Pig picking? - A comprehensive method for inspection tool selection

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T HE DIFFERENT TECHNOLOGIES available for the inspection of oil and gas pipelines, and the differences between the tools and data analysis services offered by different companies can cause confusion and lead to selections that are not ideal. Picking the appropriate inspection system to ensure the best results is increasingly complex. Picking an inappropriate tool, or failing to select useful optional extras can result in critical damage being missed, or the requirement for additional inspections. For example inertial mapping data is often offered as an option, but if the position of the pipeline is already know the perceived value may be low. However, this data can be very useful in determining the probable cause of geometric anomalies such as dents or wrinkles; having determined the cause, a more reliable assessment and decision on repair or monitoring can then be made.

Simple guidance on the tools suitable for different damage types is given in codes such as ASME B31.8S and API 1160; however there is a need for more detail, and an awareness of the benefits of additional data, increased accuracy, and the limitations of tools and data.

A structured methodology is proposed that will ensure a thorough documented inspection selection process that considers:

- The hazards or threats faced by the pipeline
- The damage that may result from those hazards (or have resulted since the last inspection)
- Inspection technologies that are capable of detecting the potential or expected damage
- The usefulness of that data for evaluating any damage and estimating corrosion growth rates, taking into account accuracy and reliability
- The feasibility of using the technologies (a simple example being that standard compression wave ultrasonic tools cannot easily be run in gas pipelines)
- Requirements for special features such as combined tools, speed control, heavy wall capability, dual diameter, etc.

T HE HISTORY OF MODERN intelligent pig inspection goes back to the late 1950's and work by TD Williamson and Tuboscope [1]. The first inspection tools with on-board recording were calliper tools for measuring the pipe bore, and magnetic flux leakage (MFL) tools for identifying areas of metal loss. These early tools were a great leap forward, but very crude by today's standards. In the intervening years a combination of factors has resulted in many different companies offering inspection services and driven the development of a wide range of new tools. These new tools are more accurate and allow the detection of many different types of defect. Examples of the factors affecting the development of the pigging industry are:

a. High profile failures such as the failure of a gas pipeline in New Mexico in 2000 that resulted in the death of 13 people [2] led to an increased regulatory and stakeholder requirement for the pipeline industry to take action to demonstrate the integrity of pipelines, with one of the prime means being internal inspection. This has driven an enormous expansion in inspection activity, and a corresponding increase in the number of companies offering inspection services.

b. Other failures such as the one at Bellingham in Washington State in 1999 [3], led to an increased awareness of the need to clearly identify and take action on particular types of damage (dent and gouge type damage in the case of the Bellingham incident). This has in

turn driven the development of new tools that can identify the damage of concern. In the case of the Bellingham incident, tools that can accurately record internal geometry, the reporting of possible metal loss in dents, and research into tools designed to detect the plastic strain caused by denting.

We now have a situation where there are many companies offering intelligent pigging services, the Pigging Products and Services Association (PPSA) website [4] lists 22 companies offering MFL metal loss inspection services.

The different technologies offered for internal inspection are extensive and include:

- Magnetic flux leakage (MFL);
- Calliper;
- Geometry;
- Ultrasonic compression wave for wall thickness measurement (UTWM);
- Ultrasonic shear wave for crack detection (UTCD);
- Electromagnetic Acoustic Transducer (EMAT); and,
- Inertial Measurement Unit (IMU);

The cost of an inspection can be significant, the disruption to normal operations can be significant, the potential impact of a stuck pig can be enormous, finally the possibility of injury while loading and unloading intelligent pigs must be considered. Hence the decision inspect should not be taken lightly.

When faced with important decisions and multiple choices a process is required. This process should ensure that choices are sensible, that they can be justified, and that there is an auditable trail.

Inspection and inspection selection is a part of the overall pipeline integrity management process, which includes other types of inspection (for example above ground surveys), management systems, training, etc.. This paper does not attempt to address the full integrity management process, and focuses only on the selection of inspection tools. It is important to be aware of the full process and the inputs that can introduce errors and directly influence the accuracy and reliability of integrity assessments completed using intelligent pig data. These are:

- The electrical and mechanical performance of the inspection tool;
- The quality of the automatic data processing algorithms;
- The expertise of the data analyst (an element of human error can be expected);
- The expertise of the engineer assessing the pipeline condition based on the inspection data;
- The quality of the data the engineer uses to complete the assessment; and,
- The accuracy of the assessment methods used by the engineer.

Overview of method of selecting a technology

The primary purpose of internal inspection of pipelines is to prevent failure. This purpose is achieved by identifying damage before it reaches a critical size and then taking action, such as completing a repair, to ensure that failure does not occur. Consequently we must select inspection tools that can identify damage that could fail. This requires an understanding of the damage which may be present, which in turn requires consideration of the hazards which cause damage and ultimately failure.

So the proposed methodology has three key elements, these are:

- Cause - Hazards
- Effect - Damage; and,
- Mitigation - Inspection

Each of these elements has two steps, as illustrated in Figure 1.

Each element requires the input of subject matter experts who have knowledge of issues such as general pipeline integrity, defect assessment, intelligent pig technology, and of course engineers with knowledge of the particular pipeline system.

Element 1: hazard identification

Hazards or threats that may affect a pipeline can be identified during a HAZID (Hazard Identification) exercise. The principle aim of the HAZID exercise is to identify all credible threats that might have caused damage to the pipeline, including those that have been detected by past surveys. There are a number of pipeline standards that provide guidance on typical threats, for example the UK pipeline design document PD 8010-4:2012 [5] lists the following threats:

- Internal Corrosion – Carbon Dioxide, Hydrogen Sulphide, Microbially Induced Corrosion, etc.;
- External Corrosion – Corrosion Under Insulation, Alternating Current Interference, Direct Current Interference, Galvanic, etc.;
- Environmentally Assisted Cracking – Hydrogen Induced Cracking, Stress Corrosion Cracking, etc.;
- Mechanical Damage – 3rd party interaction, dropped objects, sabotage, etc.;
- Natural Hazards – River crossing scouring, earthquake, Landslide, etc.;
- Operational Issues – Blockage, Incorrect operation, etc.;
- Design and Materials – Weld defects, mill defects, etc.;
- Construction – Weld defects, dents, gouges, etc.;
- Equipment Failure – Valve, flange, pig launcher/receiver, etc.; and,
- Fatigue – Thermal cycling, pressure cycling, Vortex Induced Vibration, etc.

Another threat that is often not specifically listed but must be considered is data error. Many pipelines are old and the available data on the location, linepipe type (eg seamless or Electric Resistance Welded), linepipe material grade, coating, operating pressure, etc., can be non-existent, or incorrect. Incorrect or limited data will lead to problems through the whole process from the correct identification of hazards, to the final assessment of condition and future actions.

Pipeline threats are rarely constant along the full length of a pipeline. To attempt to identify credible pipeline threats it is beneficial to segment a pipeline into separate sections that have common threat characteristics. This will generally allow clearer discussion of threats, but can lead to excessive duplication if too many segments are created. Segments can also be selected due to limitations in inspection (for example MFL inspection will be of limited accuracy in sections with a very thick pipe wall), and sections of the pipeline with known problems. Typical segments might include:

- Piggable sections
- Riser
- Subsea
- Onshore

- Mountainous regions
- Highly populated

There are of course many parameters that can be used for segmentation, but as the inspection will run through a whole piggable section the benefit of very detailed segmentation for tool selection is low (note that detailed segmentation may be needed for a full risk assessment as the consequences of failure may vary significantly from one location to the next). In fact it is better to keep the number of segments small to avoid repeating the same threats for multiple segments. It must be recognised that there will be variability within segments: an example of the segments that might be selected for a typical offshore pipeline are shown in Figure 2.

For each segment, the full list of possible hazards should be considered by a multidisciplinary team including subject matter experts in pipeline integrity, and inspection technology , and people with a sound knowledge of the design, history and operation of the particular pipeline system. This is of course a common exercise when completing a risk assessment, so it is possible that reference can be made to past risk assessment work.

During the HAZID consideration should be given to any anomalies or defects reported by previous inspections as these will be an indication of possible threats. It is likely that benign anomalies will have been detected previously (for example wall thickness variations caused during manufacture). The desirability of confirming the presence of these anomalies, even if they are not considered to present a threat to pipeline integrity, should be considered.

Element 2: damage and assessment

Having identified credible hazards the next step is to consider the type and extent of damage that may be present in the pipeline. To illustrate this step we will consider the examples of external microbially induced corrosion, seam weld manufacturing defects, and external interference. Obviously, there are a large range of different hazards, with many different possible types of damage, and it is not possible to cover everything here.

External corrosion

External corrosion is a credible threat to the integrity of most buried onshore pipelines. However, the nature of the corrosion may affect the assessment required and hence the data needed. Microbially induced corrosion is a possible form of corrosion damage if the pipeline has a tape wrap coating that has been damaged by soil stress (see an example in Figure 3), operates at a relatively high temperature, and the soils contain high levels of certain bacteria. The resulting damage may include multiple deep isolated pits (see an example in Figure 4). These pits can grow rapidly (eg, 1-2 mm per year).

Deep corrosion pits are most likely to cause a failure if they grow fully through the pipe wall. Corrosion assessment codes therefore usually limit the acceptable depth to 80% or 85% of the pipe wall [6], implying a remaining wall thickness requirement of 20% or 15%. Therefore, to complete an assessment: the defect must be identified; the remaining wall thickness is needed; and, the rate of growth is also critical for predicting safe future operation and repair or re-inspection dates.

Seam weld manufacturing

Indicators that manufacturing defects in the seam weld are a credible threat to pipeline integrity include:

- failures on hydrotest;
- weld misalignment or roof topping; and,
- cyclic internal pressure loading.

The expected damage is fatigue cracking initiating at small weld anomalies such as undercut or lack of fusion. An example of cracking developing from an artificial anomaly at the internal toe of a seam weld is shown in Figure 5.

Critical crack sizes can be calculated using pipeline material specific methods [7]. These methods require information on the depth and length of the crack. Fatigue crack growth can be calculated using standard fracture mechanics methods such as those presented in API 579 [8]. Crack growth calculations require information on the depth and length of the crack and in addition details of any misalignment or roof topping as these features create stress concentrations that accelerate crack growth [9].

External interference

It is very difficult to control all activities around long distance oil and gas pipelines, hence external interference is often credible. For a typical buried onshore pipeline the possible damage would be:

- Gouge – a gouge will tend to be a long narrow area of metal loss, possibly with some material hardening and cracking in the base of the gouge. There may be multiple gouges, and the gouges may be circumferential, axial, or diagonal on the pipe. There will also be damage to the coating.
- Dent – size depends on size and shape of indenter, force of impact, internal pressure, and pipe properties (diameter, wall thickness, material grade). Consequently a wide range of dent geometries are possible. It must be noted that multiple dents are common when there is third party damage, and denting can affect a weld and/or be combined with gouging.

Obviously it is possible for external interference to cause an instantaneous failure, but that is not something that inspection can help prevent.

The next step is to consider how this damage would be assessed if it was present, as this will define the data requirements, and hence the inspection.

Gouge

A gouge is surface damage to a pipeline caused by foreign objects removing part of the pipe wall. Most gouges found in pipelines are shallow (less than 4mm). Gouges are treated with caution because of the possibility of a 'work hardened' layer below the gouge, which can also contain cracks. The hardened layer below the gouge is caused by the heat of the damaging process, and the plastic deformation. Typically, the hardened layer and any associated cracking has a maximum depth of 0.5 mm [10]. If cracks are present they can grow due to fatigue loading. In addition this hardened layer can be susceptible to 'environmental cracking'. The gouging process will also remove the protective coating. An example of gouges caused by a back hoe is shown in Figure 6.

A gouge can be assessed based on the length of the gouge along the pipe axis and the depth of the gouge. However, industry guidance (eg ASME B31.8 [11]) requires all gouges to be removed, this is because of the difficulty of detecting associated shallow denting, and possible shallow cracking in the base of the gouge.

Dent

The assessment of dents has become increasingly complex in recent years. This is because there are a large number of dents present in pipelines, but the majority are not significant, and will not affect the integrity of the pipeline [12]. Identifying the dents which may be significant requires consideration of the following factors:

- Depth – very deep dents may obstruct the passage of pigs, restrict product flow, and disband coating.
- Strain – denting causes high strains. This can lead to cracking and very low failure pressure or short fatigue life. The strain is related to the shape of the dent.
- Fatigue – dents result in a stress concentration that reduces fatigue life. The stress concentration and hence fatigue life, is related to the shape of the dent.
- Weld – welds may be less tolerant of strain than the pipe body material, and hence more likely to have cracking. In addition, a weld creates an additional stress concentration and may contain small crack initiators that result in a further reduction in fatigue life.
- Gouge – dent and gouge combinations can result in very low failure pressures and short fatigue lives, particularly if the pipe material is of relatively low toughness.
- Restraint – A restrained dent, (that is, a dent which cannot flex outwards easily if the internal pressure is increased), has a fatigue life which is longer than that of a similar unrestrained dent. It is very difficult to inspect a pipeline internally for restraint; however, it may be possible to identify the most likely cause of the dent, and hence infer restraint.

Consequently a large amount of information is required in order to complete a reliable assessment of a dent detected by internal inspection.

Element 3: data and inspection

A clear understanding of the credible threats and associated damage, and the methods that would be used to assess that damage, should lead to well-defined requirements for data, and therefore inspection. To illustrate this step in the process, the examples of microbially induced corrosion, manufacturing related seam weld anomalies, and external interference are again considered.

The data requirements and inspection options for each of these threats are presented in Tables 1-3. Similar tables should be developed for a specific pipeline for each credible threat and damage type. These will provide the technical basis for the final tool selection.

Internal inspection should give data on defects, and can also be used to find other information such as location, and operating pressure profile, which may be very helpful in evaluating threats. However, inspection will not provide all of the data needed to address the threats identified, and other data, such as design information, and external survey data, must be integrated with the internal inspection data to ensure a complete picture.

Other issues

Before making final decisions on inspections some further issues will need careful consideration. These should include:

- Feasibility of running a particular tool - for example it is very difficult to run an ultrasonic wall thickness measurement tool in a gas pipeline.

- Flow rates – inspection tools generally perform best within a particular range of speeds. In some gas pipelines flow rates are very high, and a tool with some form of speed control may be preferable to reducing transport rates.
- Performance in thick wall sections – the defect detection and sizing performance of MFL tools may be reduced in very thick pipe sections. This may not be an issue depending on the locations where defects are expected and the probable nature of those defects. For example it is common that pipe wall thickness is increased at road crossings, however, road crossings are also locations where the possibility of third party damage is elevated. Hence reassurance is required that the gouge detection performance in thick sections will be acceptable.
- Practical limits such as short pig traps, or tight bends may result in a preference for a particular tool which is easier to run even if the technical performance is less good.
- Combo tools – many companies now offer tools that perform multiple inspections in one run. This can offer significant benefits in terms of the practicalities of running the tool. For example the number of times the pig traps are opened is reduced, which makes the operations safer. In addition data alignment can be much easier. However, there may be other compromises for example in data quality, tool length, or the ability to control tool speed.
- Tool availability – some specialist tools are only available in a limited range of diameters, and while inspection companies will build tools for specific projects this can have a significant additional cost.
- Cost – there may be significant variations in the cost for inspection with different technologies, and by different companies. For the inspection of critical components, the failure of which will have significant safety, environmental and financial implications the cheapest option is not likely to be the best. Developing the required mechanical, electronics, and software technology needed for high quality inspection is expensive, training and developing data analysts is costly, and giving the analysts the time required to thoroughly review the data will also add cost.
- Practical experience – experience of working with a particular company of pipeline system can help to ensure a reliable inspection. Technicians familiar with the pig traps and valves of a particular pipeline system are more likely to be able to ensure a reliable inspection than ones who have never seen it before.

Conclusions

1. Selecting an ILI tool is an important decision as there are significant costs and risks associated.
2. The number of choices of inspection company and inspection technology are high.
3. The inputs to the decision process are complex as they cover a wide range of technical issues (such as detection performance, accuracy, reliability, human issues and cost).
4. To ensure that the maximum benefit is gained for inspection the pig selected must address the threats identified, and therefore fit with the overall integrity management plan.
5. Inspection is primarily intended to identify damage and hence prevent failures; however, a lack of basic data such as the line pipe type is also a threat which can be addressed by inspection.
6. Internal inspection can only give limited information, and the data must be assessed with due consideration for the hazards identified, the design and operating conditions of the pipeline, and the results of other inspections which will provide valuable additional data. For example coating damage identified by external survey, may be an indicator of gouging.
7. A structured, documented, decision process will make the selection of the optimum tool more likely.

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Data Required	Inspection Options	Comment
Corrosion pit detection	MFL UTWM	Consideration should be given to the detection performance for the specific defect types and the pipeline in question of the different tools that may be suitable. For example if a particular tool has low reliability for the detection of small diameter pits it may not be suitable.
Minimum remaining wall thickness	MFL UTWM	The accuracy of different tools in identifying the minimum remaining wall thickness associated with a corrosion pit should be considered. Account must be taken of accuracy in assessment; hence tools with low accuracy may lead to excessively conservative assessments.
Corrosion rate	Repeat measurements	Measurement accuracy and reliability will affect the accuracy of any corrosion growth estimate. Tools with low accuracy will result in the calculation of high possible corrosion rates, and hence may lead to excessively conservative assessments.

Table 1 Data Requirements and Inspection Options for Microbially Induced External Corrosion Pitting.

Data Required	Inspection Options	Comment
Crack detection	UTCD EMAT	Consideration should be given to the detection performance of the different tools that may be suitable.
Crack depth and length	UTCD EMAT	Crack measurement is known to be extremely difficult. An estimate is required for crack assessment. The accuracy of the tool, particularly with respect to crack profile, should be considered, as long shallow cracks with short deeper sections are less significant than long deep cracks.
Misalignment/ roof topping	Geometry UTWM (modified)	The geometry of the weld and the pipe around the weld may not affect failure pressure, but can have a significant impact on fatigue crack growth rates. Geometry tools may detect ovality and roof topping. The identification of weld misalignment is likely to require an ultrasonic tool capable of detecting changes in sensor stand-off.

Table 2 Data Requirements and Inspection Options for Seam Weld Fatigue Cracking.

Data Required	Inspection Options	Comment
Dent detection	Calliper Geometry MFL UTWM	MFL tools have been shown to be capable of detecting very shallow residual dents.
Dent depth	Calliper Geometry	
Dent shape	Geometry	
Seam weld	MFL	Seam welds in submerged arc welded pipe are usually easy to identify. Electric resistance welded seams are difficult to detect.
Girth weld	Geometry MFL UTWM	
Presence of a gouge	MFL UTWM	It should be noted that when the pipe is deformed the metal loss detection performance of both MFL and UT tools may be reduced. In addition, a gouge does not have to be deep to be significant, and it may be below the metal loss reporting criteria of the tools. Since the gouging process will also result in coating damage coating surveys may be an additional source of data that can be used to check for the possible presence of a gouge, but note that the area of coating damage may be small, and not significant in corrosion terms if the CP system is adequate, and hence may be ignored by corrosion engineers if they are not aware of the need to look for possible gouging.
Presence of restraint (cause of dent)	IMU (possibly), preferably repeated.	IMU data provides information on pipe curvature. The shape of the pipe in the vicinity of the dent, combined with the dent shape can give an indication of the possible cause of the dent and the potential for the dent to change in the future. For example after construction ground consolidation may continue for several years, particularly if the trench creates a channel for water drainage which then washes soil out from under the pipeline.

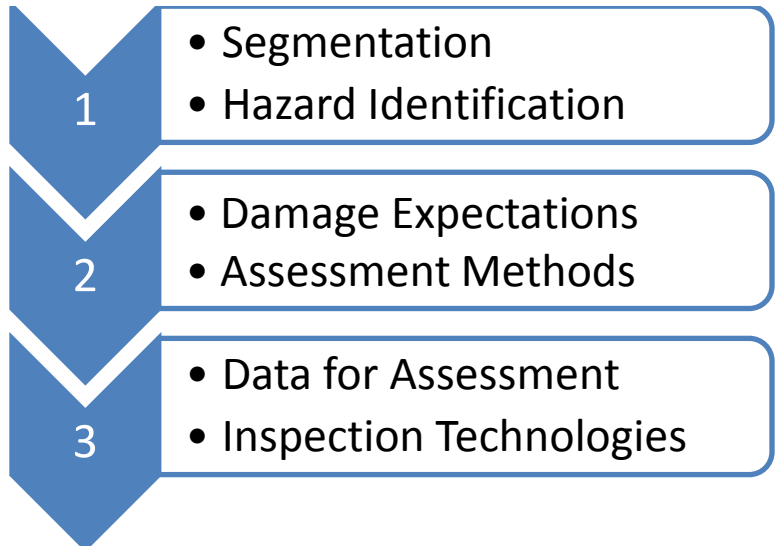**Table 3 Data Requirements and Inspection Options for Dents.**

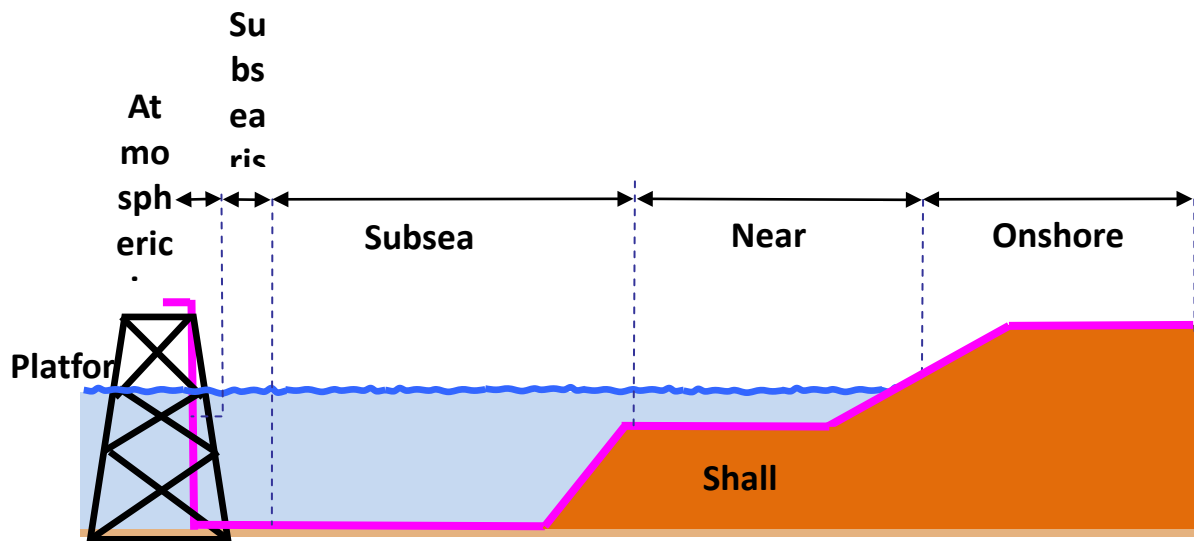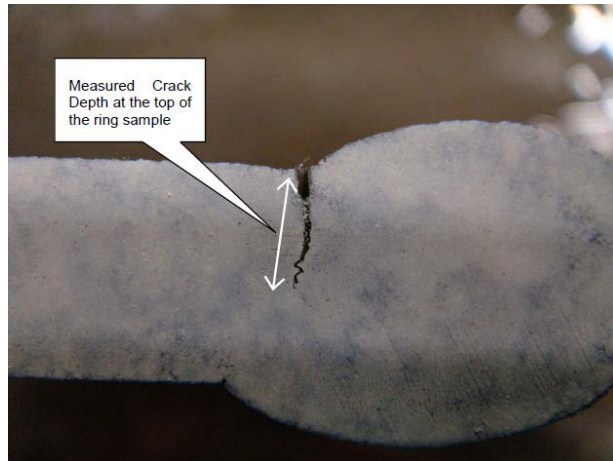**Figure 1 Inspection tool selection process.**

Figure 2 Example pipeline segmentation for HAZID.

Figure 3 Degraded coating.

Figure 4 Pits caused by microbially induced corrosion.

Figure 5 Fatigue crack from artificial weld anomaly.

Figure 6 Gouges caused by a back hoe.