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RELIABILITY ANALYSIS OF NON-DESTRUCTIVE TESTING OF TOPSIDE FLOW-LINE PIPE SYSTEM ON AGING PLATFORM:

PLANT, HUMAN AND TECHNOLOGY

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PREFACE

This thesis was made as a completion of Master of Science at University of Stavanger (UiS), study program Offshore Technology with specialization in Industrial Asset Management.

The title of this thesis is "Reliability Analysis of Non-Destructive Testing of Topside Flow-Line Pipe System on Aging Platform: Plant, Human and Technology". It summarizes the research done from September 2012 until May 2013 in cooperation with University of Stavanger and Aker Solutions MMO.

The thesis was written based on challenges met on the practical daily operation of aging platforms on the Norwegian Continental Shelf (NCS). Multiple offshore trips and direct involvement with the subject were done as part of the research.

For the completion of the thesis, I received multiple contributions in academicals, practical and also moral support. First and foremost, I would like to acknowledge all my *family* and *friends* for the moral support.

My gratitude and recognitions to *Dr R.M. Chandima Ratnayake, PhD* that has supervised and guide me all the way of this thesis and paper. I would also thank *Roy Martin Zydeman* from Aker Solutions MMO for the genuine support towards my development.

Special appreciation addressed for a sister and two brothers who made it possible for me to study at UiS; *Dyah Purnamaning Wulan*, *Shaukat Ali*, and *David Vestvik-Halvorsen*.

Stavanger, 01 June 2013,

Mayang Kusumawardhani

ABSTRACT

The quality of static mechanical systems' integrity control process on aging oil & gas production and process plants is depending upon the accuracy of the condition monitoring data. The accurate interpretation of the data significantly aids for making right decision at the right time on right location.

However, it is observed anomalies on the historical in-service inspection data records pertaining to most of aging plants under the study. Such anomalies result sub-optimal inspection decisions and jeopardizes quality of an in-service inspection program.

The uncertainties of condition monitoring data have been discussed in the literature and industrial community over the years. Number of approaches has been proposed to address various challenges pertaining to uncertainties present in the in-service inspection data. This thesis investigates the anomalies on data, and further suggests an empirical approach for quantifying the reliability of condition monitoring data to estimate the level of anomalies presents in the in-service inspection data. The sources of anomalies are explored and will try to be mitigated.

The case studies are carried out using three different platforms functioning in the Norwegian Continental Shelf. Flowline system of each plant has been selected as it has been given highest risk priority.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

NOTATION AND ABREVIATION

MT	magnetic particle
NCS	Norwegian Continental Shelf
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
O&G	Oil and Gas
PA	Phased Array
PCIDB	Piping Components Inspection Database
PT	liquid penetrant
RBI	Risk Based Inspection
RCM	Reliability-Centered Maintenance
RT	radiography testing
UT	ultrasonic testing
VT	visual testing
PT	Process Hydrocarbons, Two Phase
CoF	Consequence of Failure
PoF	Probability of Failure
DO	Drain, Open
t	nominal thickness
w	penetrated thickness
b	object-to-film distance
d	source size
f	source-to-object distance
IQI	Image Quality Indicator
mm	millimetre
NS	Norwegian Standard
ISO	International Standard Organisation
EN	European Standard

DEFINITIONS

Confidence Level	=	Indicates the portion f measurements that will fall within a given sizing accuracy
Couplant	=	A substance, usually a liquid, used between the transducer unit and test surface to permit or improve transmission of ultrasonic energy (Hellier, 2001).
Data Error	=	A deviation from correctness in data, usually an error, which occurred prior to processing the data (Parker, 1994).
Dendritic Structures	=	Dendrites are branch-like grains that exist in certain metal structures and can cause problems, particularly in stainless steel welds.
Dent	=	depression that produces a gross disturbance in the curvature of the pipe wall (as opposed to a scratch or gouge, which reduces the pipe wall thickness) (American Society of Mechanical, 2011)
Discontinuity	=	A lack of continuity or cohesion; an intentional or unintentional interruption in the physical structure or configuration of a material or component (Hellier, 2001)
Erosion	=	Destruction of materials by the abrasive action of moving fluids, usually accelerated by the presence of solid particles carried with the fluid (Powell et al., 1986).
Erosion-Corrosion	=	A conjoint action involving corrosion and erosion in the presence of a moving corrosive fluid, leading to the accelerated loss of material (Powell et al., 1986).
Hot Spot	=	A location on pipe or equipment where the condition being discussed is expected to be most severe. For example, a “hot spot” for microbial corrosion is an area of stagnant flow .
Information System		Any combination of information technology and people's activities using that technology to support operations, management, and decision-making
Inspection	=	An activity carried out periodically and used to assess the progression of damage in a component. Inspection can be by means of technical instruments (NDT) or by a visual examination.
Inspection	=	An activity carried out periodically and used to assess the progression of damage in a component. Inspection can be by means of technical instruments (NDT) or by a visual examination.
Inspection Effectiveness	=	A description of the ability of the inspection method to detect the damage type inspected for (DNV, 2010a).

Inspection Methods	=	The means by which inspection can be carried out, such as visual, ultrasonic, radiographic (DNV, 2010a).
Inspection Plan	=	Detail of inspection activity giving the precise location, type and timing of activity for each individual inspection action that is planned (DNV, 2010a).
Inspection Programme	=	A summary of inspection activities mainly used as an overview of inspection activity for several years into the future (DNV, 2010a).
Inspection Techniques	=	A combination of inspection method and the means by which it is to be applied, concerning surface and equipment preparation, execution of inspection with a given method, and area of coverage (DNV, 2010a).
NDE/NDT	=	Non-Destructive Evaluation/Testing. Inspection of components using equipment to reveal the defects, such as magnetic particles or ultrasonic methods.
Nominal thickness (t)	=	the nominal thickness of the material in the region under examination. Manufacturing tolerances do not have to be taken into account
Object-to-film distance (b)	=	the distance between the radiation side of the test object and the film surface measured along the central axis of the radiation beam
Ovalities	=	a deviation of the circular shape of the cross section of the pipeline (American Society of Mechanical, 2011). Ovality affects the entire circumference of the pipeline cross section. Ovalities usually appear in combination with a dent.
Penetrated thickness (w)	=	the thickness of material in the direction of the radiation beam calculated on basis of the nominal thickness.
Pipe	=	a pressure-tight cylinder used to convey a fluid or to transmit a fluid pressure, ordinarily designated pipe in applicable material specifications. Materials designated tube or tubing in the specifications are treated as pipe when intended for pressure service (American Society of Mechanical, 2008).
Pipeline	=	Long series of Pipes usually of large diameter often underground with few fittings & equipment's mostly Pumps & Valves mainly to control the flow, that are laid with an intention to transport any fluid whether liquid or gas over long distances (Ketan, 2012).
Piping	=	assemblies of piping components used to convey, distribute, mix, separate, discharge, meter, control, or snub fluid flows. Piping also includes pipe-supporting elements, but does not include support structures, such as building frames, bents, foundations, or any equipment excluded from ASME B31.3

		(American Society of Mechanical, 2008).
Piping system	=	interconnected piping subject to the same set or sets of design conditions (American Society of Mechanical, 2008).
Reliability	=	"repeatability" or "consistency", i.e. a measure is considered reliable if it would give us the same result over and over again (assuming that what we are measuring isn't changing) (Trochim, 2008)
Resolution	=	The ability of an ultrasonic system to discriminate between two reflectors that are close together
Source size (d)	=	the size of the source of radiation
Source-to-object distance (f)	=	the distance between the source of radiation and the source side of the test object measured along the central axis of the radiation beam.
Sulfidation	=	the reaction of a metal or alloy with a sulfur-containing species to produce a sulfur compound that forms on or beneath the surface of the metal or alloy.
$T_{measured}$	=	The reported wall thickness resulted from non-destructive testing.
$T_{nominal}$	=	The available wall thickness according to diameter and pipe class [i.e. the schedule available in the market which is greater than or equal to (corrosion allowance + Tminimum3)]
Wear	=	Damage to a solid surface, generally involving progressive loss of material, due to relative motion between that surface and a contacting surface or substance (Powell et al., 1986).

1.0 INTRODUCTION

The purpose of this chapter is to provide the basic information for Reader to understand the background and objective of this thesis

The background and issues related to the research project will be presented at the beginning, followed by the objectives, purpose and research questions. At the end of the chapter, limitations and the structure of the thesis are presented.

1.1 BACKGROUND

After the industrial age, management organization has evolved and giving technology a new role in decision making (Frankel, 2008). Technology is used to transfer information amongst decision makers, and therefore the quality of data becoming crucial for organizational performance. In managing performance of an organization, it is now necessary to manage technology for information distribution. Information creates link between decision-making and quality performance in an organization, as described in figure 1.

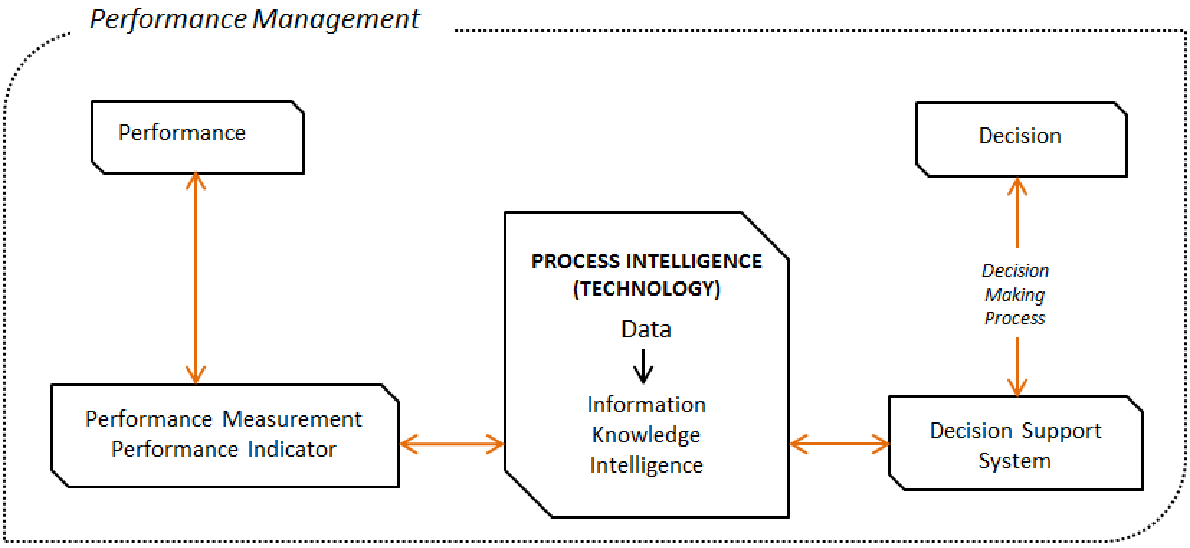


Figure 1 - Relationship between Decisions and Performance

For example, in the case of equipment performance monitoring, correct information has helped the organization to make better maintenance decision on equipment before they fail (Fidler, 2009). And also an example where decision is supporting performance, as in the case of Conoco Inc. which stated that structured decision process facilitate benchmarking and learning process, thus decision being made shall improve the (future) project performance (McGee et al., 2000). In more daily practice we can look an example from electronic equipment reliability; since design is responsible for 43% of failure in electronic equipment (Markeset, 2012), we can clearly see that even engineering decisions made earlier in the design stage will affect the future performance.

For oil and gas companies, experiences revealed that data quality could potentially beneficial or misleading (Radhay, 2008) and consequently affecting engineering service provider companies (contractors).

The quality of data (prior knowledge) will influence the output (performance) delivered by contractors, whether direct or indirectly. This is mainly caused by 1) the nature of decision-making itself that generally affected by the assumption of certain parameters based on (prior) knowledge, and 2) the impact of interdependence in modern business operation.

If we look closely from risk point of view, the gap between initial input and future output (performance) is, of course, uncertainty, and the assumption made for the uncertainty. The assumption would affect decision-making and the activity that based on it. The figure below will illustrate the relationship:

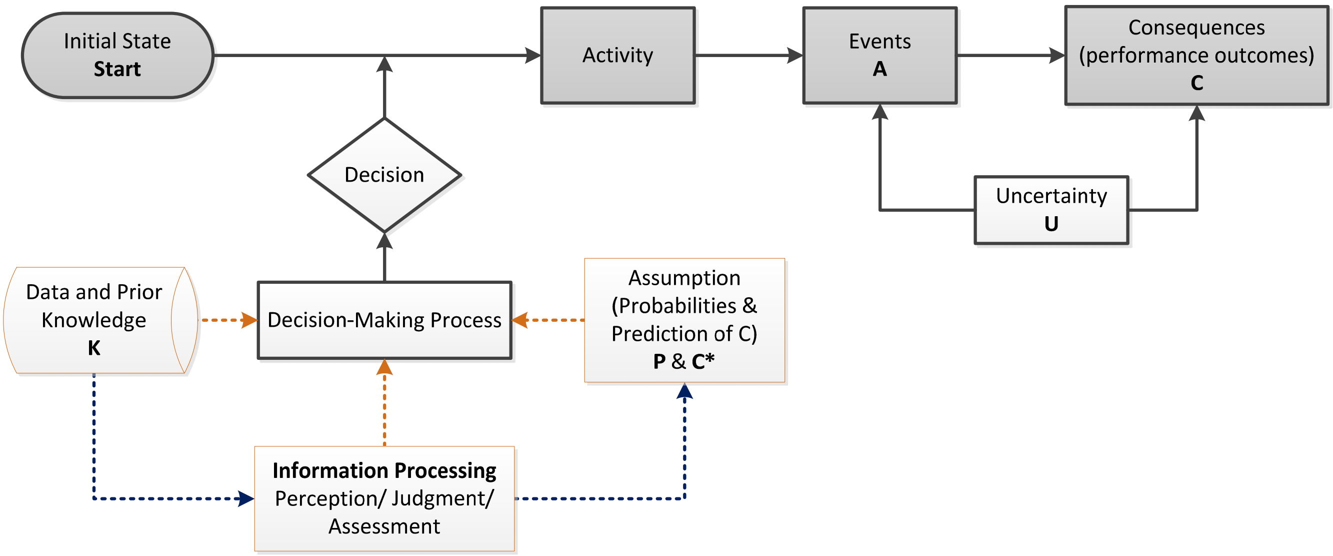


Figure 2 – How Data affecting Performance Output (adapted from Aven, 2010)

The figure is utilizing Terje Aven's (2011) definition of risk (C, C*, U, P, K), where C denotes the consequences derives from activity and the initiating events A; C* denotes the prediction of C; U denotes the uncertainty of C value; and P denotes the probability of specific events and consequences, given the background information K.

In this thesis, we would not define the exact process of decision making, since the process would vary from one condition to another. But the figure aimed to illustrate that the decision-making process is influenced by prior knowledge, whether directly or indirectly, in generating decision. This would satisfy the first reasoning, that decision-making is generally affected by the assumption of certain parameters based on (prior) knowledge. Thus quality of decision would be affected by the quality of data (prior knowledge).

The second cause related to interdependencies in oil and gas industry, where a contractor would be affected by the client (operator companies) and client's (other) contractors, at a certain degree, depending on the nature of their relationship.

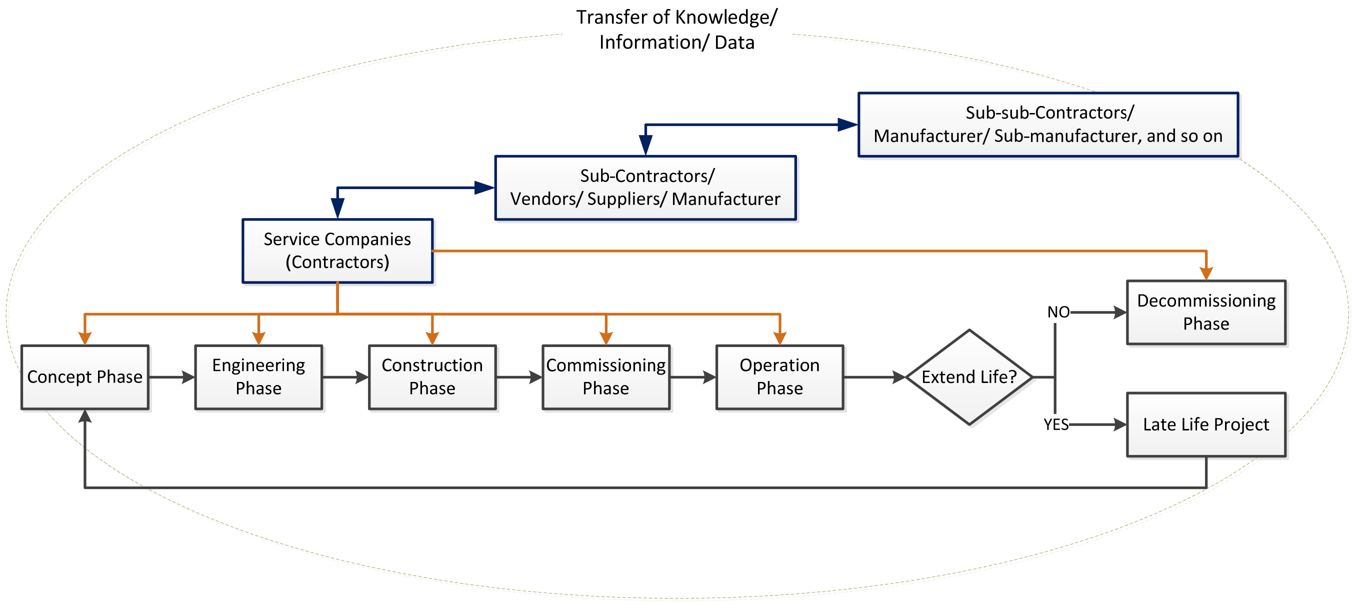


Figure 3 – Basic interdependency relationship in a lifecycle of oil and gas platform with its service companies

As we see in figure 3, in interdependency there is transfer of knowledge between the components. Let say, we will perform modification on a 20 years old piping system on the platform. The first thing we look would be the engineering data of the piping system made by contractor at engineering phase, As-Built data that made by another contractor, as well as the history of operation and maintenance made by contractor at operation phase. These data would contribute to future engineering calculation or decision. And as we understand from previously discussed decision-making process, poor quality of data could lead to poor decision.

Further challenge is to be addressed for aging platform where previous data recording is insufficient. For example, there could be a possibility of unrecorded repair or specification change being done by different contractor. These data would also affect daily operation and maintenance of a platform.

1.2 RESEARCH PROBLEM

Degradation in the aging oil supply system is seen by some as a growing threat (Volz, 2006), we can find cases of accidents or environmental pollutions due to aging or corroded pipe system all over the globe (Amnesty-International, 2012, NACE, 2010). Accidents due to pipe degradation could be prevented with appropriate condition monitoring activities, where defects could be detected and properly handled before failure.

Condition monitoring is commonly being conducted by engineering service provider companies (contractors), which rely on information, historical data and accurate interpretation of technical condition data for decision-making regarding future maintenance. With respect to pipe, monitoring activities appeared on inspection program that are made to carry out routine inspections based on the historical data.

Since platforms are on operation, the technique being used would normally be Non-destructive Testing (NDT) techniques. These NDT techniques will be planned by inspection planners before being implemented by inspectors. The inspection planners would base the plan and analysis mostly from the data available in the inspection database.

However, over the years there are numbers of anomaly found on the data against real condition or other existing data. We believe that as a result of these anomalies, there are possibilities that the inspection generates a certain number of errors. Apart from that, the NDT processes also produce some assignable errors when the NDT results are not interpreted properly.

1.3 RESEARCH QUESTIONS

Based on the research problem described above, the following research questions have been formulated:

1. What are the factors that influence reliability of historical NDT inspection data?
2. How does the reliability of historical NDT inspection data influence the integrity of ageing oil and gas assets?
3. How does the reliability of NDT inspection historical data influence the quality of technical analysis?

1.4 PURPOSE AND OBJECTIVES OF RESEARCH STUDY

The goal of this research is to enhance quality of NDT inspection data for more accurate interpretation and analysis. Furthermore, in order to reduce unnecessary financial burden and to mitigate the hazards to an acceptable level it is vital;

1. to study the reliability of NDT data based on historical data recorded in inspection database.
2. to study, how the reliability of historical NDT inspection data influence the quality of technical analysis.
3. to analyse, what are the influencing factors to the reliability of NDT Inspection.
4. to analyse, how the reliability of historical NDE inspection data influence the integrity of ageing oil and gas assets.

1.5 LIMITATION OF RESEARCH STUDY

This research is governed by some limitations, which are:

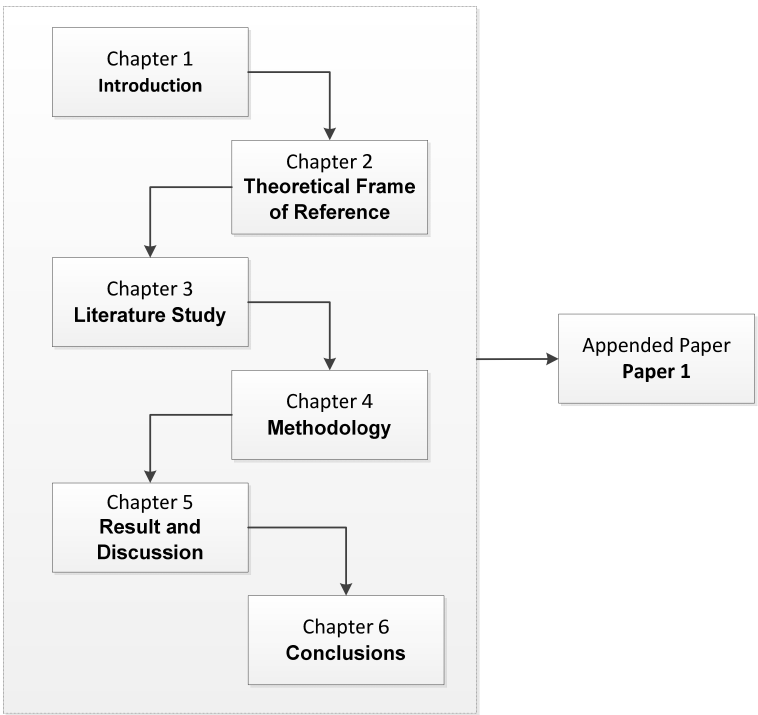
1. Due to limitation of the time, the analysis is done only on the topside flow line piping system.
2. Data used from the system is from year 1994 to 2011.
3. Data used is from platform that operates on the North Sea, Norwegian Sector Area.
4. Data is gathered from Service Company’s access point.

5. Analysis of procedures would be limited on Operator Company's required procedures.
6. Norsok Standards and other International Standards are not included in the analysis.
7. In the case studies and numerical example it is assumed that all influence factor are included in the model.

1.6 STRUCTURE OF RESEARCH STUDY

This thesis will be consisting of the following:

1. The first chapter (Introduction) provides description of the background and research problem. Thereafter, the aim, research question, limitations and thesis structure are outlined.
2. In the second chapter (Theoretical Frame Of Reference) the theoretical framework will be presented.
3. In the third chapter (Literature Study), it will be outlined and briefly discussed previous study that related to the subject. Aiming to aid the research and shows uniqueness of present research.
4. In the fourth chapter (Methodology) the chosen research design and different aspects of data collection and data analysis will be presented. Validity and reliability issues of the study will be presented.
5. In the fifth chapter (Result and Discussion) the general conclusions drawn from the research with a discussion will be presented.
6. The sixth chapter presents the research's conclusions, contributions and further research.



2.0 THEORETICAL FRAME OF REFERENCE

In this chapter, some principal theories regarding areas important for this thesis will be presented. Writer's initial assessment upon the subject would also be introduced briefly in this chapter.

2.1 INTRODUCTION

In contrast with increased fossil fuel price, technology has continuously finding new ways to harvest the reservoir reserves. When the technology succeeds, the lifetime of the field would be prolonged. Unfortunately the production asset on the respected field are normally only designed for 20 years to 30 years of operation, resulting attempts for life extension of these nearly 'expired' assets.

The business of extending life of production asset beyond their design life poses challenges and potential hazards. In aging reservoirs and production asset we would usually meet challenges related to physical degradation mechanism and changes from previous operating conditions.

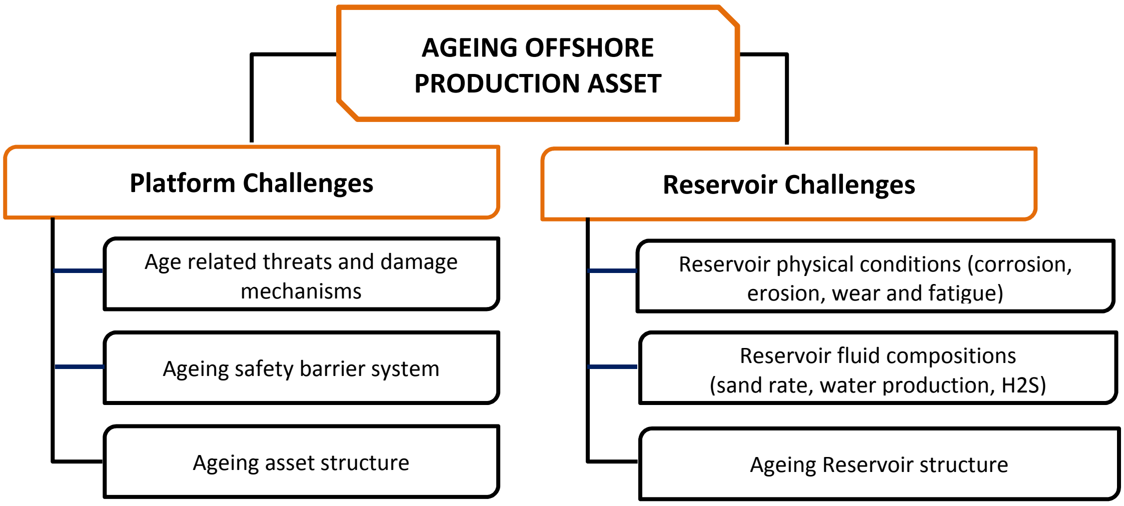


Figure 4 - Age Related Challenges of Ageing Offshore Production Asset

Other than accepting the challenges of aging platform, another solution is to offer the assets on the market. Either way, the challenges of extending mature asset persist.

Before we go further into the study, it is interesting to draw the line of what are the criteria of a platform to be called aging, as well as understanding the involved process necessary to attain inspection data.

2.2 CHARACTERISTICS OF AGING PLATFORMS

Lifetime of an asset is determined early in the initial design stage as guideline for the lifecycle plan and design requirement. Failure rate of assets will continuously increase along the time due to several factors such as inherited defects from manufacturer/fabrication, degradation mechanism and operating conditions. The increasing rate of failure can be altered through proper preventive measure such as repair, inspection and maintenance on operation. However, in late-life of asset, these preventive measures would become more frequent in order to maintain asset integrity.

In order to simplify determination of asset condition, the critical equipment could be classified equipment into a staged scale of ageing according to the integrity indicators (Wintle et al., 2006, Wintle and Sharp, 2008):

- Stage 1 : Post Commissioning ('Initial').
- Stage 2 : Risk-Based ('Maturity').
- Stage 3 : Deterministic ('Ageing').
- Stage 4 : Monitored ('Termination').

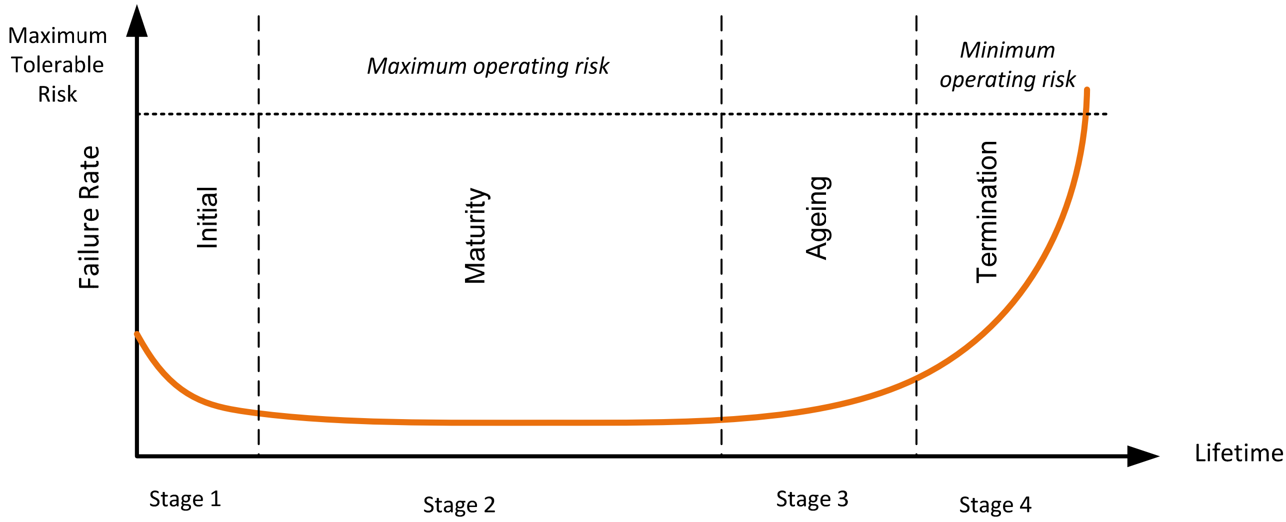


Figure 5 - Model for the probability of failure of a population of equipment and the operating risk (adapted from: Wintle et al., 2006)

Although bath-tub curve on Figure 5 is widely referred to in reliability literatures, and still forms the basis of modern reliability techniques (ReliabilitySuccess, 2011), this curve is debatable by report from Nowlan and Heap (1978) stating that 68% of failures were noted as being in the infant mortality region or in this case the 'initial stage', which occurs during installation, reassembly, after repair, after start-up and other introduction to service times.

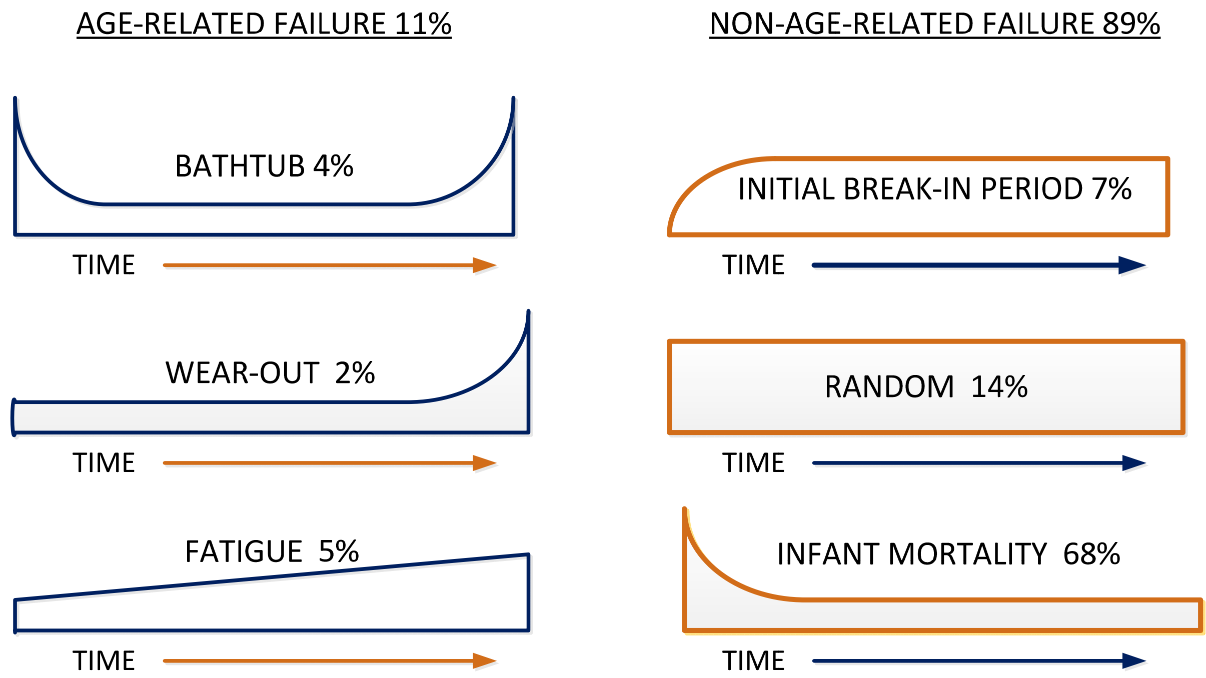


Figure 6 - Age.reliabilitv pattern: Failure Patterns applies for components (Nowlan and Heap, 1978, ReliabiliyNow, 2012)

Regardless of individual failure pattern, generally for group of components In 'ageing stage', the failure rate is increasing and it becomes more important to determine quantitatively (hence 'deterministic') the extent and rate of damage and to make an estimate the remaining life (see: Wintle et al., 2006).

At this stage, some equipment of the platform may have been replaced or modified to prolong the life of asset. Never the less, the rest of equipment that are not being renewed would require proactive approach to inspection and maintenance management. In some cases, the history of equipment could not be found due to traditional log system, changes in the system or human factors. Although static equipment such as piping and vessel are considered to be more reluctant to degradation mechanism, a risk base approach is highly recommended to prevent failure.

As the above explanation used individual equipment as an approach, the term of aging platform' becoming inconclusive when taken as a whole. But an idea from Wintle et al (2006) might satisfy this discussion:

"Ageing is not about how old your equipment is; it is about what you know about its condition, and how that is changing over time (Wintle et al., 2006)."

2.3 PIPING DEFECTS

The main defects or anomalies causing concern on piping are metal loss, material defects and external mechanical damage (Barbian et al., 1993). On aged platform's pipe system, defects which occur before or during commissioning phase (pre-service) are usually less considered than defects which occur during operation phase (in-service). This is due to:

- defects present in the pipe before the pre-service test can generally be removed or detected by the re-service test if the test pressure is high enough (Eiber and Kiefner, 1986)
- defects are normally detected during operation, and
- new spares and parts installed for replacement are normally following existing specification.

The attention to pre-service defects thou, might increase when the respected platform undergo a 'facelift'; e.g. when plant modifications or life extension is performed. Anomalies such as weld defects, gouges and dents may occur during this phase. Another consideration is the success rate of platform design, result of commissioning test and outstanding punch-list inherited to operation.

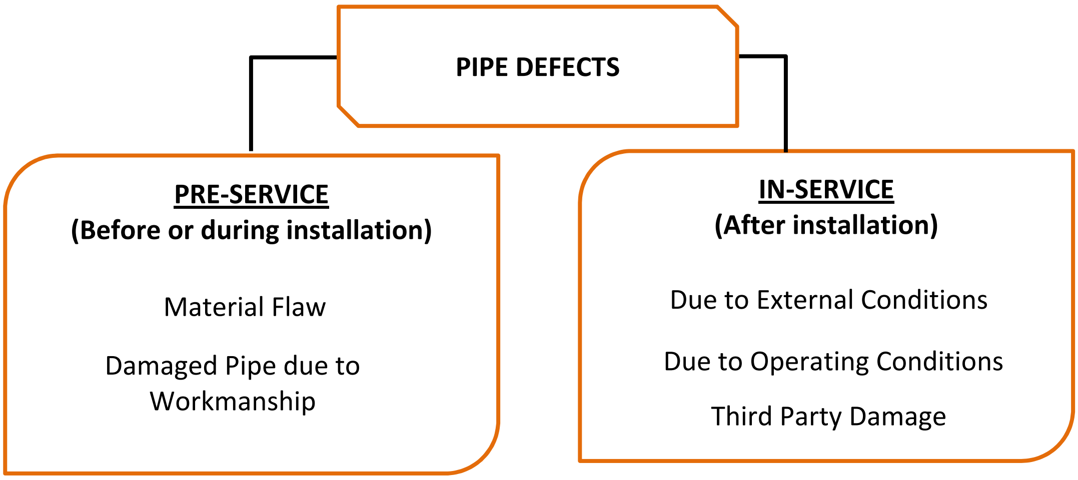


Figure 7 - Category of Pipe Defects (partly adapted from: Kulkarni and Conroy, 1991)

Even if it is assumed that there are no inherited defects from commissioning phase to operation phase, during the operation of a platform the sources of defects would still occur from day-to-day activities. These in-service defects may occur from; external (environmental) conditions, operating conditions and from third party activities (see: Barbian et al., 1993, Kulkarni and Conroy, 1991, Eiber and Kiefner, 1986).

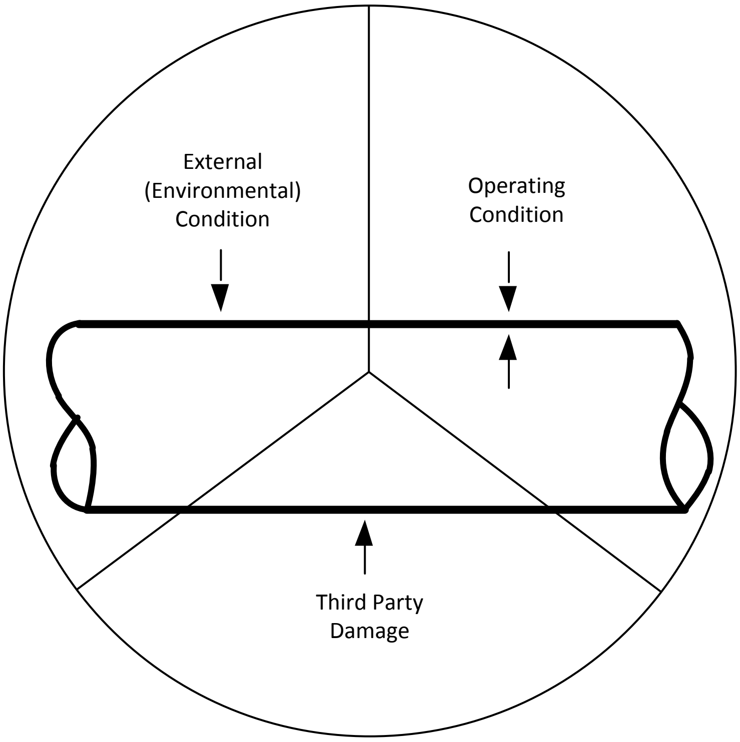


Figure 8 – Sources of In-Service Defects

2.3.1 Defect from External Conditions and Operating Conditions

External conditions and operating conditions could contribute to changes in materials that should be accounted for in design (King, 1986). In aging platform, most of the piping materials are carbon steel, thus common concern in this type of piping would be corrosion.

Basically, corrosion is caused by electric current flow from areas of a metal surface through a conducting solution (or environment). Metal degradation due to this electric current occurs at areas which are called anodes, where the electricity leaves the metal (see: Roberge, 2012, Davis, 2000). Corrosion on piping occurs when (unprotected) piping exposed to oxygen and electrolyte (e.g. water, moisture). The metal will oxidize and form the respective metal oxide on the piping surface causing loss of material.

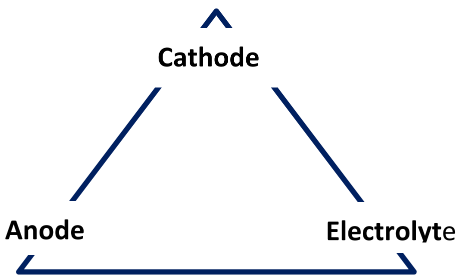


Figure 9 – Corrosion Triangle

Besides corrosion, there are other potential defects that could occur from environmental conditions and operating conditions. The table below summarized some of the most common cases found in offshore piping system:

Table 1 - Some Of The Most Common Cases Found In Offshore Piping System

Type of Defect	Description
Corrosion	Corrosion to piping may be present externally or internally. Internal corrosion is affected by characteristic of pipe (material, thickness), characteristic of piping shapes (that may cause stagnant fluid or constant/high pressure), characteristic of product (composition, amount and flow), operating pressure, operating temperature, microbiological involved in processes. In aging platform, well fluids usually contain higher concentrate of CO2 and H2S and more sour which would increase the corrosion rate. External corrosion is affected by surrounding environmental conditions where piping is located (temperature, humidity, moisture), seawater in the air, foreign line interference, droplets, insulation failure, and coating/paint failure.
Fatigue cracking	Fatigue cracking is the result of repeated application of stress to piping or by pulsation effects. Few examples are fatigue failure from pressure fluctuations in the piping, failure of piping due to cyclic stress due to poor fixing, vibration and resonance.
Stress corrosion cracking (SCC) and hydrogen brittle	They are environmentally assisted cracking due to electrochemical reaction of the material with the environment. Few examples are hydrogen-stress crack from cathodic protection and internal sulfide-stress cracking (see: Kulkarni and Conroy, 1991, Eiber and Kiefner, 1986).
Erosion and wear	In both noble and non-noble materials, erosion and wear of the piping are also sources of defect. Wear is damage due to relative motion between surface and a contacting surface or substance, while erosion is damage due to the abrasive action of flowing gases, liquids, and solids. These defects are affected mainly by product that being delivered by piping. For example high sand rate could lead to internal piping wear, and high flow rate could lead to erosion in 'hot spot' (see definitions).
Others	Other degradation mechanisms related to environmental and operating conditions are scaling, blockages, fouling, hydrogen damage, sulfidation and materials deterioration (aging).

2.3.2 Defect from Third Party Activity

Defect from third party activity is commonly occurred in a form of physical (mechanical) damage to pipe and/or coating from activity of other(s) near or around the piping. Third party activities are closely related to human error in operation, although it is not always the main cause.

Example for this type of damage are; dents and gouges, damage from excavation of equipment that contacts the piping, failure from secondary loads on the piping, defect from erection of scaffolding that accidentally contacts the pipe, dropped objects, etc (see: Kulkarni and Conroy, 1991, Eiber and Kiefner, 1986).

2.4 NON DESTRUCTIVE EVALUATION (NDE) INSPECTION METHODS: THICKNESS MEASUREMENT METHODS

Non-Destructive Evaluation (NDE) or interchangeably known as Non-Destructive Testing (NDT) is inspection of components using equipment to reveal the defects without changing its characteristics or affecting the object's ability to fulfil its intended function (see: Hellier, 2001, DNV, 2010a, ASNT, 2012).

In oil and gas industry, conventional NDE methods that commonly used are radiography testing (RT), ultrasonic testing (UT), magnetic particle (MT), liquid penetrant (PT) and visual testing (VT) (Basrawi and Keck, 2003).

From industrial experience, the techniques that are most commonly used in the North Sea for thickness measurements are radiography testing and ultrasonic testing. Another technique often used is Phased Array (PA) which is the advanced development of ultrasonic testing. Result from PA testing is quite distinguished from normal UT, thus will be discussed independently.

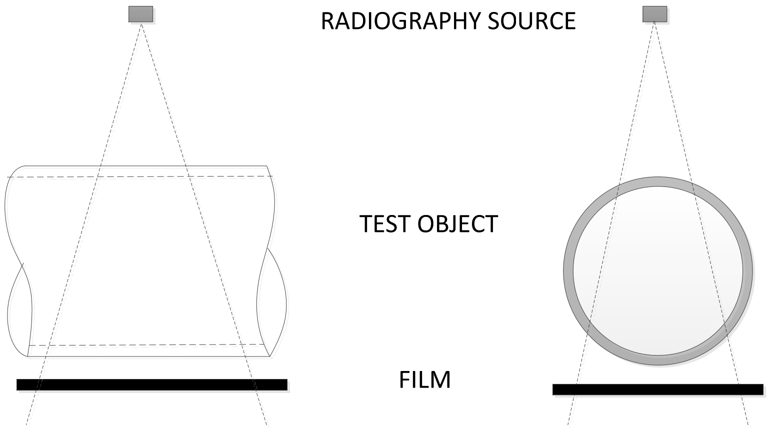
Along these lines, focus of the research lies on these frequently used techniques (RT, UT and PA). These techniques are summarized below: (Willcox and Downes, 2000, Hellier, 2001, Basrawi and Keck, 2003, Olympus, 2013, Ditchburn and Ibrahim, 2009)

2.4.1 Radiography Testing (RT)

Table 2 - Radiography Testing (RT)

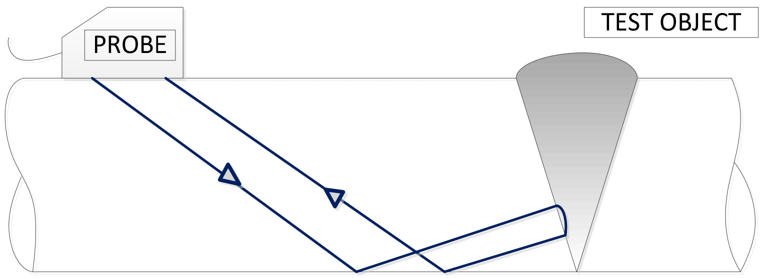
NDE Technique	Method	Specific Application	Advantageous	Limitations
Radiography Testing (RT)	A radiation emitting device emits passes through the test object, and captured by industrial film at the other end of test object. The industrial film act as a recording medium to produce a latent image of the of test object (Hellier, 2001, Basrawi and Keck, 2003, Willcox and Downes, 2000).	Thickness measurement and corrosion/erosion detection on most materials, shapes, and structures (Hellier, 2001, Basrawi and Keck, 2003, Willcox and Downes, 2000).	▪ Provides an accurate, permanent record and allows defects characterization, ▪ High sensitivity, assuming the defects causes a reasonable reduction of cross, ▪ Most widely used and accepted volumetric NDE examination, ▪ Versatile and can be used for	▪ Requires extensive experience and operator/ inspector training for conducting RT and for Radiographic Film Interpretation (RTFI), ▪ Radiation hazard, also mean that work in the surrounding area need to be stopped, ▪ Limited thickness, based on material density and energy used, ▪ Not suitable for surface defects, ▪ No indication of depth of a defect

Table 2 - Radiography Testing (RT)

NDE Technique	Method	Specific Application	Advantageous	Limitations
			many shapes, sizes and can be used for thin sections, ▪ Suitable for wide range of materials. (Hellier, 2001, Basrawi and Keck, 2003, Willcox and Downes, 2000).	below the surface, ▪ Dependent on defects orientation ▪ Film processing and viewing facilities are necessary, ▪ Not suitable for automation, unless the system incorporates fluoroscopy with an image intensifier or other electronic aids, ▪ Can be time-consuming, ▪ Costly in initial equipment and expendable materials. (Hellier, 2001, Basrawi and Keck, 2003, Willcox and Downes, 2000).

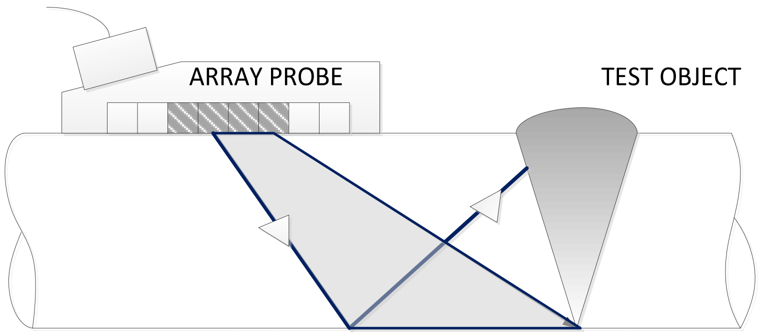
2.4.2 (Conventional) Ultrasonic testing (UT)

Table 3 - (Conventional) Ultrasonic testing (UT)

NDE Technique	Method	Specific Application	Advantageous	Limitations
(Conventional) Ultrasonic testing (UT)	A transducer pulses High-frequency sound that propagate through the test object, reflecting at interfaces (Hellier, 2001, Basrawi and Keck, 2003, Willcox and Downes, 2000). 	Most materials can be examined if sound transmission and surface finish are good and shape is not complex (Hellier, 2001, Basrawi and Keck, 2003, Willcox and Downes, 2000).	▪ Thickness and lengths up to 30 ft can be tested, ▪ Position, size and type of defect can be determined, ▪ Instant test results, ▪ Portable, ▪ Extremely sensitive, ▪ Capable of being fully automated, ▪ Access to only one side necessary, ▪ No consumables. (Hellier, 2001, Basrawi and Keck, 2003, Willcox and Downes, 2000).	▪ Requires extensive experience and operator/inspector training for performing test and for result interpretation, ▪ Depends on material attenuation, surface finish, and contour, ▪ Requires couplant, ▪ On conventional equipment, there is no permanent record available, ▪ Detection of defective test piece could only be done whilst the test is in progress, ▪ Very thin sections are difficult to inspect. (Hellier, 2001, Basrawi and Keck, 2003, Willcox and Downes, 2000).

2.4.3 Ultrasonic Phased Array (PA)

Table 4 - Ultrasonic Phased Array (PA)

NDE Technique	Method	Specific Application	Advantageous (compared to conventional UT)	Limitations (compared to conventional UT)
Phased Array (PA)	Phased Array (PA) is based on the same technique as conventional ultrasonic (wave propagation, reflection, refraction, mode conversion, and diffraction), the main difference is the method of generating and receiving the ultrasonic waves (Ditchburn and Ibrahim, 2009) 	Can be employed in almost any test where conventional ultrasonic have been used (Olympus, 2013)	▪ Increased inspection sensitivity, ▪ Increased inspection coverage, ▪ decreased inspection times, ▪ Immediate images producing, ▪ Simplified data interpretation. ▪ The beam profile is able to be modified or control, which leads to three main electronic scanning techniques that cannot be achieved using conventional ultrasonic systems; Linear scanning, Dynamic depth focussing and Swept angular (sectorial or azimuthal) scanning (Ditchburn and Ibrahim, 2009)	▪ Higher cost of training, ▪ Equipment is more complex and hence more difficult to operate than conventional instruments, ▪ first-time set-up is very time consuming, ▪ surface condition and waviness is more critical, ▪ Equipment is more expensive, ▪ There is a tendency for operators/inspectors to misinterpret result or have the wrong perception that one wide-angled sectorial scan will detect all defects in the weld. Since the ultrasonic response will depend on the (i) angle of incidence on the defects, (ii) location of the array and (iii) thickness of the plate (Ditchburn and Ibrahim, 2009).

2.5 OFFSHORE INSPECTION PLANNING PRACTICES

Following UK refinery explosion in April 2001, Risk Based Inspection (RBI) has widely used in oil and gas to prioritize inspection planning. Although there is no standardization in constructing a Detailed Inspection Plan, Norsok Z-008 which governed in Norwegian Continental Shelf (NCS), suggesting the use of consequence classification when defining criteria for prioritising work orders (NTS, 1998). Thus RBI analysis would fit in the frame.

RBI is a systematic effort to try to incorporate Consequence of Failure (CoF) and Probability of Failure (PoF) in order to plan inspection. RBI analysis could assist in prioritisation of work orders, recommendation of inspection intervals, expected damage mechanism, inspection method selection and required data to report as illustrated below (DNV, 2010a).

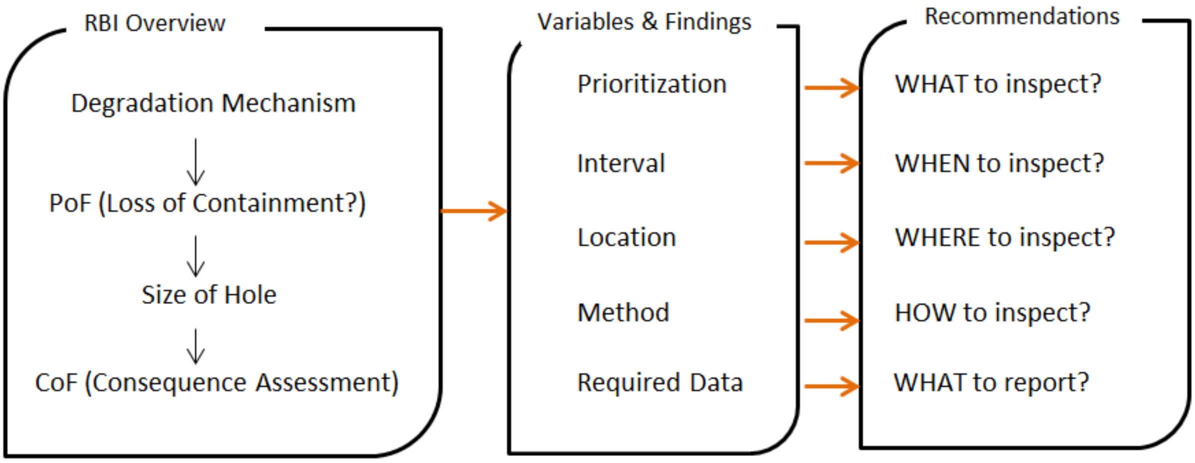


Figure 13 - Deliverables of an RBI assessment to the inspection program (adapted from: DNV, 2010a)

An Inspection Programme is also known as Inspection Strategy or by any other name; but basically it consists of a long term-view of inspection plan. It is derived from RBI findings along with other knowledge related to the degradation that is not included in the RBI.

The recommendations from RBI would be inserted as focus for inspection programme. The programme would include some area of focus where degradation potentially occurs, for example a topside flow line piping system with consist of Duplex/6 Mo material would have focus on end-hubs, T-joints, valves and places where there is specification switches between duplex/6Mo and carbon steel.

The RBI result would also affect inspection interval and prioritisation of inspection. For example, RBI result for Topside Flow line Piping System (PT) of a platform that shows high CoF and high PoF will be assigned higher priority and shorter inspection interval compared to Open Drain System (DO) with low CoF and low PoF.

The Inspection Programme would then be a base for a Detailed Inspection Plan. It acquires RBI findings, specific plant experiences, industrial experiences, regulatory and safety requirements. The Detailed Inspection Plan covers (a) type and technique of inspection; (b) preparation required; (c) the necessary inspection coverage; and (d) level or quality of inspection (DNV, 2010a).

The process to attain Detailed Inspection Plan would vary from one organization to another, but in NCS it would generally follow maintenance management work process according to Norsok Z-008. An example of the process would be as follow:

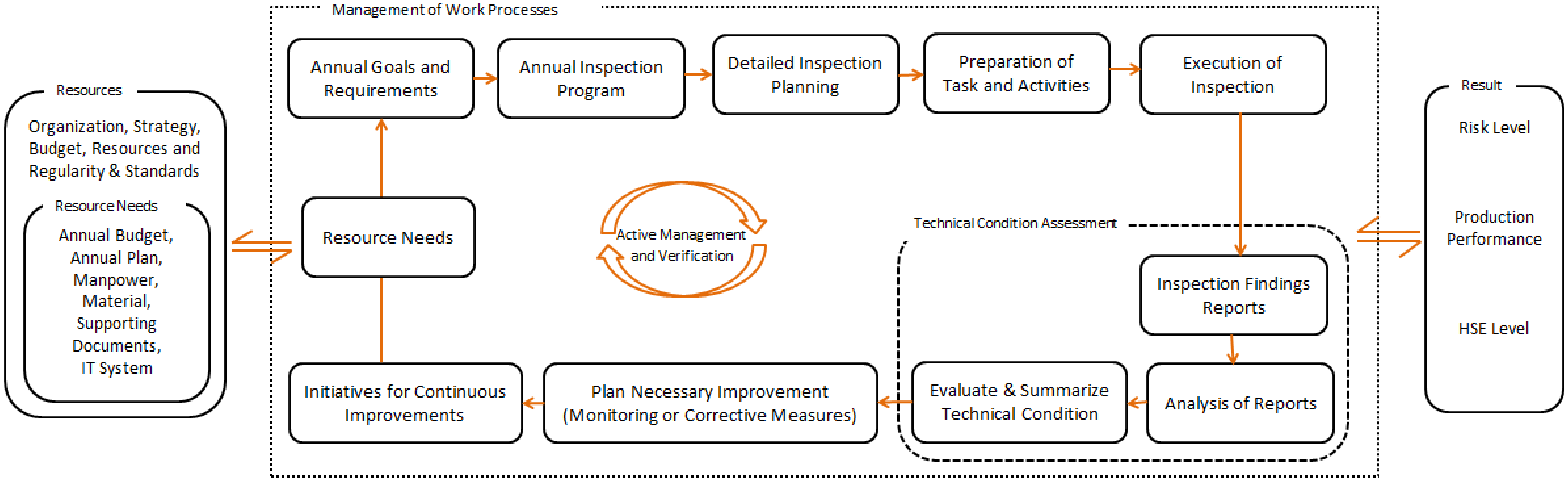


Figure 14 - Inspection Planning Process (adapted from: Ratnayake et al., 2011)

2.6 (TOPSIDE) FLOW LINES SYSTEM

In this thesis we will focus on Topside Flow Lines System due to the high level criticality of the system. We will not include assessment of manifolds in this discussion due to the restriction of time, and shall leave it for potential future assessment.

As we may have aware, in RBI analysis, topside flow lines system would indicate a high level of CoF and PoF due to the characteristic and consequences it carries. Topside Flow Lines and Manifolds System, indicated as system number 13 on Norsok P-100 (NTS, 2010), is the topside piping systems on the platform that gather and transfer the well stream starting from individual wellhead (Christmas tree) to the downstream systems (up to production manifolds) (Ratnayake et al., 2011, NTS, 2010).

Product that went through the topside flow line is unprocessed hydrocarbon biphasic directly from the reservoir. This product contains different substances such as hydrogen chloride (HCl) and hydrogen sulfide (H_2S) that dissolved into condensed water, also various salts (chlorides, sulfides, hydrosulfides) and oxide-hydroxide deposits that could formed on the metal surfaces resulting carbon steel pipe suffer from general corrosion, pitting corrosion and under deposit corrosion (Groysman and Hiram, 1997).

This particular system is considered to possess high threat for personal safety, potential loss of production and environmental damage. Based on history and experiences, the probability of failure is high particularly to carbon steel piping, but piping with duplex material is also considered having a certain probability of error due to erosion.

3.0 INTEGRITY ASSESSMENT OF TOPSIDE FLOW-LINE PIPE SYSTEM

A thorough investigation and attempt to fully comprehend the primary subject will be presented in this chapter, providing a firm base for assessment on the next chapter. Early discussions and some new concepts will also be presented as an approach towards the assessment on the next chapter.

3.1 INSPECTING TOPSIDE FLOW LINES: INSIDE THE DETAIL PLANNING

In maintaining integrity of pipe, there are series of activities that involved in the process; one of the important activities is integrity assessment. The integrity assessment is aim to evaluate technical condition of the piping system, so the necessary control measures could be taken before failure occurs.

From this description, we could see the connection with Inspection Planning Process on previous figure 15, which share the similar goal: to manage the integrity of pipe system. Now we can reason the logic that inspection is part of integrity assessment.

As the main topic of this thesis, historical inspection data is produced from Inspection Findings Reports as we refer to figure 16.

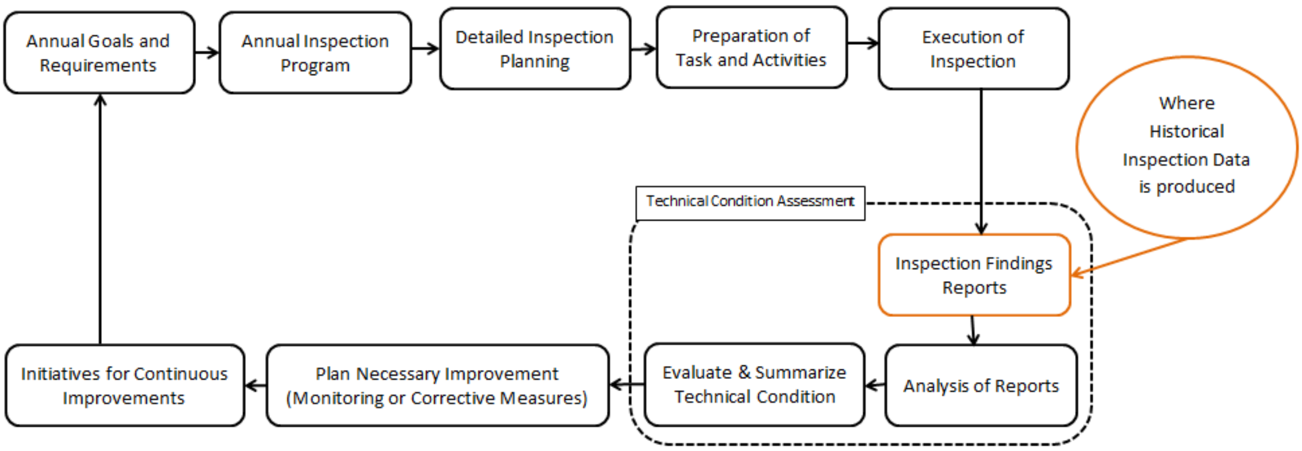


Figure 17 - Origins of Historical Inspection Data (adapted from: Ratnayake et al., 2011)

Historical inspection data is a product of the inspection execution which is originated from detailed inspection planning. Thus, it will be advantageous to comprehend the contextual of the detailed inspection planning.

3.1.1 WHAT and WHEN to Inspect: Prioritization and Interval

3.1.1.1 Risk

On section 2.5, we have briefly discussed the role of Risk Based Inspection (RBI) to prioritize and determine the inspection interval. Before we go further, we found it is necessary to draw a mutual understanding regarding risk and the related processes.

Reason is, due to the nature of risk itself that is rather subjective, and consequently the perception of risk would also be ambiguous.

Since we are referring the study to DNV-RP-G101, we should first examine their definition of risk. The standard is adapting API RP-580/581, with additional specification. Both API RP-580 and stated that *risk is the combination of the probability of an event and its consequence* (API, 2008, API, 2009). While DNV-RP-G101 sees risk as *a measure of possible loss or injury, and is expressed as the combination of the incident probability and its consequences […]* (DNV, 2010a).

The definition from DNV-RP-G101 is specifically referring risk as possible loss (undesirable outcome), and we could notice the use of 'incident' instead of 'event'. We could re-write the definition as:

Risk = (probability of incident occurring) x (expected loss in case of the incident)

Beside this, there are also other definitions of risk, one of the renowned definitions is from OHSAS 18001:2007 that defines risk as *combination of the likelihood of an occurrence of a hazardous event or exposure with the severity of injury or ill health that can be caused by the event or exposure* (BS, 2007).

Risk = Severity (Consequence) x Likelihood (Probability)

Another example of risk definition came from ISO 31000:2009 that outlined risk as *the effect of uncertainty on objectives* (ISO, 2009). The definition is referring 'risk' into positive as well as negative possibilities, which in line with the definition coined by Terje Aven (2011) that describe risk by *(C, C*, U, P, K*), where C denotes the consequences derives from activity and the initiating events A; C* denotes the prediction of C; U denotes the uncertainty of C value; and P denotes the probability of specific events and consequences, given the background information K.

Figure 2 from the first chapter illustrated this very concept of risk, and expressed Writer's preferred definition of risk. With the gap between risk definitions, there is a future possibility to develop an RBI method based on *(C, C*, U, P, K*) definition.

However, on the next sections when we explain the RBI concept in planning, we would use DNV-RP-G101 conception, since this method is the current widely used practice by the oil and gas industry in NCS.

3.1.1.2 Prioritization

DNV-RP-G101 Risk Based Inspection (RBI) utilizes the risk estimated from combining the probability of failure (PoF) and the consequence of failure (CoF). The risk is specified towards the failure from assigned degradation mechanism.

PoF and CoF can be assessed with quantitative method, qualitative method or by using a combination of qualitative and quantitative methods. The less quantitative the method is, the more expertise will be needed. Nonetheless, data used in quantitative method(s) would also need to be assigned a degree of confidence. These measures are taken to minimize the uncertainties in risk assessment.

In prioritizing component, there are two methods where risk assessment can be implemented (DNV, 2010a):

1. The first is *risk prioritisation methods* by ranking item in terms of risk magnitude, and address the highest risk item first,
2. Or with *risk acceptance limit methods* by estimating risk per item and its change with time, and address item where risk will soon cross risk acceptance limit first.

The risk acceptance limit is basically a set of criteria that established based on regulatory compliance and organization's goals (on personnel safety, environment and economical goals). It is utilized to prioritize inspection items according to their importance towards this set of criteria.

3.1.1.3 Inspection Time

Similar with prioritisation process, the decision process that could be used for determining inspection time are quantitative methods, qualitative, and semi-quantitative methods (DNV, 2010a).

Both qualitative and semi-quantitative methods are utilizing decision matrix that built for the intended purpose. And the same rule applies: the less quantitative the method is, the more expertise will be needed to estimate risk, both from a general point of view and from a plant specific point of view.

The risk acceptance limit along with specific characteristics of plant and components are also used to set a limit for inspection time, such that the inspection item is inspected and maintained before the failure time.

In order to calculate the time-to-inspection, the risk acceptance limit is altered into Probability of Failure acceptance limit (PoF_{Limit}), which set the maximum time to inspect, using the following equation (*eq. 1*) (DNV, 2010a):

$$\text{Time to } PoF_{Limit} = a\frac{t_0 - t_{release}}{d_{mean}} \qquad \textit{(Eq. 1)}$$

Where time to **PoFLimit** is the maximum time to inspect; $\mathbf{t_0}$ is the current measurement (wall thickness in mm); $\mathbf{t_{release}}$ is the wall thickness at which a release is expected, also in mm; and $\mathbf{d_{mean}}$ is the mean damage rate (or corrosion rate) in mm/year with **a** as the confidence factor to account the uncertainty of the corrosion rate (for further reading refer to : DNV-RP-G101, DNV, 2010a).

3.1.2 WHAT to Expect: Degradation Mechanism

On previous chapters, we have discussed characteristics of ageing platform and general possibilities of piping defects. We will have more in-depth analysis in this section towards the degradation mechanism on topside flow lines of ageing platform.

The challenges with flow lines are the product characteristics and an additional challenge for ageing platforms which are still using carbon steel materials for piping. We do find platform who upgraded themselves into more noble materials such as

Duplex/6 Mo, but there are still sections that remains carbon steel and this would raise another galvanic corrosion.

As a start, we will outline the variables involved on topside flow lines degradation. The figure below was taken from previous chapter, with additional details on influencing variables suggested by Ratnayake and Markeset (2010).

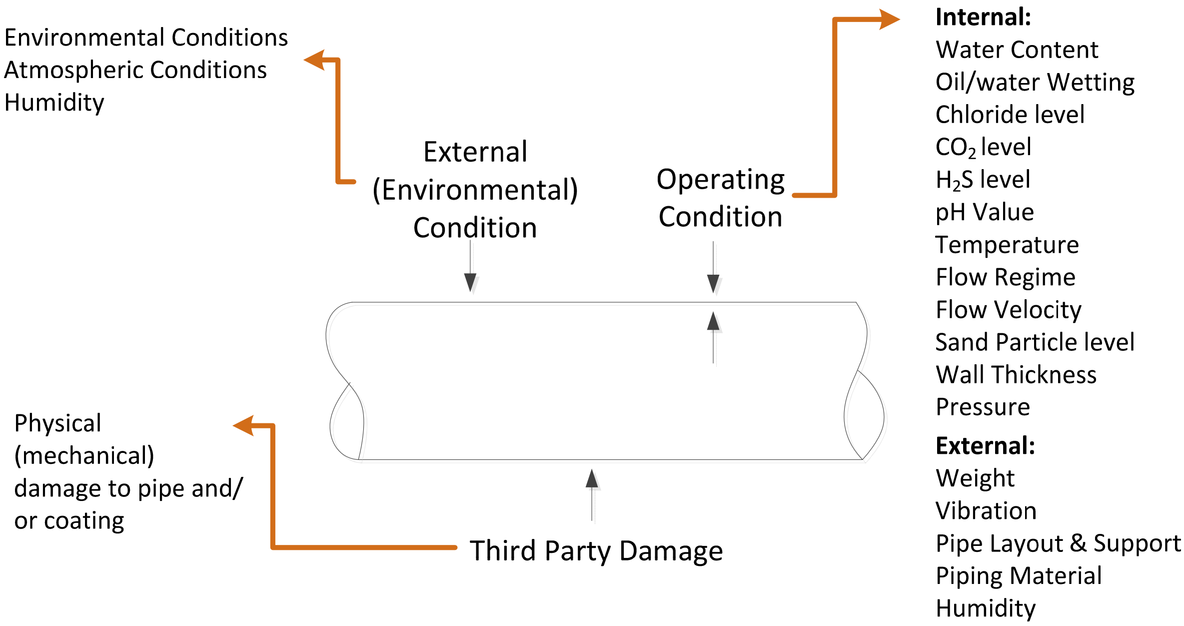


Figure 18 - Variables Involved On Topside Flow Lines Degradation (Ratnayake and Markeset, 2010)

These variables, individually or collectively, have potential to cause piping defects. For example sand particle level could lead to erosion, or extreme temperature that could lead to atmospheric corrosion or thermal fatigue cracking. Another challenge for flow line is sour environment, where H_2S presence may cause either weight loss corrosion or sulfide stress cracking (SSC) of carbon and low-alloy steels. It may also enhance chloride stress corrosion cracking (SCC) of stainless steels and other higher alloys (Tuttle, 1990).

We have briefly discussed type of defects that may occur on piping in section 2.3. In addition to that, the below would specifically list the main concerns of topside flow line piping system based on industrial experiences and DNV-RP-G101 (DNV, 2010a):

Table 5 - Main Concerns of Topside Flow Line Piping System

Damage Mechanism	Type of Defects	Description
CO2 corrosion	Uniform CO2 corrosion Local CO2 corrosion	▪ Internal thinning of uniform areas, ▪ Local internal wall surface thinning.
H_2S	▪ Sulphide stress cracking (SSC)	▪ Internal wall surface breaking crack.

Table 5 - Main Concerns of Topside Flow Line Piping System		
Damage Mechanism	Type of Defects	Description
	▪ Hydrogen Induced Cracking (HIC) ▪ Stepwise Cracking (SWC) ▪ Stress Oriented Hydrogen Induced Cracking (SOHIC)	Subsurface laminations or blisters parallel to the surface, or the combination with cracks normal or parallel to surface.
Microbiologically Influenced Corrosion (MIC)	▪ MIC in CS ▪ MIC in stainless steels	▪ Randomly distributed local corrosion on internal wall surface, ▪ Local internal wall thinning.
Erosion	Internal surface erosion	▪ Internal wear of surfaces due to sand. ▪ Internal wall thinning over an area due to impingement.
Corrosion Under Insulation (CUI)	CUI in carbon steel	▪ Local corrosion of external pipe surfaces under insulation. ▪ Thinning of external pipe surface in patches.
	CUI in stainless steels	▪ Local corrosion and pitting of external surface under insulation. ▪ Local pitting of external pipe surface.
External corrosion	External corrosion of un-insulated carbon steel	▪ Uniform and local corrosion of external pipe surface. ▪ Thinning of external pipe surface in patches.
	External corrosion of un-insulated stainless steels or titanium	▪ Local corrosion and pitting of external pipe surface. ▪ Local pitting of external pipe surface.
Local internal wall thinning or pitting	Local corrosion in connection with injection or mixing points	Local internal wall thinning.
	Flange corrosion	▪ Local corrosion due to gasket deformation or use of wrong gasket. ▪ Local corrosion in connection with water containment
	Weld corrosion	▪ Local corrosion Internal and external.
Galvanic	Local corrosion due to	On internal surface and external side.

Table 5 - Main Concerns of Topside Flow Line Piping System		
Damage Mechanism	Type of Defects	Description
corrosion	contact between different materials	
Mechanical damage	Dents and gouges, damage from excavation of equipment that contacts the piping, failure from secondary loads on the piping, defect from erection of scaffolding that accidentally contacts the pipe, dropped objects, vibration, platform movement, flow effects, etc	Internal or external local defects due to mechanical impact under fabrication, installation or in service.

3.1.3 WHERE to Inspect: Hot Spots

After being well-informed about the influencing variables and type of defects they could cause, in planning an inspection we need to find out where they would occur. There are locations on pipes where the defects are expected to be most severe, that designated as ‘hot spots’. In general, topside flow line inspection has been concentrated on areas where (Ratnayake et al., 2011):

- there are changes of flow-rates,
- there can be flow turbulence,
- there is a potential of stagnant fluid,
- areas around choke valves, and
- when there is increased flow rates, increased water production, or increased sand production.

Given the premises above, the defects are often still difficult to predict and thus care must be taken on ‘hot spots’. Based on industrial experiences, hot spots on topside flow line system could normally be found at:

Table 6 – Possible Hot Spots on Topside Flow Line	
Hot Spots for Carbon Steel Pipe	Hot Spots for Duplex/6Mo Pipe
▪ Contact area between different material specifications ▪ Dead-legs ▪ Flare and Drain lines ▪ End hubs ▪ Flanges ▪ Bends	▪ Contact area between different material specifications ▪ End hubs ▪ Dead-legs ▪ Flanges ▪ Bends ▪ Welds

Table 6 – Possible Hot Spots on Topside Flow Line	
Hot Spots for Carbon Steel Pipe	Hot Spots for Duplex/6Mo Pipe
▪ Welds and field welds ▪ Hook-up spool ▪ Spool after chokes ▪ Injection points ▪ Valves and Check Valves ▪ Choke valves ▪ T-joints ▪ Spool before the test manifold	▪ T-Joints ▪ Valves and Check Valves ▪ Choke valves

In larger scale, hot spots that are outsized could be uneconomical to inspect. For example a 5 meter pipe that consists from several spools is to be inspected. In this case the Planner would choose several sample points to detect the damage mechanism. The sample points would be the points that are more vulnerable to defects, for example bends, field welds, area with stagnant fluids or T-joints. Let us see the illustration below:

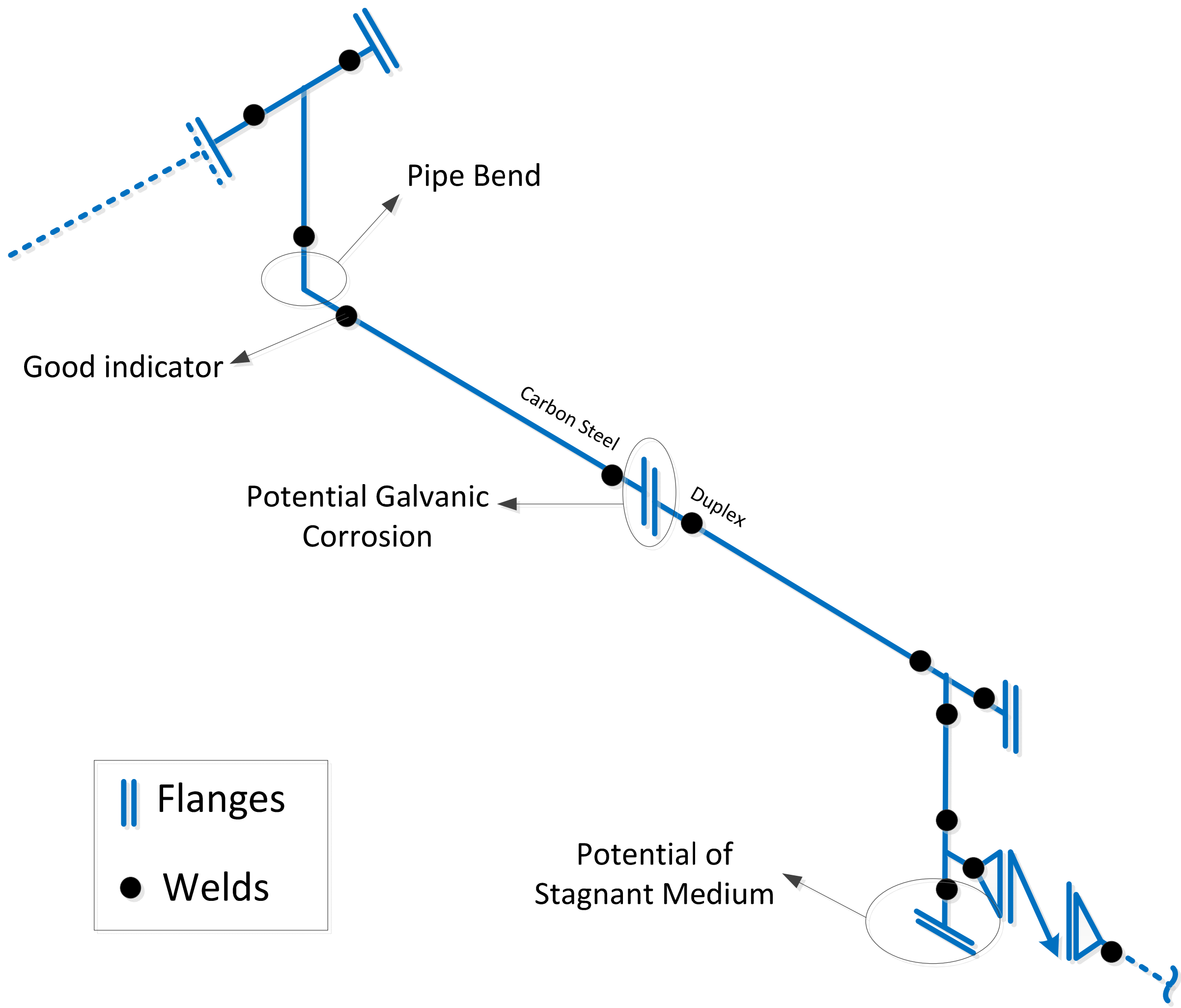


Figure 19 - Segment of pipe from isometric drawing: Hot Spots

Welds and field welds in particular could be a good indicator of technical condition of the surrounding. Field welds are more vulnerable since it is done on the field where the environment is less-controlled compared to prefabrication welds. Bends are also vulnerable due to the gravitational effect of medium that could thin the wall surface. Below is an example of radiographic image taken on a bend section of a pipe, where we can see the possible flow impact to the elbow section:

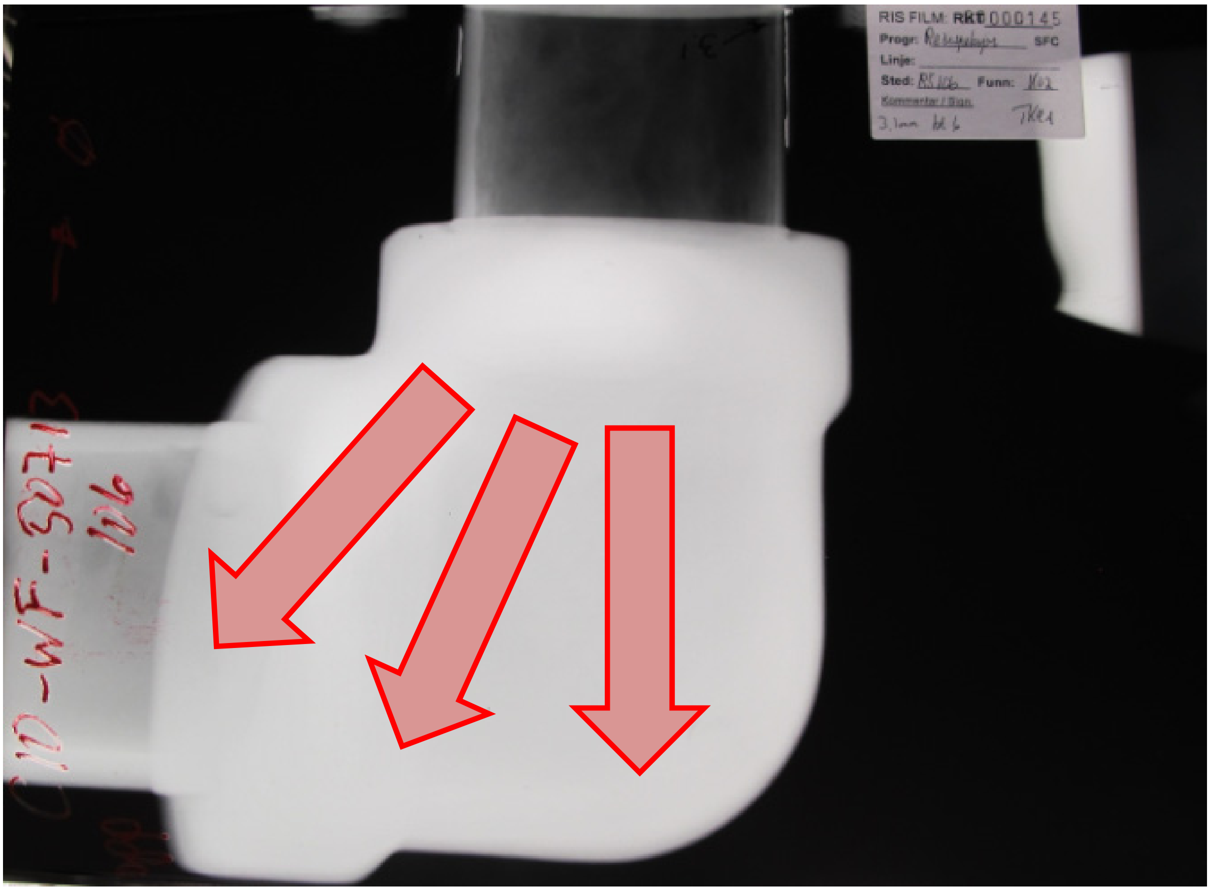


Figure 20- Radiographic Image of Bend (Courtesy of Aker Solutions MMO)

Each individual hot spot could potentially have more than one damage mechanism; depending on affecting variables (see Figure 21). For example a spool that is located after choke but before chemical injection point, could potentially be affected by MIC while spool after injection point is less likely to experienced MIC.

Figure 22 - Example of leak on a weld (Courtesy of Aker Solutions MMO)

Table 6 below summarize the possible degradation mechanism from industrial experiences for each hot spot given above:

Table 7 – Hot Spots and Possible Defects

Hot Spots	Possible Damage Mechanism for Carbon Steel Pipe*	Possible Damage Mechanism for Duplex/6Mo**
Contact area between different material specifications	Galvanic corrosions	Galvanic corrosions
Dead-legs	CO_2 corrosion, MIC, Erosion, Scale (Deposit)	Erosion, Scale (Deposit)
End hubs	CO_2 corrosion, MIC, Erosion, Scale (Deposit)	Erosion, Scale (Deposit)
Flanges	CO_2 corrosion, MIC, Erosion, Scale (Deposit)	Erosion, Scale (Deposit)
Bends	CO_2 corrosion, MIC, Erosion, Scale (Deposit)	Erosion, Scale (Deposit)

Table 7 – Hot Spots and Possible Defects		
Hot Spots	Possible Damage Mechanism for Carbon Steel Pipe*	Possible Damage Mechanism for Duplex/6Mo**
Welds and Field Welds	CO_2 corrosion, MIC, Erosion	Erosion
T-joints	CO_2 corrosion, MIC, Erosion	Erosion, Scale (Deposit)
Valves and Check Valves	CO_2 corrosion, MIC, Erosion, Scale (Deposit)	Erosion
Choke valves	CO_2 corrosion, Erosion	Erosion
Injection points	CO_2 corrosion, Erosion, Scale (Deposit), MIC (on area before injection)	Erosion, Scale (Deposit)
Hook-up spool	CO_2 corrosion, MIC,	Erosion
Spool after chokes	CO_2 corrosion, MIC	Erosion
~~Welds on the last~~ Spool before the test manifold	CO_2 corrosion	Erosion
Flare and Drain lines	CO_2 corrosion, Erosion, Scale (Deposit)	Erosion, Scale (Deposit)

Note: **External corrosion is generally expected on carbon steel and CUI is expected on insulated line.*

***Pipe with material of high-strength steels, titanium alloys and aluminium alloys are generally the most vulnerable to hydrogen embrittlement (H2S)*

3.1.4 HOW to Inspect: Planning the Inspection methods on Chosen Points

3.1.4.1 Choosing Inspection Points

Inspection is usually planned on groups of product service (See NORSOK Z-DP-002; NTS, 1996) or corrosion circuits (corrosion loops). The purpose is to have several pipes which have same or similar degradation mechanism in the same group, thus simplifying the process of choosing the inspection points.

In this case, the grouping is topside flow lines which have the same medium (crude oil) from reservoir through separator. Due to the same product, the degradation mechanism on pipes would be similar.

In planning a topside flow line inspection, the inspection points are recommended on Planner’s knowledge of:

- Inspection purpose and goals,
- Governing documents, especially Inspection Strategy,
- RBI results,

- Inspection interval,
- Technical drawings,
- Engineering data and technical condition data, for example material, thickness and corrosion allowance,
- Historical data and reports,
- Operating conditions, especially production data,
- Degradation mechanisms,
- Possible hot points,
- Planner's experience and transfer of knowledge from inspection team,

Most of the above knowledge would be gathered electronically from the Operator's Information and Communication Technology (ICT) system. Since generally inspection planning is done by Service Company, the knowledge transfer from Operator's system to Service Company's system would greatly depend on IT system. Therefore, management of data and information in both Operator and Service Company is very crucial in every aspect of the planning.

Besides availability and quality of data, Planner's experience and technical ability would also highly contribute to the quality of inspection plan.

3.1.4.2 Inspection methods

To inspect specific damage mechanism, the following methods could be use based on DNV-RP-G101 (DNV, 2010a) and practical industrial experience:

Table 8 – Inspection Methods based on Damage Mechanism

Damage Mechanism	Possible Inspection Method
CO2 corrosion	▪ Ultrasonic Testing (UT) ▪ Phased Array (PA) ▪ Radiographic Testing (RT) ▪ Visual Inspection
H_2S	▪ Usually identified pre-operation phase. ▪ Visual Inspection ▪ Ultrasonic Testing (UT) ▪ Phased Array (PA) ▪ Radiographic Testing (RT) can be used for detailed investigation after damage is identified.
Microbiologically Influenced Corrosion (MIC)	▪ Ultrasonic Testing (UT) ▪ Phased Array (PA) ▪ Radiographic Testing (RT) ▪ Visual Inspection
Erosion	▪ Ultrasonic Testing (UT) ▪ Phased Array (PA) ▪ Radiographic Testing (RT)

Table 8 – Inspection Methods based on Damage Mechanism	
Damage Mechanism	Possible Inspection Method
	▪ Visual Inspection
Corrosion Under Insulation (CUI)	▪ Opening of insulation. ▪ Radiographic Testing (RT)
External corrosion	Visual Inspection
Local internal wall thinning or pitting	▪ Ultrasonic Testing (UT) ▪ Phased Array (PA) ▪ Radiographic Testing (RT) ▪ Visual Inspection
Galvanic corrosion	▪ Ultrasonic Testing (UT) ▪ Phased Array (PA) ▪ Radiographic Testing (RT) ▪ Visual Inspection
Mechanical damage	Visual Inspection

The industrial practice of H2S cracking detection is varying from one case to another; it would depend greatly on type of material, size and operating conditions. More modern plant are often use more modern techniques due to capability of condition monitoring, where in aging platform could be uneconomical to implement.

The table below summarize possible inspection methods for each hot spot given on previous section based on practical industrial experience:

Table 9 – Hot Spots and Inspection Methods		
Hot Spots	Primary Inspection Method	Secondary Inspection Method
Contact area between different material specifications	Depending on the size, type, material and location, inspection method could vary. *For detection of galvanic corrosion refer to Table 7.*	Depending on the size, type, material and location, inspection method could vary. *For detection of galvanic corrosion refer to Table 7.*
Dead-legs	Visual Inspection	Radiographic Testing (RT)
End hubs	Visual Inspection	Radiographic Testing (RT)
Flanges	Visual Inspection	Radiographic Testing (RT)

Table 9 – Hot Spots and Inspection Methods		
Hot Spots	Primary Inspection Method	Secondary Inspection Method
Bends	Ultrasonic Testing (UT)	Radiographic Testing (RT)
Welds and Field Welds	Radiographic Testing (RT)	Ultrasonic Testing (UT)
T-joints	Visual Inspection	Radiographic Testing (RT)
Valves and Check Valves	Visual Inspection	Radiographic Testing (RT)
Choke Valves	Visual Inspection	Radiographic Testing (RT)
Injection points	Depending on the size, type, material and location, inspection method could vary.	Depending on the size, type, material and location, inspection method could vary.
Hook-up spool	Ultrasonic Testing (UT)	Radiographic Testing (RT)
Spool after chokes	Ultrasonic Testing (UT)	Radiographic Testing (RT)
Spool before the test manifold	Ultrasonic Testing (UT)	Radiographic Testing (RT)
Flare and Drain lines	Depending on the size, type and location, inspection method could vary. *For detection of erosion refer to Table 7.*	Depending on the size, type and location, inspection method could vary. *For detection of erosion refer to Table 7.*

We could see above that UT and PA are preferred methods for pipe spool and larger pipe, since the method require smooth surface thus implication on rough angled item is not advisable. Items like welds, valves or other items that not sufficient for ultrasonic testing would benefit from radiographic testing or visual inspection.

Once again the tables we have summarized are meant for aging platform, and practice could vary depending on safety or economic reasons. The list of possible techniques is continuously growing along with development of modern inspection technique and tools.

3.2 PERSONNEL CONSIDERATIONS

After completion of planning, the execution would be in the hand of NDT Inspectors on the respected platform, while additional personnel or tools might be added according to needs.

It is known that the effectiveness of non-destructive examinations is largely reliant upon the qualifications of the personnel performing and interpreting the examinations (Hellier, 2001). Therefore there are standard qualifications of NDT personnel to ensure quality of the result that will be discussed briefly before we move on to inspection process.

3.2.1 Qualifications Standards

The ruling standard for personnel qualification in Norwegian Continental Shelf (NCS) is commonly ISO 9712 (ISO, 2005). Other equivalent recognized standards or certification schemes e.g. EN 473, PCN or NORDTEST may be considered (DNV, 2012).

3.2.2 Qualification Levels

According to ISO 9712 (ISO, 2005), there are three levels of NDT personnel qualifications: Level One, Level Two and Level Three. These levels represent certification for specified skills on each NDT methods, as well as the minimum training and experience requirements.

In additional, it is mandatory for Inspectors to have satisfactory vision and be tested of visual acuity at least once a year. Site test/mock-up test is also recommended to carry out for special methods (DNV, 2012).

3.2.2.1 Level 1 (ISO, 2005)

After completing Level 1, personnel are able to perform NDT according to written instructions and under the supervision of level 2 or 3 personnel. Level 1 personnel may be authorised to:

- set up NDT equipment,
- perform the test,
- record and classify the results of the tests in terms of written criteria, and
- reporting the NDT results.

Level 1 certificated personnel are not permitted to be responsible for:

- the choice of test method or technique to be used, and
- the interpretation of the test results.

3.2.2.2 Level 2 (ISO, 2005)

Personnel that completed Level 2 certification have demonstrated competence to perform NDT according to governing procedures. Level 2 personnel may be authorised to:

- select the NDT technique for the test method to be used,
- define the limitations of application of the testing method,
- translate governing NDT codes, standards and specifications into NDT instructions to be used in actual working conditions,
- set up and verify equipment settings,
- perform and supervise tests,
- interpret and evaluate results according to applicable standards, codes specifications or procedures,

- carry out, supervise and provide guidance for all personnel or duties at or below level 2.

3.2.2.3 Level 3

Following completion of Level 3, personnel are authorized to:

- assume full responsibility for a test facility or examination center and staff
- establish, review and validate NDT instructions and procedures
- interpret standards, codes, specifications and procedures
- designate the particular test methods, procedures and NDT instructions to be used
- carry out, supervise and guide all level duties.

Technical competences completed by Level 3 certification are:

- The competence to evaluate and interpret results according to governing standards, codes and specifications,
- possess sufficient practical knowledge of applicable materials, fabrication, process, and product technology to select NDT methods, establish NDT techniques and assist in establishing acceptance criteria where none are available, and
- demonstrated a general familiarity with other NDT methods.

3.2.3 Minimum Training Requirements

For each level of certification, there is minimum duration of training requirements that covers both practical and theoretical courses. The standard ISO 9712 does not specified training requirements for PA, but it was mentioned in ISO 13588:2012 that PA operator/inspector required additional training and examinations, and shall be documented.

Table 10 - Minimum Training Requirements **(ISO, 2005) (ASNT, 2011)**

NDT Method	Level 1 (hours)	Level 2 (hours)	Level 3 (hours)
Radiographic Testing (RT)*	40	80	40
Ultrasonic Testing (UT)	40	80	40
Phased Array (PA)**	40	80	40

Note:

*For RT, training hours does not include radiation safety training.

** Training hours for PA is according to SNT-TC-1A (ASNT, 2011)

3.2.4 Minimum Industrial Experience

For all levels there are minimum durations of experience prior to examination for the upper level. When personnel is seeking certification in more than one method, the total time of experience shall be the sum of experience in each method (ISO, 2005).

Table 11 - Minimum Industrial Experience **(ISO, 2005) (ASNT, 2011)**			
NDT Method	Level 1 (months)	Level 2 (months)	Level 3 (months)
Radiographic Testing (RT)	3	9	18
Ultrasonic Testing (UT)	3	9	18
Phased Array (PA)*	3	9	18

Note:

* Training hours for PA is according to SNT-TC-1A (ASNT, 2011)

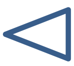
3.3 INSPECTION PROCESS: EXECUTION OF PLAN

Prior to inspection, the Inspectors would need to go through some steps to reassure that inspection technique is adequate, can be done safely and that additional services are in place. Lastly, Inspectors will need to confirm that preparations are ready and that all safety precautions are taken.

All of these steps will be presented in a form of tree diagram. Tree diagram also known as systematic diagram, tree analysis, analytical tree, hierarchy diagram, is used to break down broad categories into finer levels of detail (Tague, 1995). We will utilize tree diagram to breakdown NDT processes in detail to be analyse on later chapter.

3.3.1 Tree Diagram: Prior to Inspection

The tree diagram will begin with the current technical condition of inspection point or group of inspection points as a start of process. The actions and events are to be presented with the following nodes:

Table 12 –Tree Diagram Nodes		
Symbol	**Description**	**Representation**
	Circle	Event Nodes
	Square	Action Nodes
	Diamond	‘Go to’ Nodes
	Triangle	End Nodes

Alternative actions are shown as branches, as well as possible results on event nodes are shown as branches. On action branches, the decision-maker would need to choose from the alternatives choices

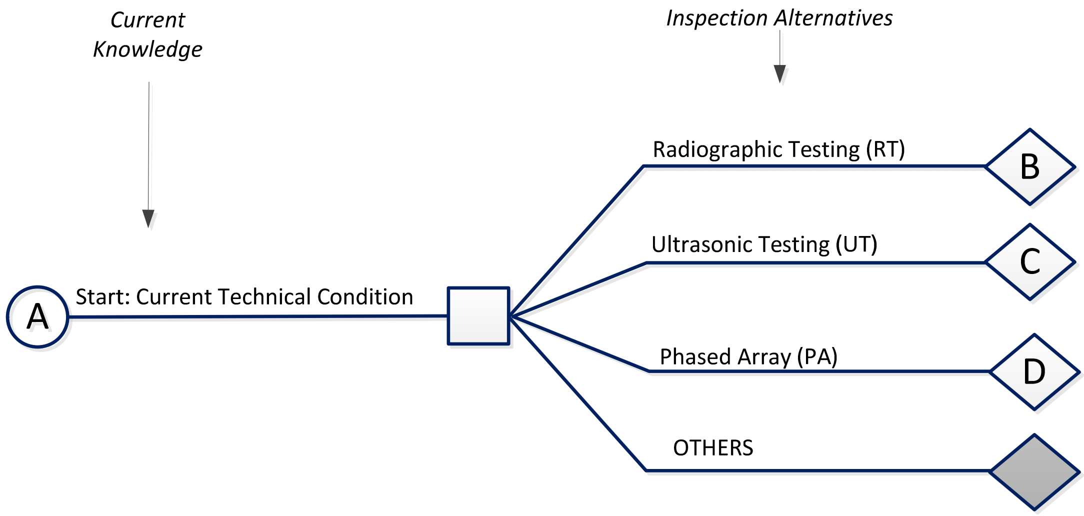


Figure 23 - Current Condition and Inspection Alternatives

The starting point represents the known technical condition of piping segment, which will change depending upon the inspection and follow-up taken. As this thesis scope would only covers RT, UT and PA, other inspection alternatives will not be discussed.

Table 13 – Inspection Alternatives

Diamond Shape	Description
A	Start
B	Radiographic Testing (RT)
C	Ultrasonic Testing (UT)
D	Phased Array (PA)

Information regarding material, parameters and condition of object, location, geometry and coating type and thickness are normally required prior to testing. Testing procedures, equipment and calibration, result acceptance level and action necessary for unacceptable indications would also need to be agreed prior to testing (DNV, 2012).

3.3.2 Tree-diagram: Radiographic Testing

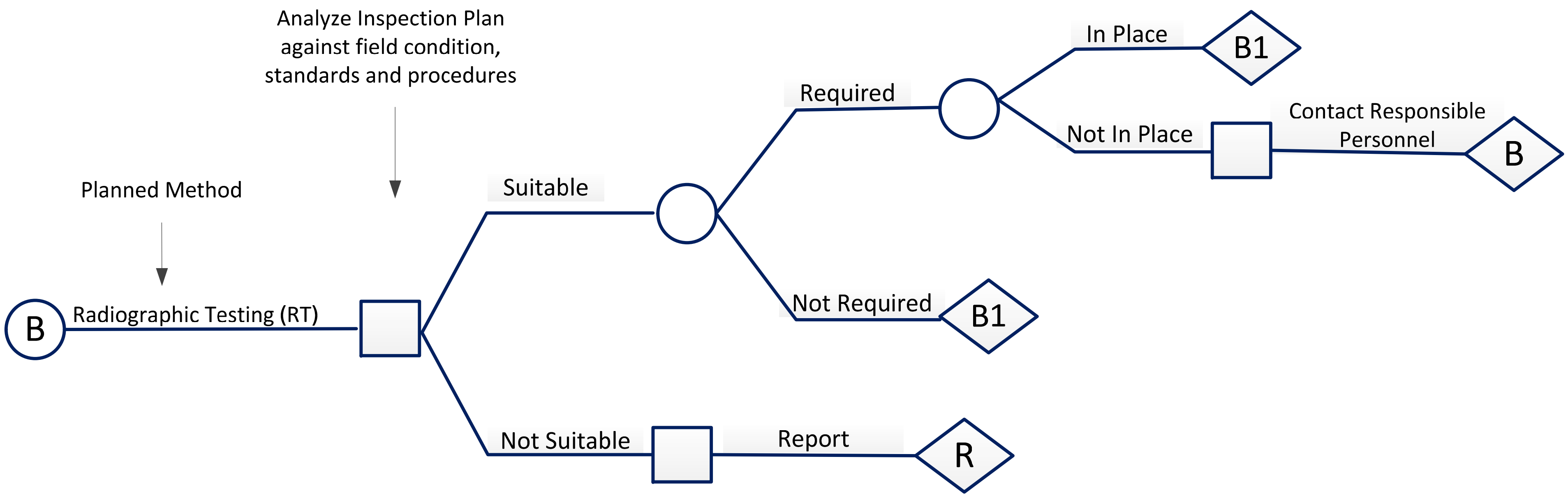


Figure 24 - Radiographic Testing Tree-diagram Part 1

Although the Inspection Plan is based on formal requirements, the Inspectors would check the plan against field condition, standards and procedure. After deciding that the plan is suitable, Inspector would identify if there is any additional equipment or service required such as scaffolding, removal of insulation or rope technique personnel. Along the process, Inspector need to highlight important variables in radiographic testing e.g. (Hellier, 2001):

Table 14– Important Variables In Radiographic Testing	
Component	**Variables**
Radiation Source	Energy source, mA (x-ray) or curies (gamma ray)
Testing Arrangement	Exposure time Distance from the radiation source to the object Distance from the object to the film
Test Object	Material type and density Material thickness Physical size of the target (for x-ray) or source (for gamma ray)
Film	Type of film Screens used Film processing (procedure development time and temperature, etc.) Film density Film evaluation/ interpretation

When all required equipment and personnel are in place, Inspector could start the preparation for NDT inspection (node B1). The tree-diagram below (Figure 25) would illustrate the decision process of RT with additional table to provide description of the tree-diagram.

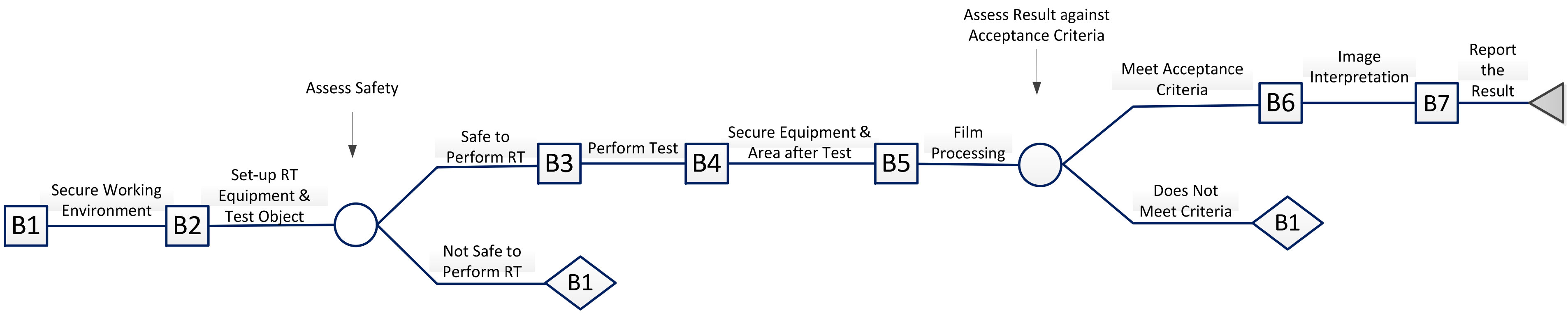


Figure 26 - Radiographic Testing Tree-diagram Part 2

Table 15 – Description of Nodes on Radiographic Testing Tree-diagram Part 2

Node	Description *(in accordance with NS-EN 444; EN, 1994)*
B1	Preparation would begin by securing surrounding working environment due to the danger of radiation. Inspectors are required to adhere to current safety rules Regulations on Radiation Protection §5 given by the Norwegian Radiation Protection Authority (NRPA, 2000).
B2	At this stage, Inspector decided which classification technique to be used. The test would be according to the chosen technique between: ▪ Class A: basic techniques, or ▪ Class B: improved techniques. Preparation of the following would be part of test arrangement: ▪ RT equipment

Table 15 – Description of Nodes on Radiographic Testing Tree-diagram Part 2	
Node	Description *(in accordance with NS-EN 444; EN, 1994)*
	▪ the surface of test object, when required, ▪ marking of the test object, ▪ prepare the necessary radiographic film according to EN 584-1 (EN, 1994)
B3	After assessing the safety of working environment, Inspector would verify whether it is safe or not to commence the test. Unsafe result would bring Inspector back to preparation stage, and safe result would give a green light to commence the test. The following would need to be given special attention upon testing (EN, 1994): ▪ The Source-to-object distance (*f*) to the source size (d), i.e. f/d, should be below the values given by the following equations: For class A: $f/d \geq 7.5(\frac{b}{mm})^{2/3}$ For class B: $f/d \geq 15(\frac{b}{mm})^{2/3}$ *Where b is object-to-film distance in mm* ▪ To reduce the effect of back scattered radiation, direct radiation shall be collimated as much as possible to the section under examination. ▪ The position of radiation beam is crucial for image quality result and as reasonably possible should be directed to the centre of inspection. ▪ The maximum area for a single exposure is calculated by the ratio of the penetrated thickness at the outer edge of an evaluated area of uniform thickness to that at the centre beam. The maximum area for a single exposure shall not be more than: For class A: 1,1 For class B: 1,2
B4	As part of the safety procedure, radiographic equipment needs to be secured after each test.

<table>
<tr><th colspan="2">Table 15 – Description of Nodes on Radiographic Testing Tree-diagram Part 2</th></tr>
<tr><th>Node</th><th>Description (in accordance with NS-EN 444; EN, 1994)</th></tr>
<tr><td>B5</td><td>After test has been performed, the film is ready for processing. The processing shall be handle with care, since in most cases film artifacts, or false indications, are the cause for the rejection of the final radiograph (Hellier, 2001).
The radiographic film is to be processed according to manufacturer's instructions. Beside manufacturer's recommendations, other influential factors for film processing are (Hellier, 2001):
▪ Developing time, temperature and washing time,
▪ maintenance of the developer and fixer solutions,
▪ agitation in the manual system during the development step,
▪ safelight condition in the darkroom, and
▪ cleanliness of processing room.
After film processing, the density of radiograph is measured using densitometer. The density of radiographs is the quantitative measure of film blackening as a result of exposure and processing, and can be expressed mathematically (Hellier, 2001):
$D = \log \frac{I_o}{I_t}$ D = density
I0 = light incident on the film
It = light intensity transmitted through the film
Total density of the radiograph in the inspected area should be:
For class A: $\geq 2,0$
For class B: $\geq 2,3$</td></tr>
<tr><td>B6</td><td>Evaluation of radiographs could be done after density readings are completed. Important steps on evaluating radiographs films are:
▪ The interpreter should be qualified and certified to perform film evaluation.
▪ The interpreter should be thoroughly familiar with the parts, dimensions, and material, and the technique that was used to produce the radiograph, how the film was processed, the standards that apply, and acceptance criteria (Hellier, 2001).</td></tr>
</table>

Table 15 – Description of Nodes on Radiographic Testing Tree-diagram Part 2	
Node	Description *(in accordance with NS-EN 444; EN, 1994)*
	▪ First, the film Interpreter would take a general look on overall image and the condition of the film to have an indication of image quality. ▪ The image quality should be confirmed by observing the Image Quality Indicator (IQI) and assuring that the essential hole in the shim-type penetrameter, or wire in the wire-type penetrameter, is clearly and discernibly displayed (Hellier, 2001). ▪ The radiographs image should be examined in a darkened room on a viewing screen with an adjustable luminance according to EN 25580, and the viewing screen should be masked to the area of interest (EN, 1994).
B7	After evaluation is complete. Test report should be written for record purposes and to give information for better understanding of the image. According to EN 444 the test report shall contain at least the following: a) Name of the testing company; b) Selected film systems, screens and filters; c) Unique report number; d) Tube voltage and current or source activity; e) Object; f) Time of exposure and source-to-film distance; g) Material; h) Type and position of image quality indicator; i) Stage of manufacture; j) Reading of IQI and minimum film density; k) Nominal thickness; l) Conformance to EN 444; m) Radiographic technique and class; n) Any deviation from agreed standard; o) System of marking used; p) Name, certification and signature of the responsible person(s); q) Film position plan, if required; r) Date of exposure and report. s) Radiation source, type and size of focal spot and equipment used;

The following picture shows interpretation of NDT image on a pipe bend. We could see that the measurement is done manually by using image ratio:

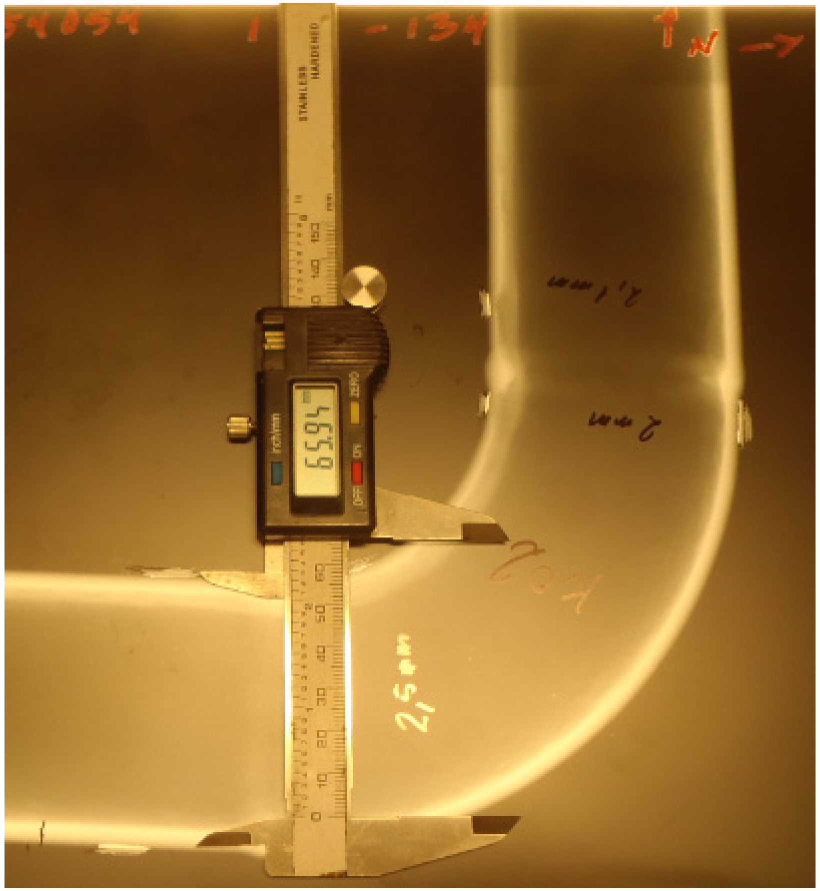


Table 16 Radiographic interpretation of Pipe Bend *(courtesy of Aker Solutions MMO)*

3.3.3 Tree-diagram: Ultrasonic Testing

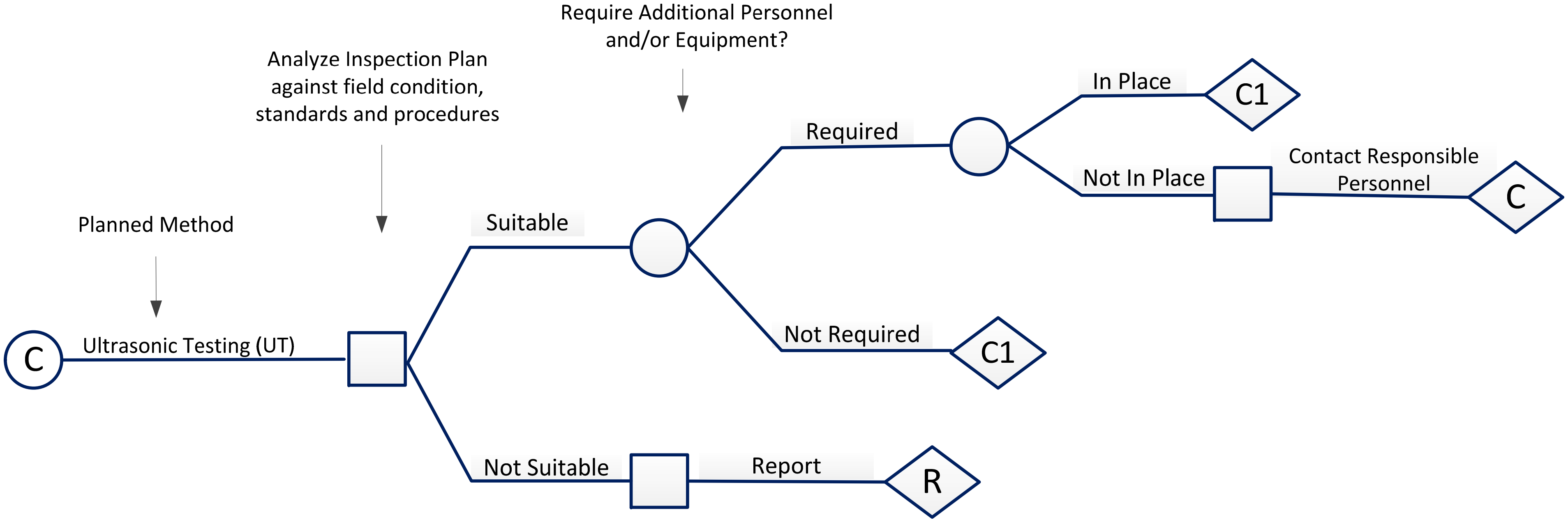


Figure 27 - Ultrasonic Testing Tree-diagram Part 1

When the method planned is ultrasonic testing (UT), the tree diagram will lead to node C. Once again, certified Inspector would assess inspection plan against field condition, standards and procedure. Although this process was previously done by Planner, but general check is common as a filtration for possible error. Specifically for the test, there are variables that Inspectors need to be aware of:

Table 17 – Important Variables In Ultrasonic Testing (EN, 1999, Hellier, 2001)

Component	Variables
Temperature	In most materials, temperature affects the sound velocity.

Table 17 – Important Variables In Ultrasonic Testing (EN, 1999, Hellier, 2001)

Component	Variables
Material	▪ Attenuation in materials: high attenuation may need lower test-frequency due to the possible larger grain size. ▪ Grain Size (of object) that could cause scatter. ▪ Resolution: Pulse length can affect the resolution characteristics of the system (see definition). ▪ Surface Conditions. ▪ Diameter and Diameter Changes. ▪ Dendritic Structures
Couplant	The amount of couplant used and the contact pressure on the transducer can create differences in signal amplitude.
Equipment	▪ Equipment setting ▪ Transducer frequency and dimension ▪ Probe selection and angle ▪ Calibration, calibration block and reference block

Example of ultrasonic scanning image of a T-joint from a topside flow line can be seen at the below figure. The T-joint was taken from operating well and we can see signs of heating on the pipe surface. The equipment use is Krautkramer USM 23 which reading has to be done manually.

<u>Table 18 - Ultrasonic Reading of T-Joint Scan *(courtesy of Aker Solutions MMO)*</u>

The following image illustrates the scanning of pipe section using automatic data storage:

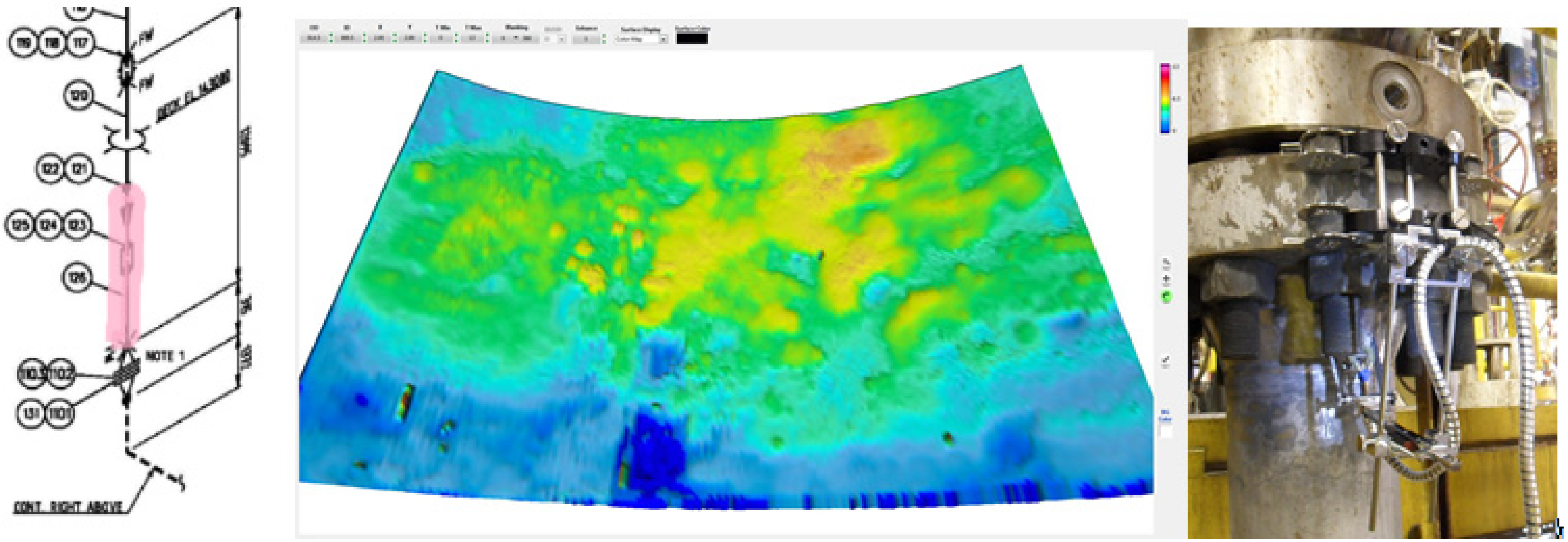


Table 19 - 3D image of Pipe Area *(courtesy of Aker Solutions MMO)*

After deciding that plan is suitable, groundwork begins with provision of required information and identifying additional equipment and/or additional personnel. For example additional personnel might be required for climbing or additional scaffolding is needed.

As soon as necessary equipment and personnel are in place, testing arrangement could begin. Figure 28 below illustrate the decision-process through ultrasonic testing and accompanied by description table based on requirements applied in Norwegian Continental Shelf.

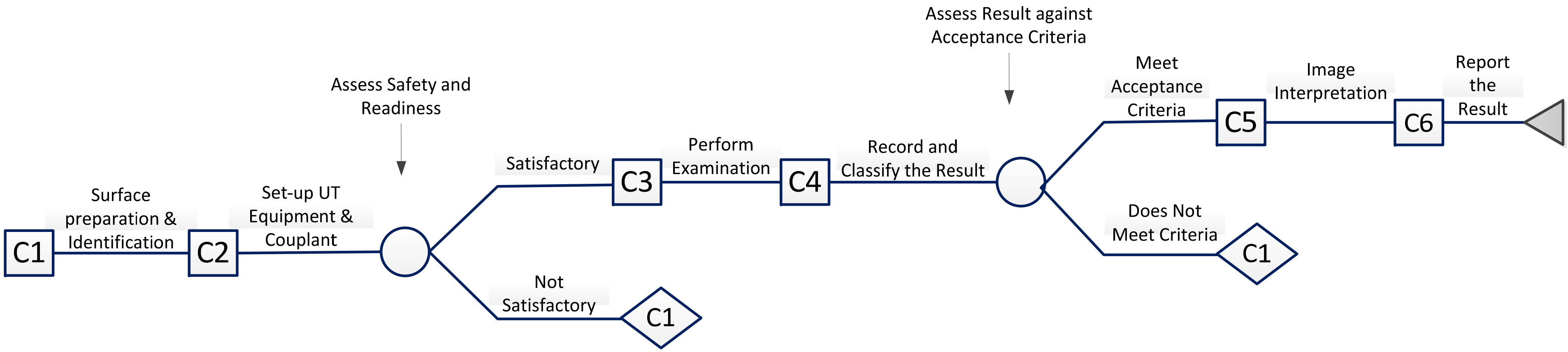


Figure 29 - Ultrasonic Testing Tree Diagram Part 2

Table 20 – Description of Nodes on Ultrasonic Testing Tree Diagram Part 2	
Node	Description (in accordance with: NS-EN 583-1 & NS-EN 583-2; EN, 1999, EN, 2001)
C1	Inspectors would begin with surface preparation as the surface finish would largely affect the results of an examination. Inspector would also apply object referencing to clearly locate the position of any reportable imperfection. When calibrating the equipment for reference sensitivity, it is essential to evaluate for any energy losses due to surface condition and apparent attenuation variations, this can be done by application of transfer correction when using reference blocks (NS-EN 583-2: EN, 2001, Hellier, 2001).
C2	At this stage, ultrasonic equipment settings are according to need and requirements, and are ready to be used.
C3	After assessing readiness to satisfactory, the examination could be performed. Compare to RT, this method requires a high level of skill and training, the qualified inspector would perform examination taking into account these following aspects: ▪ Scanning coordinates, ▪ Geometry of inspection point,

Table 20 – Description of Nodes on Ultrasonic Testing Tree Diagram Part 2	
Node	Description (in accordance with: NS-EN 583-1 & NS-EN 583-2; EN, 1999, EN, 2001)
	▪ The examination coverage, ▪ Overlap and scanning speed.
C4	The evaluation and recording levels are defined by relevant standards or applicable procedures. Depends on the tools used, in more modern equipment ultrasonic testing record could be captured and stored in software. Otherwise, evaluation would need to be done during examination. NS-EN 583-1 proposed the following techniques for ultrasonic evaluation: ▪ Pulse echo technique ▪ Transmission technique
C5	As stated in point C4, the time of image interpretation would depend on the equipment being used. But in any given conditions, Inspector with appropriate training and extended experience is required to interpret ultrasonic result. There are reports of various non-relevant indications as discontinues indications and vice-versa, thus the interpretation of manual ultrasonic testing requires greater operator/inspector skill and knowledge of the object configuration (Nachimuthu and Babu, 2008).
C6	After evaluation, Inspector would report the result in designated software application. The report would contain at least the following information (EN, 1999): a) identification of the manufacturer, and/or the order; b) complete identification of the examined object; c) place of examination; d) state of examination object; e) identification of the examination equipment used; f) reference to contractual documents (standards etc); g) reference to the examination procedure; h) name, qualification and signature of the examiner or any other responsible for the examination; i) date of examination;

Table 20 – Description of Nodes on Ultrasonic Testing Tree Diagram Part 2	
Node	Description (in accordance with: NS-EN 583-1 & NS-EN 583-2; EN, 1999, EN, 2001)
	j) results of examination and evaluation; k) any deviation from the procedure.

3.3.4 Tree-diagram: Phased Array Testing

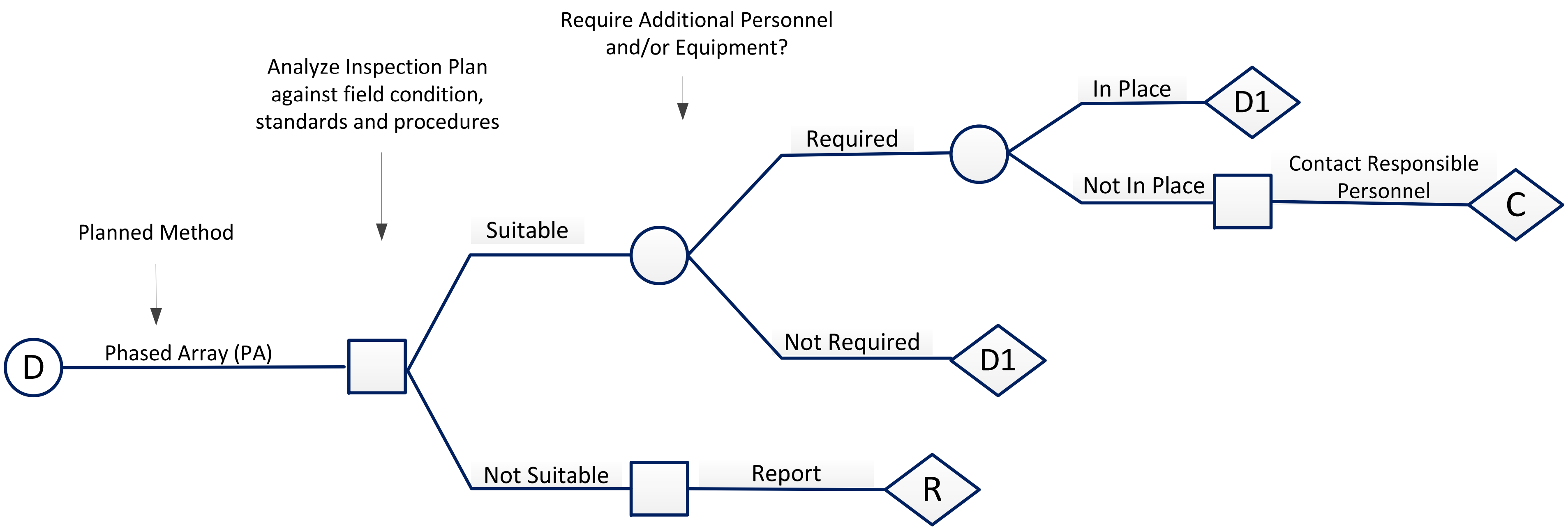


Figure 30 - Phased Array Testing Tree-diagram Part 1

Standard for Phased Array testing has only been introduced recently. ISO 13588:2012, Non-destructive testing of welds - Ultrasonic testing - Use of automated phased array technology, was adapted to Norwegian Standard on early January 2013. The standard specifies the application of phased array for semi or fully automated ultrasonic testing of fusion-welded joints in metallic materials (EN, 2012). The standard will be accompanied with EN 16392 Part One through Part Three that will cover the characterization and verification of phased array.

Generally, the variables that influenced phased array testing are similar to ultrasonic testing, the differences lies on the different equipment used and the settings based on ISO 13588:2012 requirements. Additionally, the following factors had a significant effect on the measurement: inspector training and experience, object thickness, size of defect and whether the flaws are rough or smooth (Schneider and Bird, 2010).

Prior to examination, Inspector would require written test procedure and information regarding material specification. A scan plan should also be provided, outlining the inspection coverage. Following completion of information required, the Tree Diagram below would illustrate general decision-making process for phased array testing, followed by description based on ISO 13588:2012 requirements.

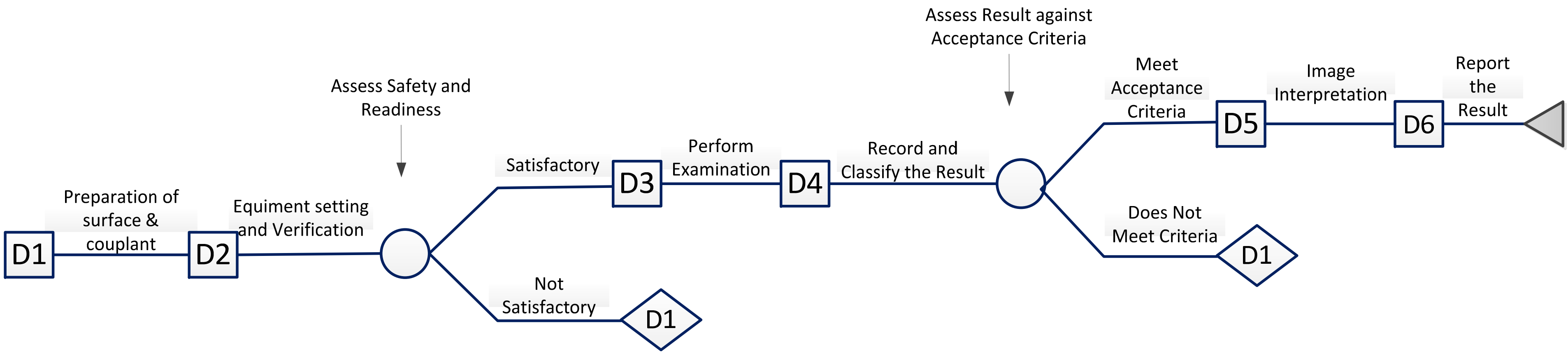


Figure 31 - Phased Array Testing Tree Diagram Part 2

Table 21 – Description of Nodes on Phased Array Testing Tree Diagram Part 2

Node	Description (in accordance with ISO 13588:2012; EN, 2012)
D1	Similar to ultrasonic testing, surface condition is very important for PA testing to deliver soundwave continuously. Phased array technique would also need a couplant, the medium that is common to use in offshore industry is water.
D2	After the test object is ready, Inspector need to set range and sensitivity of test equipment. Settings need to be checked every four hours and after the completion of testing. The same applies as in ultrasonic testing, when initial testing was done with reference block, the same reference block or alternatively smaller block with known transfer properties should be used (EN, 2012).
D3	At this stage, the test coverage should have been verified with the scan plan and demonstrated on a suitable reference block (EN, 2012). Once requirements and conditions are found satisfactory, the scanning could start. Unlike ultrasonic testing, scanning speed of PA testing is not formulated. The scanning speed of PA testing is adjusted accordingly to generate satisfactory image quality. Satisfactory image is defined as by appropriate: coupling, time-base setting, sensitivity setting, signal-to noise ratio, saturation indicator and appropriate data acquisition (EN, 2012).
D4	Since PA testing should utilize a device employing computer-based data acquisition (EN, 2012), scan data could be stored along with the set-up parameters. Depends on the software tools, variety of scanning parameter could be stored to be analysed afterwards.
D5	Before interpretation, phased array data would be assessed first for its quality. Relevant indications would then be identified, classified and determine its location and size. The final result will then be evaluate against acceptance criteria (EN, 2012). Similar to Ultrasonic testing, inspectors need to have appropriate training and experience to correctly interpret PA results. A research done have shown that there is a large variation in the ability of phased array inspectors to size defects (Schneider and Bird, 2010), thus the reported result could vary amongst different inspectors.
D6	When the acceptance criteria are met, the result would need to be reported accordingly. The report would include at least the following information (EN, 2012): a) Reference to ISO 13588:2012

Table 21 – Description of Nodes on Phased Array Testing Tree Diagram Part 2	
Node	Description (in accordance with ISO 13588:2012; EN, 2012)
	b) information relating to the object under test c) information relating to equipment d) information relating to test technology e) information relating to phased array setting, and f) information relating to phased results.

Figure 32 - Phased Array Testing on Pipe Spool (Courtesy of Aker Solutions MMO)

4.0 RESEARCH METHODOLOGY

This chapter presents the description of the research design, data collection and processes done in order to conduct a systematically research study. Validity and reliability issues of the study will also be presented.

4.1 CONCEPTUAL FRAMEWORK

The research approach towards problem is similar to risk analysis process coined by Aven (2011). The first stage is planning which include base work of problem definition and choosing analysis method. Planning is followed by data processing and risk assessment process, which involves; data collecting, processing, analysing and the determination of risk. For this research purpose, data processing and analysis is clustered separately than risk assessment, due to the extensive process that needs to be discussed distinctly. As an addition, after risk is determined, few suggestion of risk mitigation will be presented on risk treatment section.

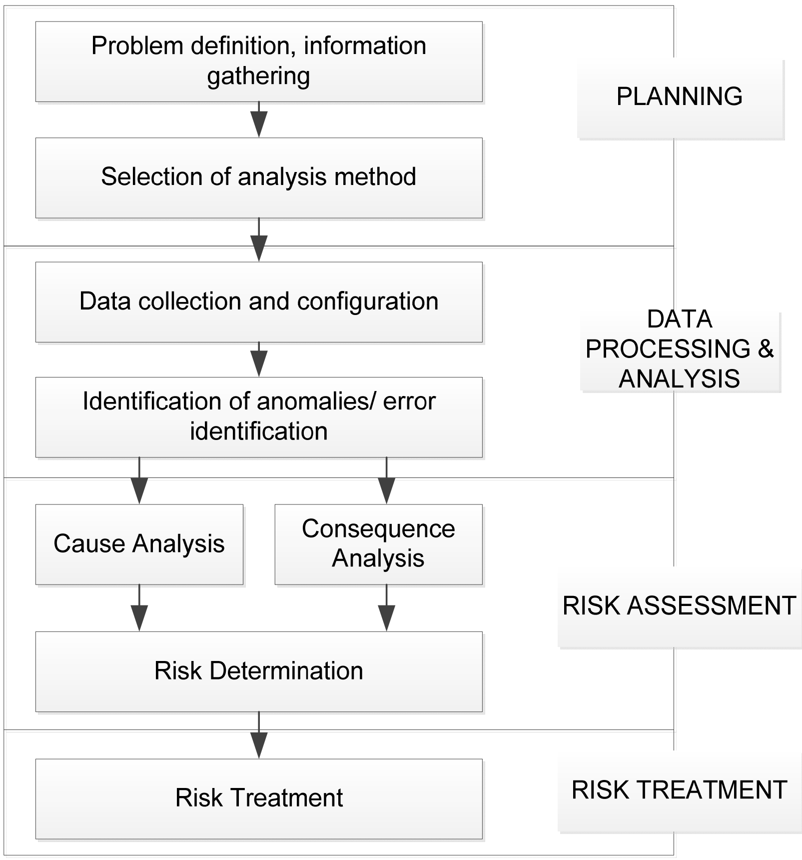


Figure 33 - Conceptual Framework (Adapted from: Aven, 2011)

4.2 DATA COLLECTION

4.2.1 Data Collection Methods

In collecting data, Creswell and Clark (2011) recommends mixing both quantitative and qualitative data collection methods to strengthen the validity of final conclusions. In conjunction with that, Yin (2009) recommends six sources of data for case studies, they are: documentation, archival records, interviews (or surveys), direct observation, participant observation and physical artifacts.

For this thesis, we would combine both recommendations and apply them in our data collection method.

Quantitative data such as documentation and archival records are collected from Operator Company's Information System, while physical artifacts and qualitative data are collected from direct interaction with NDE activities, both onshore and offshore. The table below offers classification of data origins for this thesis research:

Table 22 - Data Collection Methods

Methods	Sources	Description	Origins
Quantitative	Documentation	Technical documentations, procedures, standards and regulations	Operator's Company Information System
	Archival records	Historical inspection results, historical technical reports	Operator's Company Information System
	Physical artifacts	Inspection results, field technical condition	NDE activities both onshore and offshore
Qualitative	Interviews (or surveys)	On-the-job Survey	NDE activities both onshore and offshore
	Direct observation	Observation from field visits, both onshore and offshore	NDE activities both onshore and offshore
	Participant observation	Observation where researcher participate on the activity	NDE activities both onshore and offshore

4.2.2 Data Characteristic

The main focus of this thesis is historical NDE results that being collected from three production platforms during the same period. Supporting data for these platforms such as technical documentation and archival records are dated back to when the platform are start producing until 31 December 2011. The table below summarizes characteristic of data and its origins:

Table 23 - Data Characteristics

Case Study	Production Start	Location	Historical NDE Data	
			From	To
A	1979	North Sea, Norwegian Sector	01 January 1994	31 December 2011
B	1982	North Sea, Norwegian Sector	01 January 1994	31 December 2011
C	1985	North Sea, Norwegian Sector	01 January 1994	31 December 2011

Due to the time limitation and integrity of data, generally this research will disregard data exceeding 31 December 2011. This limitation also applies for related standards and procedures, except for Phased Array Standard ISO 13588:2012, that has just been adapted by Norwegian Standard on January 2013.

4.3 ANALYSIS OF DATA

The NDE results that are collected from historical data will be the subject of our research. This section will explain the processing of those data to find desirable output. The process is illustrated by the following diagram:

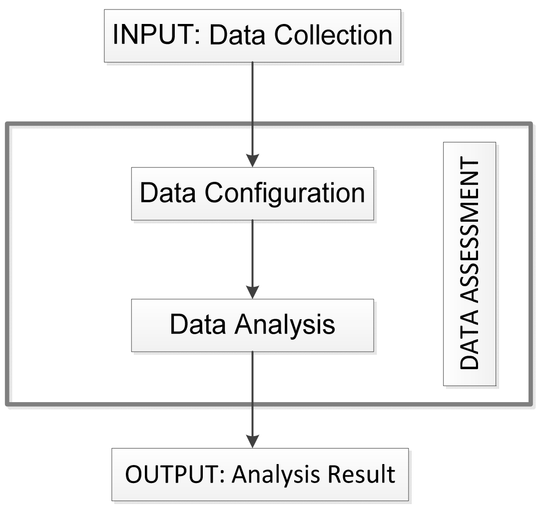


Figure 34 - Data Processing & Analysis

4.3.1 Input: Data Collection

The NDE historical data are collected from organization's information system. Information system is defined as combination of information technology (IT) and people's activities using that technology to support operations, management, and decision-making (SEI, 2007). The mapping of information system to produce input for this research is illustrated by Figure 35 which was based on operator's company information system.

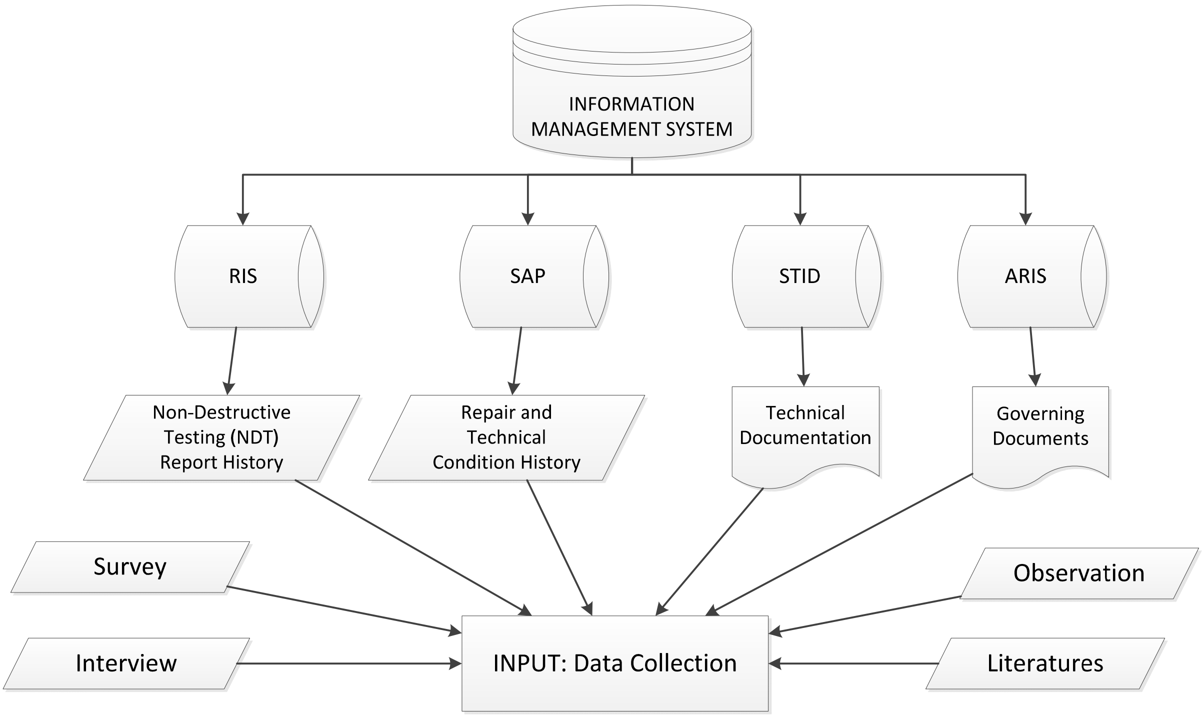


Figure 35 - Data Collection Sources for this Research

RIS, SAP, STID and ARIS are software platforms being used to handle technical information within the company. Software platform being used for NDT report history is RIS, SAP is used for technical condition history, STID is being used to handle technical documentation, and while ARIS is platform here the company store their governing documents.

4.3.2 Data Assessment: Configuration

Prior to analysis of data, first they will need to be organized and classified accordingly towards systematic analysis. Data are classified according to research needs and then assessed and filtered allowing noise and unwanted data to be sorted-out. The study required data to be classified by:

Table 24 - Data Classification Values

Sequence	Classification	Values
1	Production Platforms	Case Study A Case Study B Case Study C
2	System	Topside Piping System
3	Date of Inspection	01 January 1994 to 31 December 2011
4	Inspection Objects	Welds (under field conditions)

Table 24 - Data Classification Values		
Sequence	Classification	Values
		Welds (under workshop conditions) Bends
5	Non-destructive Evaluation Methods	Radiography Testing (RT) Conventional Ultrasonic Testing (UT) Phased Array Testing (PA)

This step is necessary to simplify the analysis and to avoid noise affecting the end result. The data then grouped into several data-sets to be analysed individually as illustrated by the following figure:.

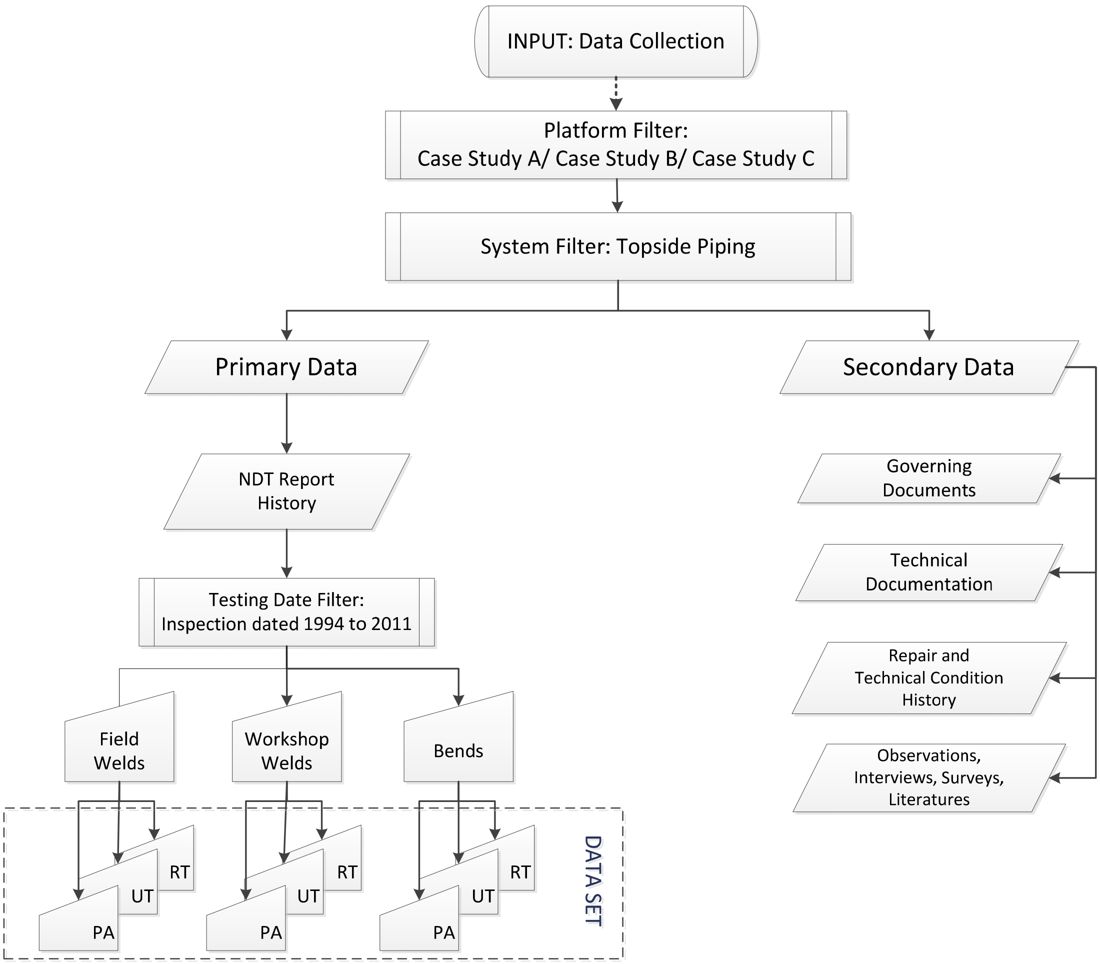


Figure 36 - Data Configuration Process Flowchart

4.3.3 Data Assessment: Analysis

The purpose of this analysis is to uncover anomalies on NDE measurement reports amongst the historical data. A satisfactory measurement value is reached through proper non-destructive evaluation and interpretation according to relevant standards as described on chapter 3. The possible anomalies on these data-sets are:

- Data value is null
- Measured wall thickness ($T_{measured}$) is larger than recorded wall thickness ($T_{nominal}$). Or can be written as: $T_{measured} \rangle T_{nominal}$.

  In some cases, recorded $T_{nominal}$ is not according to the field condition; this would usually appear on field reports or could be checked against supporting technical documentations.
- Values of $T_{measured}$ for the same inspection point are increasing and/or fluctuate by time, without any modification done on the respected pipe section.

  If T_{mi} = $T_{measured}$ at i^{th} inspection, and T_{mn} = is the last $T_{measured}$ taken, then:

  $T_{m1} \le T_{m2} \le T_{m3} \le ... \le T_{mn}$
- Note that the deviation value is not determined, thus deviation as small as 0.1 mm will still be considered as anomaly.

Besides historical NDE data, anomalies could be located through other means of records, such as documentation of findings and reports, inspection results (images) and surveys. Affirmations of anomaly are also backed-up with supporting documentations that confirms what would the satisfactory value would be as illustrated by the following flowchart:

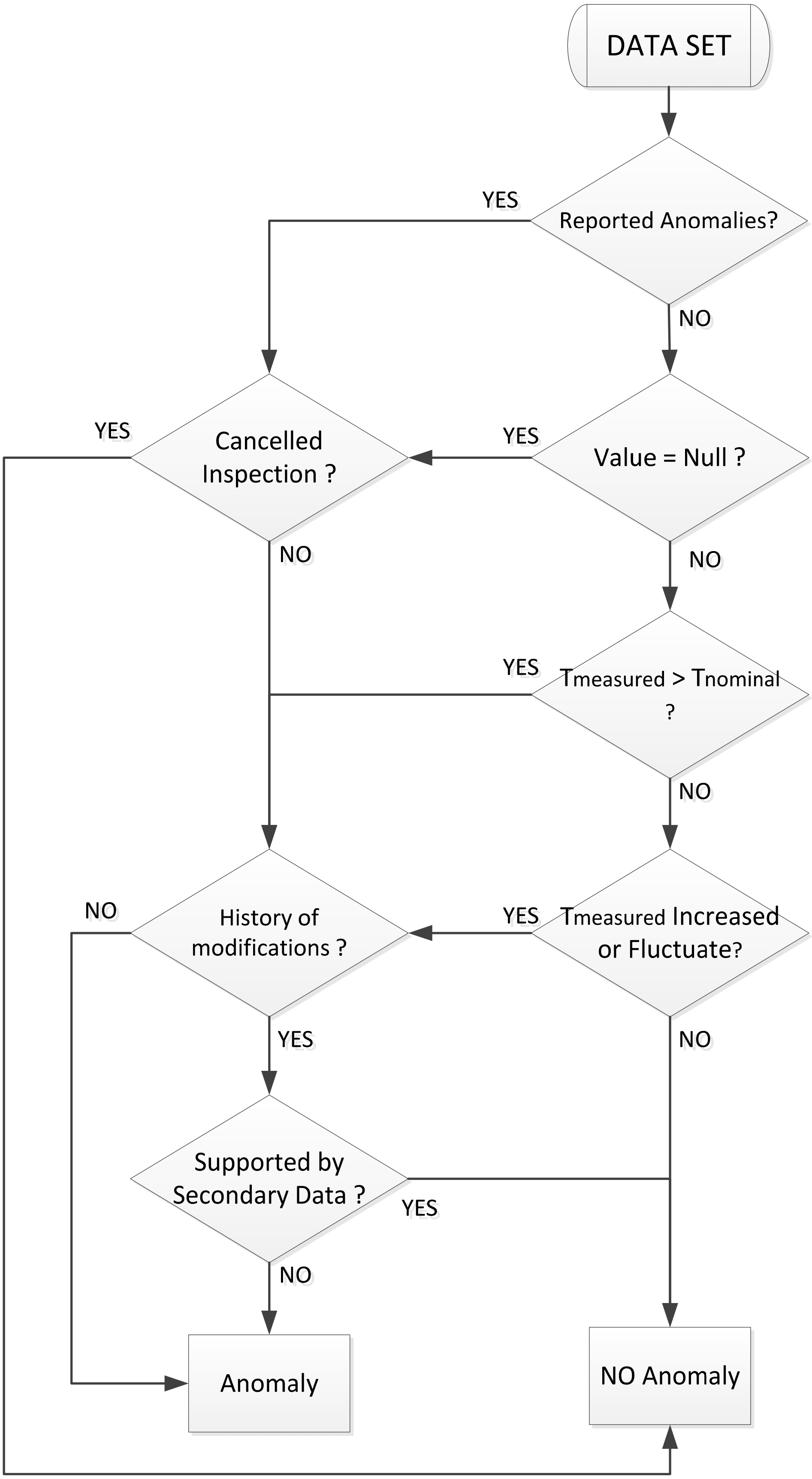


Figure 37 - Data Analysis Process Flowchart

4.3.4 Output: Outcome of Data Analyses

Output of data analysis will be presented in simplest form to communicate research outcome without being misleading. The result is expected to show the percentage of error on NDE historical data. Additionally, the results produced from data analyses would in turn act as basis for further study on human factor and operational risk in the same field.

4.4 RESEARCH VALIDITY AND RELIABILITY

Research reliability depends on the degree to which an assessment tool produces consistent results and that another researcher will be able to achieve the same results as in the study (Yin, 2009). Although the data set for this research is not publicly available, thus will be challenging to replicate, the methods used for this thesis are available and can be remanufactured with new data set suitable for the research.

According to Yin (2009), the research validity can be determined with how well the study results compare with the real life scenario. And since the research was based from real life findings, and investigations were taken from direct encounter with actual field situation, the research could be well compared with real life scenario.

5.0 RESULTS AND DISCUSSION

In this chapter, findings of research will be presented in the simplest representable form. The findings will be analysed and discussed with goal to answer the research problem.

5.1 PERCENTAGE OF ERROR

There are significant amount of time invested in locating anomalies on data, owing to the high amount of historical data and as the technique chosen was divided into automated analysis and analysis that somewhat labour-intensive.

The first question that arises at the beginning of the research was how we could identify anomaly on a measurement. A full automatic analysis would save a decent amount of time, but we might miss some information from the report. The reason was due to the inspection database that allows reporter to give additional comments besides other fixed information. Additionally, there are also other forms of engineering data that may or may not support the NDT report. The supplementary information might change the pre-assumption of data and enable the researcher to identify the root-cause.

Based on the above reason, for this research a thorough analysis would be more spot-on and comprehensive in identifying the anomalies. Thus, rest assure that the data would undergo individual investigation before it is declared of having an anomaly.

5.1.1 Welds (Under Field Conditions)

Table 25- Percentage of Error for Welds (Under Field Conditions)

METHOD	Case Study A	Case Study B	Case Study C
RADIOGRAPHY	9.16%	13.89%	15.53%
ULTRASONIC	20.95%	21.41%	15.42%
PHASED ARRAY	Disregard, insufficient data	Disregard, insufficient data	Disregard, insufficient data
Total	10.31%	17.49%	15.44%

5.1.2 Welds (Under Workshop Conditions)

Table 26 - Percentage of Error for Welds (Under Workshop Conditions)

METHOD	Case Study A	Case Study B	Case Study C
RADIOGRAPHY	8.90%	13.00%	18.77%
ULTRASONIC	12.21%	22.61%	17.10%
PHASED ARRAY	Disregard, insufficient data	Disregard, insufficient data	Disregard, insufficient data
Total	9.18%	16.12%	17.92%

5.1.3 Bends

Table 27 - Percentage of Error for Bends

METHOD	Case Study A	Case Study B	Case Study C
RADIOGRAPHY	5.15%	13.50%	19.53%
ULTRASONIC	14.64%	17.61%	10.00%
PHASED ARRAY	Disregard, insufficient data	Disregard, insufficient data	Disregard, insufficient data
Total	7.40%	13.85%	19.39%

5.2 INTERPRETATION OF RESULTS

The result shows the percentage of error from reported NDT inspection on field welds, workshop welds and bends. Overall, the radiography testing shows lower percentage of error compare to ultrasonic testing. And Case Study A shows significantly lower percentage of error amongst the three.

We can translate the data further to determine the reliability of data by applying binary models to analyse system reliability (Aven, 1992).

Consider a data-set, indicated by ϕ, comprised of n amount of data, indicated by x. The data-set distinguished in two states: ideal state (where all the data are correct) and imperfect state (where all the data are incorrect).

$$\phi = \begin{cases} 1, & \text{if the data-set is in ideal state} \\ 0, & \text{if the data-set is in imperfect state} \end{cases}$$

Let X indicates the state of data x:

$$X = \begin{cases} 1, & \text{if the data is in ideal state} \\ 0, & \text{if the data is in imperfect state} \end{cases}$$

Assume that the state of data-set is determined by the states of the data (*Eq. 2*):

$$\phi = \phi(X), \qquad \textit{(Eq. 2)}$$

$where\ \mathrm{X} = (X_1, X_2, X_3, \ldots, X_n)$

Then we can write the reliability and unreliability of the data-set as (Aven, 1992):

$P[\phi(X) = 1] = \text{Reliability of data-set, and}$

$P[\phi(X) = 0] = \text{Unreliability of data set}$

Where (E*q. 3*)

$$P[\phi(X) = 1] + P[\phi(X) = 0] = 1 \qquad \textit{(Eq. 3)}$$

The percentage of data error represents unreliability of the system, thus we can write the reliability of data-set as

$$P[\phi(X) = 1] = 1 - P[\phi(X) = 0]$$

To simplify the equation, we indicate $P[\phi(X) = 1]$ as h and $P[\phi(X) = 0]$ as g, thus (E*q. 4*):

$$h = 1 - g \qquad \textit{(Eq. 4)}$$

If we take one example from analysis result of workshop welds on Case Study A:

$$\text{Total percentage error of data-set } = 9.18\%$$

Where percentage of error represents the unreliability of the data-set, thus:

$$\mathrm{g} = 0.918$$

Then for reliability of data-set we can write:

$$\mathrm{h} = 1 - \mathrm{g}$$
$$= 1 - 0.0918$$
$$\mathrm{h} = 0.9082$$

The calculated result expressed that reliability of specified data-set is 0.9082.

The complete reliability calculations for analysed data-sets are:

Table 28 - Data Reliability for Welds (Under Field Conditions)

METHOD	Case Study A	Case Study B	Case Study C
RADIOGRAPHY	0.9084	0.8611	0.8447
ULTRASONIC	0.7905	0.7859	0.8458
PHASED ARRAY	Insufficient data	Insufficient data	Insufficient data
Total	0.8969	0.8251	0.8456

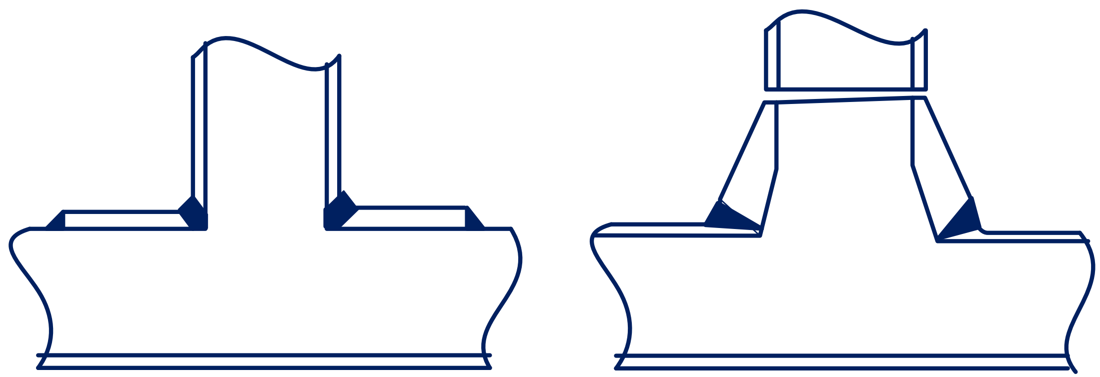
Table 29 - Data Reliability for Welds (Under Workshop Conditions)			
METHOD	Case Study A	Case Study B	Case Study C
RADIOGRAPHY	0.9110	0.8700	0.8123
ULTRASONIC	0.8779	0.7739	0.8290
PHASED ARRAY	Insufficient data	Insufficient data	Insufficient data
Total	0.9082	0.8388	0.8208

Table 30 -Data Reliability for Bends			
METHOD	Case Study A	Case Study B	Case Study C
RADIOGRAPHY	0.9485	0.8650	0.8047
ULTRASONIC	0.8536	0.8239	0.9000
PHASED ARRAY	Insufficient data	Insufficient data	Insufficient data
Total	0.9260	0.8615	0.8061

5.3 OTHER FINDINGS

When analysing the data, we discovered several other anomalies on the data. We classified them into three major groups:

Table 31 - Other Anomalies Discovered on Analysis

Group	Anomaly	Description
Inspection Database	False Data	In some cases, the inspection database registers incorrect pipe size and nominal diameter. There are basically two reactions after; either the Inspector spotted the differences and take note on the report, or the Inspector would not spot the error until there are signs of corrosion or future reports. We have also detected that for points with complex geometry, engineering data error is most likely to happen. For example for welds on branch connections, the weld size could be wrongly registered if the two connecting branch sizes are different. We also found similar case on weldolet which could potentially mislead the NDT interpretation.  Figure 38 - Reinforcing Pad (left) and Weldolet (right)

<table>
<tr><th colspan="3">Table 31 - Other Anomalies Discovered on Analysis</th></tr>
<tr><th>Group</th><th>Anomaly</th><th>Description</th></tr>
<tr><td></td><td></td><td>Total percentage of database with error per measurement are as follow:

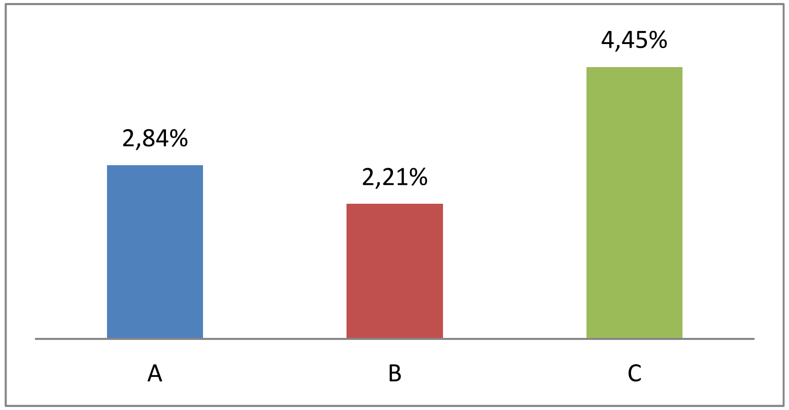



Figure 39 – Percentage of Database Error per Total Measurement

Database of case study C has the highest percentage of database error per measurement (4.45%), followed by case study A (2.84%) and lastly by case study B (2.21%).</td></tr>
</table>

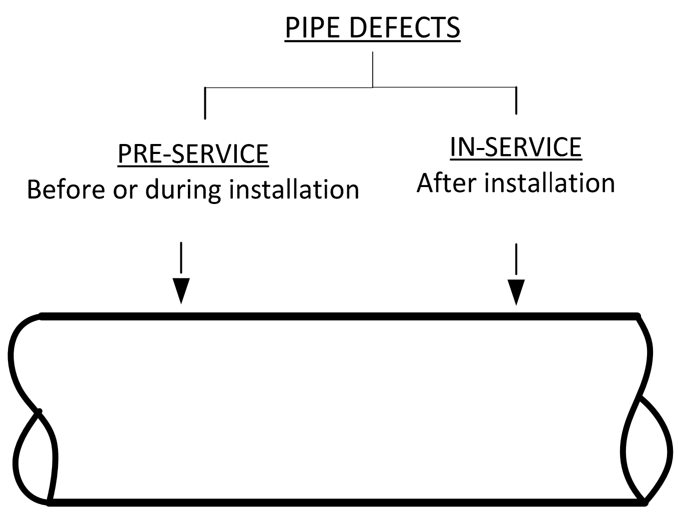
<table>
<tr><th colspan="3">Table 31 - Other Anomalies Discovered on Analysis</th></tr>
<tr><th>Group</th><th>Anomaly</th><th>Description</th></tr>
<tr><td></td><td>Manufacturing tolerance and installation defects</td><td>Previously on section 2.3 Pipe Defects, we have discussed the sources of pipe defects which generally could be divided into pre-service defects and in-service defects.


Figure 40 - Types of Pipe Defects
Afterward on the analysis we discovered that pre-service defects, if not registered correctly, affecting the pipe database and consequently the NDT inspection. Fail welds and manufacturing tolerance are exposed during routine inspections and frequently mislead the NDT interpretation.</td></tr>
</table>

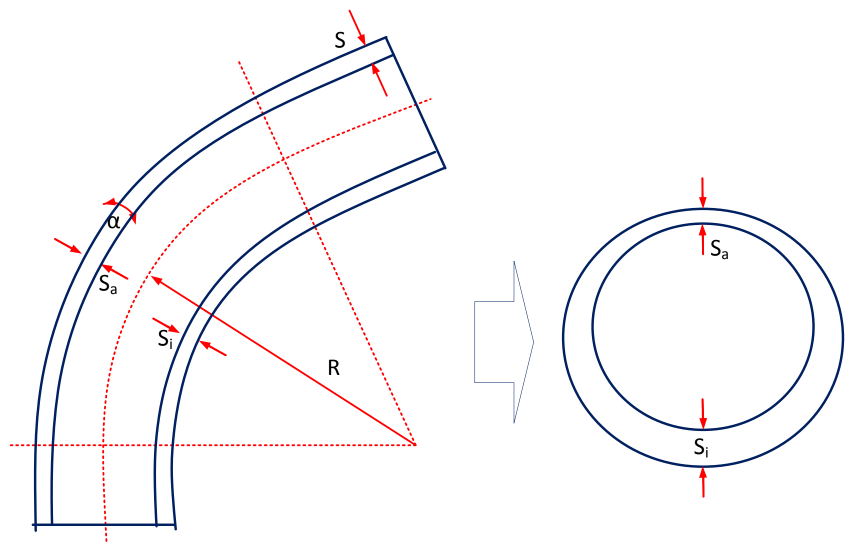
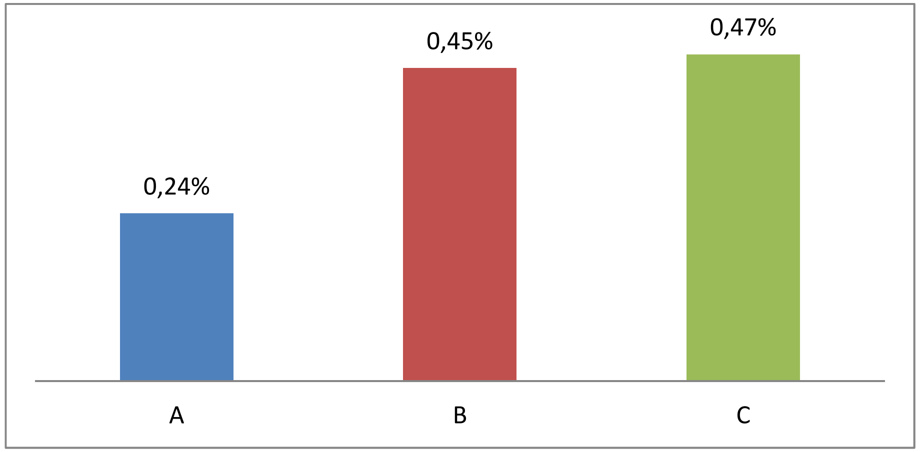
Table 31 - Other Anomalies Discovered on Analysis		
Group	**Anomaly**	**Description**
NDT Techniques	Inspection Coordinates and Pipe Geometry	In the inspection database, the pipe coordinate that need to be inspected shall be stated beforehand and also on the report. This is due to pipe geometry that could potentially have different wall thickness. The practice thou, was not always followed. Thus, NDT results are varied depend on testing coordinates. The coordinates is usually maintained when defect is found, although it does not guarantee the same measurement value. Normally inspection points such as welds, bends, welds on o-let, or T-Joints have varying thickness as illustrated with the following example:  Figure 41 - Different Wall Thickness in Pipe Bend (Bilfinger Piping, 2013, American Society of Mechanical, 2011)

Table 31 - Other Anomalies Discovered on Analysis

Group	Anomaly	Description
		The illustration shows pipe bend with bending angle α, having normal wall thickness S, wall-thickness intrados Si, and wall-thickness extrados Sa. Normally Si would have higher minimum wall-thickness than S, and Sa would have thinner minimum wall-thickness than S.
Reporting	Reporting error (due to software usage)	NDT reports are stored through Inspection database platform. To use the software, Inspector required trainings and IT support. We discovered reporting errors that related to the usage of software. Typical examples are double-reporting for the same test, typo-error and varied ways of reporting. Case study A has the lowest case of reporting error (0.24%), followed by case study B (0.45%) and the highest on Case Study C (0.47%).  Figure 42 - Percentage of Reporting Error per total Measurement The reporting error could be prevented with the presence of procedure and standardization of reporting for the software platform.

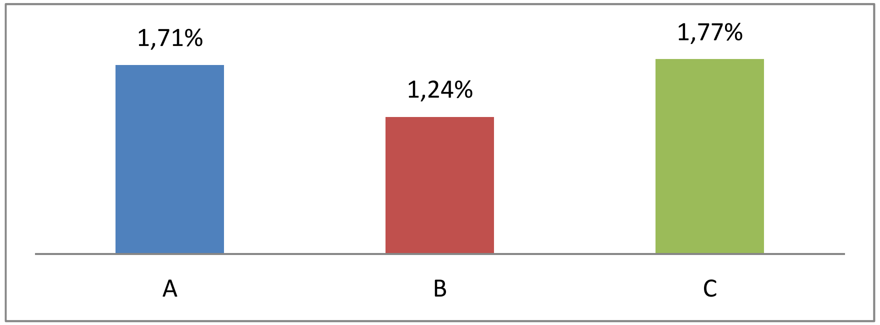
<table>
<tr><th colspan="3">Table 31 - Other Anomalies Discovered on Analysis</th></tr>
<tr><th>Group</th><th>Anomaly</th><th>Description</th></tr>
<tr><td></td><td>Null values</td><td>Surprisingly we found a decent amount of null value reports that still submitted as valid result. The result is illustrated by figure below:


Figure 43 - Percentage of Null Measurement Value
Even when the measurement values are registered on the space provided for the additional comments, the value would not registered in the history. The null value would have impact on automated data analysis, this measurement are much likely to be excluded from analysis.</td></tr>
<tr><td>False Interpretation</td><td>False indication or False measurements value with deviation</td><td>Although not often, in some cases, after indication of defect on a report, the next report would state that previous indication was incorrect.
If the deviation is not significant, the anomaly could be missed and still included in the data analysis. The fluctuation of data could affect the data analysis, especially in predicting remaining life or degradation rate. Although the average deviation value are quite low (1.8 mm for RT and 2.5 mm for UL, while PA result is disregard due to insufficient data), the value sometimes so significant (up to -229.6mm) which could create a great deviation from other data set.</td></tr>
</table>

5.4 CAUSE OF ERROR

The different percentage of error from different data-set shows that the reliability of NDT data has different result under different conditions. The hypothesis suggests that data are affected by various variables and these variables have unique value for different case study.

It is unfortunate that we could not attained sufficient data for phased array technique analysis, thus from here on, the discussion will only covers radiographic technique and conventional ultrasonic technique.

As discussed on section 3.3, we understand that NDT testing comprises from a series of actions required to indicate the technical condition of the test object. The series of actions was represented by tree-diagram which models the process in execution of NDT testing. Thus, it provides ideal simulation for assessment of the NDT process.

5.4.1 Assessment of NDT Process

Previously on section 3.3, we have listed variables that would influence each NDT techniques. These variables are controlled on NDT process that is shown on action nodes. These action nodes are affecting event nodes and consequently the end report of NDT testing. Thus, errors on NDT results are potentially derived from action nodes

There are five groups of actions that have a major influence on the process of generating NDT Report:

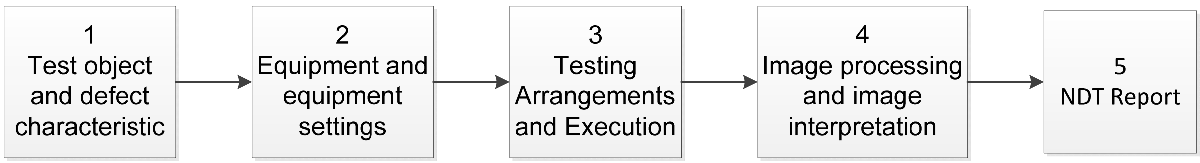


Figure 44 - Major Action in Process of Generating NDT Report

Each group are driven and influenced by various variables, mainly by standard and procedures, inspector, equipment and technical condition.

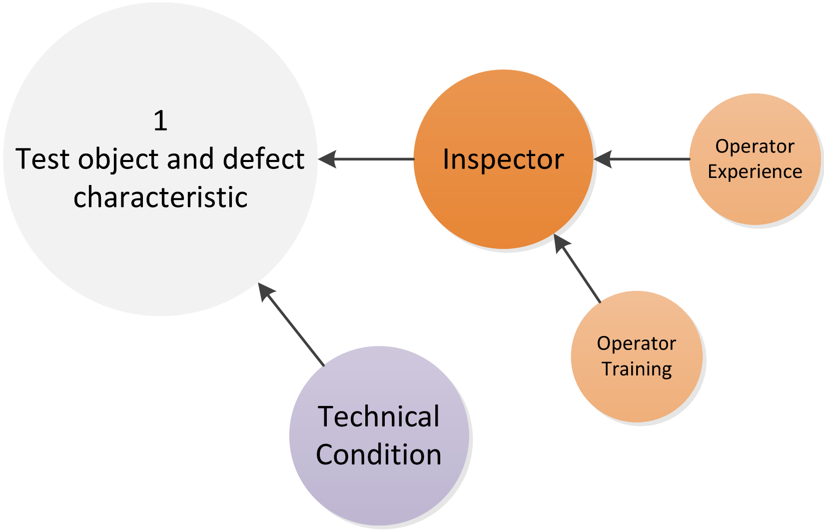


Figure 45 - Elements that Influence Test Object and Defect Characteristic

Test object and defect characteristic is the actual technical condition of the test object itself. Technical condition is a unique element that stand-alone from the rest, but affects the result of testing depend on the characteristic of object. This, once again related to inspector's ability to give correct interpretation and testing arrangement accordingly.

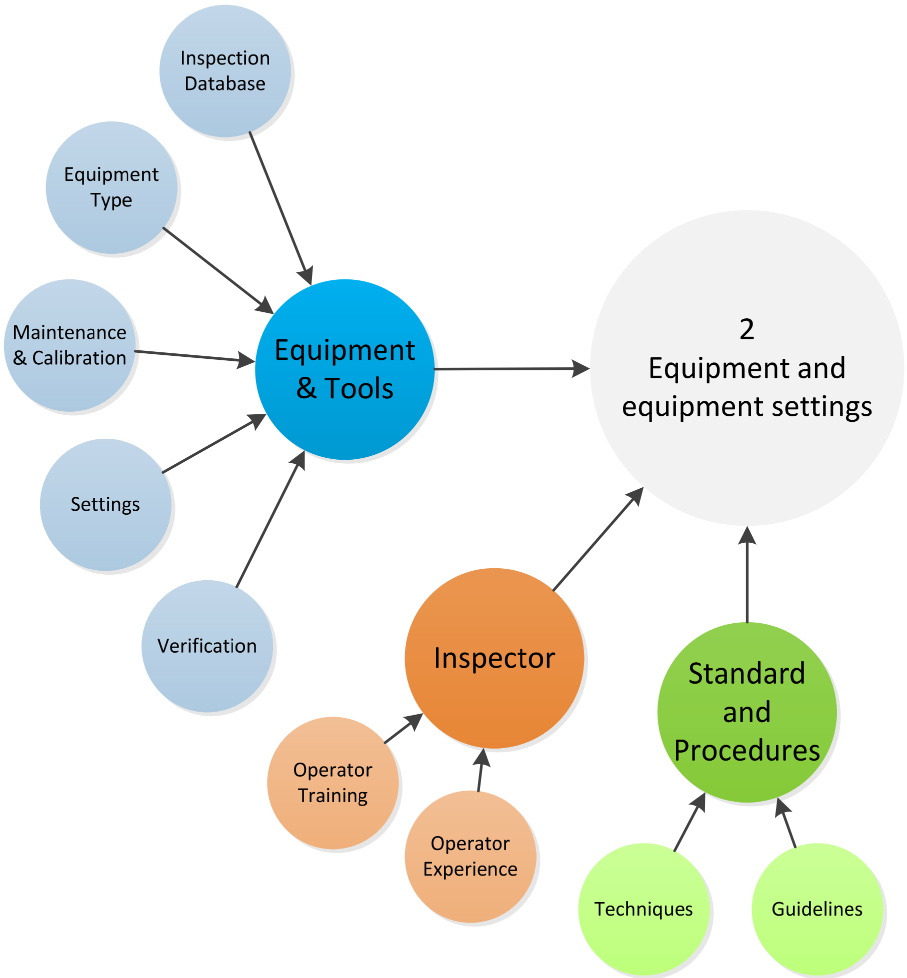


Figure 46 - Elements that Influence Equipment and the Settings

Requirement for equipment and their setting and verification are governed by standards and the organization's specific procedures. These governing documents regulated the equipment to be used and the required settings and verification. But in the field, inspectors have overall control upon all of the elements (standards, procedures, equipment and related settings). The inspectors are trained to be knowledgeable of requirements that should be adhered. As a result, the inspectors holds important role in controlling the state of equipment and their settings requirements.

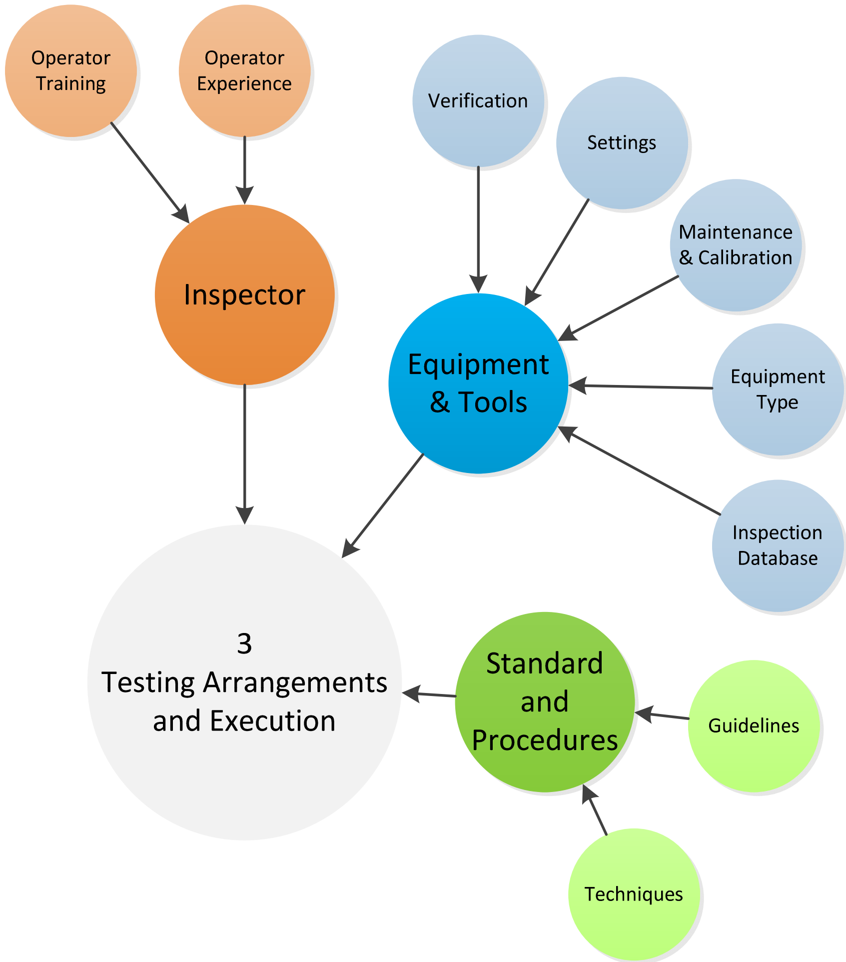


Figure 47- Elements that Influence Testing Arrangements and Execution

Besides equipment arrangement, testing condition also need to be plan according to governing documents. Execution of testing is equally essential to accomplish the intended result. The Inspector, once again, is responsible for field implication of these guidelines.

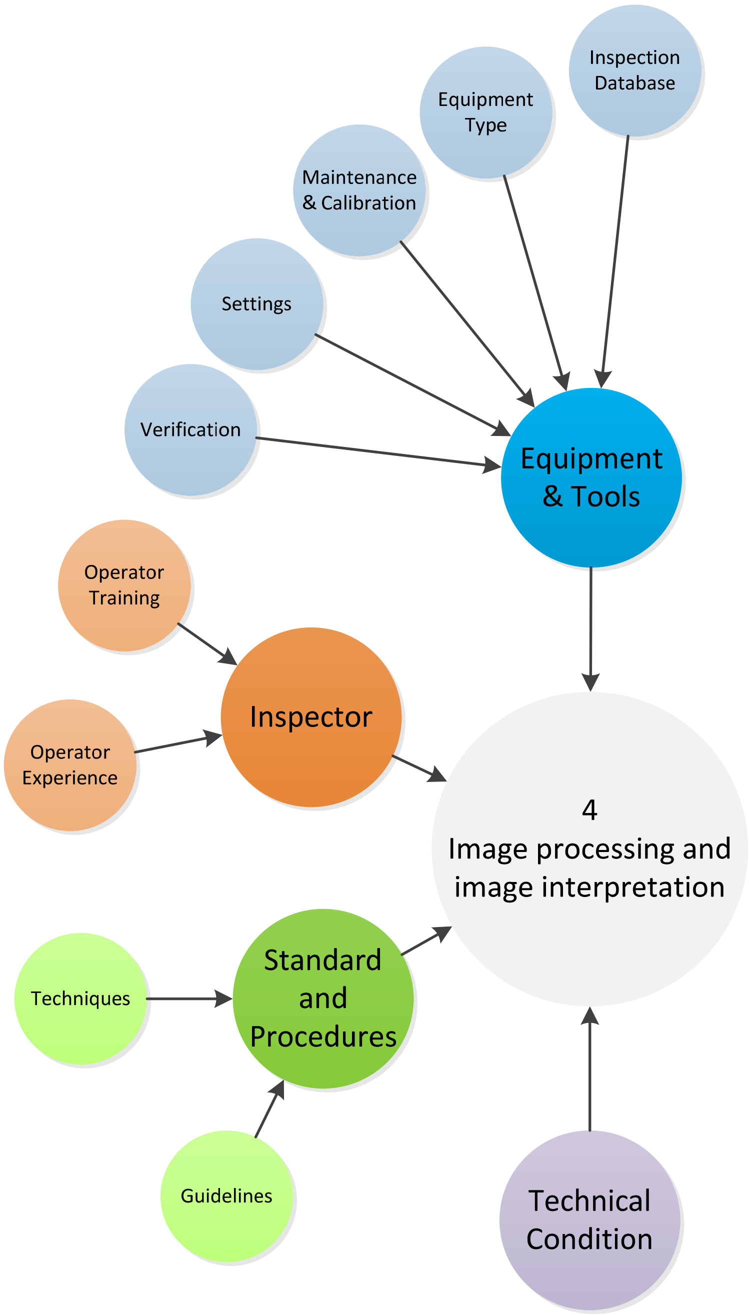


Figure 48 - Elements that Influence Image Processing and Image Interpretation

Action group number 4 has the most influencing variables of all, and therefore more potential for error.

Image processing is particularly crucial for radiographic testing due to the film utilization. While image on ultrasonic testing and phased array testing are digitally generated.

Interpretation of NDT image is considered as the most crucial step due to the complexity of task that required highly trained and experience inspector. There have also been reported cases of doubtful interpretation due to inaccuracies of interpretation (Nachimuthu and Babu, 2008, Schneider and Bird, 2010).

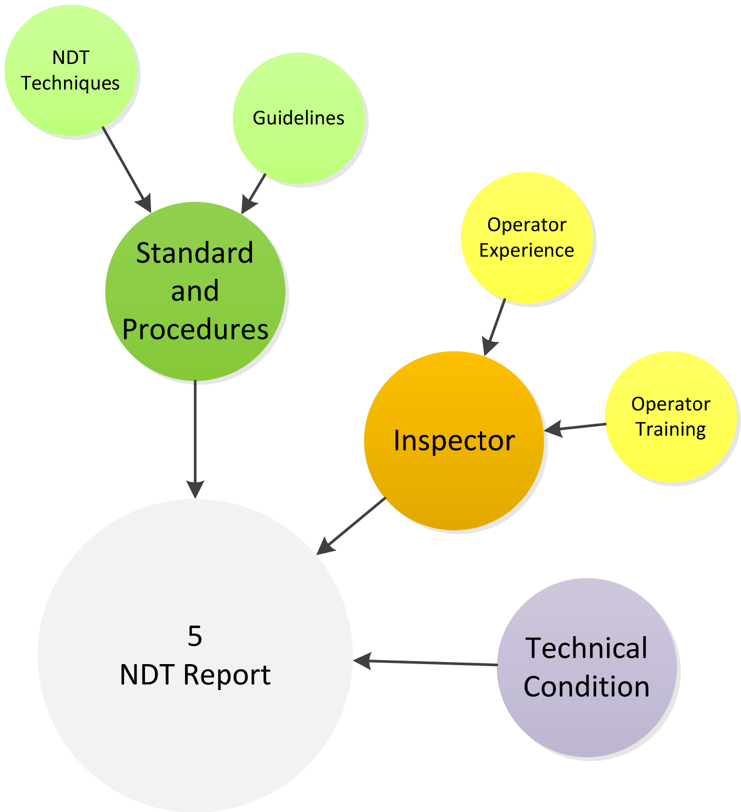


Figure 49 - Elements that Influence NDT Report

Other elements that are also linked with inspector's image sizing capability are the characteristic of defect and test object (Schneider and Bird, 2010). A thicker plate, for example, could lead to sizing errors where the inspectors tend to misinterpret large defects (Schneider and Bird, 2010).

Information that should be reported from a test result is usually formulated by the organization, while the governing standards are giving guidelines for the least information that should be reported. In this action group, the inspector is responsible to register the NDT result to the designated media (software).

In general, information regarding the test objects, equipment being used and result of the image interpretation are mandatory (EN, 1994, EN, 1999, EN, 2012). And whenever possible, the NDT image should be attached in the report.

From five previous figures, there are similar pattern on the influencing elements. All of the groups are influenced by more than one similar element. If we separate these elements from the action groups, we could draw relation between them as shown at the figure 36.

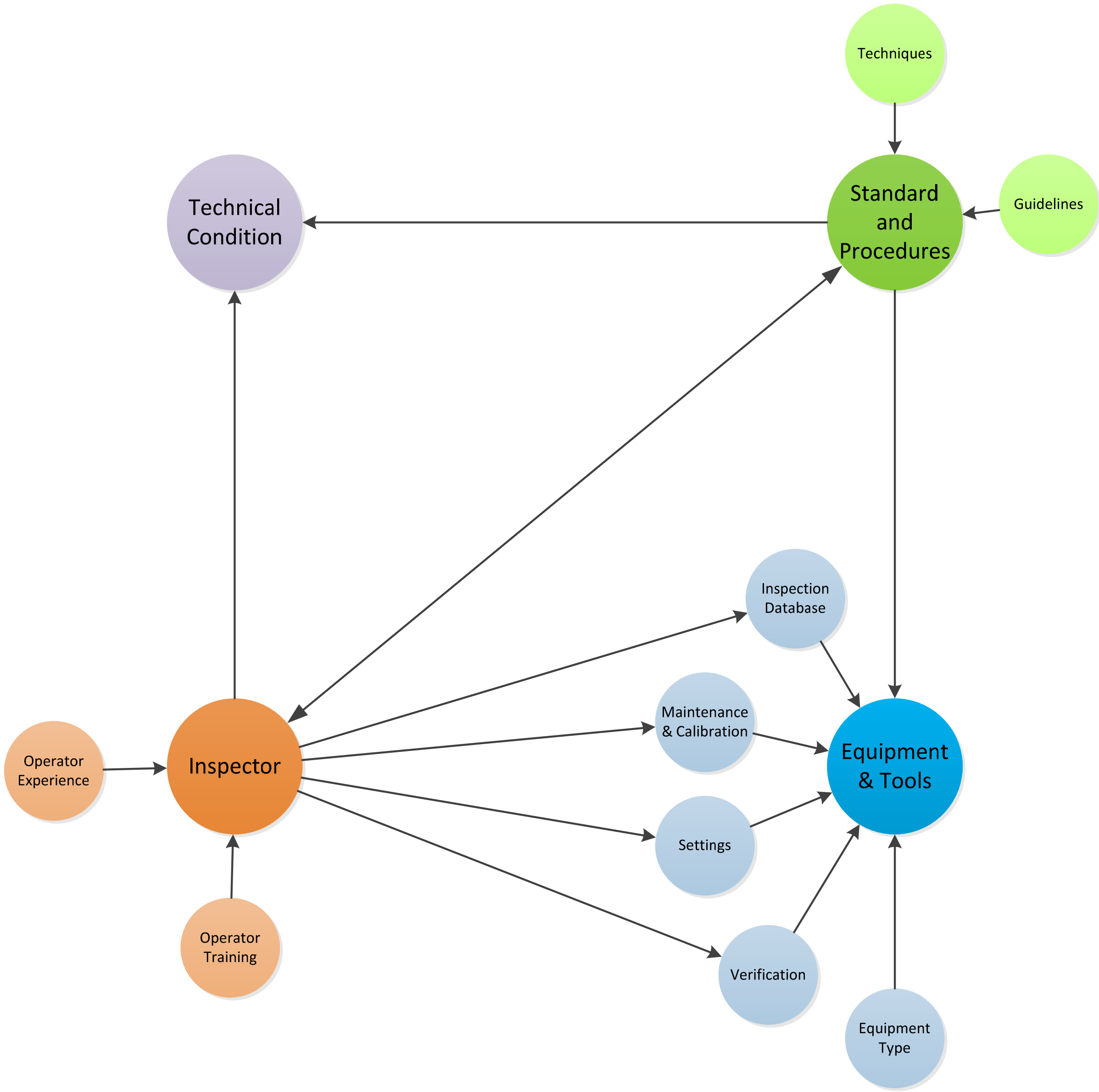


Figure 50 - Relationship between the Influencing Elements

After assessing the major elements, there are four main elements that influenced NDT result; governing documents, inspector's experience and training, equipment and technical condition as shown on Figure 37.

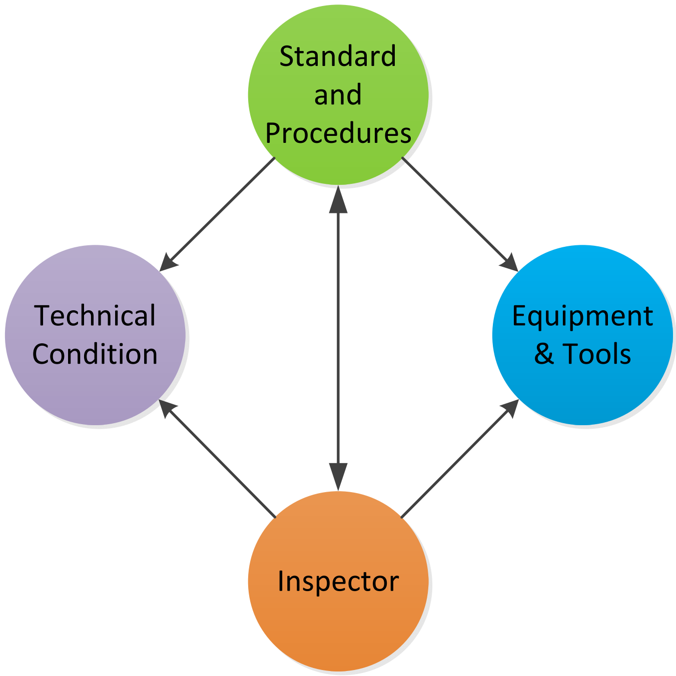


Figure 51 - Four Main Elements Affecting NDT Result

5.4.2 Major Elements Affecting NDT Result

From four elements, two of them have more influence to the NDT result. Equipment and Tools along with Technical Condition are passive elements that not actively influencing the process. On the other hand, Standard and Procedures as well as Inspectors are actively influencing the process of generating NDT report.

The table below briefly outlined the main elements that have affected NDT result, both in passive and active means:

Table 32 - Major Elements Affecting NDT Result

Elements	Role on NDT Result
Governing Documents	Governing documents has significant influence amongst others, since it has the utmost relationship with other elements. NDT practices are controlled by regulating standards and organization's procedures. These governing documents provide guidelines for inspector's qualifications, equipment requirements, preparation for test object and the NDT techniques. In more specific level, NDT procedures are derived from governing document and act as practical guideline for NDT practices. Besides NDT related documents, procedures that intended for the use of equipment, tools and inspection database shall be defined. Thus, standardization of inspection result and controlled over NDT process could be achieved.

Table 32 - Major Elements Affecting NDT Result

Elements	Role on NDT Result
	Overall, based on our investigation, it is important to outline guides related to: 1. Guidelines for NDT Practices, 2. Guidelines for NDT Techniques, 3. Personnel Qualifications, 4. Standard for NDT reporting, 5. How to use Inspection Database, and 6. Inspection planning procedure. Besides that, best practice and lesson learned documents are also useful for knowledge transfer. The technical library was also found to be outdated and procedures were not updated accordingly, thus it is advantageous to have annual review for the procedures.
NDT Inspector	Inspector (operator) has an active role for the testing; starting from assessing the technical condition, fitting the necessary test arrangement, equipment and perform the test. Inspector carries task along the NDT process as the executor of NDT tasks, interpreter of NDT result and reporting the end result. Error could also root from familiar NDT task that has become routine, known as skill-based slips and lapses (Rasmussen, 1983, Reason, 1990, Marsden and Hollnagel, 1996). A refreshment course or posters that could help Inspector to memorize the NDT process would aid to mitigate the error.
Equipment and Tools	Equipment and their settings are crucial for NDT techniques and administered by governing standards. But the operation and maintenance of NDT equipment are fully controlled by inspector. Thus, the performance of equipment is greatly depending on the inspectors (operator). We have included inspection database platform in this category, since it is part of inspection tool. In this research, we found that the software could be the cause of error due to incorrect engineering information it carries. In this case, the initial engineering data would need to be reviewed and change accordingly.
Technical Condition	Technical condition, similar to equipment, has passive influence on the process of non-destructive testing. But the characteristic of defect and test object would determine the NDT technique and has proven to influence Inspector's image interpretation.

5.5 CONSEQUENCE ANALYSIS: INFLUENCE TO INTEGRITY OF AGEING OIL AND GAS ASSETS AND QUALITY OF TECHNICAL ANALYSIS

The direct effect of data anomaly is in the reliability of inspection data, and furthermore the application that uses the data.

The data are mainly being used for RBI analysis, degradation analysis, remaining wall thickness analysis, planning for future inspection and overall technical condition analysis of the system.

In section 3, we have previously discussed that NDT inspection goal is to manage the integrity of pipe system, and is part of integrity assessment of current technical condition. Data with noise may be misleading and thus, the analysis result would be unreliable. Since these analyses depend greatly to the inspection data, if goes untreated, the data anomaly will affect the integrity of inspection planning and pipe inspection, and consequently affecting the integrity of the pipe system.

As we can see in the figure below that was taken from section 3, inspection data plays important role in the cycle of inspection planning process.

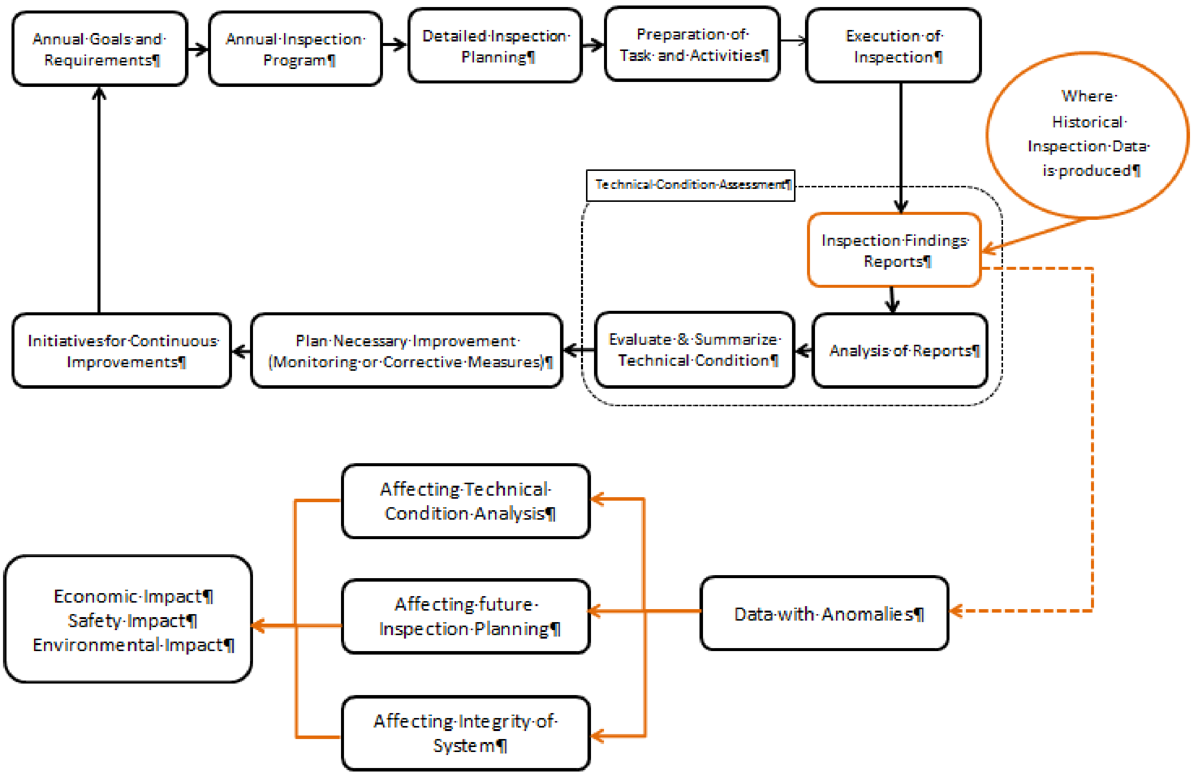


Figure 52 - Impact of Inspection Data With Anomalies

5.6 RISK DETERMINATION

As shown in figure 44, fail NDT reports could give economic impact by means affecting the maintenance cost, especially with aging platform. For example, when false indication arises few follow-up scenarios could occur; a) the inspection point is planned for re-inspection, b) the condition is worse than stated and might lead to downtime, or c) the inspection is considered as noise or error, thus will not have value; all these scenarios may leads to more inspection cost to replace or to follow-up the fail report.

In relation to environmental and safety, the anomalies could be misleading to the technical condition analysis. A defect could be undetected and lead to leakage, which in the case of flow line, could be dangerous for personnel safety and environment.

Aging platform has more carbon steel pipe than newer platforms, the remaining pipe has also degraded and closer to their end life. Besides these challenges, NDT inspections for aging platform are usually done manually. This is due to the old infrastructure of platform; make it more challenging and expensive to install automatic monitoring. Manual NDT inspection is more costly due to the high expense of manpower in Norway. Thus, NDT inspection needs to be done effectively and efficiently to prevent re-inspection or fail report.

5.7 RISK TREATMENT

During our investigations and analysis, we recorded several suggestions to mitigate the possible risk of unreliable inspection data. To accomplish this, it is necessary to take action from the root cause, which equals to the cause of data anomalies.

Table 33 - List of Suggested Approach to Mitigate Risk

Target	Recommendation	Suggested Approach	Description
Governing Documents	Providing comprehensive guidelines for personnel involved in NDT inspection.	▪ Assessing additional need of procedure ▪ Improvement and review of existing procedures in timely manner.	By providing appropriate guidelines, there are several errors that could be prevented, especially related to NDT techniques and operation and maintenance of equipment and software. From previous finding section, we discovered that there are need to create additional procedure and reviewing existing procedures. Amongst of procedures that need to be review are: a) NDT procedure to be revised to add more specific instructions (for example to insert coordinate, to not allowing null value and to take last inspection value as alternative or else declare that inspection is cancelled). b) NDT procedure to be updated to include new standards, especially ISO 13588:2012, Non-destructive testing of welds - Ultrasonic testing - Use of automated phased array technology. c) The technical library was also found to be outdated and procedures were not updated accordingly, thus it is advantageous to schedule tasks of reviewing procedure and related standards in timely manner. Meanwhile, governing documents that need to be in place are: a) Inspection planning procedure to be created to provide guidelines for Inspection Planners. Which the procedure would also instructs to include inspection coordinate in the planning, b) Procedure to guide NDT Inspectors in how to use NDT software,

Table 33 - List of Suggested Approach to Mitigate Risk			
Target	Recommendation	Suggested Approach	Description
			c) Procedure that outline standard for NDT reporting, d) Reminder-posters those are easy to be noticed. Such as posters of NDT techniques or equipment maintenance. Besides that, best practice and lesson learned documents are also useful for knowledge transfer.
Human Factors (NDT Inspectors)	Improve quality of NDT results.	▪ Raise awareness of the importance of quality, ▪ Refresher course for NDT Inspectors ▪ NDT posters ▪ Procedures in place ▪ Continuous developme nt campaign	Rasmussen (1983) suggested skill-ruled-knowledge (SRK) framework that categorized human cognitive control mechanism corresponds to decreasing levels of familiarity with the environment or task; they are: ▪ skill-based behaviour (error without conscious control), ▪ rule-based behaviour (error structured by feed-forward cognitive control), and ▪ Knowledge-based behaviour (error is goal-controlled and knowledge-based). As later known, all of the NDT Inspectors working on entire three platforms are equipped with required skill, expertise and experiences. With relation to Rasmussen's SRK framework, we could suggest that the error came from personnel are most likely skill-based slips and lapses. Slips and lapses arose from routine actions which personnel are familiar to. There are two type of errors originated from skill-based behaviour, they are error of execution (slips) and memory storage failure (lapse) (Reason, 1990). Thus to prevent this type of 'automated' error, personnel need to be constantly reminded of operation procedures to prevent deviation of action from the initial intention. Suggested approaches are similar to previous point, which is to make guidelines and easily access procedures and posters to the NDT personnel. Personnel would also need

Table 33 - List of Suggested Approach to Mitigate Risk

Target	Recommendation	Suggested Approach	Description
			to be regularly reminded to improve work quality as a continuous development. In additional, refreshment courses should also be an option when needed.
Inspection Database	Cleaning of NDT Inspection data	Establish a tool (computer program) to clean the data from anomalies before being analysed.	The simplest solution to this challenge is to establish an additional tool to distinct unhealthy data from the rest. The unhealthy data could then be analysed individually to determine further action. The program should also be able to store record of unhealthy data and follow-up actions, to prevent repetition of task. The cleaning of data shall handle the following: 1. Abnormal deviations in measurement data 2. Changes in wall thickness 3. Changes in corrosion rate 4. Cancelled inspections
	Revamp false engineering data	To review and amend false data accordingly.	From our experience, we could conclude that data quality plays more important role than the type of software. This is often a challenge for aged platforms due to the limited availability of information. In average, 2.99% of engineering data are not according to field condition. A false data could lead to false reporting, because the original wall thickness would be used as the basis thickness measurement. But even that, rebuilding the engineering database will be the last resort due to the high cost. One of alternative is to have cooperation between inspectors and inspection engineers and allocate designated personnel to repair the data simultaneously after anomaly is discovered. Naturally, the information need to have supporting data and the action is recorded and documented for reference. The process below could be taken as

Table 33 - List of Suggested Approach to Mitigate Risk

Target	Recommendation	Suggested Approach	Description
			example and implemented when applicable :  Figure 53 - Revamping Engineering Database
	Applying Sizing Tolerance	Apply sizing tolerance technique on measurement result	To anticipate the unreliability of data, sizing tolerances shall be implemented to acquire a possible variation of results, thus producing a range of possible results. DNV (DNV, 2010b) has similarly outlined the idea to be implemented as statistical model. Assuming NDT measurement data is normal distributed, the approach determine confidence level to establish standard deviation (σ) of measurement value. Alternative approach is to increase the number of standard deviation to increase the confidence level (Westwood and Hopkins, 2004), i.e. with three sigma rule as shown on figure X.

Table 33 - List of Suggested Approach to Mitigate Risk

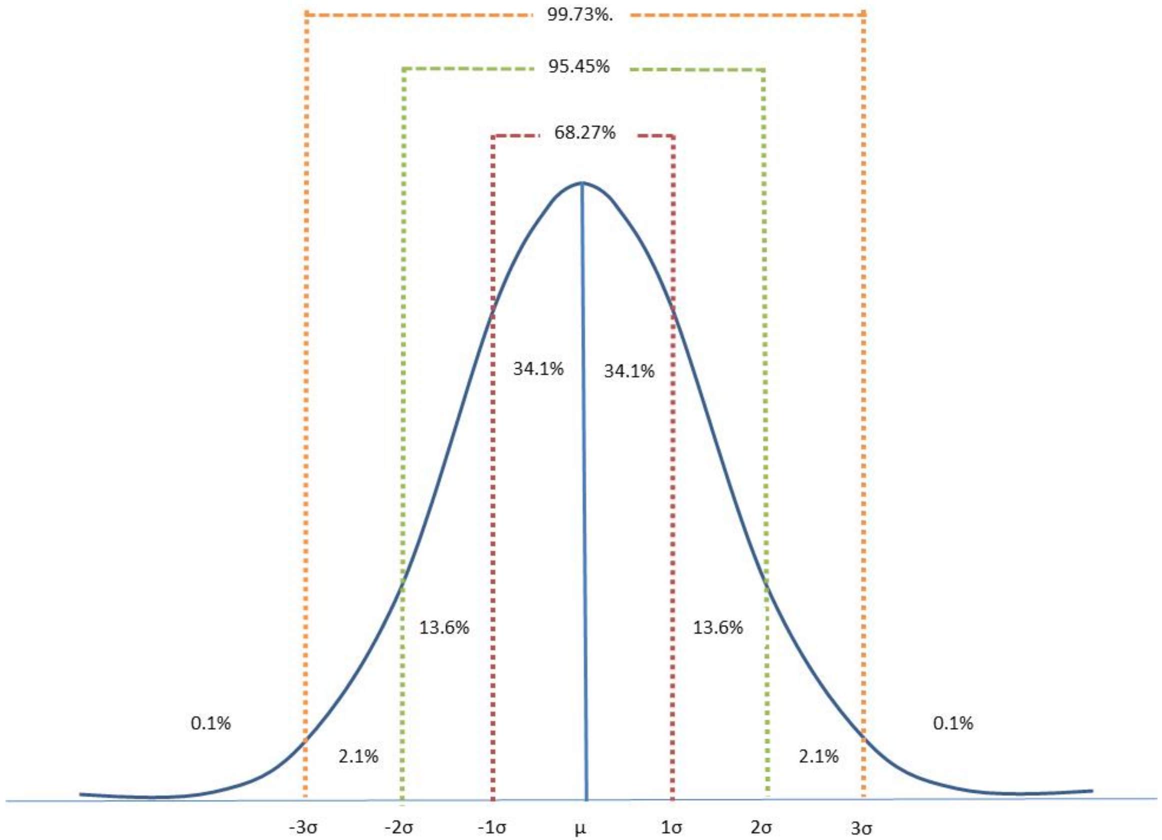
Target	Recommendation	Suggested Approach	Description
			 Figure 54 - Three Sigma Rule of Normal Distribution (Westwood and Hopkins, 2004)

Table 33 - List of Suggested Approach to Mitigate Risk

Target	Recommendation	Suggested Approach	Description
			Westwood and Hopkins (2004) relates standard deviation (σ^2) of measurement with the confidence level and give estimation of possible measurement range. For example, if x_i denotes the ith measurement taken on an inspection point with standard deviation of σ^2, then the true measurement is in the range between (Westwood and Hopkins, 2004): $$[x_i - (3 \times \sigma^2)] \leq \; xi \; \leq [x_i + (3 \times \sigma^2)] \qquad \textit{(Eq. 5)}$$ From here we could utilize the percentage of error from previous section (5.2). Since the reliability of data-set (h_i) would give estimation that a certain number of measurement are acceptable, it shall express confidence level of the data set (*see definition*). For example, the analysis result of Bend on Case study A shows 7.40% of error, which would fall on 95.45% confidence level within the normal distribution. Thus, the true measurement range can be decreased into two standard deviation: $$[x_i - (2 \times \sigma^2)] \leq \; xi \; \leq [x_i + (2 \times \sigma^2)]$$
	Applying reliability result on application of data	Estimates probability of error on data set and utilize it for data application	The analysis result presented on section 5.1 estimates the probability of error on the data-set. The presence of error on data-set would affect the application of data, for example when the data set is used to determine degradation rate or technical conditions. To minimize the error effect, several recommendation to implement standard deviation onto data analysis such as degradation rate has been heavily discussed on analysis of pigging data (Alamilla and Sosa, 2008, Pandey and Lu, 2013). Similar methodology could also be applied in the case of manual NDT measurement. Common degradation rate calculations are typically attained from two or more

Table 33 - List of Suggested Approach to Mitigate Risk			
Target	Recommendation	Suggested Approach	Description
			measurements within period of time. If x_i denotes the ith measurement taken on an inspection point, and t_i denotes the time when inspection was taken. Then the degradation rate (r) can be determined from two different inspection as shown on E*q. 6* (Pandey and Lu, 2013). $$r_i = \frac{x_i - x_{i-1}}{t_i - t_{i-1}} \quad \textit{(Eq. 6)}$$ However, Equation 6 can only be applied on ideal state where there is no anomaly present, i.e. $X_i = X_{i-1} = 1$ (see 5.2). In condition where anomaly is present, the anomaly at the ith measurement (E_i) shall be subtracted to x_i to generate the actual measurement (y_i): $$y_i = x_i + E_i \quad \textit{(Eq. 7)}$$ Thus the actual degradation rate (r_{mi}) would deviate from Equation 6 (see Eq. *8*). $$r_{mi} = \frac{y_i - y_{i-1}}{t_i - t_{i-1}} \quad \textit{(Eq. 8)}$$ From previous section (5.2.), we gather information of the error percentage from various data-set. The percentage of error expresses that a certain number of measurement contain anomaly and would estimate the unreliability (g_i) of the data-set (see Eq. 4). We have also discussed that the reliability and unreliability of the data-set are equivalent to the probability of the state of data [$\phi(X)$] (Aven, 1992): $P[\phi(X) = 1] = \text{Reliability of data-set, and}$ $P[\phi(X) = 0] = \text{Unreliability of data set}$

Table 33 - List of Suggested Approach to Mitigate Risk			
Target	Recommendation	Suggested Approach	Description
			Thus, the unreliability of data-set (g_i) would estimates the probability of error of the respected data-set, i.e. $P[\phi(X) = \phi]$. The estimation of sizing error (*E*) for the respected data-set would be equivalent to the unreliability of the data-set, i.e. $P[\phi(X) = g_i = E]$. Then the error sizing for specific measurement can be written as in Equation *9*. $E_i = g_i \times r_i$ *(Eq. 9)* According to Westwood and Hopkins (2004) the distribution of measurements error during inspection is normally distributed. Then we can estimate the range of actual measurement (y_i) as in Equation *10*. $(x_i - E_i) \leq y_i \leq (x_i + E_i)$ *(Eq. 10)* Further, since the value of g is constant for specific data-set, this indicates that $g = g_i = g_{1+i} = g_{i+n}$, which gives us the estimation of error on the actual degradation rate (E_{mi}) as in Equation *11*. $E_{mi} = g_i \times r_{mi} = g_i \times \frac{x_i - x_{i-1}}{t_i - t_{i-1}}$ *(Eq. 11)* Then the variance range for degradation rate can be modelled as on E*quation 12.* $\left(\frac{x_i - x_{i-1}}{t_i - t_{i-1}} - E_{mi}\right) < r_{mi} < \left(\frac{x_i - x_{i-1}}{t_i - t_{i-1}} + E_{mi}\right)$ *(Eq. 12)*

6.0 CONCLUSION

This chapter will outline the main conclusions of this research, research contribution, and suggestions for further researches.

6.1 CONCLUSIONS

Concluding our discussions on previous chapters, this research has generated the following results:

- Mapping of NDT processes.
- Analysis of topside flow-line pipe defects.
- Reliability analysis of topside flow-line NDT Inspection on aged platform.
- Integrity assessment of topside flow-line inspection.
- Risk analysis of topside flow-line NDT Inspection on aged platform.
- Cause of Error Analysis.
- Suggestion to mitigate the risk of unreliable inspection data.

With the generated result, the following can be concluded from the topside non-destructive testing:

- Reliability of each case study generates results varying from 5% anomaly to 20%.
- The main causes of error are; governing documents, human factor, equipment and tools, and technical condition of inspection point.
- Reliability of inspection data possess variable of influence upon integrity of piping inspection.
- Within the study case of aged platform, unreliable inspection data could lead to economical loss, safety and environmental loss.
- There is a need to improve inspection data directly onto database and also through improvement of inspection practices.

This research has also generated the following result:

- How data could affect performance output.
- That pipe geometry and inspection coordinates could influence NDT result.
- That human error on NDT Inspection could be categorized as skill-based error.

6.2 RESEARCH CONTRIBUTIONS

This research has contributed the following result:

- Root cause analysis of cause of error on NDT Inspection data
- Suggest method to quantify inspection data error
- Suggest analysis steps for inspection data reliability
- Reliability case study of topside flowline pipe system on aging platform
- Research thesis for educational purposes
- Research thesis that can assist Users to quantify data reliability
- Research thesis that can assist Users to investigate root cause of data error

6.3 SUGGESTION FOR FURTHER RESEARCHES

Due to limited time and tools of research, there are subject that are not covered in this thesis. Thus, we encourage future studies on the following topics:

- Validation and study case of calculation presented on the Risk Treatment (5.7.).
- Development of methodology for optimization of NDT process
- Analysis of Human Factor analysis of NDT process
- Analyze relationship and significance of pipe geometry to NDT inspection
- Development of inspection technique for T-joints and pipe branches.

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APPENDIX A – PAPER

Reliability Analysis of Condition Monitoring Data on Aging Plants: A Case Study From Topside Static Mechanical Systems

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Abstract- **The quality of static mechanical systems' integrity control process on aging oil & gas production and process plants (P&PPs) depends on the accuracy of the condition monitoring data. This is especially the case since accurate interpretation of the data could significantly aid the right decision-making at the right time in the right location. However, anomalies have been observed in the historical in-service inspection data records pertaining to most aging plants under study. Such anomalies result in sub-optimal inspection decisions and jeopardize the quality of an in-service inspection program. The uncertainties of condition monitoring data have been discussed in the literature and industrial community over the years. A number of approaches have been proposed to address the various challenges pertaining to uncertainties present in the in-service inspection data. This manuscript suggests an empirical approach for quantifying the reliability of condition monitoring data to estimate the level of anomalies present in the in-service inspection data and to investigate the source of these anomalies. A case study has been carried out using three different P&PPs functioning on the Norwegian Continental Shelf. The flowline system of each plant has been selected as that has been given highest risk priority.**

Keywords - ***Integrity control aging platform, NDT, in-service inspection data reliability, condition monitoring***

I. INTRODUCTION

Past experience has revealed that the quality of data records plays a vital role in the inspection and maintenance of oil and gas (O&G) assets. For instance, the level of the quality of data records determines the extent of benefits as well as potential damage to the processed data (i.e. information) [1]. Furthermore, the quality of data (prior knowledge) directly or indirectly influences the output (performance) of the corresponding data application. Hence, it is vital to develop approaches to analyze the quality of the existing data.

The challenges pertaining to the quality of data are further exacerbated in aging P&PPs. For instance, it has been observed that the in-service inspection data records regarding P&PPs indicate a significant level of anomaly. This has been due to various reasons such as, insufficient data resulting from modifications (i.e. due to the fact that after a modification the stored data may have been removed), the human error made during the inspection, evaluation of inspection results and recording, etc. Hence, data records present in aging P&PPs need to be analyzed to estimate the reliability.

In this study, the topside flowline systems of three P&PPs have been selected, as the flowline system indicates a high level of Consequence of Failure (CoF) and Probability of Failure (PoF) in RBI analysis (i.e. considered to possess a high threat regarding personal safety, potential loss of production and environmental damage). This is mainly due to the inherent characteristics and consequences such as such as 3-phase (e.g. oil, gas, water and sand) product (i.e. unprocessed hydrocarbon directly from the reservoir), and potential degradation (i.e. erosion and corrosion) [2]. A flowline system basically includes a pipe system on the top side of platform that gathers and transfers the well stream, starting from the individual wellhead (Xmas tree) to the downstream systems (up to production manifolds) [2, 3]. In the flowline system, historical data and experience reveal that the probability of failure is high, particularly due to carbon steel piping. However, piping with duplex material is also considered to have a certain probability of failure due to erosion, stress corrosion, cracking, etc. The situation becomes worse when modifications have been introduced in between carbon steel piping with stainless steel components (i.e. due to galvanic corrosion). Hence, non-destructive testing (NDT) techniques have been introduced to perform in-service inspections. The NDT inspection recommendations are planned based on the data records available in the existing information system of the respective operator company. Hence, it is vital to study the level of inaccuracy present in the recorded data in order to optimize the condition monitoring activities to maintain the integrity of the flowline system.

This manuscript proposes an approach to quantify the reliability of data records (i.e. NDT data) pertaining to the topside flowline system of an aging platform. Furthermore, it investigates the primary cause of errors. A case study has been carried out utilizing three different aging platforms functioning on the Norwegian Continental Shelf (NCS). However, the data records are only available from the middle of the 1990s, although all three platforms were built in the late 1970s or early 1980s. Data analysis has been carried out on thickness measurement locations (TMLs) [i.e. hot spots such as workshop welds, field welds and pipe bends], which have been defined by RBI analysis or plant inspection strategy as areas with potential defects.

II. BACKGROUND

A. Characteristics of Aging Platforms

The lifetime of an asset is estimated at the initial design stage as a guideline for making lifecycle plans and to satisfy design requirements. The failure rate of assets continuously increases over time due to several factors such as inherited defects from manufacturer/fabrication, potential degradation mechanisms and operating conditions. The increasing failure rates due to the age of operating assets are mitigated through proper preventive measures such as repair, inspection and maintenance. However, in the late-life of operating assets, the demand for preventive measures becomes more frequent in order to maintain asset integrity, which may not be economically justifiable. Hence, it is vital to determine the extent and rate of the degradation quantitatively, making an estimate of the remaining life or extending the operating life of the assets [4].

B. Topside Flowline Degradation Mechanism

In general, the main defects or anomalies present in the piping components are attributed to metal loss, material defects and external mechanical damage [5]. The challenges of maintaining flowline are mainly dependent on product characteristics. The flowlines which have been made of non-stainless steel materials in the aging platforms pose additional challenges. In most of aging platforms, critical sections of flowline segments (e.g. hook-up spool) have been upgraded using noble materials (e.g. 6MO, duplex, etc.). However, such modifications exacerbate the challenges, for example, necessitating monitoring for galvanic corrosion. Fig. 1 illustrates the factors affecting the degradation of topside flowlines [6].

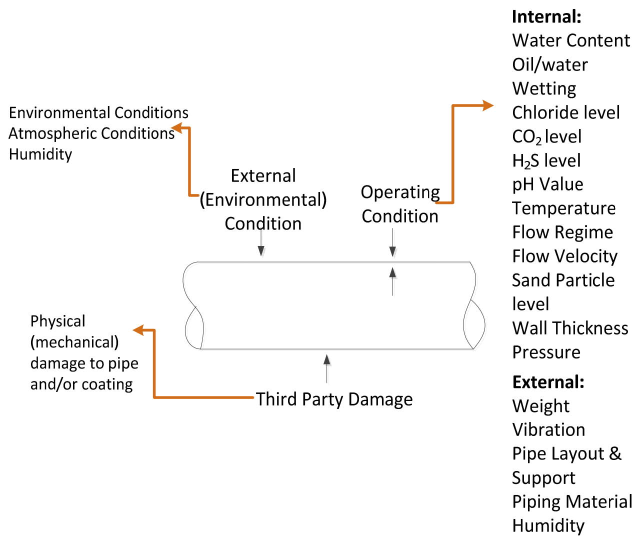

Fig. 1. Factors affecting the degradation of topside flow line systems [6].

III. ASSESSMENT OF DATA

A. Data Collection

The NDT measurement records (also referred to as historical data) were collected from the piping inspection database (PIDB) available in the P&PP owner's data management system. Fig. 2 summarizes the data (i.e. primary and secondary) and information collection sources which have been utilized in this study.

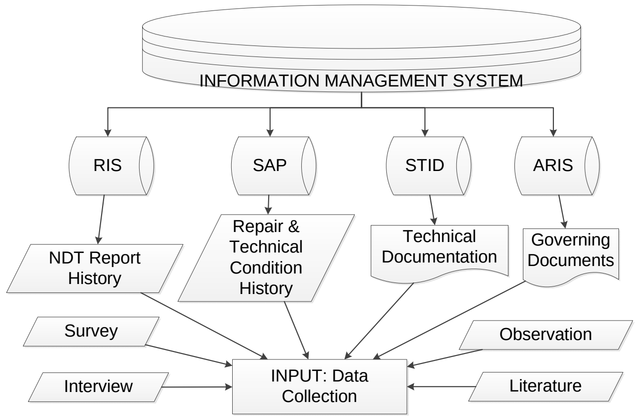

Fig. 2. Data collection sources.

The primary data have been retrieved from internal sources [i.e. the enterprise resource planning (ERP) system], whilst secondary data have been retrieved from external sources (surveys, interviews, observation and literature). The different software that has been utilized includes: RIS, SAP, STID and ARIS. Whereas RIS and SAP have been employed to retrieve NDT measurement records and reports to investigate the history of the technical condition, STID has been utilized to retrieve technical documentation, and ARIS has been employed to retrieve governing documents.

B. Data filtering and retrieval

The collected data were in raw format. Hence, they were organized and classified to a level sufficient to perform analysis. Basically, the data were classified focusing on the study objectives (i.e. to study the anomalies present in the NDT measurement records). The aforementioned enabled simplification of the analysis and avoided noise affecting the end results. Fig. 3 illustrates the primary and secondary data retrieval process adopted in this study.

Following the data retrieval process illustrated in Fig. 3, the collected data are assessed and filtered to avoid noise and unwanted data into several data-sets. The data are filtered into the most commonly used NDT techniques on the selected three P&PPs, which comprised of Radiography Testing (RT) and Ultrasonic Testing (UT).

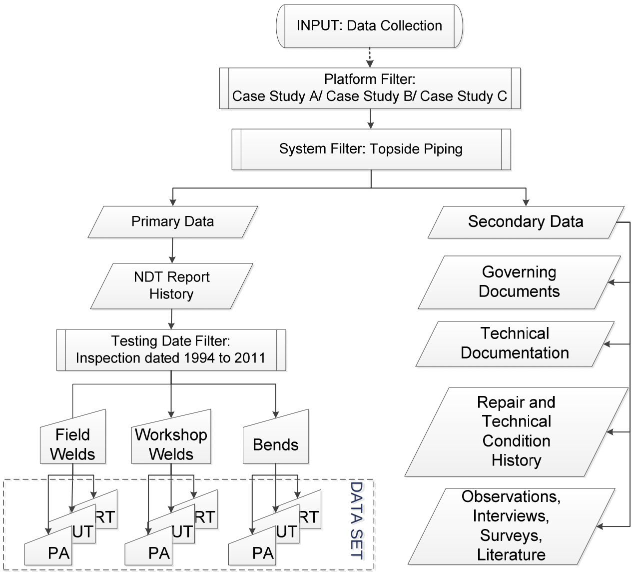

Fig. 3. Primary and secondary data filtering and retrieval process.

C. *Analysis of Data*

The purpose of the analysis is to estimate the anomalies present in the NDT measurement records available in the PIDB. Essentially, if an NDT measurement is carried out, evaluated and interpreted as intended (i.e. as specified by the procedures, standards and regulatory authorities) by competent personnel, then it shall be accurate. However, human and organizational error dominates and is reflected as anomalies present in the NDT records in this process [7, 8]. The observed anomalies in the collected NDT measurement records are as follows:

- Data value is null
- Measured wall thickness ($T_{measured}$) is larger than recorded wall thickness ($T_{nominal}$) which is given in (1).

$$T_{measured} > T_{nominal} \quad (1)$$

  Note: In some cases, the existing values of $T_{nominal}$ in the PIDB are not in accordance with the physical configuration. It is possible to retrieve this information from the NDT measurement records under the comments field. There are other instances where $T_{nominal}$ indicated in the iso-metric preventive maintenance (PM) drawings and PIDB are not same.
- The values of $T_{measured}$ for the same TML shall be identical or decline over time, provided that there are no modifications performed on the corresponding piping segment (2).

$$T_{m1} \geq T_{m2} \geq T_{m3} \geq \ldots \geq T_{mn} \quad (2)$$

where

$T_{mi} = T_{measured}$ at i^{th} inspection

T_{mn} = the last $T_{measured}$ taken

In general, anomalies present in two ways: (1) due to an error during the NDT inspection and recording; (2) due to an existing errors in the PIDB or PM iso-drawings. Fig. 4 illustrates the data analysis approach employed in this analysis.

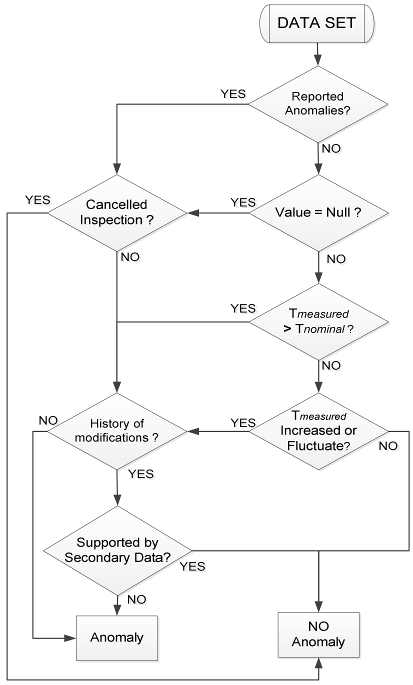

Fig. 4. Data analysis process flowchart.

IV. ANALYSIS RESULT

A significant amount of time and effort are allocated to isolating the anomalous data from the raw data retrieved from the PIDB. The analysis procedure is composed of two approaches: (1) automated analysis using the Microsoft Visual Basic for Applications (MS VBA) and (2) manual data handling (i.e. reading comments, checking against secondary data, etc.), which aim to cover all information produced by the reports and other data sources.

A. *Percentage of Anomalies*

In essence, the total number of anomalies existing in the selected number of NDT records was counted and the percentage of anomalies was calculated. The results of the NDT data analysis are shown in Table I, Table II and Table III.

TABLE I
PERCENTAGE OF ANOMALIES FOR FIELD WELDS

NDT Method	Case Study A	Case Study B	Case Study C
RT	9.16%	13.89%	15.53%
UT	20.95%	21.41%	15.42%

Total	10.31%	17.49%	15.44%

TABLE II
PERCENTAGE OF ANOMALIES FOR WORKSHOP WELDS

NDT Method	Case Study A	Case Study B	Case Study C
RT	8.90%	13.00%	18.77%
UT	12.21%	22.61%	17.10%
Total	9.18%	16.12%	17.92%

TABLE III
PERCENTAGE OF ANOMALIES FOR BENDS

NDT Method	Case Study A	Case Study B	Case Study C
RT	5.15%	13.50%	19.53%
UT	14.64%	17.61%	10.00%
Total	7.40%	13.85%	19.39%

The results reveal that a significant number of anomalies are present in the collected data. Hence, data are not sufficiently reliable for making inspection recommendations.

B. Interpretation of Results

The reliability of data has been estimated using the calculation procedure suggested in [9]. Based on the aforementioned approach, each data-set can be distinguished into two states: (1) ideal state [i.e. all the data satisfy as 'No Anomaly' (ref.Fig.4)], and (2) imperfect state [i.e. all the data satisfy 'Anomaly' (ref.Fig.4)].

where
φ = the state of the selected NDT measurement data-set
n = the amount of NDT measurement records in the selected data-set
X_i = binary variable to represent the state of the i^{th} individual NDT measurement record

Then the state of the i^{th} individual NDT measurement can be distinguished into:

$$X_i = \begin{cases} 1, & \text{if all the data satisfy as 'No Anomaly' (ref. Fig.4)} \\ 0, & \text{if all the data satisfy as 'Anomaly' (ref. Fig. 4)} \end{cases}$$

Assuming that the state of the selected NDT measurement data-set is dependent on the state of each individual NDT measurement record, the state of the selected NDT measurement data-set becomes [see (3)]:

$$\phi = \phi(X) \quad (3)$$

where
X = $(X_1, X_2, X_3, \ldots, X_n)$
$\phi(X)$ = the state of X

If P denotes probability, then the reliability and unreliability of the NDT measurement records [see (4)] are given by [9]:

$P[\phi(X)=1]$=reliability of the selected data-set

$P[\phi(X)=0]$=unreliability of the selected data-set

Then the state of the data-set equals to (4):

$$P[\phi(X)=1] + P[\phi(X)=0] = 1 \quad (4)$$

Further, we can write the reliability of the data-set as:

$$P[\phi(X)=1] = 1 - P[\phi(X)=0] \quad (4.1)$$

Tables IV, V and VI illustrate the reliability of NDT measurement records for: field welds, welds carried out under controlled conditions (i.e. workshop welds), and bends, respectively.

TABLE IV
DATA RELIABILITY FOR FIELD WELDS

NDT Method	Case Study A	Case Study B	Case Study C
RT	0.9084	0.8611	0.8447
UT	0.7905	0.7859	0.8458
Total	0.8969	0.8251	0.8456

TABLE V
DATA RELIABILITY FOR WORKSHOP WELDS

NDT Method	Case Study A	Case Study B	Case Study C
RT	0.9110	0.8700	0.8123
UT	0.8779	0.7739	0.8290
Total	0.9082	0.8388	0.8208

TABLE VI
DATA RELIABILITY FOR FOR BENDS

NDT Method	Case Study A	Case Study B	Case Study C
RT	0.9485	0.8650	0.8047
UT	0.8536	0.8239	0.9000
Total	0.9260	0.8615	0.8061

V. DISCUSSION

The study carried out in this manuscript reveals that the reliability of NDT measurements (i.e. of the flowline systems) is not satisfactory in the selected offshore P&PPs. The reasons for unreliable NDT measurement records are mainly due to four influencing factors: (a) standards and procedures, (b) human factor (NDT inspector), (c) equipment and tools, and (d) technical condition. The interrelationships between the influencing factors are illustrated in Fig. 5.

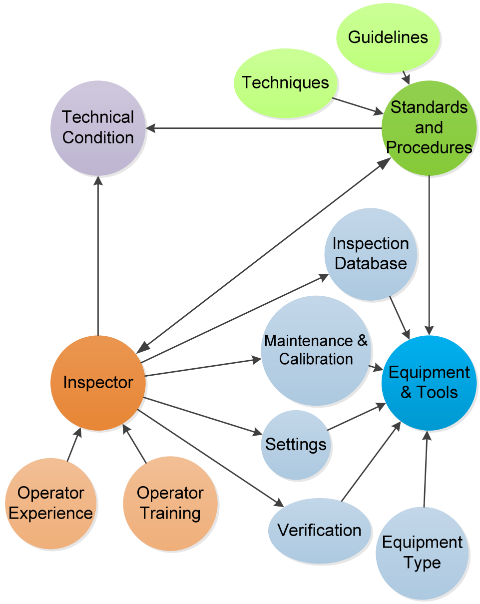

Fig. 5. Relationship between the influencing elements.

Among the four variables, two indicate active influence (i.e. standards & procedures and NDT inspectors), and the other two indicate passive influence (i.e. equipment & tools and technical condition). The current study and other related studies [10] also revealed that the characteristics of defects and test objects, such as complex geometry, manufacturing tolerance, size of defects, etc., also influences the inspector's image interpretation. However, the anomalies caused by NDT inspectors could also be derived from familiar NDT task that have become routine, known as skill-based slips and lapses [11, 12].

VI. CONCLUSION

Condition monitoring of aging P&PPs is vital to mitigate potential HSE issues. From the P&PPs' owners' point of view, it is essential to have approaches to perform inspection of their operating assets at an economically viable level. This manuscript illustrates an approach to estimate the reliability of NDT measurement records. It is vital to know the dependability of existing data in order to make reliable future inspection recommendations as well as to assure the quality of an inspection program.

Future studies should be carried out to estimate the integrity of operating assets based on the reliability of existing data.

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