IN-LINE INSPECTION, THE MISSING LINK IN FLEXIBLE PIPE INTEGRITY MANAGEMENT

Paul Birkinshaw, ROSEN UK & Tom Steinvoorte, ROSEN EU

Abstract

In-line inspection (ILI) has been widely adopted as a key source of data for the integrity management of traditional rigid steel pipelines. In the case of flexible pipelines however the deployment of ILI technologies remains an unfulfilled aspiration.

After some early investigations within ROSEN into the development of an ILI tool that can inspect multi-layer unbonded flexible pipes, a more focused R&D project was kicked off in 2019. This initiative resulted in significant progress in understanding the key inspection challenges and also resulted in the adaptation and development of existing technologies to be able to provide a base level of inspection in flexible pipes.

Since this time, ROSEN has also significantly enhanced capabilities in the deployment of different inspection technologies in a number of challenging offshore applications.

This paper provides an overview of the challenges faced by operators in managing flexible pipe integrity, the current state of development in ROSEN's flexible pipe ILI capabilities and then explores some of the potential [and perhaps novel] solutions for deployment of such inspection systems.

1 BACKGROUND

Globally there is now a large quantity of flexible risers in operation (dynamic applications), with a significant number approaching or exceeding their original stated design life (estimated to be 75% exceeding 15 years of operation). Additionally there is a large number of installed subsea flexible jumpers and production tie backs in operation (static applications), with an increasing trend to select flexibles for such applications. Moreover, in many cases these assets now exceed the original stated design life and it is becoming necessary justify life extension to align with extended field life.

An ongoing challenge for operators is therefore to develop and implement robust and cost effective Integrity Management (IM) strategies to ensure that these critical assets are being operated correctly, failure risk is minimised and the desired remnant life is attained. A significant missing link in this for flexible pipes (when compared to rigid pipeline systems) is the availability of an ILI tool that can inspect multi-layer unbonded flexible pipes.

2 CURRENT FLEXIBLE PIPE IM PRACTICE

IM practice for existing flexible-pipe systems is steadily evolving, from distinct approaches adopted by individual operators, to methods more akin to those adopted for rigid pipelines. This includes tailored asset integrity management approaches (sometimes coined as Flexible Integrity Management Systems or FIMS) to define the key inspection, monitoring and testing routines to be implemented.

Currently the following key elements can typically be recommended within a generic FIMS cycle targeting flexibles:

- Monitoring operating conditions and bore fluid composition
- Visual inspections
- ROV inspection
- Annulus testing
- Vessel motion and weather monitoring

Other possibly less common items include:

- Annulus gas sampling / monitoring
- Polymer coupon aging checks
- External scanning systems
- Magnetic stress measurement tools
- Flexible riser fatigue analysis

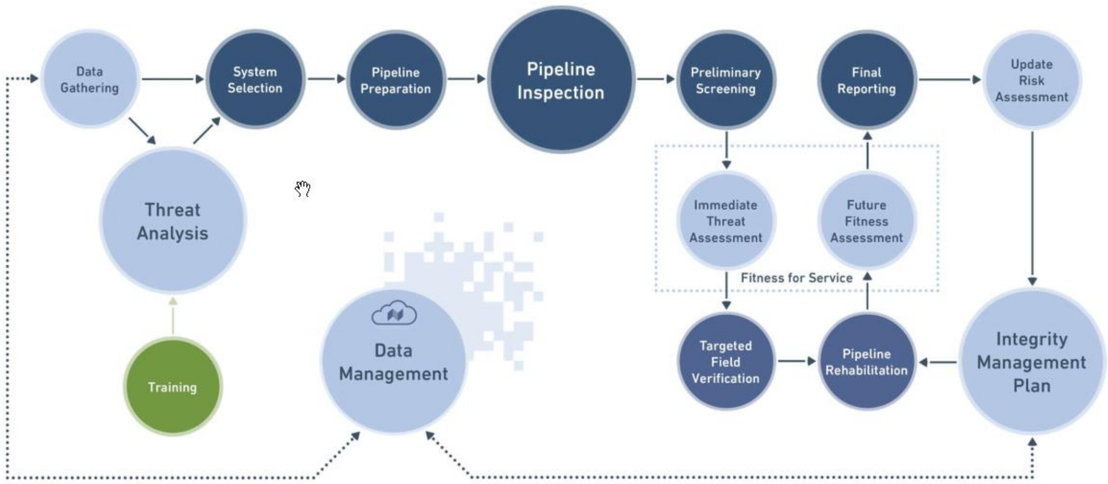
At present using ILI tools is not considered to be a 'go-to' inspection option for flexible pipe sections.

Ultimately, in any overarching asset integrity management system (AIMS) process there is a symbiotic relationship between an AIMS process and the asset inspection requirements.

In the case of rigid pipelines, ILI technologies have needed to evolve extensively over time to be able provide reliable high resolution condition data to facilitate operational integrity decision support within a Pipeline Integrity Management System (PIMS). This interdependence can be seen in Pipeline Integrity Framework adopted by ROSEN in Figure 1, with threat assessment always a key input to pipeline inspection tool (or method) selection.

Over time, this has led to the development of an extensive range of sophisticated ILI tools to address a wide range of key threats and associated pipeline degradation mechanisms including corrosion, geometric anomalies, pipe material properties and cracks.

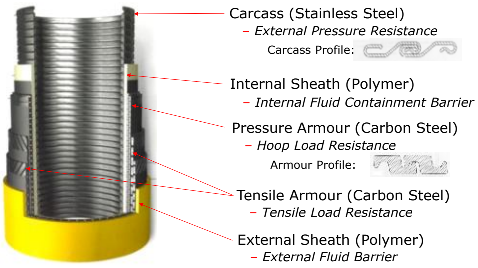
Figure 1: **ROSEN's Pipeline Integrity Management Framework**



3 DEVELOPING AN ILI SOLUTIONS FOR FLEXIBLE PIPES

In 2016 ROSEN initiated a project to look into the development practical ILI solutions that can provide reliable and meaningful inspection data to support the IM of unbonded flexible pipes.

The complex, multi-layered construction of unbonded flexible pipe presents an obvious and distinct challenge when compared rigid carbon steel pipes,



Through this initiative, ROSEN set out initially to better understand the key drivers for flexible pipe inspection based on integrity needs to help decide what level of inspection performance might be required to acquire sufficient useful information for IM decision support.

This focused R&D approach essentially involved the four following phases:

- Phase 1 – Acquiring a better understanding the key integrity threats and likely associated degradation or damage mechanisms
- Phase 2 – Investigating the performance of existing ILI technologies based on historical ILI runs in piggable pipeline systems containing flexible sections
- Phase 3 – Conducting a testing program to explore evaluate inspection performance in flexibles using Magnetic Flux Leakage (MFL) and Internal Eddy Current (IEC) techniques

In addition to the above steps it was however recognised at an early stage that in order to provide a practical solution to the wider market for the ILI of flexibles a further step was necessary:

- Phase 4 – Identifying practical solutions for the deployment of flexible pipe ILI tools

The progress and outcomes of phases 1 to 3 above are summarised in Section 4. Due changing market conditions and operational constraints development work was paused in early 2020.

Considering Phase 4, while there are cases the inspection of flexible's might be possible using conventional free swimming ILI tools (i.e. where flexibles are included within a piggable pipeline system), the deployment of an ILI tool for a significant number of flexible pipe applications is usually more challenging. The complex installation configuration of many flexile pipe sections coupled with a lack of traditional pigging facilities means that they are generally considered to be unpiggable. This is particularly the case for dynamic flexible riser systems hooked up to directly complex topsides production facilities or FPSO turret systems.

In effect what this means is that it is [arguably] difficult to develop an 'off the shelf' solution for the ILI of flexibles and more bespoke inspection solutions for individual applications will be necessary for many critical applications.

ROSEN's approach to provide solutions for challenging pipeline inspections in applications similar to this is summarised in Section 5.

4 ILI TECHNOLOGY DEVELOPMENT PROGRESS AND OUTCOMES

4.1 Understanding the key Integrity Threats

To understand the main flexible pipe integrity threats, industry data regarding observed operational incidents and failure events was consulted. A comprehensive record was available through an industry Joint Indusrty Partnership (JIP), the Sureflex JIP[1], and the resultant report which documents reported incidents of damage and failure.

Using the Sureflex data, combined with in-house subject matter expertise with respect to the manufacture and installation of flexibles, ROSEN were able to build up a picture of the most common failure modes and the likely damage mechanisms or target anomalies for inspection.

Figure 2: J000621-00-IM-GLN-001 – Damage / Failure Cause

Damage / Failure Cause	Number of cases, by Status								Total No.	%
	Installed (not operating)	Operating (minor defect / damage)	Shut-down (integrity concern)	Damaged (failure initiator)	Failed - Leak	Failed - Rupture	Failed - Connected System Failure	Recovered- Before Design Life		
Line Recovered Proactively - No significant damage / defect identified			23						**23**	**3.9%**
Carcass Failure - Fatigue					1				**1**	**0.2%**
Carcass Failure - Multilayer PVDF Collapse		1	7	24	4				**36**	**6.2%**
Carcass Failure - Tearing / Pullout		1		5	3				**9**	**1.5%**
Internal Damage - Pigging				2					**2**	**0.3%**
Internal Pressure Sheath - Ageing			13	1	17				**31**	**5.3%**
Internal Pressure Sheath - End Fitting Pull-out			11	3	19				**33**	**5.7%**
Internal Pressure Sheath - Fatigue / Fracture / Microleaks		2		2	9				**13**	**2.2%**
Internal Pressure Sheath - Smooth Bore Liner Collapse		1			5	3			**9**	**1.5%**
Tensile Armour Wire Breakage - in / close to end fitting					3				**3**	**0.5%**
Tensile Armour Wire Breakage - in main pipe section				2		1			**3**	**0.5%**
Tensile Armours - Birdcaging				4	14				**18**	**3.1%**
Corrosion of Armours - Major / Catastrophic				1	13	4			**18**	**3.1%**
Corrosion of Armours - Moderate		1	3	2				3	**9**	**1.5%**
Annulus Flooding - Cause Unknown		19	4	40				1	**64**	**11.0%**
Annulus Flooding - Defective Annulus Vent System	2	10		5					**17**	**2.9%**
Annulus Flooding - Outer Sheath Damage - Ageing / Fracture		1		4					**5**	**0.9%**
Annulus Flooding - Outer Sheath Damage - Mechanical / Impact / Wear	1	27	15	79				2	**124**	**21.2%**
Annulus Flooding - Permeated Liquids		2							**2**	**0.3%**

4.2 Reviewing Historical ILI Data

An initial review of numerous data set for historic ILI runs was carried out to help understand the relative performance of different ILI tool technologies. This highlighted the most promising solutions to provide some level of useful inspection in unbonded flexible pipe sections.

This review reinforced conclusions of some earlier test work that an MFL solution has some potential in providing some level of inspection of the inner pressure armour wire subject to limitation of 'lift off' introduced by the intervening none metallic pressure sheath and a [none ferrous] inner carcass where fitted (in the case of rough bore flexible pipe).

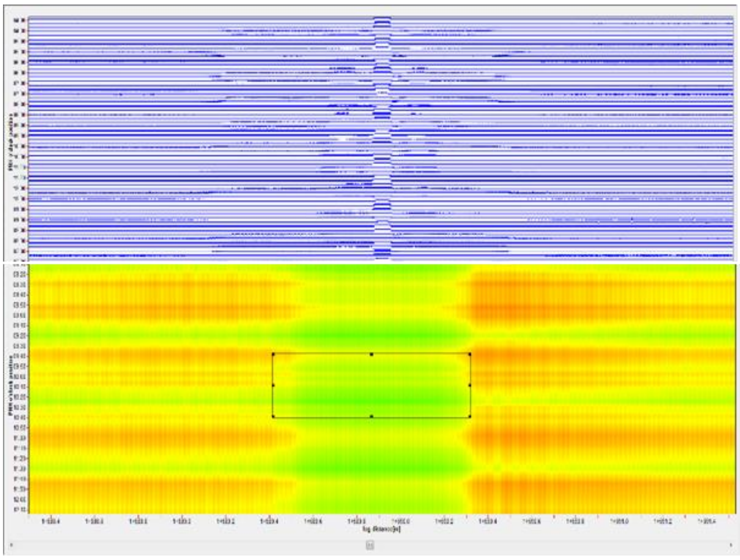
It was also identified the Internal Eddy Current (IEC) inspection technique, typically used to provide an enhanced inspection for shallow internal corrosion, was also potentially a good candidate for inspection of the inner carcass layer.

The data review also revealed other useful insights to help inform the condition and status of a flexible pipe system. This included being able to detect and locate major ancillary components associated with flexible riser systems such as the location of Mid Water Arch (MWA) units and bend stiffeners (see Figure 3).

Furthermore it was recognised that with the addition of a standard ILI Inertial Measuring Unit IMU or mapping unit), the option to give an accurate representation of riser curvature configuration is potentially a very usefully input to enhance dynamic analysis and fatigue life assessment.

[1] J000621-00-IM-GLN-001 - Flexible Pipe Integrity Management Guidance & Good Practice Rev 1 - September 2017

Figure 3: Pressure Armour ILI data (MFL) showing location of MWA



4.3 Arrangements for Testing

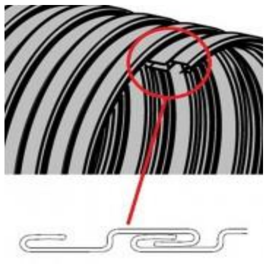
In 2016, ROSEN acquired 15m section of 9” unbonded flexible pipe to use for pull through testing services. This supplemented an existing short dissected section of flexible pipe (available from earlier preliminary investigations) facilitating internal access for lab testing of sensors.

Figure 4 shows the pull through and lab testing arrangement at the ROSEN test facility in Lingen, Germany..

Figure 4: Flexible Pipe Pull Through and Lab Test Setups

4.4 Summary of Test Results

4.4.1 Carcass Inspection



The interlocked carcass layer is the main component that provides flexible pipe with the strength to resist collapse. Pipe collapse strength is influenced by the interaction between the carcass, polymer pressure sheath, and pressure armour. The interaction between these layers is further governed by whether the annulus is dry or flooded, and by whether the flexible pipe is straight or bent.

The pull through tests conducted focused primarily of what level of carcass inspection could be achieved to directly address the threat of failure in this layer.

It is important to note however that the overall carcass condition, and any observable irregularities in the carcass itself, can be a very good indicator of problems in the other outer layers including the polymer pressure sheath, and the pressure and tensile armour wires. For example any overall carcass irregularities or deformation may have been caused through an over bending incident also impacting other layers and overall structural integrity.

The pull through testing, in conjunction with refinements to the standard ROSEN IEC sensor unit, has demonstrated that it is possible to provide a very accurate representation of the carcass structure and also to detect anomalies introduced into the carcass structure. Refer to Figure 5 Figure 6 and Figure 7

This test programme ultimately resulted in specific sensor unit (known as a DRD sensor) being developed specifically for flexible pipe carcass inspection.

Figure 5: Flexible Pipe DRD Carcass Data

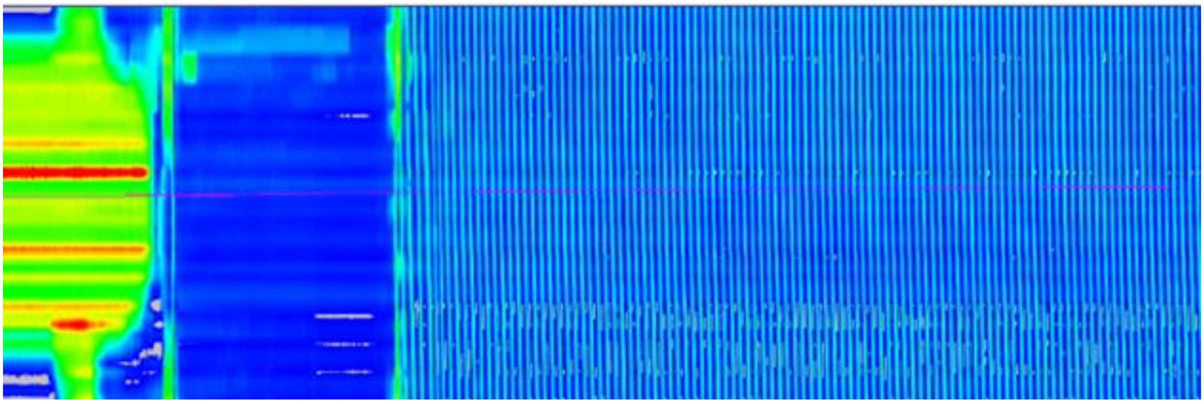


Figure 6: Carcass Pitch and Gap Measurement

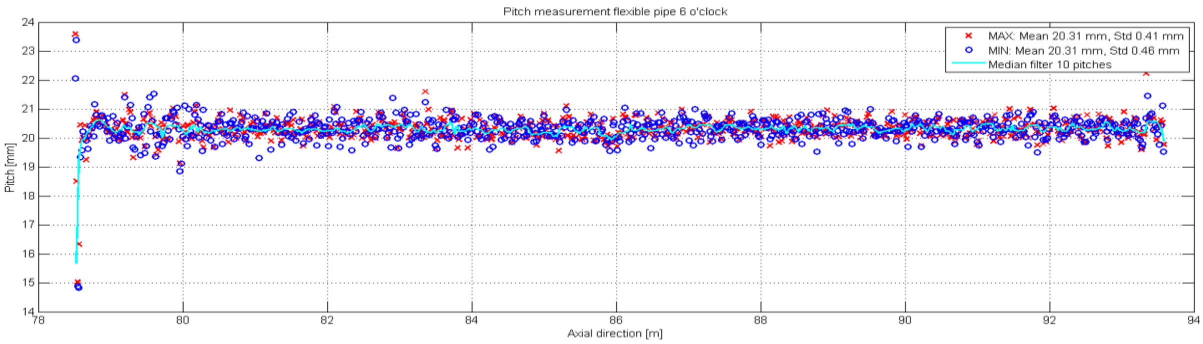
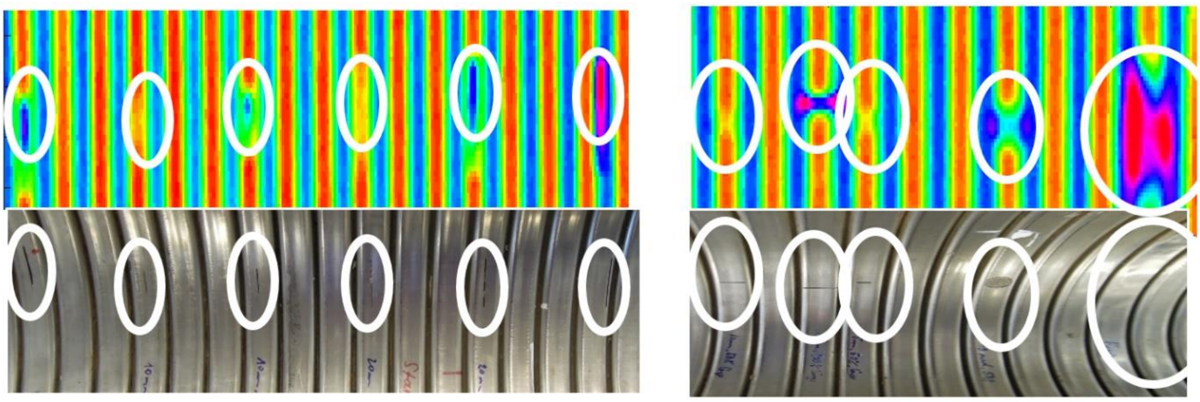


Figure 7: Carcass Cracks, Corrosion and Erosion



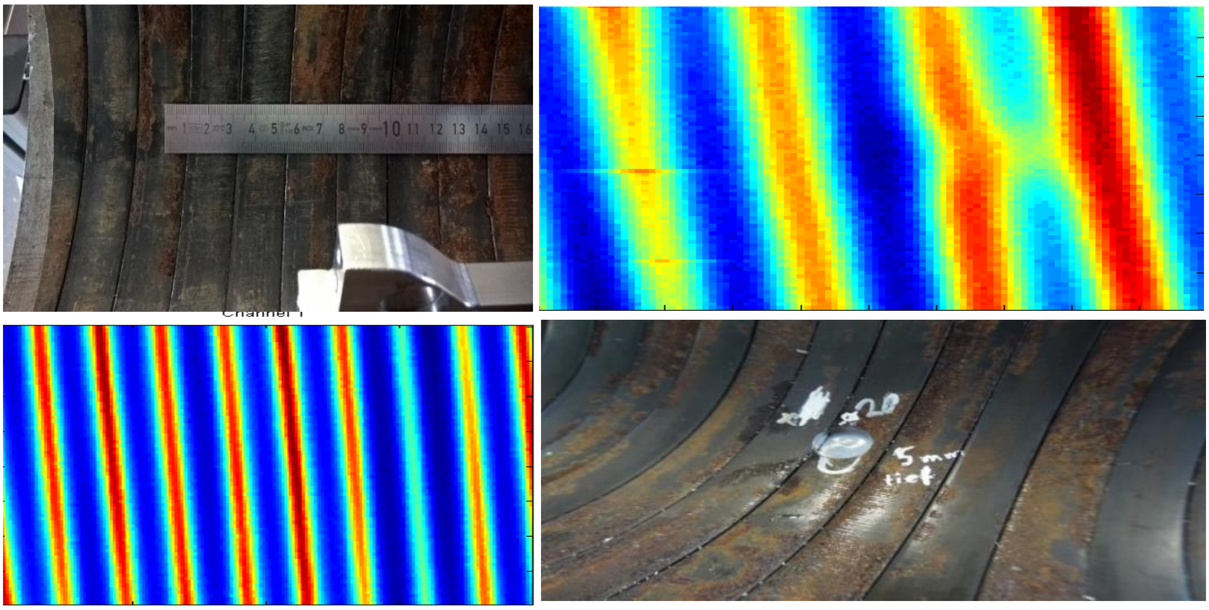
4.4.2 Pressure Armour Inspection

Being able to reach out into the carbon steel pressure armour wire (the next metallic layer in the structure) was investigated further through lab testing. The significant challenge with inspecting this layer is the standoff distance of the sensor with the presence of the underlying layers (the non-ferrous carcass and pressure sheath) which can typically result in a 'lift-off' between 10 and 20mm.

The lab testing conducted did however validate that it is possible the clearly see the regular pitch of the pressure armour wires enabling the ability to identify irregularities such as loss of interlock. Further testing also showed that it is possible to distinguish anomalies introduced onto the pressure armour wires offering the potential for the detection of corrosion and other metal loss anomalies (e.g. broken wire) resulting in a local reduction in cross sectional strength.

This testing has therefore demonstrated that useful characterisation of the pressure armour layer is possible through ILI. It was also concluded that an enhanced the level of inspection in this layer (to achieve good results with up to 20mm standoff) can potentially be achieved with modifications to the yolk arrangement of the MFL system to help project the magnetic field into the pipe structure better. Figure 8 shows examples of the test data for the pressure armour layer.

Figure 8: Amour Wire Inspection Bench Testing



4.5 Testing Outcomes and Conclusions

Although a complete ILI solution to identify all credible damage mechanisms in flexibles is not yet available, the testing of adapted current ILI technologies has demonstrated that ILI tools already have the potential to reveal a lot of useful information regarding the condition of and current integrity status of unbonded flexible pipe.

Examples of this include:

1. Confirmation of end-fitting location and the potential to identify changes in the end-fitting
2. Confirmation of carcass condition at the end-fitting to demonstrate that it is free of damage
3. Confirmation of general carcass condition and that there is no loss of interlock
4. Identification of local deformation that may be a precursor of collapse
5. Detection of anomalies in the carcass material such as erosion (thinning), corrosion and cracking
6. Confirmation of the presence and location of the mid-water arch and associated clamp
7. Confirmation of the presence of the bend stiffener and bend stiffener latching mechanism

8. Confirmation the general condition of pressure armour layer (e.g. irregularities and loss of interlock)
9. Detection of pressure armour wire metal loss anomalies
10. Flexible riser curvature configuration using IMU mapping systems

While individually these individual items might arguably have limited value when assessing the integrity overall of a flexible pipe section, using a combination of different observations can provide a very good picture of the current condition of an unbonded flexible pipe section.

ROSEN is also confident that through further testing in the future, together with more customisation and tuning of existing ILI tools and inspection techniques, that the current capabilities can be enhanced significantly.

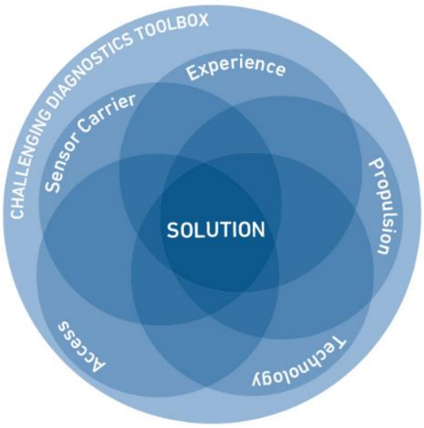
5 ROSEN ILI SOLUTIONS FOR CHALLENGING PIPELINE APPLICATIONS

5.1 Introduction

To address the ILI of 'difficult to pig' pipelines systems ROSEN have a dedicated business line, the ROSEN Challenging Pipeline Diagnostics (CDIA) team.

The CDIA team's primary role is to address the challenges preventing a pipeline from being inspected with conventional inline tools. At high level these challenges fall into one or more to the following categories:

- Pipeline system configuration
- Line pipe properties
- Pipeline operating conditions



Through the establishment of the CDIA team and from experience gained over many years, ROSEN have now acquired an extensive and growing 'toolbox' of ILI options employing a wide range of different tool deployment methods and numerous different inspection technologies for a diverse range of challenging pipeline inspection applications.

Although each individual pipeline usually presents a unique challenge, building a dedicated tool for every application is not always feasible. However, the flexible toolbox approach adopted by ROSEN enables that existing inspection technologies and tool deployment solutions to be adapted to suit a new specific set of challenges or circumstances.

5.2 Examples of ROSEN CDIA Case Studies

To illustrate how the ROSEN tool box approach has been be implemented for several challenging pipeline ILI applications in recent years the following summary case studies are presented.

These case studies demonstrate that many of the challenges overcome in these application are directly relevant to the challenges and perceived barriers presented in flexible pipe and riser applications.

The extensive range of technology solutions and associated resources and expertise available within the CDIA toolbox includes:

- Integrity review and threat assessment support
- Engineering feasibility studies, including flow assurance support
- Project planning, HAZID review and project management
- Comprehensive pipeline preparation solutions, including proving, cleaning and sediment profiling
- A wide range of sensor technologies, including MFL, UT, EMAT, TOFD and IEC
- Specialised tool deployment options, including free-swimming, robotic, tethered, etc.
- Auxiliary equipment, including temporary traps, pumps, winches etc.
- Tool tracking and monitoring systems
- Post inspection integrity assessment support

5.2.1 Bidirectional Pigging Solution for Loading Line

Inspection of a 30" pipeline connecting shore-based installation to a subsea pipeline end manifold (PLEM). The PLEM connected to a buoy by a flexible hose for the critical task of loading tankers. Due to its position in wider the pipeline network this pipeline was deemed a critical asset in the operators asset portfolio, since there was no alternative means to import or export the product. The loading line in this case, by design, could not be inspected with conventional inspection approaches

Key challenges:

- Single access
- No traps – Subsea Line end
- Pipeline Cleanliness concerns
- Single flow direction in normal operation

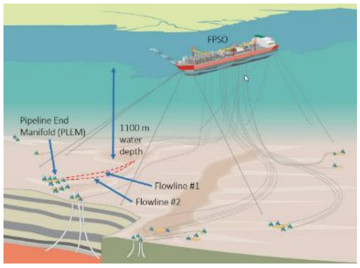
ROSEN solution:

- Turnkey project execution including pumps, frac tanks, temporary pipe modifications and liquid handling to facilitate BiDi pigging
- Asymmetrical cleaning/gauging pigs
- Custom built tool stopper plug as a contingency tool for overshoot
- Subsea tool approach monitoring system
- 30" bi-directional MFL inspection system

5.2.2 Deep Water Flowline Inspection from FPSO

Corrosion inspection of two subsea 8 km flow lines with 10/12" diameters and pipe wall thicknesses ranging from 12.7 mm to 31.6 mm located in water depths of 1100 m. It was possible to configure these lines in a loop but there were concerns about subsea valve operability

Key challenges:



- Inspection from FPSO in 1100m water depth
- 10/12" dual diameter application
- Concern about subsea valve operability (stuck pig risk)
- Heavy pipe wall thickness

ROSEN solution:

- Bidirectional cleaning and gauging tools
- Tailor made bidirectional UT ILI tool – allowing reverse pigging contingency option
- Pump testing to prove tool passage ahead of operations

5.2.3 Ultra Compact ILI Solutions for Restricted Access

Inspection multi-phase infield pipelines with 3-way ball valve access during regular operations (metal loss inspection).

Key challenges:

- Launch access through a pigging valve
- Tight bends throughout pipeline length
- Limited pipeline construction information
- Flow / pressure fluctuations (well-flow characteristics)
- Multiphase medium
- Heavy debris deposits
- High temperatures and velocities

ROSEN solution:

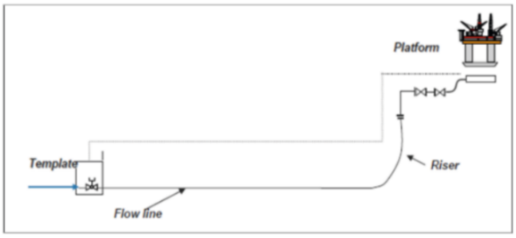
- Ultra compact ILI tool optimum flexibility and passage
- Bidirectional capability and low minimum passage requirement
- Integrated electronics and battery unit within the magnetizer body
- Strong and flexible magnetizer
- High-resolution MFL sensors
- Buffer for the protection for ILI tool and valves
- External referencing system
- Loading and retrieval equipment

5.2.4 Umbilical Inspection Solution

Inspection of a 1.3km 8" flow line system for corrosion and cracks (first time inspection). Theoretically a temporary subsea trap could have been installed underwater to conduct a conventional ILI however, the support vessel and the ROV for the subsea launch, among other things, would have incurred excessive costs and risks for the operator

Key challenges:

- Concern about girth weld cracks in addition to corrosion
- No pig traps
- No subsea launch or receive option
- Platform space constraints



ROSEN solution:

- Self-propelled umbilical (tethered pigging solution)
- Vertical loading solution to overcome space constraints
- Real time data for tool position control
- Corrosion, geometry and circumferential cracking (TOFD) inspection capabilities
- TOFD scanning of individual girth welds
- Onsite reporting of results