HOW TO DEVELOP & DELIVER THICK WALL MULTI DIAMETER OFFSHORE INSPECTION SOLUTIONS: A CASE STUDY

By: Martin Bluck, PII Pipeline Solutions, United Kingdom

Abstract

This paper includes three brief case studies on successful inspections of deep sea pipelines, highlighting the technical challenges faced and the critical aspects of solution development and inspection program delivery.

In addition, a generic approach will be described for the development of complex off-shore applications that helps manage the technical & commercial risk for both operator & ILI vendor in delivering a holistic in-line-inspection solution.

1. BP Mardi Gras Case Study

BP built and operates the Mardi Gras Transportation System (Figure1) in the Gulf of Mexico exporting 1 Million Barrels oil per day & 1.5 Billion Cubic Feet gas per day from 5 strategic major deep water developments through 500 miles of pipelines. Pipelines range from 16" to 30" diameter, including multi-diameter lines, in water depths down to 2,250m

BP chose to develop an intelligent pig in parallel with the design and build of these pipelines to assure high levels of long term pipeline integrity. The configuration of the pipeline system was designed & developed in parallel and in collaboration with the intelligent pig program to ensure piggability.

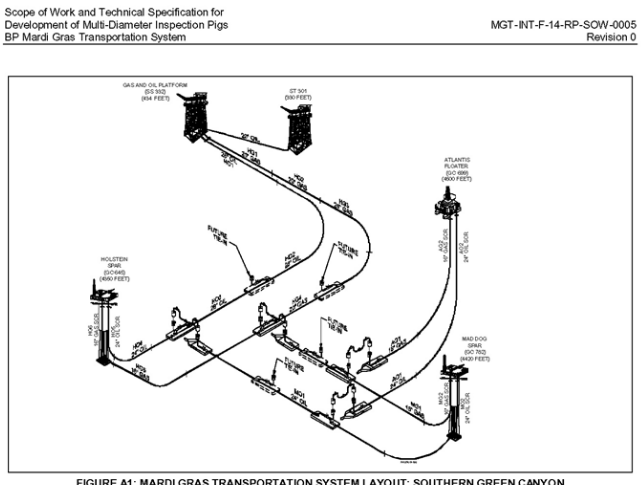


Figure 1: BP Mardi Gras System

The pig development project goal was to design, manufacture, and test a multi-diameter, high pressure MFL inspection tool that would navigate & inspect 24"-30" multi-diameter lines with asymmetric unequal vertical wyes, jumpers, and flex-joints, in water depth leading to a max working pressure of 400 bar (2x existing tool design pressure) at seabed. The MFL inspection tool was also required to inspect very heavy wall pipe - wall thickness up to 35mm.

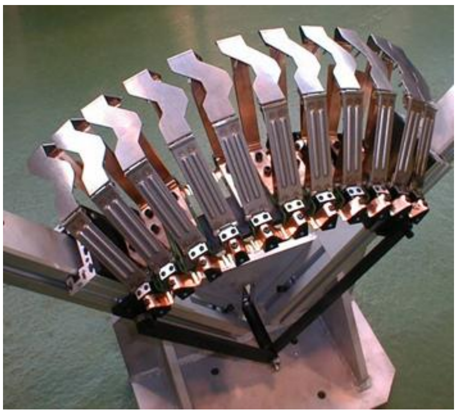


Figure 2: Z-Sensor

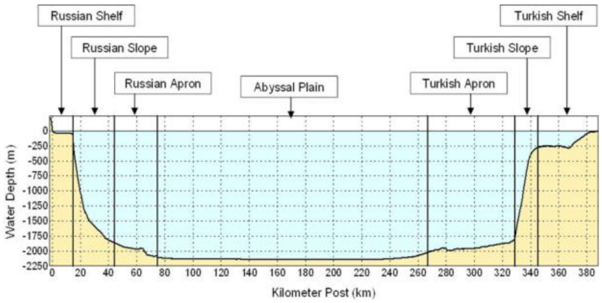
A collaborative phased approach overcame the technical challenges described above and resulted in the successful inspection of Mad Dog-Ship Shoal (24" x 134km) & Proteus-Endymion (24"/28"/30" x 256km). Features of the project were an early & extensive collaborative risk assessment (FMEA) where 200 potential failures were considered, the development of novel Z-Sensor (Figure 2) & tow-bar arrangements, and the rigour of final Systems Integration Testing.

Significant track record has been established for this technology with 16 pipelines & 1,800 km inspected, including other thick wall, high pressure, single & multi-diameter pipelines.

2. Blue Stream Case Study

The Blue Stream Pipeline system is a strategic gas export system which starts with a 56” pipeline crossing southern Russia, before forming two parallel 24” interconnector pipelines 380km & 387km in length traversing the Black Sea and culminating at Turkish landfall in Samsun (Figure 3). These pipelines are a 50/50 joint venture between Gazprom & ENI. This asset provided the first direct export route between Asia and Europe, and is critical to security of gas supply to Europe now and for decades to come.

Figure 3 & 4: BSPC Interconnector Pipelines



At the time of construction in 2001 this was the deepest pipeline in the world; 2,140m (Figure 4) sub-sea with extremely thick wall pipe of 32mm to cope with pipeline pressures of 250 bar and potentially up to 400 bar. Ball valves, barred tees, reduced bore tees (83% OD), buckle arrestors, and an internal epoxy coating added complexity to what was already considered to be an “unpiggable” pipeline.

The in-line inspection program goals were to clean the pipelines then complete geometry, out of straightness (strain), and metal loss surveys with the provision for pig tracking & pig recovery. A phased approach was taken starting with a Desk Top Feasibility study and culminating in the Inspection Program itself. Snamprogetti, now trading as Saipem, were appointed as the Lead Engineering Team to support the management of the project. So, phase milestones had to be agreed not only between PII and BSPC but also Snamprogetti.

After almost 2 years of development and extensive testing (after almost 60 pull throughs in BSPC pipe spools the internal coating was polished to a high sheen rather than destroyed, the equivalent of 240 years of pig runs), PII were in a position to launch the first pigs across the Black Sea. Teams of engineers stationed in Russia and in Turkey supervised each base activity. The MFL pig at the receive in Turkey can be seen in Figure 5, after 380km and almost 3.5 days in the pipeline. All tools were successfully tracked and received on time as predicted by the software modelling tool used by Snamprogetti. Both pipelines were successfully inspected and reported to BSPC.

Figure 5: BSPC MFL Pig at Receive

3. CATS Case Study

CATS is the Central Area Transmission System, which delivers 20% of the UK’s gas through a 404km pipeline from the Central North Sea to the processing Terminal in Teesside on the North East coast of England. CATS is a Joint Venture operated by BP.

This 36” diameter pipeline constructed in API 5L X65 steel has predominant wall thickness of 28.4mm with 33.9mm on-shore, and an MAOP of 179.3 barg (sea-line) and 125 barg (land). It has an external coating of Coal Tar Enamel plus 50mm concrete weight coat and an internal coating of Fusion Bonded Epoxy.

Figure 6: CATS Pipeline

Additional features included a 1,400kg Non-Return Clapper Valve at the riser base, multiple Tees (6 in total from Andrew, ETAP, Banff) and a J-Block Vertical launch. Negotiation of the Tees Tunnel Section and a significant dent due to anchor drag were additional considerations, along with the fact that the pipeline had never been pigged and was therefore of unknown cleanliness.

In this collaboration BP undertook the proving of the line whilst PII were responsible for the cleaning, magnetic pre-conditioning & MFL inspection. BP provided the Clapper Valve test rig shown in Figure 7, which was extensively used in the testing & acceptance phase to ensure all pig types could pass & survive this challenging feature.

Figure 7: CATS Clapper Valve Test Rig

After three proving/profile runs, four cleaning runs, and one magnetic pre-conditioning run the 36" diameter thick-wall MFL inspection pig was vertically launched from North Everest on 13th November at 17:05. It was received at the CATS Terminal Teesside on the 16th November 03:00 58 hours later with data download completed and Data Quality Assessment confirmed shortly thereafter.

The success of this program was down to good planning and that adequate time was allowed, all pigs were vigorously tested for fatigue against the high risk features, a Progressive Pigging philosophy made sure the final inspection was not attempted before the pipeline was ready, and partner approval was required and given at every stage.

4. Generic Approach

A consistent approach was taken to developing the solutions for the 3 complex off-shore applications described briefly above, to manage the technical and commercial risk for both owner/operator and ILI vendor to successfully deliver a holistic inspection solution.

In each case a Desktop Feasibility Study was undertaken to define the engineering & inspection solution to successfully navigate and inspect the sub-sea pipeline in question, and to provide a phased milestone plan and budget cost estimates up to and including delivery of the final inspection report.

Such a Desktop Feasibility Study would typically consider the following elements:-

- Data Gathering & Risk Assessment
- System Design
- System Performance (Predicted)
- Ancillary Requirements
- Design Verification & Testing
- Inspection Methodology
- Program Phasing & Milestones

Each element is described in more detail in the paragraphs that follow.

4.1 Data Gathering & Risk Assessment

It is essential to gather as much information about the pipeline construction and the anticipated operating parameters as early as possible in the process. A 'pipeline questionnaire' is completed with the pipeline owner/operator to capture data on the pipeline and inspection requirements.

Information gathered on the pipeline construction would typically include:- pipeline length, diameter(s) material(s), wall thickness(es), bends, bores, off-takes, valves etc. with particular interest in the location, size and orientation of the most challenging geometrical features to be navigated and the facilities at launch & receive.

The capability of an in-line inspection system to navigate & inspect complex pipeline geometry is heavily influenced by pipeline operating parameters including product, pressure, flow, & speed. Information on product make-up (e.g. H_2S content), pressure, and temperature is also required as an input to system design to ensure stable performance and survivability in the operational environment.

At this point an initial Risk Assessment is carried out comparing the captured data and requirements with in-line-inspection tool capabilities. The purpose being to identify any risk to the inspection vehicle safely negotiating the pipeline and its features; any risk of damage to the inspection vehicle, the pipeline or the environment; or risk to providing the client with high quality inspection data on time.

Part/Function	Potential Failure Mode(s)	Potential Failure Effects	SEV	Potential Cause(s)/Mechanism(s) of Failure	OCC	Current Design Controls	DET	RPN	Recommended Action(s)	Responsibility & Target Completion Date
What are the process steps/ parts	In what ways can the process step/parts go wrong?	What is the impact of the Failure Mode on the customer?	How severe is the effect on the customer?	What are the causes of the Failure Mode?	How often does the Cause or Failure Mode occur?	What are the existing controls and procedures that prevent the Cause or Failure Mode?	How well can you detect the Cause or Failure Mode?	Calculated	What are the actions for reducing the occurrence, decreasing severity or improving detection?	Who is responsible for the recommended action?
MV:Sensor fingers	loss of finger	loss of inspection data, material left in pipeline	5	crushing	5	partial shields fitted	4	100	Test during pump throughs	

Figure 8: Example FMEA

Each risk identified is categorized as 'High', 'Medium', or 'Low' with mitigation actions identified to reduce the risks to an acceptable level. This would typically be captured through a FMEA (Failure Modes & Effects Analysis Figure 8) carried out by the client/vendor team. The highest risks at this stage of the project often arise from lack of data, site surveys can be effective at reducing these gaps.

4.2 System Design

The main body of work for a feasibility study involves a focused multi-disciplinary engineering team working together to design the inspection system solution. Numerous iterations are typically required before all the trade-offs have been identified and optimized to arrive at a proposed system configuration.

The Magnetic Vehicle (MV) is typically the vehicle with the most complex design challenge, due to the need to negotiate complex pipeline geometry whilst saturating pipe-wall in a range of wall thicknesses with sufficient magnetic field to enable a good inspection, and house and protect the main corrosion sensors at the same time.

Over the years PII has developed a number of techniques using 3D CAD tools to allow rapid re-scaling and re-orientation of the magnetizer assembly to arrive at an initial 3D model. The 3D CAD lay-outs generated can then be examined and enhanced in the context of the specific pipeline geometry and fixtures & fittings that will be encountered.

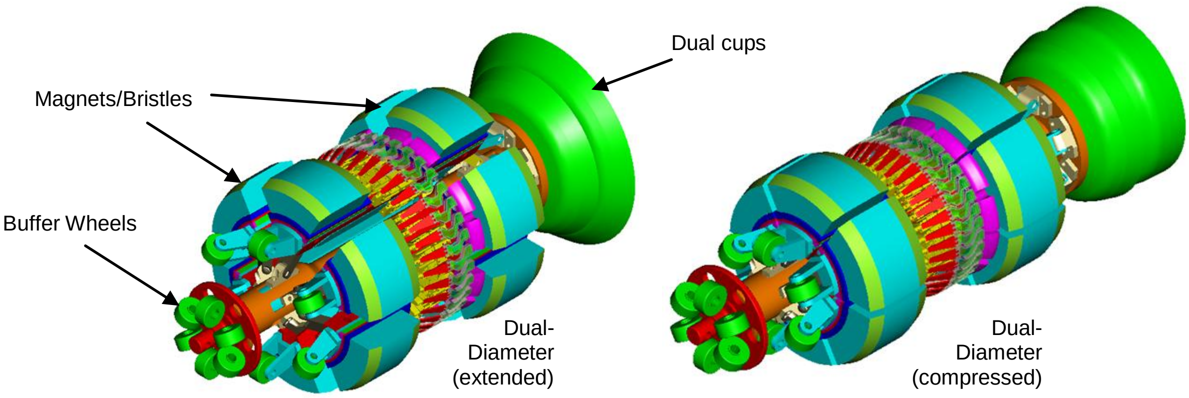


Figure 9: Example Dual Diameter MV CAD Layouts

ILI systems, MFL in particular, are typically designed to be driven from the front by cups and flaps located on the Magnetic Vehicle (MV). However, in off-shore sub-sea lines it is not unusual for there to be off-takes, wye pieces, changes in diameter which would result in loss of drive if it were from the MV alone.

Options for enhanced drive include: cups/flaps on the rear of the MV, an extra drive module (EDM) in front of the MV, an EDM at the rear, cups /flaps on other modules (e.g. instrument vehicle). All are valid options to be considered, evaluated and modelled in isolation or in combination depending on the application(s) under consideration (Figure 10).

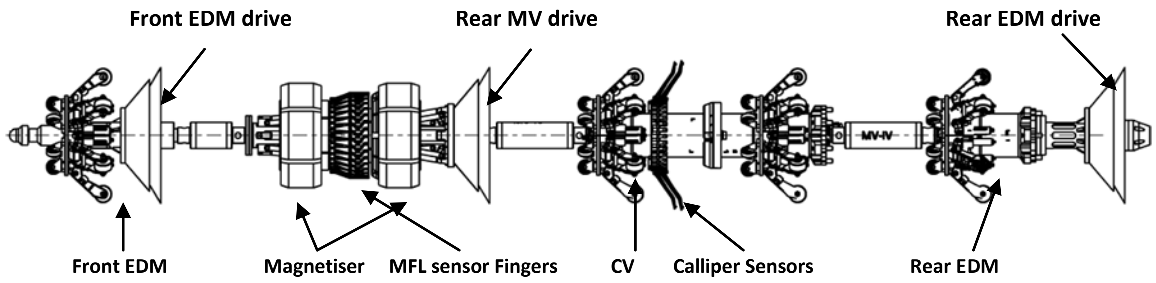


Figure 10: Example Overall Vehicle Train

Conventional MFL trains with rigid inter-vehicle tow-bar and joints driven from the rear are at risk of jack-knifing in the pipeline potentially leading to a stuck pig. Pii has overcome this issue with the development of a flexible semi-rigid tow-bar which allows the pig to be driven from the rear or even to get pushed by a recovery vehicle (should it be required) without the risk of jack-knifing.

The electronics design of a typical MFL system comprises sensors and associated harnessing located outside the pressure vessels with the rest of the data acquisition system mounted in the Calliper/Instrumentation Vehicle (CV/IV) and the EDM pressure vessel (Figure 10).

The MV carries the MFL main corrosion sensors which are connected via inter vehicle harnesses to the CV/IV. The Calliper sensors for geometry assessment are located on the CV/IV connected via marshalling boxes. An extra battery pack is accommodated in a pressure vessel in the rear EDM.

Inspection systems are typically designed for a pipeline of a single diameter, however experience shows that dual or multi-diameter pipelines off-shore are not uncommon. In this case additional complexity is added to the design of the MFL sensor arrangement in particular if a minimum spacing and specification is to be achieved in more than one diameter.

Electronics Sensor Marshalling Units for both MFL and Calliper sensors are typically external to the main pressure vessels to minimize the length and diameter of pressure vessels required for improved bore & bend passing capabilities in complex geometry pipelines.

Detailed electronics system drawings and wiring diagrams are required to ensure a viable electronic systems design is achieved. Maximized re-use of existing and proven sensors, marshalling units, harnessing, and sub-systems throughout minimizes risk.

4.3 System Performance

Predicted mechanical performance is derived directly from 3D CAD models and simulation of passing of specified geometric features (Figures 11, 12).   Typical predicted performance characteristics would include length, weight, minimum bend radius, minimum bore, size & orientation of off-takes, wyes etc.

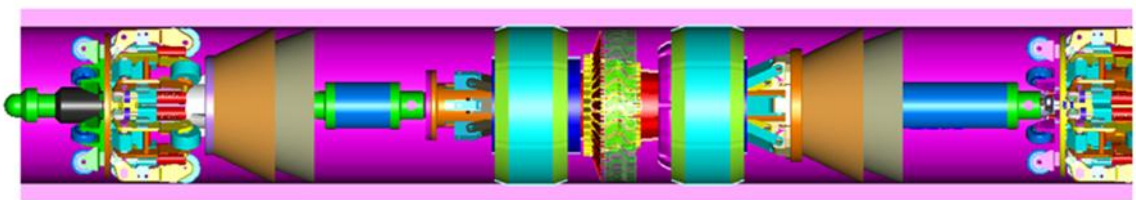


Figure 11: Example in Local Full Bore

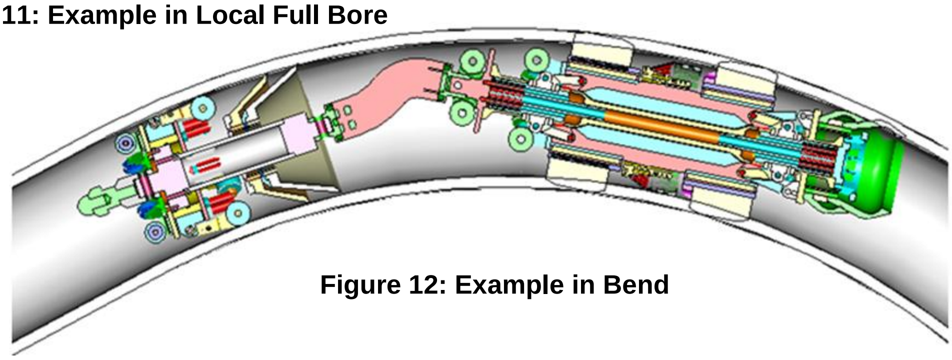
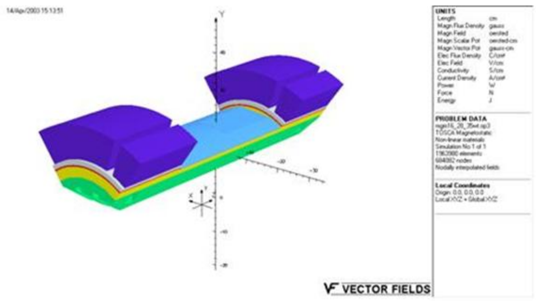


Figure 12: Example in Bend

Operational system performance parameters also need to be predicted. Tool range in time and distance are calculated from battery capacity and power consumption under anticipated operating conditions, along with data storage capacity. Maximum temperature and operating pressure versus requirements are predicted based upon proven performance and pressure vessel calculations. Performance is predicted for the operating parameters provided with typical limitations stated, the design and performance can be significantly impacted by the inspection media e.g. presence of H_2S.

The most complex performance prediction for an MFL system is the detection and sizing capability in the range of diameters, wall thicknesses, and speeds to be encountered. A typical model would be for a single diameter pipeline, typically with a solid body/return path scheme with an annular arrangement of magnets and long bristles for inspection trap to trap (Figure 13).



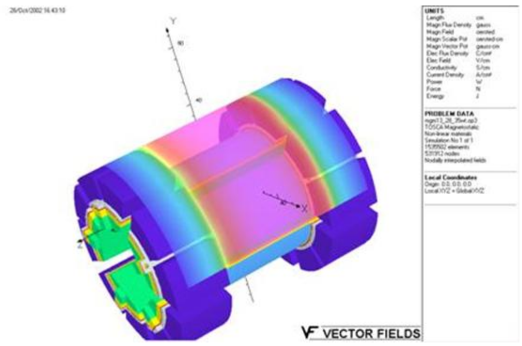


Figure 13: BSPC Magnetic Modeling

However for a multi-diameter application a segmented body design with articulated magnetizer bars is required for magnetic performance to be maintained across a range of diameters. In a high speed gas line additional complexity is added with the need to manage pig speed with a variable gas by-pass control system which requires a hole through the centre of the MV.

An accurate prediction of performance requires an experienced physicist and a sound magnetic model that can easily be modified to predict the level of magnetic field introduced into the pipe wall over a range of diameters, wall thicknesses, and speeds. It is the level and stability of the magnetic field in the pipe wall in the sweet spot of the main corrosion sensors that determines the detection and sizing accuracy performance that can be achieved.

4.4 Ancillary Requirements

As previously stated, the main body of the work in the feasibility study is focused on the design of the inspection system. However, a successful program requires the inspection tool to be launched and received safely and efficiently, and for the line to be prepared so that high quality inspection data can be captured for analysis. This requires the design of a holistic solution including ancillary equipment in addition to the inspection system itself.

Figure 14: BP Cats Vertical Launch

The ILI tool itself requires appropriate equipment to be handled and worked on safely, including manipulators and lifting beams for larger tools. Specific equipment for launch & receive is typically required for what is often a unique tool in a limited working area e.g. vertical launch from an off-shore platform (Figure 14).

Proving tools are frequently required to confirm pipeline geometry features and provide positive confirmation that the higher order ILI technology can successfully navigate the pipeline. Similarly specialist cleaning tools may be necessary to remove debris from the pipeline that would provide a barrier to the collection of high quality inspection data.

Pig tracking solutions need to be considered in order to track and accurately locate any and all pigs during the program. In a sub-sea environment this can be critical, particularly in the event of a pig stopping. This would be covered under the Risk Assessment with a ‘Recovery Pig’ or ‘Rescue Pig’ designed for the specific application with enhanced bore passing, bend passing, & drive capabilities.

As a minimum potential handling, launch and receive equipment requirements should be considered in the Desktop Feasibility Study phase with concepts/options identified to address any specific areas of risk or concern identified.

4.5 Design Verification &Testing

This is a critical phase of the project, and can be one of the most expensive if it is done as rigorously as it should be. During the design verification & testing phase a comprehensive series of tests at component level, assembly level, and system level are conducted to demonstrate the inspection system will satisfy the client and pipeline requirements. In the event that that the FMEA has identified high risk items additional rigorous testing of new and/or critical components/assemblies will be conducted.

Tests at the component and assembly level typically include:- Pressure, Temperature, Force/ Deflection, Shock & Vibration, Dynamic, and Life Testing. Re-testing of existing proven components/sub-systems is not required for an equivalent application.

System level tests include:- Mechanical Proving, Pump-Throughs, Database Pull-Throughs, and full System Integration Tests (SIT). Mechanical Proving requires the fabrication of a test rig (or rigs) that includes all the challenging pipeline features the ILI system will be required to pass. The facilities need to be available to pump or pull high drag MFL system through fabricated test rig(s) at speeds up to 5 m/s to demonstrate system capabilities.

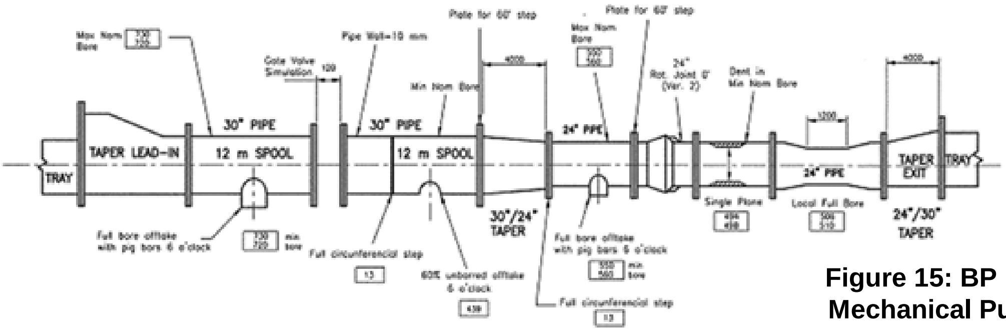


Figure 15: BP Mardi Gras Mechanical Pull Test Rig

Pump-Throughs at a system or assembly level are carried out to determine blow over pressures, leakage around cups, fixed by-pass capabilities, and variable by-pass capabilities. Again, significant infrastructure is required to support these tests, and some bespoke pressure vessel test rigs may need to be fabricated for specific applications.

Database Pull-Throughs are conducted to gather the data to derive the detection & sizing specification predicted by the magnetic modelling in the ‘System Design’ phase. Test line builds are constructed covering the required range of pipeline diameters and wall thicknesses with a sufficient range of defects engineered into the pipe spools (internal & external) to provide a statistically significant sample of features for specifications to be developed. Multiple pull-throughs at a range of speeds are conducted to ensure repeatability. The development of the sizing models themselves using the gathered data is an extremely specialist task carried out by experienced mathematicians.

Figure 16: BP Mardi Gras SIT

All of these tests – component level, assembly level, system level - are routinely carried out at PII Pipeline Solutions, Magnetics Centre of Excellence in Cramlington, UK. In some cases the client may have their own facilities already tailored to the specifics of the application at which additional Design Proving can be conducted (Figure 16).

4.6 Inspection Methodology

PII advocates an inspection methodology that is called Progressive Pigging. This dictates that the outcome of a pig run (whether it be a cleaning pig, gauge pig or inspection pig) is evaluated and understood before the next pig is launched.

This allows the next pig or run conditions to be modified depending upon the outcome of the previous run (Figure 16). The benefit of this methodology is that it gives the pipeline owner flexibility to adjust the pigging operation to suit the situation encountered.

Progressive Pigging builds up a picture of the pipeline over several runs, learning from each previous run and allowing the following run to be more focused and targeted towards a particular action or outcome. The Progressive Pigging approach makes it possible to optimize the program as the pipeline conditions and circumstances dictate.

The following is an indicative selection of pigs that might be run in a challenging sub-sea pipeline:

- Pig Type 1 (Soft Body Poly Cleaning Pig)
- Pig Type 2 (Soft Body Poly Cleaning Pig with Gauge Plate)
- Pig Type 3 (BIDI with Gauge Plate)
- Pig Type 4 (Hard Body Cleaning Pig)
- Pig Type 5 (Calliper with drive elements)
- Pig Type 6 (MFL Inspection Train)

There is no right answer or set limit to the number of cleaning runs required with Pig Types 1-4, the situation needs to be assessed after each run as described in the progressive pigging methodology.

Ultimately all of the pig types would be specified and designed for the pipeline length, features, & operating conditions to be encountered in the pipeline to be inspected. They would not typically be off the shelf items.

Figure 16: CATS Cleaning Run 1

4.7 Program Phasing & Milestones

In this paper the Desktop Feasibility Study and its content have been described in detail as the critical first step in developing solutions for the in-line-inspection of complex off-shore pipelines. Effective management of technical & commercial risks for both operator and ILI vendor requires the program of work to be broken down into manageable phases throughout. A typical phasing would be as follows:

1. Desktop Feasibility Study
2. Preliminary Design (including NTI)
3. Detailed Design
4. Procurement, Manufacture, & Assembly
5. Testing & Specification Development
6. Inspection Program
7. Post-Inspection Review

An overall assessment of budget and timeline would be an output of the feasibility study with a best case worst case spread, this would also be broken out by project phase. The end of each phase, or risk toll-gate, provides the opportunity to identify and address any gaps in the data or risks highlighted before moving on to the next phase of work. The detailed scope, timeline, deliverables and costs for the next phase of the project would then be agreed with a revised estimate for the remaining phases. As the project proceeds the risks are progressively reduced and then retired, tightening up the timeline & cost estimates for the remainder of the project.

Right to left, or backwards, planning is not uncommon as such a program is often driven by a pipeline coming on line or a required inspection date to meet a regulatory requirement. However, it is important that the process is started early enough that there is sufficient time to complete each phase in full before moving onto the next, to avoid carrying forward a higher than necessary level of risk.

Conclusion

As the (3) case studies prove, the technical challenges associated with the inspection of deep sea pipelines can be overcome when certain critical success factors are followed. At a minimum, success requires sustained engagement between the pipeline owner/operator and an ILI vendor with the right technology, skills, & experience.

Additional critical success factors include an early start to the project (ideally in parallel with the design & construction of the pipeline); a Desktop Feasibility Study to initiate the project; a phased approach with formal approval of risk tollgates/major milestones; and collaboration between all key stakeholders throughout. The Desktop Feasibility Study ensures that expectations and challenges are understood early in the process, highlights major risks and potential mitigations, provides confidence that a holistic solution can be found, and establishes a phased timeline and budget cost estimate for the life of the project.

Reference

[1] BP Mardi Gras - Case Study, October 2011; Bill Herron, PII Pipeline Solutions; SPE Pipeline Integrity Management Workshop, Abu Dhabi
(2) A Challenging Offshore Inspection in the Black Sea - Case Study, April 2012; Mick Mills, PII Pipeline Solutions; Pipeline European Client Conference 2012.
(3) BP CATS Pipeline Inspection Project, March 2011; Paul Clayton, PII Pipeline Solutions; Offshore Mediterranean Conference, Ravenna

Notes