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MASTER'S THESIS

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Abstract

In Nature, most of all Metals evolve as stable ores of chemical compounds like oxides, sulphides or carbonates. Lot of energy is required to refine and make them useful for some means for every Industry.

Corrosion on metals can reverse an unnatural process back to a lower state of energy, easily as simple. It eats away metal in outdoor furniture and automotive bodies, leaving the surface with bad appearance and if it is not treated at right time, eventually it will lead to failure. Corrosion causes rusting the cookware and tarnishing of silver parts. Of greater importance, corrosion takes place on Steel bars in reinforced concrete result in failure of highway section, damage to big buildings, even collapse of towers that may take lives of many and leads to significant loss of resources. Hence, Corrosion prevention would be an important step for any industry, especially oil and gas Industry where corrosion is a serious ageing mechanism which impacts the equipment of Subsea, Surface, refineries and process plants.

The present study is on localised corrosion happen in Safety Joint, inner sleeve and most design feasible corrosion monitoring equipment based on cost measures has been identified. Different types of Corrosion monitoring equipment's for offline and online monitoring are discussed and GE RADAR Inspection with use of Ultrasound inspection technology has been identified as most feasible equipment. Equipment tool head can pass through safety joint bore during scheduled inspection intervals and which could take photographs of slots of inner sleeve where there is continuous flow of sand particles, due to accumulated sand on pressure chamber of safety joint which would create a threat of corrosion or erosion corrosion.

Second feasible solution for corrosion monitoring would be real time installed corrosion monitoring device called Clamp on Corrosion Monitoring equipment, considering the investment Cost (Development and Installation Cost) of clamp on corrosion monitoring equipment, changing the material of to corrosion resistant alloy with required strength (Alloy 718) would be more effective solution for Safety Joint Inner Sleeve.

Acknowledgement

This thesis has been challenging and interesting. It could not be accomplished with the degree of completion without the support and help from a number of resources.

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I would like to thank my husband, Sivakumar Kumaresan and my son, Pavan Krishnan for supporting me and providing fun filled atmosphere at home. Their words and smiles are source of encouragement for me.

At Last, I owe everything and dedicate this thesis to my parents at India, Ramachandran Parayi and Sujatha Ramachandran. They both held my hand during my first step as a kid and since then never left it. Thanks for making me what I am today.

Abbreviations:

ART	Acoustic Resonance Technology
CEM	Corrosion Erosion Monitoring
CM	Corrosion Monitoring
CoF	Consequence of Failure
CRA	Corrosion Resistant Alloys
CS	Cross Section
LCS	Low Carbon Steel
DFI	Design, Fabrication and Installation
EC	Eddy Current
EFM	Electric Field Method
EMAT	Electromagnetic Acoustic Transducer
ER	Electrical Resistance
FSM	Field Signature Method
GW	Guided Wave ICT Information and Communication Technology
ID	Inner Diameter ILI In-Line Inspection
JIP	Joint Industry Project
LPR	Linear Polarization Resistance
MFL	Magnetic Flux Leakage MTBF Mean Time Between Failures
NCS	Norwegian Continental Shelf
NDT	Non Destructive Testing OD Outer Diameter
OG	Oil & Gas
PoF	Probability of Failure
PSA	Petroleum Safety Authority
ROV	Remotely Operated Vehicle
SJ	Safety Joint
TOFD	Time of Flight Diffraction
UT	Ultrasound transducer
WT	Wall Thickness
ZRA	Zero Resistance Ammeter

Selection of Corrosion Monitoring Equipment for Subsea Safety Joint

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1. Introduction

1.1 General

Over the past 15 years, Significant regulatory and compliance demands in the Oil and Gas field of system assessment experience is of dynamic shifts in Riser and pipeline asset ownership. The owners and shareholders expect performance growth economically through increasing the system availability requirements and delivery targets. Now we have limited opportunity to expand the infrastructure at remote arctic locations, such as deep water offshore areas and not easy to manage reservoirs with unconsolidated mud (sand).

Proper Material Selection and Introduction of Corrosion control technologies are required for the more difficult offshore areas where we spend excessive amount for repair and replacement if failure happen in these locations.

Reference to Appendix S of Oil and Gas Exploration and Production book, Gregory and Mohammed (2012) mention that O&G Industry spend 1.372 billion dollars for Corrosion Prevention and Control. It can be seen in pie chart below that explains, 50% percentage of structural failure/damage is due to Material flaws/defect, Internal or external corrosion.

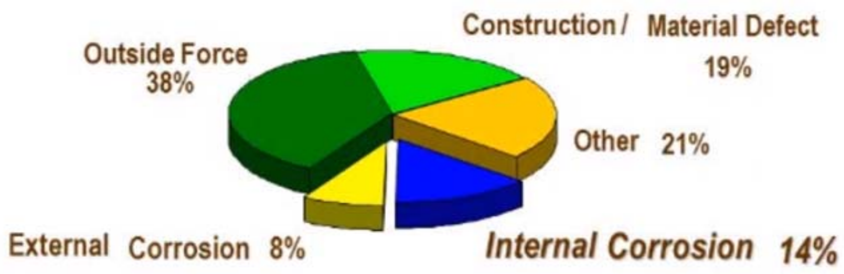


Figure 1.1: Causes of OG Structure Damage – Pie Chart

(Figure Reference: Oil and Gas Exploration and Production book)

Corrosion happens due to oxygen on surface equipment and can also be found on subsea down hole with the same culprit(oxygen) introduced due to pressure maintenance activity, water flooding, gas lifting and due to corrosivity of completion and work over intervention fluids.

Downhole tubing, pressure vessels, Riser Joints, Flexible risers, surface pipelines and storage tanks in O&G industry are subject to internal corrosion in contact with moist environment (Water), which is further enhanced due to the presence of hydrogen sulphide(H2S) and Carbon di oxide(CO2) in the gas phase.

1.2 Need and Motivation

As explained in the pie chart figure 1.1, 22% of structural damage to the equipment is due to external and internal corrosion. In the present study, there is a need of corrosion monitoring equipment which could monitor and report the corrosion happen on the inner sleeve of the safety joint due to the continuous flow of well bore and completion fluids. Motivation behind identifying a corrosion monitoring equipment is as below

- Safety Joint is the weak-link system of the work over mode, if corrosion happens, then it will functionally fail before the designed load of failure.
- Corrosion Monitoring would help to monitor corrosion damage which would happen over time.

1.3 Scope of the Thesis

Failure in pipelines and its equipment cause explosions, fires and release of dangerous gas and toxic substances. It is not only dangerous but also expensive to repair the system. It is in every single aspect of Oil and Gas Industry from drilling, crude oil Production, Storage, Processing and Transportation, More in specific, start from generalized corrosion damage cause due to oxygen abundant atmosphere on offshore structures/systems and to more specific, SSC (Sulfide Stress Corrosion) Cracking due to Wet H2S on Steel Parts.

Corrosion causes wall thickness to decrease in offshore Riser Systems and Pipes in a predictable manner in contact of water, also due to continuous flow of sand through the Riser System.

Selection of Corrosion Monitoring Equipment for Subsea Safety Joint

The OG Industry experience corrosive environment in four different operational phases as below

1. Completion and Work-over (CWOR) Operations
   As Work over equipment's is not for continuous usage, hence sea water and residual water in combination with oxygen from the ambient air will promote corrosion unless mitigating actions are taken to preserve the equipment
2. Corrosion during production operations
3. Transportation and storage of Crude Oil
4. Refinery operations

The focus of work is on localised corrosion issue that happens on inner sleeve of safety joint which would use for work over operations. Corrosion Prevention, Corrosion Conditioning and Corrosion Monitoring are three different ways to handle corrosion.

Present study covers identifying Design feasible and cost effective condition monitoring equipment to monitor the inner sleeve Corrosion issue of subsea safety Joint. Also Identification of possible ways to improve design to prevent corrosion based on Cost Measures and Efficiency.

In the following chapter, provided explanation on technical description of the Subsea safety Joint which has a threat of corrosion problem on part called inner sleeve, moist environment developed on part due to continuous flow of sand from pressure balancing chamber into production bore.

2. Technical Background

In the year 2014, GE Oil and Gas NPI Team started standardizing Subsea riser Joint called Safety Joint according to ISO 13628-7 with Norsok compliance. Riser is a Pipe/Conduit that provides a temporary extension of a subsea oil well to a surface facility. A set of Riser Joints will be stacked together for any Work over Subsea System. The term work-over define activities of Oil Well Intervention such as wireline, coiled tubing or snubbing to the expensive operations like pulling and replacing an existing completion. All systems have a weak point. It is critical in the case of a work-over riser containing produced fluids or gases that the failure point is above the subsea containment valves in the Emergency Disconnect Package (EDP), Lower Riser Package (LRP) or Xmas Tree. Safety Joint is a Weak link connection of the work-over System. A safety joint is one of the Riser joint to be located in a Work - Over riser Stack between a floating structure and subsea equipment at a location in the WO riser stack above a stress joint.

2.1 Technical Description of Safety Joint

As explained above, the Safety Joint will be incorporated into the middle of a standard riser joint and will allow the riser to part at a pre-determined load to be defined by the global riser analysis. As risers work over a range of pressures and may be subjected to full differential pressure the connection should be pressure compensated to allow a single arrangement to have the maximum range of operating conditions.

Work-over risers are subjected to a number of operational scenarios which require to be considered in the design and capacity of the Safety Joint. These include tree installation and recovery, over pulls to confirm connector lock or to release a stuck connector, normal well test and well intervention with and without bore pressure, riser hang off due to weather or batch setting, vessel drive off, and are used on all rig styles. Tethered or Dynamically Positioned (DP) provide the major justification for safety joints to allow for worst case scenarios where the method of station keeping fails and the drilling/work-over vessels moves away from the optimum operational envelope above the well.

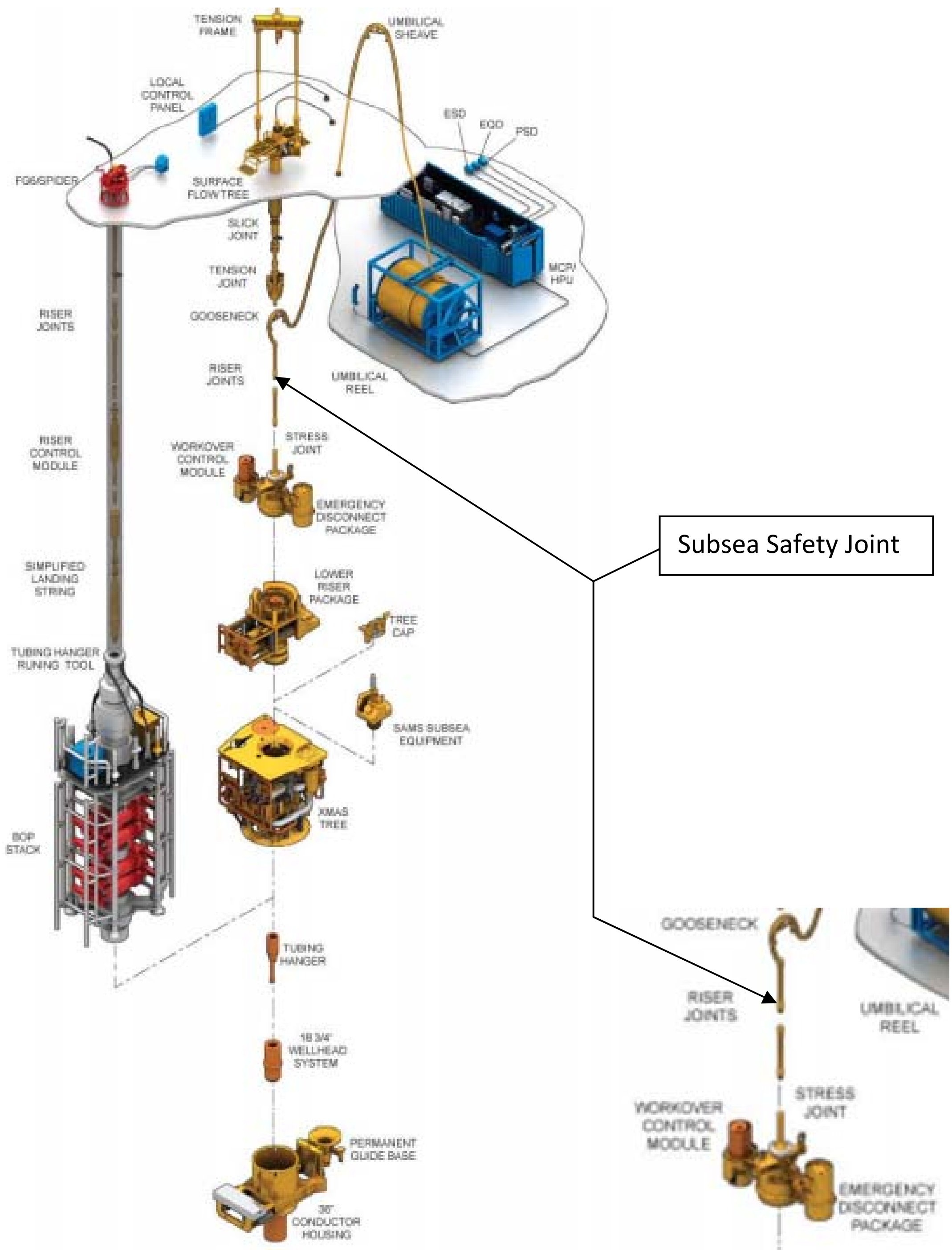


Figure 2.1: Work-Over Riser Mode

Reference location of safety joint: FMC (2010)

Safety Joint separates at a pre-set axial load, independent of pipeline pressure, to avoid damage of Subsea Equipment. If safety joint designed and employed in conjunction with optional downstream and upstream check valves which also avoid great environmental damage and product loss. Tension load will be transferred through the inner sleeve to the body via shear pins as shown in figure 2.1. When a potentially damaging external force equal to or if shear-pin exceeded the load rating, the pins shear and the joint separates, preventing damage to subsea equipment. As pressure-compensating piston was employed to balance the hydrostatic loads such as external water pressure or internal pipeline pressure, hence safety joint will not separate due to hydrostatic loads. If we need to change the rated separation load, number of shear pins/bolts could be changed.

During normal operations the mating components forming the pressure balance chamber remain relatively stationary with respect to one another. A slight stretching of the Safety Joint Inner Sleeve causes a relative displacement. To initiate disconnect the external riser tension has to exceed the predetermined break load of the calibrated weak shear pins or bolts. So in simple, Safety Joint is used to protect the CWOR system and subsea equipment in the event of accidental loads caused by excessive top tension.

2.2 Function of Safety Joint

A Safety Joint is being developed for use in GE CWOR systems. Such equipment is used for well intervention and completion, and can be subject to well clean-up. During well clean-up reservoir fluid is allowed to flow through the CWOR system back to the drilling vessel. Large quantities of debris and sand may be expected to be present during this initial stage of flow from a new well. The Safety Joint includes a pressure compensating chamber that is exposed to bore fluid and pressure. The Safety Joint relies on a pressure balance chamber to function as intended. This chamber is exposed to the well bore. During activation of the Safety Joint a set of calibrated studs will elongate and break, and thus allow the Safety Joint to separate. When separating the pressure balance chamber is closing up and reducing in volume. If excessive amounts of debris collect in the chamber this may impede the ability of the Safety Joint to separate. Debris accumulation in the pressure balance chamber (refer figure 3.0) shall be limited to a level where the remaining free volume ensures the piston is free to stroke the required length to disconnect. As reference to figure 3.0, rectangular slots provided on the inner sleeve would help flushing the sand into the bore.

3. Problem Definition

If pressure balance chamber fills with debris/sand above the level of hydraulic ports, there will be a chance of blocking the ports & results in no further access to the flow inside the chamber. Accumulated sand could be flushed through rectangular holes (Figure 3.1) on the inner sleeve, it will create corrosion environment as well as erosion issue due to high velocity flow of sand.

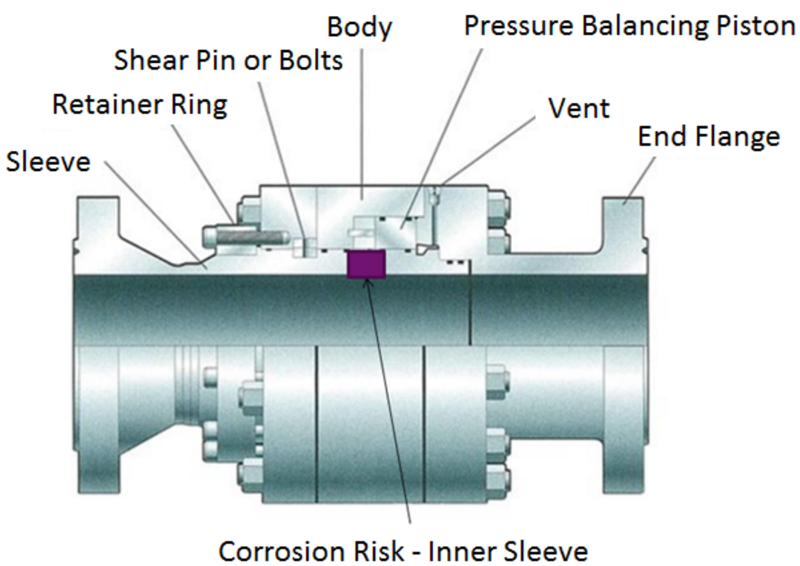


Figure 3.0: Subsea Safety Joint from General Internet Source

As the inner sleeve parts exposed to flowing and stagnant well bore fluids, completion fluids and sea water, it will have moist condition over the slots, it has risk of corroding the wall thickness of the inner sleeve, Purple Highlighted area as shown above figure 3.0.

3.1 Detailed Study of the Problem

Safety Joint contains pressure balance functionality as defines already that acts to counteract the separation force exerted by the well bore pressure. Inner sleeve of the safety joint as shown in figure 3.1 has rectangular slots which helps flushing of accumulated sand. Inner sleeve designed to withstand an axial tensile load that needs to be transferred through this section. Hence if required to increase the slot size to promote flow in and out of the pressure balance chamber, any significant loss of cross section must be controlled.

The rectangular slots of the inner sleeve have a smaller cross section, and thus higher utilisation levels. They also have a much larger ratio of exposed surface area to cross section. Hence they are more critical from a corrosion and erosion point of view.

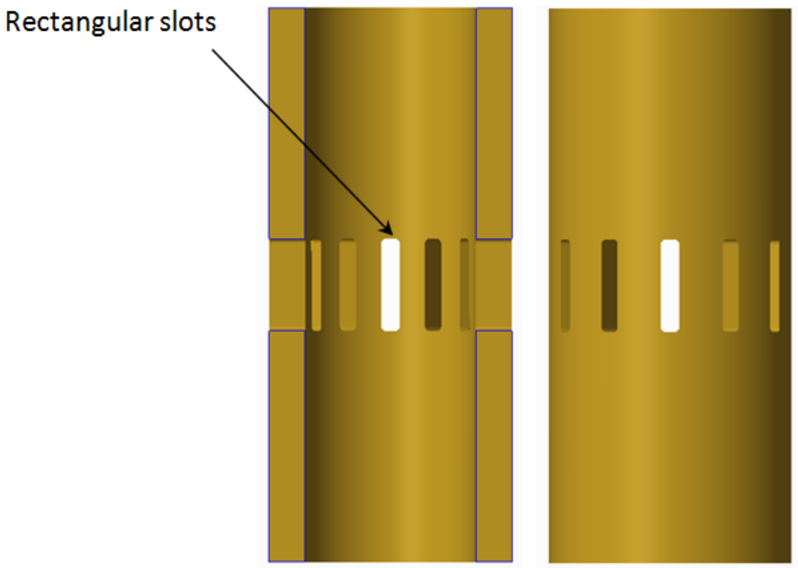


Figure 3.1: Inner Sleeve, Subsea Safety Joint

3.2 Effects of Sand Accumulation

- Sand/debris particles enter the chamber and cause damage to the piston seals as they move slightly up and down on the sealing surfaces.
- The sand/debris fills up the chamber such that the pressure balance ports become blocked and the pressure balance is no longer effective.
- The sand/debris fills up the chamber such that it prevents connector separation.

3.3 Sand Slurry Testing Results

The flow test of the sand particles inside safety Joint was simulated at IRIS as per flow loop with real time assumptions. Common form of corrosion is rust, sand flow testing figure 3.1 for rusted inner sleeve slots of safety joint after a week of sand slurry testing.

Figures 3.2 : Sand Slurry Test Set Up & Unpainted Rusted Inner Sleeve Slots

3.4 Material Information of Parts

Material of Inner sleeve is Grade F22, Low Alloy Steel (F22/2-1/4 Cr 1 Mo/UNS K21590) with 2.25% chromium, chemical composition as shown table below from Vendor, Speciality Metals for reference.

C	Mn	Si	P	S	Cr	Mo
0.05-0.15	0.30-0.60	0.50 max	0.040 max	0.040 max	2.00-2.50	0.87-1.13

Table 1: Chemical composition of Inner Sleeve

Material of the inner sleeve is low alloy steel and required Mechanical Yield strength is 80KSI

3.5 Coating Specification of the Safety Joint

Outer diameter of the inner sleeve(seal surfaces) are cladded with CRA, but inner surfaces of rectangular taper slots are not cladded or coated, continuous flow of sand to the safety Joint bore would cause wet atmosphere and create an issue of corrosion, also depending on the content of sand and speed of flushing of sand would cause erosion corrosion. Better coating selection would reduce chances of corrosion.

4. Literature Overview

Corrosion is change in material due to its reactions with environment. Change in material may be deep Cracks or Pitting; it will reduce fatigue strength of the material.

Reference from Denis (2005), Basic Mechanism of Corrosion Cell is cell formed by two metals placed next to each other or kept at large distances which is immersed in an electrolyte (here it is sea water) joined by (oxygen) Conductor. One electrode will corrode quickly than other is called the anode, it leaves free electrons on sea water, loses positive metal ions and a net negative charge. Other electrode which receives the positive metal ions is called cathode. Electrons keep travelling from anode to cathode using oxygen as conductor; electrolyte forms a complete circuit as shown in the figure 4.1

Conductor : Oxygen

Electrolyte : Sea Water

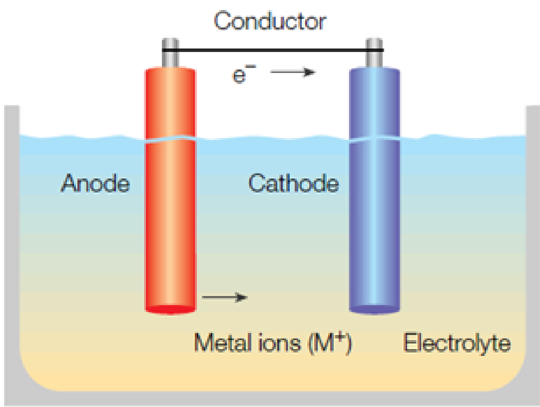


Figure 4.1: Corrosion Cell Illustration from Denis (2005)

Rust is common problem and simple example of corrosion which exist in nature. Let us assume iron is exposed to atmospheric air (oxygen) in the presence of moisture leading to formation of rust, 2Fe2O3(s) Iron (III) Oxide and 2fe +3 cl-1(s) Iron (III) Chloride and chemical redox reactions as below

Oxidation Reaction:

$$4Fe(s) + 3O_2(g) \rightarrow 2\,Fe_2O_3(s) \text{ Oxidation State of Fe is } 0 \rightarrow +3$$

Reduction Reaction:

$$2\,Fe^{0}(s) \quad + \quad 3\,Cl^{0}{}_2(g) \;\rightarrow\; 2\,Fe^{+3}\,Cl^{-1}{}_3(s)$$

4.1 Oil & Gas Field Corrosion Forms

Oil field corrosion can take different specific forms of pitting, crevice corrosion, metal wastage, inter-granular corrosion; these involve carbonic acid or dissolved oxygen as corrodants. Other forms of oil field corrosion like Blistering, Embrittlement, Sulfide Stress Cracking, Corrosion Fatigue, and Stress Corrosion Cracking induced by Hydrogen sulphide.

Types of corrosion classified depending on oil field environment as follows

- Uniform Corrosion
- Electrochemical Corrosion (Galvanic, Crevice, Pitting, Stray Current Corrosion)
- Chemical Corrosion
- Microbiological Corrosion

Basic Types of Corrosion common in OG Industry can be discussed in detail in the upcoming pages of thesis and figures are referred from Linda (1994) written book called corrosion in the petrochemical industry.

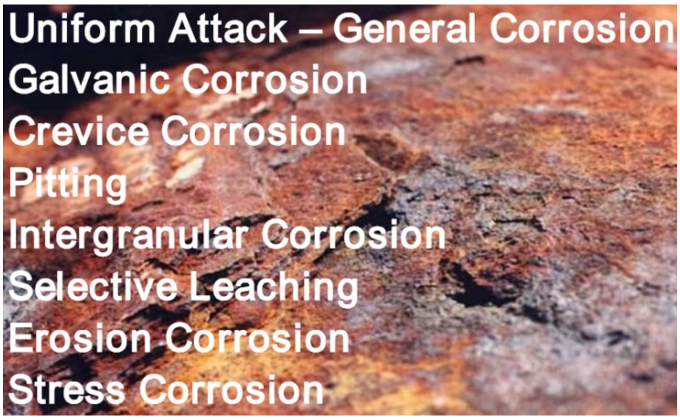


Figure 4.2: Basic Types of Corrosion common in OG Industry

4.1.1 Galvanic Corrosion

Potential difference created due to immersing the two dissimilar metals on conductive medium. Metallic cells form crystals, it will tend undergo inter-granular corrosion. If the size of anode is big compared on size of cathode, problem seems to be more critical as shown below figure 4.3

Figure 4.3: Galvanic Corrosion of Dissimilar Metals, More Anodic Metal Corrodes

4.1.2 Crevice Corrosion

It is localised corrosion type mainly happen in confined spaces of oil field where there is a gap/crevice between two metals or metal or non-metallic parts as shown as below figure 4.4

Figure 4.4: Crevice Corrosion

4.1.3 Stray Current Corrosion

AC and DC Currents exist inside the earth passes through the conductor; it will turn the arrival point into cathodic area. Place where current leaves or departs will become anodic and corrosion start happenings. Most likely, stray current corrosion will create due to cathodic protection systems of OG Equipment.

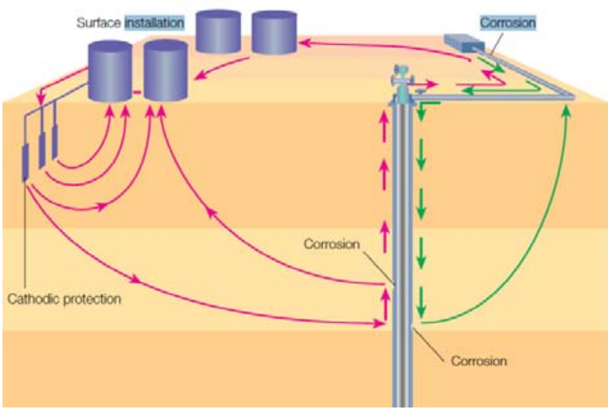


Figure 4.5: Stray Current Corrosion

4.1.4 Pitting Corrosion

It is close neighbour of crevice corrosion, where a defect due to wear, small scratches or impurities on the surface will start the process of corrosion, figure 4.6 as shown below

Figure 4.6: Pitting Corrosion due to scratches, impurities

4.1.5 Inter Granular Corrosion

Inter Granular Corrosion will happen close to welds, when precipitate particles form on the metal surface, Corrosion form along the metal grain boundaries.

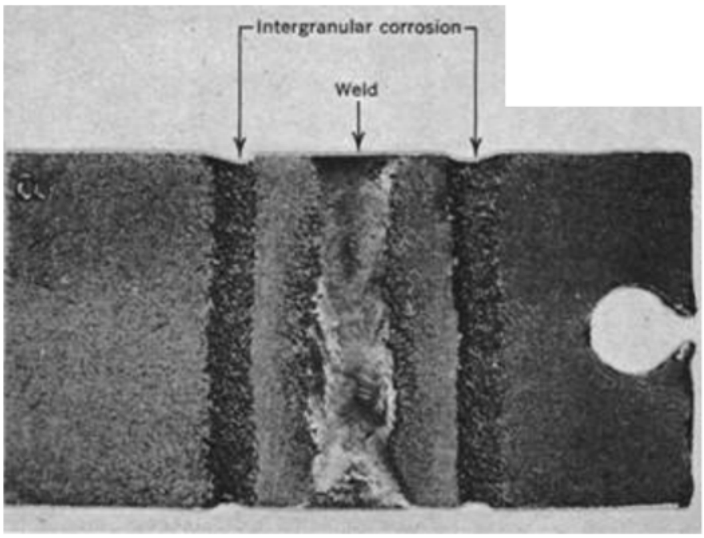


Figure 4.7: Intergranular Corrosion due to precipitate particles close to welds

4.1.6 Selective Leaching

Leaching the preferred metal, For example: Dezincification, Zinc removed from Brass

Figure 4.8: Selective Leaching of Zinc

4.1.7 Stress Corrosion Cracking or Stress Corrosion

SCC is the combined action of a corrosive influencing environment and stress which leads to the formation of a Stress induced crack in a metal. This type of corrosion will take place after a period of lifetime or after satisfactory service, all of sudden and rapidly due to the residual stresses of the material. Examples of material/environment pairs which intend to stress cracking as below like brass and ammonia, SS and chlorides, HSS and Hydrogen

Figure 4.9: Stress Corrosion Cracking

4.1.8 Erosion Corrosion

Erosion corrosion is a degradation of surface of material due to impinging turbulent liquid, abrasion caused due to flow of mud, due to mixture of particles in fast flowing liquids, Sand or due to cavitation, Erosion corrosion will happen due to some form of Mechanical Action as explained. Subsea Riser or Pipe Line Systems experience corrosion/erosion effects due to zones of water drop outs, critical pipe bends, Localized flow, slugging will cause turbulence inside the system.

Figure 4.10: Erosion corrosion

According to the location of the corrosion issue, it is also divided widely as External and Internal Corrosion

External Corrosion

Galvanic or contact corrosion a type of external corrosion appears due to dissimilar metals joined together by conductor in the presence of an electrolyte, it will form a state of true battery. In this, one metal corrode quick called anode and other one called cathode.

Internal Corrosion

Internal Corrosion will happen due to the wet conditions and environment. Acid Concentration, high temperature, content of harsh chemicals during electro-chemical reactions will increase speed of corrosivity.

Thesis deals with corrosion issue on inner sleeve rectangular slots where there is wet condition due to the sand slurry, well bore and completion fluids to the Safety Joint internal bore. Localised Corrosion as well flow assisted corrosion is two types of corrosion we discuss predominantly in this thesis.

4.2 Corrosion Rate

Corrosive characteristics of a well can be identified by inspection of surface equipment, analysis for materials used, organic acids and Iron, mainly carbon-di-oxide, Corrosion Coupon tests, and Tubing Calliper surveys. Each OG well has different operational conditions with different atmosphere and environment. The Relative corrosion rate changes with respect to environment, it can be explained in the below figure 4.11

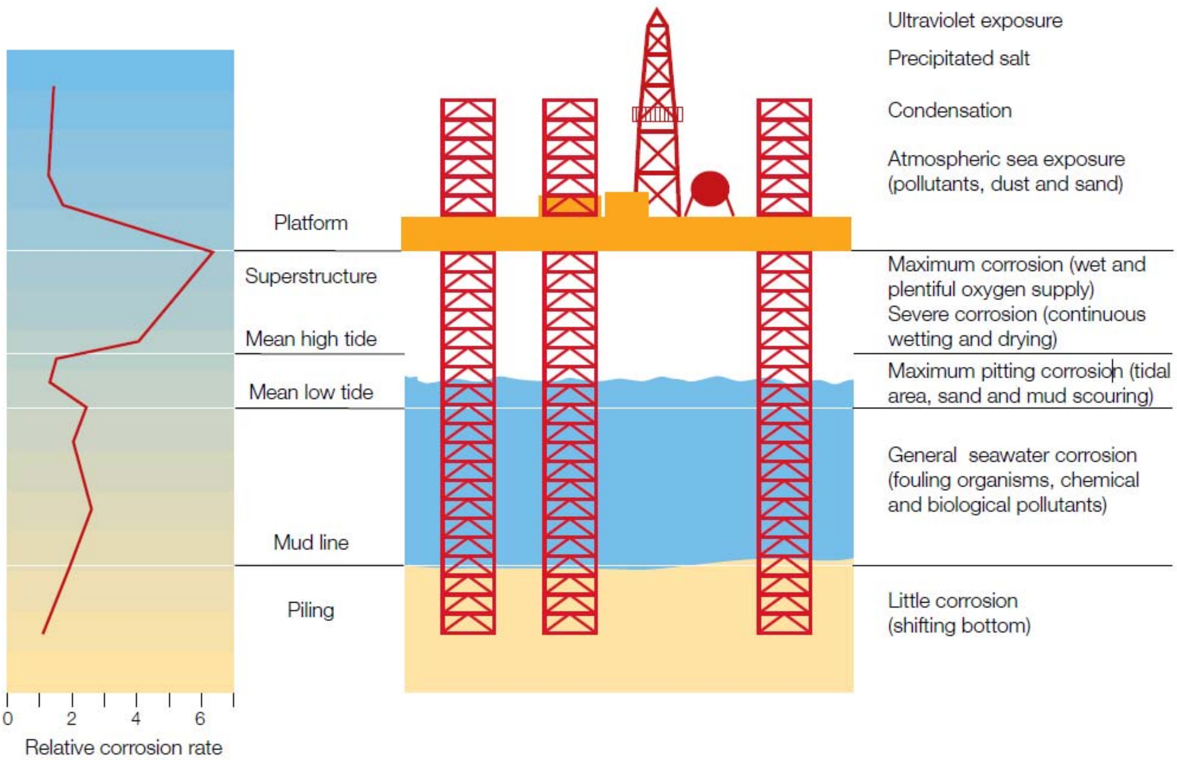


Figure 4.11: Relative corrosion rate changes with respect to environment

We can determine corrosion rate through measuring the potential or by calculating whether the metal or alloy will tend to corrosion due to the set of environmental conditions. But measuring potential will give more appropriate corrosion rate.

Rate of corrosion can be estimated from polarization curve of the metal surface. When current passes through the metal, degree of potential difference is proportional to function of the amount of electric current applied. The curve will provide detailed picture of corrosion anodic/cathodic reactions.

4.2.1 Factors Influencing Rate of Corrosion:

Corrosion rate determinate by analysing various factors as explained below are most vital ones to build a corrosion cell. Reference from Bony (2013), factors influencing corrosion has been explained in detail

Primary factors influencing Corrosion Cell:

1. **Nature of the Metal:**

   Reactive Metals like Sodium, Potassium, Magnesium and Zinc which has lower reduction potential (Anodic) are more susceptible for corrosion. Noble Metals like Gold, Silver, Titanium, and Platinum which has higher reduction potential (Cathodic) are less susceptible for corrosion. Figure referenced in SSINA Knowledge Base has listed below are materials from more anode to more cathode or Noble Materials.

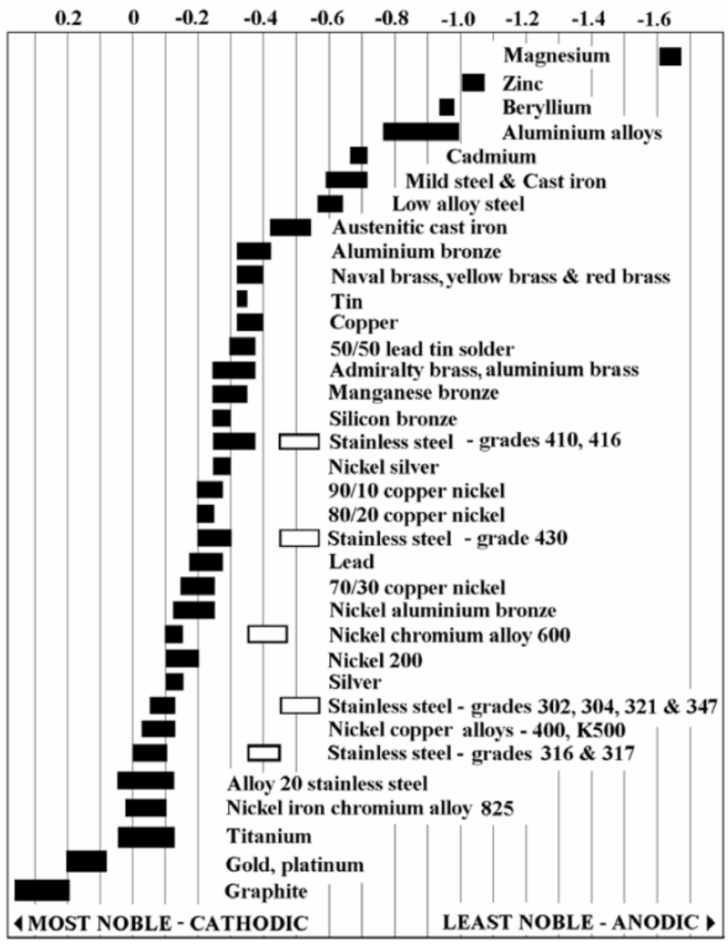


Figure 4.12: Anode to Noble Materials

(Reference from SSINA Knowledge Base)

2. **Surface State of Metal:**

   Fine grains of the metal, Large surface area will increase the probability of metal undergo corrosion. Rough Surface finish will form more air concentration cells due to the ups and downs of the surface will suffer more corrosion. Smooth surface finish will help to overcome corrosion.

3. **Nature of the corrosion Product:**

   Corrosion Products will act as a Protective Film which requires being insoluble, Non Porous, stable and uniform to avoid corrosion.

4. **Hydrogen over Voltage:**

   If hydrogen over voltage of metal is higher, cathodic reaction will be slow and corrodes slowly. If it is higher, Hydrogen gas is evolved easily at cathodic area; cathodic reaction will take place quickly, so it will increase the rate of Corrosion.

Secondary Corrosion Influencing Factors

Referred from Bony Simon (2013), List of factors affect the rate of corrosion

1. **pH of the Medium: Low pH – High Corrosion**
   - pH > 10 – It form a hydrous oxides protective coating around Iron, So Corrosion will be less
   - 3 < pH < 10 – Presence of Oxygen required to build corrosion cell
   - pH < or equal to 3 – chances of severe corrosion due to continuous release of Hydrogen gas at cathode.

   For Example aluminum, Zinc in highly alkaline medium will cause corrosion

2. **Temperature :**

   When temperature increases, corrosion rate increases. High temperature will increases the conductivity of the aqueous medium and end up increased diffusion rate.

3. **Presence of Oxidizing Agents:**

   If medium has more oxidizing agents, it will increase corrosion on noble metals as well. Presence of oxidizing agent will increase rate of corrosion.

4. **Humidity:**

   Corrosion rate increase at humid/Moisture atmosphere than in dry conditions. Moisture in air helps to build corrosion cell (electro chemical cell) on the surface

5. **Presence of Impurities in the environment/atmosphere:**

   Impurities like Hydrochloric Acid, SO2 are acidic in nature which has potential to increase the rate of corrosion. These impurities in the environment will react with conductive medium (Moisture in the atmosphere) and form Sulphuric Acid, so Metals like Iron will tend to corrode.

6. **Conductance of the medium:**

   Presence of conductive elements in the atmosphere will help the rate of corrosion. Electrons will run faster in conductive medium to build corrosion cell quicker. This is the reason corrosion rate is high in sea water than fresh water.

7. **Area Effect:**

   Large Cathodic Area and Small Anodic Area – Rate of Corrosion is high

   Small Cathodic Area and Large Anodic Area - Rate of Corrosion is Low

   It is because of electrons leave from Anode (Smaller Area) will be consumed by cathodic which has larger area to receive.

8. **Polarization Effect at Anode and Cathode Area:**

   Polarization of cathode or anode decreases the rate of corrosion. Due to anodic polarization, effect of oxidation reaction decreases with dissolution of metals as metal ions.

4.3 Estimation of Corrosivity of Environment

Corrosivity of the OG Field environment varies one field to another. There exists different environmental conditions depend on Oil or Gas Field. Below listed Techniques are used to estimate the corrosivity of environment.

- Integrity Monitoring
- Water Phase Testing
- Failure Analysis
- Deposit Analysis
- Inspection Techniques
- Visual Observation

4.4 Corrosion Monitoring Overview

Corrosion monitoring is a type of Condition Monitoring technique is focused on wall thickness loss and Material internal defects in Riser systems and Pipe Lines. Measuring technologies ensure accurate measurement on localised defects or cracks due to corrosion, But less accurate measurement for over all monitoring of the system.

Internal Corrosion Monitoring required on most critical spots where corrosion in risers or pipelines near sea bed. It can be placed on shore facility or topside facility, but installation requires specific and special consideration for critical areas. Both non-intrusive and intrusive type of monitoring could be used on these locations.

4.4.1 Condition (Corrosion) Monitoring PSA Requirement

According to" Regulations relating to conduct of activities in the Petroleum activities (The Activities Regulations) – § 47 Specific requirements to condition monitoring of structures and pipeline systems" the following requirement is given by the PSA:

Condition monitoring shall be carried out in respect of new structures during their first year of service.

With regard to loadbearing structures of a new type, data shall be collected from two winter seasons in order to compare them with the design calculations, cf. the Facilities Regulations Section 16 on instrumentation for monitoring and recording.

With regard to pipeline systems where fault modes may constitute an environment or safety risk, cf. Section 43 on classification, inspections shall be carried out to map possible corrosion of the pipe wall. Parts of the pipeline system where the lay condition or other factors may cause high loads, shall also be checked.

The first inspection shall be carried out in accordance with the maintenance program as mentioned in Section 44 on maintenance program, however at the latest two years after the system has been put into operation.

PSA describes requirements of Scheduled Maintenance Intervals of Pipeline Systems. Safety Joint shall be inspected two years after the installation.

4.5 Corrosion Monitoring Techniques

4.5.1 Electro Chemical Corrosion Monitoring

Principle:

Potential Difference or Drop in potential due to the induced current passes through test specimen which is corroded. Corrosion rate is measured due to the reference potential to the reduced potential depending upon the chemical reactions such reduction/oxidation reactions. An electric field pattern is generated by passing a current through metal element section to be monitored, potential difference is measured through sensing the pattern of electrical field.

Classification of electro chemical corrosion techniques based on principle as discussed below

1. **Electrochemical Potential Monitoring**

   Reference to Lazzari (2005), in his patent, he explained corrosion monitoring of steel reinforced bars embodied on concrete structure, Where invention discuss about measuring the potential of a steel pipe buried inside the ground. It is monitored using the reference potential to the reduced potential due to the corrosion happened. Potential of small area measured through wire electrodes connected to steel reinforcement integrated with concrete structure.

   Hertz (2006) in his patent for heat control of water system, he build a cell with anode and cathode inside the heat control system, he has applied the potential 50mv to 1v and measured the deposit formation and corrosion rate through the current between anode and cathode.

   Mihai explained the method of corrosion monitoring through measuring the current induced between two sensors, localised corrosion happen in between these two sensors. It helps to find the amount of reduction/Oxidation reactions.

2. Polarization Method

Polarization method helps monitoring the rate of corrosion and coating damages of the part. Niblock (2006) explained in his patent based on measurement through LPR sensors (Linear Polarization Resistance Sensor), two or more sensors placed at a distance of 2mm or more for corrosion monitoring. These sensors consist of electrodes with same material of the metal to be monitored. When a small potential drop applied, rate of current flow will be measured through which Corrosion Current Density will be estimated.

3. Electrochemical Impedance Spectroscopy (EIS)

EIS method generates perturbation signals on the working electrode through passing the Low Amplitude sinusoidal voltage wave. The corrosion rate can be estimated or predicted by current response curve of the respective frequency and voltage. The impedance measurements are derived from frequency-response analyzers and amplifiers, which are more convenient and faster, compared regular impedance bridges. Method based on interfacial phenomena to interpret the capacitance values and equivalent resistance.

4. Electro Chemical Noise

This method based on Noise Signal and the harmonic content of the current response created due to monitoring of corrosion potential of a single electrode placed, a metastable pitting can be found by applying a noise signal to the electrode assembly.

Electrical Field mapping technology used on two methods called FSM and Pin to Pin EFM.

Field Signature Method

The outside of the Riser wall embedded with pins , electric current passed through the Riser Pipe, voltage measured between the pins(electrodes). When corrosion takes place, electric field pattern will be changed; voltage measurement taken will be compared with original measurement which in-turn provides a value of change in wall thickness. First measurement is called as signature which is same as geometry of specimen and later measurements are compared with signature. In 1980, Commercial ownership of FSM Technology was acquired by Company called Corr-Ocean. This EFM concept of FSM Corrosion Monitoring equipment was first installed in 1991 at offshore and 1994 at Subsea Environment. Field Signature Method is non-intrusive and positioned on outer diameter of Riser or pipeline, it can monitor internal condition of riser, field welds and base material reduction.

According to Wold (2007), the resolution and accuracy FSM depends on below factors

- Wall thickness of specimen to be monitored
    - Thin Wall = Better resolution
- Distance between sensing pins (electrodes)
    - Longer Distance = Generalized Corrosion
    - Shorter Distance = Localized Corrosion
- Frequency of measurement intervals
- Availability of electric power

Suppliers:

- Corr-Ocean – FSM Technology
- Fox-Tek Pin-Point EFM (Electric Field Mapping)

Corr-Ocean FSM

As already mentioned, it is non-intrusive equipment where externally placed array of wired and brazed sensing electrodes mounted over outer diameter of the riser pipe. Sensing electrodes and its Clamps which help to connect the electricity are permanently installed, instrumentation can be detachable. Since 1994, Corr-Ocean has installed 50 FSM systems. 20 Systems out of them are not working properly due to various issues like signal and connectivity problems, communication errors.

Figure 4.13: Field Signature Method Technology CorrOcean

According to Corr-Ocean, they have stopped installing FSM Systems on subsea due to above said problems. Corr-Ocean mentions that up to 20km cable lengths still possible and acceptable to use FSM Technology.

Fox-Tek EFM

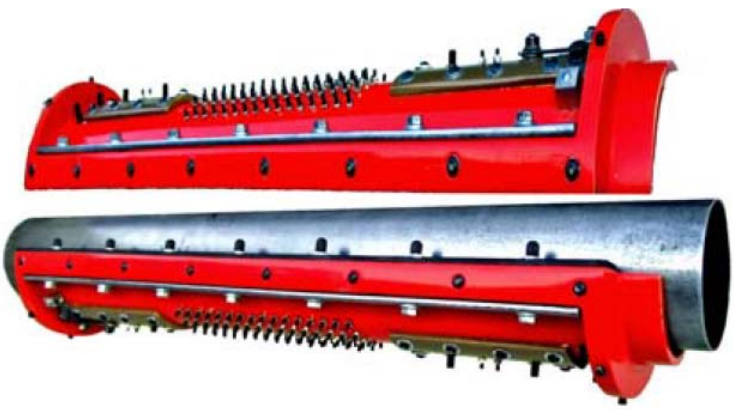


Figure 4.14: Fox-Tek Electric Field Mapping

Fox-Tek EFM is as clamp around, two-piece assembly as shown in the figure, array of electrodes assembled circumferentially. The cup point set screws are positioned on fiber glass sleeve using special inserts. Those screws are used to make electrical contact between sensing electrodes. This technology has installed offshore but not subsea still.

Advantages of EFL:

- Non-Intrusive technology
- Supplier Claim extremely high sensitivity
- Good Value of MTBF (Mean time before failure) for permanent installed systems.
- Coverage Area is large compared to other methods

Limitations of EFL:

- It doesn't distinguish between external corrosion, localised corrosion or material loss.
- Compensation required on high temperature to change the resistivity of material
- History data, Baseline data of original inspection are required
- Output is not absolute wall thickness reduction; it is change in wall material loss.
- Interpretation of results will affect due to conductive scales/depositions on the outer diameter of riser pipe.
- Communication and signals is a big challenge due to environment of the specimen.

4.5.2 Electrical Resistance Monitoring (ER)

Principle:

Resistance in the metal Element is directly proportional to metal loss due to corrosion of the specimen. Principle of the Electrical Resistance Monitoring is determination of corrosion or erosion through identifying the change in resistance.

ER technique is indirect corrosion rate determination of a polarized structure. Electrical resistance probe principle explained as below figure from Jezmar (2002)

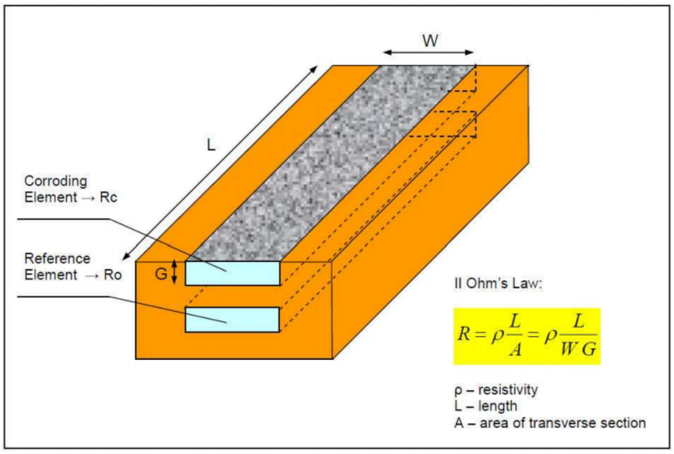


Figure 4.15: ER Probe – Corrosion Loss Measurement

Corrosion on the metal decreased with cross sectional area and subsequently electrical resistance will increase. Metal element in the form of strip, plate, wire or a tube, then corrosion found to be uniform, change in resistance is directly proportional to increase in rate of corrosion with output as loss of metal.

ER Probes are well adapted to any application or any corrosive environment, Simple to use, well proven in practice and easy to measure.

ER probes are available from two suppliers for Permanent Subsea Installations as below

- Teledyne Cormon – Ceion Technology (RPCM Spool and PTEC ER Probe)
- Emerson Roxar – Sen-Corr CM Sensor ER Probe

Figure 4.16: Teledyne Cormon - RPCM Spool and PTEC ER Probe

Figure 4.17: Roxar – Sen-Corr CM Sensor ER Probe

Advantages:

- High Sensitivity in the measurements
- Real time and offline monitoring possible

Limitations:

- It is intrusive method of monitoring
- Monitoring surface area is limited
- Challenging to predict the corrosive environment of the pipe to monitor
- It is difficult to identify appropriate locations to install the device

4.5.3 Ultrasonic Sensor Technology

Principle:
Piezo electric ultrasonic thickness gauges built with using ultrasonic array of sensors permanently placed to provide wall thickness readings over a section of Riser Pipe. Sensors can be arranged axial as a six o clock position or arranged circumferential around the pipe section in-order to measure/detect localised corrosion.

Supplier:

GE Rightrax Monitoring System:

System consists of M2 Sensor and DLI (Data Logger Instrument) Sensor is flexible, self-adhesive ultrasonic transducer array in use of pulse echo technique to measure wall thickness. Sensors are permanently attached to the riser pipe to be monitored, at critical locations where there is historical data available for erosion or corrosion. Accuracy of wall thickness measurement: 0.2mm

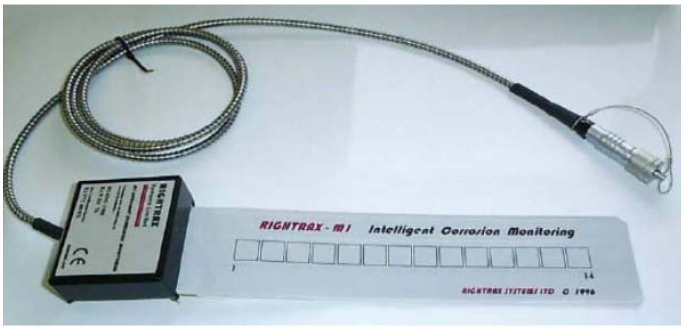


Figure 4.18 : GE Rightrax Monitoring System

Sensor-link Ultramonit System:

The Ultramonit system is non-intrusive; it can monitor the erosion/corrosion rates of Risers and Pipelines using ultrasonic pulse-echo method.

Clamp on instrumentation with ultrasound sensors are placed circumferentially as same as FSM Design. Resolution is 1/100 mm. It is built with multiple transmitters and receivers with ROV Access. It is easy to assemble and moved to different places, be used for verification of inspection data at critical locations

- In 2003, Prototype of Ultramonit was installed at kårstø

Selection of Corrosion Monitoring Equipment for Subsea Safety Joint

- In 2009, fully developed system installed at Baltzersen

Figure 4.19: Sensor-link Ultramonit System

Advantages:

- Easy to install, Non-intrusive inspection
- ROV Access available, remote operations possible
- Online monitoring of performance and feedback about the performance of corrosion inhibitors

Limitations:

- Communication errors reported and limited experience of using this technology

Clamp-On Corrosion Erosion Monitoring (CEM):

Ultrasonic signals from clamped on sensors pass through the pipe wall thickness, these waves form mode called lamb mode where a group of acoustic guided waves, are exploited to provide a mean value of wall thickness loss relative to the original values of measurement. Eight EMAT (Electro Magnetic Acoustic transducers) are placed to monitor up to 2 meters of pipe length. Signals propagate and follows the wall thickness between placed transducers, operate in pitch-catch mode as shown in the figure below. It will measure average wall thickness and not minimum wall thickness

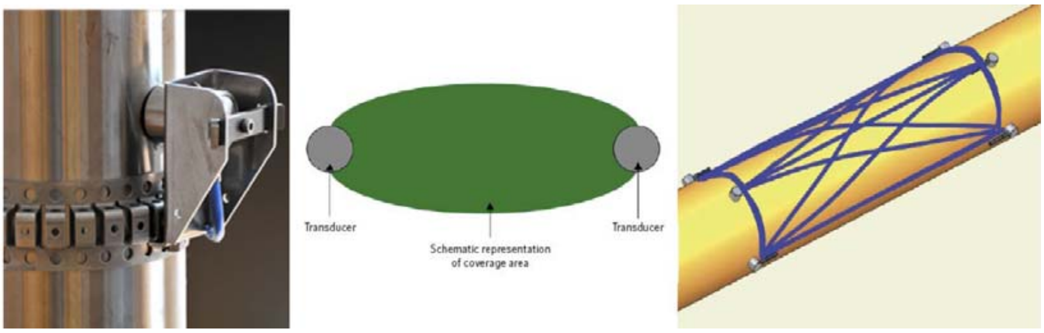


Figure 5.20 : **Clamp-On Corrosion Erosion Monitoring (CEM)**

Detailed discussion about clamp on monitoring system will be included in the upcoming chapters of thesis.

4.5.4 Electromagnetic field Technology (Intelligent Pigging)

Internal inspection using pigs is old concept, shell deployed first intelligent pig in the year 1961 and early form of pigs is straws and its travelling through the pipeline will create squealing noise of the pig. These pigs are built with same size as pipeline internal diameter. Intelligent pigging is very efficient way to identify the corrosion due to welding, internal cracks, dents, deposits, Scales formation. Some pigs will be used for cleaning and others are used for inspecting. Intelligent Pigging system has self-contained measuring instrumentation which could travel in traverse to the pipeline internal diameter and record the change in wall thickness. Sensors measure integrity of pipeline wall using electro-magnetic field sensors.

Intelligent Pigging System can be used for below activities:

- Detection of wall thickness loss
- Mapping and Profiling of pipelines
- Product sample collection
- Crack and Leak detection
- Inspection to collect photos of internal surfaces
- Pipe Bend measurement or Erosion rate

Selection of Corrosion Monitoring Equipment for Subsea Safety Joint

- Wax/Scales deposit Measurement
- Pressure and Temperature Monitoring

Different Types of Pigging Systems:

1. Ultrasonic US Pigging (piezoelectric and EMAT)
2. Magnetic Flux Leakage (MFL)
3. Optical Intelligent Pigging (video, laser)
4. Physical (caliper) Inspection Tools

1. Ultrasonic transducer Intelligent Pigging:

These Pigs could operate on pipelines which are filled with fluids and gases. Based on UT & EMAT Technology, provide ultrasonic scanning without direct contact on the inner diameter of the pipe wall. Ultrasonic frequency range above 20 kHz and it has potential to detect small defects which could be very sensitive for the competent operator to interpret and detect.

Pulse-Echo Piezoelectric UT:

In this method of ultrasonic inspection, UT connected to a diagnostic tool is passed through the internal diameter of the Work over riser system. Ultrasonic wave form was received through reflection and attenuation. Intelligent pig systems based on reflection wave form called reflection pulsed waves. Ultrasonic transducer sends and receives pulsed waves, as the echo (sound) reflect back to the equipment. Reflected waves may be detected from interference from back of the wall or imperfection within the wall material. Outputs delivered as amplitude of signal, reflection intensity and the distance, reflection arrival time.

Time of flight diffraction (TOFD):

TOFD can be distinguished from pulse echo ultrasonic inspection, it detect diffracted pulses of low amplitude from defects or irregularities. Two probes for a receiver and for a transmitter are passed through the pipeline and placed close to either side of the test location of the specimen, UT wave travels along the internal diameter between the receiver and transmitter probes. A- Scan Instrument records the values and stored in internal memory for analysis. To get cross-sectional view of the defect area of the pipeline, these A-Scans stacked together to provide B-Scans or D-Scans

Supplier:

GE RADAR Inspection System:

Riser Active Data Acquisition Recorder is a fully automated inspection tool or system that traverses the ID of a Riser joint (both production and annulus lines) using field proven ultrasonic technology to measure the riser joint pipe wall thickness and assess the quality of end Connection welds.

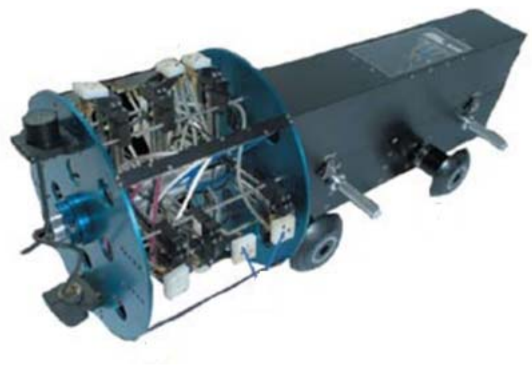


Figure 4.21: GE RADAR Inspection System

As GE RADAR System is compactly designed this allows maximum portability, provide continues power supplies. System consist of redundant system, Video recording system, Scanners and software analysis monitor, Automated Data logger and printer with spare kits are installed inside the Container, It can be erected anywhere at site. Connections like water, power and air which required running the GE RADAR system to be supplied from site.

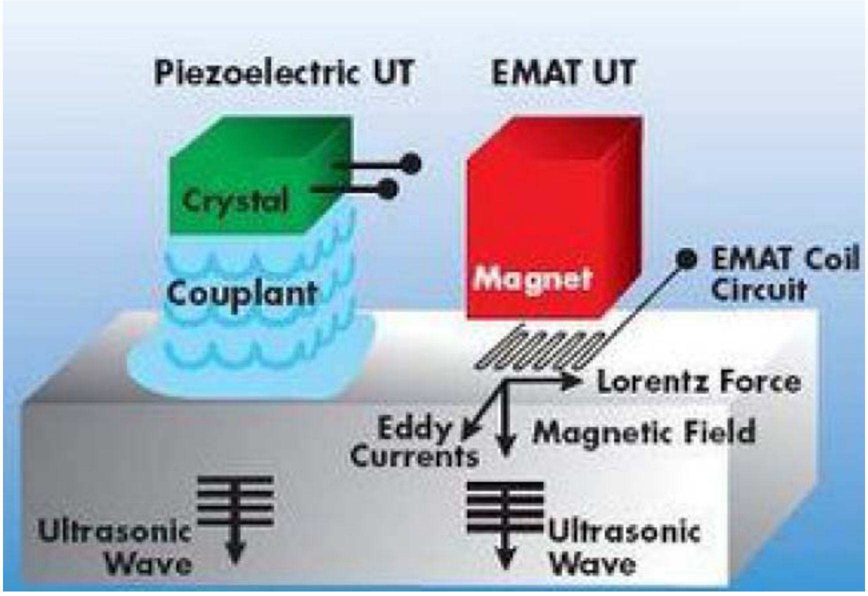


Figure 4.22: Illustration of Piezoelectric UT and EMAT UT

4.5.5 Electromagnetic Acoustic Transducer (EMAT):

EMAT which generates ultrasonic waves in the pipe wall material and pulse reflected from the wall will induce variable current in the receiver side. These electric signals are interpreted by in built software to provide internal defects information of the pipeline.

- Speed of ultrasound is directly proportional to depth of each crack
- If we can identify partial reflection from an ultrasonic wave, then there is a crack in the pipeline.

4.5.6 Optical Inspection:

Optical pigging system include forward mounted camera with lighting which help to approach the internal diameter of the pipeline, direct visual inspection on internal features. Lights from camera will flattens the wall surface optically, fluid in the pipe to be transparent to provide better resolution of the camera inspection

4.5.7 Caliper ILI tools

Caliper tool used to detect the restriction in the circumferential geometry of the Riser Pipe.

4.6 Corrosion Prevention

Reference Charles (2005), Corrosion Mitigation methods are quite useful and important to avoid Corrosion damage structure failures, Loss of resources and heavy recovery cost incurred OG Industry. It should be considered during the design stage of offshore risers and pipelines itself. Coating on outside of the risers will provide first level protection against harsh sea water. If there is internal corrosion risk as related this thesis scope, without considering special treatment, this could be handled through change of Material to Corrosion Resistant Alloys such as Alloy 600, Duplex stainless steel or 13 Cr Stainless Steel. Generic Corrosion Control flow chart (figure 4.23) and few guidelines to protect metal and prevent corrosion are as below.

- Material Selection
- Corrosion Mitigation Methods
- Corrosion Resistant Alloy Cladding/Lining
- Coatings
- Cathodic Protection
- Inhibitors

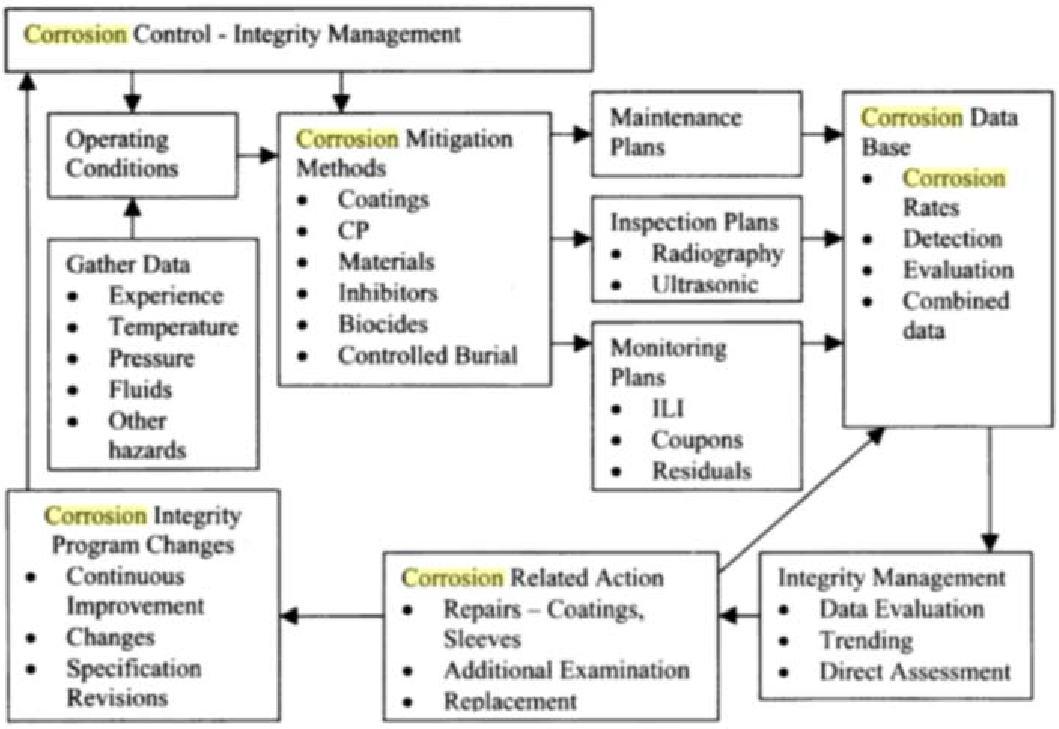


Figure 4.23: Referred from Charles (2005), Corrosion Control Flow Chart

4.6.1 Right Material for Right Design

Proper Material and coating selection play a major role to avoid corrosion. But cathodic protection would be most economical to use below the water line.

Steel is the most important material used in every critical part of the oil and gas industry from production phase to the processing phase to the distribution of the refined petroleum products. Safety Joint, Inner sleeve designed with material Low carbon Steel which contains 2% of Cr is highly resistant to hydrogen sulphide cracking, carbon-di-oxide and high temperatures (435° F) common in the deepest wells of Oil and Gas. It also contains 1.2 % of molybdenum which helps to increase corrosion resistance and Strength of alloyed steels. Basically background of selecting this material due to its stress/rupture properties, It can withstand high pressure and high temperature and also cost effective material.

4.6.2 Corrosion Resistant Alloy (CRA) Cladding

Lining/cladding provide relatively cost effective solution through welding a relatively thin corrosion barrier of an expensive CRA on a substrate of inexpensive structurally strong material. For Example: In chloride and oxidizing acidic environments, Grade 2 titanium can be cladded on Steel using resistance bonding or interlayered to avoid contamination of titanium with iron. It is more economical than manufacturing the big part with expensive material. As stated, other than material selection, to protect material from corrosion, we can employ Corrosion Resistant Alloy (CRA) cladding, Alloy 625 cladded on the OD of low alloy steel surface where there is chance of corrosion. Reference to Sohan L. Chawla () written Corrosion Control Book, General guideline for selecting cladding process is described as table below

Other widely used Permanent Corrosion Protection Techniques:

- Tin plating
- Galvanization
- Coating
- Enameling
- Copper plating

Criteria	LL	RW	TS	WO	RC	EC
Metallurgical Compatibility						
Compatible				×	×	
Incompatible	×	×	×			×
Permissible Corrosion Rate						
High: requiring thick allowance	×			×	×	×
Low: thin cladding layer		×	×			
Type of Equipment						
Basic	×			×		
Complex		×	×		×	×
Mechanical Requirements						
Basic	×					
Rigid		×	×	×	×	×
Cost						
Low to high ranking (1 to 6)	1	4	5	3	2	6

LL = Loose lining, RW = Resistance welding, TC = Thermal spraying, WO = Weld overlaying, RC = Roll cladding, EC = Explosion cladding

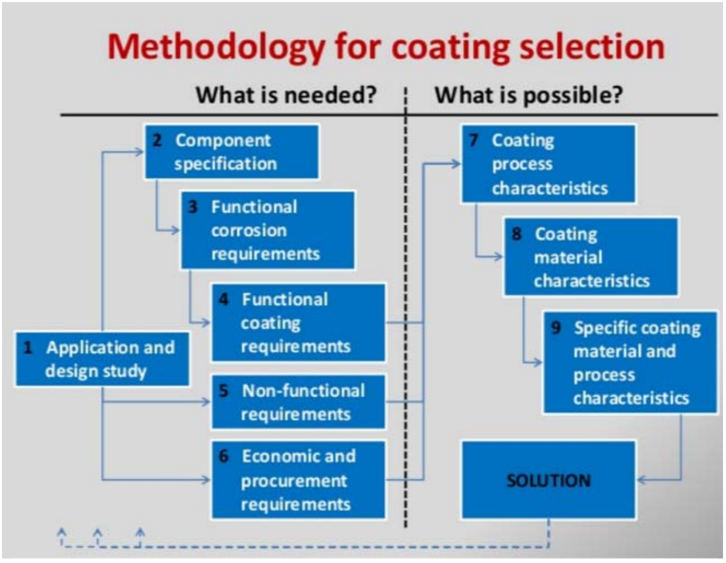
Table 2: General Guide for selecting Lining/Cladding processes for Equipment

The nobility of the metal determine metal`s tendency to chemically convert into an oxidized state which found to be vital for the development of corrosion reactions. For example, zinc is less noble than iron. That means that it has a greater electrochemical tendency to convert into chemical compounds than iron has. If an object made partly of zinc and partly of iron is placed in an aerated water solution, the zinc will corrode first and leaving the iron practically not corroded as long as the zinc remains in contact with the iron. In another situation the relatively less protective properties of corrosion products on surfaces determine the corrosion rate.

A practical application of this is the common practice of covering iron with zinc ("galvanizing").This treatment is useful because zinc corrodes slower in outdoor environments than iron, since the zinc corrosion products in the atmosphere are more protective for the metal compared to porous iron corrosion products.

4.6.3 Coating Selection:

All metals (excluding noble ones) in presence of oxygen become chemically unstable. Metal Oxide would be stable state. Metals covered with metal oxide will act as a corrosion barrier on metals surface; it will avoid resulting into corrosion. So coating selection plays an important role in anti-corrosion principle.



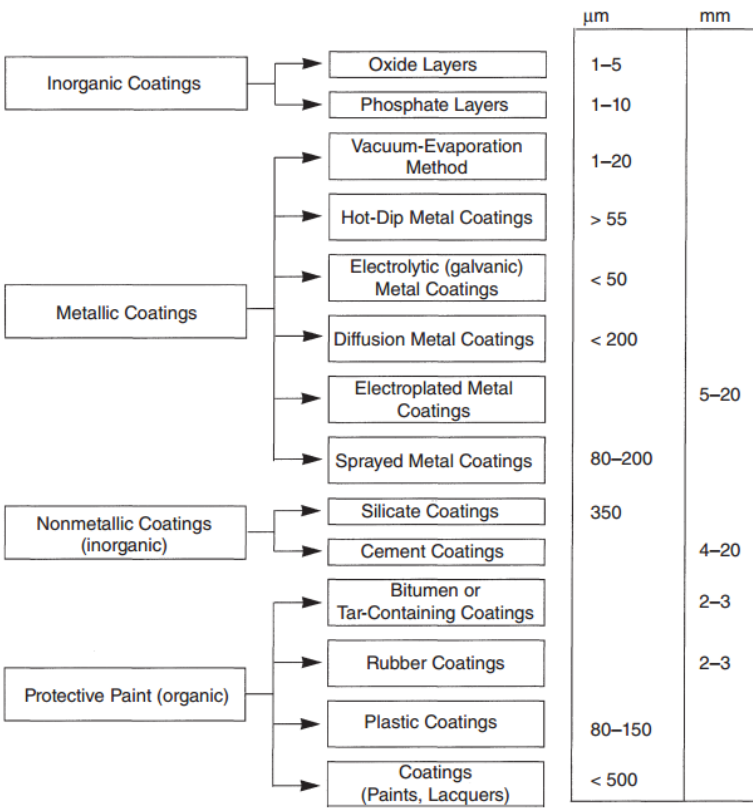


Figure 4.24: Reference from Peter (2011), Corrosion Protection Coating Procedures

4.6.4 Corrosion Protection Coatings

- **Thermal Spray Aluminum and Zinc**: Coating process in which heated or melted aluminum/Zinc sprayed on a surface to protect corrosion and mechanical damage.
- **Xylan Coating (Fluoropolymer based Coating):** It is application of thin film (PTFE, PFA) on target surface for Corrosion Protection.
- **Phosphate Coating:** When phosphate process solution in contact with metal, pickling reaction will create on the surface of metal, it provides minimal corrosion protection and anti-galling properties.

4.6.5 Cathodic Protection

CP can reduce the potential difference between the cathode and anode to a less neglected value. Reduction of potential difference is due to the polarization effect of the cathodic site to the most potential anodes. Corrosion current reduction is based on ohm`s Law Principle. It is explained on below figure 4.25, a steel pipe buried inside the ground protected with magnesium anode connected with coated copper wire. Magnesium most anodic will corrode and save the steel pipe from corrosion.

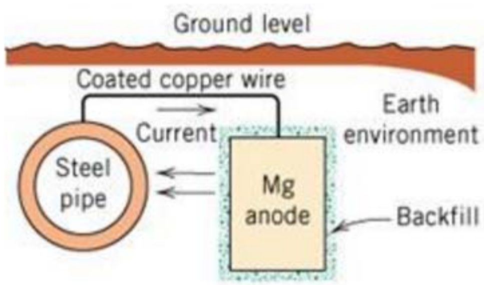


Figure 4.25: Cathodic Protection of steel pipe using Magnesium Anode

Rust is the common form of corrosion, above mentioned information are compiled in 'Rust's A Must' poetry by Watson (1966) as below

Mighty ships upon the ocean
Suffer from severe corrosion,
Even those that stay at dockside
Are rapidly becoming oxide.
Alas, that piling in the sea
is mostly Fe2O3.
And where the ocean meets the shore
you'll find there's Fe3O4.
'Because when the wind is salt and gusty
Things are getting awful rusty.

We can measure, we can test it
we can halt it or arrest it.
We can gather it and weigh it
we can coat it, we can spray it.
We examine and dissect it
we cathodically protect it
we can pick it up and drop it.
But heaven knows we'll never stop it!
So here's to rust, no doubt about it
Most of us would starve without it.

In the upcoming chapter, we can discuss the most feasible corrosion monitoring instrumentation which found to be suitable for safety joint, inner sleeve localized corrosion.

4.7 Corrosion Monitoring of Safety Joint

After detailed review of the problem, we can justify our thoughts about the Erosion Corrosion issue on Safety Joint. Flow Accelerated Corrosion (FAC) in Riser Joint Systems is a common problem in oil and gas industries or piping systems of Power plants and process industries. When carbon or Low alloy steel exposed to path of flowing water, flow accelerated corrosion will form and dissolve the protective oxide layer present on the surface of the low alloy steel. It will cause wall thickness thinning in joints, Bore of the riser Joint, can lead to leaks, and sometimes may also lead to system failure if it is unaddressed.

Few activities described below would be required to identify the location and need of a monitoring system:

- Ultrasonic examination of selected locations
- Engineering analysis of the pipe section/ Riser Joint
- Non-Intrusive Wall thickness Measurement

4.7.1 Basic Steps involved in condition monitoring technique

1. Identification of critical System or Component affect due to Corrosion:

Component of the safety joint which get directly affected is Safety Joint inner Sleeve. As explained earlier due to sand flowing through the inner sleeve slots of safety joint would further increase the probability of corrosion as well as erosion.

2. Design and Development of Continuous Condition Monitoring System:

Selection of the right location, erection/Orientation of the sensor is vital to the success of the corrosion monitoring device.

3. Data Collection and Reporting:

History data/Reference values/tables are derived from the existing condition of the equipment and during the real-time or offline maintenance interval Monitoring. Corrosion rate can be derived from the instrument and direct measurement of wall thickness loss compared with the original or reference baseline measurement.

5. Condition Monitoring Equipment for Safety Joint

5.1 ROXAR SUBSEA SEN-CORR CM SENSOR

Measure corrosivity of Pipeline fluids and provide quick response with high accuracy. Tip of Probe is the measuring element of the sensor which is installed to the bore of the pipe line or outer wall of the pipe as flush mounted at consecutive distances between the test specimens. Pressure rating of device is 10000 psi/13000 psi.

When corrosion sensing probe tip exposed to any in-line corrosion, there will be increase in electrical resistance which is directly proportional to the corrosion rate within measured period. Roxar Field watch, windows based UI and data storage software for ensuring reliable and safe operations.

Figure 5.1: Roxar subsea Sen-Corr CM sensor and its application

Advantage:

- Measures accurate corrosion rate and provide rapid response.
- Electrical Resistance measurement principle is used for detecting metal loss at wall thickness
- corrosivity of well bore fluids can be monitored
- Avoid the risk of shutdown/failure.
- Usage of corrosion inhibitor will be optimized.
- Help to justify the selection of low cost carbon steel.
- Corrosion models are used to provide precise feedback to the system.
- If project require to measure temperature and pressure in addition to corrosion rate, it can integrated as dual electronics combined Sensor.

Limitation: Roxar subsea Sen-Corr CM sensor will be difficult to erect for our application. It will not able to measure erosion, or corrosion due to residual fluids or moisture that may be particular to the safety joint due to the more complex geometry than a straight pipe.

Feasibility Study:

Subsea Sen-Corr Sensor can be erected at two places of the safety Joint, the assembly to be redesigned to mount the sensors at a distance between end faces of the inner sleeve, Safety Joint. It will complicate the system level design due to intrusive type of inspection.

5.2 GE RIGHTRAX CORROSION NON-INTRUSIVE MONITORING SYSTEM

GE Rightrax Corrosion Non-Intrusive Monitoring System consist of an intelligent data Logger and monitoring Sensor which could measure direct material loss from localized corrosion.

It consists of M2 Sensor, Portable Data Logger, ATMS (Automated Thickness Monitoring System)

1. **M2 Sensor:**

Figure 5.2: M2 Sensor

M2 Sensor has operating range -25° C to 120° C with wall thickness resolution to 0.2 mm. It can support 70 m long extension cables with M2 Sensors. It has built in identification strip and a temperature sensor. For Operation, single high temperature coaxial cable connected with sensor.

2. **Portable Data Logger (DL):**

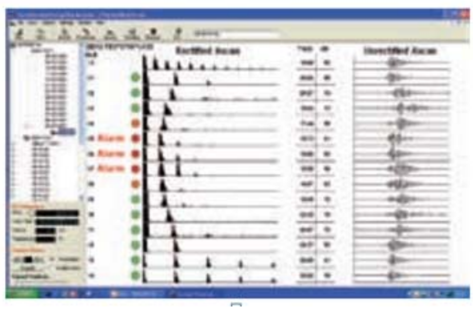


Figure 5.3: Portable Data Logger (DL)

Portable Data Logger (DL) provides direct thickness readings in mm or inches from M2 Sensor. Any unskilled personnel can easily access and interpret the values, Principle and some features are same as ultrasonic flow detector combined with automatic signal processing technology to determine wall thickness from the A-scans

Data Logger store records and use A-scans to fetch recent measurements. The data can be used on PC, Downloaded for further post processing and analysis as shown in figure 2.3. It is supplied with a connecting leads, User manual, a Charger and a data download software with a carry case (bag).

3. **Automated Thickness Monitoring System ATMS:**

Reference to Figure 2.4, automated version of the GE Rightrax Corrosion Non-Intrusive Monitoring System has been certified to operate at zone 2 locations. It has been designed for permanent installation on process pipelines and plant which demands accurate and repeatable wall thickness measurements values. WLAN (Wireless LAN) system can be used for data analysis and interpretation for any locations. There are three variations for different applications as shown below

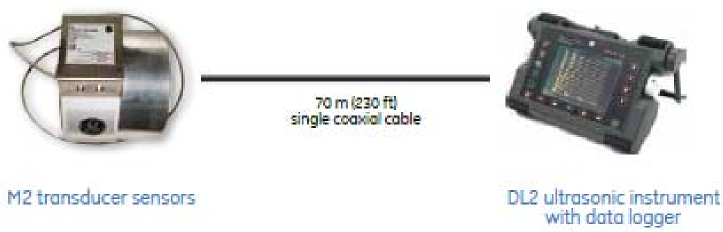


Figure 5.4: Portable Low Temperature (LT) Installed Manual System

Figure 5.5: Portable Low Temperature (LT) Installed Automated System

Figure 5.6: Portable High Temperature (LT) Installed Automated System

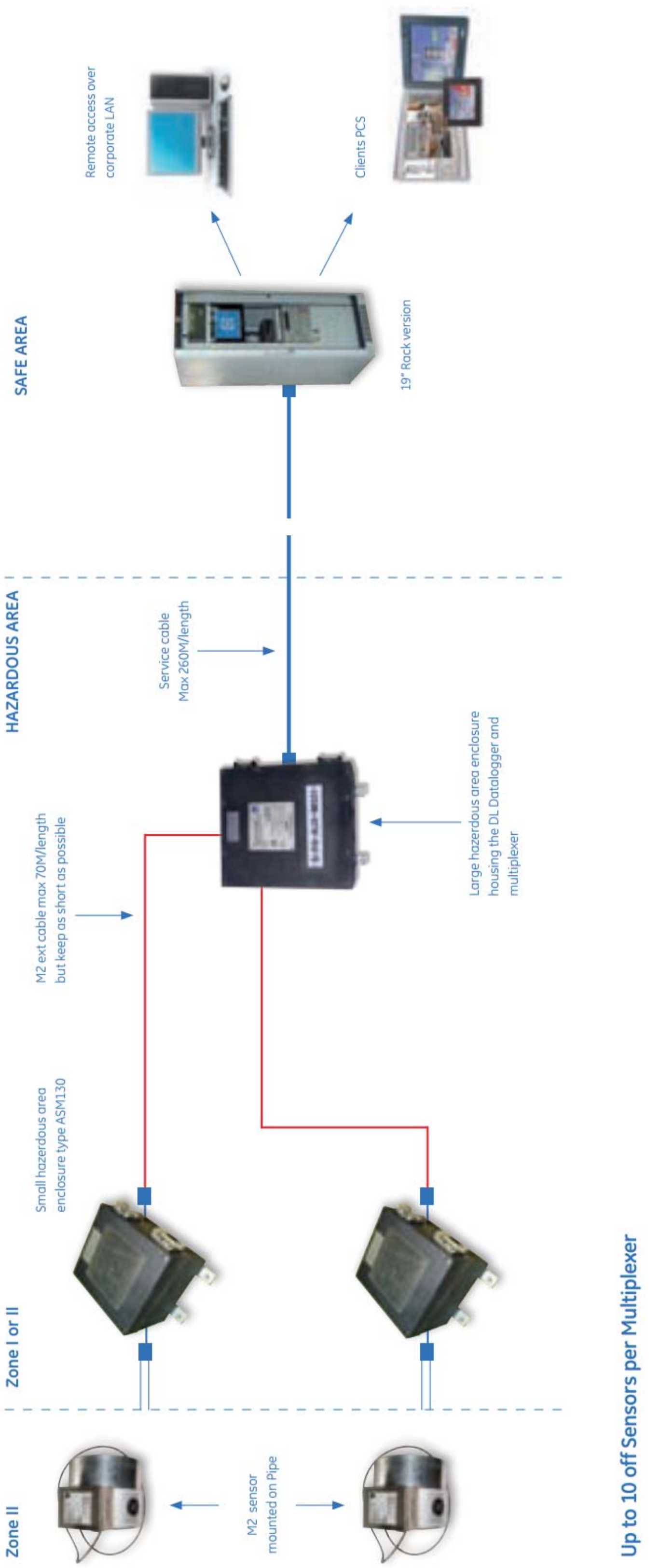
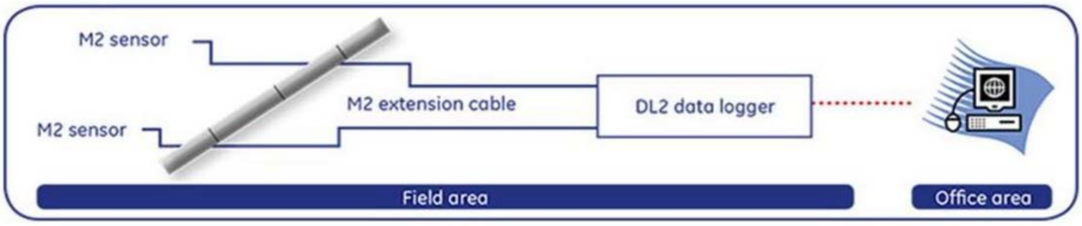


Figure 5.7: GE Rightrax Corrosion Non-Intrusive Monitoring System



Portable System

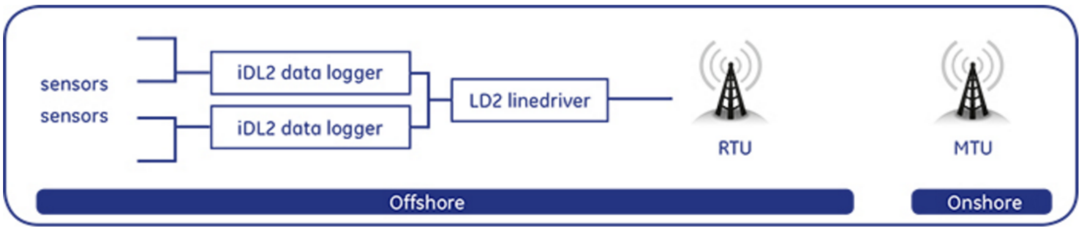


Figure 5.8: Semi-Automated System

Feasibility:

Feasibility of using Portable Low Temperature (LT) Installed Manual System for safety Joint can be used for corrosion monitoring of inner sleeve with M2 Sensors installed inside the Bore, Close to the rectangular flat or taper slots where we identified the risk of corrosion. A single coaxial cable passes through the work-over riser Joint and it will be connected Ultrasonic data logging device. A maintenance plan can be built to monitor the inner sleeve every year and logged wall thickness loss information can be converted to A-Scans using a computer.

Advantages:

- Non-Intrusive inspection during periodic maintenance intervals
- Operate temperature ranges from -40° C up to 120° C
- It can measure wall thickness up to 4”
- Measurement Accuracy of 0.2 mm
- Remote Locations – inaccessible areas, Manned and unmanned offshore platforms, remote pipeline installed site locations.
- Early warning systems: can be utilized to provide warning, trending, alarm info and data whenever required.

Limitation:

This equipment can be installed for this application of corrosion monitoring of the riser joint, but only possibility of offline measurement as referred to figure 2.3, Portable Low Temperature (LT) Installed Manual System. It could only check the wall thickness loss of the pipe section. It cannot check the ligaments width.

5.3 GE RADAR INSPECTION SYSTEM

The Abbreviation of RADAR mention **Riser Active Data Acquisition Recorde**r is a fully automated inspection tool or system that traverses the ID of a Riser joint (both production and annulus lines) using field proven ultrasonic technology to measure the riser joint pipe wall thickness and assess the quality of end Connection welds. Safety joint inner sleeve internal diameter can be inspected completely onsite using RADAR System. Traditional Inspection approach will waste valuable time in transporting the riser to the land, need to remove the buoyancy and coating if required.

As Data collection relies on ultrasonic energy, all equipment need to be precisely calibrated. Inspection procedures and Calibration standards have been developed specifically for the system. Optimal accuracy maintained through calibration in regular set of intervals before and after the installation. Only three technicians require for operating this equipment. We can decide on fourth technician if there is a requirement to perform additional dimensional and NDE Inspection in order to provide advanced and comprehensive site/field inspection results.

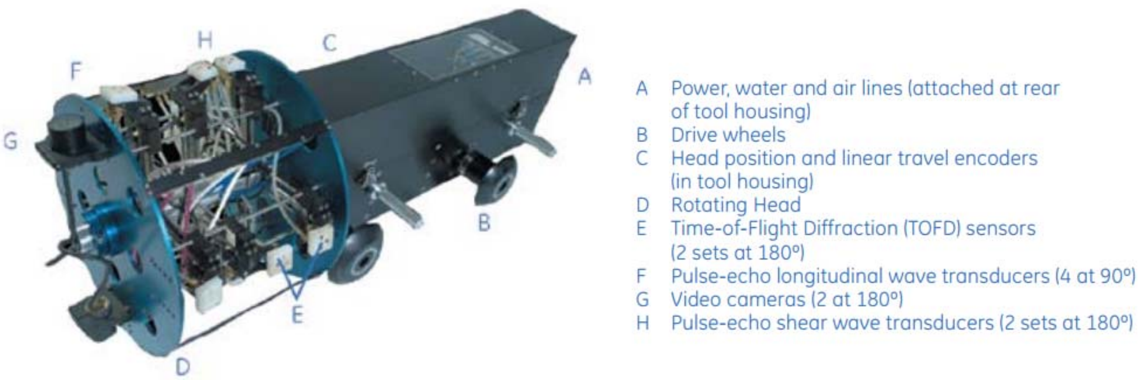


Figure 5.9: GE RADAR Inspection used for Marine Riser Inspection

(Picture Courtesy: GE)

As GE RADAR System is compactly designed this allows maximum portability, provide continues power supplies. System consist of redundant system, Video recording system, Scanners and software analysis monitor, Automated Data logger and printer with spare kits are installed inside the weather resistant mobile Work station/Container, It can be erected anywhere at site. Connections like water, power and air which required running the GE RADAR system to be supplied from site.

Three Tool configurations:

Reference to GE Technical Brochure, It has three variant of tools used for different sizes of risers as shown in below figure 5.10

- Large diameter tool is used to monitor the Marine Risers (drilling and production risers) which has 19-24 inches diameter.

- Small diameter tool is used for small pipe diameter range from 3 to 4.5 inches in diameter

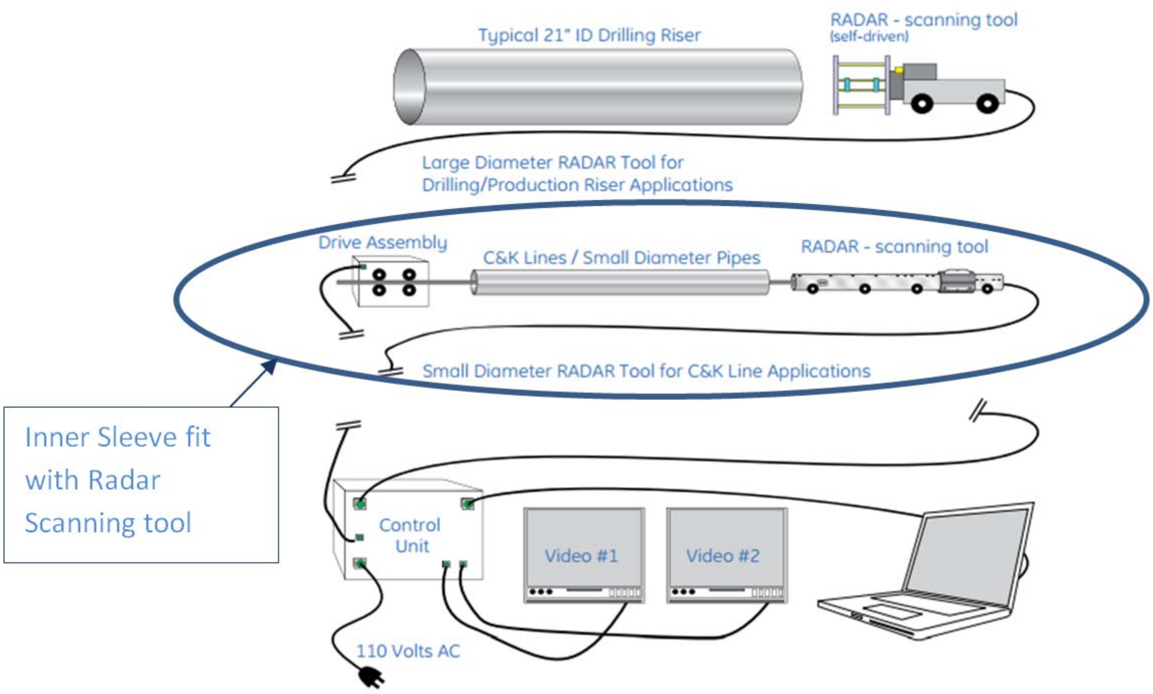


Figure 5.10: Three Variants of the GE RADER System depending on Size of Riser

Each tool is designed with unique characteristics using series of technologies to perform in-line riser offline or real-time inspection at site. Head of the system can rotate 180 deg. Transducer are installed in three sets, could work together to determine orientation, specific type of corrosion, Specific Location and size of the corrosion.

Three Technologies/ Operating Principle of GE RADAR System:

Let us assume as different situations to explain the how different technologies of RADAR System be selected and used for inspecting the same.

1. **TOFD (Time of Flight Diffraction):**

Let us assume Weld flaw in the Riser Pipe as per below figure 5.11.

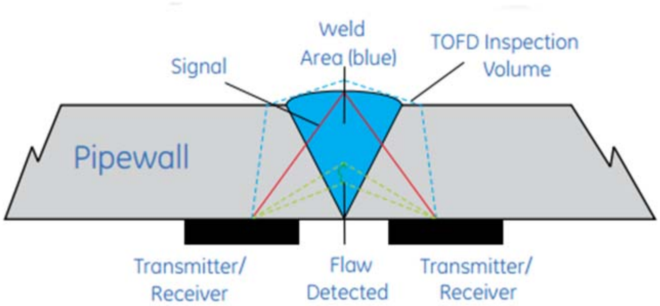


Figure 5.11: Time of Flight Diffraction (TOFD)

Detected Flaw/Irregularity and Inspection Volume (Blue Dotted Line)

Two transmitters monitor the entire volume of the area of interest. Transmitters which are spaced 180 degree apart will send inclined ultrasonic waves into the pipe wall. When there is a flaw detected, energy from weld flaw will get diffracted and picked by installed receiver (which are 180 degree apart) as shown in the figure 5.11. The system process offline as well as real-time and estimate out-line of flaw and displayed on B-Scan system. It is capable of detecting smallest flaw size as 0.031

2. **Pulse-echo shear wave**

Let us assume weld flaw is at root and cap region as depicted in figure 5.12

Four transducers are used to inspect the weld root and cap regions. Two transmitters and two receivers are spaced 180° apart to inspect the entire length of weld section along the circumference of the Riser pipe. When there is flaw at root or cap, it will create an echo due to overlapping signals due to the existence of flaw

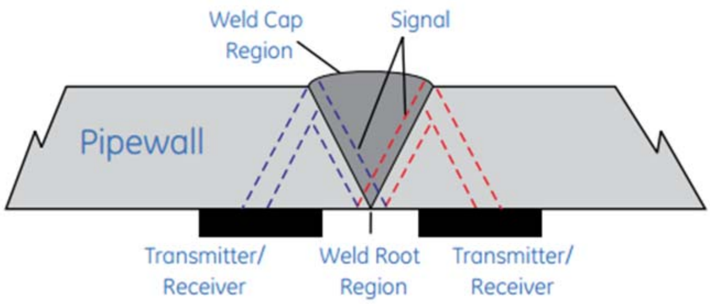


Figure 5.12: Pulse-echo shear wave

3. **Pulse-echo longitudinal wave:**

   Let us assume situation where entire wall thickness of the riser joint need to be inspected as shown in figure 5.13. It has four transducers to inspect the Riser pipe wall thickness. These transducers are located near the front of the tool and they are spaced 90° apart for increased inspection data acquisition speeds. Data is collected and displayed immediately as a color-coded wall thickness map, all anomalies shown both numerically and graphically.

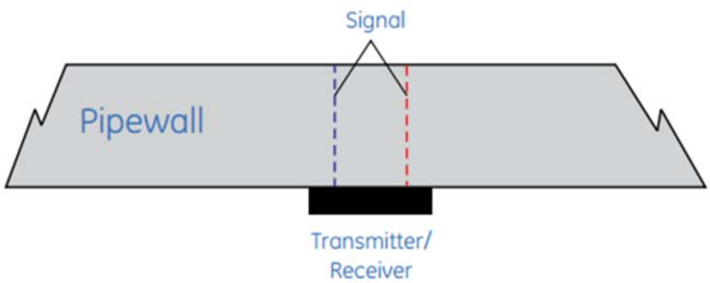


Figure 5.13: Pulse-echo longitudinal wave

Analysis and reporting:

1. **Inspection Values/Parameters:**

   Reporting criteria is flexible to modify and customize for each application of use. Analysis program incorporate acceptance criteria based on industry standards and can be flexible to adapt alternative customer standards

Figure 5.14: Video imaging of interior of the Riser Body

2. **Color-coded thickness map**

Ultrasonic irregularities (flaws, corrosion) data is displayed in colour codes (as shown in figure) determined by defect position and depth around the circumference and along the length of the riser.

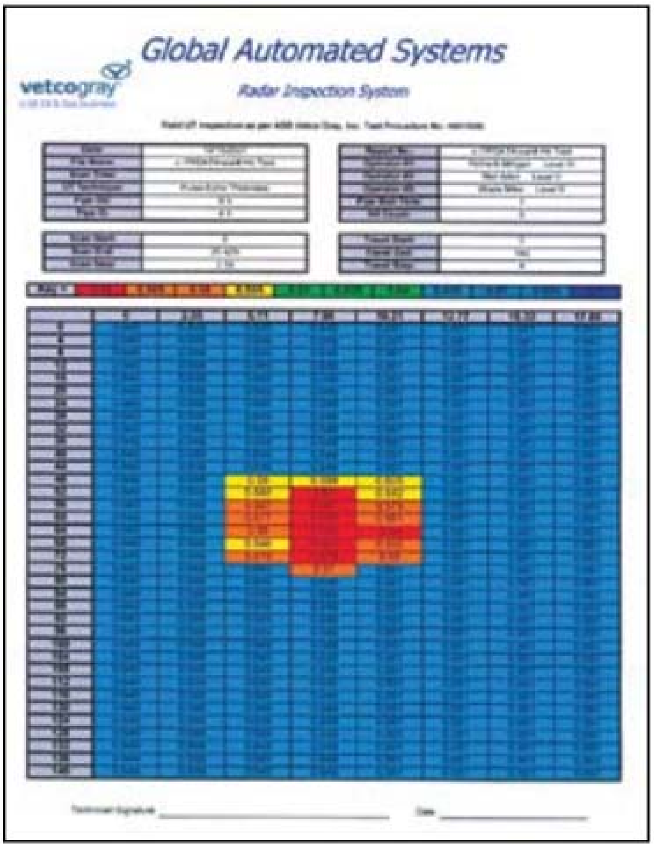


Figure 5.15: Colour coded Riser Wall thickness Map Display

3. B-scan display:

Critical waveform data and the B-Scan images created from these waveforms to accurately identify and assess flaws.

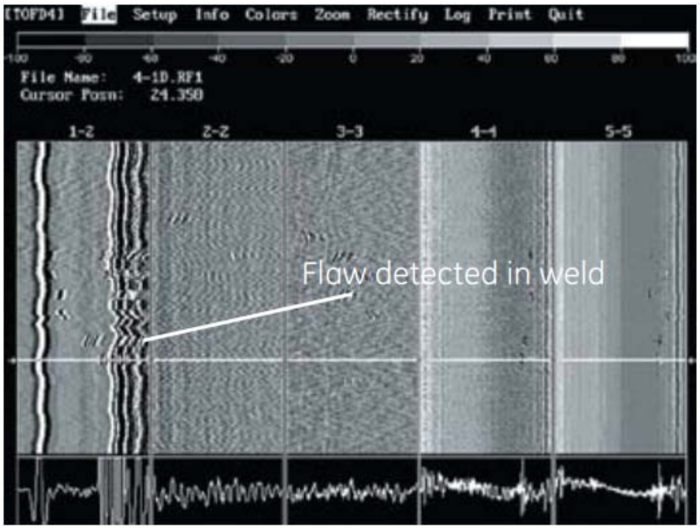


Figure 5.16: B- Scan Display show flaws at weld section

Seamless presentation

The system`s analysis programs and data collection system operate on a single software platform and analyses data are displayed in two presentations. On-board video

Each tool has on board video camera, it helps to record the completer inspection run of the riser joint internal condition.

Advantages:

- System provides Effective/Economical way for managing risk through detecting flaw/corrosion/Lifecycle wear of the riser joints.
- It enables accurate measurements depending on the acceptance criteria of the industry standards
- It will Identify the flaws at right time, quick decision making and instruct repair if necessary
- Ensure safety and security through digital storage of data for easy access retrieval in order to help avoid unplanned maintenance operations or rig shut downs due to sudden failure.

- GE Radar tools are certified by DNV and used worldwide for crack detection and metal loss due to Corrosion/Erosion.

Limitation of the Tool:

- GE RADAR System is not permanently installed system, it is a tool used to run during inspection schedules.so proper planning of scheduled maintenance is needed.
- Skilled technicians required to be appointed in conjunction with the tool

Feasibility Study of the System:

GE Radar System with Small diameter tool with Pulse-echo longitudinal wave technology found to be more appropriate variant among the other tools of the GE Radar System for Corrosion monitoring of the wall thickness of the Safety Joint, Inner Sleeve. Small diameter Radar system can be passed through 7 inch ID of the inner sleeve. In built Video camera can record the corrosion/Erosion issues of the inner sleeve rectangular slots during pre-planned maintenance intervals of offline monitoring. After Onsite inspection of inner sleeve complete, video files will be saved on Internal Server, it can check for wall thickness reduction for period of time and provide colour coded wall thickness reduction map display.

5.4 CLAMP-ON CORROSION-EROSION MONITORING SYSTEM

Clamp-On Corrosion-Erosion Monitoring System is an ultrasonic inspection instrument designed to measure the wall thickness loss over a defined section of pipe or riser. It will be connected with ROV, preinstalled system, with retrievable/installable electronics system.

Figure 5.17: Clamp-On CEM Real time/ Offline Corrosion-Erosion Monitoring System

Operating Principle of Clamp-On CEM:

This instrument exploits the Acoustic properties of Guide Lamb waves and it will send active ultrasound to detect the change in wall thickness of Riser Joint, Inner Sleeve relative to the reference wall thickness values collected during the installation phase.

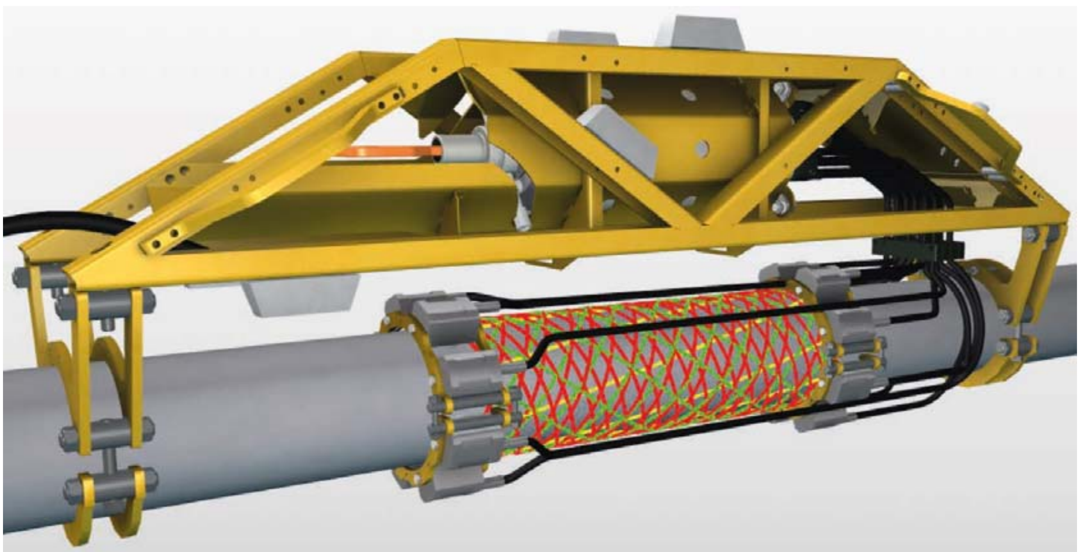


Figure 5.18: Signal paths between multiple transducers on a subsea CEM system

Instrument can install 32 transducers which could transmit and receive signals to and from each other to form a grid of signal over a defined area of the inner sleeve as shown in the figure 5.18, this can monitor precisely any kind of changes in wall thickness of the Safety Joint using acoustic guided lamb wave theory.

Acoustic Guided Lamb Waves are those Lamb like waves are guided between two parallel surfaces of the defined area of the test specimen. It is capable of propagating relatively long distances in structures. The irregularities or flaws are detected when they scatter or reflect the impinging wave, then reflected or scattered wave reaches sufficient amplitude.

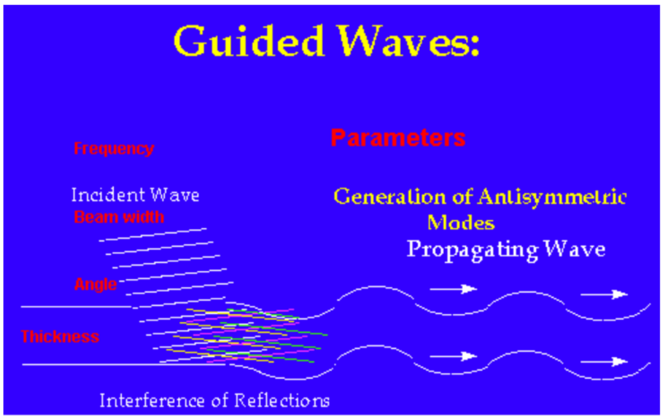


Figure 5.19: Acoustic Guided Lamb Waves/Guided Ultrasonic Waves

Lamb waves follow path of curvature of the defined structure and detect the subsurface irregularities or flaws with a single sided pitch catch measurement which could be difficult to interpret and complicated to use. Lamb wave measurements are retrieved from the number of relative transducers positioned around the inner sleeve, Image can be reconstructed using the principles of tomography for a larger region, It help technicians to interpret the results easily E.g. Wall thickness loss due to corrosion

Based on number of transducer in built on the instrument, the area of coverage and accuracy/sensitivity may change. With selection of right number of transducer will provide more reasonable picture of corrosion of inner sleeve with 100% coverage. This instrument capable of detected flaws in wall thickness of inner sleeve as little as 1%

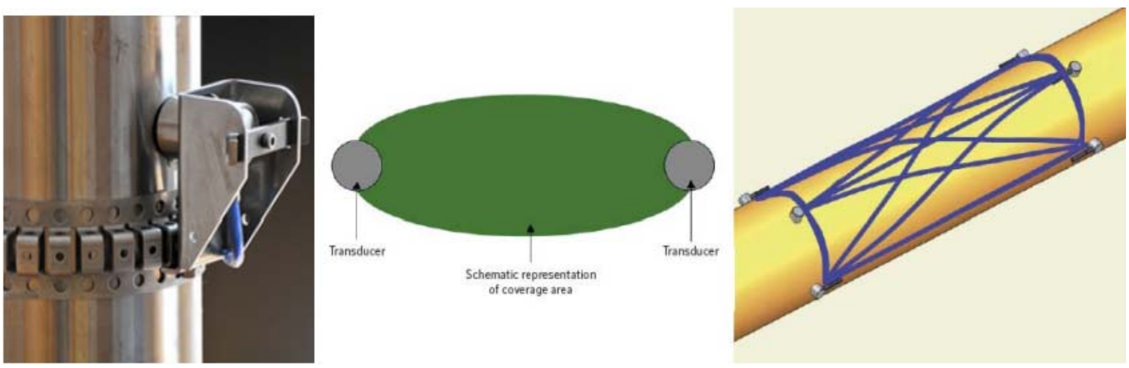


Figure 5.20: Clamp On Monitoring System – Illustration of Working Principle

According to Kevin (2002), Lamb wave measurements are made using number of relative positions of transducers (projections) around the perimeter of the area of interest, then image reconstructed tomographically for a large region using double cross-hole geometry to provide an easily interpretable colour coded quantitative map of the location/parameter of interest. Corrosion detection is possible through monitoring changes in arrival time signals. Typical Lamb Wave Dispersion curves recorded on the system for a material will look like in the figure 5.21 & 5.22.

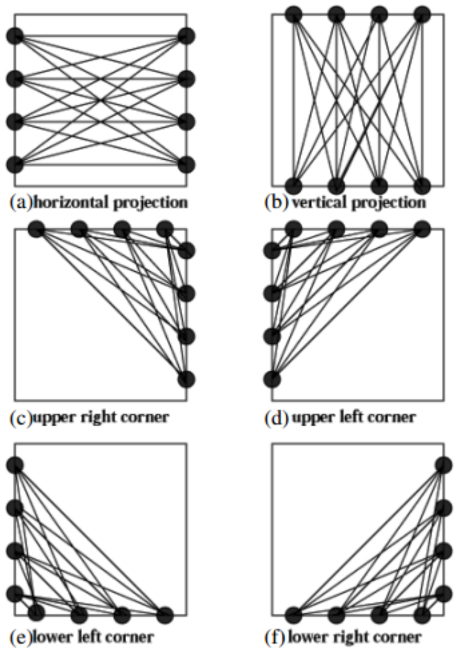
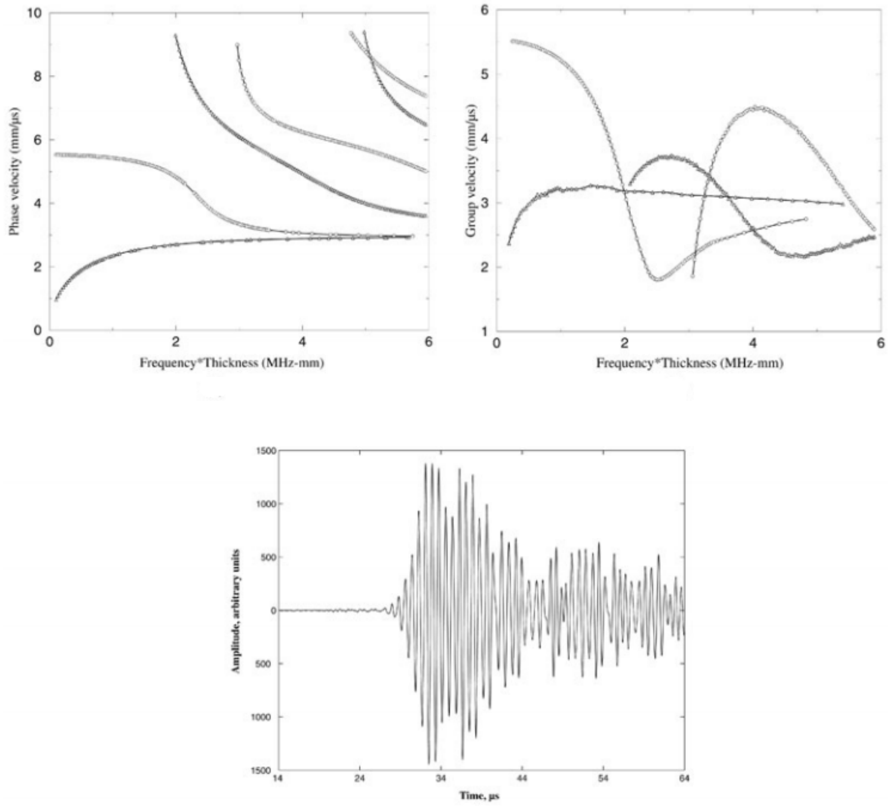


Figure 5.21: Six Possible Cross-hole projections with four transducers.



Lamb Waves Dispersion Curves

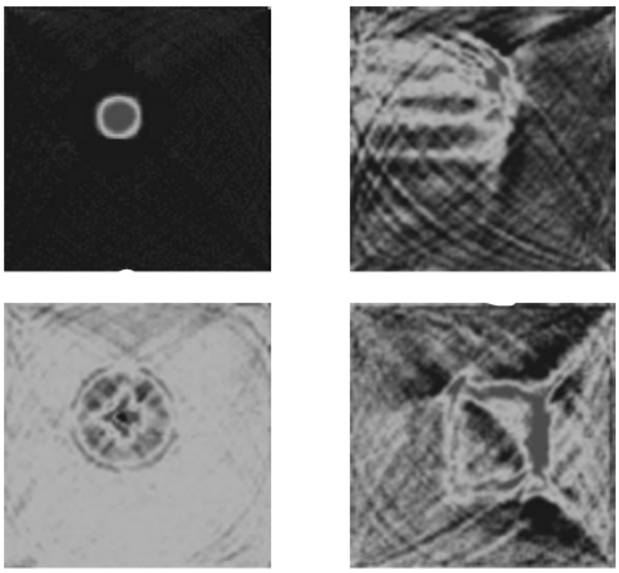


Figure 5.22: Reference Kevin (2002), Double Cross-hole Tomographic Reconstruction of a Plate

Data Management software collect the arrival times of the signals and with use of known distance between transducers, it is transformed to velocity domain which is less scattered can be truncated using empirical rules. Projected data transformed into time domain and fed to the algorithm which used for reconstruction of the same.

Installation of the CEM System:

The system is clamp-on to the existing part, so it very easy to install. As there are no moving parts, it will be maintenance free robust design. After installation, there is no requirement for recalibration. As it can measure entire section of inner sleeve, there is no probability of missing corrosion or erosion issue. It will precisely measure every slot of the inner sleeve, safety joint up to 2metres of length depending on position of transducers.

System can use for real time monitoring stations to Stand-alone monitoring stations into existing infrastructure

Key Specification of the CEM System:

- Method of operation: Active ultrasound waves w/ Electro Magnetic Acoustic transducers
- Minimum pipe OD: 6"
- Sensitivity: 0.1% of wall thickness
- Power supply: 12-36 VDC, 6W nominal
- Pipe OD/Wall thickness >8
- Electronic working temp.: -20 °C to 60 °C (-4 °F to 140 °F)
- Maximum coverage area: 3 m^2 (32 ft^2) with 8 transducers
- Electronics: 8 / 32 channel CEMAT with automation controller
- Repeatability: ±0.04 % of wall thickness
- Wall thickness range: 0.158" to 1.378" (4 to 35 mm)
- Communication: Serial/Acoustic/ Dual Ethernet
- Wall material: Conductive metals and alloys (Inner Sleeve – Low Alloy Steel)
- Pipe temperature: -20 °C to 150 °C (-4 °F to 302 °F)
- Design depth: 3000 m (9842 ft.)
- Design life: 30 Years (10+ Years for ROV mounted system)

Feasibility Study of CEM System:

To Erect the CEM System on Corrosion risk safety joint section requires redesign of CEM System. Number of transducers is required to be selected properly with respect to the OD of safety joint and area of coverage required for the travel of lamb waves. Visualization of Metal loss data analysis using principles of tomography are set to obtain required cross section of the rectangular slots of the inner sleeve where there is a risk of corrosion due to wet conditions and also risk of erosion due to continuous flow of sand.

5.5 CORROSION MONITORING EQUIPMENT SELECTION

Selection of Most Feasible Equipment for Corrosion/Erosion monitoring of Safety Joint, Inner Sleeve:

Corrosion Monitoring Device	Design Feasibility	Technology	Product Cost	Installation and Maintenance	Supplier
Subsea Sen-Corr CM sensor (Offline Monitoring)	Redesign of Safety Joint required. Design wise not feasible due to intrusive type of inspection	Electrical Resistance measurement Principle Measure: Loss of Material	350 K Nok	Intrusive Device Maintenance Operations Required	Roxar Emerson Subsea Sen-Corr Offline Monitoring
Rightrax Corrosion Non-Intrusive Monitoring System (Offline Monitoring)	Portable Low Temperature Installed Manual System can be feasible with least modification Difficult to measure both width and CS	Ultrasonic Inspection Method using Array Sensors Measure : Rate of Metal Loss	750 K Nok for Semi automated Version	Non-Intrusive Device, Portable, easy to install during Maintenance Operations	GE Measurement Systems
RADAR System Offline Monitoring	Small diameter tool if feasible to use without redesigning SJ for offline monitoring during scheduled maintenance intervals	Acoustics (Pulse-echo longitudinal wave)	1 M Nok for Tool, Installation of software portal and analysis unit	Non-Intrusive Device. Offline monitored at Pre-planned Maintenance Intervals	GE Measurement Systems
Clamp On CEM System	CEM System design changed to make it	Acoustics technology	4.5 M Nok (including	Non-Intrusive Device, easy to	Clamp On

(Offline and Real time Monitoring)	feasible to use. No Design modification required on safety Joint	Lamb Guided Waves Double cross hole tomography	Design Modification and Development cost)	install Offline method during Maintenance Interval. Real time Monitoring possible	

Table 3: Corrosion Monitoring System Selection

According to the selection table, GE RADAR Offline inspection found to be most feasible according to design, Installation of the corrosion monitoring equipment. As it will provide low amplitude signals which get diffracted and provide direct measurement of wall thickness material loss from colour coded thickness map.

5.6 EROSION - CORROSION MONITORING EQUIPMENT

Sand production in OG wells is very common problem, can cause wear and rapid erosion at the pipe bends, flow lines, valves and as well as chokes. Quick detection is very essential to prevent failure. Intrusive probes via access fittings to monitor erosion are most effective. But design of the safety Joint, Inner sleeve limit to use acoustic sensors to detect the erosion due to the continuous flow of sand from the pressure chamber non-intrusive technique. Let us discuss few intrusive/non-Intrusive methods as below for Erosion Monitoring for SJ, referred from Technical Paper NRI, 2010.

Instrument	Supplier	Measurement Technique	Installation	Characteristics
Acoustic Sand Detector	Roxar	Acoustic – detects solids	Non Intrusive, clamp on type	Single instrument. Listens for solids impacting on internal surface of flowline. Can be calibrated to measure quantity of sand if flow conditions remain relatively constant.
	ClampOn	Passive acoustics sensor technology		The sensor is installed two pipe diameters after a bend, where the particles/solids impact the inside of the pipe wall, generating an ultrasonic pulse. The ultrasonic signal is transmitted through the pipe wall and picked up by the acoustic subsea sensor.
High Sensitivity ER Probe	Teledyne Cormon Limited	ER (Electric Resistance) principle with Ceion technology - Measures metal loss rate	Intrusive via access fitting	Angled head type installed directly in flow stream. Element metal loss relative to reference element causes change in electrical resistance.
	Roxar	ER (Electric Resistance) principle - Measures metal loss rate		Four independent sensing elements measure increased element resistance as they are exposed to sand erosion.
	Rohrback Cosasco			Angled head or cylindrical type installed directly in flow stream. Element metal loss relative to reference element causes change in electrical resistance.

Table 4: Erosion Monitoring System Selection

5.7 MATHEMATICAL RELATION/EQUATION FOR CORROSION RATE

Corrosion rate can be primarily expressed in two ways

1. Weight Loss per unit time per unit area (mg per square dm per day)
2. Rate of penetration or Penetration rate, the thickness of metal lost due to corrosion in metric units(mm per year)

Reference to Technical Paper of Oyediran (2006), the corrosion rate during testing is measures as reduction in weight of the part of known area over a fixed period of time.

$$\text{mpy (mils per year)} = 12w/APt$$

Where t = time, in years

W = loss of mass over period of time t/kg

P = density of material of the part, kg/m^3

A = Surface Area, m^2

Factors required to be considered for corrosion rate of the Riser Joint as discussed below are Subsea Well dependent. As Safety Joint is a generic Work-over riser Joint could be used for different subsea wells. Nature of the environment vary depending on the below factors

- Well Fluid Data (Wellbore Fluid, H_2S, CH_4, CO_2)
- Corrosivity of the fluid (MPY Rates)
- pH range of the well
- Operating temperature
- Flow rate - Increased flow rate increase access of oxygen
- Relative Humidity
- Velocity of electrolyte
- Oxygen concentration
- Condition of the metal surface with debris

Material Cost Relation:

Cost-rating equation is given by

$$\text{Cost rating} = CX_p/\sigma_d$$

Where CX_p = Cost per unit Mass in (\$/kg)

σ_d = Design stress, N/mm^2

P = Density, kg/m3

Corrosion rate variations for different materials to be used for inner sleeve are discussed and compared with cost benefits for appropriate material selection in the next chapter. Alternative material selection depending upon corrosion rate will prevent the inner sleeve from corrosion.

6. Alternative Solution: Material Substitution

Low Alloy Steel (Inner Sleeve Raw Material) can be substituted with CRA (Corrosion Resistant Alloys)

6.1 ALLOY 600 Material

Alloy 600 is a common Austenitic engineering material for any application which requires corrosion resistance. It is a perfect blend of Nickel-Chromium-Iron alloy which presents high strength, Corrosion Resistance and Good Workability.
Due to high Nickel content of alloy 600, it is resistant to corrosion due to inorganic and organic compounds. As Alloy 600 fabrication process ensure fully stress relieved prior to use, so it will be extremely resistant to chloride ion SCC (Stress Corrosion Cracking). Chromium provides resistance to oxidizing conditions due to corrosive fluids or high temperatures.
Alloy 600 is not hardenable by precipitation method of heat treatment. It is hardened or strengthened by cold working.

Chemical Composition:

	Ni	Cr	C	Mn	Cu	Si	S	Fe
MIN	72.00	14.00	--	--	--	--	--	6.00
MAX		17.00	0.15	1.00	0.50	0.50	0.015	10.00

Table 5 : Chemical Composition of Alloy 600

Properties:

Alloy 600 is very stable, Solid Solution alloy at austenitic state. Only precipitated phases are chromium carbide, as well as two other compounds titanium nitrides, titanium carbides called as Cyanonitrides. These compounds are not affected by heat treatment and are stable at all temperatures.
Alloy 600 doesn't undergo embrittlement at high temperatures, so it is creep resistant, also possess high fatigue strength.

Static corrosion Test Data:

Reference to specific vendor data, alloy 600 tested for static corrosion in caustic soda (molten state)

Corrosion Rate, Mils per year depending on the temperature in Fahrenheit as below

Temperature, °F	750	932	1076	1256
Alloy 600	1.1	2.4	5.1	66.4

Table 6: Corrosion Rate of Alloy 600

6.2 ALLOY 625 Material

Alloy 625 is a twin version of Alloy 600 with little addition of niobium, it reacts with molybdenum to provide high stiffness character to alloy matrix. ALLOY 625 can give high strength without heat treatment process. Due to high alloy content such as Nickel and chromium, it can withstand severe corrosive conditions through providing high resistance to chemicals which tend to oxidise. Nickel and Molybdenum together avoid consequences of pitting and crevice corrosion. Niobium content acts to stabilise the alloy during welding process and avoid inter-granular cracking. Mainly used in chemical Processing units, Nuclear Reactors, Marine and Aerospace industries.

Chemical Composition:

Nickel	58.0 min.	Silicon	0.50
Chromium	20.0 min.–23.0 max.	Phosphorus	0.015
Molybdenum	8.0 min.–10.0 max.	Sulfur	0.015
Iron	5.0	Aluminum	0.40
Niobium (plus Tantalum)	3.15 min.–4.15 max.	Titanium	0.40
Carbon	0.10	Cobalt (if determined)	1.0
Manganese	0.50		

Table 7: Chemical Composition of Alloy 625

Properties:

Alloy 625 is a face-centred-cubic alloy and it is matrix stiffened on solid-solution. Pitting Resistance Equivalency Numbers (PREN) of Alloy 625 is 40.8, High stability of alloy 625, does not undergo embrittlement even exposed to extended periods in the high temperature range(1000° to 1800°F)

Corrosion Rate in Sea Water:

Selection of Corrosion Monitoring Equipment for Subsea Safety Joint

(Reference to Table of Vendor Data)

ALLOY	Corrosion/Erosion Rate	
	mpy	mm/a
Alloy 625	Nil	Nil

Corrosion Rate in Acidic Environment:

ALLOY	Acetic Acid Concentration	Corrosion/Erosion Rate	
		mpy	mm/a
Alloy 625	10%	0.39–0.77	0.01–0.019

Table 8: Corrosion Rate of Alloy 625

6.3 ALLOY 718 Material

Alloy 718 is Ni-Cr Precipitation Hardenable Alloy with significant amounts of molybdenum, Niobium and Iron with little addition of titanium and aluminium. It has good weld ability with corrosion resistance and better mechanical properties than Alloy 600 & 625. Excellent Creep Strength at high temperatures (700°C). Alloy 718 is an age hardenable alloy which could be machined into any complex components.

Most favourable properties of Alloy 718 are High Hardness and Strength properties at high temperatures, Low thermal conductivity and tendency to strengthen.

Chemical Composition:

	Ni	Fe	Cr	Nb	Mo	Ti	Al	C	Co	Si
Inconel 718	Bal.	19.45	18.30	5.30	3.00	1.04	0.58	0.03	0.07	0.09

Table 9: Chemical Composition of Alloy 718

Properties:

Alloy 718 has good corrosion resistance to any Corrosive Medium. Nickel helps to resist corrosion happen due to inorganic and organic environment. It also is useful in combating chloride-ion stress-corrosion cracking. Chromium avoids corrosion due to oxidizing medium and prevents sulphur attacks. Alloy 718 contributes excellent pitting resistance due to Molybdenum content.

Corrosion Resistance:

ALLOY	Corrosion/Erosion Rate	
	mpy	mm/a
Alloy 718	Nil	Nil

Table 10: Corrosion Rate of Alloy 718

6.4 Material Selection Based On Material Cost

Weight of the inner sleeve Part of Safety Joint = 94 kg

Material Cost Calculation of Low Alloy Steel

1 kg of Low Alloy Steel is priced 145 Nok/kg depending size/dimension and quantity required.

Cost of Material = 145 x 94 = **13775 Nok**

Material Cost Calculation of Alloy 625

1 kg of Alloy 625 is priced 330-350 Nok/kg depending size/dimension and quantity required.

Cost of Material = 350 x 94 **= 32900 Nok**

Material Cost Calculation of Alloy 718

1 kg of Alloy 718 is priced 400 Nok/kg depending size/dimension and quantity required.

Cost of Material = 400x94 = **37600 Nok**

Alloy 718 is work hardened material, it would take more effort to machine complex parts, hence machining cost of Alloy 718 would be high compared to F22

7. Discussion and Conclusion

7.1 Discussion

Based on Corrosion/Erosion monitoring equipment's discussed earlier, Roxar Corr-Sensor is simple to install, But Safety Joint would require design modification to install the Corr-Sensor intrusive System.

- Ge Rightrax Monitoring system technology relay on ultrasonic pulse diffraction and communication signals, if there is a signal loss due to environmental challenges, it will end up crack detection error during planned maintenance interval.
- Clamp On real time or Offline monitoring system need modification to accommodate on safety Joint, Inner Sleeve. As development cost of the Clamp On instrument is 4.5 mNok, the need of this equipment cannot be justified for Job production where it can be expected that low volume of Safety Joint ordered per year.
- GE Radar Inspection has flexibility to monitor the safety Joint during maintenance intervals without pulling the full work over riser system. For retrieving the riser system for inspection will require extensive rig time which is more expensive than installation of the monitoring equipment. Comparing all equipment's according to design feasibility and cost benefits, GE RADAR Inspection System is found to be most feasible for corrosion monitoring of the Safety Joint.

- Alternative solution for preventing the inner sleeve from corrosion is finding an alternative material which can resist oxidation and prevent corrosion. Based on Cost rating of different corrosion resistant Nickel-Chromium Alloys, Alloy 718 is a cost effective alternative material which could be substituted to prevent corrosion.

7.2 Conclusions

GE Radar Inspection has been identified as most suitable Corrosion/Erosion monitoring for offline inspection during planned maintenance intervals. Output is direct wall thickness measurement that could be easily interpreted and measured from color coded map display and B-SCAN display. Installation and Maintenance cost of the GE RADAR Inspection is 1 mNok approximately. Visual Inspection with disassembly and assembly of inner sleeve can predict periodic lifetime check but it will consume more time and effort. Hence Installation and maintenance cost of the GE RADAR System can be considered as Investment cost to monitor corrosion and to save the work over riser system from unaddressed structural Damage.

If safety joint ordered low volume per year, hence alternative material substitution is found to be cost effective solution for safety Joint corrosion prevention rather than erection of monitoring System. Alloy 718 is Corrosion Resistant Ni-Cr Alloy with excellent stiffness and corrosion resistant property. Alloy 718 with mechanical yield of 120 KSI can be used as inner sleeve material where rectangular taper slots can be protected due to Nickel and Chromium, Molybdenum content of the High strength Alloy.

7.3 Recommendation

If Safety Joint is ordered low volume per year, Alloy 718, 120 KSI is high strength, corrosion resistant material which could be strongly recommended solution for preventing corrosion issue.

7.4 Future Scope

Future scope of the project can be identifying the most feasible design change of the slot size/shape to avoid erosion consequences without affecting the function of the safety Joint. CFD can be performed for different shape optimization of the existing slot of the inner sleeve. More detailed Erosion simulation can be done with more impact angles and higher velocity of sand particles. Results can be compared with CFD results to get proper optimization of slot dimensions. Depending on results, design of the inner sleeve slots can be improved to avoid erosion.

7.5 References

All references of the corrosion monitoring equipment and technology based on product brochures of respective supplier like Clamp-On, GE and Roxar

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