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Evaluating Non-Destructive Testing (NDT) Methods used for the Inspection of Flowlines on Offshore Production Facilities

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Stavanger, June 2011

Sina Zahirian

This thesis is dedicated to my fiancé, Sona, whose serenity and patience is boundless and has always stood by me and kept my spirits up during writing it…

Abstract

The importance and criticality of the processes and equipments within the Oil & Gas industry highlights the requirement for more reliable, available and maintainable production activities and facilities. These requirements can be fulfilled by prevention of failures through reducing the downtime and wastage of material. Besides, prevention of failures helps the companies to stay away from their unwanted catastrophic consequences. Therefore, having effective and efficient inspection and maintenance management programs seems to be of paramount importance to keep all these facilities in process. Among all the inspection methods, the use of Non-Destructive Testing (NDT) methods is increasing rapidly due to their remarkable advantages such as high quality, accuracy, flexibility, and etc. which are of interest for those who are involved with inspection and maintenance programs. All the advantages of NDT methods encourage companies to apply them for the inspection of flowlines which have the most criticality among all the processing equipments.

Among all NDT methods, Radiographic Testing and Ultrasonic Testing are among the most used ones for the inspection of flowlines. These methods are explained within this thesis to see their limitations, advantages and disadvantages. Thereafter, all NDT methods applied for the inspection of flowlines on offshore production facilities are evaluated to see which ones have had more accurate and reliable results. The frequency of these methods is also investigated in this dissertation. Aforementioned evaluations reveal the most important influencing factors that can affect the frequency and accuracy of each particular NDT method. Underlying reasons of some exotic results which companies may confront within their inspection plans and programs are also pointed out in this manuscript. All these factors and influencing parameters can be used in developing matrixes and frameworks for the selection of the proper NDT method(s) which should be used for inspection purposes. Some of the matrixes that are in-use by one of the leading companies in Oil & Gas industry are updated regarding the results of mentioned evaluations. The thesis is carried out with one of the leading engineering services providing companies located in the Norwegian Continental Shelf (NCF).

Contents

Introduction

Non-Destructive Testing (NDT) interchangeably known also as Non-Destructive Evaluation (NDE) has proven to be a cost saving and beneficial technique to be used in oil & gas industry. NDT is also interesting for those who are willing to improve their operations by decreasing downtime and final cost of product to be competitive in the global market. Hellier (2001) defines NDT at Non-destructive Evaluation Handbook as a test or evaluation performed on any kind of equipment to test the material integrity without changing its characteristics or destroying it in anyway. Any kind of defects and discontinuities within the material can affect its efficiency, maintainability and serviceability. A similar description of NDT defined by American Society for Nondestructive Testing (ASNT) is:

> "*The determination of the physical condition of an object without affecting that object's ability to fulfil its intended function*"

NDT can save millions of dollars for industries by reducing the failure related costs. NDT covers the inspection of almost all equipments in the oil & gas industry from storage tanks to pipes and from heat exchangers to valves and etc. For instance, NDT can help operators in order to make sure that a pressure vessel will withstand the calculated (designed) pressure and has the desired burst strength. This can be achieved without destroying the vessel or causing any harm on that. Besides, NDT can be used to determine the physical and mechanical characteristics of the material. For example eddy current testing can be used to measure the changes in the impedance of a carbon reinforced plastic composite in order to assess fibre volume fraction in it (Li et al., 2008). Estimating the grain size of the material using ultrasonic attenuation measurement can be another example of applying NDT for determining the physical characteristics of material (McClements, n.d.). Overall, NDT methods can be applied for:

- Thickness measurements (Crouzen et al., 2006; Baltzersen et al., 2007)
- Classification of materials (e.g. Magnetic Flux Leakage (MFL) can only be used for magnetic material) (Classifying into e.g. Magnetic, Plastic, Polymer, etc.)
- Assessment of the chemical composition (changes in chemical composition caused by e.g. corrosion can change the material response to the NDT test)
- Evaluation of surface characteristics
- Determining areas with high stress concentration (Zhang and Yang and Xu, 2009)
- prediction of material behaviour
- etc.

Non-destructive testing can be used for various purposes on offshore processing facilities including: structural inspection, weld and surface inspection, inspection of insulation or the corrosion under insulation, inspection of lifting equipment and finally all the static offshore equipment (vessels, pipes and etc.).

In addition to what is mentioned above, the classification of equipment is of the paramount importance when NDT technologies are considered. Flowlines are one of the most critical equipments which take the well stream from the Christmas tree to the production manifold. In case of inspecting the flowlines, wall-thickness is the momentous representative of flowline's status. Therefore, an effective inspection plan with proper intervals is needed to focus on such critical points in the plant. (Ratnayake and Markeset, 2010).

One of the significant benefits of applying NDT is that it provides in-service inspection (ISI). ISI enables us to inspect and monitor the condition of the equipments and facilities without interrupting the ongoing operations. The facilities can continue working while non-destructive tests are being performed on them.

One of the major investments in non-destructive testing is on human resources (Basrawi, 2004). Since operator's interpretation is very important and has a high effect on the results, therefore certified and well-trained personnel that have passed various stages of training is required. As long as the NDT technologies are getting improved and advanced rapidly, effective implementation and use of NDT can only be achieved through updated training. This should be followed both for advanced technologies and the conventional ones(Basrawi and Aramaco, 2003). Even in Visual Testing (VT) which seems to be very simple, when it comes to remote inspection by means of borescopes, fiberscopes, and video technology the necessity and importance of good training and certification becomes clearer (Chinthalapudi and Hassan, 2005).

Type of defect is another factor that should be considered by operators. Operators should be aware of the defect classification. Wear, corrosion, erosion, crack, leakage and fatigue are among the most important failures that contribute to equipment degradation. Therefore, with respect to the classification of defects, there are three major categories:

- *Type of defect*: consists of categories such as erosion, corrosion, material deformation, cracks, fractures, leaks and etc.
- *Shape of defects*: round, linear and etc.
- *Size of defects*: small, medium or big.

All these factors play a major role in the selection and evaluation of the NDT methods. For instance, Magnetic Particle Testing (MPI) is more efficient in detecting cracks, while Thermography is better to be used for the detection of cracks, corrosion and leaks.(Bøving, 1989).

Taking the shape of defects into consideration results in a more effective and efficient usage of NDT methods. For instance, Dye Penetrant Testing gives better results when the shape of the defect is round (Bainbridge, 2002). Likewise, Magnetic Particle Testing is proper for the detection of linear discontinuities such as cracks (Bainbridge, 2002).

The operator should be aware that some cracks and defects can be beneficial and not even harmful for the equipment (Ravi, 2010). If small cracks are positioned in a way that they can hinder the propagation of bigger cracks, or they can change the propagation direction to a relatively safer way, they are considered to be beneficial and useful for the equipment (Ravi, 2010).

Benefits of Non-Destructive Testing

There are many reasons that industries are applying NDT methods for inspection purposes including:

- Providing better quality of products
- Reducing costs and increasing production
- Detection of unwanted failures in the very beginning phase
- Providing the ability to inspect the equipments in operational state
- Reaching to higher levels of reliability
- Gaining consumer satisfaction
- Avoiding or reducing downtime and wastage of material

NDT provides a better understanding of flaws and defects existing in the equipment by clarifying the type, size, position and orientation of defects. This results in prevention of malfunctioning of the equipments and processes. The ability of having in-service monitoring provides outstanding savings of cost and time, increased productivity and minimum risk of having failures.

Major NDT methods used in the oil industry

NDT technologies are characterized into two major categories: Conventional methods, and Advanced technologies. The term “conventional” refers to those NDT technologies that are being used since 1950's and have proven to be effective routine testing methods within industries. These technologies include (Basrawi and Aramaco, 2003):

- Radiographic Testing (RT)
- Ultrasonic Testing(UT)
- Magnetic Particle Inspection (MPI) known also as Magnetic Particle Testing (MPT)
- Liquid Penetrant Testing (PT)
- Visual Testing (VT)
- Thermal/Infrared Inspection (IRI)

The second category- called Advanced Technologies- includes those methods that are started to be used over the past few years. Recently achieved advances and improvements of inspection technologies pushed the companies and industries toward using newer methods in their daily operational activities. The list of advanced NDT methods includes:

- Advanced Electromagnetic methods
    - Eddy Current Testing
    - Remote Field Technique (RFT)
    - Externally Referenced Remote Field Technology (XRFT)
    - Saturated Low Frequency Eddy Current (SLOFEC)
    - Electromagnetic Acoustic Transducers (EMAT)

- Advanced Ultrasonic technologies
    - Phased Array
    - Time-of-Flight Diffraction (TOFD)
    - Creeping Head wave Inspection Method (CHIME)
    - M-Skip (Complementary method of CHIME)
    - Guided Wave Ultrasonic Testing
- Advanced Thermographic methods
    - Scale Mapping
    - Mechanical
    - Electrical
- Vibration/Stress Measurements
- Digital Radiography
- High Energy Radiography

For instance, Electromagnetic acoustic transducers (EMATs) are a new way of applying ultrasonic testing. This method has the same basics as UT but it doesn't need any liquid couplant. This provides a faster way of examining the pipeline and pressure vessels. This method is also more suitable than conventional UT to be applied in higher temperatures (Basrawi and Aramaco, 2003). Use of Guided wave ultrasonic testing is also rapidly increasing within the oil and gas industry. It provides a good detection of flaws from far further distances in compare to conventional UT. This is achieved by introducing bulk UT waves with quite lower frequencies than for conventional UT and EMAT UT techniques (Basrawi and Aramaco, 2003). High Energy Radiography enables the operators to inspect quite higher wall thicknesses up to 20 inches of steel, while this is just 3 inches for the conventional radiography (Basrawi and Aramaco, 2003).

The advantages of using advanced NDT technologies include:

- Better coverage
- Better documentation and storage
- Cost-effective operation

- Clearer and more precise interpretation of results
- Higher probability of detection of defects
- Better imaging and sizing of defects
- More comprehensive reports
- Ability of repeating the test
- etc.

In addition to all aforementioned advantages, NDT provides the possibility of sending the data from remote distances to analyzing locations and perform the so called “remote analysis” (Harrison, 2009).

Within the thesis more information about most used NDT methods, their areas of use, and HSE consideration related to them will be provided. All influencing parameters including: type of defects, existing limitations and geometry factors, type of material and material’s characteristics and etc. will be explained within this manuscript.

Thesis Methodology & how the questions are solved

The focus of the thesis is on those methods that are mainly used by one of the Oil & Gas leading engineering services providing companies located in the Norwegian Continental Shelf (NCF).

As it comes from the title of the thesis, the scope is to evaluate the non-destructive testing methods used for the inspection of flowlines on offshore production facilities. In order to achieve this goal, the data and information including the inspection results and in-use matrixes from the mentioned company are gathered. Besides some interviews are held with the employees of the department of inspection of this company including level 2 and level 3 inspectors and planners to explore their knowledge and acquire in-depth understanding of the strategies, influencing parameters and etc. The most used NDT methods for inspection purposes are evaluated to see how frequently they have been used and how much reliable and accurate they are. Thereafter, recommendations are provided within chapter 6 regarding the results of analyses to reflect the results of evaluations clearly.

Two most used NDT methods, Radiographic Testing (RT) and Ultrasonic Testing (UT) are described at the first two chapters. Limitations, advantages and disadvantages of both methods are discussed. Then the data of inspection results are evaluated at the following chapters to see how accurate the NDT methods were and how frequent they have been used. Aforementioned evaluations reveal the influencing factors which affect the frequency and accuracy of the NDT methods used. They also reveal some of the underlying reasons of exotic results which companies may confront within their operational activities and data sheets.

These results can be used by companies in developing matrixes for the selection of the most appropriate method(s) for inspection purposes. Besides, this will help those who are willing to find the underlying reasons of results, assisting them in dealing with the data.

1. Introduction to flowline inspection

Flowline is one the most critical components of the system which carries the stream from the wellhead (X-mass tree) to the production manifold (Ratnayake and Markeset, 2010). Some factors such as temperature, environmental conditions, material composition and etc. contribute to flowline inspection plans. Wall-thickness is one of the most important factors that highly influences the decision making procedures in inspection plans. Wall-thickness measurements' results can show the degree of corrosion, erosion and some of the other influencing factors' contribution to the degradation process.

Therefore, based on the experience and some standards such as ASME B31.3, some requirements and levels are determined for wall-thickness monitoring and measurement. Planners determine, T_{min3}, T_{min1}, T_{min2} and $T_{nominal}$ as wall-thickness levels. T_{min3}, so called "virtual failure state" is the final limit of degradation for the flowline. If the flowline's wall-thickness passes this limit and gets thinner, then maintenance activities such as repair or replacement are required to take place (Ratnayake and Markeset, 2010).

Despite the fact that T_{min3} is the final limit for any degradation process, it should be considered that the virtual failure state is not the only factor that determines the time of replacement or repair. Some equipments are replaced because of the company's replacement policy. A reason for such a policy is that the equipment is close to reach the virtual failure state limit, so it cannot be left for the next replacement activity (Ratnayake and Markeset, 2010).

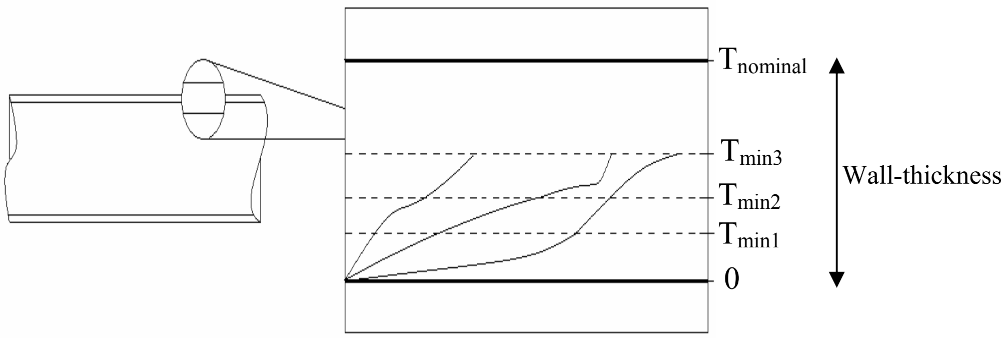


Figure 1. 1- Three different degradation processes of wall-thickness of a pipe

As it is shown at Figure 1.1, the propagation of degradation in the wall of a pipe can be different depending on the degradation rate and its direction. Degradation mechanisms are dependents on other factors such as time, environmental condition, H_2S content, CO_2 content, sand particle content, HSE considerations and etc. They will be discussed in detail at chapter 6 in order to highlight their role as influencing factors on NDT methods' frequency and accuracy and NDT methods selection processes.

In order to have a better understanding of the relation between these factors, a graph is provided here at Figure 1.2 (Ratnayake and Markeset, 2010) which clearly shows how corrosion allowance (CA) affects the other design parameters.

The distance between $T_{nominal}$ and 0, is the pipe's wall-thickness according to the pipe class and its dimension (Ratnayake and Markeset, 2010), and since T_{min3} is the virtual degradation limit therefore we can say that the distance between T_{min3} and $T_{nominal}$ is the minimum wall-thickness that is allowed depending on the factors and calculations stated at ASME B31.3. First of all T_{min3} is defined based on the determined criteria in ASME B31.3 (such as pressure limit) and then with respect to the Corrosion Allowance (CA) T_{min1} and T_{min2} are defined by these formulas:

$T_{min1} = T_{nominal} - CA$ (1.1) , $T_{min2} = T_{min3} + CA$ (1.2)

As it is clear from the formulas above, depending on the CA, T_{min2} can be either bigger or smaller than T_{min1}. If the pipe deteriorates beyond the limit then a maintenance activity, i.e. a replacement or repair, should be deployed as soon as possible. All these limits are determined through comprehensive procedures and calculations which consider all the existing factors affecting the pipeline at the time. The NDT technologies deployed in inspection activities should be able to clearly show the differences in wall-thickness. This fact attracts the attention toward the fact that how reliable the chosen NDT method is for detecting defects in the flowline.

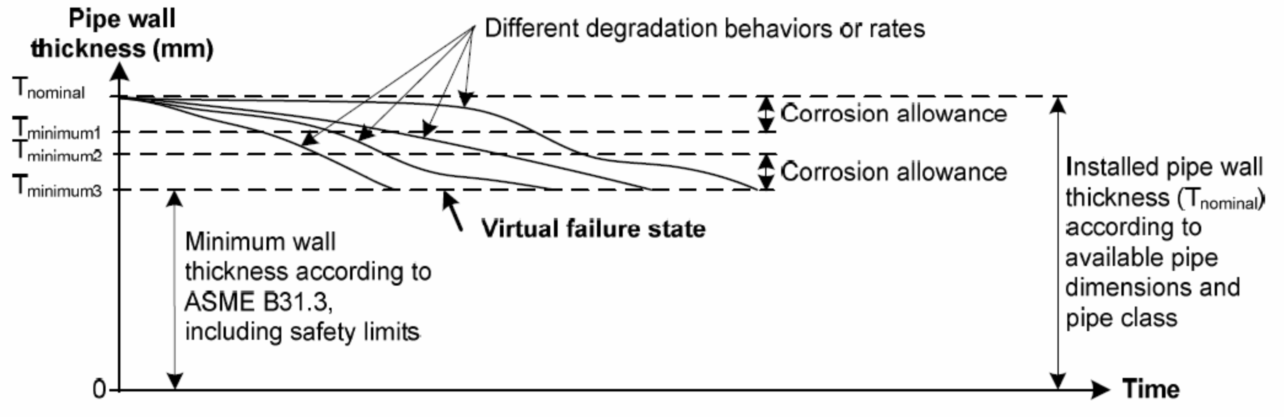


Figure 1. 2: Degradation process showing the relation between wall-thickness reduction and time (Ratnayake and Markeset, 2010)

In addition to the fact that T_{min2} can be less than T_{min1} in some cases, it should be considered that all these criteria can vary as the operational parameters vary by time. T_{min1} and T_{min2} play the role of alarms for companies in a sense that if T_{min1} is passed then it shows that the tolerance range and corrosion allowance are passed, and if T_{min2} is reached then it shows only corrosion allowance is remained to reach T_{min3}.

T_{min3} can vary depending on the changing operational parameters. Pressure and temperature of the flow get reduced by time as the production continues. When the production enters the reduction zone, then the design criteria of pipe are totally changed. Since the pipe is designed based on the worst probable operational conditions, T_{min3} can be increased regarding the new conditions. For example if there is a pitting observed in the wall-thickness which has reached T_{min3}, it doesn't necessarily mean that the pipe should be changed. Still it can remain in the operational state since the operational parameters are changed. Therefore, all these variables can be updated based on the new operational condition in order to keep the existing pipes in working status. This procedure will happen to T_{min1} and T_{min2} as well as T_{min3}. Therefore based on these limits, inspection plans get ready and prepared.

Another influencing factor in flowline inspection programs is type of the material. There is a maintenance policy being followed by the company which is replacing the pipes made of carbon steel (CS) with the ones that are made of Duplex material. Duplex material requires fewer amount of inspection and this decreases the cost of operations by time.

The list of NDT methods that are used for the inspection of flowlines in this offshore field includes:

- Inspection with Borescope
- Eddy Current Testing
- Pulsed Eddy Current
- Magnetic Particle Testing
- Phased Array
- Dye Penetrant Testing
- Radiographic Testing (Contact method- Tangential method)

- Ultrasonic Testing (and Time of Flight Diffraction)
- Visual Inspection (and Video Inspection)
- Safe Radiation
- Thermography

Within chapters 2 and 3, the descriptions of two most used methods (RT and UT) are provided. Descriptions include the procedures of performing the test, limitations of the methods including geometrical limitations, HSE considerations, type of material, type of defects and some other related factors and issues which influence the frequency and accuracy of the methods. This is of interest in this thesis since the results of evaluations are understood better and deeper if they are combined with an in-depth understanding of the methods themselves. After describing each method, the accuracy and frequency of applied NDT methods will be evaluated and related conclusions will be made.

2. Radiographic Testing of flowlines

After describing the flowline inspection principles at chapter 1, as one of the major inspection methods used for the flowline inspection by the company is Radiographic Testing (RT) this chapter is allocated to descibe this method. Within this chapter the limitations, advantages and disadvantages of this method are explained and discussed. Some of the new technologies of RT are also introduced and described within this chapter. The aim of this chapter is to provide a comprehensive picture of RT, which will be useful in further evaluations within the following chapters.

Radiographic Testing (RT) is one of the conventional NDT methods which has been in use over decades and is still being used by companies around the world. It is considered as the second most common method after Visual Inspection among the NDT methods which are being used by the industries (Matzkanin, n.d.). By deploying RT for inspection purposes, there is the possibility of inspecting the interior parts of the equipments. It should be mentioned that RT is the only NDT method that can be applied to every type of material (Shull, 2002). One of the major advantages of RT is its documentation capability. RT provides images of the object under inspection. Thus all these photos can be stored as documents of the inspection and can be used in further planning for maintenance and monitoring purposes. But interpretation of these images is then an important issue in radiographic testing. RT is based upon two major source types including X-rays and gamma radiation. The basic way of applying radiographic testing is illustrated in Figure 2.1.

All the distances shown in the picture below are just for illustrating the whole test and do not reflect any kind of scale. The distance between the film and the object should be as minimized as possible (Bainbridge, 2002).

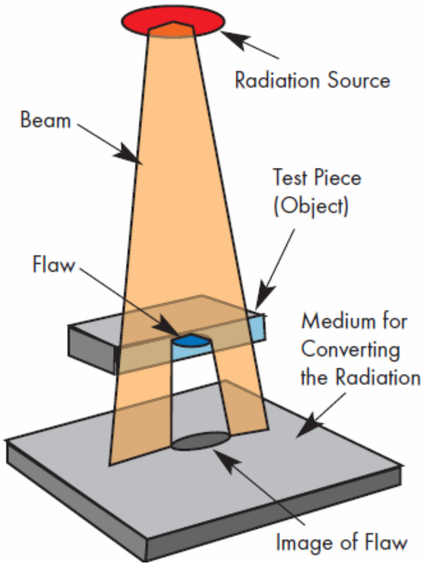


Figure 2.1: Typical Radiography testing setup (Matzkanin, n.d.)

At Figure 2.2 the relation between the blackness and the amount of exposure is shown. The more exposure to the radiation, more white is the image on those parts on the film, and vice versa, the less the exposure to the radiation, the blacker the picture will be at those parts. But conversely, on images acquired by digital detectors the picture is blacker on those parts that the exposure is more to radiation (Shull, 2002) (Figure 2.18). This can be confusing for the operators so that special skills are needed in order to avoid any type of misinterpretation of the images.

The choice between X-rays and gamma radiation depends on some factors such as thickness, contrast level and etc. For example X-rays typically work with lower amount of energy than gamma rays. The thickness is another parameter which influences the results. For example at thicknesses more than 50 mm, the use of gamma rays increases significantly (Bainbridge, 2002).

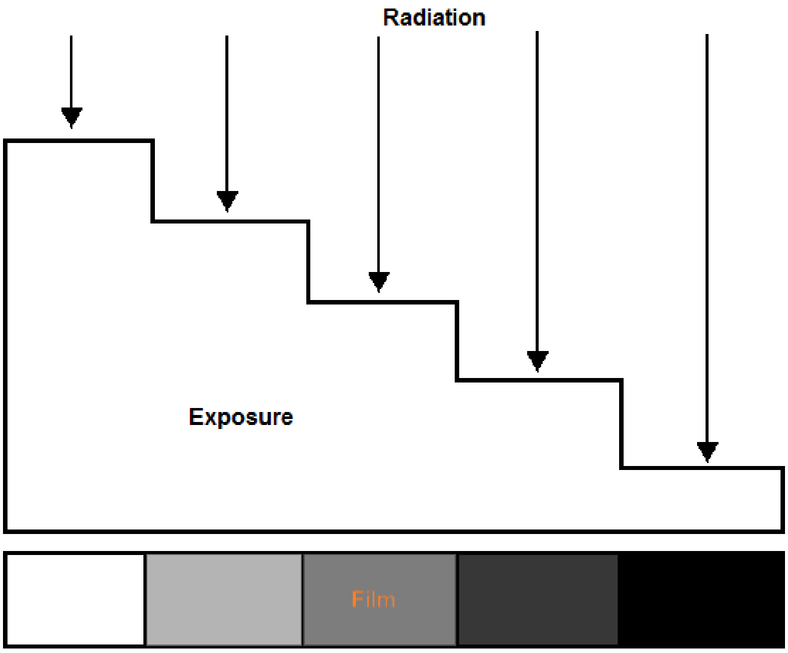


Figure 2.2: the relation between exposure to radiation and blackness (Loland and Lid, n.d.)

Based on the amount of blackness, the corrosions are found. In order to have an estimation of the amount of corrosion, two points are chosen near to the area that the corrosion is observed in the image. It can be a small hole on the image or a large area depending on how large the corrosion is. One point (dot) is chosen from the blacker part which shows corrosion and the second dot is chosen from the background area that is used as the base and original blackness. Any deviations from this reference number shows deviations in thickness. Based on the data acquired from these two dots the amount of corrosion is calculated by the use of diagram shown on Figure 2.4.

In Figure 2.3 two different types of devices are shown which are used for measurement of the blackness on images. This device, which in Norwegian is called “svertningsmålere”, gives a number that shows how much the blackness is on a particular point of the picture. One can put the probe of this device on desired points on the picture and get the related numbers. The blacker the point, the higher number gives this device. Using these numbers the amount of corrosion can be calculated.

Figure 2.3: two types of blackness measurement devices (Svertningsmålere) (Source: Hartmann.no)

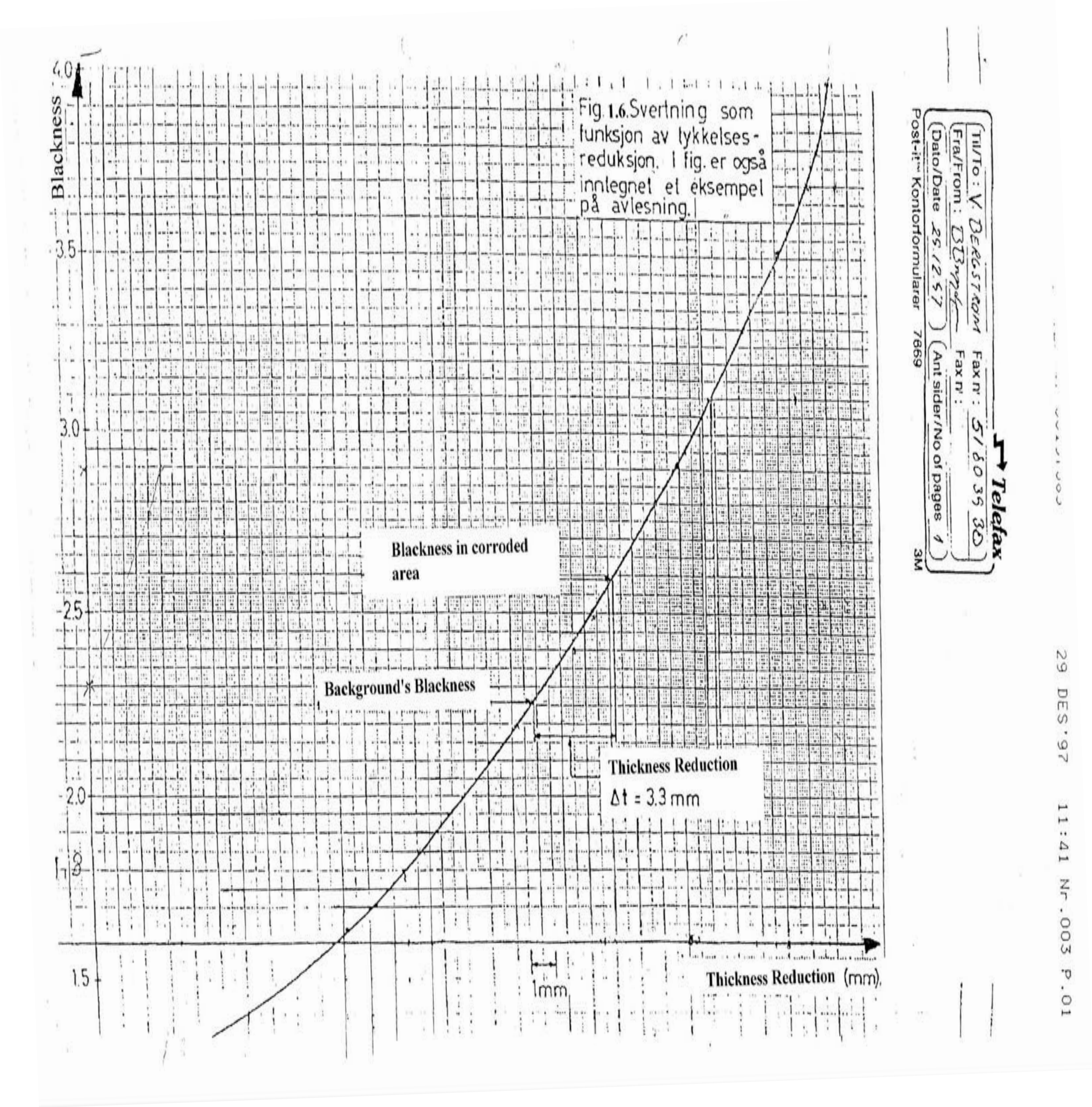


Figure 2.4: The curve used for the calculation of thickness reduction using two points from the picture: from background and from the corroded area

An example here is provided to show how one can use the diagram shown on Figure 2.4in order to measure the amount of corrosion in a specific part:

Using the blackness measurement device for the picture of bend shown at Figure 2.5, these numbers are acquired:

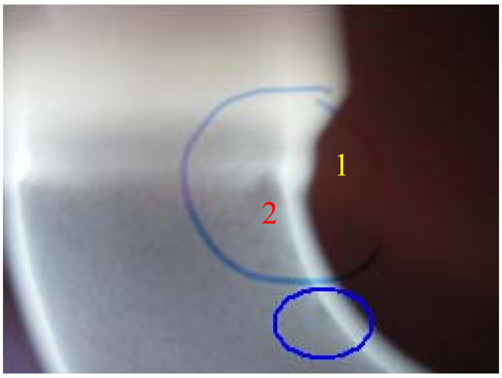


Figure 2.5: A radiographic picture of a bend, two blue circles show the corroded areas

The blackness of background (1): 2,3
The blackness of corroded area (2): 2,6

As shown at Figure 2.4, the related numbers should be followed from the Y-axis which is for the amount of blackness, and then followed until they intersect with the curve. Then the related values on X-axis which indicates the thickness reduction are read. The difference between two points on the X-axis is 3,3 mm in this example (each small square is 0,5 mm). Therefore the thickness reduction can be calculated by applying radiographic testing by means of easily using the curve.

2.1 X-radiation

X-rays have energy 100-100,000 times greater than the energy of the visible light, and because of this energy they can pass through the material that the visible light cannot. The amount of X-ray that can pass through a material depends on the following factors (Shull, 2002):

- Material composition
- Density of the material
- Thickness
- The energy of the X-ray

Interpretation of images needs special skills but this also can be achieved by experience and working a lot with the images.

2.2 Gamma radiation

The electromagnetic radiation is called gamma radiation. The way that gamma radiation is emitted and produced goes back to the fact that some of the atomic nuclei of radioactive material are unstable and tend to break down to reach stable conditions. During this breaking down and decaying process the nuclei emits energy in the form of radiation (Bøving, 1989). Gamma radiation absorption by the material depends on the following factors:

- The wavelength of the radiation
- Composition of the material
- Thickness of the object

Both in X-rays and gamma radiation as radiation passes more through the material the darker the film becomes on the image produced and, on the contrary, the more the ray is absorbed by the material the lighter is the image in those spots (Bøving, 1989). This fact helps the operators in determining whether corrosion exists or is happening in the material or not since the differences in the thickness of the material attenuates the radiation by various degrees. This also makes it possible to see the interior parts of the materials. For example if steel rods are inside of a concrete segment, by radiographic testing we can see the condition of the steel rods also since the differences of composition of the material attenuates the radiation by different degrees.

2.3 RT practical considerations

2.3.1 Interpretation of images: Generally the images taken from digital detectors are bright where there is a higher amount of photons passed through the material and dark where most photons are absorbed by the material. This is called a “positive image”. This can be confusing for the operators working with analog films changing the films to digitized ones. This is due t the fact that pictures are dark where there is high absorption of X-rays by film and brighter where less absorption has occurred (Shull, 2002). At Figure 2.18 a result of digital radiography using digital detector is shown. Therefore interpretation and working with the pictures needs special training. For example at the pictures shown at Figures 2.13-2.15 different results of weld inspection are shown. Interpretation of each picture and finding out the defect types and shapes resulting in these pictures is the primary step and of course the most important one in radiographic testing.

2.3.2 Cost, density, and size of equipments: are among the influencing factors that should be taken into consideration when the method is evaluated. Radiographic testing method is considered as one of the expensive NDT methods, so it should be financially assessed and approved whether it is reasonable to use this method or not. Different sources of radiation have different associated costs, size and heaviness. For example the cost associated with Cobalt 60 is relatively more than the cost of Iridium 192. Cobalt 60 has quite heavier equipments. This affects the frequency of this method since inspectors are willing to work with easy-to-handle equipments.

2.3.3 Space & Access: The required space to perform the test or the accessibility to the point is one of the important factors. Enough space and good access to the point make inspectors more willing to use RT. On the other hand if the access is hard, the frequency of the method decreases significantly. This fact will be shown within chapter 4 by evaluations and inspection results.

The location of the equipment and its geometry which is going to be inspected has significant importance since the operator needs enough space to place the film and the source of radiation in correct positions to get the required image from the desired part. For example at the second spool after X-mass tree toward the production manifold there are three injection points that are used for the injection of chemicals into the pipe for maintenance purposes. This part which is shown at Figure 2.6 is one of the hardest parts for the radiographic testing to be applied. The geometry effect makes the situation very difficult for the inspectors to lay the film on the pipe.

The required space is not good enough here and the accessibility to this point is poor, but the criticality of this part is high. This is one of the critical spots within flowlines, thus it requires more frequent inspection. The damaged wall of this part due to welding operations, and the existence of turbulence due to the direction of chemicals and the flow in this spot, result in faster degradation of this part. Therefore the high criticality of this part and poor existing conditions require for RT to be performed, make inspectors to use ultrasonic testing (UT) instead. This results in higher frequency of UT and fewer frequency of RT. Poor accessibility results in less accuracy of results also. Therefore, space and access have a high effect on the results of inspections performed. This fact will be shown at chapter 4, by historical data.

The access to the green part of pipe shown at Figure 2.6 is very hard and almost impossible to the level that inspectors prefer to use ultrasonic testing for that.

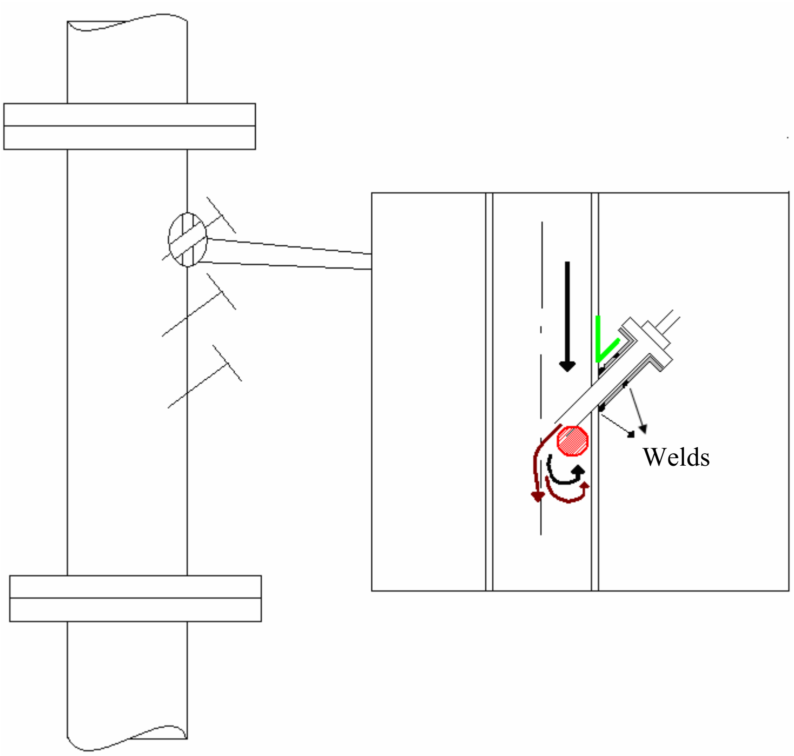


Figure 2.6: the problem of turbulence (red circle) and difficult access (green line) at injection points

At the pictures below you can see the real welded part which has gotten corroded to a level that a leakage has occurred. These pictures relate to the same location mentioned above where the presence of chemicals and weakened wall thickness of pipe make the pipe more susceptible to be corroded. The corroded part is shown at Figure 2.8 and Figure 2.9 and a leakage is also clear on Figure 2.7 below.

.

Figure 2.7: the effect of welding and turbulence leading to a leakage

Therefore as it is shown above, the access to the desired part of the equipment that the operator wants to inspect is of the paramount importance. This should be considered when one wants to plan for inspections and perform them.

Figure 2.8: Corrosion due to presence of chemicals and turbulence and welded wall

Figure 2.9: Corrosion at the point that chemicals are injected to the pipe

As another example of problems in having difficulties in getting access to the desired part, a valve at Figure 2.10 is shown. This valve is welded to a pipe at point number 1. The location of this valve and the pipe as it is shown at the picture creates poor access to the welded part for inspection. Also you can see from Figure 2.11 the image gained using radiographic testing for this part. As you can see from the numbered parts, the welded part is very white which can be an indication of high thickness in that part. Therefore almost nothing can be interpreted about the welded part and its condition.

Normally radiographic testing is held for such parts in order to be sure that the pipe inside the valve is installed correctly and enough space is provided for the thermal expansion within the pipe. But poor access to the point to place the film and equipments makes it harder for inspectors to perform RT.

Figure 2.10: welded valve to a pipe, difficult to inspect

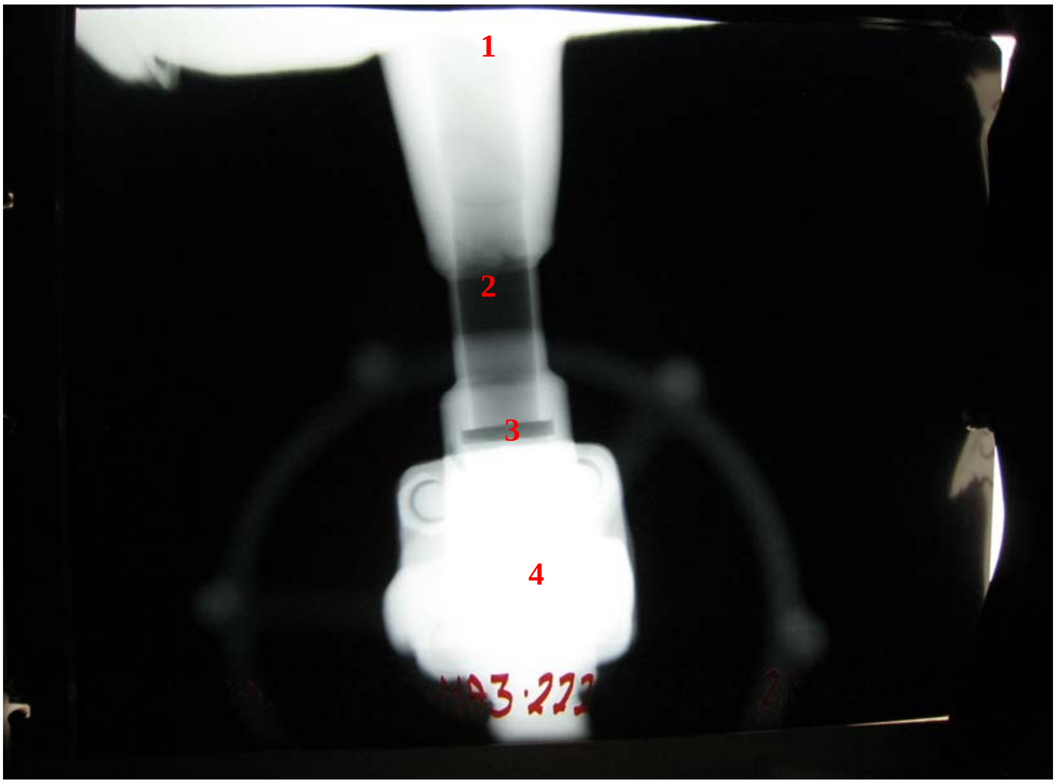


Figure 2.11: Result of Radiographic test of the part

The numbers of pictures above relate to:

1: Welded part
2: The pipe inside the valve
3: Space left for the thermal expansion
4: Valve

As it can be seen from the picture, parts 1 and 4 are quite hard and impossible to be judged of having corrosion or not.

2.3.4 Thickness: The effect of thickness on radiation source selection is shown at table 2.1 below. The relation between the thickness of the material and the energy range of X-ray and gamma radiation's source indicates that for a specific range of thickness there is a specific range of X-ray and a specific gamma radiation source. This can be of practical considerations for operators when they perform RT. Depending on film type, contrast and some other influencing factors, operators choose the appropriate source of energy for radiographic testing. Thickness influences the frequency and accuracy of the methods also. For thick part in T-joints radiographic testing by using Cobalt 60 is recommended. But since the cost and heaviness of this radiation source are relatively higher than for the other ones, inspectors use UT instead. This increases the frequency of UT and decreases the frequency of RT. The effect of the thickness together with cost on NDT methods is shown by evaluations performed on historical data at chapter 4.

Table 2. 1: Relation among Thickness, X-ray energy rang and gamma-ray (Bainbridge, 2002)

Thickness	X-ray Energy Range	Gamma-radiation source
≤ 5 mm	Up to 130 kV	Thulium 170
1 - 15 mm	Up to 230 kV	Ytterbium 169
10 - 40 mm	175 – 410 kV	Selenium 75
20-100 mm	275 kV – 4 MeV	Iridium 192
40 – 200 mm	410 – 4 MeV	Cobalt 60

2.3.5 Film type: Film type is another factor that should be considered when radiographic testing is of interest. Film is defined in terms of grain size and contrast. The amount of exposure the film receives determines its density. The visibility of changes and defects depends on the gradient of the curve of density against exposure. This also can be interpreted as the contrast of the film. Density of 2 – 3 is usually considered as a good choice for meeting the visibility requirements on one hand and the contrast on the other hand (Bainbridge, 2002).

Influencing factors to select the appropriate type of film are:

- The composition of the material,
- Size of the equipment
- Shape of the equipment
- Weight and location
- Type of radiation source
- Kilo voltages available with respect to x-ray equipment or the available intensity of gamma radiation (Larson, 2011).

2.3.6 The location of the source and the film and corresponding distance from each other*:* is another consideration that is important for the operators. If there is any access to interior part of the pipe, then either the source or the film can be located inside or outside of the pipe. Generally, there are three possibilities to choose among:

- Film outside, source inside
- Film inside, source outside
- Both film and source outside

Unsharpness of pictures gained can be a result of poor location of source and object. If the beam is produced from an area not from a single point it can end up in unsharpness of the defect on the picture. Therefore source's size, source to item distance and object to detector distance are the influencing factors of controlling unsharpness (Larson, 2011). At the picture below an effect of source size on the image taken with RT is shown:

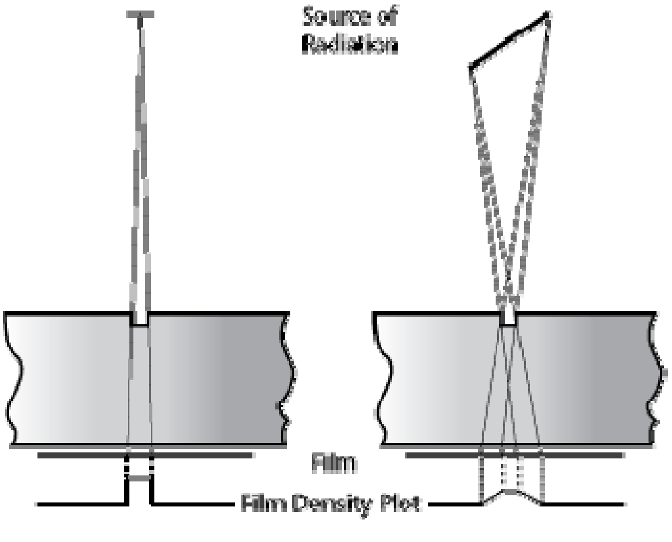


Figure 2.12: the effect of source size on having unsharpness at the image (Larson, 2011)

2.3.7 Defect type: Defect type is one of the important influencing factors on the efficiency of each NDT method playing a major role at RT as well. Defect type, its orientation and location are among the decision making factors which are highly critical in selection of the appropriate method. Volumetric defects are easier to be detected than planar ones by using RT. This is more understandable when one considers the tolerance of defect to beam direction. It is obvious that volumetric defect has tolerance against the beam in each direction which is not the same for planar defects. The most important parameters of defects for RT are their morphology, size, orientation and opening (Bainbridge, 2002).

Although radiographic testing is in a sense more reliable and efficient to be implemented for volumetric defects, but it can be used for planar ones as well. For planar cracks with wider openings (gapes) radiographic testing is more reliable than cracks with small openings. Therefore, it can be concluded that in order to gain the best results from radiographic testing; the source of the beam should be placed in a way that the direction of beams is parallel to the plane of defect. Therefore its tolerance to beam increases and resulting in its easier detection (Bainbridge, 2002).

2.3.8 Material's effect: is very important when conducting RT is of interest. Different types of steels and alloys have different impacts on the attenuation of X-rays or gamma rays. This means that radiographic testing should be carefully designed in a way that takes different material composition effects into consideration. Radiographic testing can be applied for almost all types of material and this can be considered as one of its advantages. The effect of type of material on NDT methods is shown within the evaluations done at chapter 4.

2.4 Radiation Hazards (Safety Considerations)

Although radiographic testing is one of the most used NDT methods in the oil and gas industry, but its radiation hazards is one of its significant disadvantages. This hazard can show itself in terms of long time of exposure to low level energies, or short time of exposure to high level energies. This can be interpreted as the same effect of harmful exposure (overexposure) to heat, light and other regular sources of energy that humans are experiencing them in their normal life.

Humankind has been living with radioactive elements and material during its existence, but in the recent years some achievements have been gained enabling the humans to use the radiation in its beneficial way. Humankind has become enabled to use it in agricultural research, medical diagnosis and therapy, industrial gauges, non-destructive evaluations and etc (Shull, 2002).

Radiation measurement devices such as dose rate meters, scintillation counter, pendosismeter (PDM), and thermoluminescent dose mete (TLD badge) (Raad and Kuiper, 2009) can be applied to determine radiation levels in order to avoid any unwanted accidents resulting from lack of knowledge about the amount of radiation or existence of hazardous conditions.

Like almost all industrial accidents, radiography accidents can also be caused by ignorance and lack of caution of the operator. In some cases operators are in hurry because of the lack of time for inspecting plenty of equipments remained. There have been some cases that the operator has changed the equipment under X-ray radiation without considering the speed and the energy of radiation existing there at the environment. These cases have been resulted in loss of arms or finger of inspectors in their severe consequences (Shull, 2002). The lack of caution of inspectors can also result in overexposing the other worker and employees working at the same environment. Shielding and informing all the people working there should be considered at the earliest stages of the test. At the table below, the effect of certain amount of radiation on human is shown.

Table 2.2: Radiation dose and its heath effect (Shull, 2002)

Radiation Dose (in Sv /or Rem)	Health Effect
0,25 Sv (25Rem)	Non-detectable
0,5 Sv (50Rem)	Temporary changes in blood
1 Sv (100Rem)	Nausea and fatigue
2- 2,5 Sv (200-250 Rem)	Single death happens
5 Sv (500 Rem)	Half of recipients die!

In order to have a better understanding of the radiation dose, brief definitions of them are provided here. The SI unit of radiation dose is called “Gray” (Gy) (after the British physicist Louis Harold Gray) and it is equal to 1 Joule/Kilogram (amount of unit energy by unit kilograms). Gray is the absorbed radiation dose. But for X-rays and gamma rays there are other units, such as Sievert (Sv), which are so called equivalent dose. Equivalent dose refers to biological tissues while absorbed dose refers to material. Below the relation between different units is provided:

- 1 Gy = 100 rad
- 1 Sv = 100 Rem

Governmental rules, special training, use of measuring devices are all effective in reduction of radiation hazards and overexposures in performing the test. The inspector (radiographer) should be aware of all the regulation and is responsible to check the situation regarding all existing safety regulations and should make sure that all of them are met. The related HSE considerations have resulted in fewer applications of RT than the expected and planned ones. This fact is shown at chapter 4 by evaluations performed on the historical data.

2.5 Advantages and disadvantages of RT

Advantages and disadvantages of each NDT method are among the factors that determine whether one should use that method or not. Implementation of radiographic testing provides documentation ability for the operators which can be considered as the first advantage of RT. Since the final product of each test is an image, this image can be stored for further analyses. Documentation ability has its own advantages. The probability of misinterpretation of results is minimized since each image can be reviewed by multiple operators. It should be mentioned here that working with the pictures and analyzing them requires special skills that should be gained by passing different stages of training. At the pictures below different types of defects of a weld are depicted and the radiographic results of those defects are shown. These images show that how well-trained and skilled the inspector should be in order to interpret the correct conclusion out of the pictures. Figures 2.13 – 2.15 show the importance of interpretation.

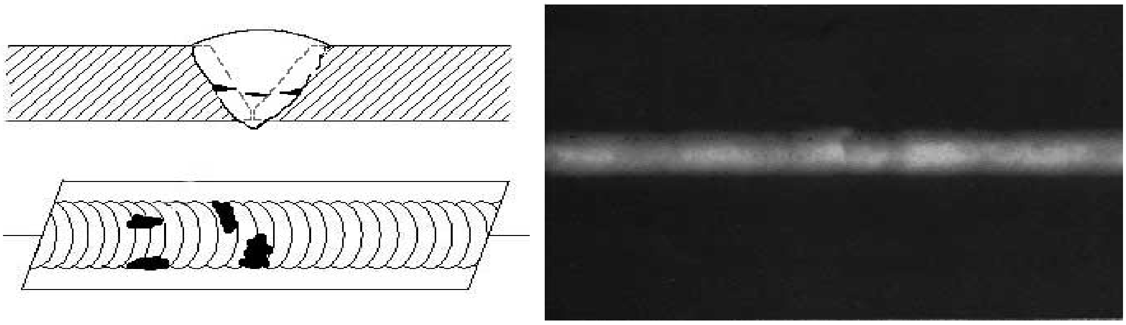


Figure 2.13: Interpretation Importance: Cold Lap – weld metal does not properly fuse with base metal (Larson, 2011)

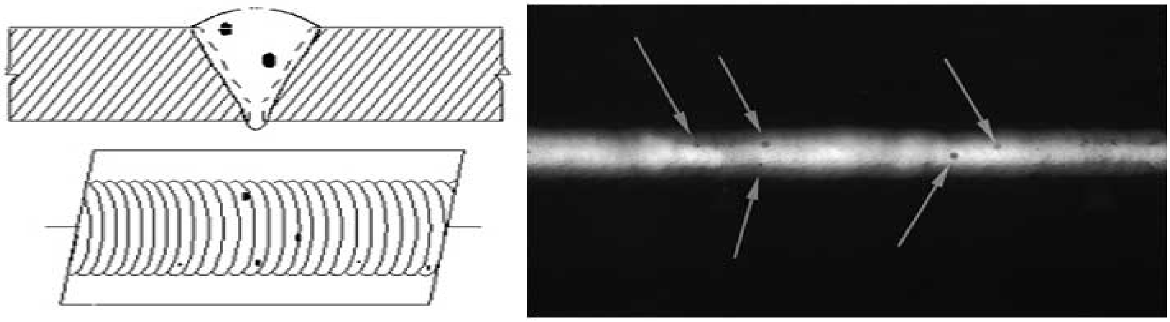


Figure 2.14: Interpretation Importance: Porosity – result of gas entrapment (Larson, 2011)

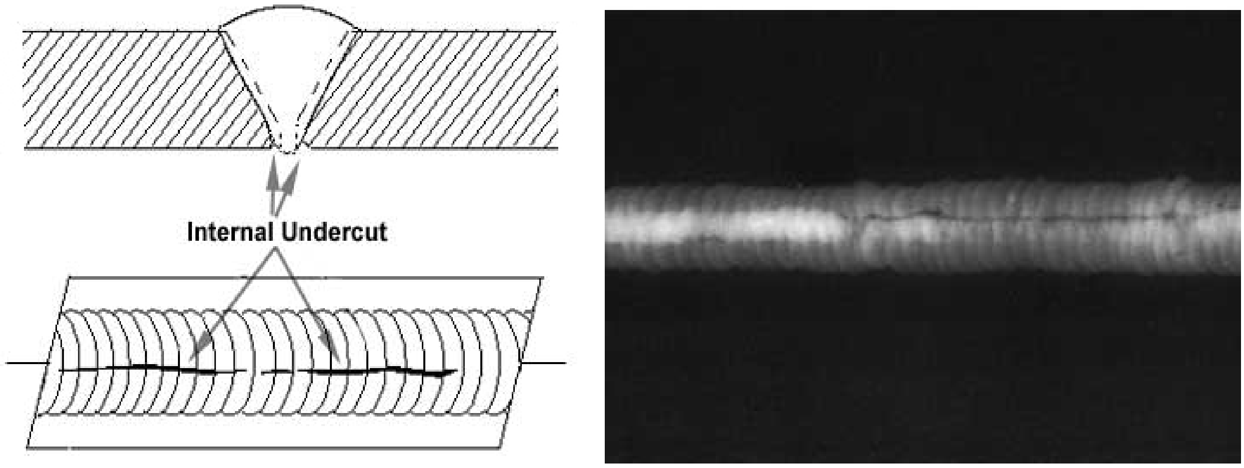


Figure 2.15: Interpretation Importance: Internal Undercut – erosion of the base metal beside weld (Larson, 2011)

It is the inspector's responsibility to correctly interpret the pictures and find out the exact type and shape and orientation of the defects. If one defect is mistakenly figured out as another type then the subsequent inspection and maintenance program will be different from the correct one. It can even affect the next inspection date since some defects do not need immediate actions and are left as they are but still monitored in certain intervals to avoid any unwanted failure.

By storing the images, the analysis of historical data becomes easier. Documentation of the images helps the operators to easily follow the degradation mechanisms at the desired part. This advantage, in a sense, increases the reliability of radiographic testing since the results gained are pictorial, and not numerical. Pictorial results can be overviewed by various operators to make sure that true interpretation is accepted, while numerical results such as those for UT are basically dependent on the operator's skills and experience.

Detection of internal defects is the second advantage of RT. It is also possible to rotate the object and inspect it from different directions and sides to find the exact orientation of defect. Providing the ability of observing the interior parts, one can verify the assembly and installation of equipment by using RT.

Any variations in composition of material can be found out using radiographic testing. As it is mentioned above, different materials have different impacts on the attenuation of rays, so that they provide different results. This provides the capability of detecting any variations within the material composition (Bainbridge, 2002).

High thickness of material creates significant challenges in implementation of RT. As depicted in Figure 2.11, since the thickness of the pipe and equipment is high in the welded part, so the picture is so white, thus small defects are hidden in the produced picture and cannot be clearly seen. Therefore RT cannot be a good choice for equipments with higher wall-thicknesses.

The impact of radiation to health and environment can be considered as another disadvantage of radiographic testing since a few seconds of being exposed to radiation can result in sever injuries. The high voltage needed to create radiation is dangerous for human health also.

After all, in order to summarize the advantages and disadvantages of radiographic testing in NDT programs, the Table 2.3 is provided here.

Table 2. 3: Advantages and Disadvantages of Radiographic testing

Advantages	Disadvantages
Provides pictorial results	Requires special skills for interpretation of pictures
Provides Documentation ability	Requires specific orientation
One result of inspection can be reassessed by different professionals	Expensive
Detection of internal defects	Dangerous (Radiation hazards)
Detection of variations in composition of material, thickness measurement, etc.	Ineffective for planar cracks
Can be used for all types of material	Not good for surface defects

2.6 Table of important parameters of Radiographic Testing

All these information can be organized and reviewed in a useful table as provided below. This table can be used to understand the influencing parameters on radiographic testing and it can be considered as a helpful tool for decision making situations.

Table 2. 4: table of parameters of radiographic testing

Defect type (that ET can detect)	Voids – Cracks (with rather big gape) – Inconsistencies and inhomogenities of materials – Density changes – Weld defects – Erosion – Corrosion – Leakage
Type of material	All types of material with all shapes and forms (Metals, Nonmetals, composites and mixed materials)
Size of discontinuities and defects	-Defects with the size that have at least 1% difference in absorption with regard to surrounding area (Matzkanin, n.d.) - Detection of flaws as small as 0,001 inches by advanced systems (Matzkanin, n.d.)
Limitations	- Thickness limitation (refer to table 2.1) - Film type limitations - Access to both sides of the object is needed - Exposure time, and amount of voltage are critical parameters - Radiation hazards - Orientation of beams with respect to the crack orientation is critical (parallel) - Gamma radiation is not as sensitive as X-ray
Areas of application	-Can be applied to joints, Welds, Pipeline (Flowline), reinforced concrete, castings, electronic assemblies, aerospace, marine and automotive components -Gamma radiation is used when the material is dense or thick or there are limitations to use X-ray.

2.7 Recent technologies of RT

Computed Radiography (CR), Digital Radiography, High energy digital radiography, and X-Ray Inspection Simulation (XRSIM) are among recent technologies of radiographic testing methods. Each one of these methods has its own advantages and disadvantages.

2.7.1 Computed Radiography (CR)

Basically computed radiography has the same principle as conventional radiography as discussed before. But instead of films, some types of imaging plates are used in CR. These plates are generally photo-stimulated phosphor plates. After the image is taken on the plate, a laser reader is applied to convert the light to electrical signal that can be digitized. Then special software is used to optimize the picture to fit the determined standards. This can be considered as a major advantage of CR since there is the possibility of editing the picture with respect to the image density and contrast after the exposure time. Then determining the size of flaws and defects is done using the software which is much easier than the conventional form of radiography. However, special skills are required to work with the software.

The benefits of computed radiography can be summarized as follows:

- There is no need for a dark room in order to produce the image
- Exposure time can be reduced to 50%
- Rapid image processing
- Plates can be used several times
- Cost effectiveness and Communication
- Reduction of lab equipment

However, the heaviness of CR equipments should be considered since it takes a lot of energy for inspectors to move the equipments from place to place. This also reduces the speed of inspections. One of the level 2 inspectors was complaining about this problem in an interview. He mentioned that this is the main reason that they (operators) prefer to keep on using the conventional method. He said that time is critical and they have to perform a certain number of inspections until a specific deadline and report the results. Using computed radiography they are only able to perform quite fewer numbers of inspections.

Scanners and printers are needed in CR. Working with the software needs special skills. It makes this method not that interesting for the operators who are used to work with the conventional form of radiography. These operators can easily interpret images and prepare the reports in a short time for the management with conventional RT, but by using computed radiography there becomes a stressful situation for them to finish the inspections and prepare the reports which decreases the effectiveness of the method.

The images produced from computed radiography, as operators say, are not much greater, and have less sensitivity than traditional x-ray photos.

But recent technologies has achieved smaller and lighter plates that are easily portable, but these plates and the image quality they produce, and their sensitivity should be approved with respect to the standards by any company willing to use them.

2.7.2 Digital Radiography

It should be mentioned that Digital Radiography (DR) is not the same as computed radiography since the similarity of names is confusing for some people. In fact computed radiography is a kind of digital radiography but associated with using of phosphor-covered plates (Raad and Kuiper, 2009). As it is mentioned earlier, in computed radiography there is a scanner/reader which reads the data from a plate/cassette and transfers it to the software/processor. But in digital radiography there is no plate or cassette. The imaging data are transferred directly from the detector to a computer without any need for a reader. The similarity of both methods is in the digital form of the image acquisition process. The differences between two methods goes beyond the only difference mentioned and covers areas from steps required to perform each method to image quality and costs associated. Both digital and computed radiography provide the possibility of improving the image interpretation and diagnostic strength. Both provide the opportunity of gaining images with less noise together with lower exposure time. But since the radiation dose is less in digital radiography than its amount in CR so it is potentially preferable regarding the HSE considerations.

Heaviness of the plates still remains as a problem in digital radiography. As some of operators believe, the quality and contrast of pictures taken cannot meet the specified standards. At the figure below some different types of digital detectors are shown. These detectors transfer the image acquired to the computer.

Figure 2.16: Three different types of digital detectors, the models are (from left to right): DXR250, DXR250RT, DXR250V (Source: GE-msc.com)

Depending on the needs and required quality of pictures and portability requirements of detectors, there are more varieties of digital detectors in the market. For example the three models shown above are deployed by General Electric Company (GE). Digital detectors are different from each other regarding their characteristics and functionalities. These characteristics are:

- Amount of noise on the picture
- Resolution parameters
- Areas of use
- Image acquisition rate
- Weight
- Easiness of setup and preparation process

The use of the third model mention above (DXR250V) for corrosion inspection is shown at the picture below. This picture shows that the thickness of detector is important in its placement for inspection purposes.

Figure 2.17: Digital detector used for digital radiographic inspection of a bend (Source: ge.com)

Misinterpretation caused by the difference between the pictures produced by conventional and digital radiography can be another issue that needs training and special skills to avoid any misunderstanding that leads to wrong reports and consequently wrong actions. At Figure 2.18, an illustration of the picture produced by digital detectors is shown. The picture relates to a copper vessel with steel insert from a side view. The ruler in the picture is for scaling the picture and providing an estimation of size of the vessel to have better understanding. The effect of heaviness and cost of the relative equipments is discussed within the evaluations performed at chapter 4.

Figure 2. 18: the picture gained from a copper vessel by using digital radiography

For a comparison between CR, DR and conventional radiography, the major parameters considered are image quality and speed. Raad and Kuiper (Raad and Kuiper, 2009) show that the image quality of CR in its best case is almost the same as the conventional radiography with finer grain films but its speed is almost five times faster. But CR images with rather less quality (the least quality) are ten times faster than conventional radiography.

The best quality that can be achieved by DR is close to the quality of fine grain films (type D3) of conventional radiography. For the same quality of DR and conventional images, DR is 20 times faster than conventional method. This even goes beyond and reaches speeds up to 200 times faster than conventional radiography, however this is for the time that the least image quality of DR is compared to the best quality of conventional radiography (Raad and Kuiper, 2009).

It should be noticed that the speed considered here is the speed of acquiring the image after exposing the object to radiation. In fact this speed relates to image producing process either from taking the film to the dark room and producing the image in conventional radiography or transferring data from digital detector to the computer and observing the image taken. This speed doesn’t take into account any of the preparation process factors prior to shot (radiating) which are those factors that inspectors complain about them. As discussed previously, lifting, handling and moving the detectors in DR and plates in CR from place to place are exhausting for the inspectors and reduces the speed of inspection. In computed radiography, inspectors will need trolleys to carry the plates while they can just handle tens of them by hand or carrying them in hand-bags in conventional radiography during inspection.

An overall comparison is provided here at Table 2.5 in order to highlight the differences between CR, DR and conventional radiography. This considers all the influencing factors such as speed, mobility, contrast, size, shape and etc. For instance, by using softwares in digital radiography, noises can be reduced significantly and the transparency and resolution of the pictures can be adjusted as desired.

Table 2.5: Comparison between influencing factors for selection of DR, CR or conventional radiography

Factor / Method	Speed	Mobility	Contrast	Image Quality	Flexibility of Sensors	Cost
DR	Fast(est)	Difficult	Adjustable	High ⁽¹⁾	Thick plates (heavy) (rigid)	High ⁽³⁾
CR	Fast	(most)Difficult	Adjustable	Medium	Thin plates (flexible) ⁽²⁾	Medium
Conventional Radiography	Low	Easy(est)	Non-Adjustable	High	Thin films (light) (flexible)	Low

(1) Image quality in DR highly depends on exposure parameters and the software used

(2) Contrary to DR, CR plates can be bent to fit the curvature of component

(3) A flat DR panel detector is approximately about € 15000, while a CR plate is about € 750

2.7.3 High Energy Digital Radiography (HEDRad)

Higher wall-thicknesses were described as the major challenges in RT. By using HEDRad operators will be able to inspect interior parts of a valve and other thick wall equipment without the need to have internal access. This also results in reduction of inspection time. HEDRad provides new applications of radiographic testing by extending the range of energy levels currently applied in conventional radiography (European Community, n.d.).

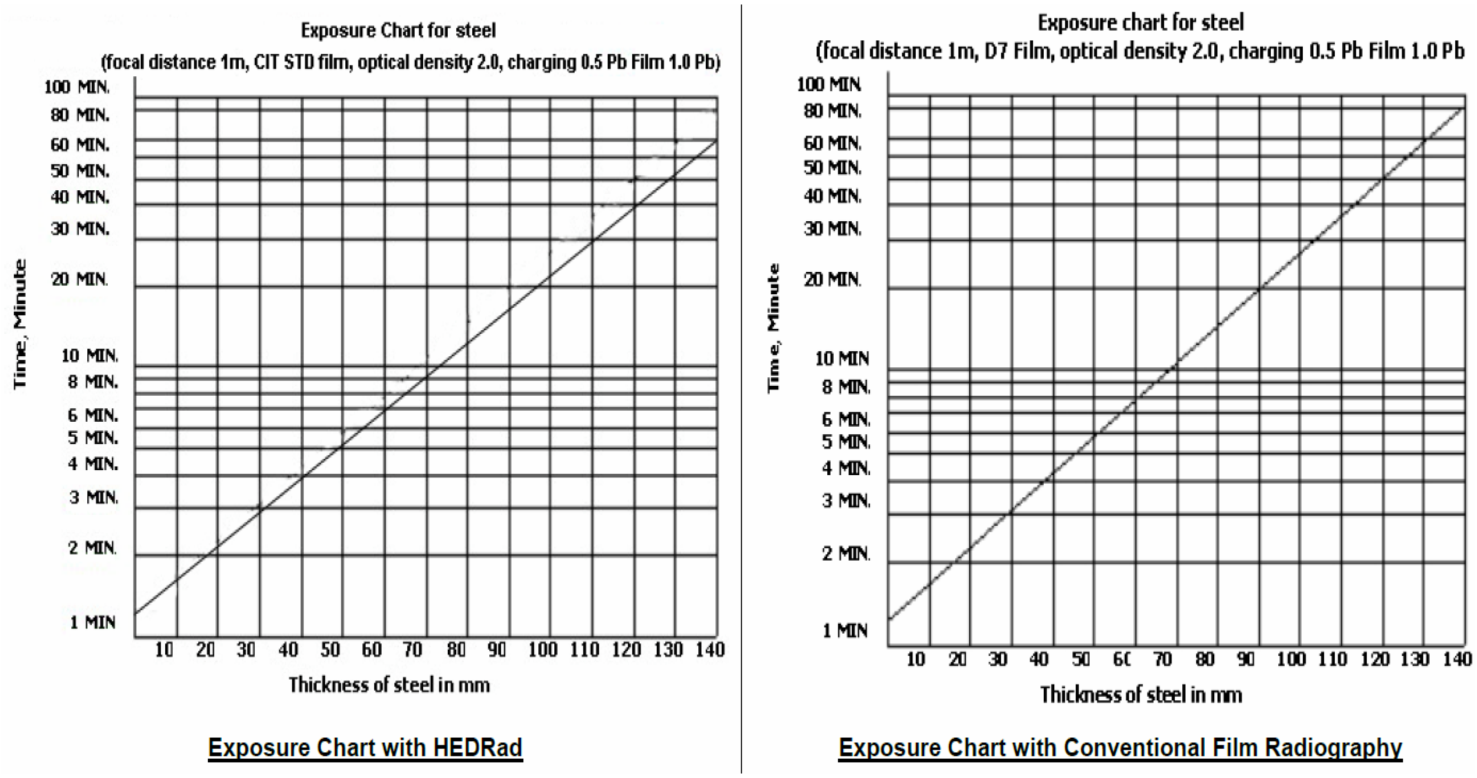
The benefits of HEDRad are:

- It's film free
- Chemical free inspection method
- Meets the standards and regulations
- Environment friendly
- Time saving method which requires rather less exposure (40% saving in exposure time)
- Provides in-service inspection of equipments with thick wall ranging from 40mm to 150mm which generally need downtime(European Community, n.d.)

HEDRad requires an enhanced computed radiographic scanner and reader system which can operate at high radiation energies. This method provides an image with less noise and with an acceptable quality.

A comparison between the exposure time needed for the HEDRad and Conventional radiography is shown at figure below.

HEDRad requires 2.5 MeV X-ray betatron system and DR 1200 computed radiography system which is designed for high energy radiography. This method can be applied for various materials type consisting of: steel, carbon steel, austenitic steel, stainless steel, and mild steel which generally are the materials used in thick wall equipments. HEDRad can be used for the inspection of welds, pressure vessels, storage tanks, boilers, inplant piping, valves and castings.



Exposure Chart with HEDRad

Exposure Chart with Conventional Film Radiography

Figure 2.19: Comparison between HEDRad and conventional RT with respect to the exposure time (European Community, n.d.)

2.7.4 X-Ray Inspection Simulation (XRSIM)

One of the most outstanding recent advances in NDT is the development of computer modeling. This provides the capability of evaluation of inspectability of components in a virtual environment. Computer aided design (CAD) models are deployed in order to accurately simulate the real physical situation to images. Using XRSIM, the operator can give the material parameters such as size, location and etc., and the data related to the defect to the software. Then he/she can input the film size and type, the location of source and the orientation of beams (Larson, 2011). The resulting picture will be quite similar to the real one.

This is a big advantage for operators, since they can adjust the exposure time and other parameters, and this enables them to have a picture of the result of the test in their mind. This will result in reduction of cost and elapsed time. The ability of adjusting the parameters reduces the number of tests needed for a specific radiographic inspection and it also increases the quality and accuracy of the image and data gathered. A greater number of problems with much more varieties can be explored and many unwanted interruptions and undesired problems can be avoided in the real operation.

When an operator wants to inspect a newly installed or replaced part, and he/she doesn't have specific criteria for the new equipment, this method will be of interest. Since all the parameters that affect an inspection can be entered as input to this software and therefore there can be an estimation of energy range, focal point and other influencing factors in operator's mind when confronting the real situation. This will result in more accuracy of results.

The disadvantage of this method is that the densities of the CAD model and the real component may not match each other. At Figure 2.20 a schematic of XRSIM is shown.

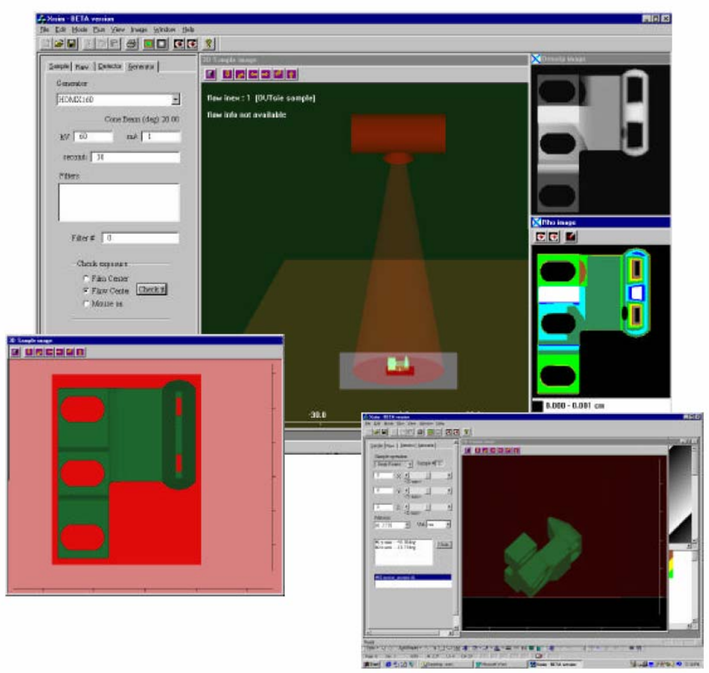


Figure 2.20: XRSIM software

2.8 Conclusion

Although RT is one of the leading NDT methods used for flowline inspection purposes, but some of its disadvantages such as radiation hazards, the need for more space to perform the test, heaviness of its equipment and etc. make companies to think of other easier methods with less or no hazards to apply instead. In some cases, there is the need to evacuate a certain area to perform the test. This interrupts with the other operations and activities going on within the plant. On the other hand, the advantages of this method such as documentation ability, precise results of test (if the test meets all the requirements) and etc. keep this method still as one of the most preferred methods for flowline inspection purposes. Advanced technologies associated with this method, try to have less radiation hazards along with better quality of pictures. Besides it should be mentioned that this method can be applied for any type of material and this itself is a remarkable advantage for this method.

The requirements and limitations of this method should be considered when the evaluations are being done on the results of RT. The procedures and instructions of this method described in this chapter showed that this method needs highly trained operators who are able to precisely perform the test and accurately interpret the images. Its limitations can affect the frequency of using this method. Within the following chapters, the influencing factors will be discussed and recommendations will be included.

3. Ultrasonic Testing of flowlines

After explaining the principles of RT at the previous chapter, Ultrasonic Testing (UT) as one of the other major inspection methods used for the flowline inspection by the company will be described in this chapter. Within this chapter the limitations, advantages and disadvantages of this method will be explained and discussed. The aim of this chapter is to provide a comprehensive picture of UT, which will be useful in further evaluations within the following chapters since UT is one of the most used NDT methods. The reasons behind applying this method are important when the frequency of this method is being investigated. Basic principles of UT are of paramount importance since all the new technologies of UT such as TOFD and Phased Arrays use these principles to detect defects. These two advanced UT methods are considered as recommended methods which are going to be explained in detail within chapter 5.

UT is basically dependent on the way that sound wave passes through the material. The frequency of vibration of sound waves in ultrasonic testing is so high that human is not able to hear that, and actually this is the reason that it is called ultrasonic. The frequency of ultrasonic waves is higher than 20,000 vibrations in a second (Hertz) which is the maximum frequency for an audible sound wave for the human (human can hear sounds with frequencies higher than 20 Hz and lower than 20,000 HZ). The frequency of sound waves produced in ultrasonic testing in NDT ranges from 50 Hz to as high as GHz! The way that the sound way passes through the solid material (as well as air and liquid one) can be predicted and represented mathematically (Shull, 2002).

Although UT principles seem to be complicated because of all those mathematical calculations, it is based on very simple procedures. With the help of mathematics, inspectors are capable of producing their desired kind of waves by transducers so that they will be able to have better understanding of the solid material's nature including its thickness, its elasticity, its defects and so on (Shull, 2002).

Sonic waves propagate in solids near to 15 times faster than their speed in air. On the other hand sound waves cannot pass through vacuum at all (Shull, 2002). By considering this feature of sound waves, NDT inspectors use ultrasonic testing to measure the elastic properties of material, its density and geometry, structure, detecting defects and above all to inspect any changes in material's composition since different composites have different effect on the sound wave. Size, shape and position of flaws can also be determined and the severity of defects can be measured and evaluated respectively.

The basic method of ultrasonic testing is transforming a voltage pulse to an ultrasonic pulse using a transducer, and then transmitting this pulse into the object by placing the transducer on that. The signal travels through the object with respect to its geometry and existing defects and then is either transmitted to another transducer or reflected back to the original transducer. The first principle which the signal is transmitted from one transducer to another one is called "pitch-catch method", and the other principle which the signal is reflected back to the original transducer is called "pulse-echo method". On both of these methods, the signal is then transformed to an electrical pulse, and then can be observed and read using an oscilloscope (Shull, 2002).

For describing how the process goes on, a typical pulse-echo system is illustrated at Figure 3.1. This system consists of a transducer/receiver, displaying part and other functional units. A pulse transducer is a device that sends the pulse into the object and receives it at the end after the pulse has traveled through the object (Larson, 2011). During the time that pulse passes through the material, defects and flaws affect its way and a small portion of the pulse will be sent back to the transducer/receiver before it hits the end of the object. This creates smaller reflection indications than the initial pulse and the end pulse. At the picture illustrated you can see the effect of a flaw within an item on the pulse. All these pulses will be received by the receiver and will be shown on the displaying device.

Ultrasonic testing is based on acoustics which refers to time-dependent vibrations in material. All materials are made of atoms and atoms can be forced to vibrate or oscillate about their equilibrium position. There are many patterns of vibrations of atoms that some of them, not all of the, are used at ultrasonic testing. Acoustics is about the movement of particles which consist of several atoms in order to produce mechanical wave. Depending on how the particles oscillate, there are four different waves that propagate within the material. These four different principles of wave propagation include: shear waves, longitudinal waves, surface waves and in thin materials plate waves. Longitudinal and shear waves are the most used ones of them in ultrasonic testing (Larson, 2011). Surface waves travel through the surface of material and can penetrate the object as long as their wavelength. Plane waves have almost the same features as surface waves, but they can go within the material and penetrate it up to a few numbers of wavelengths.

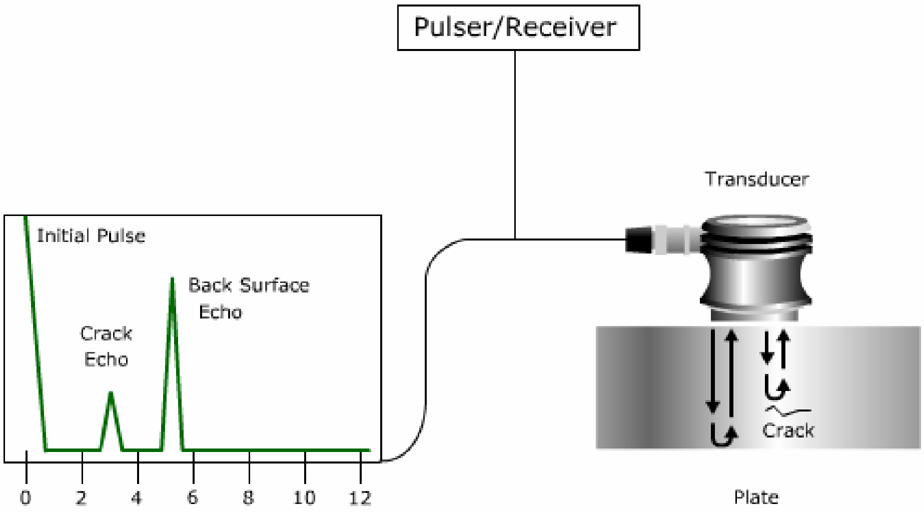


Figure 3.1: typical pulse-echo UT system (Larson, 2011)

Longitudinal waves oscillate at the same direction as the wave propagation direction. These waves are also called pressure or compressional waves since there are forces in this type of waves that force the wave (compress the wave) and then expand it (decompress the wave). Another name for longitudinal wave is density wave since the particles' density fluctuates as the wave propagates. Shear waves are weaker in compare to longitudinal waves and particle vibration transverse the direction of wave propagation direction and is perpendicular to wave direction. At figure below an illustration of both waves is provided. (Larson, 2011)

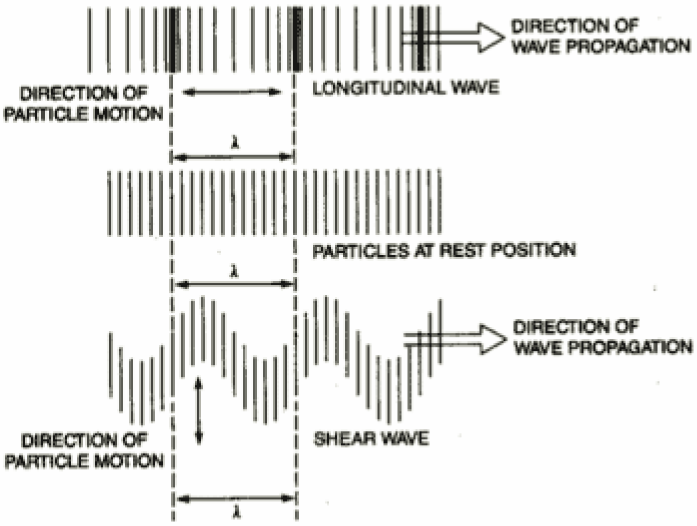


Figure 3.2: longitudinal waves vs. shear waves (Larson, 2011)

The wavelength (λ) is shown at the picture above and its relation with the velocity and the frequency of the wave is shown at the formula 3.1.

$$\text{Wavelength } (\lambda) = \frac{Velocity(v)}{Frequency(f)} \qquad (3.1)$$

As it is clear from the formula, assuming that the velocity of the wave remains the same and is constant, by increasing the frequency of the wave, its wavelength will be decreased, and this is one of the most important influencing factors in ultrasonic testing. As a rule of thumb, the size of the defect should be bigger than one-half the wavelength in order to have a good chance of being detected (Larson, 2011). Determining the appropriate wavelength is a challenge for the inspectors in designing and implementing phases of the inspection.

The other most used terms in ultrasonic testing are sensitivity and resolution and describe the technique's ability to detect the flaws. Sensitivity represents the technique's ability in finding out the small defects and it increases with decreasing wavelength. Resolution, on the other hand, refers to the technique's ability of finding out the defects that are close to each other inside the material or are located near the part surface. Just like sensitivity, resolution increases as the frequency increases. In other words decreasing or small wavelength leads to high sensitivity and resolution. (Larson, 2011)

As discussed earlier, the speed of sound wave in solids is almost 15 times higher than its speed in air. Since the surface of the objects under inspection is not absolutely clean and smooth and there are some small holes and up-and-downs on the surface of object, which probably cannot be seen by the naked eye, the air becomes trapped between the probe and the surface, therefore the speed of sound after quitting the probe will be significantly decreased by the effect of air existing there between the probe and the surface. In order to remove this problem and exclude the air and its effect on the speed of sound, inspectors apply a suitable gel couplant to ensure transmission of ultrasound to the items being inspected. In the following pictures the different steps of applying the gel for running ultrasonic testing are shown:

Figure 3.3: different steps of applying ultrasonic gel (couplant) to the surface of the item [Source: iqs-nde.com]

3.1 UT practical considerations

As in any NDT method, there are some practical considerations which should be taken into account by inspectors in designing, planning and operating phases of inspection processes. If these are not carefully considered and enough attention is not paid to them, it will result in poor design, poor selection of key inspection points failures and etc. It is tried to gather all considerations and put them all together in this part of chapter which is provided below:

3.1.1 Attenuation: The first practical factor that can influence the result of the ultrasonic testing is attenuation. When the sound wave passes its way through the object, its intensity attenuates and diminishes with the distance. All materials have a weakening effect on the sound wave. This weakening effect initiates from three basic factors: scattering, absorption and beam scattering.

Scattering is the reflection of the sound wave when hitting discontinuities to different directions other than desired ones. In other words, scattering is the phenomenon which the sound wave deviates from its original direction due to reflection, refraction and diffraction. Beam scattering, the second influencing factor on attenuation phenomenon, is the geometrical expansion and divergence of a non-planar wave-front. Absorption, on the other hand, is the conversion of sound energy to other types of energy. The challenge for the inspector is to create a balance between these factors in order to decrease the amount of attenuation. As a rule of thumb, for low frequency waves (large wavelength), there will be large beam spreading losses, and low scattering losses. Vice versa, for the large frequency waves (low wavelength), there will be low beam spreading losses while there are large scattering losses. (Shull, 2002)

3.1.2 Acoustic Impedance: (Z) mathematically is described as sound pressure (p) divided by the particle velocity (v) and the surface area (S), that an acoustic wave with frequency (f) is passing through that. The formula is shown below (Shull, 2002):

$$Z = \frac{p}{vS} \qquad (3.2)$$

The behavior of sound wave when it encounters a boundary is the basic of ultrasonic testing method. Any changes within the object consisting, voids, cracks, inclusions, coating and etc. can be easily figured out considering the differences in elastic properties or acoustic impedances of materials existing within the object. Acoustic impedance is important to be considered because (Larson, 2011):

- The difference between two materials’ acoustic impedance will determine the acoustic transmission and reflection
- It is an influencing factor in the design of ultrasonic transducers
- It can be used for the evaluation of absorption of sound in a material

3. *Interaction:* In addition to acoustic impedance, one should consider the impact on interaction of several waves. When this interaction occurs, the amplitude of the sound pressure or particle displacement at any point of interaction will be the sum of the two or several individual waves at that point. At the figure below an illustration of three different possible interactions is provided:

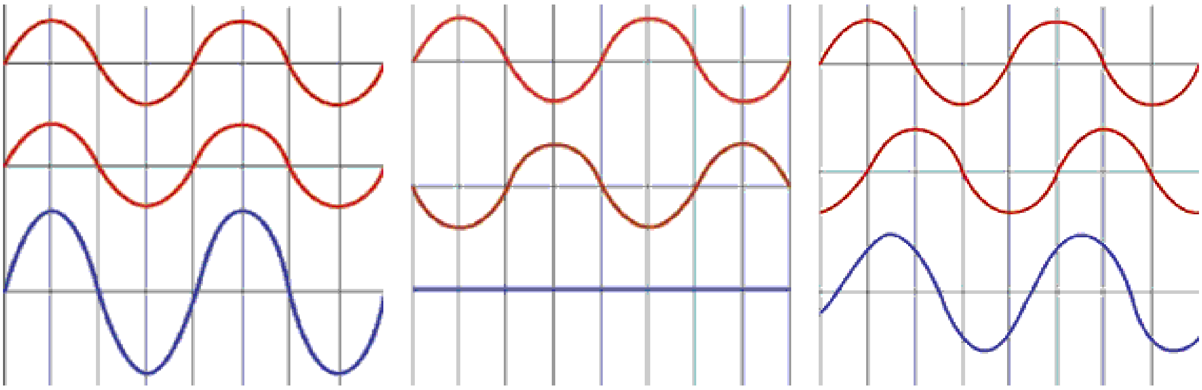


Figure 3.4: interaction of two individual waves (Red) and the resulting wave (Blue) (Larson, 2011)

At the first image from left, two identical waves are considered. This situation is called "in phase" so that the peaks and valleys of both waves are exactly the same, and the resulting effect will be doubling the displacement of each particle. But the second picture (the one in middle) is the opposite of the first one. Two waves are called "out of phase" and cancel each other's effect out, and in other words they eliminate each other. The last one but is neither *in phase* nor *out of phase,* and the resulting image will be just the sum of the two individual waves at each point.

3.1.3 Transducers: as discussed earlier, the basic principle of the ultrasonic testing is the conversion of electrical energy to acoustic energy and vice versa. This is achieved by the use of transducers. Since sending and receiving sound waves are done by transducer, its type and limitations will determine our ability and existing limitations in ultrasonic testing method. Depending on the method of creating ultrasonic wave, there are three main various transducers including: Piezoelectric, Electro Magnetic Acoustic Transducer (EMAT), and laser (optical) methods (Shull, 2002). Therefore choosing the proper transducer with regard to existing limitations and performing the optimal test and acquiring the precise results will remain as a challenge and important practical consideration to be taken into account.

- Piezoelectric transducer: this is the most common transducer used in ultrasonic testing methods. The transformation of electrical energy to acoustic energy and vice versa is done by using an active element in piezoelectric transducer. The active element is a polarized material (imagine a thin disk) with two electrodes attached in its opposite sides to its surface. When a current is applied (alternating voltage pulse) the disk will contract and expand, creating an ultrasonic wave. Conversely, if an ultrasonic wave passes through the disk, the disk will expand and contract, creating an alternating voltage pulse between the electrodes (Shull, 2002; Larson, 2011). This shows how a piezoelectric transducer can act both as a generator and as a receiver. The quality of both generated and received ultrasonic wave depends on the material properties of the piezoelectric transducer (since the transducer can be made of various materials) (Shull, 2002). Generally piezoelectric transducers vibrate at the fundamental frequency determined as:

$$f = \frac{V(\text{crystal})}{2d} \qquad (3.3)$$

There are two types of effects of piezoelectric material, direct and indirect effects, which each one of them refers to generating or receiving materials' quality. *Direct piezoelectric effect* describes the phenomenon that the piezoelectric material responds to the mechanical stress by creating an electrical charge on its surface. Therefore this effect relates the mechanical deformation to output charge and is considered as an indication of the quality of the receiver. On the other hand, *indirect piezoelectric effect*, describes the phenomenon that the piezoelectric material responds to an electrical field by creating mechanical deformation. Therefore it relates the electrical input charge to the output stress so that it is an indication of quality of the generator. (Shull, 2002).

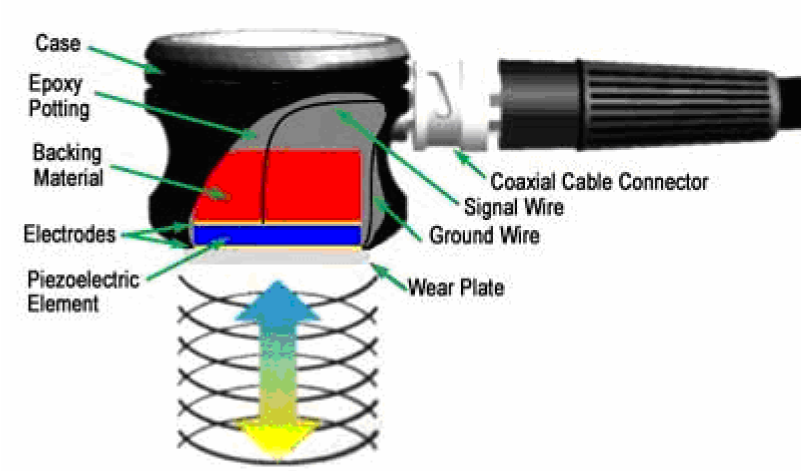


Figure 3.5: different parts of a piezoelectric transducer (Larson, 2011)

There are two types of available piezoelectric material. Some are natural and the others are artificially made. Quartz (SiO_2) and tourmaline are probably the most well-known naturally available piezoelectric material. Artificially made piezoelectric materials include ceramics (such as barium titanate, lead zirconate titanate), PVDF (polymeric film) and etc. But one should consider that the artificial piezoelectric material should be poled to align the piezoelectric (ferroelectric) domains. Piezoelectric material can also be categorized with respect to: types of waves generated, broadband or narrowband, transducer's face and etc. (Shull, 2002). The transducer's efficiency depends on its function. Some transducers are perfect to function as transmitters and generators and this does not necessarily mean that they are also good receivers. The ability of the transducer in finding defects near to surface needs efficiency in both receiving and generating properties of the transducer. To evaluate the efficiency one should also consider the bandwidth which is the range of frequencies applicable by that special transducer (Larson, 2011).

- <u>Electromagnetic Acoustic Transducer (EMAT):</u>

Electromagnetic acoustic transducer enables inspectors to have high speed inspection for those parts that surface contact is prohibited. One of the features of this method is that there is no need for couplant to effectively transmit the sound to the object material since the sound wave is directly generated within the material. In Figure 3.6, a schematic comparison between piezoelectric transducer and EMAT is shown.

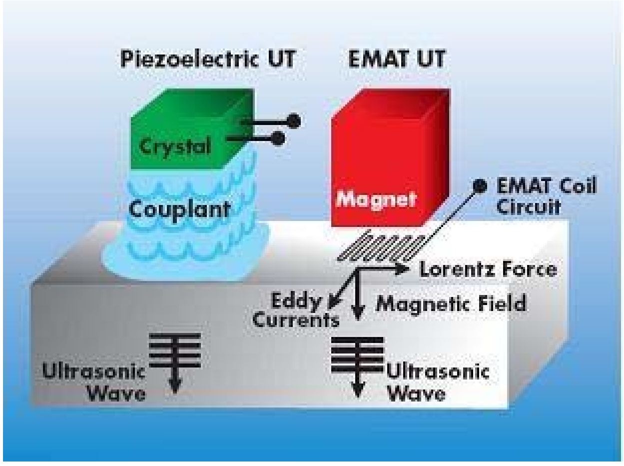


Figure 3.6: Piezoelectric UT vs. EMAT UT (Source: innerspec.com)

A coil circuit is placed near to the surface of the electrically conducting object and the current I is sent through that with the desired frequency. This current generates magnetic field $\vec{B}$. The alternating magnetic field will induce an equal eddy current but with opposite direction in the surface of the object. The eddy current is induced at the very thin layer of the surface of the material called skin depth. When this eddy current is produced in the magnetic field in metal surface, it experiences the Lorentz force in the air gap (Starman, n.d.):

$$\vec{F} = \vec{I} \times \vec{B} \qquad (3.4)$$

This force will result in generation of elastic sound wave within the object from the surface.

For describing the detection of ultrasonic wave process, one can easily consider reversed process of generating the wave. Particle vibrations caused by existing magnetic field create a current in the material which induces a current in coil. Therefore, the magnitude and the frequency of the ultrasonic wave is transferred to a measurable current which is flowing in the coil. (Shull, 2002)

The main advantages of EMAT include:

- It is a non-contact method.
- There is no need for couplant.

- It can be deployed at high temperatures. Since immersion results in evaporation and gaseous mixtures of evaporated couplant causes loss of coupling. Instead the transducer can be cooled by cold air (Starman, n.d.).
- There is no or less surface preparation of the surface before test. The only requirement is to provide a clean surface of object.
- EMAT provides an easy way of producing shear bulk waves and shear guided waves

Disadvantages of EMAT include:

- Complicated techniques are needed to exclude the noise from the raw signal since EMAT transducers produce low raw signal (Starman, n.d.)
- EMAT cannot be efficiently and effectively applied for ceramics and plastics, and it is only limited to magnetic and metallic material (ferromagnetic material) (Starman, n.d.)
- The equipment needed to perform the test are rather big in size

- Laser (optical) methods:

Laser-based UT is one of the common ultrasonic testing methods that is relatively able to operate in long distances and this makes the laser-based inspection one of the methods that can be applied in certain areas and applications. One of the other features of this method is that both of its two components including laser-generation and laser-detection can be used in combination with other transducers. On the contrary, this method has low sensitivity, and it is susceptible to vibrations. This method needs special operator training to gain the proper skills and it can damage the object surface.(Shull, 2002)

In laser (optical) generation process, a high energy pulsed optical beam is imposed to the item's surface. Depending on the behavior of beam after striking the object surface, material's ability in absorbing the energy and the energy density of the pulse, there are two types of the interaction between the optical beam and the object surface: Ablative and Thermoelastic (Shull, 2002; Caron et al., 1998). The absorbed energy by the surface converts to thermal energy leading to thermal expansion of the material surface. This rapid expansion creates thermoelastic ultrasonic wave which goes through the object materials. But there is a limit for laser intensity since higher intensities lead to surface melting and vaporization. The laser power density at vaporization point is called ablation threshold (Caron et al., 1998).

As discussed before, detection and generation processes in the other two transducers is simply like each other but with the only difference that the detection process is just the conversed process of the generation. But laser detection is not the conversed procedure of its generation process. Laser waves are detected by the other two transducers, EMAT and piezoelectric transducers. (Shull, 2002)

After all, it should be noticed that each probe has its own directivity which means each probe has a certain amount of coverage on certain parts of the object. Shape of the defect, e.g. volumetric void, will influence the shape and type of the probe we use. In the following parts another practical considerations will be introduced and discussed.

3.1.4 Geometry effect

Geometry effect is seemed to be one of the most important and influencing factors in non-destructive testing methods. It can create problems for the UT inspectors by limiting the access to surfaces for scanning probes. Limited access does not allow the inspectors to move the probe easily on the surface and scan the object. It can also cause slips, lapses and mistakes by the inspectors since limited access just makes the operator more tired and uncomfortable leading to loss of concentration. It can restrict the coverage of welds by different probes. The other affect that geometry can have on test results, is that it can lead to creation of echoes which will interfere the waves coming back from defects and flaws, so that it can mislead us to the point that we may conclude there is no defect within the object. The echoes in welds can be produced by the weld roots and caps, improperly fused areas, and from the end wall. (Bainbridge, 2008)

Thickness effect is one of the other geometry parameters that affects the type of probe to be chosen. For thicknesses less than 8 mm or very thick components special types of probes are required (Bainbridge, 2008).

As it seems, inspector's skills and the way he/she is trained will be very important in performing the test. In the design phase, all the geometry aspects of the items should be considered and it is recommended that in this phase, there should be a level 3 inspector present in the team to give ideas and feedback to the designers in order to have the most effective plan as possible (Bainbridge, 2008).

3.1.5 Material effect

Materials that are attenuative, or have properties that distort the ultrasonic beam, such as austenitic steel, need more attention and consideration and they need special UT methods to be used for them. Distortion of beams can create high amounts of noise and distracts operators from finding out the defects. Inspectors need special qualifications and skills to use UT methods for such materials. (Bainbridge, 2008)

3.1.6 Coating, Painting effect

Any changes within the object including voids, defects, flaws and changes in the type of material of the object will interfere with the ultrasonic wave resulting in attenuation, wave distortion and noise creation. This reduces the effectiveness and efficiency of the ultrasonic testing since the background noise is increased and the signal received from the defect will be reduced. Wavy and undulating surfaces reduce the efficiency of coupling leading to poor and incorrect estimations of size and position of the defects. All these mentioned parameters can increase the probability of making mistakes by the operator. To avoid this, it is recommended to check for bonding and attenuation to have effective inspection procedures in case that the removal of painting and coating is not possible. (Bainbridge, 2008)

3.1.7 Inspector performance

As well as other NDT methods, operator's performance has a significant impact on the results of this test. Like radiographic testing, interpretation of results is very important and operators should pass special courses of training to acquire the required skills, since noises and echoes can make the situation very hard for the inspector to conclude what type and what size of defect is there within the material.

As discussed above, unlike ultrasonic testing, some NDT methods such as radiographic testing provide documentation ability for us that decreases the effect of mistakes and lapses made by operators. In radiographic testing there is a picture- a document- as a result of each inspection, so that every single inspection test's result can be review and re-commented by different experts and this, in a sense, increases the reliability of this method since some factors such as inspector's motivation and mood cannot influence the results that are going to be reported. Each picture can be reviewed and reassessed helping operators and managers to be sure of the conclusions. But unfortunately unlike RT, ultrasonic testing highly relies on inspector's mood and motivation, his/her degree of vigilance at the time of inspection. The inspector moves the probe on the surface, gives proper angles and etc. and read the results on the screen of the device. How to move the probe, how to give right angles and parameters like that, and above all reading the results from the screen all highly depends on the operator's mood and vigilance.

In order to avoid such misinterpretation and mistakes, a reasonable time should be allocated for the inspection and there should be enough breaks in between different inspections. It is recommended that each test should be repeated for a couple of times and use of semi-automatic inspection should also be of consideration. For example, for those inspectors that want to work with weld examination, they should be qualified in accordance with EN473/NORDTEST level II or equivalent.

3.1.8 Thickness

Thickness of the material is of the most important influencing factors of the ultrasonic testing. Instructions for ultrasonic weld examination are provided in standards and frameworks by the company, describing each necessary step and required parameters. For instance, the effect of thickness is described in one of the mentioned frameworks stating that the angle of probes (straight beam probes) to give a sound angle of 45°, 60° or 70° will vary depending on the thickness of the item and the weld geometry. This shows the impact of thickness as one of the decision criteria of ultrasonic testing.

In the chapter related to standards there are various matrixes showing the wall thickness and pipe diameter's effect on selection of the appropriate method.

3.2 Advantages and Disadvantages

With regard to what is discussed until now, the advantages and disadvantages of ultrasonic testing method are as follows:

Advantages:

- UT is flexible, portable and has high sensitivity and high penetration depth.
- It is applicable in wide range of industries
- UT is able to detect subsurface defects
- Unlike radiographic testing, there is no health or environmental risk involved
- It can be applied both in contact and non-contact ways
- It can be applied for all types of material from biological to metal and ceramics
- Highly accurate and capable of sizing and positioning of the defects
- Can measure density and material properties and can be used for complex geometries

Disadvantages:

- It requires highly-trained and well-skilled operators
- There is the need for gel or couplant in contact methods which are the most used ones
- Unable or not efficient in detecting planar defect that are in parallel with the direction of sound wave
- Some geometries can not be inspected by UT
- Can be very expensive

3.3 Conclusion

The conventional UT is highly dependent on the level that the operator is trained. Basically all NDT methods require skilled and experienced operators, but this requirement is amplified in UT. Even in some cases, when the operators want to be sure of the ultrasonic results, they apply RT for verification. On the other hand, UT has no health or environmental hazards. Advantages of UT combined with recently introduced technologies offer this method as one of the most preferred NDT methods by the companies around the world. New technologies using basic principles of UT explained in this chapter are rapidly being used regarding better quality of results they give. Limitations, advantages and disadvantages of UT explained in this chapter should be considered when the frequency and accuracy of this method are being investigated.

4. Evaluation of the NDT methods used for flowline inspection

Depending on the demands and requirements of planners and inspectors there are numerous matrixes available in the oil and gas industry. Some of these matrixes and tables are developed within different organizations that are in charge of creating standards such as DNV, ASME and etc. Below you can see one of the major matrixes that is used by inspection planners in this company. As you can see, depending on the pipe diameter and wall-thickness there are two recommended NDT methods to be used. The first method is in priority and says that first this method should be used for the inspection of such part, if not the second method will be applied. This matrix shown here is directly translated from Norwegian to English to ease reading and understanding. This table is provided for the inspection of flowlines.

Note! The abbreviations used for NDT methods are changed and described under the table. This is due to the data sheets and tables that the company uses and are all used here within the evaluations.

Table 4.1: selection of NDT method depending on the pipe diameter and wall-thickness

Pipe diameter	Wall-thickness (mm)	Inspection item	Inspection method (prior)	Inspection method (second)	Comments
6″ - 8″	> 21	Weld	RK(1)	UL(2)	UL for verifying the corrosion
6″ - 8″	> 21	T- Joint	VIS	RKT(3)	
6″ - 8″	> 21	Pipe	UL	RK	
6″ - 8″	> 21	bend	UL	RK	

(1) RK stands for radiographic testing- contact method
(2) UL stands for ultrasonic testing
(3) RKT stands for radiographic testing tangential method

As I mentioned above, the data for production flowlines will be used. But it would be better and useful to go through the data to have some statistical results in mind before starting the desired assessment.

4.1 Evaluation of recommended methods for pipes

4.1.1 Evaluation of the number of inspections (frequency) using each method

First of all the data related to all flowlines from the X-mass tree to the production manifold of this offshore field are gathered. The production wells are considered here. For instance A20 is a production well at this field. How to filter the data to get the desired ones is an issue here. What is done here, is to filter the data related to a certain production well. Then all data related to just A20 (which is the number of production well) get filtered regarding the item or part being inspected. Therefore in this step here, the data is filtered for the pipes (by excluding data for flanges, end-caps, bearing, welds, and T-junctions). The diameter of this pipe is 8″. So it falls to the third category of the matrix above. As it is told in the matrix, the first recommended (main) method is ultrasonic testing (UL) and the second one is radiographic testing- contact method.

The graph shown below is provided by counting the number of inspections performed using UL, RK and VIS (visual inspection) for pipes of flowline number A20. It should be noticed that visual inspection is not the recommended method according to the matrix shown above. However, this chart shows that plans can be made and changed based upon the inspectors’ experience and planners’ expectations. In order to reduce the costs, when they feel that the trend of corrosion in a part is clear and predictable, they just perform visual inspection. VIS can be a reliable method for the inspection of certain parts if the inspectors have the required skills and experience.

The second important point that Figure 4.1 illustrates, is the application of RK as the second recommended method by the matrix while it has been deployed only once. This is an indication of reliability of UL and its role and importance for the inspectors.

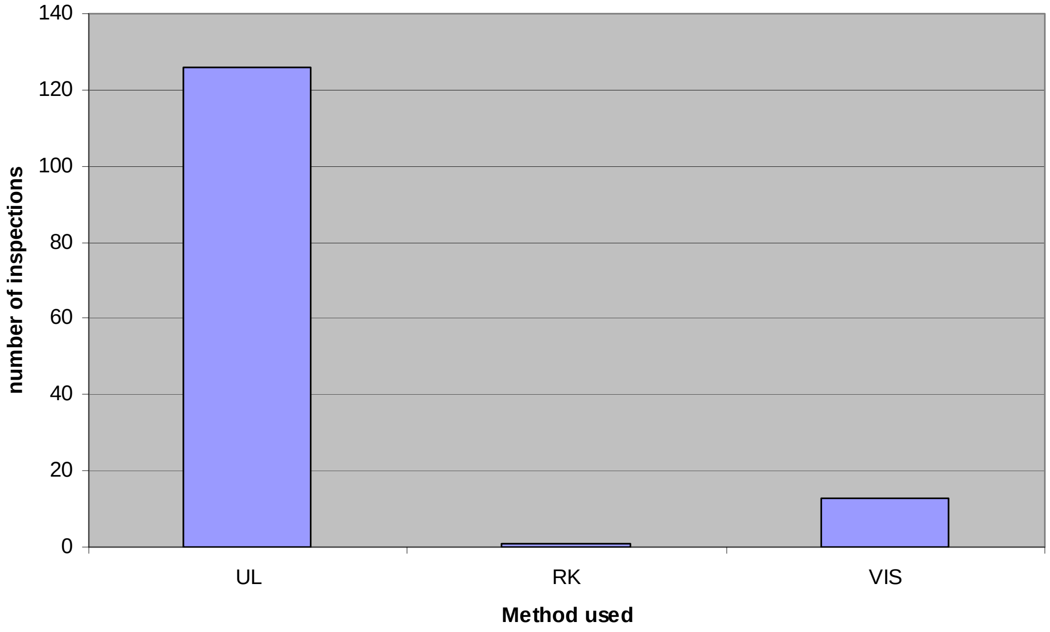


Figure 4.1: number of inspections done vs. the used methods for Flowline A20

By looking at the chart above, we can see that 126 inspections have been done by using ultrasonic testing, one with radiographic testing and 13 with visual inspection. It should be mentioned that these inspections have been performed within the period of 11 years.

This will be more interesting if we do the same procedure for another production well. A13 is the second production well considered here. The same procedure for filtering the data is applied for that. The flowline has two diameters on its way from X-mass tree to the production manifold including 1″ and 8″. However, the pipes with 8″ diameter is considered here.

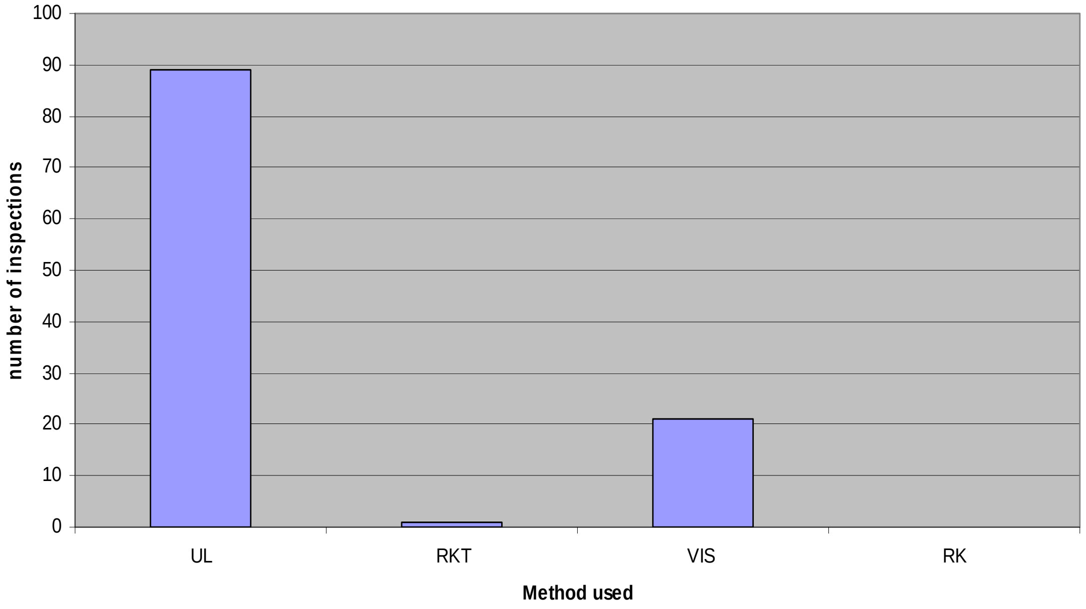


Figure 4.2: number of inspections done vs. the used methods for Flowline A13

By looking at the results of inspection and the chart shown above, it can be concluded that ultrasonic testing, as expected, is the major method used for inspection of pipelines. But instead of contact method for radiographic testing, which is the one recommended by the table 4.1, the tangential method of RK is used (RKT). Visual inspection is also used despite the fact that it wasn't recommended by the table. The chart shows that for the inspection of the flowline of 8″ diameter for well A13 from X-mass tree to the production manifold, Ultrasonic testing has been used for 89 times, RKT once and Visual inspection for 21 times within the period from 2000 to 2010. These charts reveal some important points:

1. Instead of RK, RKT is used in some inspections
2. Visual inspection is one of the most used methods while it is not recommended by the matrix

In order to explain the reason that some flowlines have been inspected quite more often than the other ones, all the factors that influence the frequency of inspections should be taken into consideration. These factors include:

- Installation date
- Type of material
- Finding rate
- Sand production of each well
- Water content of the flow in each well
- Flow velocity
- Etc.

As elderly installed the pipe becomes, more frequent inspections are required. Obviously some factors such as faster degradation rate as time elapses after installation will make the pipe more and more vulnerable to corrosion, erosion and all other degrading mechanisms during its lifetime. Increased number of finding rate is a clue of degradation taking place in the part and this brings the need for more precise monitoring and frequent inspections. Overall, the pipe will be corroded faster and faster if the amount of each one of aforementioned factors increases.

In order to explain the reason that RKT has been used instead of RK one should consider two points of view from both inspectors and planners. Planners believe that this replacement can happen because of the inspector's decision at the last moment in the field depending on the conditions of the part. Also they believe that RKT is generally better than RK for duplex material since duplex material has less wall-thickness than carbon steel, and regarding the degradation mechanisms RKT is preferred in some cases to RK. On the other hand inspectors say that in some cases in order to verify the result of ultrasonic testing, if possible, they use radiographic testing- tangential method. But one also should keep the fact in mind that RKT is more recommended for pipes with small diameters and it is very hard to be used for 8″ pipes and if used, the results cannot be reliable that much unless inspectors clearly explain the procedure and convince the others that the results are reliable enough to be used in further planning. In addition to all these possible reasons, we should pay attention to comments written by inspectors. Normally in such cases, inspectors explain why they used such method.

The application of close visual inspection method while it is not recommended by the matrix is the other considered observation here. Since the criticality of flowlines is high, in certain time intervals, inspectors stop the flow within a flowline, open the flanges and visually inspect the flanges (different points) for any type of defect. During this process, planners usually ask inspectors, when they open the flanges, they should take a look to the interior part of the pipe until the distance it is possible to be inspected visually. So this is more like that they manage the time and they use the time of visually inspecting flanges also for visually inspecting the pipes for any type of degradation. For example when an end-cap is opened to be visually inspected, the end-cap, the flange, the T-junction and welds around that, and obviously the pipe within this area all will inspected visually and reported separately for each category of them. Therefore there will be no specification of visual inspection in the matrix, but it will be performed during other visual inspections planned for other parts and will be reported within pipe's category. These inspections all are done by highly trained and skilled operators. On the other hand one cannot neglect the effect of visual inspection on further plans and programs. Visual inspection provides a good picture of the real situation and the acquired results out of that are very beneficial for further plans. In some cases when there seems to be a degradation trend happening at a specific spot on the pipe, the best practice to understand the real situation will be visual inspection. For example, if there is a pit on wall of a pipe, by using ultrasonic it becomes concluded that there is 3,5 mm pitting. By performing UL the year after, pitting seems to be 0,5 mm and this just doesn't make sense and the reason can be the difference in angles of probes and beams which are not the same in two cases and probably the inspector is not paying enough attention in performing the test. Therefore, a good way to get a true picture of the situation in mind can be visual inspection. Therefore, VIS (close) always exists in all inspection plans.

In order to have a comprehensive look at all methods used for all production wells the charts below are provided. All pipes have the diameter of 8″. It should be noticed that for the charts below, general visual inspection (VISG) and near visual inspection (VISN) are combined to one category called VIS. General visual inspection is used to get the picture of whole pipe in mind, but near visual inspection is for a specific part in the pipe that is inspected nearly and carefully and sometimes by using video cameras.

The results of number of inspections using Ultrasonic Testing (UL) is sketched against the production wells. By looking at this chart which is provided at Figure 4.3, we see that there are high numbers of UL inspections performed for wells A10 and A17. An outstanding decrease in the number of UL inspections is seen for well A30. There can be the possibility that A30 flowline is mostly composed of pipes with diameters less than 8″ or the number of other types of inspections used is more than UL. Therefore in the following charts and paragraphs these possibilities will be evaluated.

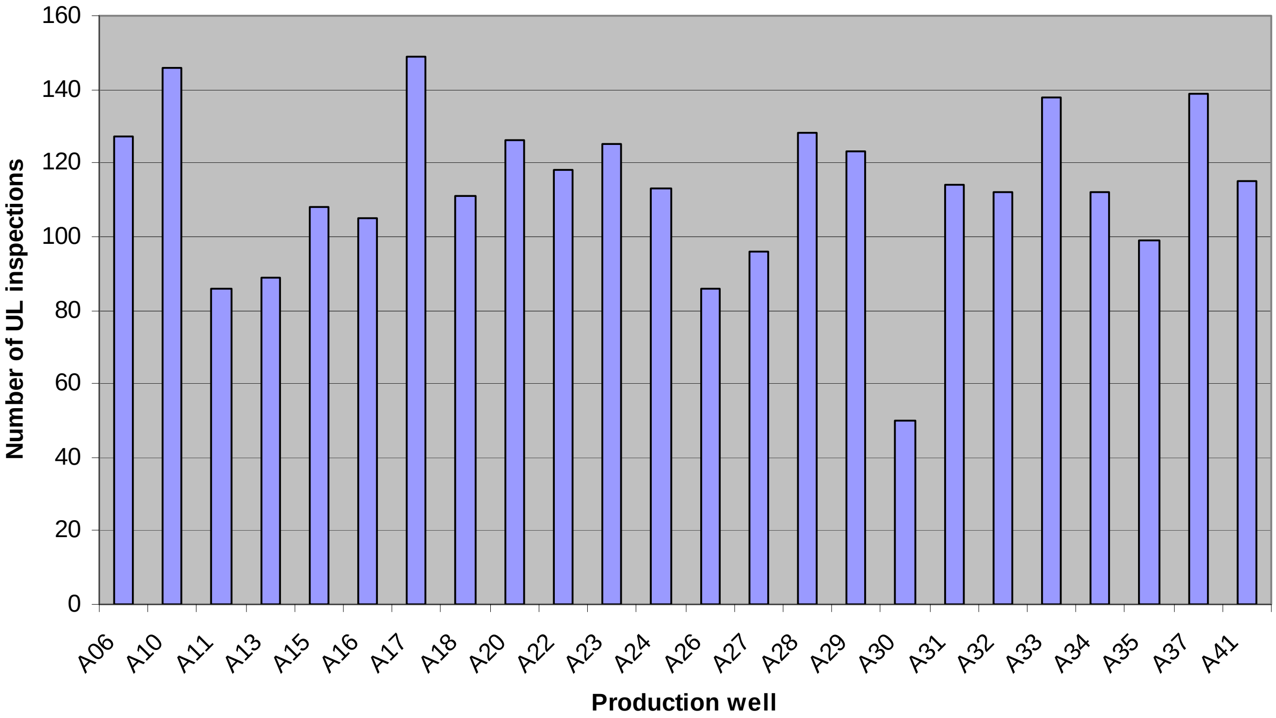


Figure 4.3: Number of UL inspections for each production wells

RKT is just applied for flowlines A13, A26 and A41.The other flowlines had no inspection by RKT. However, A13 with one, A26 with 6, and A41 with 4 RKT tests are among the ones that should be carefully seen in order to see what the reasons were for deploying RKT while it is not recommended by the matrix. In the evaluation section of this part the underlying reasons will be discussed more in details.

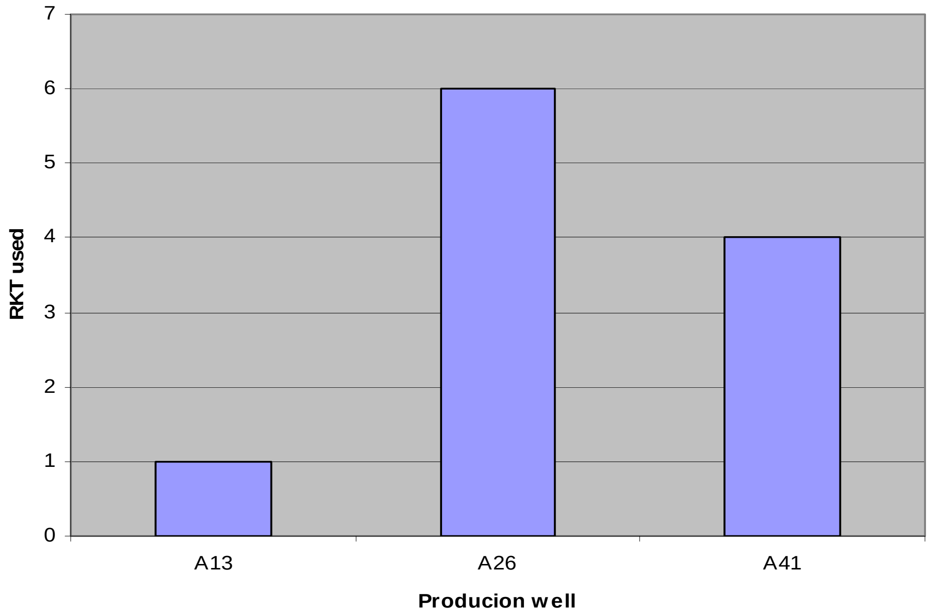


Figure 4.4: number of RKT used since it's just used in these 3 flowlines

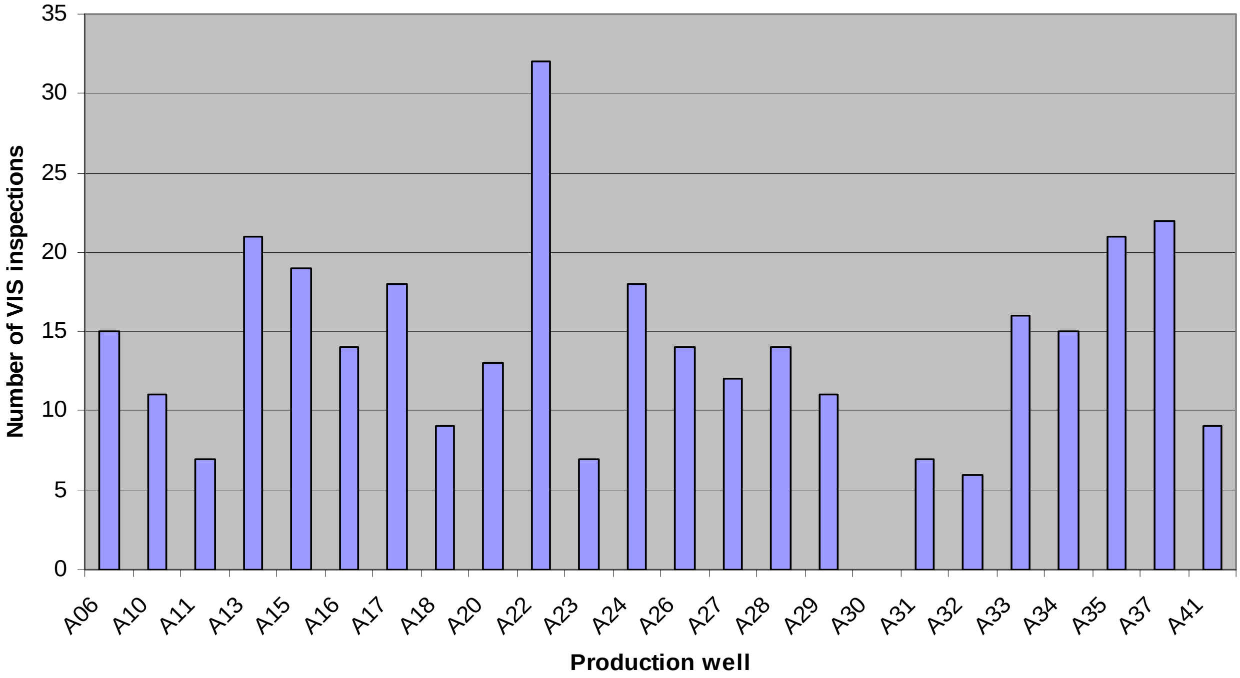


Figure 4.5: Number of VIS inspections for each production well

The frequency of visual inspections is shown at Figure 4.5. In this chart the exotic results are observed in A22 and A30. A22 which had the number of UL inspections near to the average amount (average number of UL inspections is 113,125), has a significant increase in number of visual inspections. The average number of visual inspections done for all 8″ pipes in this field is 13,79 and therefore, A22 with 32 visual inspections has a significant amount of visual inspection which in case is of interest to be evaluated in order to see the underlying reasons. Also flowlines from wells A11, A23, A31, and A32 are among the ones with rather few number of VIS inspections.

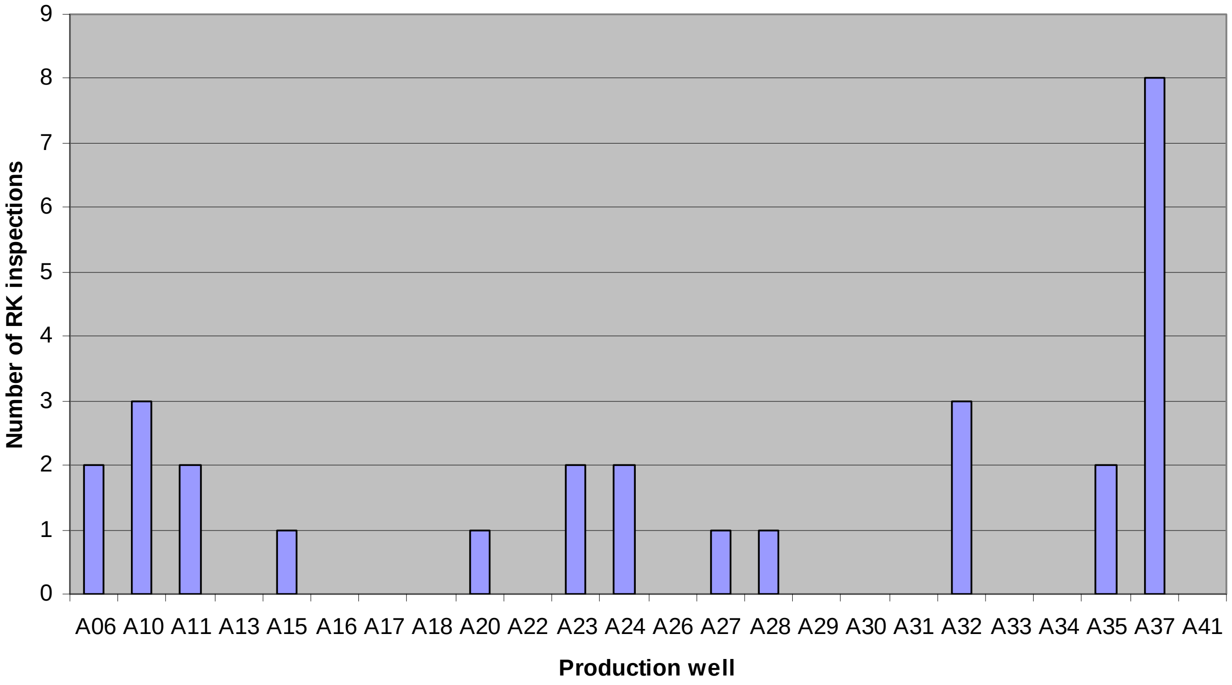


Figure 4.6: Number of RK inspections for each production well

RK (radiographic testing- contact method) as recommended by the matrix (table 4.1) is the second method that can be used for the inspection of pipelines with 8″ diameter. As it can be seen from the chart in Figure 4.6, the average number of inspections done by RK is 1,16 and A37 with 8 times has the highest number of inspections by RK.

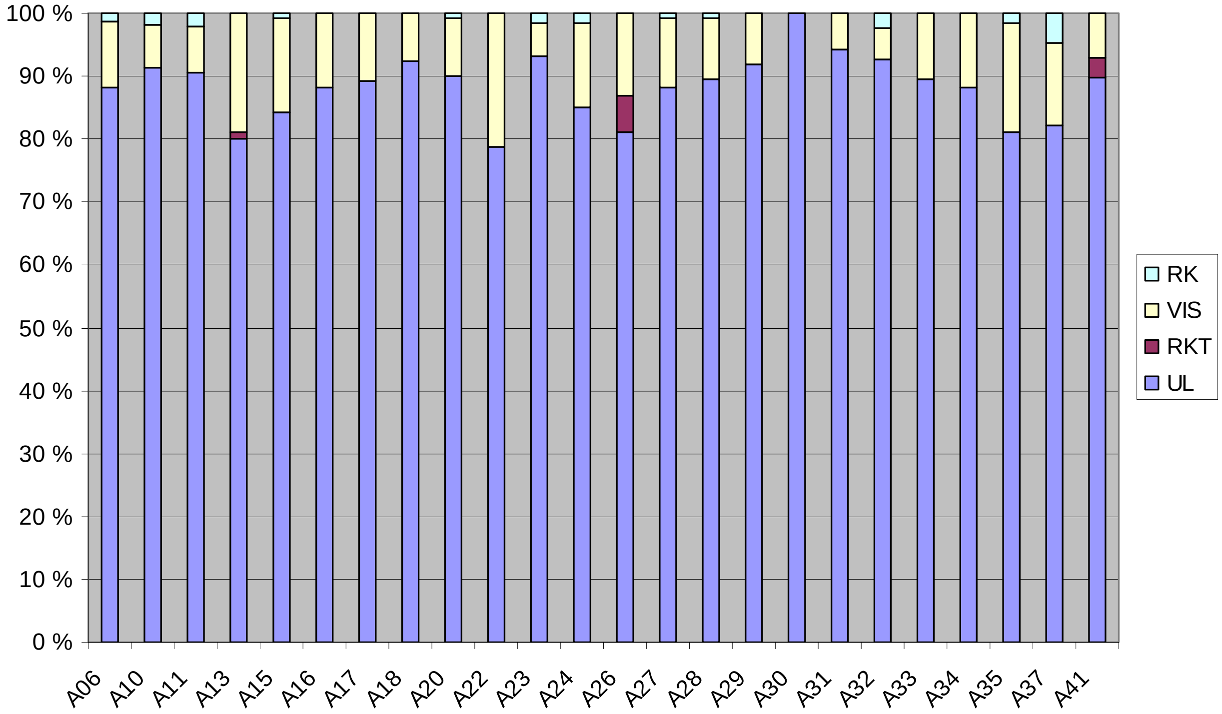


Figure 4.7: Percentage of each method used in inspection of each flowline

As it comes from the last chart, near to 80%- 90% of the inspections for each flowline are done by ultrasonic testing which was expected since this method is recommended as the first method to be used by the matrix. The remained part is almost covered by visual inspection which is not mentioned in the matrix; however, it is just a necessary part of the inspections.

This chart shows the importance of visual inspection which is not considered that imperative by the matrix. The picture that visual inspection gives to the operator's mind of the severity of damages, corrosion or any other type of degradation is the most useful result of the inspection.

Another point that should be noticed from the chart is that in some cases instead of having RK, RKT is used. This is going to be assessed here to see if it is useful and efficient; it should be put in the matrix as a recommendation.

4.1.2 Evaluation of results of charts

1- In the charts it is seen that for A30 there is neither radiographic testing nor visual inspection used for inspection purposes. It is just ultrasonic testing that is used, and UL itself is just used for 50 times within the period of 8 years, and this is just strange when someone looks at the results. There are various reasons that are going to be explained here. It is of concern in order to see if UL was not an efficient method for A30 and similar wells then this matrix should recommend other methodsfor such parts. The underlying reasons are revealed after various interviews with top employees and planners:

- *Change in well's definition*: since the pipe is installed in 1979, there is the possibility that first it was in use for injection purposes but from 2002 until now, it has been used as a production well, therefore less amount of inspection performed thus less information available, since the data are for production wells' inspection results..
- *Change in type of material*: the type of material is changed to 6MO then the pipe is kind of new thus there is less need for inspection.
- *Presence of dangerous chemicals*: visual inspection for pipes (just the pipe itself, without considering welds, flanges and etc.) in some cases is difficult since the interior part of the pipe is very dirty due to the presence of chemicals, sand, and all other sullied stuff. Use of some devices becomes almost impossible thus the situation becomes hardly possible to apply visual inspection. Besides, in some cases, it is worthless to just visually inspect the pipe in a long distance. As a result, visual inspection is not one of the highly recommended NDT methods to be performed on pipes. It is not providing any precise explanation of the condition of pipe since there is no preparation prior to visual inspection of pipes and in some parts presence of some dangerous or really dirty material makes it impossible to perform visual inspection
- *Zero production*: Zero production was the primary reason that the employees were thinking of. Considering the fact that the company knows e.g. a certain well will be out of production for a certain period of time then they can stop the inspection until it returns to the production state. Therefore the data related to inspection results get decreased significantly. However, this wasn't one of the underlying reasons here for this case.
- *Few finding rate:* Within the inspection period of 8 years, there are only 2 findings that indicate corrosion in pipe wall. This shows that this flowline is located in an area that the probability of corrosion or erosion or any other kind of degradation is very low. Therefore, with respect to rationalizing the resources it is not logically true to spend money and time for those areas that are not in critical conditions.

This well's material is 6MO (6 percent Molybdenum) and this type of material needs quite fewer amount of inspection and if there seems a need for an inspection UL will be sufficient to get good results. Since this type of material doesn't need high amount of inspection, using a complete scan of ultrasonic testing will be quite enough and efficient in order to find any flaw. Even visual inspection can be time consuming and wastage of energy for those parts that are believed to be good enough not to have flaws. On the other hand, this well mostly consists of pipes with 1″, 2″ and 6″

diameters which are not considered in the evaluations here since the matrix (table 4.1) focuses on 8″ diameter pipelines.

2- A22 has a high number of visual inspections: when someone looks at the results of inspections performed for well A22 observes that there is a significant increase in the number of visual inspections performed for flowline A22. As mentioned earlier, the average number of visual inspection for production wells for pipes of flowlines is 13,79 and A22 with 32 inspections seems odd. The underlying reasons could be:

- If the client doesn't inject enough chemical for the protection of pipe, therefore the number of visual inspections increases in order to check for any kind of unwanted corrosion or erosion. The increased number of visual inspections can help the planners to prepare more precise and efficient inspection programs.
- This can also happen if the quality of pipe is bad since it is getting more and more degraded as time goes on.
- If there is any sudden increase in sand production, water content, H_2S content and all other corroding parameters. This will force the company and inspectors to monitor the pipe more frequently in order to have better control on the pipe.
- Material Type: if the material type of the pipe is duplex then there will be no need to perform some of NDT methods such as ultrasonic testing. Instead to have a better picture of the pipe in mind, number of visual inspections increases for these certain pipes in compare to those with carbon steel material.

3- Number of RKT inspection is of consideration and as previously mentioned, the comments column should always be considered when some strange results are observed. Application of RKT can happen regarding the loss of wall-thickness. Planners and engineers consider the fact that all pipelines are created and installed based on the design criteria which are for the worst conditions that can exist (highest pressure and temperature). But after years of operations when the wall-thickness is less than what it was before, it doesn't necessarily mean that it should be replaced or repaired. In such cases, designers and engineers evaluate the available pressure and temperature, which can be extremely reduced because of the less reservoir pressure and changes in other existing conditions. Thus if they see that those criteria are far less than the design criteria, they can define a new $T_{Nominal}$ and new criteria such as T_{min3}. Therefore, for the thinner wall-thickness existing now, there can be a new determined wall-thickness or $T_{nominal.}$ Therefore, the corroded wall-thickness can be considered as a new wall-thickness for new existing conditions. Therefore if inspectors observe that the wall-thickness is low enough to use RKT, they will go for that.

4- In A26, which has 6 RKT inspections for 8″ diameter pipelines, when the comment column is looked, in front of all these 6 RKT inspections it says that this pipe in this spot has 2″ diameter and not 8″. Therefore, it is concluded that the wall-thickness is low enough to apply RKT. These sorts of things can happen when the drawings and data are being created for the first time. Pipes with 8″ diameter have branches with 2″ diameter. But within the data sheets, these spots are categorized under 8″ diameter. This can be considered as human mistake and ignorance in planning and preparing phase. Therefore the RKT used for A26 sounds correct and reasonable. This is the same reason for the use of RKT for A41. 3 out of 4 RKTs have been applied for a 2″ diameter pipe which is wrongly indicated as 8″ diameter pipe. Other factors such as type of material should be considered since RKT can, in some cases, be applied for duplex material even in high diameter pipelines since duplex material has quite little wall-thickness. Therefore, there is usually a reason behind applying RKT.

4.1.3 Evaluation of accuracy of each method used

To have a better picture of the results, it would be interesting if the results of inspection for just one specific spot within the plant get evaluated. This can be an indication of the accuracy and reliability of the methods used. In both UL and RK, and in general in all NDT methods, interpretation of results remains as a challenging and important issue for the operators and planners. Misinterpretation can lead to poor planning and therefore undesired failures.

To do so, thickness variations within pipes in certain spots within a period close to 10 years will be evaluated. Misinterpretation can be found out if the results reported are unusual. For example if the wall-thickness is 25,4 mm, after applying ultrasonic testing the wall-thickness becomes reported 22 mm. This shows that a degradation process is going on within the pipe and it is damaging the pipe. After one year, ultrasonic testing is again applied for the same spot at pipe and the wall-thickness becomes reported as 25,4 mm. This shows that the result reported last year had misinterpretation and probably the operator, while performing the test, was careless and didn't read the device properly. Such misinterpretations being reported are supposed to be less in radiographic testing since the result of the tests are documented as produced pictures and can be reviewed and re-commented by various experts. As a result, the wall-thickness reported is more reliable and accurate in RK than some other NDT methods which the result is totally up to the inspector, his/her mood and skills.

As the first step, the flowline of well A18 is chosen to be evaluated in different spots. The spool number one is chosen. The spot is R1 and the results of inspections are graphed in Figure 4.9. The tables of results that are used for this graph are also shown at table 4.2.

The criteria chosen here for the evaluation is the variation of TT (Teknisk Tilstand in Norwegian which means technical condition in English) against time. The reason that TT is chosen here is that it is actually a very comprehensive indication of the corrosion and the remained wall-thickness since it takes T_{min3}, $T_{nominal}$, and amount of corrosion or erosion (e.g. pit depth) all into account. TT is determined in percentage and if the wall-thickness has no corrosion or any type of deterioration then TT will be equal to 100%, but if the corrosion and degradation has reached T_{min3} which is the ultimate failure state then it'll be 0%. In other words, TT reveals the condition of remained wall thickness regarding T_{min3} (virtual failure state). The way that TT is described and calculated is shown below:

If for example the wall-thickness is 25,4 mm, and T_{min3} is defined as 15,5, therefore the remaining wall-thickness will be:

$$25{,}4 - 15{,}5 = 9{,}9 \text{ mm}$$

Now imagine that the measured wall-thickness is 24 mm. This shows that there has been 1,4 mm corrosion. Therefore the remaining wall-thickness up to T_{min3} will be

$$9{,}9 - 1{,}4 = 8{,}5\text{mm}$$

Now in order to get TT, we can devide 8,5/9,9 and multiply it to 100 to get the number in percentage. Therefore we'll have:

$$8{,}5/9{,}9 = 0{,}86 \; ; \qquad TT = 0{,}86 * 100 = 86\%$$

This data is actually the same for the inspection results of 28.11.2009 which is shown below at table 4.2. The figure below can be used for better understanding of TT.

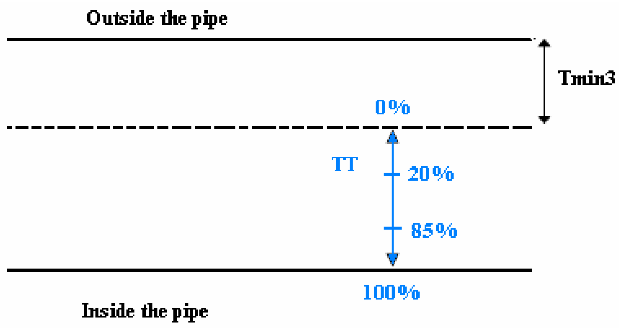


Figure 4.8: TT and T_{min3} and the way TT is assumed in the wall-thickness

At the picture above, bottom of the picture is assumed to be the interior part of the pipe. Therefore internal corrosion is considered here. TT is 100% at bottom and it decreases to 0% going upwards up to $T_{min3.}$ Since the corrosion happening externally can usually be handled and removed by painting and such things, therefore it is of more importance to consider the internal corrosion here.

The results of the inspections for a specific spot R1, at spool 1 from the flowline of A18 are shown below.

Table 4.2: Inspection results (TT) for A18 , spool one, spot R1

Inspection date	TT
10.09.2000	100%
29.09.2001	100%
22.10.2002	100%
22.09.2006	100%
28.11.2009	86%
25.10.2010	100%

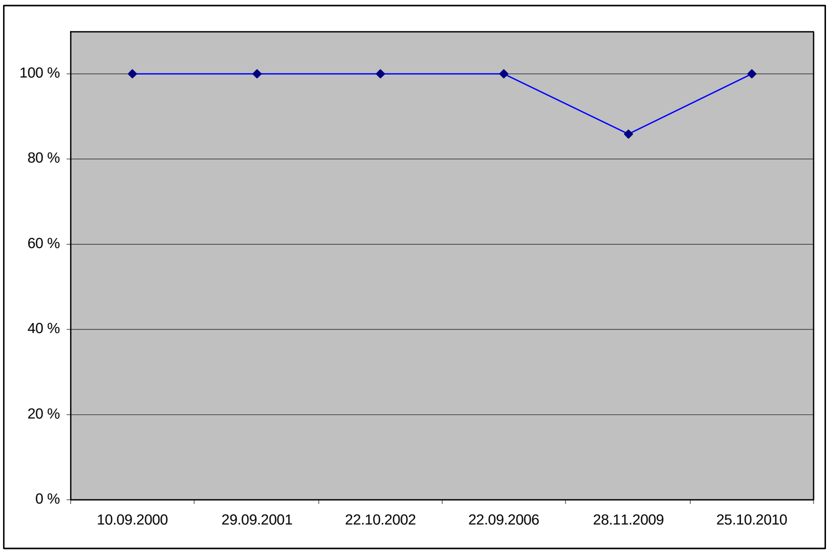


Figure 4.9: TT against time for A18 , spool one, spot R1

The results of ultrasonic inspections are graphed against time in Figure 4.9 above. The result of UL on 28.11.2009 seems to be strange since the trend shows there is a corrosion going on from 22.09.2006 until 28.11.2009 and this shows a requirement for another inspection. But after performing the next inspection after one year, the result is 100% stating no corrosion. This is not the same as what was expected. The reasons for such thing can be:

1. Misinterpretation of results: Ultrasonic testing is highly dependent on the operator's skills and experience in interpretation of results and performing the test itself. For example if there is a volumetric void within the wall-thickness, the angle of the probe thus the angle of beams will affect the results being shown on the screen. Coatings, isolations can negatively affect the results and distract the operator by creating lots of background noise and etc.
2. Differences between the skills of different inspectors: this is more perceptible in the following example provided below. The test is probably performed at 28.11.2009 by two different inspectors. The first one figures out that there is corrosion leading to have 94% TT. The second inspector finds out that the corrosion is happening in another direction leading to

91% TT. After all, after one year, another inspector performs the test and observes no corrosion. This leads to such strange results when one looks at the historical data.

The graph shown at Figure 4.10 is for the results of UL inspections of pipeline (8inch diameter) of the Flowline of well A18, spool no.2, the spot R1.

Table 4.3: data of inspection for A18,sp2,R1

Inspection date	TT
29.09.2001	100%
04.10.2010	100%
28.11.2009	94%
28.11.2009	91%
25.10.2010	100%

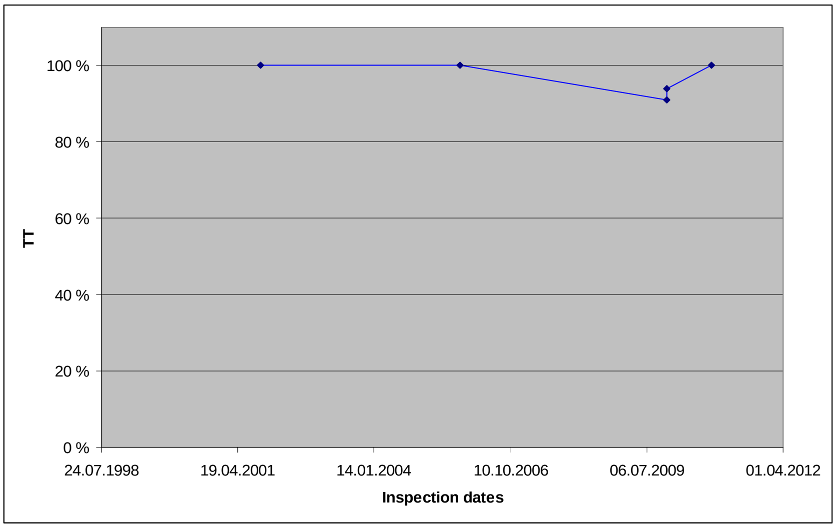


Figure 4.10: TT against time for A18,Sp2, R1

The second point being evaluated here shows unusual results. The trend shows that there is corrosion that has happened during the time from 04.10.2005 to 28.11.2009 and TT has reached 91% during this period. The first corrosion indicated says that TT has reached 94% and by looking at the comments of inspections, it says that this corrosion is happening in the pipe which is horizontal and it is between 8 and 10 o'clock. This means that if you divide the pipe to four areas, like the picture shown below, it can be regarded as the clock. Therefore the area between 8 and 10 o'clock (shown in red below) will be the corroded area figured out by ultrasonic testing.

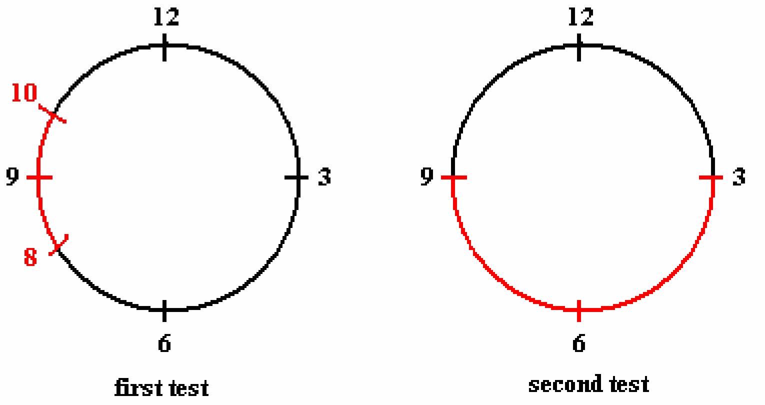


Figure 4.11: dividing the pipe like a clock to show the corroded area

The next inspection performed at the same date shows that the corroded area is between 3 o'clock and 9 o'clock and TT is 91%. But again here by looking at the comments it determines the distances of both corrosions from certain spots that shows these two corrosions are happening in two different spots but in the same pipe and spool. Therefore inspectors plan for a whole pipe ultrasonic scanning for the next year for that spool. By performing the inspection a year after, no corrosion becomes detected. The reasons behind such result are the same as the ones mentioned before.

Such analysis will be more interesting for those parts, like welds, that two or more than two methods are used for the inspection of same spot. Then the results can be compared and conclusions made based on them. This will be done in the following parts as it is going to be used for the evaluation of the matrix provided at table 4.1.

4.1.4 Conclusion

As the final conclusion, the matrix's recommended methods for pipes including ultrasonic testing and radiographic testing seem to be the most efficient and effective ones. Therefore, it is better to just keep this matrix as it is for pipes. Visual inspection can be used as a complementary method for information and data gathering about the pipes for further planning. It can also be used for determining the critical spots which need an immediate quantitative inspection perfomred. As discussed previously, when inspectors stop the flow in a certain flowline to open a certain flange for inspection, normally they take a look at the interior parts of the pipe and they report the observations within RS category which is dedicated for the inspection results of pipelines in data sheets. Visually inspecting the pipe in large distances doesn't seem rationally true and existence of chemicals and dirty stuff within the pipes pushes inspectors toward using methods that provide the ability of inspecting the interior parts of objects without causing damage neither to the human nor to the object itself. Therefore, UL and RK will be the highly recommended methods for pipes. Therefore, if a column was added to the matrix, so-called third method, visual inspection could have been mentioned there. But it is not considered as one the main inspection methods for pipes; however, still existing as one of the main influencing methods in inspection planning programs.

4.2 Evaluation of recommended methods for welds

4.2.1 Evaluation of the number of inspections (frequency) using each method

Welds are among the most important parts of flowlines and weld inspection is one the challenging areas in inspection plans programs. Welds play an important role in flowlines since every defect within them can cause weak joints of pipes thus less tolerance for existing high pressure and other design criteria. Defects within welds can also lead to leakages. Going through the data, it is seen that welds are categorized based on the location they are made. There are two main different types of welds: pre-fabricated welds in workshop conditions, and field (on site) welds.

Fabricated welds in workshop conditions are made in controlled environment, within certain temperature, pressure and all the other influencing factors. Therefore, as these influencing factors are controlled more, the presence of flaws and defects within the weld decreases. On the other hand, when considering field (on-site) welds, the temperature, moisture, and in general, environmental factors are rather out-of-control and can vary a lot, making the welding operation harder, requiring more attention and caution during welding process. Since the environmental factors vary, more flaws and defects are expected, and this increase the frequency of inspections.

Within the raw data base available, fabricated weld in workshop condition is shown by SV, and field weld is shown by SW. As expected, there is a difference in the way they are shown in P&ID drawings. SV is shown by a dot, while SW is shown by a dot with a cross on it (Figure 4.12).

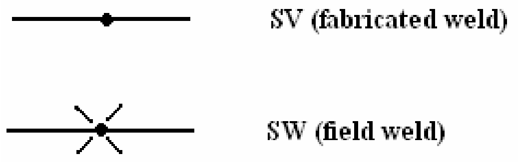


Figure 4.12: SV and SW symbols on a P&ID drawing

As you can see from table 4.1, two methods are recommended for the inspection of welds including Radiographic testing (contact method) (RK) and Ultrasonic testing (as the second method) and within the comments column it says that UL can/should be used for the verification of

RK results. Besides, in order to provide sizing and positioning picture of the flaw, UL can be performed.

Time of Flight Diffraction (TOFD) is the most promising ultrasonic testing method to be used for the weld inspection. High accuracy, storability of results and its quality has made this method as an alternative for the radiographic testing. Although TOFD is restricted to be used in some companies regarding its expenditures and requirements for highly trained operators, but its uses are just increasing within the industries all over the world. In the following chapters TOFD will be suggested as an alternative. This can be risky for companies, since it requires new investment, new equipment and highly trained operators.

The same procedure of analyzing the frequency of methods is followed here as done for pipes previously. Then those welds that are inspected by multiple methods will be considered in order to see which method has had the most accuracy thus more reliability.

The first flowline to be considered is just randomly selected from the list of production wells and it is the flowline of well A17. The data will be first filtered according to SV (fabricated welds) and then SW (field welds) and then put together to see the comprehensive results of inspections for welds. All data is first filtered for 8″ diameter pipes.

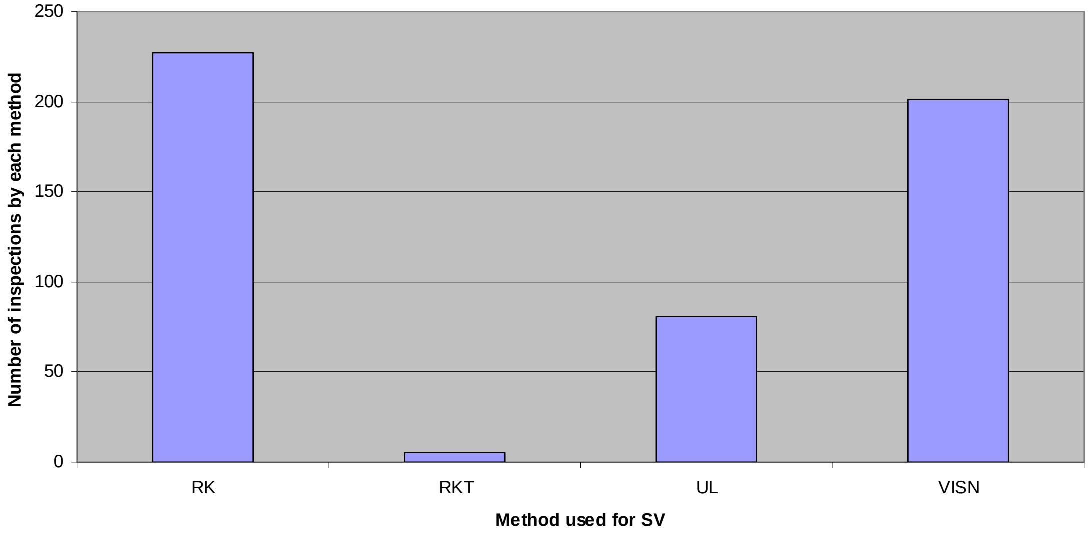


Figure 4.13: number of inspections using each mentioned method for SV (A17)

Providing the chart according to the data, we can see that within almost 10 years of inspection, RK 227, RKT 5, UL 81, and VISN 201 times have been used for the inspection of fabricated welds. Therefore the most used method is RK (as expected since it is the first recommended method by the matrix). But like before (for pipelines) visual inspection has been used as one of the major methods. The reasons behind this can include all the previously mentioned ones related to pipelines e.g. when an end-cap is planned to be inspected, after opening the end-cap, welds around it in the T-junction will also be visually inspected and reported under the category of VISN. Ultrasonic testing (conventional) is the third primary method to be used and as matrix says, it will primarily used for the approval of the results of RK or in some cases for sizing and positioning the defects. The strange thing that is seen in this chart is the use of RKT for the inspection of welds of pipes with 8″ diameter, and this means that the picture produced will be extremely white and using this method doesn't make any sense here. But as mentioned in the previous part for pipes, there are some points which are indicated as a part of 8″ diameter pipes. But actually they are the points where other 1″ or 2″ pipes get branches from the 8″ one.

The chart for data related to SW of A17 is shown below.

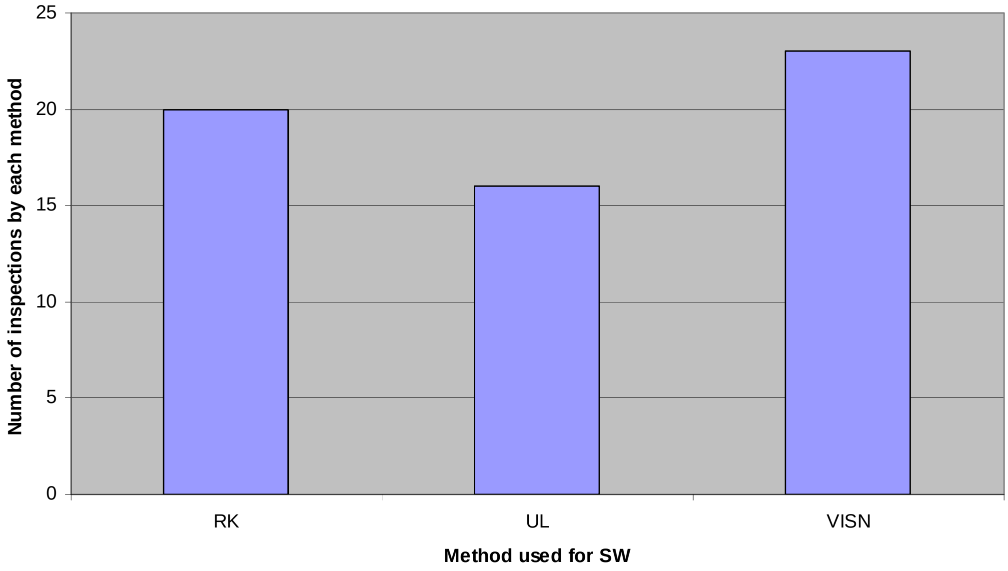


Figure 4.14: number of inspections using each mentioned method for SW (A17)

The chart shows that the number of inspections for SW is extremely less than the number of inspections for SV (almost one tenth). The reason behind this can be the fewer number of SW available on site, and that most companies prefer to have fabricated welds on pipes since there are fewer flaws on them regarding the controlled environment, less need for controlling the welding process and etc.

The second flowline to be evaluated is A35. This flowline shows an extremely strange result which is the number of RKT used.

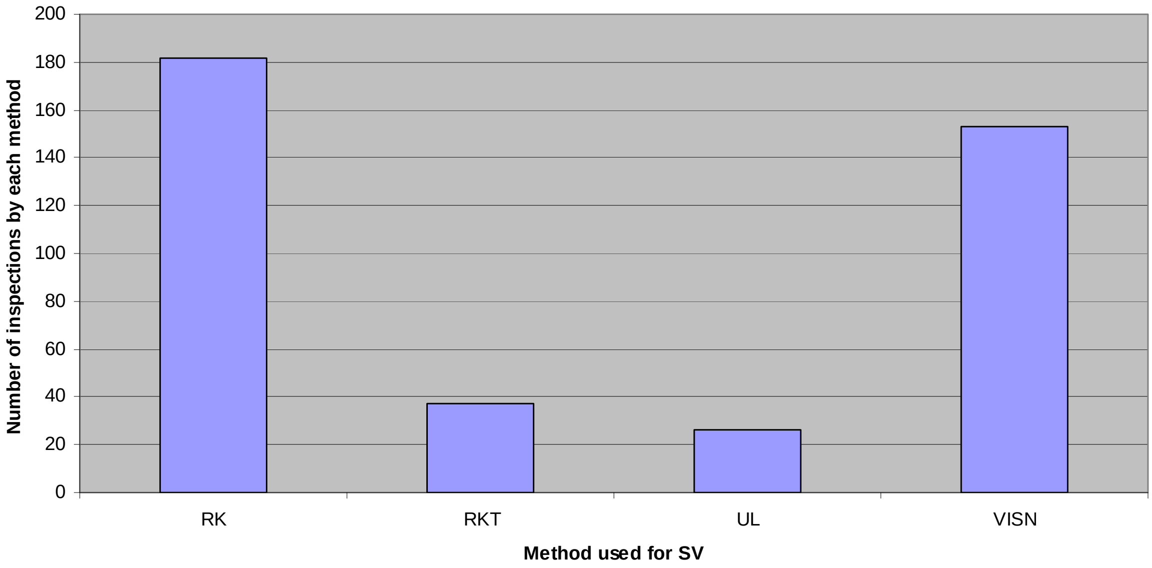


Figure 4.15: number of inspections using each mentioned method for SV (A35)

As it can be seen from the chart, the number of RKT used for the inspection of welds on 8″ diameter pipes is more than the number of ultrasonic inspections used for them. This is while RKT is not supposed to be used for 8″ diameter pipes and is not recommended by the matrix also, but on the other hand UL is supposed to have high number of frequency since it should be used (in some cases) for the verification of the results gained by RK.

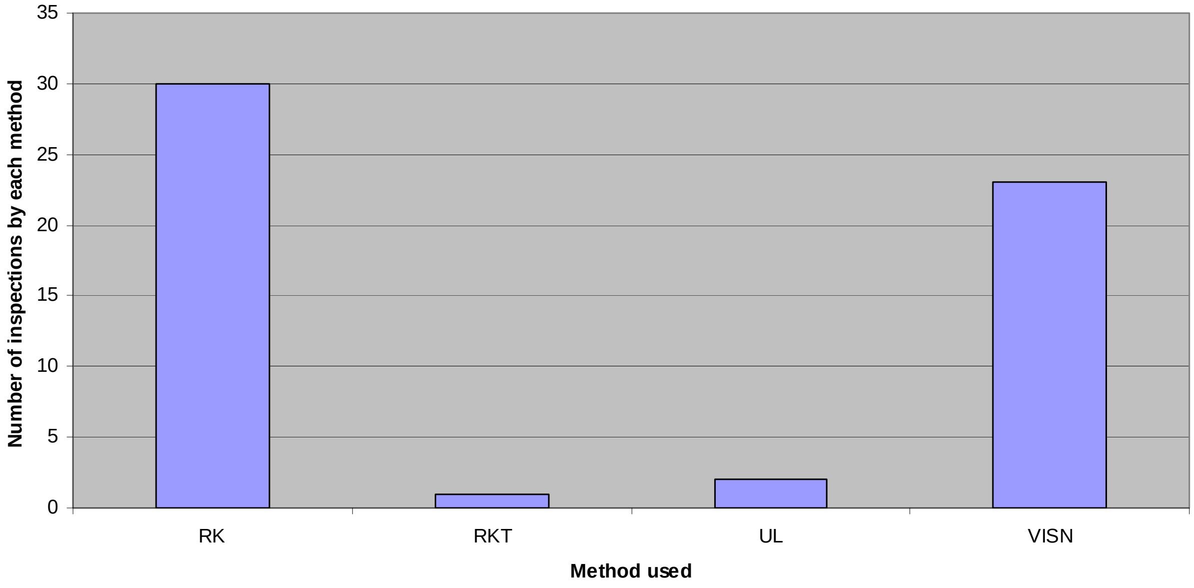


Figure 4.16: number of inspections using each method for SW (A35)

Therefore there are some points coming out of from charts that should be assessed to see what the underlying causes of such results were. The points that should be focused and explained include:

- High number of visual inspections
- RKT used in most of flowlines (8″ diameter) (RKT more than UL in some cases)

The charts below show the frequency of each method used for the inspection of both fabricated welds (SV) and field welds (SW) in 8″ diameter flowline of production wells.

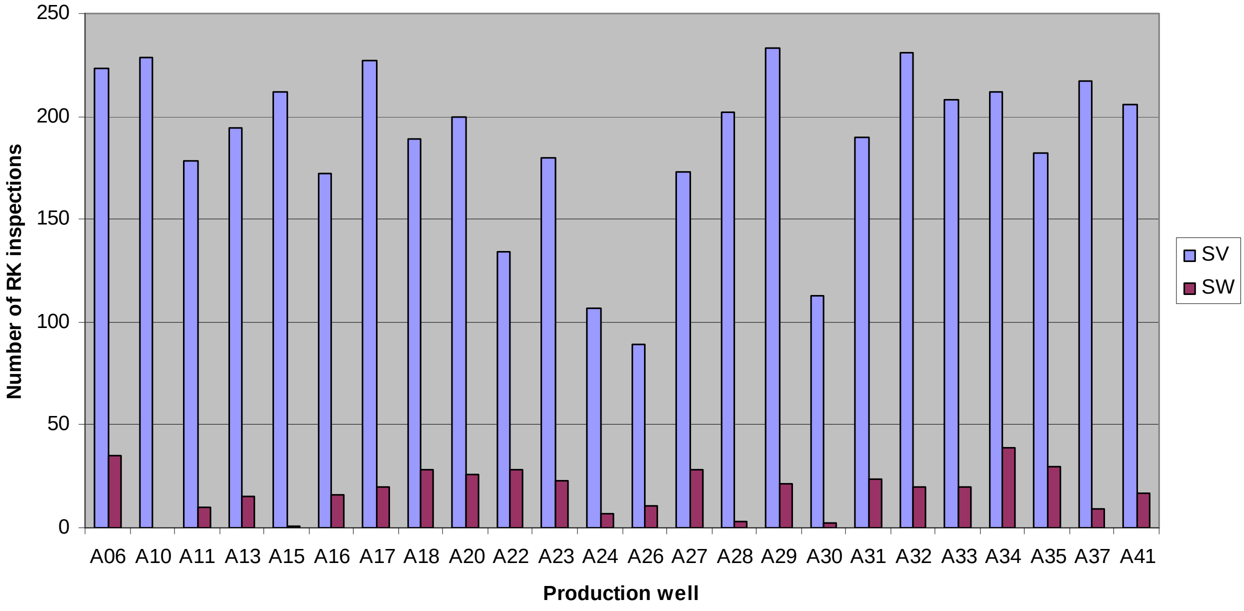


Figure 4.17: frequency of RK performed for the inspection of welds in 8″ diameter flowlines

The chart above shows that the average is somewhere between 160-180 for SV and this shows that the number of RK used for SV of some flowlines' welds is quite a few number such as the one for A26. But it is important to see how many times UL or VIS has been used since in some cases inspector has a good access area on the weld and while performing UL for pipe, he/she decides to go on to the welds existing beside that pipe. UL can be used, but the precision that RK has for application in welds, makes planners to apply RK more than UL.

Hard access to some points as mentioned at chapter 2- Radiographic testing of flowlines- can also affect the number of radiographic testing performed. Figure 2.10 provided at chapter 2, can be mentioned here as one the parts which performing RK can be difficult and challenging for the inspectors and even if performed the results won't be clear enough to judge about the condition of that part. Therefore in such points inspectors prefer to go for ultrasonic testing rather than radiographic testing.

Fewer numbers of inspections performed for the inspection of SW can show that there are fewer numbers of filed welds than fabricated welds. This is rationally true since industries are willing to have as less number of field welds as possible since the existence of defects and errors within field welds is much higher than fabricated welds due to controlled environmental condition in fabricated welds.

But among the data for SW, it is seen that there have been no RK inspection performed for the welds of flowline of A10 and there is just one RK test performed for A15, and quite few numbers for A28 and A30. The reason underlying this result will be of consideration at the evaluation part.

The following chart shows the number of RKT inspections performed for welds of production flowlines with 8″ diameter.

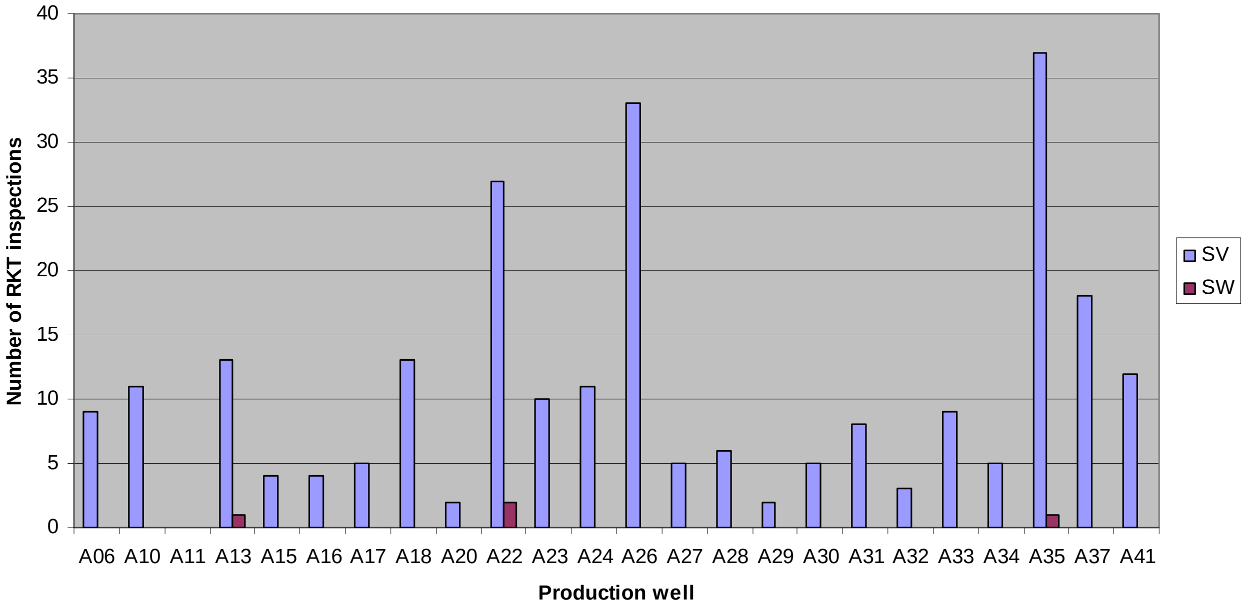


Figure 4.18: frequency of RKT performed for the inspection of welds in 8″ diameter flowlines

It gets more interesting here since A26 shows that it has quite a lot of RKT inspections performed for the inspection of its SVs. Whatever the reason behind it can be, it had the least number of RK inspections and this can be an indication of the fact that there is a lot of mistakes and wrong pointed spots within this flowline since if all spots had 8″ diameter, then this high number of RKTs done couldn't be acceptable. The other reasons of applying RKT mentioned in the previous part for the 8″ diameter pipelines can be true here as well. This is the same issue with A35 and A22 with rather high number of RKT.

Looking at the bars of SW in the chart, we see that there have been no RKT inspections for almost all of the field welds, except A13, A22 and A35. There is no indication of 1″ or 2″ within the comments column and this can be an indication of wrong application of RKT because of lack of experience of inspector or poor data sheet available for them. Because in some cases, when there is no indication of the thin diameter within the allocated column, planners look at the drawings in order to find out the underlying reason and in most of them they figure out that there is a branch of 1″ or 2″ diameter pipe from the 8″ diameter pipe and since the welded part's diameter is neither 8″

nor 1″ or 2″- it is bigger than 2″ and less than 8″- it is just written and defined under the category of 8″ diameter. This is also sort of poor categorization of the data but there seems no other way of changing the categories since it will be time consuming and useless as long as all the planners are used to deal with that sort of data and strange results.

The chart below shows the frequency of the UL inspections performed for the inspection of welds for the production flowlines with 8″ diameter.

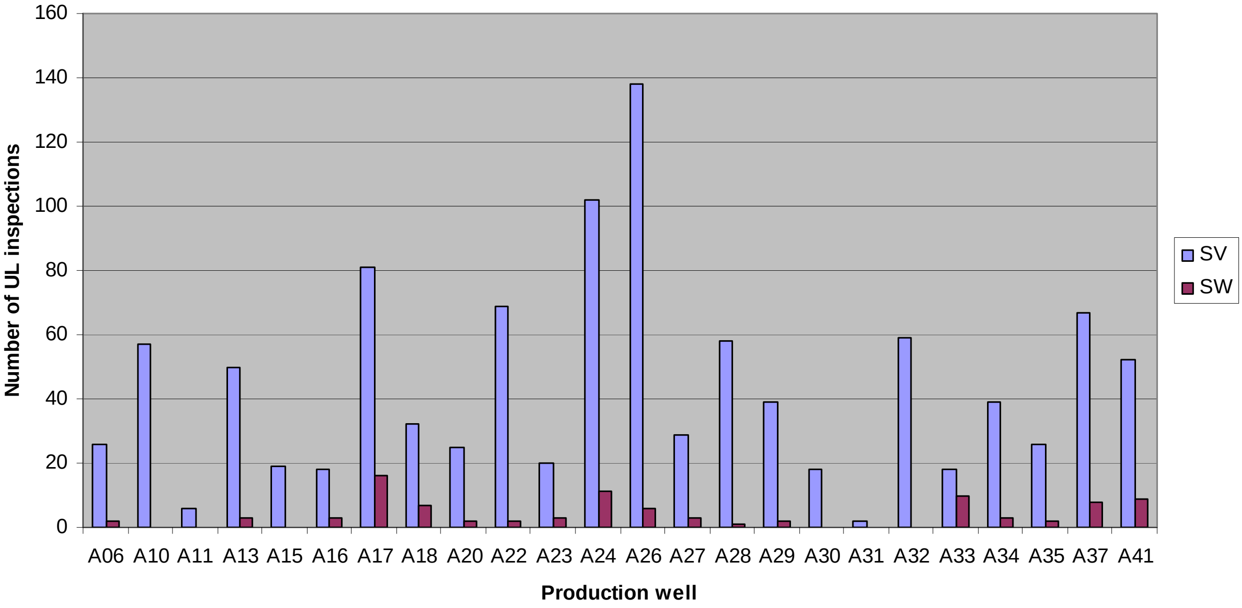


Figure 4.19: frequency of UL used for the inspection of welds in 8″ diameter flowlines

Looking at these results of SV, A26 again is an exotic one with the highest number of UL inspections. While the average of UL inspections for SV is 43,75, A26 with 138 is far more than that. Remember that it had the least number of RK and a high number of RKT (which is an indication of poor data set). Other considerable points here are A11 and A31 which have quite few (6 for A11, and 2 for A31) number of UL inspections. This in compare with some other flowlines such as A26 and A24 can be on consideration in the evaluation here. The question remains here that why some flowlines have quite fewer numbers of RK inspections for welds in compare to the UL inspections performed for them while RK is the first recommended method by the matrix (table 4.1)? No indication of UL inspection for SW of A10, A11, A15, A30 and A31 can be of concern also

The chart below (Figure 4.20) shows the frequency of visual inspections performed for the inspection of welds, SV and SW, of flowlines with 8″ diameter.

The reason behind using visual inspection for welds can be the same as the ones mentioned for pipelines previously. For example in the inspection of an end-cap, when the end-cap is opened the welds can be visually inspected also and reported within SV category.

The strangest points within all these charts seem to be A10 and A15 which have any kind of NDT inspection for SW (A15 has only one RKT test performed). The only reason for this is that there is no field weld for the flowlines of A10 and A15. All welds are fabricated welds as the industry designs the construction of flowlines prior to construction phase so that there will be less need to have field welds since welding out in the field is very hard and normally full of defects. Industries try to connect the prepared spools with flanges and avoid on-site welding. But if there is going to be a modification then there will be the need for field weld.

All these mentioned points seen from the charts are going to be discussed and evaluated within the next part of this chapter.

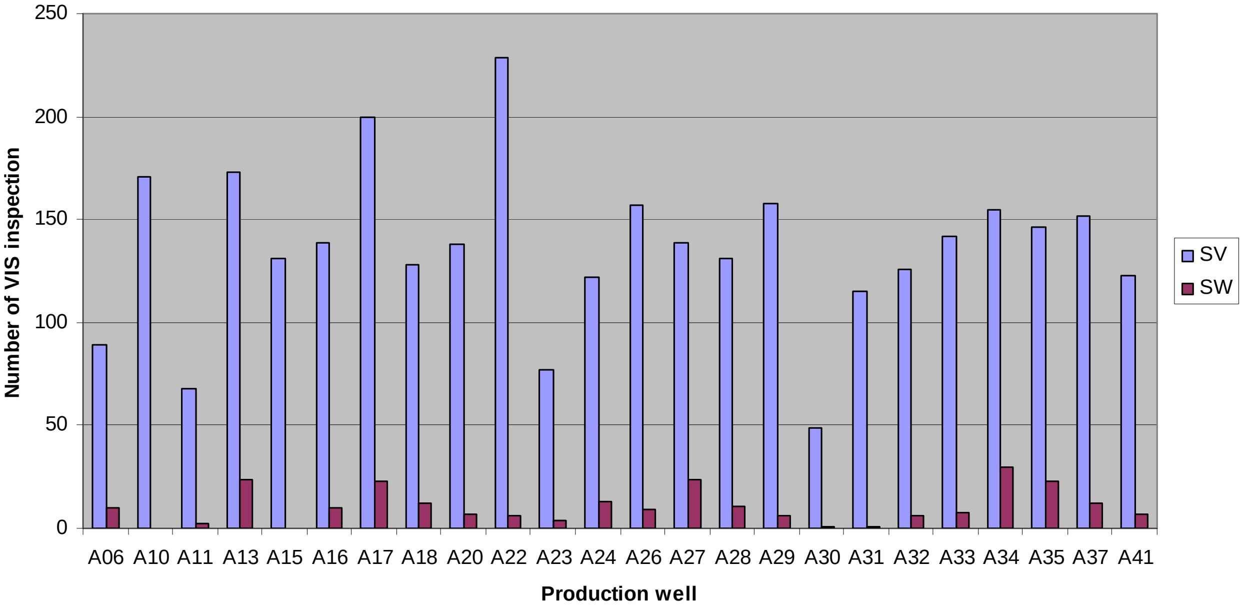


Figure 4.20: frequency of VIS inspections done for the inspection of fabricated welds (SV) in 8″ flowlines

After all, the chart below shows the percentage of each method used for the inspection of each well. This can provide a picture in mind of the amount of different kinds of inspection for each flowline's welds.

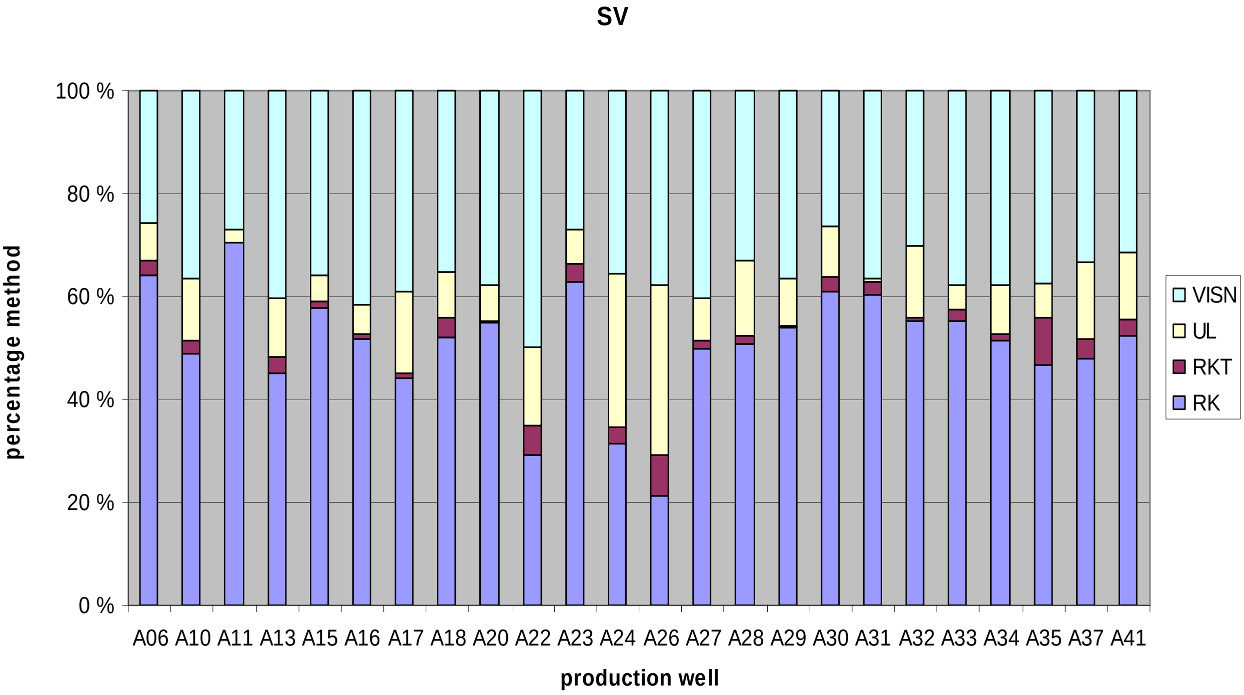


Figure 4.21: Percentage of each method used for each 8″ flowline's fabricated welds (SV)

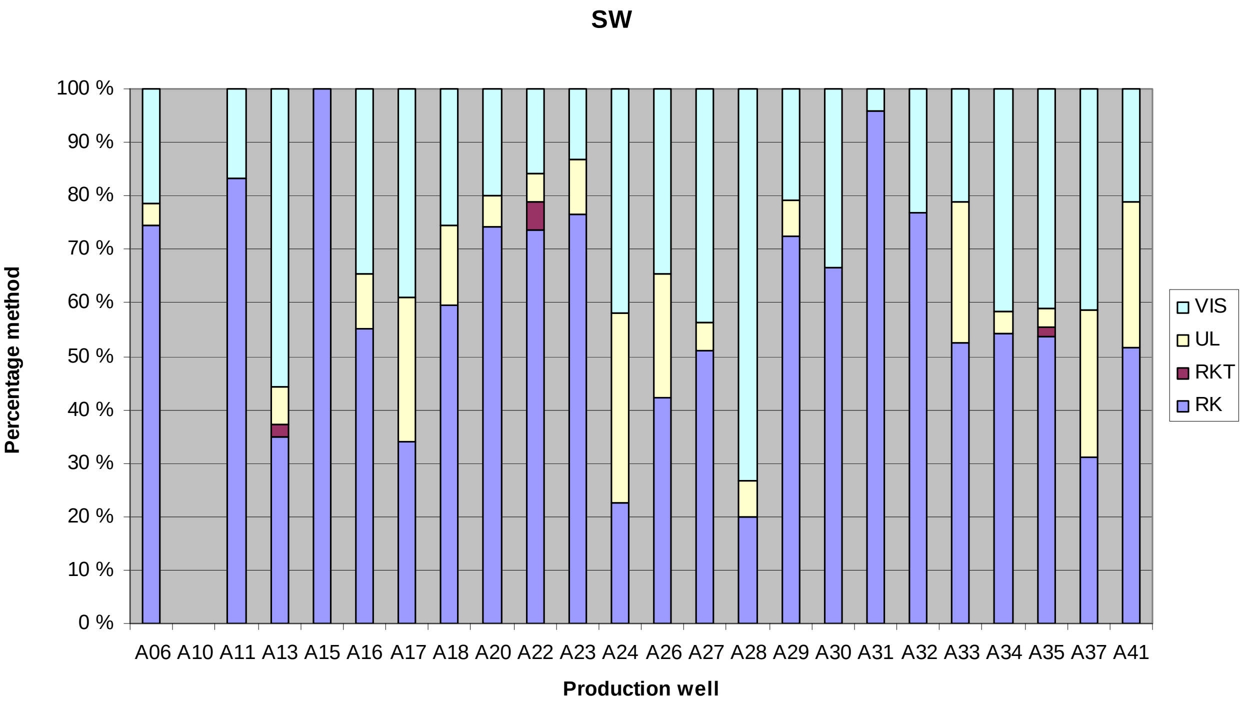


Figure 4.22: Percentage of each method used for each 8″ flowline's field welds (SW)

Some SW welds have got more ultrasonic testing than radiographic testing such as the one for A24 and almost the same amount for A17, and A37 and this is going to be considered at the next part.

But before going to the evaluation part there is an interesting thing left to be pointed out here and that is the use and application of other methods for the inspection of welds. This is the primary goal of this chapter and it is about finding out the frequency of application of recommended methods that can be an indication of the method's reliability for the company as well as finding out the other methods used for the inspections which are not recommended by the matrix. This is of concern here because using other methods can show the fact that the company is willing to apply other methods than the ones specified by the matrix and this is all because new methods and technologies are going to replace the existing conventional methods.

The historical data show that there have been two other methods including Phased Array, and Penetrant Testing are performed for the inspection of fabricated welds. Inspection with Borescope has been planned but cancelled due to the required equipments unavailability.

The chart provided at Figure 4.23 shows that where and how many times they have been applied in the inspection programs. The yellow column shows the method phased array which has been applied 6 times in two days in a row (21.02.2009 to 22.02.2009) for the inspection of 6 different fabricated welds. It was able to find corrosions ranging from 1 mm up to 4,4 mm in 4 out of these 6 inspections. This is interesting because in all those 4 points which phased array was able to find the corrosion the other methods including radiographic testing and visual inspection were unable to find it in a short time interval before that. These points and the thickness variations measured by different methods will be of concern in the following parts.

Inspection with Borescope shown in red in the chart 4.23, has been planned to be performed for a fabricated weld on the flowline A26 but since the equipment needed to perform the test were not available at the time, therefore the inspections were cancelled.

Penetrant testing shown in blue in the chart has been performed once for the fabricated welds of flowlines and that one was at A16. It didn't find any corrosion while just a few days before that corrosion was observed at the same spot (weld) by visual inspection and just about 6 months before that the corrosion was detected by radiographic testing (RK). But inspectors weren't satisfied enough with the result of penetrant testing since the result was not the same as was expected regarding the trend of corrosion before that. Therefore a year after applying PEN, they used RK and it didn't find any corrosion again! This spot will also be considered at the following parts.

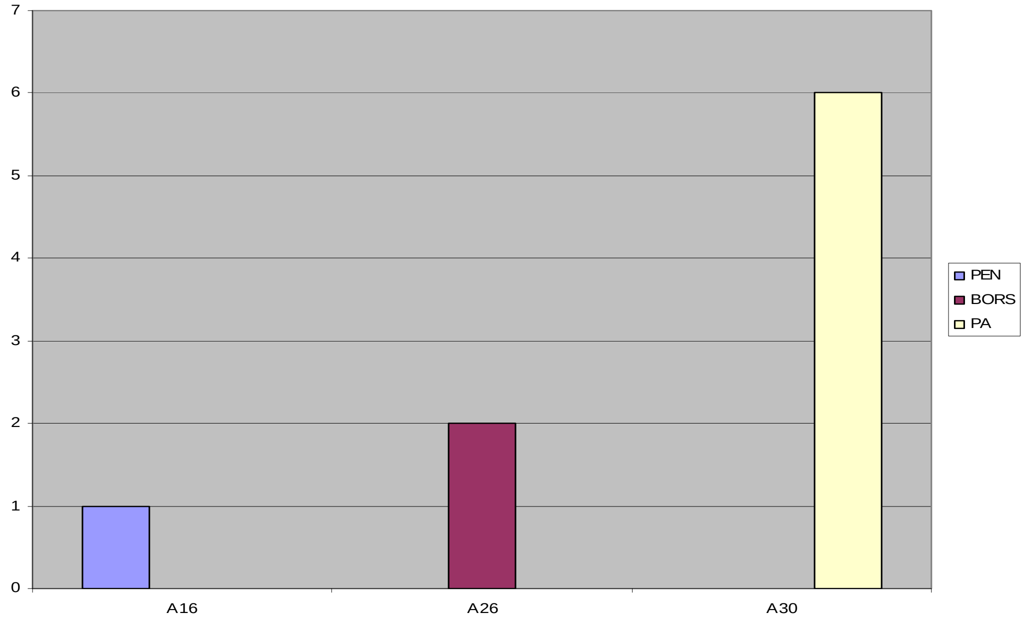


Figure 4.23: frequency of other methods used/planned for inspection of some fabricated welds of flowlines

4.2.2 Evaluation of results of charts

From the charts provided at the previous chapter, some points should be focused on and some underlying reasons for some of the results should be revealed and evaluated to understand and learn from the historical data. Learning from the historical data has been always the primary objective of the management since it keeps the company aware of the existing problems. It also distinguishes the potentials for some other problems so that the industry can avoid them by applying the appropriate procedures. The other reason that the historical data should be evaluated is to keep the company updated. When the data shows a trend that is not satisfying the management enough, it can be concluded that there is a need for the application of new technologies or other methods into the operations.

Some of the points were focused and discussed before but some others are going to be focused and discussed here including:

1. There is no indication of inspection of field welds (SW) for A10 8″ diameter flowline. A15 has almost the same issue but with just one RK inspection done. The question is that if there is a SW weld in the 8″ diameter flowline of A15, why only one RK inspection is performed within the period of approximately 10 years. The reason for having no inspection data for the SWs of A10 is of concern here also.

As discussed before, the reason for having no inspection data can be having no field weld (SW) within the 8″ diameter flowline. Since field welds contain various errors regarding the changing and uncontrolled environment, companies try as much as possible in order to avoid having field welds by precisely designing the modules, flowlines and everything else so that they can just put different parts together and connect them to each other by using flanges and not welds. But in some cases there is the need for some modifications and therefore there becomes the need for having field welds. By looking at the drawings of A10 it is seen that there are 2 SWs within the flowline but there seems to be a mistake within the data that probably SW is indicated by SV wrongly!

The reason for having only one inspection (RK) for A15 remains as a question still. But there can be a reason behind that and it is when inspectors inspect and monitor all the surrounding points of a weld and there is no corrosion or any other type of degradation detected, it can be concluded that there will be no or at least not serious degradation happening to the weld. Thus the number of inspections for the weld decreases as the information about the surrounding points increases.

2. While looking at the data, A26 shows kind of out-of-order results since the matrix recommends that for the inspection of welds, the first recommended method is radiographic testing-contact method, and the second method that can be used for the verification of the results of RK is ultrasonic testing. But the data related to A26 shows that there have been 89 RK tests, 33 RKT tests, 138 UL test and 157 VIS inspections performed. This is on the contrary of what the matrix recommends. The number of UL inspections is much higher than the number of RK inspections and there have been 33 RKT inspections performed.

There are two main reasons to explain this result here. First of all it is HSE considerations which push planners and inspectors to use ultrasonic testing more since radiographic testing harms the inspector and the surrounding people by emitting beams. Radiation hazards always are of concern when it comes to radiographic testing. When there is a good access to the wanted area ultrasonic testing can provide quite reliable results and therefore it is better to reduce the radiation hazards by using UL instead.

The second reason is the access which was mentioned in the previous part. When there is a hard access to the wanted spot to put the film and source and provide the precise and desired distance of source to film to perform radiographic testing, inspectors go towards applying ultrasonic instead. Pictures of such areas are provided at the chapter 2.

3. There is no indication or recommendation of using RKT in the matrix because the application of RKT for high diameter pipelines is pointless since the picture produced will be extremely white because of the increased path that the beam should travel through in order to reach the film. After looking at the comments column it becomes revealed that for example for A26 from total 33 RKT inspections, most of them are performed for 1″ or 2″ pipes which are wrongly indicated as 8″ diameter pipes within the data sheet. This wrong categorization can be because of human or software mistakes or it can show that for that specific point there has been no other way to define it under a specific category such as 1″ or 2″ diameter pipes’ category. The reason behind this is discussed before, and it is showing that in some spots when for example a 2″ pipe is welded to an 8″ pipe, the diameter of pipe in the welded part will be bigger than 2″ and less than 8″ and this makes it difficult for planners and designers to specify them within a specific existing category. So usually they are indicated as 8″ but there should be always some description of the situation in the comment column for the planners and analyzers not to get confused by the results.

4.2.3 Evaluation of accuracy and reliability of each method used

The purpose is to see which one of the methods used was more reliable in a sense that it has given more precise results and has found out the defects that the other methods were not able to find out. To do so, those points are chosen which more than one method is applied for its inspection and different results are acquired. By looking at the trend of inspection results it can be concluded that which method has had the most precision. The criteria to be evaluated are the same as for the previous part and it is TT. More information about TT and the reason that it is chosen as a criteria for the evaluation is discussed at 4.1.3.

As for the first point to be evaluated, a fabricated weld on the 8″ diameter flowline of A20 which is a production well at the field is chosen. The reason is that 3 different methods have been applied for the inspection of this spot including VIS, UL and RK. The results are shown at the table below and the variations in TT are shown at the chart provided at Figure 4.24.

Table 4.4: inspection results for A20, SP3, S3

INSP_DATE	METHOD	TT
01.04.2000	RK	30 %
06.06.2000	VISN	35 %
01.03.2001	UL	35 %
27.05.2001	VISN	35 %
28.03.2002	RK	25 %
25.05.2002	VISN	35 %
21.03.2003	RK	25 %
12.04.2004	RK	20 %
22.02.2005	RK	25 %
21.06.2005	VISN	40 %
20.02.2006	UL	35 %
13.04.2007	UL	45 %
29.04.2009	RK	45 %

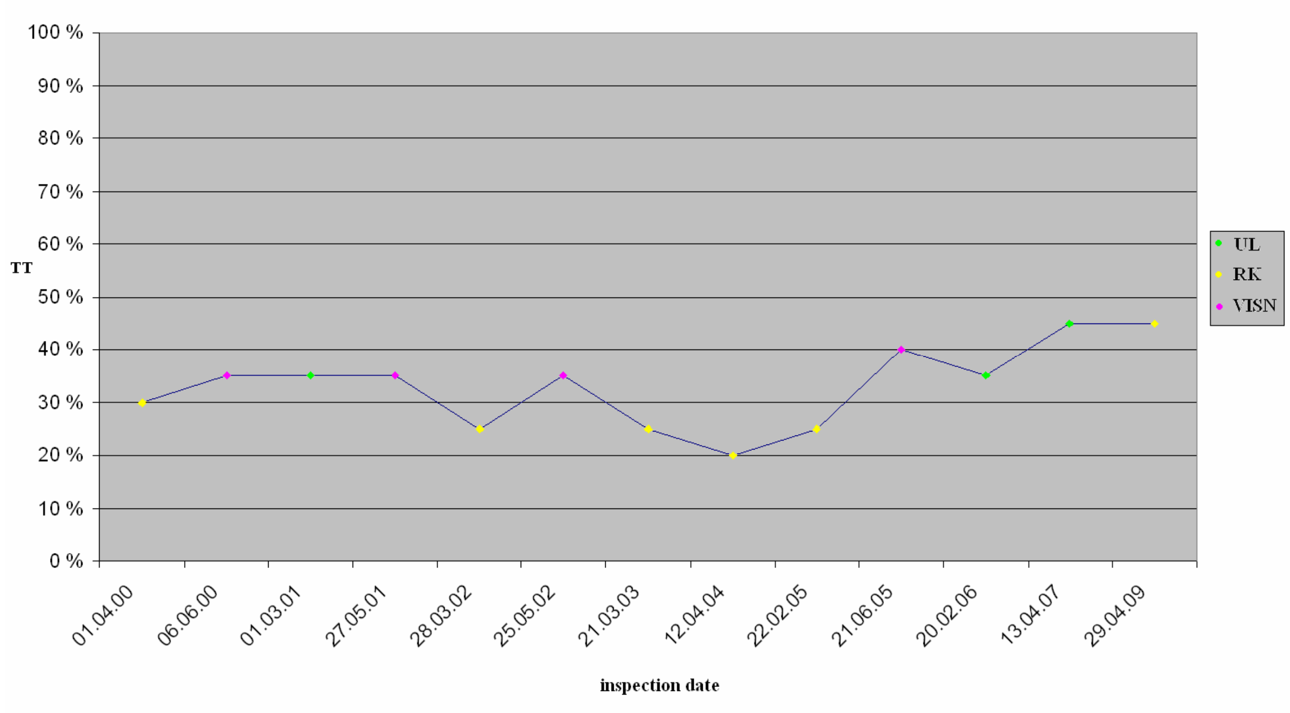


Figure 4.24: TT against time for A20, SP 3, S3

This trend of degradation highlights the dangerous situation of this part since its difference from 100% has been always more than 50%. This chart itself shows that how much variations exist between results of different methods. Looking at whole trend, it is seen that normally the results of radiographic testing are lower- and in a sense more precise- than UL and VISN. For this spot UL has not been used directly after RK for the verification of that and there is always a VISN in between.

The average of all TTs equals to 33%. Now by looking at the results of inspections, it is seen that almost all of the RK results (except the one at the end) are lower, and all the results of UL and VISN are the same as or higher than the average.

Another spot going to be considered here is a fabricated weld at the 8″ diameter flowline of A15, spool 1 and S1. The results are varying a lot in a sense that making a conclusion about the technical condition of the weld is difficult. But it is observed that all TTs less than 100%, which show there is a degradation happening, are discovered by RK and this can be an indication of the importance of RK in weld inspection.

The results are provided at table and chart below for better understanding.

Table 4.5: inspection results for A15, SP1, S1

INSP_DATE	METHOD	TT
28.02.2000	RK	100 %
05.03.2002	RK	86 %
20.03.2002	RK	100 %
12.05.2002	VISN	100 %
13.04.2004	UL	100 %
20.03.2005	RK	86 %
31.05.2005	VISN	100 %
05.05.2006	UL	100 %
09.06.2007	VISN	100 %
06.04.2008	RK	100 %
24.04.2008	RK	76 %

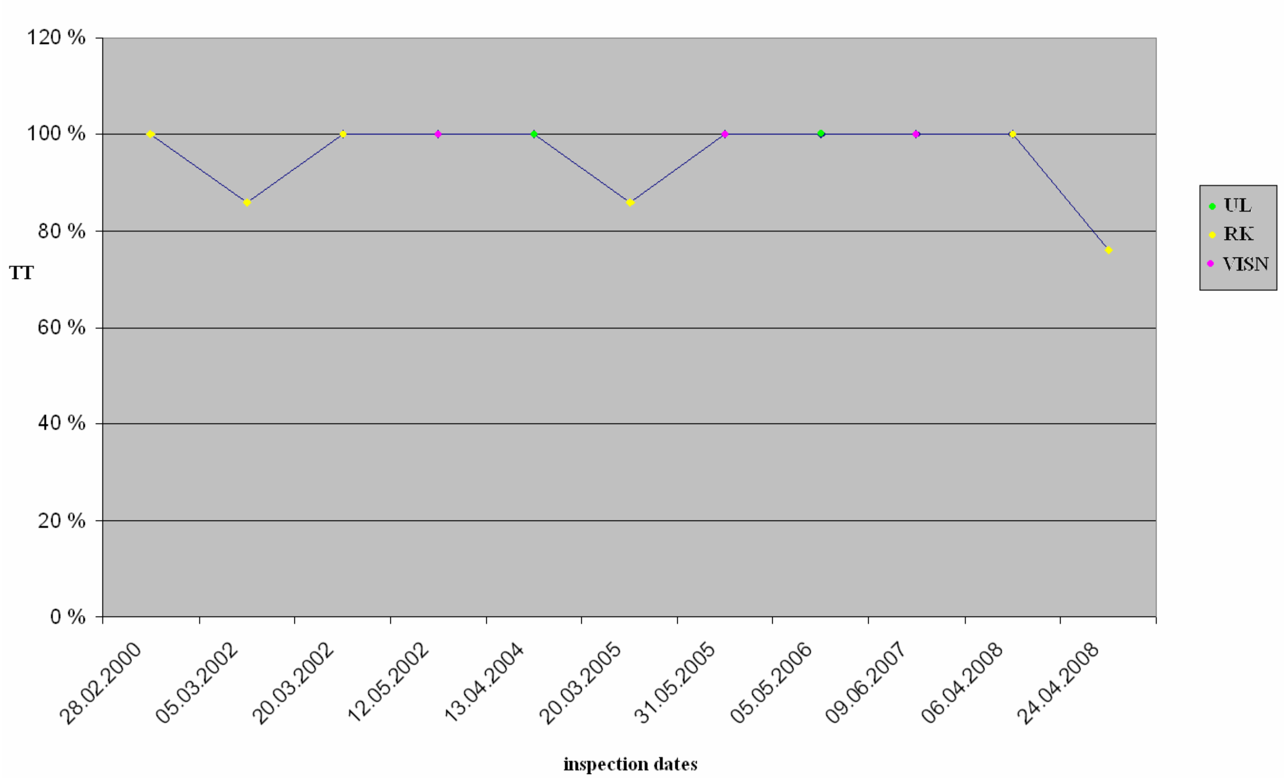


Figure 4.25: TT vs. inspection dates for A15, SP1, S1

It is seen that it is only radiographic testing that was able to find out a defect within the wall-thickness of the weld. The other two methods have been always implying that there is no defect in the weld. But actually there are two other spots which RK has reported 100% TT after the first detection on 05.03.2002. This can be explained by the direction of beams. As discussed in chapter 2, the direction of radiographic beams is of the primary importance in RK. Also the location of film and source are very important in the detection of flaws. But if all factors are met and film and source are placed in the appropriate positions, the defect can be detected as it has happened three times here for this spot. This shows how precise is the radiographic testing. But one should consider its hazards as well when planning for that.

In the charts provided below, other points within the plant are chosen to be evaluated. All the charts are put together and with the discussion made before some conclusions can be made for these charts.

The points chosen here are the ones that another method (other than the ones recommended in the matrix) is chosen for the inspection of that point. These methods are generally the ones that the company is willing to use them in its future inspections or even to replace them with the existing NDT methods. For example phased array is a method that is supposed to replace UL in future.

Table 4.6: inspection results for A30, SP11, S1

INSP_DATE	METHOD	TT
12.12.2002	RK	100 %
21.02.2009	PA	76 %
08.09.2009	VISN	100 %

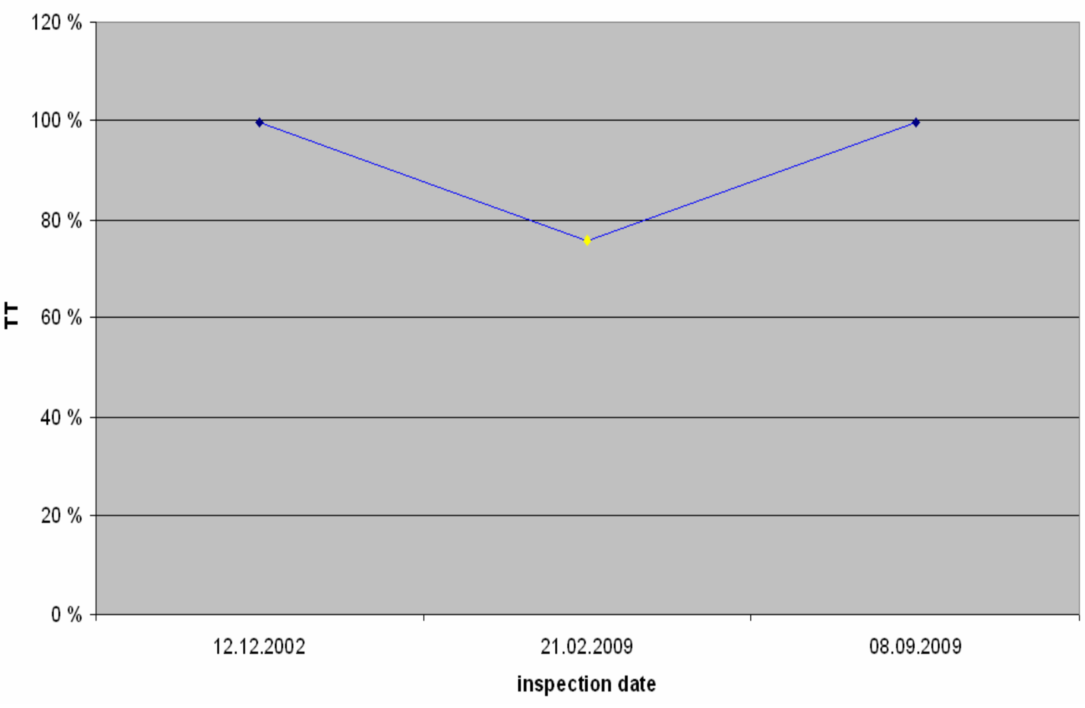


Figure 4.26: TT vs. inspection dates for A30, SP11, S1

The yellow point shows the inspection result using phased array. It is obvious that phased array was able to find a defect which the other two methods, RK and VISN weren't able to figure it out. Therefore the result of near visual inspection performed 7 months later cannot be reliable since it says there is no corrosion.

Table 4.7: inspection results for A30, Sp11, S2

INSP_DATE	METHOD	TT
13.12.2002	RK	100 %
21.02.2009	PA	56 %
26.03.2010	RK	100 %

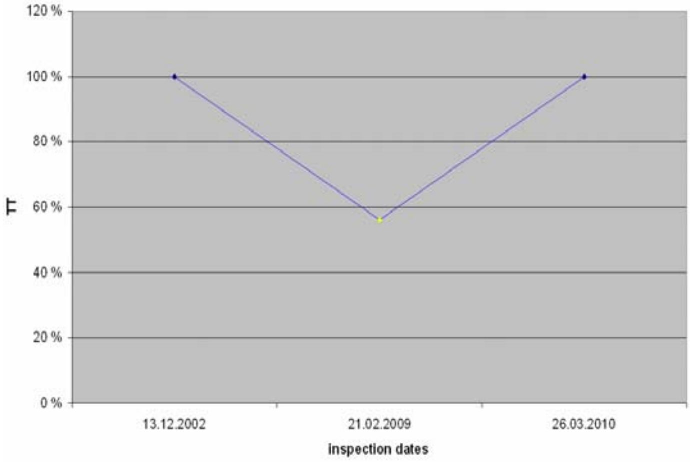


Figure 4.27: TT vs. inspection dates for A30, SP11, S2

The chart shows that phased array was able to indicate TT as least as 56% which is so noticeable when comparing it with radiographic testing that although it is said that it is the best method for the inspection of welds, but actually it is in a sense less reliable in compare to PA.

Another conclusion can be made here. When there is a huge difference between the results of PA and RK, since RK is a very precise method in the inspection of welds, it can show that the inspector’s performance and skills weren’t good enough during application of phased array and probably some misinterpretations have occurred.

Table 4.8: inspection results for A30, Sp 14, S5

INSP_DATE	METHOD	TT
09.12.2002	RK	100 %
10.01.2006	RK	100 %
22.02.2009	PA	76 %

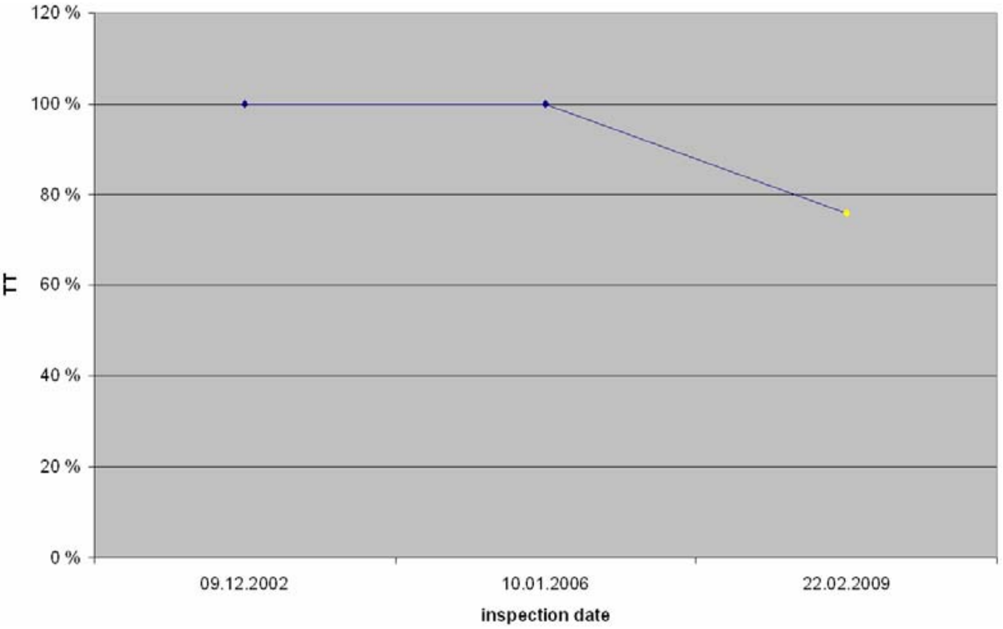


Figure 4.28: TT vs. inspection dates for A30, SP14, S5

As it is shown in this chart as well, the result of PA is totally different from the two RK test performed before than that. This can be another indication of the fact that PA is more reliable and accurate than RK in inspection of welds.

4.2.4 Conclusion

By looking at the results of charts it can be concluded that RK is more reliable and accurate than UL. But on the other hand, regarding the HSE considerations, the application of RK is limited. RK can harm the inspector and people around it thus UL is preferred in most of the cases. This effect can be observed in the inspection results of A26 SV, A28 SW which the number of UL inspections is more than RK while RK is more accurate and is recommended as the first method by the matrix. UL inspection is easier to be applied for the inspection also, and when it is applied for the inspection of pipe, it can be used also for the surrounding welds on that pipe also and this can be used faster than radiographic testing, however the results won’t be that reliable.

Use of other methods, and in a sense new methods, for the inspection of welds such as phased array or penetrant testing shows that for example phased array has shown more precise results than even radiographic testing and beside it should be considered that phased array has no radiation hazard. Therefore there are two major advantages over radiographic testing and this is why the policy of the company is to use this method more and replace it instead of the conventional ultrasonic testing. All these methods will be discussed in details in the chapter allocated for the recommended methods.

4.3 Evaluation of recommended methods for T-junctions

Two recommended methods for the T-junctions include Visual inspection and Radiographic testing- tangential method. Visual inspection is the first recommended method as using gloves and touching the wall-thickness looking for any type of defect seems a cheap and reliable method to find flaw. But this needs the flow to be shut down.

It should be noticed that tangential radiography is not recommended for pipes because if there is pit corrosion and it is positioned like the one illustrated at Figure 4.29, the size of the isolated pit will be underestimated.

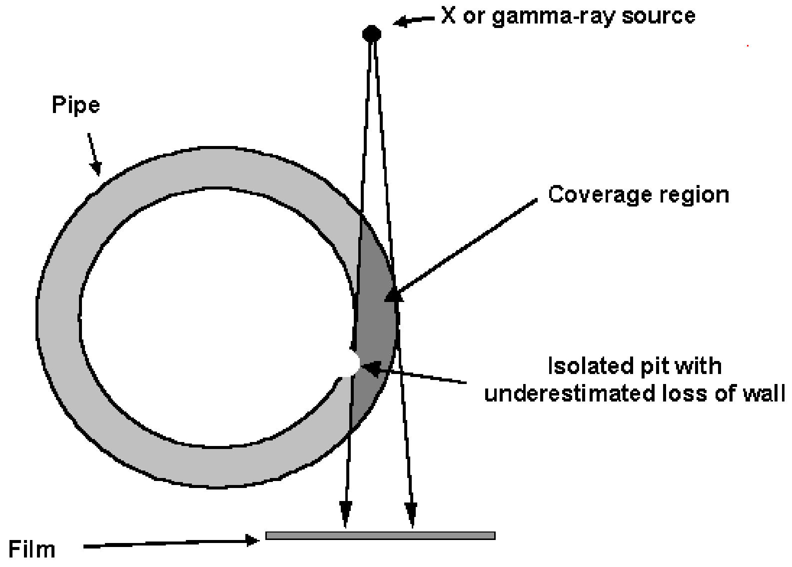


Figure 4.29: underestimation of size of isolated pipe in tangential radiography (Burch and Collett, 2005)

Tangential radiography is very efficient and reliable when applied for extended wall corrosion (Burch and Collett, 2005). This will be the reason for the recommendation of RKT to be used here for T-junctions but not for pipes or welds since the major corrosion happening in T-junctions is extended wall corrosion due to the velocity and the direction of flow while the major degradation in welds and pipes is isolated pit corrosion.

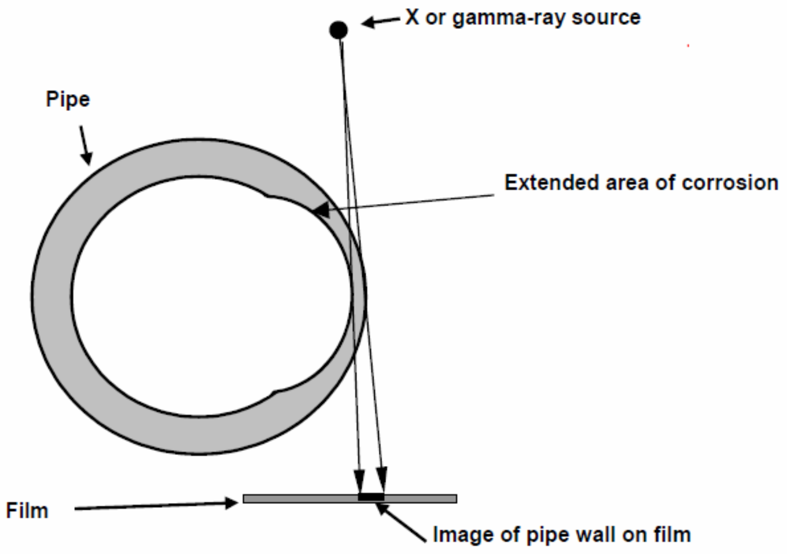


Figure 4.30: tangential radiography for extended area of corrosion (Burch and Collett, 2005)

Therefore as it is seen at the figures above, tangential method will be perfect for the inspection of T-junction. The reason that UL is not recommended, is because of the difficulties that exist for the positioning of the probe in T-junction. It won't be in contact with the surface of the object and therefore the amount of noise can increase and the accuracy decreases.

But another factor that should be considered here is the selection of the proper source for tangential radiography. As recommended by the table 2.1 at chapter two, Cobalt 60 will be a good choice to be used for the inspection of T-junctions considered here since the T-junction has wall-thickness more than 21 mm and the pipe diameter is 8″. The size of the film for this size of t-junctions is recommended to be 300*400 mm.

Now the data of inspection results will be considered here to see the practical issues related to the recommended methods.

4.3.1 Evaluation of the number of inspections (frequency) using each method

The data will be filtered for 8″ diameter T-junctions for the production flowlines. The charts provided below show all the inspection methods' frequencies used for the inspection of flowlines.

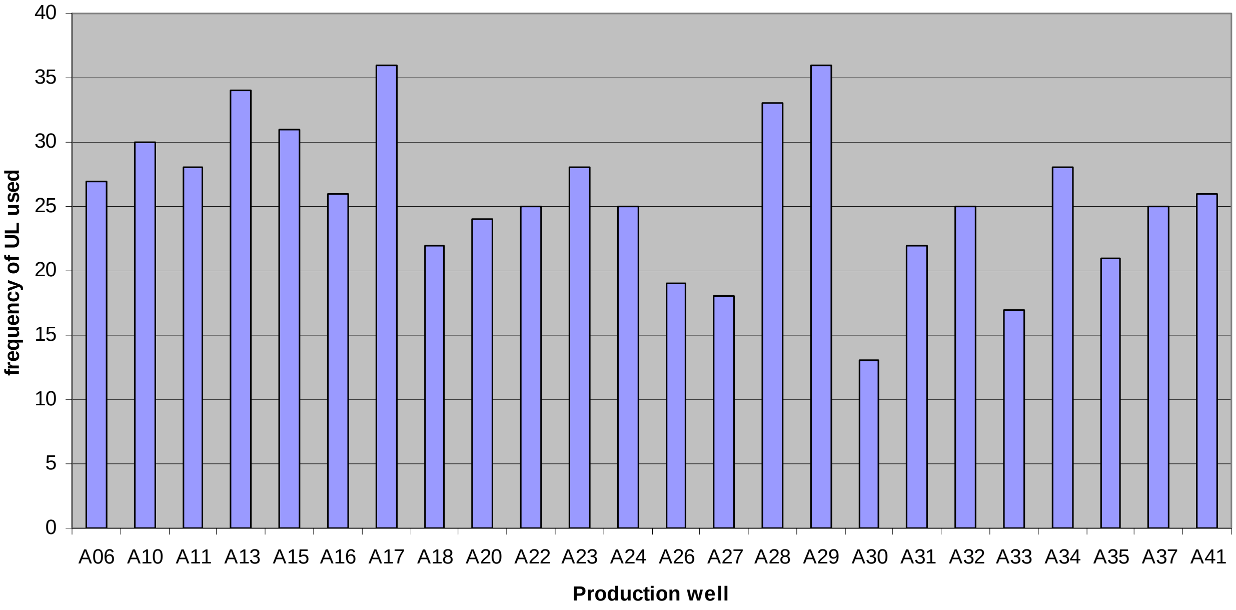


Figure 4.31: number pf UL inspections performed for each production well's T-junctions

As shown at the chart above, although UL is not one of the recommended methods for the inspection of T-junctions but it shows that it has been applied as a major NDT method for this area. Wall-thickness variations are of concern here and after VIS and RKT, UL is a method that can be considered as efficient to be used for tee-junctions.

After stopping the flow, inspectors can put on gloves and touch the pipe and inspect its condition. This can provide a good picture in inspector's mind of the real situation, helping him more on commenting about it when reporting the results to the management.

The data related to the visual inspections performed for T-junctions is graphed for each production well's flowline at the chart below.

By going through the data, it becomes clear that UL has been used instead of RKT for the inspection of tee-junctions. The difficulties of applying RKT for T-junctions which will be discussed further in conclusion part, makes ultrasonic testing as the second most used method after visual inspection for this part. It seems that considering the advantages and disadvantages of both ultrasonic testing and tangential radiography, and with respect to all practical limitations that the company has, e.g. in budget and equipment, makes ultrasonic testing to weight more and thus to be applied for the inspection of t-junctions with 8″ diameter and more than 21mm wall-thicnkness.

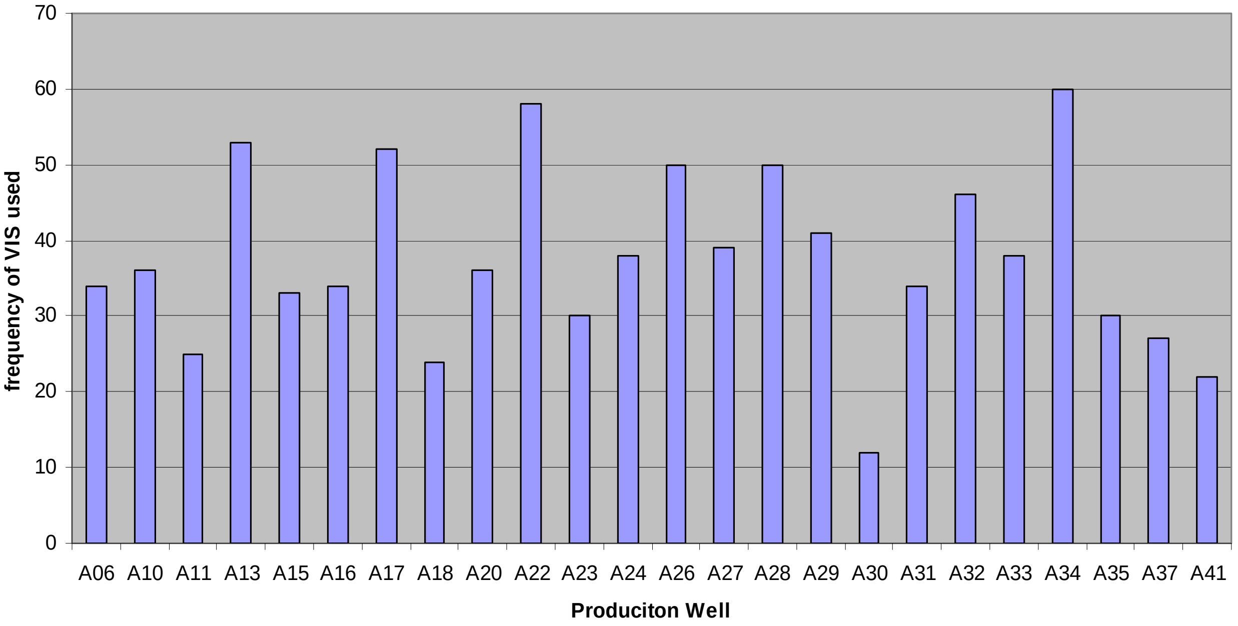


Figure 4.32: number of VIS performed for the inspection of T-junctions

The chart below shows the proportion of each method used in the inspection of T-junctions of flowlines of each well.

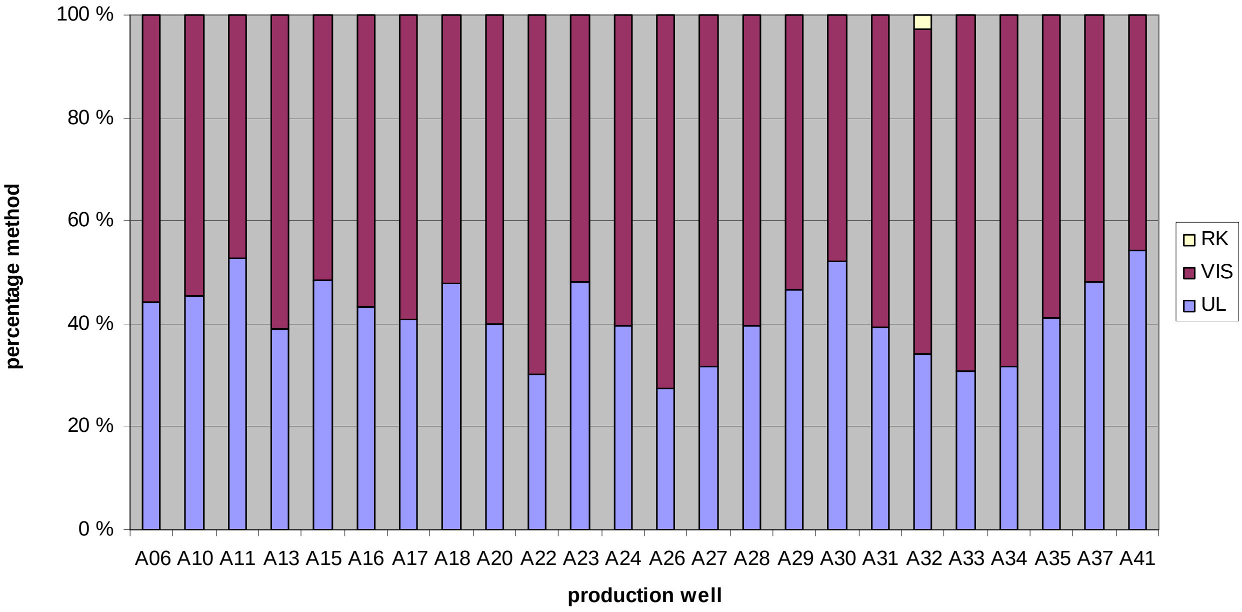


Figure 4.33: proportion of each method in the inspection of T-junctions

As shown at Figure 4.33, the major methods used for the inspection of T-junctions are ultrasonic testing and visual inspection. There is no indication of RKT as recommended as the second method within the data.

4.3.2 Evaluation of the reliability and accuracy of methods used

In order to see the accuracy of UL for the inspection of tee-junctions, a spot is chosen to be considered here which there are three corrosion finding reports for that. The data is provided at table 4.9 for further discussion.

Table 4.9: inspection results of A23, SP6,F2

INSP_DATE	METHOD
23.08.2001	UL
24.11.2001	VISN
15.11.2003	VISN
14.11.2005	VISN
31.08.2006	UL
07.01.2008	VISN
13.01.2009	VISN
21.03.2010	VISN
26.10.2010	UL

The red colored results are indicating that degradation has been observed. This table shows that the degradations have been found only by visual inspection and ultrasonic testing was unable to find out the defect.

By looking at the comments column it is seen that the inspectors have written that it is clear that about 4-5 mm corrosion has occurred here, but it is hard to measure it with ultrasonic testing. This is an indication of the inaccuracy of ultrasonic testing in tee-junction inspections.

Some other randomly chosen spots within flowlines confirm the discussion above again. These spots are shown below together with their place on the plant.

Table 4.10: inspection results of A24, Sp3, F2

INSP_DATO	METODE
20.11.2010	VISN
11.10.2008	VISN
02.09.2006	VISN
13.05.2003	VISN
13.08.2002	UL
20.10.2001	VISN

Table 4.11: inspection results of A29, Sp2, F2

INSP_DATO	METODE
26.11.2000	VISN
05.10.2001	UL
30.11.2002	VISN
05.12.2004	VISN
16.09.2006	UL
02.01.2007	VISN
12.01.2008	VISN
18.01.2009	VISN
30.04.2010	VISN

While UL is recommended to be applied in order to verify the results of VISN, the tables and data above show that VISN was more capable than UL in detecting defects. UL was unable to show the degradations taking place at the part. The comments column should be looked in such cases to see the comments related to the observations of inspectors. This fact shows the importance of VISN in inspection programs and its capability in detecting defects and degradations.

But after all, since ultrasonic testing is cheap and doesn't have any heavy equipment, it can be used faster and easier to measure the amount of degradation. Visual inspection remains as the major inspection method here.

4.3.3 Conclusion

The reason for not using RKT is that for the inspection of T-junctions with 8″ diameter and 21 mm wall-thickness, as the table 2.1 suggests, the best way to produce the desired picture, is to use cobalt 60 as the radiation source and a 300*400 mm film (based on the calculations for choosing the proper size of film which are not of concern here).

Cobalt 60 has heavy and expensive equipment. Therefore it takes more time to apply it for each test and it is expensive also. Beside, the HSE considerations should be taken into account. The matrix suggests the best methods, but in practice there are more issues like the ones mentioned here that make the inspectors to think about another method to apply for T-junctions. Cost, time, and radiation hazards bring ultrasonic testing as another choice for the inspectors to use it in their operations.

But here the question is that "Should ultrasonic testing replace tangential radiography in the matrix?". The question comes from the fact that although tangential radiography is recommended by the matrix but it is not used even once in the inspections performed by the company. Is it a poor recommendation of the matrix or is it because of the existing limitations that eliminate tangential radiography as a good NDT method of inspecting tee-junctions?

By interviewing the inspectors, it becomes clear that the recommendation of matrix is not a poor one. By applying the appropriate source (cobalt 60) and a proper size (300*400) and type of film and also by placing the source in its best position which is top of the t-junction, we can get the desired picture revealing the existing condition of t-junction. Since it is extended corrosion that occurs in wide scale within the pipe in junction, it is more reliable and precise to use RKT. But since there are radiation hazards, with rather higher cost of RKT (in compare to UL) and its heavy equipment (related to cobalt 60), the company prefers to apply ultrasonic testing instead, however the results won't be as precise and clear as tangential radiography, but it just helps the inspectors to have roughly a picture of the condition in their mind.

Therefore there seems no reason to replace RKT by UL in the matrix since regarding the type of degradation happening in tee-junctions, RKT is a reliable and accurate method to be applied for that.

4.4 Evaluation of recommended methods for Bends

Regarding the matrix provided at table 4.1, the recommended methods for the inspection of bends are first and second respectively UL and RK.

Filtering procedure of the data will be similar to the previous parts. Like before, the data will be first filtered for bends and then 8″ diameter pipes. Then with respect to the number of the production flowline, the methods will be evaluated regarding their frequency and efficiency of use.

4.4.1 Evaluation of the number of inspections (frequency) using each method

Following the procedure mentioned above, we get the charts and data provided below which are of interest in the analysis here.

After filtering the data an interesting result is revealed. There is no result of inspection for the bends of production flowlines. Aren't there any bends in 8″ diameter production flowlines?

The answer is No! There are no bends in 8″ diameter production flowlines. It is very common not to have bends in bigger diameter pipes since end-caps are used instead. End-caps usually have thick plates that once in 4-5 years are inspected and if needed are replaced easily. But if bends are used, they will be eroded much faster due to the thinner wall-thickness they have and the replacement operation is much harder than the one for the end-caps.

In addition to the difficulties of replacing bends, since they get eroded and corroded faster, therefore the need for replacement increases, as a result the cost of maintenance will be higher and thus this makes it more expensive.

Therefore with respect to the easiness and less cost of the use of end-caps, bends are avoided to be installed within the structure of pipelines of the plant. But as for pipelines, UL and RK remain as the best recommended methods for the inspection of bends.

4.5 Errors in results

Going through the results there seems to be some errors as mentioned earlier. These errors can be results of human mistakes in performing tests, human mistakes in making reports, or lack of experience and training and etc. Within this part of this chapter such errors will be pointed out and discussed. The evaluation will start with choosing some points in some flowlines and then see how many times the result of wall-thickness measured has been reported strangely so that it can be an indication of mistakes or misinterpretations of observations.

The results of inspections for 4 welds are shown below. T(målt) is an indication of wall-thickness measured. All welds relate to 8″ diameter flowlines.

Table 4.12: T(målt) for A06, Sp2, S1

inspection date	T(målt)
07.08.2000	25,4
19.05.2002	24,5
10.08.2002	25,4
10.08.2002	25,4
03.06.2003	25,4
05.06.2003	25,4
05.04.2005	25,4
06.04.2005	23,5
06.02.2007	25
05.03.2008	25,4

Table 4.13: T(målt) for A10, Sp10, S1

inspection date	T(målt)
28.05.2000	25,4
12.05.2001	25,4
08.06.2004	25,4
09.06.2005	24
27.11.2006	25,4
05.06.2008	20
25.05.2009	20
21.11.2009	25,4

Table 4.14: T(målt) for A10, Sp7, S8

inspection date	T(målt)
08.06.2004	23
16.05.2007	24
18.05.2009	24,5
21.11.2009	25,4

Table 4.15: T(målt) for A10, Sp1,S2

inspection date	T(målt)
14.06.2000	22
25.05.2002	21
25.06.2004	21
05.07.2006	21
22.05.2007	22
21.08.2010	22

These four welds were just some sample examples of the thing that is going to be discussed here. This evaluation will be more interesting if all the welds of a certain flowline get considered. Thus we can see that how many mistakes have happened within a certain number of inspections. This evaluation can be done for flanges, pipes, T-junctions and etc.

Here the 8″ diameter flowline related to the production well A10 is of consideration. This flowline has 1008 different fabricated welds which are shown on P&ID diagrams. For all these welds total number of 479 inspections are planned within the period between 28.05.2000 and 02.09.2010. By filtering the data regarding the specific parameters of a certain weld, number of mentioned mistakes occurred in inspections are counted carefully.

In order to clarify how the numbers of mistakes are calculated, consider table 4.12 above. As shown with red borders, the wall-thickness measured is increased once from 23,5 to 25, and for the second time from 25 to 25,4. Therefore within the inspection results of this specific weld, two exotic results are observed since increasing wall-thickness regarding the degradation processes does not make any sense. Following the same principle in table 4.14, we'll see that there are 3 increases reported for the wall-thickness which does not make sense.

Therefore counting the mistakes starts. Inspection results show that for the welds of this flowline on its path from the x-mass tree to the production manifold there have been 54 cancelled observations out of 479 observations. These cancellations can be because of lack of equipment, absence of inspector and etc. Also those observations with no report of wall-thickness are not considered in this evaluation. Therefore there remain 425 true and correct inspections.

Among the results of these 425 inspections, there are 42 strange and absurd results which cannot be considered as true and reliable result for following the trend of corrosion or erosion within the production flowlines since they show a strange increase in wall-thickness which regarding the degradation processes happening in production flowlines is considered as an absurd result.

The chart below shows these portions clearly.

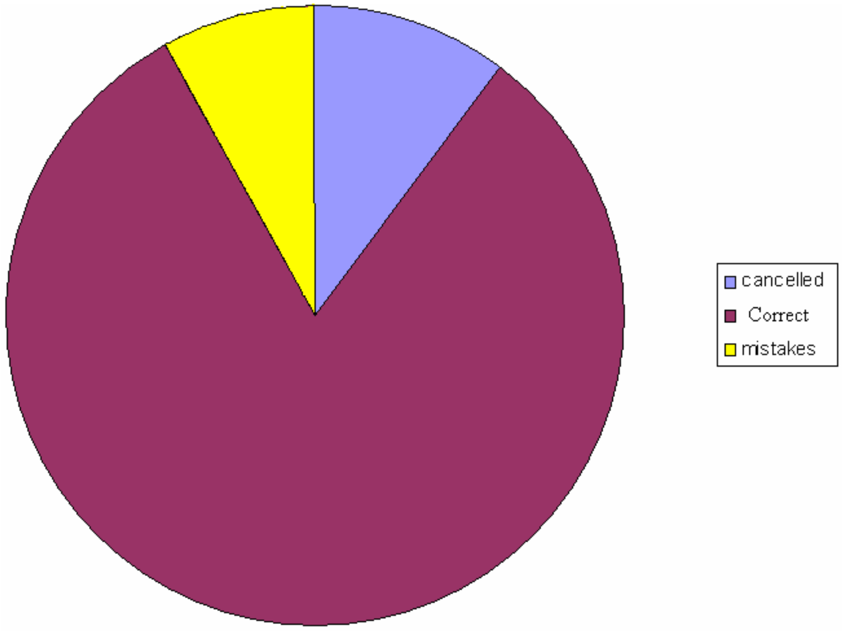


Figure 4.34: Portion of mistakes regarding the performed weld inspections for A10

The same procedure for analyzing the number of mistakes is followed here for the inspection results of pipes. From the total number of 160 inspections planned to be performed on pipes, 2 inspections are cancelled. Among the 158 performed inspections, 22 inspections have shown exotic results since the newer inspection performed shows increased wall-thickness in pipe which is meaningless with regard to the degradation occurring in production pipes.

An example is provided at table 4.16 below which has a cancelled observation and 3 errors in inspection results.

The chart provided at Figure 4.35 shows all the inspections with proportion of cancelled ones and the ones with errors in results. This chart provides a better understanding of the amount of mistakes that have happened. These mistakes can be a result of an error in making reports or a result of poor inspection. Poor inspection refers to those ones performed by an inspector with less experience and training. Poor inspection can be a result of applying improper method for the inspection. But when planning for the further inspections, the trend is considered though there are mistakes within results.

Table 4.16: T(measured) for A10, Sp1, R1

INSP_DATE	T(MÅLT)
09.06.2000	19
17.05.2001	20
25.05.2002	19,5
17.06.2003	20
25.06.2004	19
08.06.2005	18
20.08.2005	0
04.07.2006	18
09.06.2008	18
02.06.2009	19
02.09.2010	19

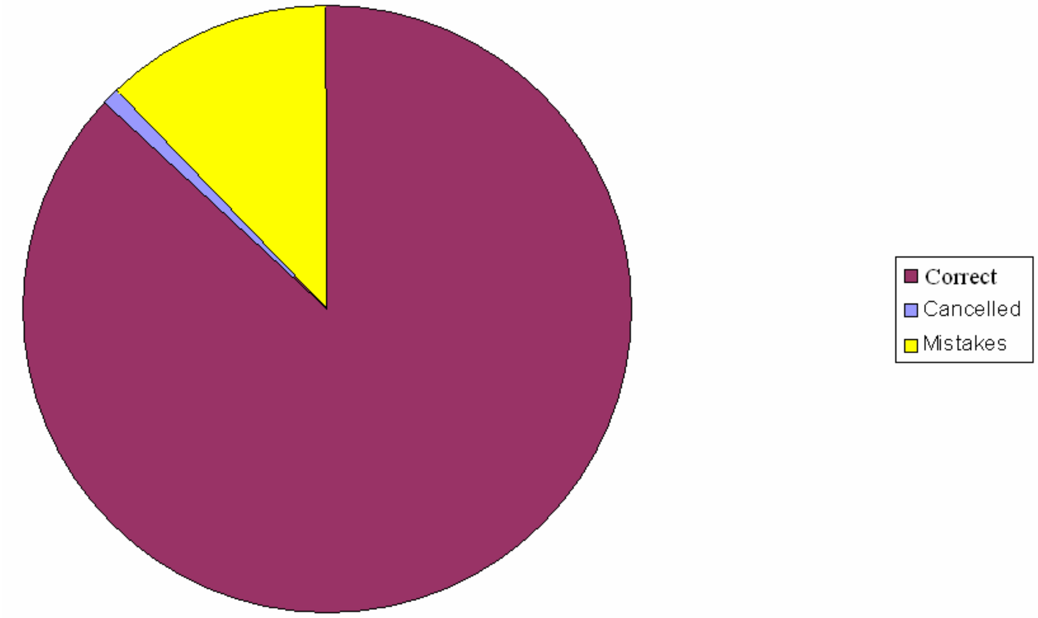


Figure 4.35: Portion of mistakes regarding the performed pipe inspections for A10

It is of interest to the same sort of analysis for the inspection of T-joints within the 8″ diameter flowlines here. Condition monitoring of T-joints has been always a significant challenge in inspection and maintenance management programs. This is mainly due to the fact that they are not uniform in wall-thickness which is discussed and shown at part 4.2. The flowline of production well A10 is considered here again. 66 inspections have been performed in total. Among all these 66 inspections, there are only 5 out-of-order results with no cancelled observations.

Finally the chart below puts all these numbers together and shows an overall conclusion on the amount of inspections planned, performed, cancelled and those with mistakes in reports.

This chart provides a percentage of each category. For example by looking at the column of pipe inspection results, it seems that almost 85% on the inspections planned have performed and have reported correct and expected results. But about 2% of the inspections have been cancelled due to the lack of equipment or other unseen events that affect the inspection. The remained 10-12% have reported results which are not considered as correct and show unusual trend of degradation regarding the ongoing degradation.

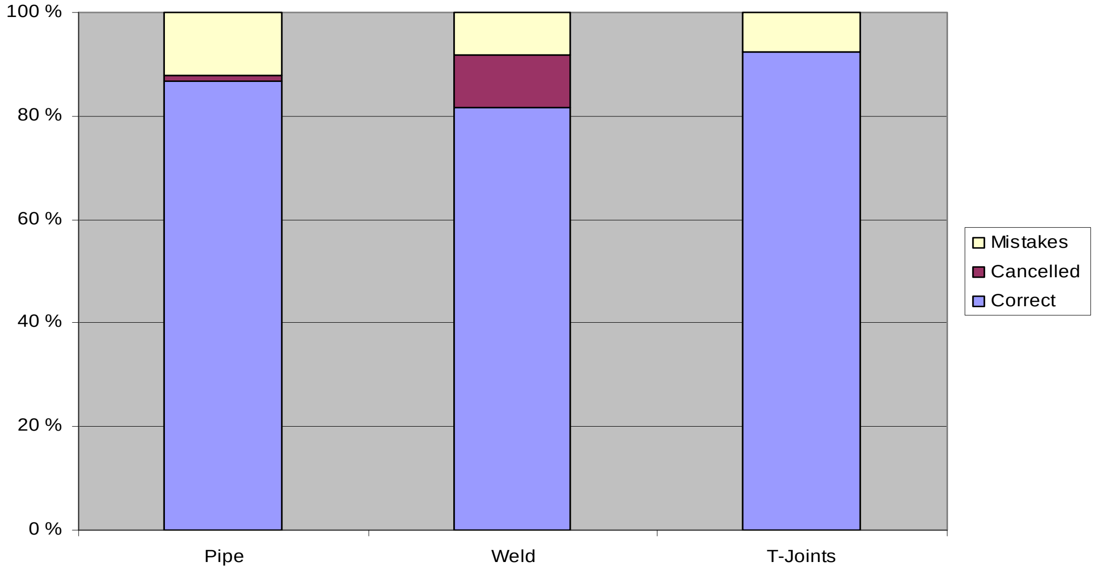


Figure 4.36: proportion of inspections with mistakes in results, cancelled ones, and correct ones to total number of inspections planned

4.6 Findings and results from the evaluations

The most important results of the evaluations done at the previous parts that should be remarked here include:

1. Visual inspection has been always considered as an important method which plays a major role in inspection plans and programs. Although VIS is not a recommended method for most of parts by the matrix, but historical data show that it is always performed and its role in detecting defects cannot be neglected. Visual inspection can be used for:

- Visual inspection can be used for information gathering on the existing situation of pipes, welds, junctions and etc. This information can be collected in a short time with rather high reliability. As shown at part 4.3.2 which was about the evaluation of the methods performed for the inspection of T-junctions, visual inspection was the most important and reliable method for that part. In some points in the flowlines, while UL was unable to detect flaws, visual inspection was always indicating the presence of defects.

- Visual inspection can be used for fast checks for getting some background for further plans. For example when visually there seems to be a defect within the interior part of a pipe, planners will ask inspectors for performing e.g. radiographic testing or UL for sizing or positioning of the flaws.

- While visually inspecting pipes, welds, and etc. some points which seem are critical can be detected rather faster than the other methods which need some equipments.

These were just a few benefits of visual inspection. Although visual inspection cannot be as precise and accurate as other methods in determining the exact amount of corrosion or in defining the size of flaw, but its role and importance cannot be neglected since it can provide a really good background in one's mind of the ongoing degradations within the different parts.

2. Well definition can change by time. For example if a certain well is producing oil and gas now, after passing e.g. 10 years it can change its definition and it can be used as a water injection well afterwards. Therefore all its inspection intervals and all recommended methods for its inspection will change as well. This is the reason of having a few amounts of inspections for some wells. Their definition is changed and they have either stopped functioning or are being used as injection wells so far.

3. *Zero production* can cause the inspection programmes to be stopped. As mentioned above after passing a certain time, a well can be stopped of producing oil or gas and therefore all the inspections for that will be cancelled in the future. But this well can start functioning if the reservoir gets enough pressure by injections and other factors and can produce oil and gas again. Therefore this well will be back in production but with less pressure and temperature.

4. *Change in design criteria* such as pressure and temperature by reduction of production rate by time can lead to changes in the recommended inspection methods and inspection intervals. When for example a flowline is designed to tolerate 20 bar, the methods for its inspection will be ultrasonic and radiographic testing. But as the time passes and the production rate decreases, the criteria will change as well. For example T_{min3} will be the first criterion that will change as the pressure and temperature of the flow decrease. Change of T_{min3} will change the inspection intervals and methods as well. Maybe it will be recommended that for the new situation with decreased pressure and temperature, and with changed T_{min3} visual inspection would be good enough and in alerting conditions more accurate methods should be deployed to get a good picture of the condition in mind. This can be done due to the instructions in reducing cost and time of inspections.

5. *The client* plays a major role in operations as well and its dedication to its responsibilities will influence all other main branches of the operation such as maintenance, modification and inspection. For example when a client neglects its responsibility which is to inject chemical for prevention of scale, corrosion and other expected degradations, the result will be higher amount of inspection of pipes and injection points and all other related parts of plants. This is the reason that for some parts of flowlines the amount of inspection shows a sudden increase in compare with the historical trend. By going through the underlying reasons, it becomes revealed that the client has refused to perform its responsibilities and therefore the amount of inspection has increased regarding faster degradation and the increased need for more information about the situation in order to avoid any kind of failure.

6. *Material type* is always an influencing factor in the selection of NDT method. It can be seen that after changes in the material type of some flowlines, the inspection methods performed change as well. For example, while RKT seems to be worthless to be performed in high diameter pipes made of carbon steel, it seems rational to be used for the same diameter pipes but made of duplex material since duplex material has less wall-thickness.

7. *Human mistakes* are always of consideration. It is mentioned for a couple of times within the context that probably the use of RKT instead of RK while RK was the recommended method, was either a mistake by operators (which doesn’t seem rational, since all the operators are highly trained and skilled) or a mistake within reports which will be again considered as human mistake. Such mistakes can confuse the planners in making further inspection plans and can cause poor interpretation on the existing condition of the desired parts.

8. *Poor categorization of data* seems to be another challenge for the inspectors. For example as you saw within the context, there are some points that cannot be categorized under neither 8″ nor 2″ diameter pipe due to the welded part which has none of the mentioned diameters. This can increase the time that takes for the planners to suggest further inspections since each time they have to go through bunch of drawings to find the exact point and recommend the proper method. When they observe that for a 8″ diameter pipe RKT is performed. They go through the drawings and find out that the point is actually a welded 2″ diameter pipe, so the recommended method cannot be RK but it should be RKT. If they do not look at the drawings and recommend RK to be performed regarding the suggestion of matrix, it will result in the confusion of inspectors since they see that they should perform RK based on the plan, but actually RKT is more accurate based on their experience.

9. *HSE considerations* are the other influencing factor which can totally change a recommended method when it comes to the real practical experiment. For example when

considering the reasons that why RKT is not used even once for the inspection of T-junctions, one of the reasons is that the HSE regulations doesn’t allow the frequent use of RKT because of its radiation hazards. With respect to the fact that HSE considerations are becoming stricter and harder every day, it seems that the use of radiographic testing is getting decreased. HSE considerations can change a method for example from RKT to UL for the inspection of T-junctions.

10. Access to the point is another consideration that affects the selection of methods. As discussed in chapter 2, there are some points which are quite hard for the radiographic testing to be performed for them. Therefore inspectors prefer to use ultrasonic testing instead. As a result the location of part is a very important and influencing factor in the selection of NDT methods. When it comes to the injection points, where there is a lot of corrosion due to existing turbulence there, inspectors will go for ultrasonic testing since placing the film, source and such factors are making radiographic testing less accurate and just more difficult for the inspectors to use.

11. Cost and portability of equipment are the other influencing factors in the selection of NDT methods. As illustrated at part 4.3 which was about the evaluation of recommended methods for T-junctions, the use of RKT for 8″ diameter pipes and 21 mm wall-thickness requires cobalt 60 as the source of radiation. Cobalt 60 has expensive and heavy equipment which makes it almost impossible for some companies to use. As in the example provided here, although RKT seems to be the best practice for T-junctions, but its high cost and difficulties in moving from place to place eliminate it as a practical method for the mentioned parts.

As another example, in computed radiography which is discussed at chapter 2, heaviness of plates brings the inspectors to a point that they neglect its other advantages and prefer the conventional radiography still to use in their operations. Therefore, although some methods are better on paper, but when it comes to real practical experiments some other factors influence the applicability of the method.

All these mentioned factors are among the most important influencing factors that affect the selection procedure of NDT methods and these are not all influencing factors. These factors seem to be influencing in the selection process since the results of the analyses performed in the previous parts prove them. There are other factors such as the classification of equipment, classification of safety areas, amount of risk involved in each part and etc. which highly affect a method to be selected for inspection. For example in those areas that the existence of sparks and radiation is forbidden, even if RK is the most accurate and efficient method, it cannot be used and some other methods become applied instead. Therefore regarding the analysis performed here, most of the influencing factors in the selection of NDT method for the evaluation of offshore static equipment are revealed and are recommended to be considered when the companies make matrixes for their own plants and structures.

5. NDT methods recommended to be applied

Beside the recommended methods by the table 4.1, companies always try to update themselves with the developing knowledge of the new technologies and methods. New technologies are not always as good as they seem to be at first. Many factors such as cost, applicability of the method regarding the existing limitations, HSE considerations and etc. affect the efficiency and reliability of the method. Companies willing to apply new technologies usually test those new methods in certain areas with expected results and evaluate them and if the results are good and the expenses are reasonable, then they start to deploy them in other parts of the plant.

As mentioned earlier, in some parts although some methods are suggested by the matrix but the existing limitations don't allow the company to apply them in inspections. For example the matrix recommends RKT to be used for the inspection of tee-junctions with 8″ diameter pipe and more than 21 mm wall-thickness, but HSE considerations, heaviness of cobalt 60 equipments, expensive equipment, the need for highly-trained operators and radiation hazards force the company not to apply RKT for the inspection of mentioned parts. But this fact does not necessarily mean that the matrix is wrong or the recommended method should be changed.

Therefore, within this chapter, some other new methods that are recommended for certain parts will be considered and recommended in a new matrix developed by the end of this chapter.

5.1 TOFD (Time of Flight Diffraction)

Time of Flight Diffraction has been in use for a long time (developed in late 1977's) and it has proven that it is one of the best methods that can be applied, or even should be applied, for the inspection of welds. TOFD was used for sizing flaws at first, but it opened its way through the NDT methods as a technology in finding defects as well as sizing them. A comprehensive study performed by the Netherlands Welding Institute (NIL) shows that in most of the cases TOFD can be applied instead of radiography for the inspection of welds. This study calculates the probability of detection with each method and provides the graph shown at Figure 5.3 which shows the probability of detection of radiographic testing (RT), ultrasonic testing- pulse echo and TOFD. (Roux, 2005)

The basic principle of TOFD is shown at the pictures 5.1 and 5.2. As you can see, the basic difference between TOFD and UL is the diffracted energies. In the conventional ultrasonic, the energies are reflected from the defects to the probe and their position and size become figured out. But in TOFD the energies are diffracted from the tips of the defect and then are absorbed by another (not the same) probe on the other side of the defect. This makes TOFD capable of accurately measuring the defect size, its location and orientation. (Mondal and Sattar, 2000)

The principle of this method is based on the fact that diffracted waves have different velocity than the reflected ones, and since the diffraction of longitudinal waves is stronger than for shear waves, longitudinal waves are preferred to be used in TOFD (Mondal and Sattar, 2000).

The main **advantages** of this method are:

- High probability of detection (Figure 5.3)
- TOFD does not depend on the orientation of defect (Mondal and Sattar, 2000)
- Documentation ability since the result of the test is provided as a permanent record (Mondal and Sattar, 2000)
- For wall-thicknesses more than 25 mm, the scanning speed is much faster than for radiographic testing (Mondal and Sattar, 2000)
- Very efficient in flaw sizing
- TOFD can be used in high temperature environments (up to 250 degrees C) (Lawson, 1997)

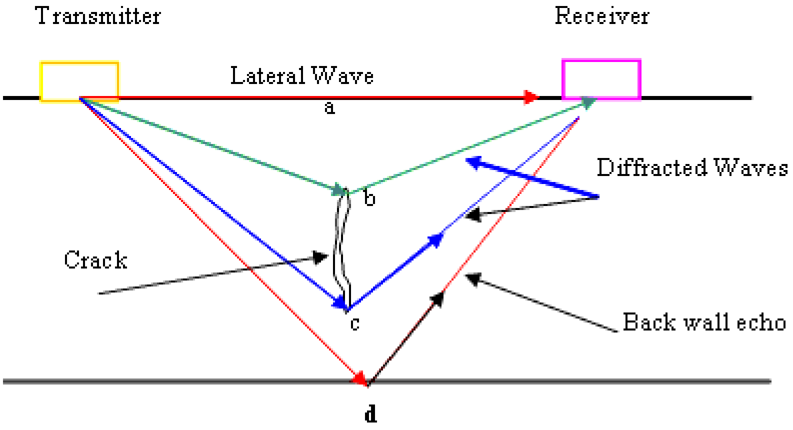


Figure 5.1: basic principle of TOFD (Prabhakaran and Wong and Teng, 2004)

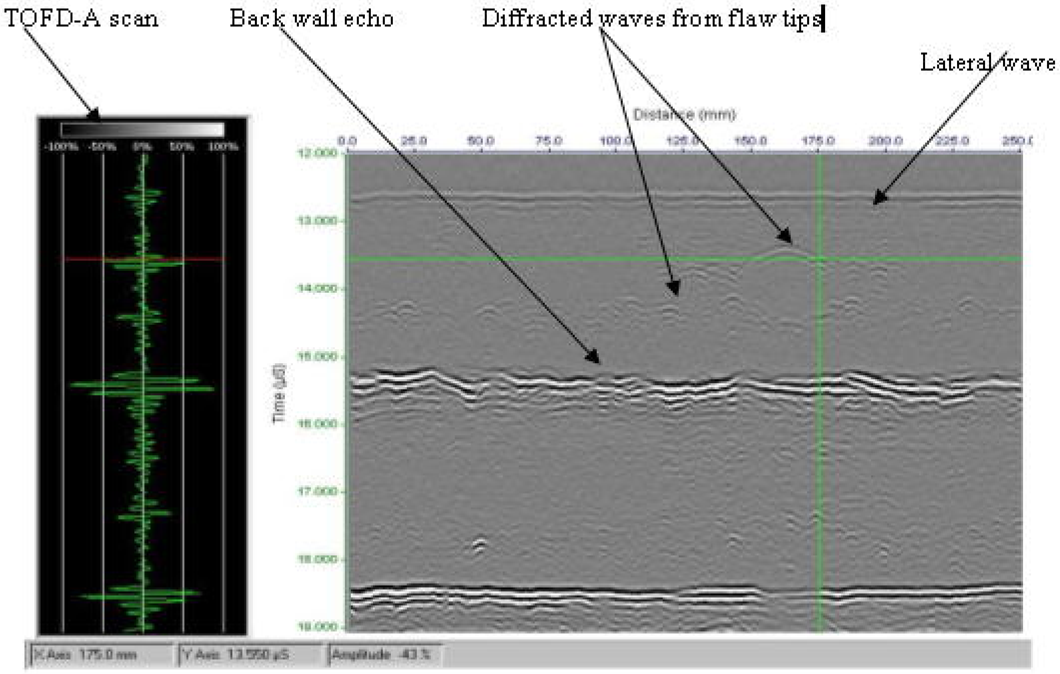


Figure 5.2: result of TOFD (Prabhakaran and Wong and Teng, 2004)

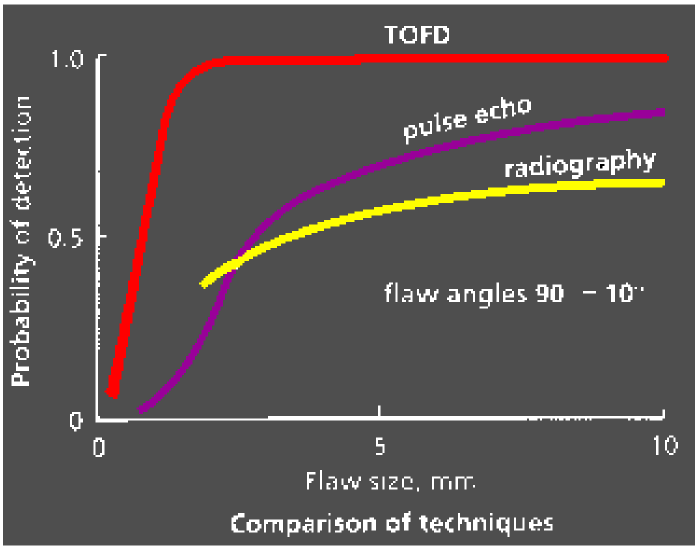


Figure 5.3: Probability of Detection for NDT methods (Erhard and Ewert, 1999)

The main **disadvantages** of this method are:

- As the results of experiments done in the laboratory by Erhard and Ewert in 1999 show, TOFD is not efficient for detection of crack-like defects. (Erhard and Ewert, 1999)
- Adjusting the appropriate sensitivity level is a challenge. If the sensitivity level is adjusted above electronic noise level, the produced image will show a lot of diffracted echoes from very small defects and inhomogenities which doesn't mean that the quality of weld is not good. On the other hand if the sensitivity level is set on a low level the image will display no diffracted echoes.(Mondal and Sattar, 2000)
- Interpretation of pictures sometimes turns to be very hard since the diffracted echoes from the actual defect are mixed with noises from existing inhomogenities.(Mondal and Sattar, 2000)
- TOFD is not suitable to be applied for the detection of small cracks at backside. At in-service inspection of welds the very important issue is to find out the defects at the backside of the pipe or container. Echo amplitudes diffracted from the tips of cracks which are so close to the backside wall are very small and almost impossible to be distinguished. For such cases, conventional ultrasonic testing is recommended. (Mondal and Sattar, 2000)
- The frequency of the probe should not be less than 10 MHz (Mondal and Sattar, 2000)
- The angle of the defects is not always close to vertical and this makes the situation a bit difficult for TOFD to find it out

- There should be always a certain distance between two probes. Therefore if for example there is a wall, or a pipe branch or anything else that can disrupt the certain distance between two probes therefore the application of this method turns to be impossible.

After all the discussion above it seems that TOFD has a quite good advantage over radiographic testing. In some cases which TOFD seems not to be as efficient as desired, conventional ultrasonic testing is suggested. With respect to the HSE considerations getting stricter day to day for the radiographic testing, TOFD seems to be an efficient replacement for that.

Roux (2005) has done a comprehensive experiment to compare radiographic testing with TOFD. The number of welds examined in his experiment is as follows: (Roux, 2005)

Total welds being inspected both by RT and TOFD:	136 welds
Number of welds with no defects (confirmed by both methods):	17 welds
Number of welds with defects detected only by RT:	22 welds
Number of welds with defects detected only by TOFD:	67 welds
Number of welds with defects detected by RT & TOFD:	47 welds

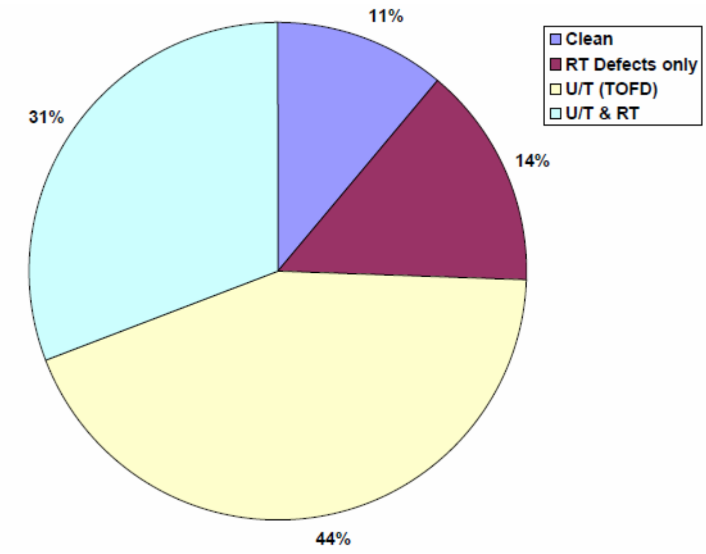


Figure 5.4: Comparison of TOFD and RT (all welds) (Roux, 2005)

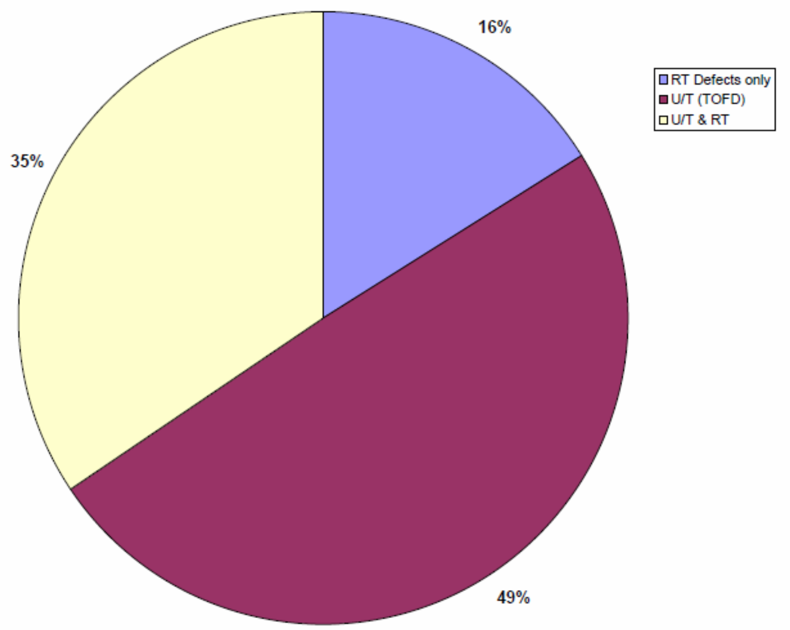


Figure 5.5: Comparison of RT & TOFD for welds with defects only (Roux, 2005)

By adding 49%+35%, we get that the probability of detection of TOFD was 84%, while the PoD was 51% for radiographic testing. It should be mentioned that the interpretation and skill of the operator have influenced the gained results. But from the results above it seems that TOFD has the ability of replacing RT in weld inspection.

Some of the other advantages of TOFD over RT are: (Roux, 2005)

- *Scan time versus exposure time*: since the wall-thickness being evaluated here is more than 21 mm (as the matrix says) it needs more exposure time and stronger sources of radiation such as cobalt 60. Ultrasonic methods do not slow down by increased thickness. Therefore TOFD with the possibility of providing a picture from the test is a good replace for RT.
- *Radiation hazards*: special HSE considerations are always required when cobalt is the source of radiation. X-ray and gamma rays are always problematic to the personnel working around the test place in field operations. Sometimes large areas should be evacuated for the safety of people just to perform the radiographic inspection.
- *Accuracy*: radiographic results are not always accurate to show the depth of flaw. This can be overcome by using ultrasonic rapid detection technique.

- *Cost savings*: in compare to RT, TOFD has a slight increase in cost. But considering all costs related to interference of RT to other activities and the high productivity of TOFD, the overall cost reduction for the project using TOFD becomes significant.

5.1.1 Conclusion

Regarding all discussion above about the advantages and disadvantage of TOFD and the experiment performed to compare TOFD with RT, TOFD can replace radiographic testing in weld inspections. In special cases where the crack is near to the backside, conventional ultrasonic testing can be used as the second recommended method to verify the results. But like all the other NDT methods, the best practice would be using a combination of RT and TOFD at inspections. The best practice is to find out how different NDT methods can interact with each other in order to increase the inspection efficiency rather than evaluating them to find which one can replace another one. For example if tomography is of consideration, RT can be applied not only to detect planar defects but to determine the depth of flaw as well. But then again the strict HSE consideration should be taken into account and the best combination should be figured out in order to increase the efficiency and effectiveness of the inspection. TOFD has opened its way to NDT methods and is vastly applied with many companies and has proven to be efficient and reliable. After all, these results with related comments will be applied to the recommended matrix in order to update it. This matrix is provided at the end of this chapter.

5.2 Phased Array

Since phased array (PA) is basically an ultrasonic method, therefore the principal procedures of performing the test and its basic characteristics such as wave propagation, reflection, refraction, mode conversion and diffraction still remain the same (Ditchburn and Ibrahim, 2009). But the differences between the conventional ultrasonic testing and phased array make this method one of the leading NDT methods in industries. Its applications are increasing day to day and more companies are willing to adopt it in their inspection programs.

The differences of two methods lie under their probes and wave-fronts. While in conventional ultrasonic testing (UT) a monocrystal probe is used, in phased array a multi-element probe, usually made of 32–128 elements, is deployed (R/D Tech Corp., 2011; Ditchburn and Ibrahim, 2009). The monocrystal probe creates an ultrasonic wave propagating with a single refraction angle. But in PA, the multi-element probe creates many small cylindrical waves which eventually combine with each other and generate an overall wave-front. The elements in this probe can be arrayed in different patterns but the most used one is the linear pattern (Ditchburn and Ibrahim, 2009). Each of the small wave-fronts generated by each element can be time-delayed or synchronized for amplitude and phase which is considered as one the most important features of phased array.

The main difference of two methods is the use of "computer-controlled excitation" in phased array. Therefore there becomes the possibility of defining different amplitudes and delays for individual wave-fronts. All these features of PA, make the opportunity to have a focused ultrasonic beam with the possibility of defining its parameters as desired. These parameters include: beam angle, focal distance, and focal spot size.

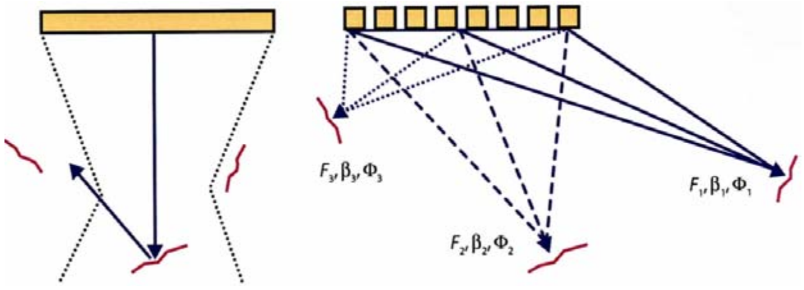


Figure 5.6: detection of disoriented cracks with monocrystal (UT) (left) and multi-element (PA) (right) probes (source: R/D Tech)

As shown at Figure 5.6, the beam generated by monocrystal probe is mono-directional while it is multi-angled for the phased array probe. Therefore most of the cracks with different orientations can be detected using the phased array method.

The probe elements create the ultrasonic beams at slightly different times. The echoes from the desired focal point hit these elements at various but computable times. Then all these received echoes are time-shifted according to focal law and then summed together. The overall sum is the result of the responses from the desired point so the other echoes from other points which are not of consideration are attenuated not to interrupt the resulting sum. Figure 5.7 shows all these steps clearly. (R/D Tech Corp., 2011)

The major advantage of phased arrays is its picture producing and storage over conventional ultrasonic testing which was quite dependent on the inspector's interpretation and skills. Plotting the data to a 2-D layout, so called "S-scans" creates the opportunity of reviewing the pictures by different operators in order to be more certain of the results. By moving the probe in different directions, various pictures can be gained from the same defect and this increase the information acquired about the defect size and its position and shape. A combination of shear waves and longitudinal waves can be used in phased arrays method and this is very helpful in positioning and sizing the defects by little probe movements.(R/D Tech Corp., 2011)

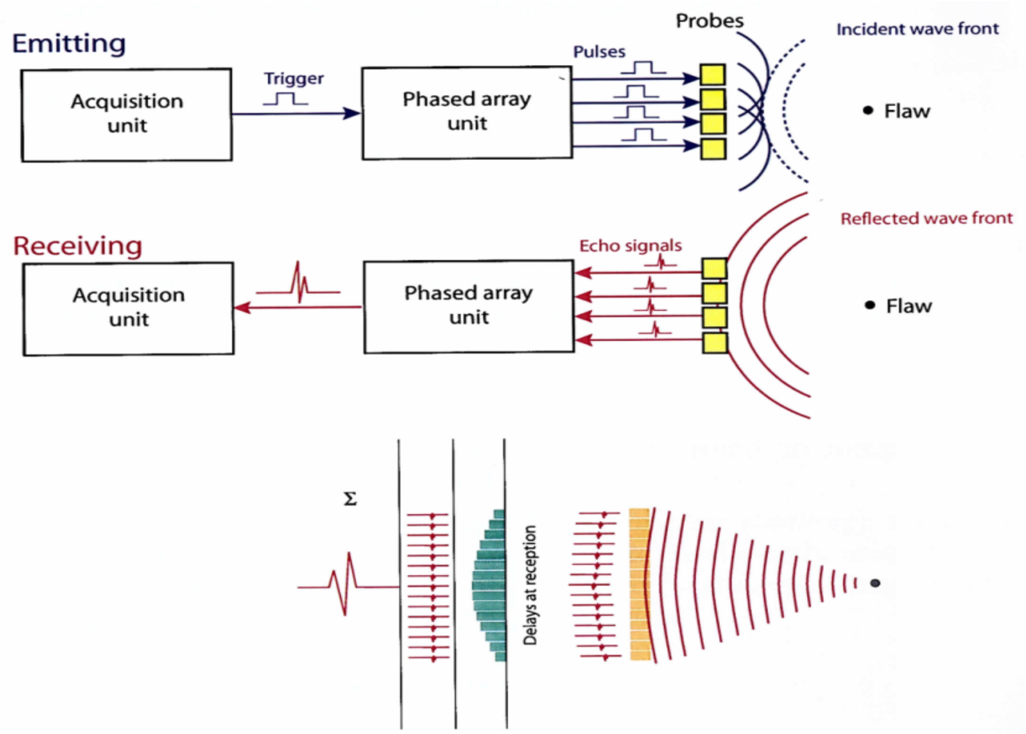


Figure 5.7: time delay and sending and receiving multiple beams (same phase and amplitude) (source: R/D Tech)

The phased array's device is shown at figure below.

Figure 5.8: phased array's device (R/D Tech)

Those parameters that determine the delay time include: aperture of the phased array probe active element, type of wave, refracted angle, and focal depth. In the picture below some examples of delay values from each element are shown. This figure shows three different beam angles of longitudinal waves ranging from -30° to +30°.

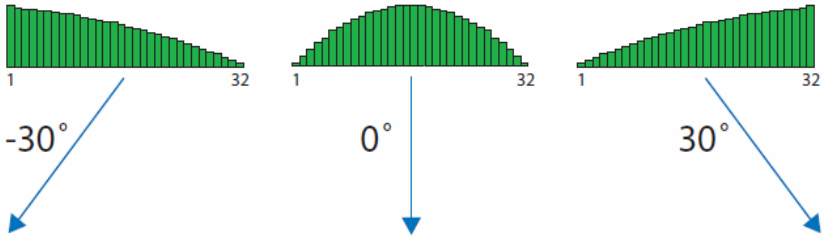


Figure 5.9: delay values of elements for three angles of longitudinal waves in phased arrays (R/D Tech Corp., 2011)

Using a static probe over four different artificial defects the picture shown below has been gained.

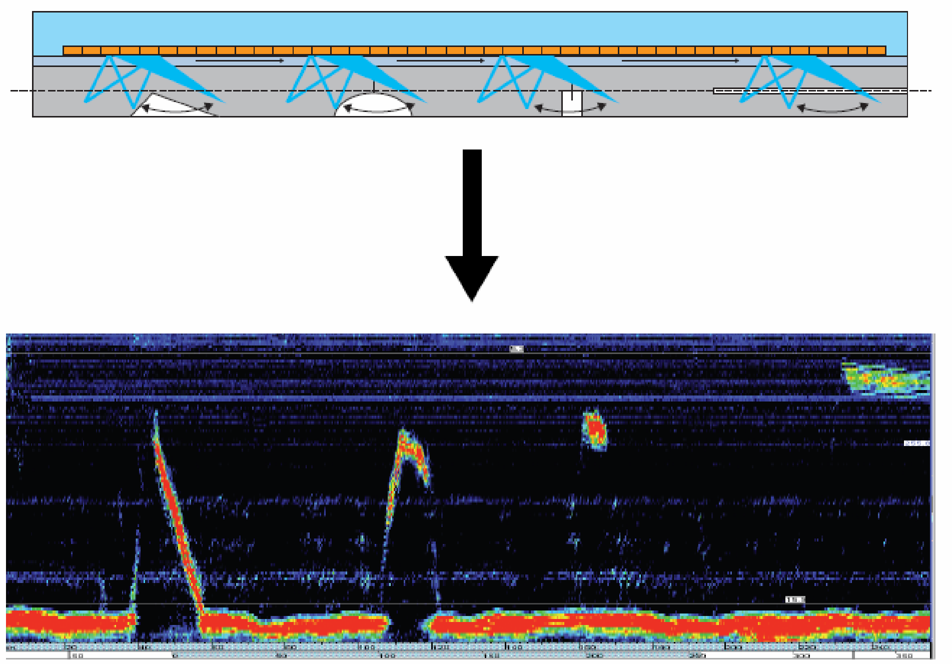


Figure 5.10: picture produced from a static probe over four various defects (R/D Tech Corp., 2011)

The capability of modifying the parameters of generated beam in PA provides three scanning techniques which cannot be deployed and made using conventional UT. These three scanning techniques are described below with related pictures of them provided at Figure 5.11: (Ditchburn and Ibrahim, 2009)

- *Linear scanning*: the desired profile of wave is achieved using all elements. The desired focal point is then achieved using this pattern. If larger probes of phased arrays consisting of 128 elements are applied, the distance covered by the wave in a single test of phased array will be equal to the movement of the conventional UT probe as long as the phased arrays probe.
- *Dynamic depth focusing*: giving different parameters to the focal law, the focal point can be changed and moved along the nominal beam axis.
- *Swept angular scanning*: known also as sectorial scanning, is used when the scanning is required to be performed in special angle. This technique applies the focal laws to steer the beam at the desired angle or sweep it in a wider angular range.

Using a combination of all these three techniques can provide a better way of scanning that cannot be achieved using the conventional ultrasonic testing method.

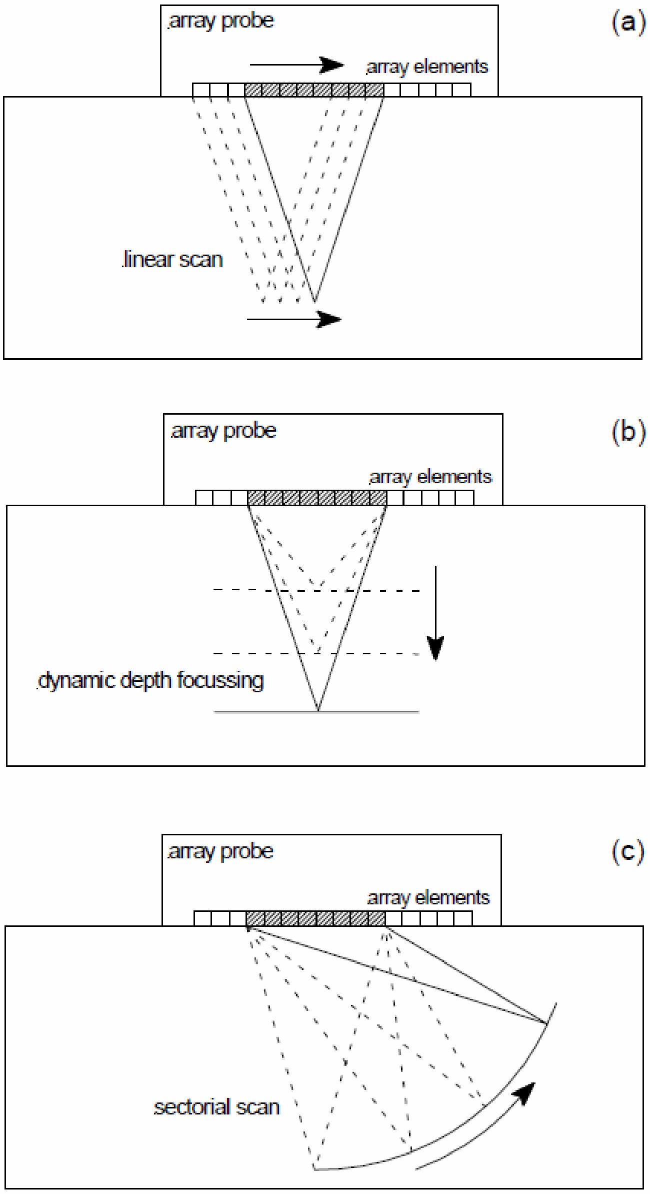


Figure 5.11: three scanning techniqes: a) linear scanning, b) depth focusing, c) sectorial scanning

5.2.1 Advantages and disadvantages of Phased Arrays

Regarding the explanation of the main features of PA testing method mentioned before, the main **advantages** of this method are as follows:

- *Increased inspection sensitivity:* regarding the capability of determining the direction and shape of the beam the sensitivity of this method to existing defects is higher than the conventional UT. The ability of defining the desired angle makes inspector capable to send the beam perpendicular to the face of expected defect. (Ditchburn and Ibrahim, 2009)
- *Increased coverage:* by defining the desired angle of the beam and with regard to the high number of elements (up to 128) and the ability of arranging all these elements in desired patterns, the coverage of PA is way higher than UT. (Ditchburn and Ibrahim, 2009)
- *Less inspection time:* electronic scanning rates are quite faster than mechanical scanning rates which are used in conventional UT. Characteristics of phased arrays probe (consisted of up to 128 elements) make a phased array test equal to multiple conventional UT

inspections. In addition, there is less need to change the entire probe and reset all the parameters to perform the inspection is PA. (Ditchburn and Ibrahim, 2009)

- *Flexibility:* each single array of elements can provide various inspection patterns using the electronic setup files. (R/D Tech Corp., n.d.)
- *Complex inspections:* regarding the features of PA, it can be applied effectively for geometrically complex components. It can be programmed to inspect such components with different patterns, angles ad modes.
- *Higher reliability:* less moving parts make a more reliable inspection system.
- *Documentation:* one of the major advantages of this method is that it produces a picture out of each inspection so that it can be used by different operators and experts to be judged and to report the closes result to the real condition of the part.

One of the big challenges of inspections, as mentioned at the previous parts, is the access to the point. This challenge is quite common in weld inspections. Phased array solves this problem by sectorial scanning technique described before. Phased array is particularly suitable for weld geometry and using the sectorial scanning the beam can sweep through a wide range of angles. Also the image produced can be observed instantly and the array of elements can be changed (if required) in order to get a better picture and more accurate sizing and characterization of the defect from different points of views (Ditchburn and Ibrahim, 2009).

Below there is a picture of the application of phased array for a complex geometry of a nozzle with detection of cracks (Erhard et al., 2000):

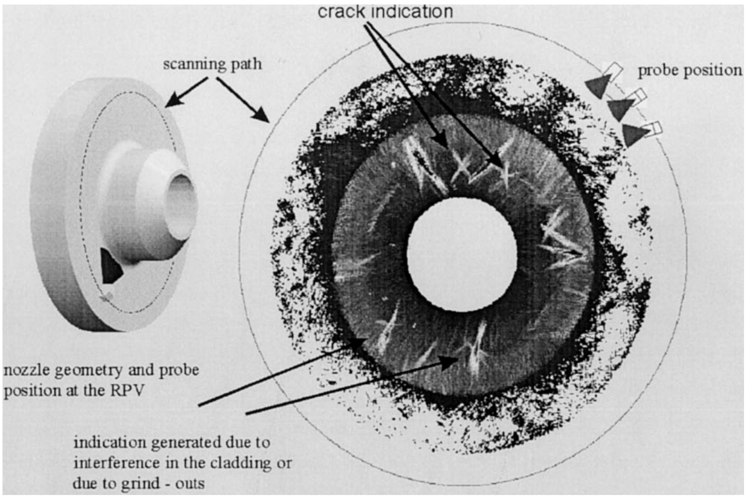


Figure 5.12: Nozzle inner radius inspection with PA (Erhard et al., 2000)

Beside numerous advantages of PA over conventional UT, there are some limitations and disadvantages that the company should be aware of that, since the application of PA will not be reliable if the operator does not know how to properly deploy this method with regard to its all limitations.

The **disadvantages** of PA include (Ditchburn and Ibrahim, 2009):

- *Complexity:* the procedures and equipments of phased arrays are way more complicated than UT and this makes it harder to be applied appropriately. Getting confused with the numerous data modes displayed on the instrument can happen for an inexperienced inspector. Unskilled operator can also get wrong results if he/she does not choose the proper array, angle and other parameters. This limitation, however, can be overcome by providing training and introductory courses for the involved operators.

- *Time consuming:* the start-up procedure of PA takes more time than conventional ultrasonic testing. Arranging the elements' arrays, sweeping angle, scan pattern and etc. needs quite longer time than conventional UT. But it should be mentioned that once all these parameters are set-up, they can be saved and retrieved quickly for subsequent inspections.
- *Cost:* phased array equipment is almost twice expensive as much as those for conventional UT. Its probes are sometimes five times as much expensive as monocrystal probes for conventional UT. Despite the versatility of PA probes, every one of them cannot be deployed for every inspection. Some areas and parts require their own kind of probe so that the inspector should have all the needed probes with him/herself available.
- *Lack of standards:* although some standards are prepared, but there is still the lack of standards for phased array. For example in 2008, ASTM International issued a standard about the performance characteristics of phased array. But this is not enough for this method and more is required.

5.2.2 Conclusion

As a conclusion, and regarding all the characteristics of phased array technique, it is going to replace conventional ultrasonic testing in most areas of application. All the disadvantages of this method can be overcome by training and gaining more experience. Higher cost of this method can be considered as an investment since it gives better and more reliable results in compare with conventional UT. Those areas with complex geometry and also with high criticality are no longer a challenge for operators if they can invest on applying phased array.

6. Recommended tables

Within this chapter, regarding all the explanations, discussions and evaluations done within the thesis and also considering some standards which are mentioned within the context and bibliography, matrixes that are recommended to be used by the companies in their inspection plans and programs are shown.

6.1 NDT selection matrix regarding specific parts

Regarding the discussion about the two most used methods in inspections of flowlines, including radiographic testing and ultrasonic testing, and explanation of all their characteristics, advantages and limitations provided at chapter 2 and chapter 3, and then the evaluation of the recommended methods by the matrix at chapter 4, two methods, including TOFD and phased array, were recommended to be considered in the updated version of that matrix in chapter 5.

This updated matrix is shown at table 6.1 below. It should be mentioned that those methods which are proved to be the best practice are remained unchanged in the matrix. For example, the recommended methods for the inspection of T-junctions are still the same. But the slash mark (/) used at the matrix shows another NDT method as an alternative that can be used beside the other mentioned method.

For instance, at the recommended methods for the inspection of T-joints, the first priority goes to Visual inspection. But for further evaluation, tangential radiography (RKT) and phased array are recommended. This is due to all evaluations performed at chapter 4. Those evaluations showed that despite the fact that RKT is the second recommended method by the matrix, but considering all the existing limitations, its application is close to impossible. In addition, high number of UT (UL) inspections performed shows the desire of the company for a cheaper but reliable method for confirmation of results gained by visual inspection. Therefore, after explaining the phased array method and its limitations and advantages at chapter 5, this method is recommended as an alternative to be used beside visual inspection. Tangential radiography cannot be omitted from the matrix since if proper source and money is allocated and ready, RKT is quite reliable and efficient NDT method to be used for the inspection of T-joints.

Table 6.1: NDT selection matrix regarding parts

Pipe diameter	Wall-thickness (mm)	Inspection item	Inspection method (prior)	Inspection method (second)	Comments
6″ - 8″	> 21	Weld	TOFD/RK	PA/UL	TOFD in applicable areas, UL for verifying the defect, UL when the crack is close to backside
6″ - 8″	> 21	T- joint	VIS	RKT / PA	
6″ - 8″	> 21	Pipe	PA	RK	
6″ - 8″	> 21	bend	PA	RK	

In this matrix, all conventional UL inspections are replaced by phased array, since the experience of those companies that apply PA instead of UL has shown quite a high satisfaction of results. But still the lack of standards or acceptance criteria remains a challenge in application of PA. Further information about PA is provided at chapter 5.

Regarding all radiation hazards that radiographic testing has, RK is the second recommended method for the inspection of pipes and bends. Phased array is quite a reliable and efficient method to be used as the first method (instead of conventional UL) and in cases of any need for more detailed information, inspectors can choose radiographic inspection to perform.

6.2 NDT selection matrix regarding degradation mechanisms

Another type of matrix is provided and shown here which recommends the proper NDT method regarding the specific degradation mechanism(s) going on within the part. This matrix considers the systems which the flow is passing through them, the degradation mechanisms, and the methods themselves. A noticeable point of this matrix is the recommendation of phased array and TOFD for some types of defects. As discussed at chapter 5, TOFD is becoming one of the leading NDT methods for the inspection of welds. Therefore it can be deployed for the inspection of the most of the degradation mechanisms which can occur in welds. This is the same for phased array method explained earlier with characteristics that makes it possible for this method to replace conventional ultrasonic testing in most of the application areas.

In order to exactly know how NDT methods are recommended based on the degradation mechanisms, the degradation processes occurring in a flowline should be understood. Degradation processes of a flowline can highly affect the production rate and system efficiency. As shown at Figure 6.1 (Ratnayake and Markeset, 2010), the influencing factors on degradation processes are mainly comprised of erosion, corrosion and stress. Degradation processes affect the efficiency and accuracy of the NDT methods. Therefore, the operators who are performing the non-destructive tests should be aware of the type, size and position of defects to get the most reliable results. Inspection planners should be able to evaluate degradation factors such as corrosion rate, sand production rate and etc. to provide an efficient inspection plan. This plan should have appropriate intervals since for shortening of intervals will increase the inspection cost while lengthening them can increase the probability of failure.

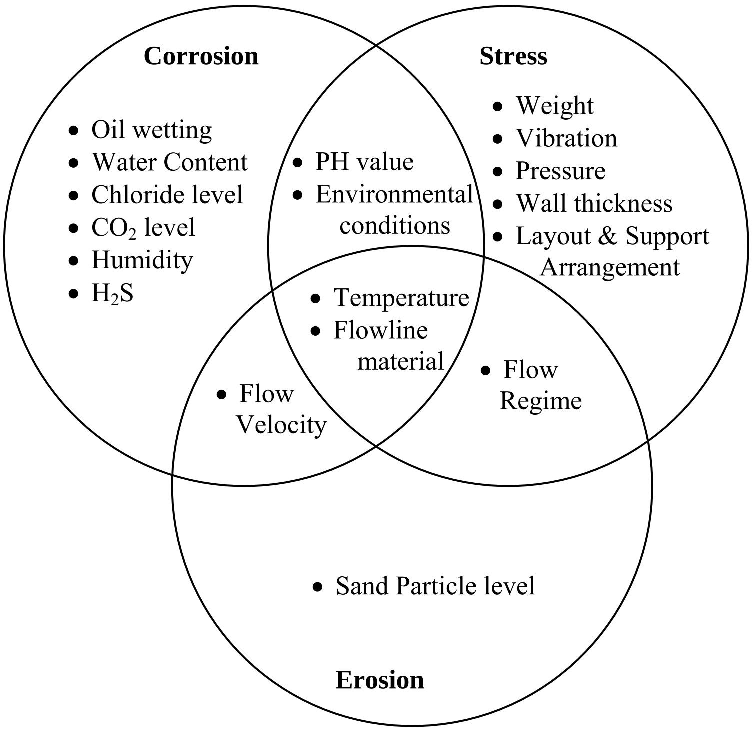


Figure 6. 1- Degradation factors of flowlines (Source: (Ratnayake and Markeset, 2010))

The figure above clearly shows the different factors influencing the degradation process with their relations to each other.

Flowlines can be degraded both internally and externally. Internal degradation is basically because of the stream flowing inside the flowline while external degradation can be mainly a result of bad environmental conditions. Corrosion is the most common degradation that happens in pipelines (Ratnayake and Markeset, 2010). Corrosion is the chemical process of degradation so that material is chemically changed before removal, and it highly depends on time elapsed. Therefore it can be concluded that the flowline's material has a significant impact on corrosion rate and the way it extends over the pipe.

Erosion, on the other hand, is the physically removal of material without any chemical changes in their compositions. Sand particles' amount and size will highly affect the level and the rate of erosion within the pipelines. Flowline's material plays an important role here as well.

The aim of this part is to provide a table for selecting the proper NDT method depending on the degradation mechanisms. This table is very useful if it is considered together with the results of evaluations performed at chapter 4, and the characteristics of most used NDT methods described within chapters 2, 3, 5 and 6. Different types of degradations are explained at the following parts and then all together are considered within the matrix shown at the last part. Of course the chemical reactions of degradation processes are not of concern within this manuscript.

6.2.1 Galvanic Corrosion

Galvanic corrosion occurs when two metals are in electrical contact with each other and both are immersed in an electrolyte. The anode in this reaction is the metal with more negative potential so the cathode will be the other metal with more positive potential. Depending on the environment, there are different galvanic corrosion series which can be used in order to determine which metal of the galvanic couple will be corroded first. The most used one, known as "Galvanic series" is shown at Figure 6.3. The most anodic (least noble) metals are the most reactive ones which are to the right end of this chart, while the most cathodic (noblest) ones which are the least reactive ones are to the left end of that.

At Figure 6.2, a picture of galvanic corrosion for the galvanic couple consisted of stainless steel and carbon steel is shown. The bolt is made of stainless steel while the body of the tanks is made of carbon steel. Therefore the carbon steel is the more reactive metal in this situation and gets corroded faster than stainless steel.

Figure 6.2: Galvanic corrosion of a tank

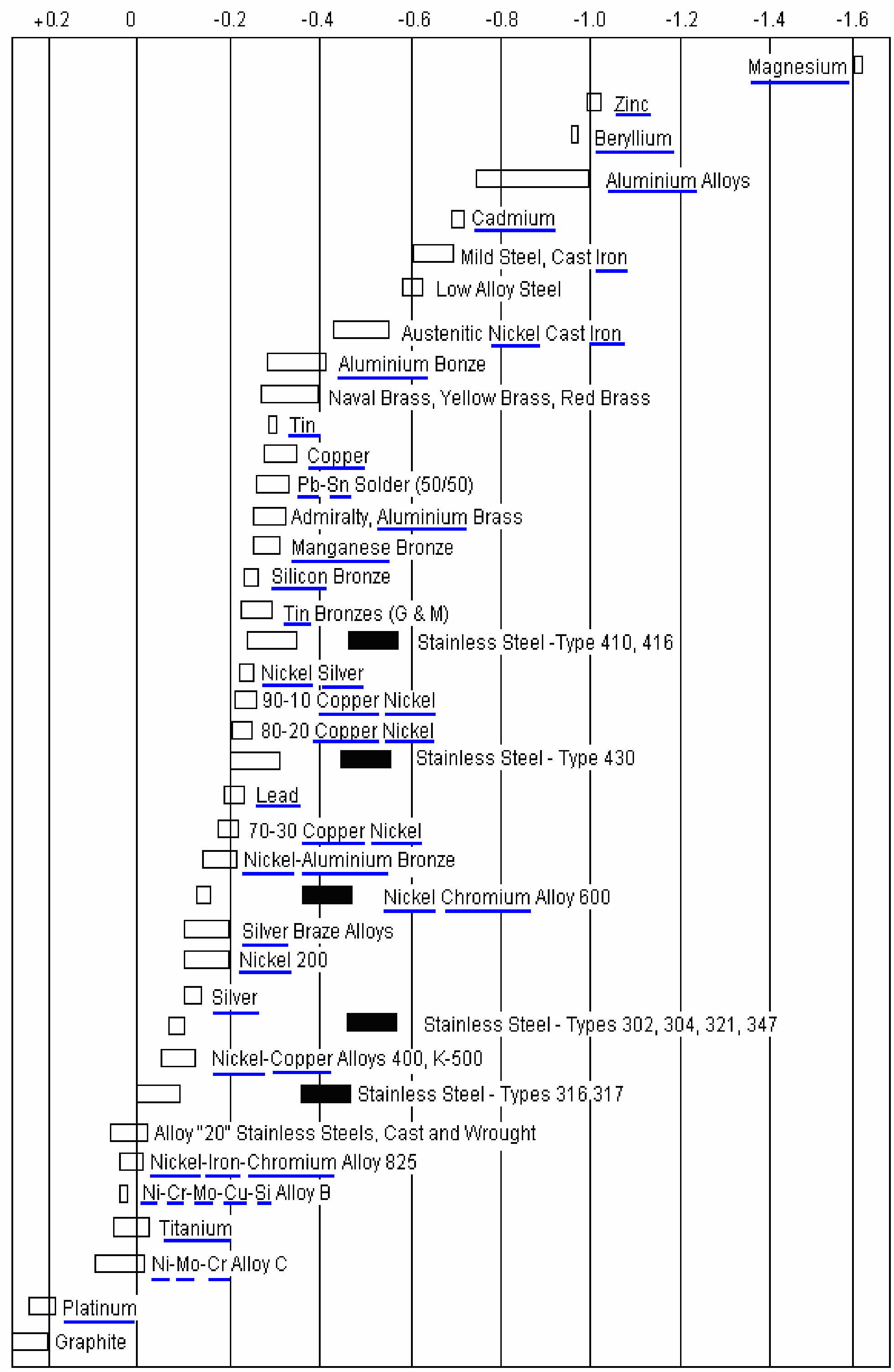


Figure 6.3: Galvanic Series (Source: westcoastanodes.co.uk)

An illustration of ionic flow between anodic and cathodic metals is shown below.

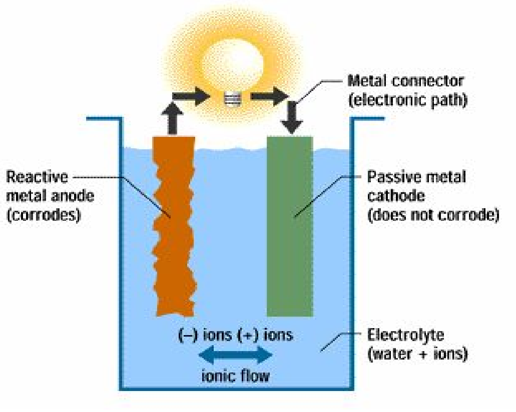


Figure 6.4: Galvanic corrosion (Source: met-engineering.blogspot.com/2009/06/principles-of-corrosion.html)

6.2.2 CO_2 Corrosion

CO_2 corrosion is one of the most common types of corrosions in the Oil & Gas industry due to the existence of the CO_2 in the crude oil and natural gas coming out from the oil/gas reservoir.

If CO_2 of the oil or gas stream gets dissolved in water which is usually contained in the oil/gas flow, carbonic acid (H_2CO_3) will be formed. This acid is very corrosive to the low alloy steel such as carbon steel. This acidic flow has lower PH value now and it leads to local wall thinning or pitting corrosion on carbon steel.

CO_2 corrosion increases if oxygen and organic acids are present in the environment, since they dissolve the protective Iron carbide scale and they also prevent further scale formations (Nalli, 2010).

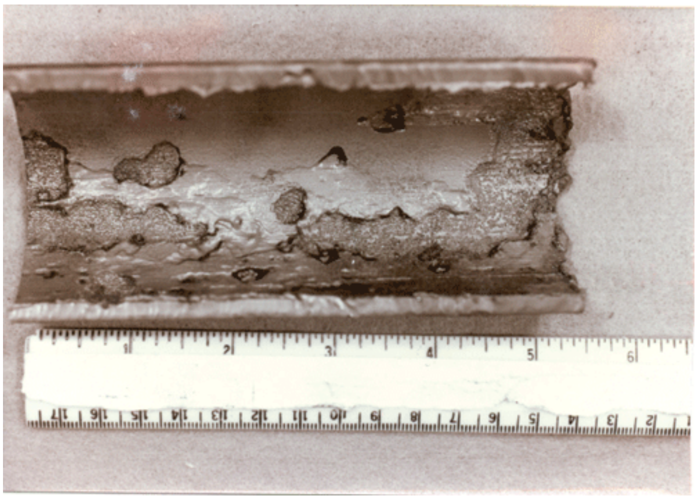


Figure 6.5: Mesa attack- a form of CO_2 corrosion in flowing environment (Source: octane.nmt.edu/waterquality/corrosion/CO2.htm)

6.2.3 Microbiologically influenced corrosion (MIC)

Microbiologically influenced corrosion (MIC) is a result of the activities of bacterial microbes happening in an environment which has all four required conditions together including metals, nutrients, water and oxygen. This type of corrosion is very aggressive and it can lead to major pipeline failures within a short period of time. When MIC starts to take place, the consumption of metal occurs and this can lead in pitting or even tubercles. MIC can result in plugging the pipe and valves, or pinhole leaks. It can also change the smell and the color of water. One of the ways to detect MIC is to analyze the liquid flowing within the pipe to see whether it contains bacteria or not (Kent et al., n.d.). The presence of fatty acids, sulphates together with bacteria can help MIC to occur. In some cases, the use of flow improvers and such chemicals can contribute to MIC. MIC can be an issue for stabilized oil systems, drain systems, water injection systems and parts with temperatures from 0°C to 80°C. (DNV-RP-G101, 2010)

Figure 6.6: MIC in wet fire sprinkler system (Source: http://www.stroudsystems.com/pm_fss.html)

6.2.4 Elemental sulphur corrosion

The major difference between sulphur and elemental sulphur is their state in nature. Sulphur is gaseous while elemental sulphur is solid. Elemental sulphur has the yellowish color and sulphur smell the same as the sulphur itself. It is less predictable and it can be created even it is not identified in the initial gas composition which is going to be transported. During the time that the gas passes through different networks and it receives various chemical reactions, those molecules that contain sulphur, release elemental sulphur. This is due to the existing temperature, pressure and environmental factors that make the condition ready for sulphur to turn to solid state and form elemental sulphur. (Pack and Trengove, 2007)

The existence of sulphur is highly dependent on the characteristics of the gas. But it can arise from the contaminations containing sulphide as well. Considering the various chemical and physical reactions that happen within the pipeline, some contaminations such as hydrogen sulphide (H_2S), carbon disulphide (C_2S) and carbonyl sulphide (COS) get formed. All such contaminations are prone to release sulphur in gaseous state. When this gaseous sulphur meets the required temperature and pressure it changes directly from gas to solid resulting in the formation of elemental sulphur. In other words, when there seems to be a great pressure drop at the contaminated site, the probability of formation of elemental sulphur increases. (Pack and Trengove, 2007)

Elemental sulphur needs costly and excessive maintenance since its consequences are catastrophic and it also reduces the reliability of the gas supply. Its consequences can be the equipment failure, total disruption of gas transportation, or extensive damage to rotating plant. (Pack and Trengove, 2007)

This elemental sulphur then reacts with the iron element (Fe) of the pipe and leads to the corrosion. Figure 6.7 illustrates the elemental sulphur deposition in a pipeline.

Figure 6.7: deposition of elemental sulphur

6.2.5 Stress-Corrosion Cracking (SCC)

For SCC to take place, the combination of a corrosive environment with mechanical stress is needed to be present on a susceptible material. There are different types of SCC while every one of them has its own special name. For example “Season cracking” is a term that refers to that type of SCC which leads to cracking on brass in an environment that contains ammonia (Cottis, 2000).

This type of flaw does not create significant wall losses but it remarkably reduces the material strength which leads to mechanical fast fractures and catastrophic component and structure failures. Hence, SCC seems very rare but if it takes place then the consequences will be very costly and destructive. (Cottis, 2000)

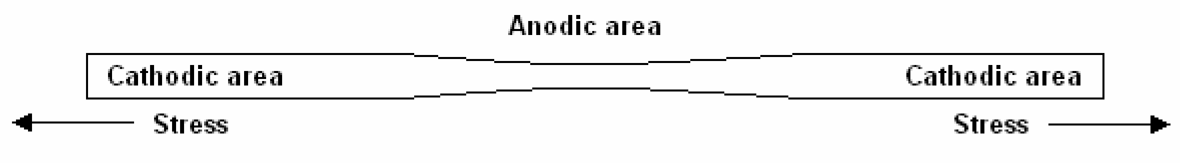


Figure 6.8: Stress Corrosion Cracking (Source: http://octane.nmt.edu/waterquality/corrosion/envinduced.htm)

The crack mode is identified as three categories (Cottis, 2000):

- Intergranular: Cracks go along the grain boundaries
- Transgranular: Cracks go across the grains
- Mixed: Combination of the two above

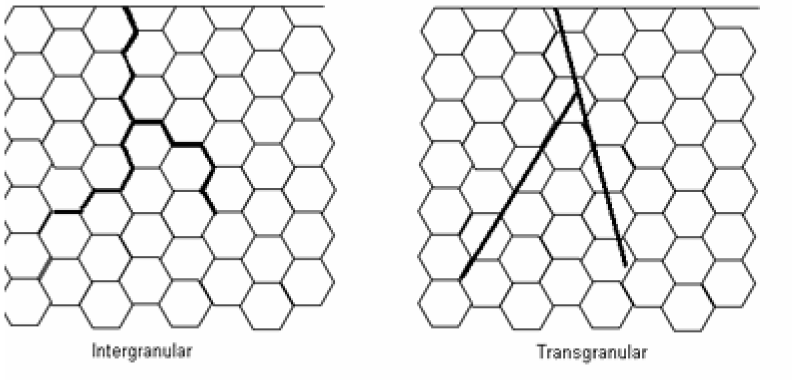


Figure 6.9: Intergranular and Transgranular SCCs (Source:http://octane.nmt.edu/waterquality/corrosion/envinduced.htm

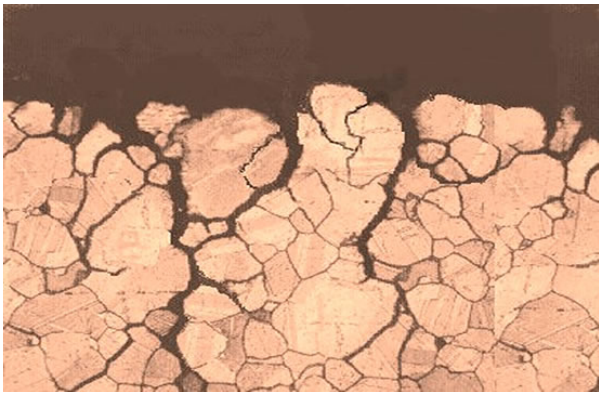


Figure 6.10: Intergranular SCC in a copper alloy (Source: cdcorrosion.com)

6.2.6 Hydrogen Induced Cracking (HIC)

HIC is quite common to happen when susceptible steels are exposed to aqueous environments which contain hydrogen sulphides. HIC is a mechanical crack caused by the transition of hydrogen atoms to hydrogen molecules (gaseous state) at internal interfaces between non-metallic material and base metal when the hydrogen atoms penetrate to the internal structure of steel (S.Al-Sulaiman et al., 2010).

Hydrogen can be present in the environment due to welding processes, hydrogen gas storages, and low PH that is usually present in the environment as a by-product of general corrosion. For example the presence of H_2S as a source of hydrogen is quite common in petrochemical processing plants and the presence of this substance is one of the most important reasons of hydrogen induced cracking.

Figure 6.11: HIC in a high stress pipe (source: http://octane.nmt.edu/waterquality/corrosion/H2S.htm)

After describing the Characteristics of different degradation mechanisms, the matrix is provided below which recommends the proper NDT methods to be used for any specific degradation. The matrix considers the features and characteristics of each NDT method. This matrix is based on the information provided at DNV report (DNV-RP-G101) and NDT related books (Bøving, 1989; Shull, 2002) and also the data gathered from the data base acquired from the company. The matrix is shown at table 6.2.

In order to describe fluid systems, the same abbreviations as introduced in DNV report (DNV-RP-G101, 2010) are used here, including:

PL: Process Hydrocarbons, Liquid. Contains some gas but mainly is hydrocarbon liquid with some water.

PT: Process Hydrocarbons, Two Phase. Contains oil, gas, water, sand, also CO_2 and H_2S

PW: Produced Water System. Contains water with dissolved CO_2 and H_2S.

PV: Process Hydrocarbons, Vapour. Contains dry hydrocarbon gas, CO_2 and H_2S

6.3 Conclusion and summary

Regarding the characteristics of each type of corrosion and degradation explained in this chapter, the table 6.2 is provided to recommend the proper NDT method(s) to be used for detection of that type of degradation. DNV-RP-G101 provided by DNV (DNV-RP-G101, 2010) and NDE Handbook (Bøving, 1989) are the resources used to provide this table. However, the characteristics of the equipment being inspected, the existing conditions and limitations and other influencing factors have a high effect on the selection of the appropriate NDT method to be used for inspection purposes. This table, together with the results of the evaluations performed at chapter 4, can be useful for the companies in the process of selecting the appropriate NDT method for inspection purposes.

Table 6.2: NDT selection matrix based on the degradation mechanis

	UT	RT	CVI	Video Inspection	Long Range UT	MFL	DPT	ET	MPT	PA	TOFD	NDE method combination	Comments
Uniform & Local CO_2 corrosion - Fluid Systems (PL, PT & PW)	×	×	×	×	×					×		×	- Relevant for carbon steel (CS) - Potential erosion problem in PT - Potential MIC problem in PL, PT & PW - Potential erosion-corrosion problem, If water content is more than 20%, - Dead legs if water content is between 5% and 20%
Uniform & Local CO_2 corrosion - Gas Systems (PV)	×	×	×	×	×					×		×	- Relevant for carbon steel (CS)
Microbiologically influenced corrosion (MIC) in CS	×	×	×	×	×	×				×	×	×	- Probability of occurrence increases with reduced flow - MIC is not generally expected in materials other than CS (e.g. SS) in anaerobic systems
Erosion	×	×	×	×	×	×				×		×	- Major influencing parameters: sand, flow velocity and grain size - Valve type is important when erosion is of consideration
Leaks	×	×	×				×	×		×		×	
Elemental sulphur corrosion	×	×	×			×				×		×	- possibility of its formation due to a reaction of oxygen in a wet gas environment - Increased corrosion rate if chloride is present
Local corrosion in connection with injection points	×	×	×							×		×	- Increased corrosion rate if there is turbulence
Cracks	×	×	×				×	×	×	×	×	×	
Stress-Corrosion Cracking	×									×	×	×	- Acoustic Emission as complementary method
Local Corrosion of SS in utility water systems	×	×	×							×		×	- Major influencing parameters: oxygen concentration and Fe-ions in water
Oxygen contamination corrosion	×	×	×							×		×	- The combination of oxygen and CO_2 will increase the corrosion rate.
Deformation	×		×			×				×		×	
General corrosion of CS in utility water systems	×	×	×	×		×				×		×	- Major influencing parameters: oxygen concentration and Fe-ions in water
Galvanic Corrosion	×	×	×							×	×	×	- Material type and surrounding material type should be considered
Hydrogen induced cracking (HIC)	×	×								×	×	×	- Relevant to low-alloy-rolled steels. It is not of consideration in offshore process piping. In some cases it has to be evaluated for further periodic inspections.

7. Overall Conclusion and Summary

Within the chapters 2 and 3 allocated to the explanation of the most used NDT methods for inspection purposes including Radiographic Testing (RT) and Ultrasonic Testing (UT), the characteristics and limitations of these methods were described. These limitations play a major role in the frequency of the methods and highly influence their accuracy. All the limitations are considered in selecting the proper NDT method for the inspection of flowlines.

Besides by evaluating the historical data acquired from one of the leading engineering services providing companies located in the Norwegian Continental Shelf (NCF), the factors and parameters which influence the frequency and accuracy of the NDT methods were revealed. These factors such as the cost and weight of the equipment associated with the NDT methods along with accessibility to the point and HSE consideration affect the frequency of the method being used and the accuracy of the results acquired. In addition, the client’s roles and responsibilities, well’s definition, production rate, material type and etc. not only have influences on the frequency of the NDT methods used, but also affect the amount and volume of the inspections performed. There should always be a factor related to uncertainties associated with the inspection plans. The data should be categorized precisely and the related P&IDs should be made accurately since they have a direct effect on the precision of the plans and test performed.

In addition to all the factors mentioned, the underlying reasons of some exotic results were revealed by the evaluations. When the underlying reasons of these are known, planners and inspectors can take them into account when they are dealing with work packages. This can help them not to be distracted by unusual data and enables them to focus on the true trend of degradations. The knowledge and the experience of the personnel involved play an important role here.

All these factors and influencing parameters summed up with the explanation of some recently introduced NDT methods and resulted in two important tables provided at chapter 6. The first table focuses on the specific parts within flowlines and suggests the proper NDT methods to be applied for inspection purposes. In addition to all these important factors and parameters, type of degradations is very important in the selection of the appropriate NDT method. This factor was also considered in chapter 6 resulting in the second important table. The explanation of the major degradation mechanisms helps to understand why a specific NDT method is suggested within the table. However, one of the limitations of the thesis was that there were few data related to the recently introduced and applied NDT methods. It was tried to cover and overcome this limitation by using scientific papers and other useful sources of information.

The results of the thesis can be very useful for the companies looking for the factors and parameters that can affect their inspection plans and programs. These factors have a high effect on the frequency of the NDT methods applied for inspection purposes. If these parameters are considered carefully, then the results will be more accurate and reliable. Revealing the underlying reasons of exotic results help inspectors and planners to follow the true trend of degradation mechanisms. Besides, This thesis opens research areas to for making NDT selection matrixes and etc.

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