUTHOR



**Royden Peter De Souza**

Saudi Aramco

Senior Engineer(Subject Matter Expert)

[royden.desouza@aramco.com](mailto:royden.desouza@aramco.com)

# Combined defect assessments using Phased Array Inline Inspection technology

S. BENICHO, A. LEMAIRE, T. HÉRAUD, C. SENA, M. SERVAIS > TRAPIL

## Abstract

For some years now, TRAPIL has been operating its XTRASONIC-NEO ILI tool which embeds phased array probes and enables the detection, location, identification and sizing of dents, metal loss and cracks anomalies in liquid product pipelines in a single run. This Phased Array UT tool is an emerging technology and makes possible a wide range of settings.

Understanding the capabilities of in-line inspection tools is a key component of an accurate integrity management system. TRAPIL carried out an evaluation of the performance of its XTRASONIC-NEO on its test bench and its real pipelines in order to build its specifications. This qualification was presented previously.

However, general ILI tools specifications are constructed on the assessment of the tool performances on single defects not taking into account the potential interactions between defects. In 2020, TRAPIL decided to initiate an innovative approach by evaluating the potential of its Phased Array tool for the detection and sizing of combined defects.

In order to evaluate its XTRASONIC-NEO performance, TRAPIL has selected a list of defects to be implemented for the testing of the tool, manufactured them on test sections of pipes, supervised the campaign and reported the results.

As a result, a wide range of features was evaluated including plain dents, metal loss features, dents interacting with welds, dents interacting with metal loss, notches in plain dents, notches in dents interacting with welds and notches in dents interacting with metal loss. Pipeline operators are concerned about dents and even more about dents combined with metal loss that have already been known to result in major failures. This is particularly important in areas that are difficult to access like in urban areas. Being able to detect - even more than size - these defects may help reduce failures.

## 1. XTRASONIC-NEO, main key specifications

Trapil has already identified all of the advantages of Phased Array Technology over conventional UT, and has been operating its XTRASONIC-NEO ILI tool for some years now.

With this kind of Phased Array UT probe multiple features can be used to steer the beams, focus them and scan with a single transducer assembly. Beam steering can be used for mapping components at appropriate angles (Figure 1). This can greatly simplify the inspection of components and defects with complex geometry. Electronic focusing enables the optimisation of the beam shape and size at the expected defect location, as well as the further optimisation of probability of detection. The capability of focusing at multiple depths also improves sizing of critical defects for volumetric inspections (Figure 2).

Focusing can significantly improve signal-to-noise ratio in challenging applications, and electronic scanning across many groups of elements means that C-Scan images can be produced very rapidly.

The aims of TRAPIL's new in-line inspection tool are:

- The improvement of worksite safety and limitation of operating costs and downtime through the use of very small and compact tools; XTRASONIC-NEO is the only combined ILI tool no longer than 1.5m (e.g. from 20" up to 22" diameter). Most of the time, a crane is not required.

- The detection, location, identification and sizing of dents, metal loss features and crack anomalies in water, oil or refined product pipeline in a single run.
- The availability of smart services for specific requests for inspection of dual diameter, bi-directional inspection and short bend radius.
- The measurement of wall thickness in channeling corrosion or damaged inner wall.
- The sizing of crack depth based on the latest methodologies.

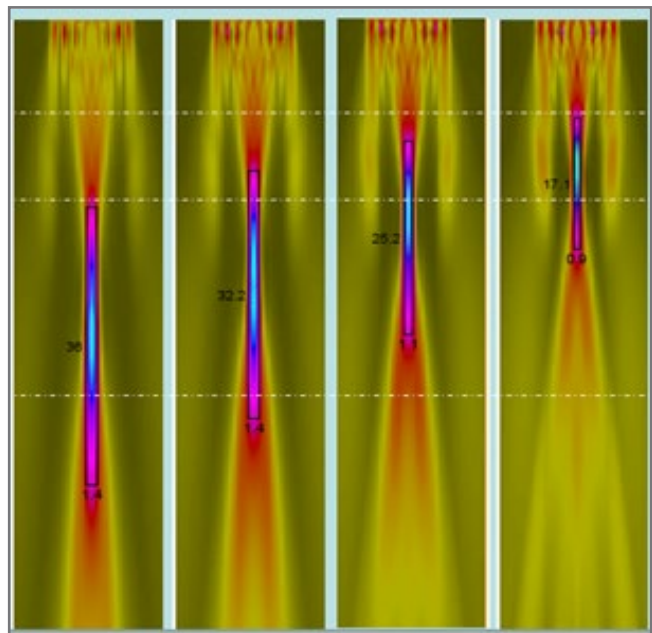


Figure 2: Electronic focusing

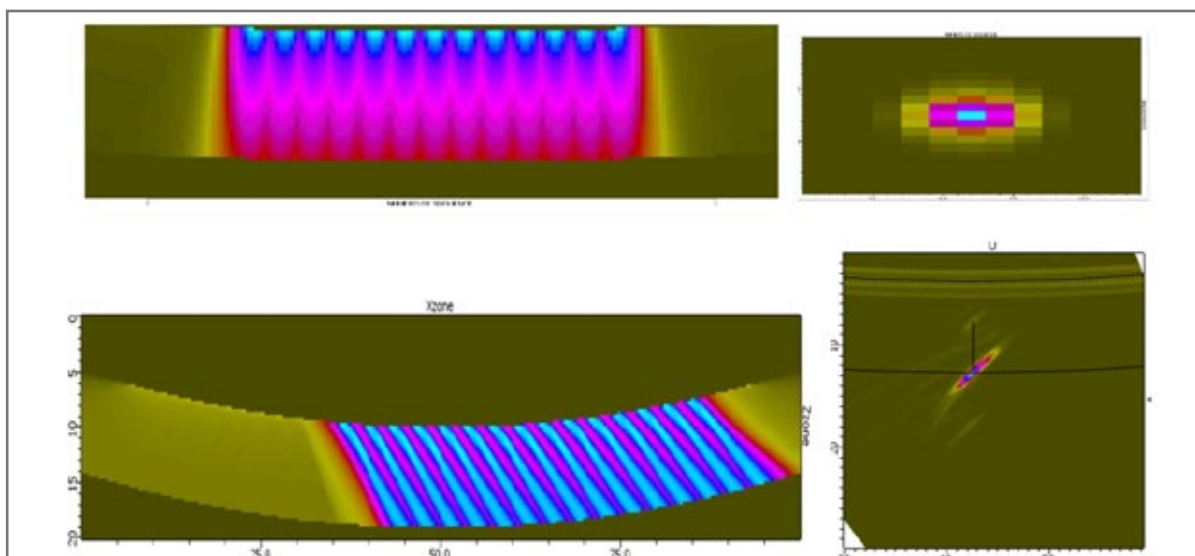


Figure 1: Beam steering (0° longitudinal wave and 45° shear wave on left hand side and defect mapping (corrosion and crack on right hand side)



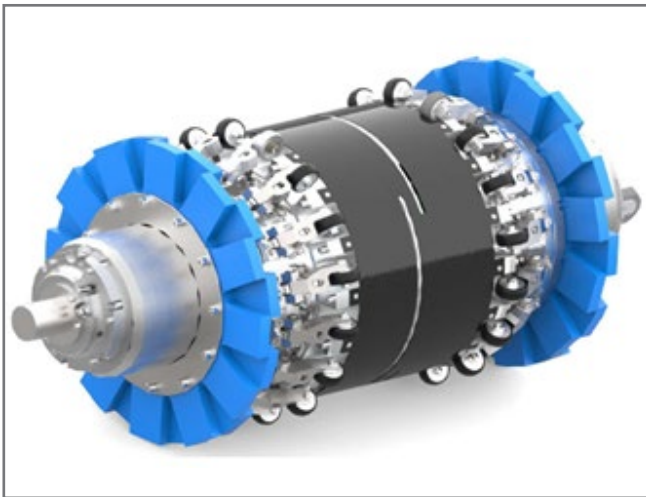


Figure 3: XTRASONIC-NEO 20/22"

## 2. Objectives of the study related to combined defects

Combined defects that may be present in pipelines are a significant hazard and raise particular technical difficulties for their characterization.

Trapil has engaged in a study to evaluate the detection and characterization performance of its XTRASONIC-NEO tool for this type of defects.

This project is divided as follows:

- Establishment of a defects list
- Implementation of the defects on the test bench and sizing this defects using a laser scan in order to establish a reference point
- Evaluation through digital simulations including:
  - modelling of sensors, definition of the nominal acoustic configurations and defects, calculating beam/defect response in Standard Conditions,
  - finding the optimal acoustic conditions and calculating its beam/defect response,
- Implementation of the standard and Optimal Conditions on the XTRASONIC-NEO tool and inspection in real conditions on the test bench
- Analysis and conclusion

## 3. Framework of the study

### 3.1 Establishment of a list of defects

To conduct this study, it was agreed to produce two

different types of dents, dents with an abrupt change in the curvature of the pipe wall or kinked dents and dents with a smooth change in curvature of the pipe wall or plain dents. In addition, it was agreed to associate each of them with a notch and/or a loss of metal in the base material of the tube and/or in the weld area.



Figure 4: Hydraulic press tip (spherical on the left or cuneiform on the right)



Figure 5: Hydraulic press used to simulate the dents on the pipeline

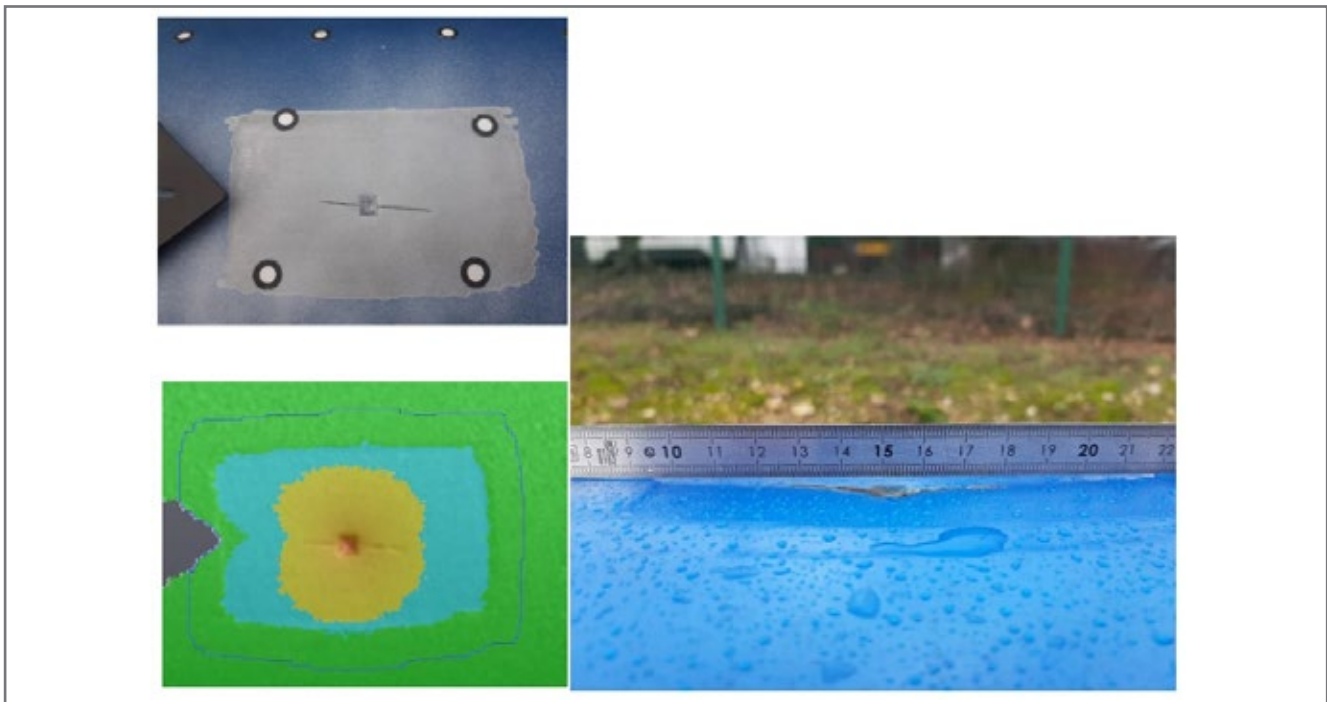


Figure 6: Picture and laser scan of a combined defect (kinked dent) E413

#### Kinked dents:

Kinked dents are often associated with third-party aggressions. They are characterized by abrupt geometric deformation profiles. As a result, it is difficult to obtain a reliable measure of this type of defect. Third-party pipe aggression (such as the bucket blow) is likely to create a sharp kinked dent on the tube. This deformation generates a concentration of stresses in the background favouring the creation/spread of cracks. The objective is to reproduce this type of anomaly on the hydraulic bench in order to evaluate the XTRASONIC-NEO technology response (in the broadest sense: Phased Array inline inspection) in terms of detection and sizing.

#### Plain dents:

Like kinked dents, plain dents with a more spherical-profile display microstructural changes in the stressed material. These changes can result in fragile areas of plastic deformation. These areas are subject to a concentration of stresses and become more sensitive to the creation/spread of fatigue cracks (in pipelines subject to operating pressure cycles).

Unlike the kinked dents, the plain dents has a smooth and steady profile. Today, TRAPIL technologies and analytical methodologies allow the fair detection and

sizing of plain dents combined with loss of metal inside (>90% reliability). Indeed, these combined defects consist in areas of high concentration of stresses (brutal reduction of section - geometric deformation) and therefore also conducive to the formation of cracks.

The objective is to reproduce this type of anomaly on the hydraulic bench in order to evaluate the XTRASONIC-NEO technology (in the broadest sense: Phased Array inline inspection) in terms of detection and sizing.

#### 3.2 Evaluation through digital simulations

To complete this study, TRAPIL used the CIVA digital simulation tool. This software platform allows you to model ultrasonic sensors, acoustic configurations, the tube and defects.

The objective of this theoretical study was to evaluate the detection and sizing performances in "standard" conditions and to propose optimizations of ultrasonic parameters for the studied combined defects. Before introducing the evaluation framework, it may be useful to remind the two UT control modes present on the XTRASONIC-NEO tool. To control the geometry and thickness of the pipeline, longitudinal 0-degree -waves are applied (Figure 7). To detect and size cracks, 45°- shear wave are applied (Figure 8)

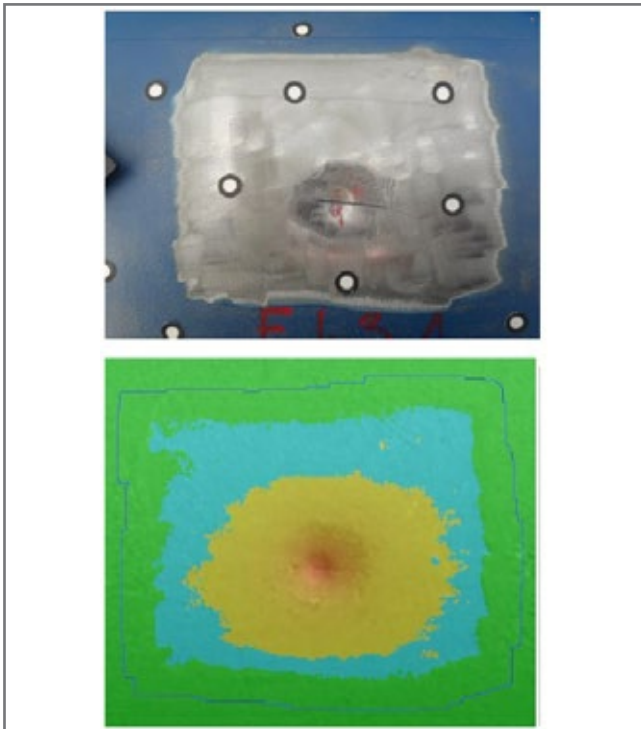


Figure 7: Picture and laser scan of a combined defect (plain dent with a notch)

### 3.2.1. Definition of Standard Conditions

The parameters of the Standard Conditions (Longitudinal wave with an active aperture of 4 elements, without focus and a shear wave with an active aperture of 16 elements and a simple deviation at 45 degrees), developed to allow the detection and characterization of indications in the non-affected area have

limited theoretical performances on spherical dents and insufficient on cuneiform dents.

In fact, the dents have more or less pronounced slopes that involve the deviation of longitudinal waves and therefore significant loss of echoes to the right of the defect, these slopes change the angle of incidence  $\theta_d$  and therefore the angles of the transverse waves that allow the detection of cracks (Figure 9).

### 3.2.2. Definition of Optimal Conditions

The multi-element probes embedded in the XTRASONIC-NEO tool offer many possibilities of settings to conduct this research. It was chosen to limit the variations in parameters as follows:

- The active aperture
- The focus of the beams
- The angle of incidence
- The type of waves

There are other ways to optimize the focal laws for the detection and characterization of combined defects, such as the separate receiving emission on the same multi-elements probe (Tandem, TOFDT, ATFM... etc.) but this is not the subject of the present study because it would require software and/or hardware improvements to the current system.

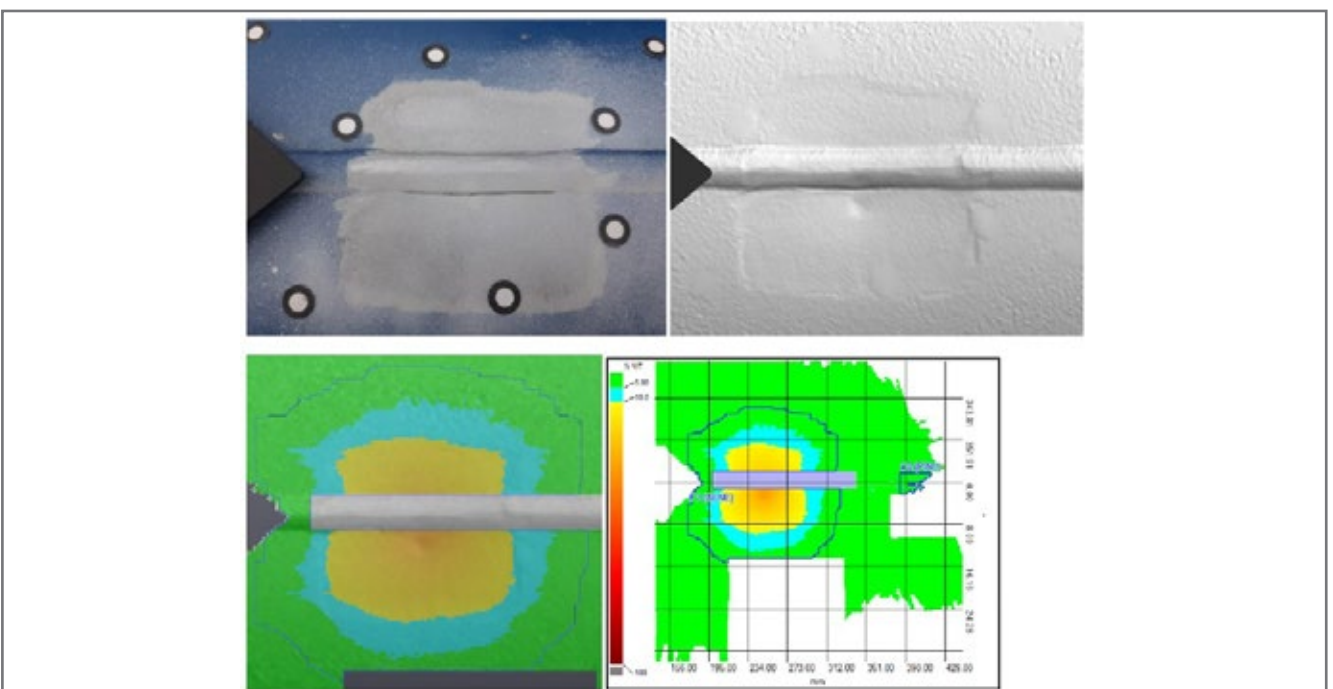


Figure 8: Picture and laser scan of a combined defects (plain dent with a notch on the seam weld) E425



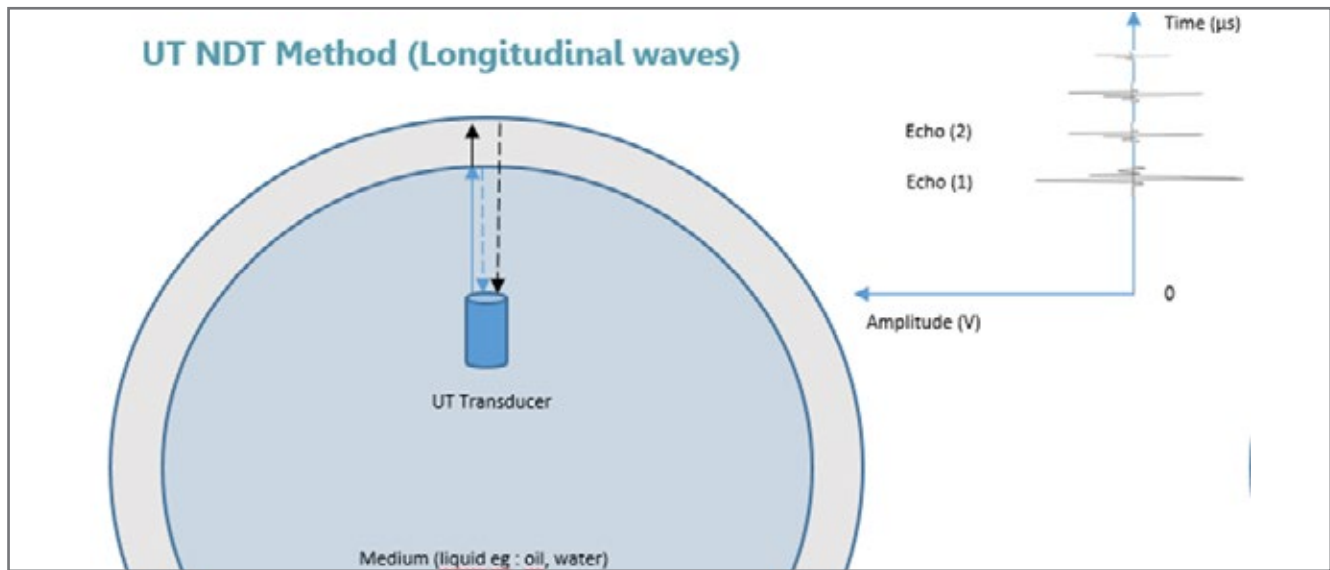


Figure 9: Principle of transmission of UT longitudinal waves 0°

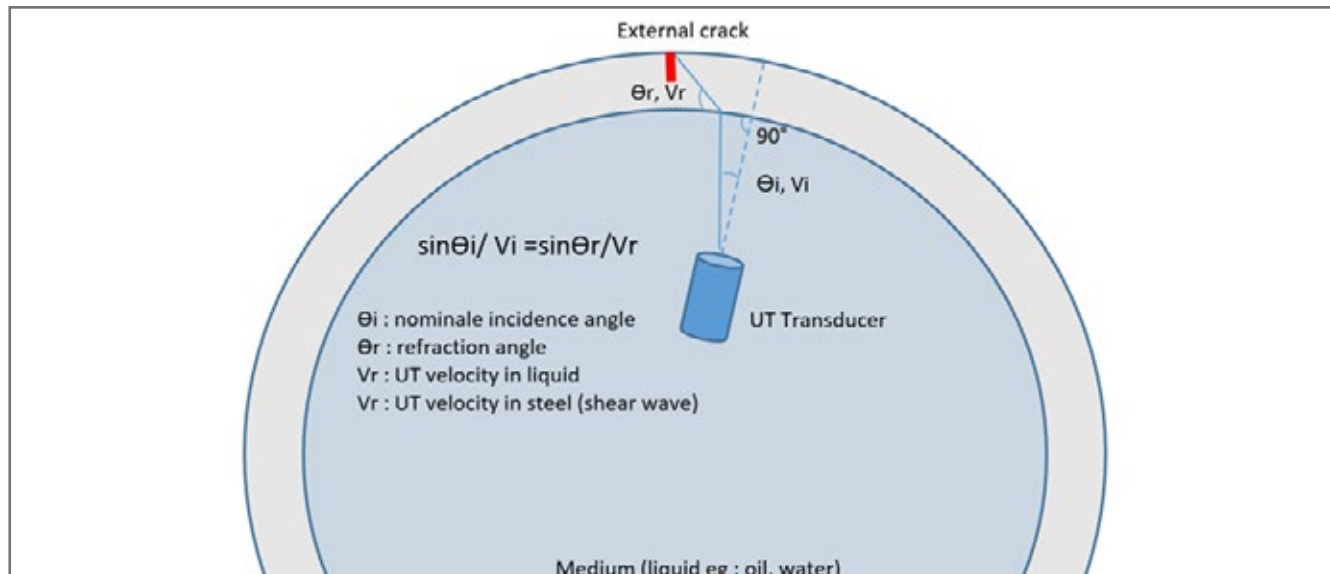


Figure 10: Principle of transmission of UT shear waves 45°

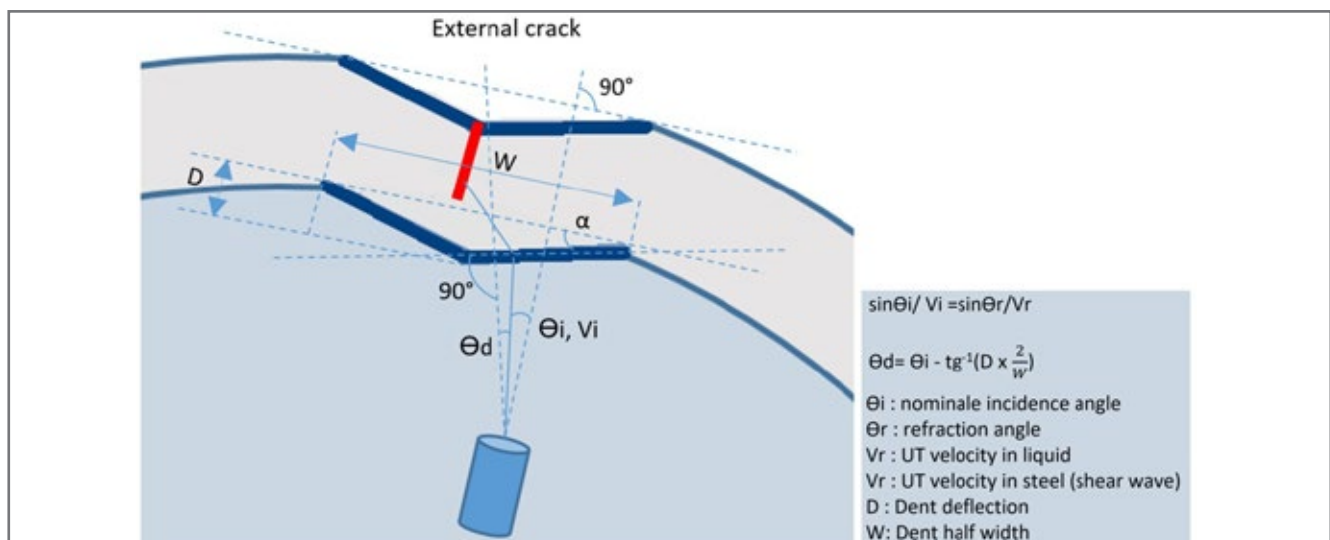


Figure 10: Principle of transmission of UT shear waves 45°

### 3.2.2. Definition of Optimal Conditions

The multi-element probes embedded in the XTRASONIC-NEO tool offer many possibilities of settings to conduct this research. It was chosen to limit the variations in parameters as follows:

- The active aperture
- The focus of the beams
- The angle of incidence
- The type of waves

There are other ways to optimize the focal laws for the detection and characterization of combined defects, such as the separate receiving emission on the same multi-elements probe (Tandem, TOFDT, ATFM... etc.) but this is not the subject of the present study because it would require software and/or hardware improvements to the current system.

These exploratory simulations led to the following conclusions:

#### Kinked dents:

No solution showed improvement considering the current limitations. However, software and/or hardware modifications would open up new paths of reflection, for example with the TOFDT method.

#### Plain dents:

Some solutions made it possible to improve the detection performance at the bottom of the dent. A strategy seems to work for the spherical dent with longitudinal waves at  $0^\circ$  (LW $0^\circ$ ) and shear waves at  $45^\circ$  (SHW $45^\circ$ ): the increase in energy at the level of the dent thanks to the focusing, without altering the reference amplitude (little change in the amplitude of the reference echo in the non-affected area). It results in a better detection performance similar to the one in standard conditions on non-affected areas and an improved detection at the level of the dent. In SHW $45^\circ$ , knowing that the wedge-effect is similar for angles of 35 to 55 degrees, a strategy is to use a  $55^\circ$ -angle on the non-affected area to counter the deviations caused by a spherical dent. Indeed, these features tend to lower the angle of refraction. It was therefore decided : to increase the active aperture from 4 to 8 elements with a 7 mm-focusing from the inner wall for the longitudinal wave; to apply a

70-degree refraction angle in the steel with a 3 mm-focusing from the inner wall for the shear wave (Figure 10 and 11).

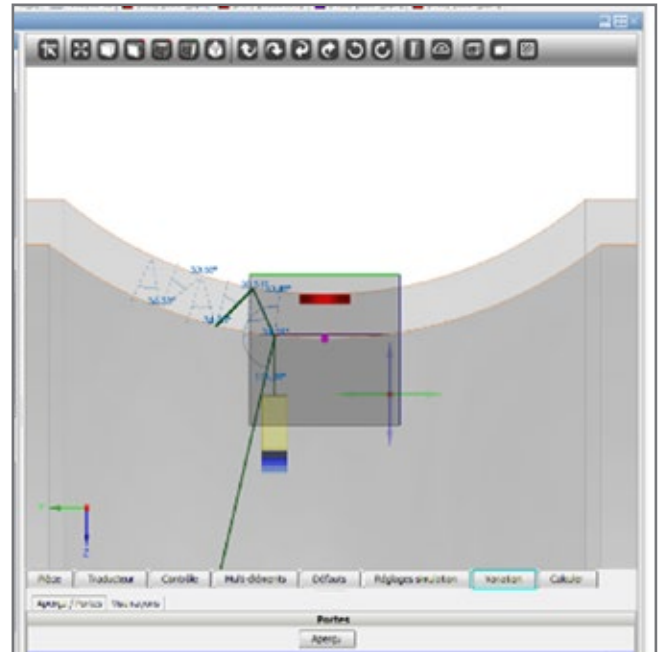


Figure 12: Model of simulation with longitudinal waves LW $0^\circ$  on a dent with metal loss

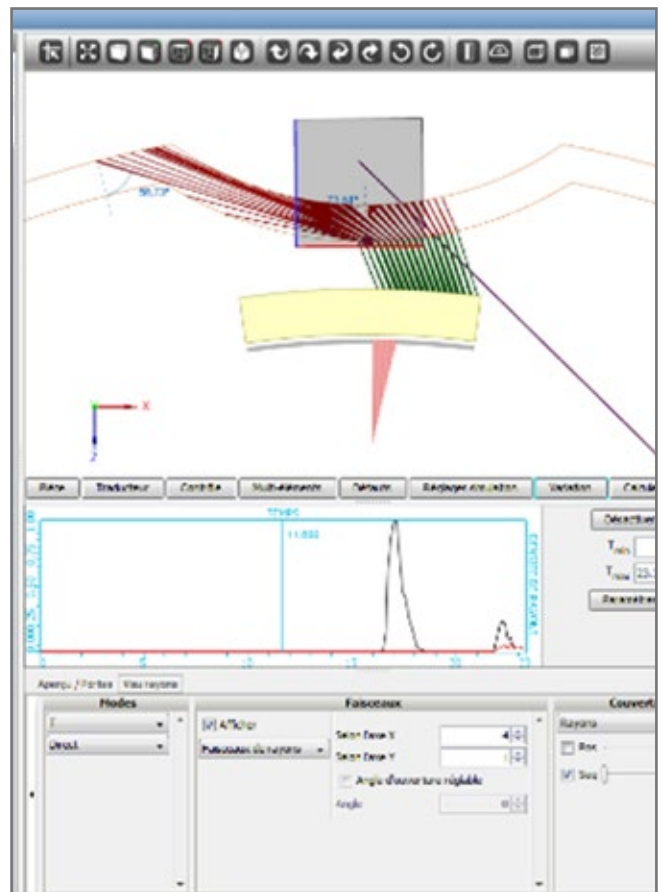


Figure 13: Model of simulation with shear waves SHW  $45^\circ$  on a dent with cracks

### 3.3. Implementation of standard and Optimal Conditions on the XTRASONIC-NEO tool and inspection on the hydraulic test bench

In order to establish the detection and sizing performance of the defects studied, experimental tests were conducted on TRAPIL's hydraulic test bench. Indeed, TRAPIL has a test bench located on its site in Poissy in the Paris region (20"x70m). This bench has several dozen of defects like loss of metal, dents, notches in the base material of the tube, in seam welds and girth welds (Figure 12). For this study, some fifteen additional defects were implanted. The list of defects evaluated in this study was presented previously in table 1.

The XTRASONIC-NEO tool is bi-directional. It was agreed to carry out 7 successive runs based on standard acoustic conditions and 7 runs based on optimal acoustic conditions.

## 4. Results of the analysis

Data from the different inspections were gathered and analysed through a software displaying echoes and amplitudes of the different longitudinal and shear waves.

The flowchart on the next page specifies the different steps of this analysis.

The objectives of this study is to determine the probability of detection and sizing of the XTRASONIC-NEO inline inspection tool regarding combined defects. Two different settings of the tool have been studied: the standard and Optimal Conditions.

Probability of detection (POD) and sizing have to be determined for each type of anomaly composing the combined defect (metal loss, dent, crack-like).

### 4.1. Metal loss

#### 4.1.1. Probability of Detection

The Probability Of Detection, POD, is the probability that a feature with size "a" will be detected by the ILI tool (POF 2016). This probability has to be compared in standard and Optimal Conditions in order to evaluate the performance for each condition.

Table 2 compiles the metal loss anomalies used for this study. As a reminder, those anomalies are located in plain dents with notch. It corresponds to E431, E432, E433, E434 and E435 (Table 1).



Figure 14: Hydraulic test bench in Poissy.



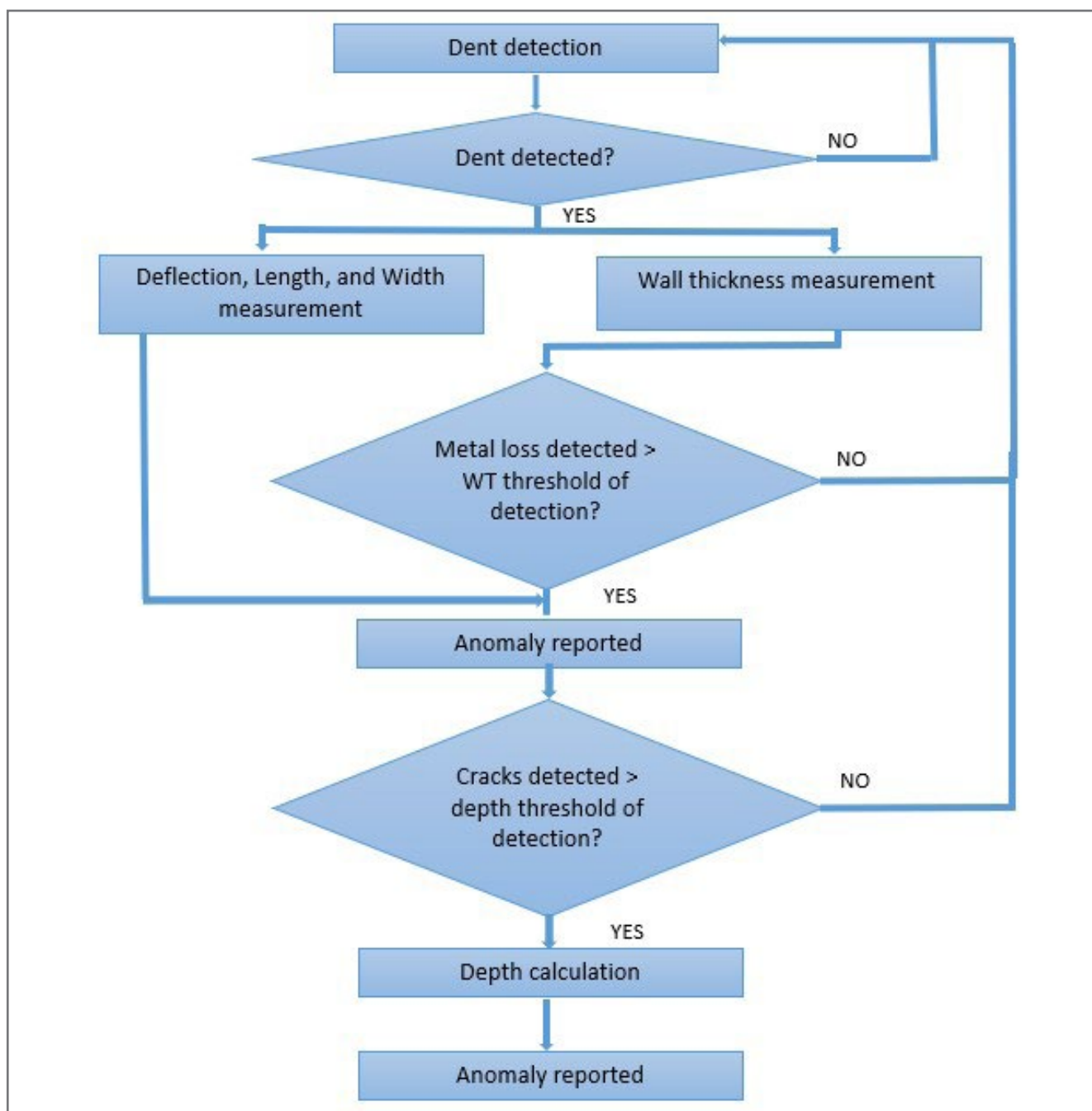


Chart 1: Specification of the different steps of this analysis

Anomaly type	Number on the bench test	Total available	Total detected	% detected	Conditions
External metal loss	5	35	32	91%	Standard
	5	35	34	97%	Optimal

Table 2: Metal loss anomaly statistical sample for POD and sizing

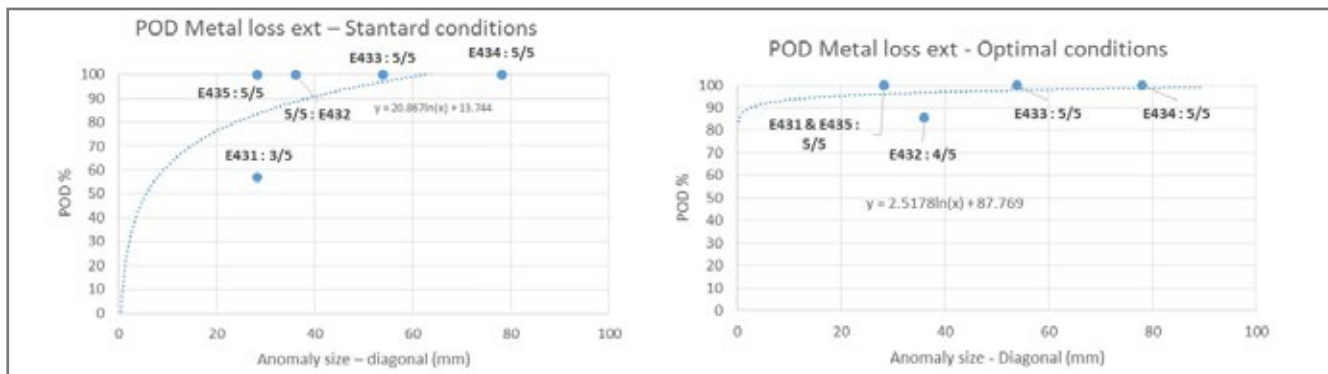


Figure 15: POD of external metal loss in standard and Optimal Conditions

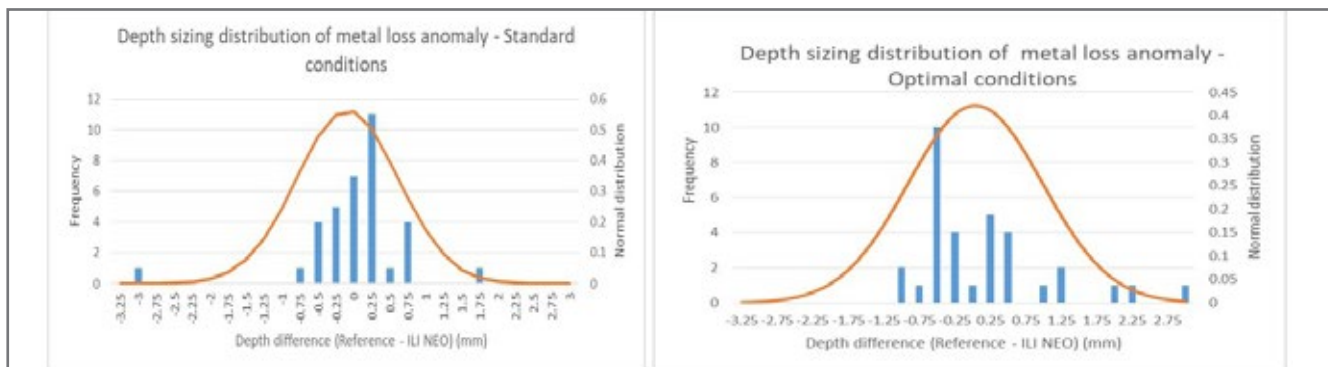


Figure 16: Depth sizing for metal loss with standard and Optimal Conditions

Figure 15 illustrates metal loss size (diagonal in mm) depending on probability of detection under the two different conditions.

Figure 15 enables to conclude:

- Standard Conditions: Metal loss detection at Probability of Detection of 90 % (POD = 90%) requires a minimum anomaly size of 39 mm in diagonal.
- Optimal Conditions: Metal loss detection at Probability of Detection of 90 % (POD = 90%) requires a minimum anomaly size of 2.4 mm in diagonal. Mathematical model enables us to obtain this value, however, we should retain 20 mm which is our tool specification for POD at 90%.

Even if the results are equivalent in both conditions, the Optimal Conditions enable a better POD for metal loss in plain dent.

#### 4.1.2. Sizing

Metal loss sizing was carried out on all anomalies detected in table 2. Depth is the parameter the most interesting to evaluate in this study in contrast to length and width. Metal loss lengths and width could not be

measured into a geometric anomaly.

Figure 16 enables to conclude:

- With Standard Conditions :
  - Average gap : -0.09 mm -> ILI tool tend to be conservative
  - Standard deviation : 0.71
  - Accuracy at 90% certainty : +/- 1.1 mm
- With Optimal Conditions :
  - Average gap : 0.04 mm
  - Standard deviation : 0.94
  - Accuracy at 90% certainty : +/- 1.5 mm

Metal loss in dent sizing results show an equivalent performance in both conditions.

#### 4.2. Dent

##### 4.2.1. Probability of Detection

Table 2 compiles dent anomalies using for this part of the study. For reminding:

Anomaly type	Number on the bench test	Total available	Total detected	% detected	Conditions
External dent	15	105	76	72%	Standard
	15	105	78	74%	Optimal

Table 3: Dent anomaly statistical sample for POD and sizing

- There are two types of dent (plain and kinked) -> 5 kinked dents; 10 plain dents.
- These anomalies are always combined with notch and/or metal loss (in the base material or in the weld area).
- The POD was calculated for all types of dent: it corresponds to all the anomalies in Table 3.

However, Figure 17 (dent size/height depending on POD) shows a difficulty to detect every kinked dent. Indeed, the kinked dents E411, E412 and E415 are not detected because they present a very low height / little deflection (<0.5% OD).

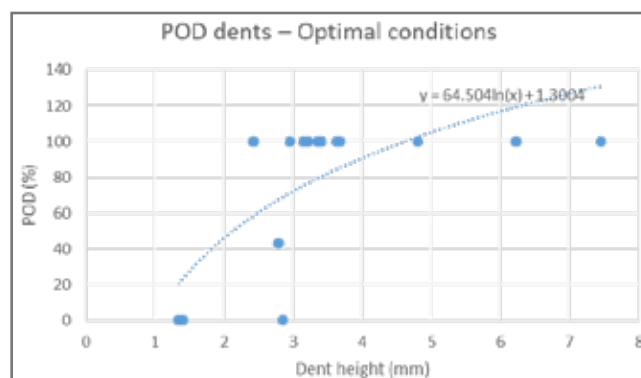


Figure 17: POD of external dent in Optimal Conditions with kinked dent



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Anomaly type	Number on the bench test	Total available	Total detected	% detected	Conditions
External dent	10	70	69	99%	Standard
	10	70	70	100%	Optimal

Table 4: Dent anomaly statistical sample for POD and sizing (excluding kinked dents)

Nevertheless, it can be concluded that the POD shows better results on kinked dents under the Optimal Conditions.

Table 4 compiles the second statistical sample used for POD calculation regarding plain dent. It excludes kinked dents as explained before. Figure 18 illustrates plain dent size (height in mm) depending on probability of detection under the two different conditions.

Figure 18 enables to conclude:

- Standard Conditions: Dent detection at Probability of Detection equals to 90 % (POD = 90%) requires a

minimum anomaly size of 0.05 mm.

- Optimal Conditions: All plain dents have been detected.

However the statistical sample do not contain enough small height dent (< 2mm) to obtain a representative distribution of results. Optimal Conditions enable a better POD regarding dent.

#### 4.2.2. Sizing

Dent sizing was carried out on all anomalies detected in Table 4. Height is the most relevant parameter that must be considered for evaluation in this study.



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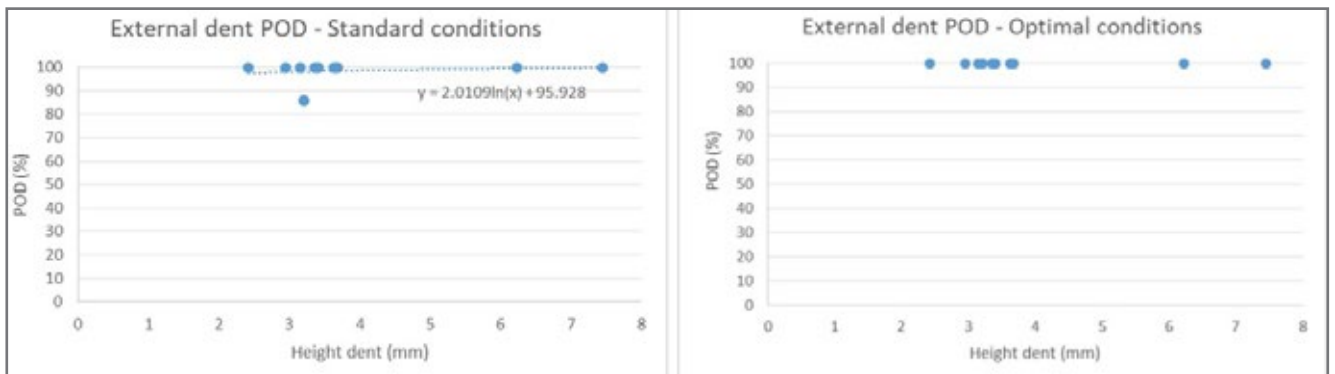


Figure 18: POD of external plain dent in standard and Optimal Conditions

Figure 19 enables to conclude:

With Standard Conditions :

- Average gap : 0.92 mm
- Standard deviation : 0.69
- Accuracy at 90% certainty : +/- 1.1 mm

With Optimal Conditions :

- Average gap : 0.82 mm
- Standard deviation : 0.81
- Accuracy at 90% certainty : +/- 1.3 mm

Plain dents combined with metal loss or/and crack like sizing results show an equivalent performance in both conditions.

#### 4.3. Crack-like feature

Crack like anomalies are the main issue in this study: is it possible to detect and size this kind of anomaly present into a dent or even more, into a dent plus metal loss? This is the topic of the following content.

Statistics takes into account all the anomalies.

#### 4.3.1. Probability of Detection

All the anomalies of the study (Table 1) were retained to calculate the POD and sizing of crack like.

Table 5 compiles the statistical sample of crack likes using for this part of the study. Figures 20 illustrates crack-like size (relative depth = Depth/Pipe thickness) depending on probability of detection under two different conditions.

Figure 20 enables to conclude:

- Standard Conditions: It is unreliable to determine a probability of detection at 90% in this case. The probability of detection of crack-like features depends on the type of dent where they are located. Crack-like features in kinked dent were not detected. We can explain it by the fact that those kinked dents were not detected initially (see the flowchart above, the deflection was too low).
- Optimal Conditions: Crack-like detection at POD = 90% requires a minimum anomaly size of 10% in relative depth not considering the kinked dents that were not detected E411, E412, 415 (see flowchart above).

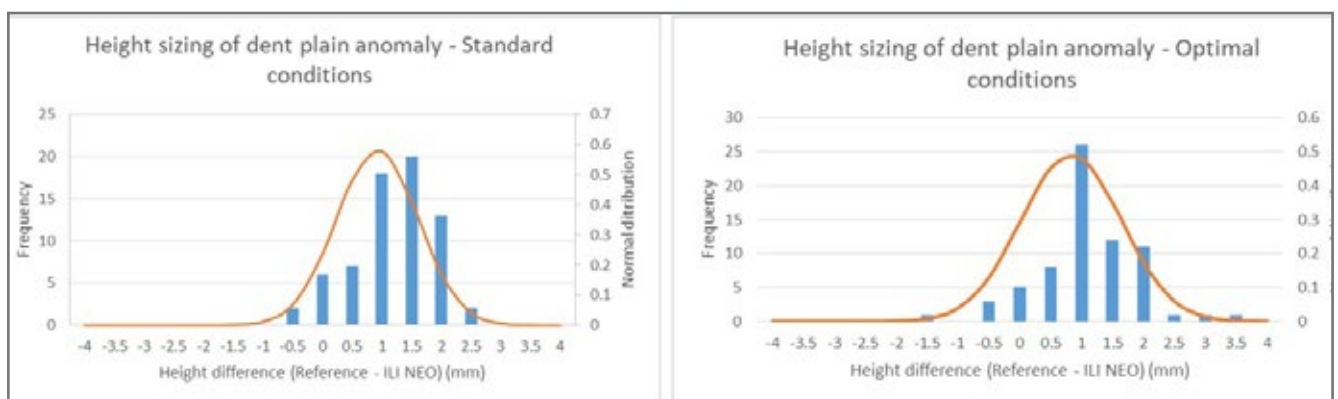


Figure 19: Height sizing for dents with standard and Optimal Conditions

Anomaly type	Number on the bench test	Total available	Total detected	% detected	Conditions
External crack like	15	105	72	69%	Standard
	15	105	89	85%	Optimal

Table 5: Crack like anomaly statistical sample for POD and sizing

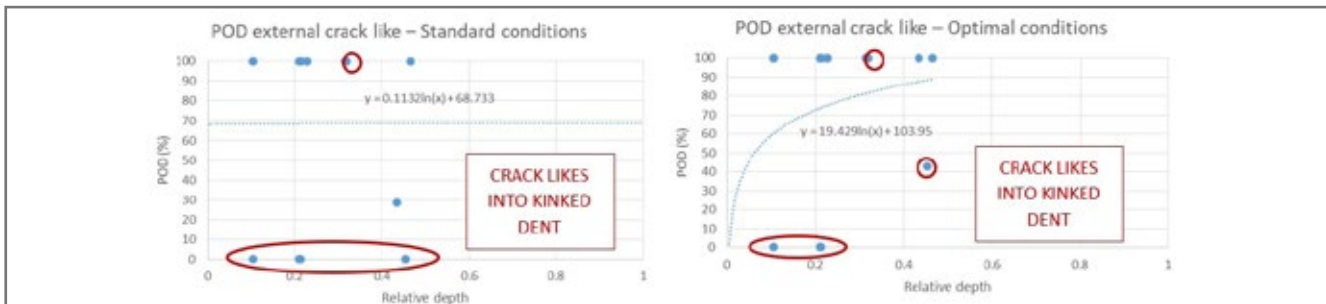


Figure 20: POD of external crack-like in standard and Optimal Conditions (all anomalies)

#### 4.3.2. Sizing

Crack-like sizing was carried out on all anomalies detected in table 5 except those with depth  $\leq 1$ mm (the usual reporting threshold for crack-likes features excluded combined defects). Depth is the most relevant parameter that must be considered for evaluation.

Figure 21 enables to conclude:

With Standard Conditions :

- Average gap : 0.38 mm
- Standard deviation : 1.01
- Accuracy at 90% certainty :  $\pm 1.6$  mm

With Optimal Conditions :

- Average gap : -0.19 mm
- Standard deviation : 1.07
- Accuracy at 90% certainty :  $\pm 1.7$  mm

Crack-like features combined with dents (with or without metal loss) sizing results show an equivalent performance in both conditions. Results show a real capability in the sizing of crack-like features in combined defect (in plain dent as well as in kinked dent).

## 5. Conclusions

This study made it possible to tackle the assessment of combined defects using the Phased Array Inline

Inspection technology embedded in the XTRASONIC-NEO tool and to leverage the great flexibility of its multi-element probes. The theoretical approach of numerical simulation was very useful in targeting the most relevant control modes while offering an optimal configuration which in practice showed its advantages while maintaining good detection performance in non-affected areas. As the experimental results indicate, spherical defects are better detected and characterized through the optimization of acoustic models. Thus, this study makes it possible to establish a POD greater than 90% for combined defects associated with an accuracy at 90% certainty in the measurement of the depth of cracks, metal loss, height of dents close to  $\pm 1.5$  mm. These results are particularly promising compared to that of non-combined crack defects ( $\pm 1$ mm). Kinked dents remain difficult to detect, but other ways were identified and allow us to remain optimistic in order to better characterize them in future developments. This study was performed in a short period of time and will require complementary essays to improve the results. This first stage of validation of the XTRASONIC-NEO technology on a test bench will be pursued and completed with inspections performed under real operating conditions. This will allow to extend this evaluation to real defects while enriching TRAPIL's analysis methods.

### Glossary

**C-Scan:** refers to the image produced when the data collected from an ultrasonic inspection is plotted



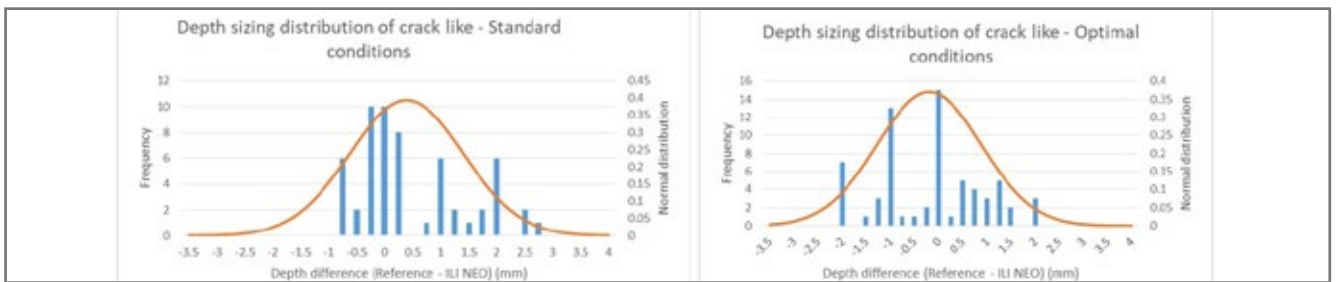


Figure 21: Depth sizing for crack-like features in Standard and Optimal Conditions (all anomalies)

on a plan view of the component. The true definition according to BS EN 1330-4:2000 is the 'Image of the results of an ultrasonic examination showing a cross-section of the test object parallel to the scanning surface.' However, the C-scan does not have to be a single cross-section but often shows a combination of measurements obtained through the whole thickness.

**Combined features/defects:** Features that appear at the same location but at different (Inner and outer) surfaces.

**Standard Conditions:** Longitudinal Wave 0°, active aperture: 4 elements, no focusing and Shear Wave 45° refraction angle in steel, active aperture: 16 elements, no focusing.

**Optimal Conditions:** Longitudinal Wave 0°, active aperture: 8 elements, 7 mm focus of the inner wall, Shear Wave 70° refraction angle in the steel with a 3 mm focus of the internal surface.

## AUTHORS

### Reference

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**Stéphane Benichou**

Trapil

Head of the R&D ILI Department

[sbenichou@trapil.com](mailto:sbenichou@trapil.com)



**Arnaud Lemaire**

Trapil

Head of the ILI Department

[alemaire@trapil.com](mailto:alemaire@trapil.com)



**Timothée Heraud**

Trapil

Head of the Product Quality and Measurement

Department

[theraud@trapil.com](mailto:theraud@trapil.com)

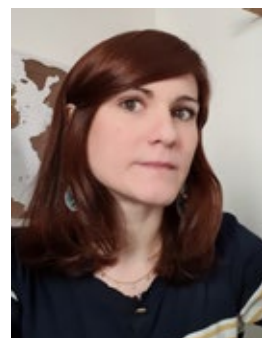


**Chloé Senah**

Trapil

Head of the ILI analysis Unit

[csenah@trapil.com](mailto:csenah@trapil.com)

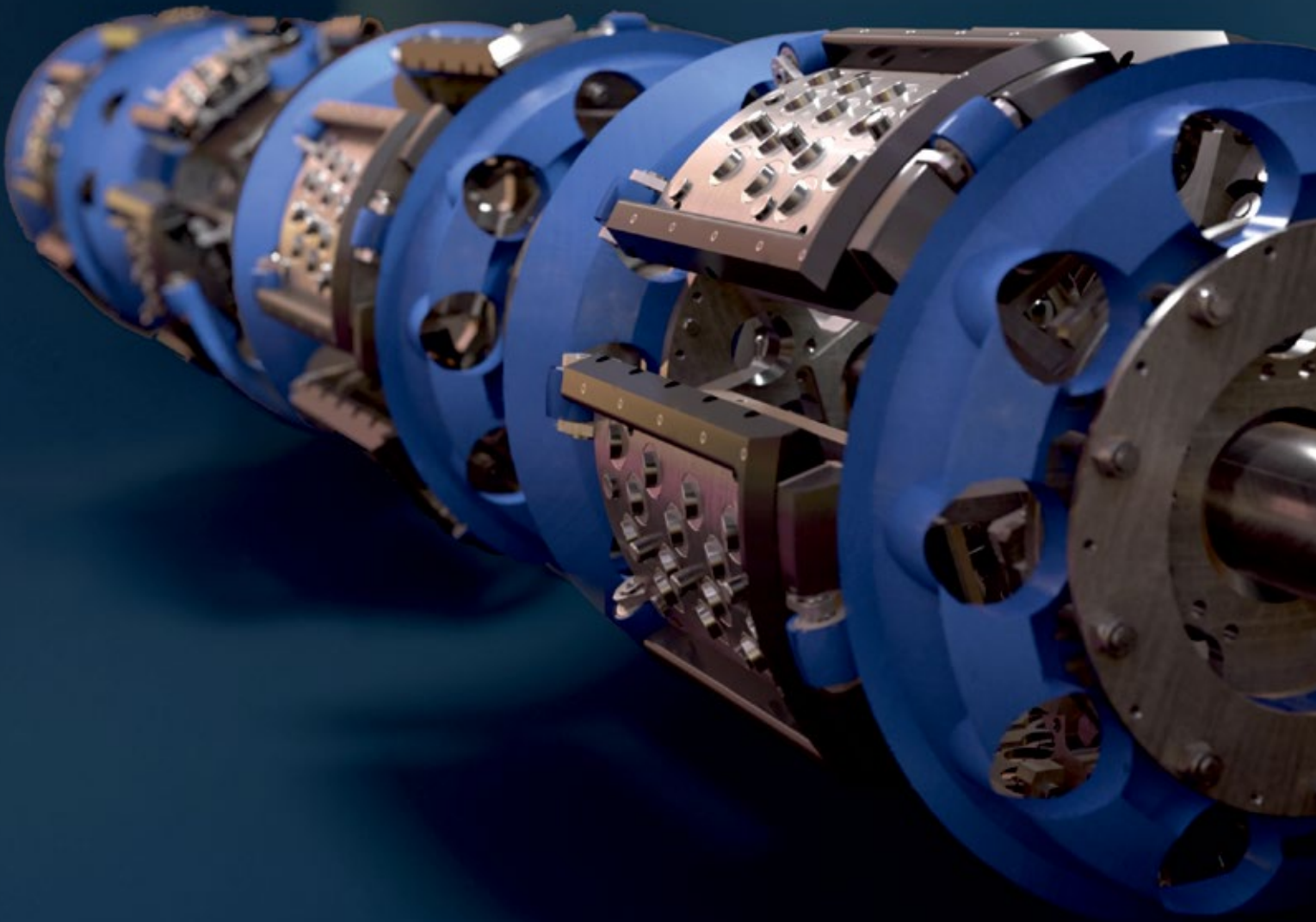


**Manon Servais**

Trapil

Strategy and New Business Development Manager

[mservais@trapil.com](mailto:mservais@trapil.com)



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## Progress and challenges in pipeline theft detection

H. SMITH > ATMOS INTERNATIONAL

### Abstract

In recent years, the global pipeline community has made a lot of progress in detecting and locating theft activities. Technologies have been developed and applied to several pipelines worldwide. While these technologies are contributing significantly to the early detection and location of illegal tapping points, the key challenges vary from one country to another. The main consequence reduction factors span social, economic, political and legal situation in each region.

Sophisticated evolutions in illegal tapping operations also play a major role in the need to have an advanced theft detection system. This paper will review the progress made in theft detection and the strategies different pipeline operators use. It also discusses the key challenges in specific parts of the world in addressing pipeline theft activities.



## 1. Introduction

It is estimated that \$133 billion worth of crude oil and refined products are stolen or adulterated each year<sup>1</sup>. Pipeline theft is common in countries such as Nigeria, Mexico, Iraq, Indonesia and Russia<sup>2</sup>. However, since 2010, there has been a rise in theft activity globally including in Europe and other regions with countries such as Belgium, Turkey and the United Kingdom being affected.

The 2019 Tlahuelilpan pipeline explosion in Mexico stressed the serious consequences of illegal tapping points, demonstrating the impact theft activity had on networks by weakening the infrastructure.

Significant improvements have been made in the last few years to provide futureproof technology to pipeline operators that stay ahead of evolving theft methods. One of these technologies has been leak detection systems (LDS). These systems have undergone extensive hardware and software improvements to help improve theft detection capabilities. This has been through non-intrusive hardware, battery powered sensors for remote and high consequence area (HCA) pipelines and offline data analysis services.

These technologies have been deployed on many pipelines around the world and have been successful in detecting and locating tapping points. In some cases, these solutions have helped to reduce and even deter further theft activity.

This paper will explore the improvements that have been made to theft detection technology and how they have been applied to different countries around the world.

## 2. Sophisticated pipeline theft operations

Pipeline thieves are well organized and run sophisticated operations. Their resources include commercial grade welding equipment, measuring instruments, night vision goggles and vans with modified suspension or exit holes in the floor. They are also well trained, with the engineering skills and knowledge needed to avoid detection. There are a host of different tactics thieves use when stealing from pipelines:

- Pre-installing the tapping point, hose, associated valves and equipment before a pipeline is commissioned
- Selecting remote and well-hidden sites such as abandoned buildings eg farms
- Burying and covering the hose pipe and all other devices underground
- Opening theft valves very slowly to generate small pressure change over a long time period ("the patient thieves")
- Maintaining the theft rate below flow meter repeatability level. Eg 0.1% of pipeline throughput
- Carrying out the activities at night
- Stealing often but small volumes each time
- Injecting water into the pipeline while taking oil out
- Performing thefts at multiple locations along the same pipeline
- Using dangerous techniques including angle grinding and plastic equipment
- Adapting vehicles such as old milk tankers or vans with upgraded suspension to handle the weight of fully filled IBCs (Intermediate Bulk Containers)
- At worst thieves drive a stake into a pipeline and use rags or clothes to slow the flow out of the pipeline

With this wide variety of tactics, there are three core requirements of a theft detection system:

- Sensitivity: detecting the small product withdrawal
- Accuracy: locating the tapping point as accurately as possible
- Response time: detecting the product withdrawals as quickly as possible

In the following sections we will discuss the theft detection solutions that meet the above requirements:

- Negative pressure wave
- Statistical volume balance
- Theft Net service

## 3. Negative pressure wave

The negative pressure wave (NPW) method used by Atmos Wave provides a high rate of sensitivity through the 60 Hz sample rate. This technology relies on high-speed analog pressure sensor readings to identify whether a leak or theft has occurred. This type of system acquires and analyzes the pressure data

at a frequency much higher than the typical 5 second Supervisory Control and Data Acquisition (SCADA) rate, capturing data at 60 samples a second (60 Hz)<sup>3</sup>. Specialized equipment is needed to acquire data at such a high frequency.

The high acquisition rate allows the opening and closing of theft events to be detected and located, even when the valves are opened and closed slowly to avoid arousing suspicion.

As Han and Kim<sup>3</sup> pointed out, the main advantages of this system are:

- Accurate leak location within meters of the actual location
- Short detection time for all leak sizes
- High sensitivity provided through the 60 Hz sample rate

These are the key features in effectively detecting thefts in all operating conditions. Figure 1 shows an example of theft events being detected by the NPW system.



Figure 1: An example of a theft event generating 0.1 bar pressure drop

A further improvement has been the advancements in hardware options. Solutions such as Atmos Eclipse have been developed to provide non-intrusive flow, pressure and temperature measurement instrumentation that has cellular, radio and standard RS485 and ethernet communications. This allows theft detection systems to be deployed on pipelines with limited instrumentation or on pipelines where additional hardware will improve the performance of the system.

In remote locations where power and communication are an issue it can be challenging for pipeline operators

to deploy technology to detect pipeline theft activity. Atmos Odin is a battery powered data acquisition unit with an internal pressure sensor that can be deployed in these types of locations.



Figure 2: Atmos Eclipse installed

The internal GPS acquires an accurate location and time lock while Atmos Odin is transported to the installation site, the device will then continually log the GPS data with measurements from its internal pressure sensor for up to 21 days. Data collected by Atmos Odin is then analyzed by Atmos engineers.

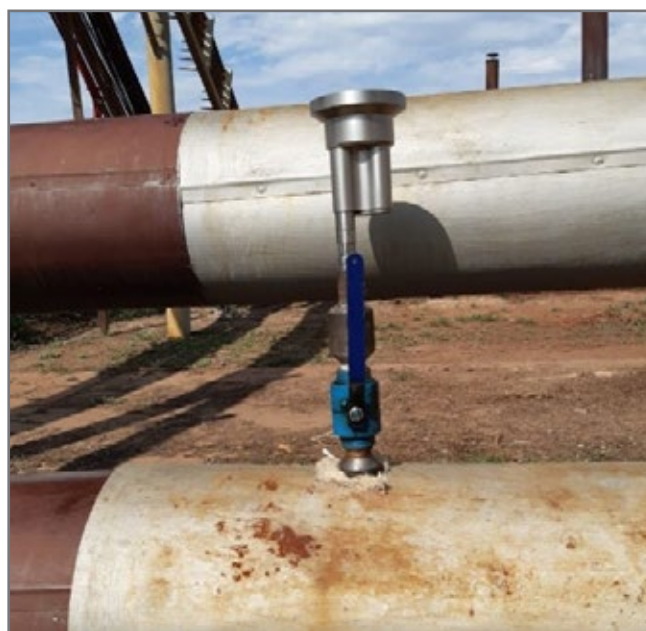


Figure 3: Atmos Odin installed

#### 4. Statistical volume balance

This type of LDS relies on the pressure and flow measurements taken from a pipeline. It uses the existing instrumentation and connects via existing SCADA, Programmable Logic Controller (PLC) or Remote Terminal Unit (RTU) systems. This system monitors the difference between the inlet and outlet flow corrected by the inventory change. This is also referred to as the Corrected Flow Difference to determine whether the pipeline is in a leak condition.

The statistical hypothesis testing method is known as the Sequential Probability Ratio Test (SPRT)<sup>3</sup>, it is applied to the corrected flow difference to decide if the probability of a leak has increased.

The main advantages of this system are:

- Low false alarm rate
- Detecting leaks under steady-state, transient and shut-in conditions
- Accurate leak size estimate
- Leak location accuracy improved through higher data sample rates

The location accuracy is improved through the higher data sample rates. In addition to this, adding Atmos Wave Acquisition System (AWAS) units to a statistical

volume balance system like Atmos Pipe enables fast scanning, improving the leak location to be as accurate as +100 meters with correct conditions. Fast scanning can also be added by connecting to SCADA systems that support historical reads using OPC UA, allowing pressure data reading at a higher rate (50 ms to 100 ms).

Since the theft rate is usually below the flow meter accuracy and repeatability level, it is difficult for this technology to detect small thefts under running conditions unless false alarms are accepted. The system includes an additional theft module for detecting thefts during shut-in conditions to maintain reliability for both leak and theft detection. Figure 4 shows an example of it working.

#### 5. Atmos Theft Net

As theft rates become smaller, it becomes necessary to lower the minimum leak size for the theft activity to be detected. However, in doing this, it can result in an increase in false alarms as the identified flow and pressure are mostly below the instrument repeatability and process noise level.

Atmos Theft Net is an offline service that allows improved leak location accuracy and sensitivity without unnecessary false alarms. The service combines portable and fixed hardware and software solutions with offline data analysis by an experienced engineer. The engineer's ability to interpret data helps theft to be located down to a few meters. Atmos Theft Net uses pressure data collected at 60 Hz sample rate and sent to a central location via a cloud-based service.

The data is then filtered to present only the relevant information required and the locations of the illicit tapping points are reported to the pipeline operators.

Atmos Theft Net has been operating for a few years and substantial knowledge and insight have been gained through the delivery to clients. Combined with improved technology and hardware, the service provides a high-level of reliability.

It is well documented that online leak/theft detection systems have to find a balance between sensitivity and false alarms<sup>3,4</sup>. Some leak detection systems

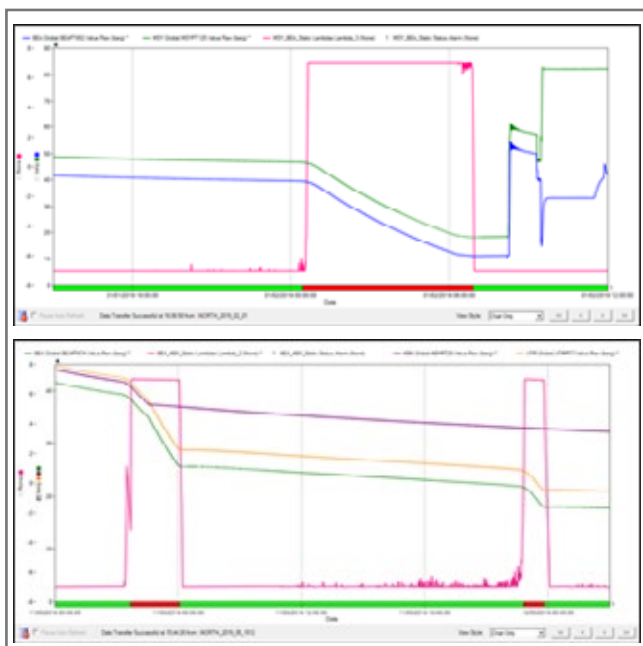


Figure 4: Data showing statistical theft detection during shut-in period (red bar at the bottom indicates a theft alarm)



can detect leaks as small as 0.5% of nominal flow-rate without the issue of false alarms. However, this becomes an issue as the majority of theft events are less than 0.3% of the nominal flow-rate. The capability to analyze the data offline has allowed the location and detection of theft to within 5 meters for thefts as small as 0.1% of the nominal flow-rate in static and running conditions.

Combining Atmos Theft Net with a single or multi method online leak detection system allows for a more reliable theft detection system with the ability to effectively deal with all types of theft events. In the last two years, this combination of negative pressure wave, statistical volume balance and offline analysis has successfully detected and located over 900 tapping points worldwide.

## 6. Detecting thefts globally

The LDS technologies discussed in this paper have been applied to theft detection on numerous pipelines all over the world, including regions such as South

America, Europe, and Africa. The use of Atmos Theft Net and LDS has led to the detection and location of many illegal tapping points, such as an oil withdrawal through a 12 mm hole that was attached to a 1.5 km (0.9 mile) long underground hosepipe in Europe.

The theft detection systems have even detected the theft of samples between 10 and 20 liters of product from some pipelines during static conditions. These small samples are usually extracted to check what fluid is in the multi-product pipeline before a full product withdrawal is commenced.

The combination of intrusive and non-intrusive hardware has led to the detection and location of a 2 inch tapping point with a leak location accuracy of 40 m. Use of the battery powered portable data logger Atmos Odin has led to the detection of a tapping point in Congo with a leak location accuracy of 20 m. Figure 5 shows the tapping points located.

Theft detection equipment was installed in India to locate a tapping point that had been active for 9 weeks.



Figure 5: Selection of tapping points located by Atmos Odin in Congo

The system provided a location accuracy of 10 m. The tapping point was buried inside a man-made tunnel.

In Mexico several tapping points have been detected and located by the theft detection systems, in some cases stopping fuel tankers being stolen (30,000 L). One theft location uncovered equipment that had been stolen from the pipeline itself, in an attempt to try and sabotage the theft detection system. In more serious cases, a pipeline rupture has been detected and located quickly in Nigeria when illegal pipeline activity went wrong, causing a fire on the pipeline.

Several examples will be presented to illustrate the difficulties and successes that come with detecting and locating tapping points.

### 7. Example 1: Theft with double taps

In the space of four months in 2019, two theft events were detected in the UK by both statistical volume balance and negative pressure wave systems with the leak location improved further using offline data analysis (Atmos Theft Net). Both theft events had a leak location error of less than 50 m.

The thefts were found on a multi-product pipeline with varying diameters of 6-14 inches across a total network length of 650 km. Small quantities of product were stolen during both events. A total of 4 m<sup>3</sup> was removed before the tapping point was located. These events were detected in minutes of the tapping point being opened by the online leak detection systems, however, locating them took a few days due to the thieves hiding their activities very well.



Figure 6: Tapping point exposed by the pipeline operator

These events highlight the sophistication that the thieves will go to remain hidden and how they can avoid being detected by using a double tapping point technique.

### 8. Example 2: Theft activity that is hard to locate

This example highlights the difficulty that often faces pipeline operators when they are trying to find an illegal tapping point. The theft detection system provided a location accuracy of 20 m. Figure 7 shows the aerial view of the pipeline section where the tapping point is located.



Figure 7: Aerial view of the buried pipeline section

The tapping point was so well hidden by the thieves that nothing was visible externally. The pipeline operator completed a line walk along the pipeline and they could not see any sign of the tapping point.

A surveillance team was set up to monitor the area during the night. In the morning they located the tapping point very close to the walk pathway. This tapping point has been buried in a farmland and the hose has been trenched to keep it well hidden.

### 9. Example 3: Theft detected using non-intrusive hardware

Atmos installed a leak and theft detection system on a pipeline in Europe. The pipeline is 12 and 8 inches with a total length of 105 km transporting multi-product. Due to limited instrumentation at one of the stations a non-intrusive Atmos Eclipse unit was installed to provide pressure readings. This unit paired with an intrusive sensor at another station helped to detect multiple theft events.



Each time, the thieves would steal up to (6000 L). The location provided by the system was 40 m away from the actual 2 inch tapping point. This theft highlights that even with limited instrumentation on the pipeline, non-intrusive hardware can be installed to achieve the high levels of sensitivity and accuracy required for a good theft detection and location system.

#### 10. Example 4: Theft operations in Mexico

A tapping point was found 60 m from the location reported by the theft detection system. The pipeline operators found a sophisticated theft operation due to a burnt-out truck near the extraction point. Stolen pipeline equipment was also located at the site, this was likely used as an attempt to outsmart the theft detection system.



Figure 8: Selection of images showing theft activities discovered in Mexico

#### 11. Key challenges to address pipeline thefts in specific parts of the world

While the theft detection systems have located hundreds of tapping points and counting in Costa Rica and over 30 tapping points in the UK, these countries have had different levels of effectiveness to their theft problem due to different challenges faced.

Theft prevention strategies have been so effective in the UK that the theft numbers were reduced from the high of 17 in 2015 to 0 in 2020. The same can be seen in most of Europe where there has been a clear reduction in theft activity due to a combination of theft detection technology, law changes and proactive actions by

pipeline operators. With increased line walks, fly overs, operator training, stricter punishments for theft activities and better government and police backing. As discussed in the latest ConcaWE report (Performance of European cross-country oil pipelines May 2021) these efforts have paid off and the trend of theft activities has been reducing since 2016 from 112 events to 13 in 2019, with a provisional 8 incidents reported in the first 9 months of 2020<sup>5</sup>. Even with this success continued focus is required.

Pipeline theft is a deeply entrenched problem in some countries, due to the ongoing social, political, and economic issues. These circumstances create dangerous non-state actors and organized crime groups like Mexican drug cartels, the Italian mafia, Eastern European criminal groups, and Nigerian rebels. For example, Pemex in Mexico loses an estimated \$1.3 billion per year through 13,000 fuel thefts. Pipeline operators in Nigeria are also hit hard by theft activities, estimated loss at \$18 billion per year<sup>1</sup>.

The theft problem remains severe in Costa Rica<sup>6</sup> and other countries due to organized crime groups targeting the pipelines to finance their expanding operations with relatively low criminal punishments. High fuel prices in the country have also seen increased makeshift gas stations appearing to sell stolen fuel<sup>7</sup>.

A thief can be paid up to 3 million colons (about \$5,000) to install a tapping point, this is much higher than the average monthly salary in the country. In 2019 the police response had largely been ineffective most often resulting in just the capture of young men carrying out the thefts instead of the organized crime groups. A record number of thefts were seen in 2019 as the police were also dealing with a spike in violence, drug trafficking and human smuggling. This highlights that resourcing has been a major influence<sup>6</sup>.

Another factor is ease of access to the pipelines in remote areas. In Europe, most of the illegal tapping connections were found in open countryside<sup>5</sup>. A large percentage of Costa Rica pipelines are remote and above ground making them easier to target by thieves.

However, there is some light at the end of the tunnel in Costa Rica since 2020 when the Legislative Assembly approved a new law that more strongly punishes



crimes related to the theft of state fuel, as well as for trafficking or receiving illegally obtained products<sup>8</sup>.

Causing damage to the national fuel system will be punished with a prison sentence of six months to four years, and if the act causes a spill, the penalty will range from four to six years.

The theft of fuels will be punished with a prison term of 5 to 15 years. For the illegal transportation and distribution of fuels, the penalties range from one to four years in prison, while for the receipt of illegally obtained fuels it is punishable from one to five years in prison.

With the advancements in technology and law changes Costa Rica could see a reduction over the coming years though the economic and social factors also need to be reviewed and considered.

## 12. Conclusions

It is important to differentiate theft from leak detection. Theft detection not only requires high sensitivity but also expert analysis as well as specialist technologies. As thieves continue to use multiple methods to avoid being detected, with theft rates below 0.3% of the nominal flow-rate, theft detection systems must become more sensitive than when they were originally designed.

Using a multi-method approach with both effective leak detection and offline analysis (Atmos Theft Net) has enabled LDS to become more sensitive, therefore enabling them to detect small volumes of product loss. Theft location accuracy has also dramatically improved down to a few meters. New hardware such as non-intrusive sensors and battery powered data loggers allow for more pipelines to be covered than previously thought possible.

Countries like the UK have adopted a layered approach to theft reductions, combining new technology with law changes and aligning government and police forces onto the issue. Theft can be a complex issue for many countries, with the likes of Mexico and Nigeria facing challenges of tackling the social, economic, and political issues that are intertwined with pipeline theft.

Technology such as theft detection systems will always play a part in successfully uncovering theft activities. That's why it's vital to implement a system where advancements are made as thieves' tactics change and improve. There has been good progress made in theft reduction but there's more that can be achieved.

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## AUTHOR



**Harry Smith**

Atmos International  
Sales and Senior Research Engineer  
[harry.smith@atmosi.com](mailto:harry.smith@atmosi.com)

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