

University of Southern Queensland  
Faculty of Engineering and Surveying

**A Case Study in Failure Analysis and Material Selection of Corrosion  
Under Insulation (CUI) of Piping Components in Oil and Gas**

A dissertation submitted by

**Florentino Cale**

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## ABSTRACT

Corrosion in facilities and equipment in the oil and gas industry can result to a loss of product containment and explosion, which ultimately lead to significant financial loss and environmental damage. One of the severe types of corrosion challenges that is pervasive particularly on pipeline facilities is corrosion under insulation (CUI). Most engineering materials are susceptible to most types of corrosion due to different environmental factors such as temperature, condensation, corrosive environment, flow regime and active-passive related parameters. Different types of corrosion are classified into different modes depending on these environmental factors. The purpose of insulating pipes varies on different systems to prevent heat loss or heat gain. The research shows that at least 85% of heat loss is reduced on the first inch of insulation and 95% of heat loss is reduced on several inches compared to what it would be from uninsulated surfaces. Insulation also acts as a protection to personnel, emissions reduction, condensation, freeze protection and noise reduction.

This study is primarily focused on investigating the failure analysis of corrosion under insulation (CUI) of piping components in oil and gas facilities. Based on available literature review, part of the investigation is about the material selection of different engineering materials used on piping components to at least mitigate or prevent CUI.

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**Florentino Cale**

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## Table of Contents

<b>Chapter 1</b> .....	13
<b>INTRODUCTION</b> .....	13
<b>1.1 Chapter Overview</b> .....	13
<b>1.2 Background</b> .....	13
<b>1.3 Project Aim</b> .....	14
<b>1.4 Project Objectives</b> .....	14
<b>1.5 Overview of the Project</b> .....	14
<b>Chapter 2</b> .....	16
<b>LITERATURE REVIEW</b> .....	16
<b>2.1 Chapter Overview</b> .....	16
<b>2.2 Corrosion Process of piping components</b> .....	16
<b>2.2.1 Environment affecting factors</b> .....	19
<b>2.2.1.1 Temperature</b> .....	19
<b>2.2.1.2 Condensation</b> .....	20
<b>2.2.1.3 Corrosion Product and deposits</b> .....	20
<b>2.2.1.4 Flow Regime</b> .....	20
<b>2.2.1.5 Active – Passive Related Parameters</b> .....	21
<b>2.3 Types of Corrosion Mechanism</b> .....	23
<b>2.3.1 Uniform Corrosion</b> .....	23
<b>2.3.2 Pitting Corrosion</b> .....	25
<b>2.3.3 Crevice Corrosion</b> .....	27
<b>2.3.4 Galvanic Corrosion</b> .....	28
<b>2.3.5 Intergranular Corrosion</b> .....	29
<b>2.3.6 Erosion or Abrasion Corrosion</b> .....	30
<b>2.3.7 Stress Corrosion Cracking</b> .....	31
<b>2.3.8 Atmospheric Corrosion</b> .....	33
<b>2.4 Corrosion Under Insulation (CUI)</b> .....	34
<b>2.4.1 CUI Mechanism</b> .....	35
<b>2.4.2 Factors Contributing to CUI</b> .....	37
<b>2.4.2.1 Air Pollutants</b> .....	37
<b>2.4.2.2 Marine Environment</b> .....	38
<b>2.4.2.3 Environmental Conditions</b> .....	38
<b>2.4.2.4 pH Effect</b> .....	39

2.4.2.5	Service Temperature .....	39
2.4.2.6	Insulation Materials .....	40
2.4.2.6.1	Calcium Silicate .....	40
2.4.2.6.2	Expanded Perlite .....	41
2.4.2.6.3	Glass and Mineral Fibres .....	42
2.4.2.6.4	Cellular Glass/Foam Glass .....	42
2.4.2.6.5	Polyurethane and Polyisocyanurate .....	43
2.4.2.6.6	Elastomeric Foams .....	43
2.4.2.6.7	Aerogels .....	44
2.4.2.7	Mechanical Design of Equipment and Insulation Installation .....	44
2.4.2.8	Mechanical Damage .....	45
2.5	Thermal Insulation System .....	45
2.6	CUI Failures in Piping Components .....	46
2.6.1	Insulated Industrial Piping .....	46
2.6.2	CUI Mechanism on Piping .....	48
2.6.3	CUI Failure in Stainless Steel Piping .....	49
2.6.4	CUI Failure in Carbon Steel Piping .....	50
Chapter 3	.....	53
Failure analysis	.....	53
3.1	Chapter Overview .....	53
3.2	Failure Analysis of CUI of Piping Components .....	53
3.2.1	Visual Inspection .....	53
3.2.2	History of Failed Components .....	55
3.2.3	On-site Examination and Sampling .....	56
3.2.4	Non-Destructive Testing .....	57
3.2.4.1	Magnetic Particle Inspection .....	57
3.2.4.2	Liquid Penetrant Inspection .....	58
3.2.4.3	Ultrasonic Inspection .....	59
3.2.4.4	Radiography Inspection .....	60
3.2.5	Chemical Testing .....	60
3.2.6	Mechanical Testing .....	61
3.2.6.1	Uniaxial Tension Testing .....	62
3.2.6.2	Uniaxial Compression Testing .....	62
3.2.6.3	Bend Testing .....	62
3.2.6.4	Hardness Testing .....	63
3.2.6.5	Impact Toughness Testing .....	63

3.2.7	<b>Metallography Analysis</b> .....	63
3.2.7.1	<b>Light Microscopy</b> .....	64
3.2.7.2	<b>Scanning Electron Microscope</b> .....	64
	<b>Chapter 4</b> .....	65
	<b>Material Selection</b> .....	65
4.1	<b>Chapter Overview</b> .....	65
4.2	<b>Material Selection Process</b> .....	65
4.3	<b>Corrosion Resistance Material Selection</b> .....	66
4.4	<b>Types of Metallic Materials</b> .....	69
4.4.1	<b>Cast Iron</b> .....	69
4.4.2	<b>Carbon Steel</b> .....	69
4.4.3	<b>Low Alloy Steel</b> .....	71
4.4.4	<b>Stainless Steel</b> .....	72
4.4.4.1	<b>Austenitic Stainless Steel</b> .....	73
4.4.4.2	<b>Super Austenitic Stainless Steel</b> .....	74
4.4.4.3	<b>Duplex Stainless Steel</b> .....	75
4.4.5	<b>Nickel Base Alloy</b> .....	76
4.4.6	<b>Copper Base Alloy</b> .....	77
4.4.7	<b>Titanium</b> .....	78
4.4.8	<b>Aluminum Alloys</b> .....	79
4.5	<b>Material Selection Decision Justification</b> .....	79
	<b>Chapter 5</b> .....	82
	<b>Discussion and Recommendation</b> .....	82
	<b>Chapter 6</b> .....	84
	<b>Conclusion</b> .....	84
	<b>References</b> .....	85
	<b>Appendices</b> .....	90
	<b>Appendix A – Project Specification</b> .....	90
	<b>Appendix B – Project Resources</b> .....	91
	<b>Appendix C – Project Planning</b> .....	92
	<b>Appendix D – Risk Assessment</b> .....	93
	<b>Appendix E – Assessment of consequential effects and ethics</b> .....	96



## List of Figures

Figure 2.1: Reactions taking place in an actively corroding metal. a.) Oxidation reaction, b.) oxidation and reduction reaction. ....	17
Figure 2.2: Reactions taking place in a passive corroding metal.. ....	18
Figure 2.3: Mild steel corrosion rate with temperature: in (1) water equilibrium with atmosphere; (2) constant oxygen content in closed circuit.. ....	19
Figure 2.4: The effect of flow rate velocity on the corrosion rate of an active metal.. ....	21
Figure 2.5: The effect of flow rate velocity on the corrosion rate of a passivating metal.....	21
Figure 2.6: Fe-Cr alloys in dilute aerated sulphuric acid solution Evans diagram. ....	22
Figure 2.7: A ferritic and an austenitic stainless steel aerated 5% sulphuric acid solution Evans diagram. ....	22
Figure 2.8: Result of uniform Corrosion.....	23
Figure 2.9: Types of pitting corrosion. ....	25
Figure 2.10: Pitting corrosion initiation and propagation stages. ....	26
Figure 2.11: Schematic process of an occluded cell.. ....	26
Figure 2.12: Sample of crevice corrosion.....	27
Figure 2.13: Types of crevices (a. Incomplete weld penetration, b. and c. joints, d. seals, e. presence of a probe).....	28
Figure 2.14: Sample of galvanic corrosion.....	28
Figure 2.15: Galvanic corrosion of less noble metal M by coupling with more noble metal N.....	29
Figure 2.16: Sample of intergranular corrosion.....	30
Figure 2.17: Sample of erosion or abrasion corrosion.....	31
Figure 2.18: Stress corrosion cracking condition representation by means of Venn diagram.....	31
Figure 2.19: Example of SCC related failure of a carbon steel.....	32
Figure 2.20: Intergranular SCC on grain boundaries.....	32
Figure 2.21: Stress corrosion cracking propagation appearance: a) intergranular, b) transgranular, c) delta river transgranular.. ....	33
Figure 2.22: An LPG line suffered atmospheric corrosion.. ....	34
Figure 2.23: Corrosion under insulation uncoated insulated steel pipe.....	35
Figure 2.24: Insulated carbon steel CUI mechanism corrosion cell.....	35
Figure 2.25: Real application of CUI in action.....	36
Figure 2.26: Temperature as a function corrosion rate of CUI.....	37
Figure 2.27: Three different environments with relative rate of metal loss.. ....	38
Figure 2.28: The effect of pH at room temperature on corrosion of iron in aerated water.. ....	39

Figure 2.29: Block and pipe thermal insulation relationship between thermal conductivity and temperature.....	41
Figure 2.30: Susceptible areas of piping system to water ingress.....	47
Figure 2.31: Insulated type 321 stainless steel failed region.....	49
Figure 2.32: Type 304 stainless steel cracking under insulation.....	50
Figure 2.33: CUI of carbon steel pipe.....	51
Figure 2.34: CUI of carbon steel pipe support..	51
Figure 2.35: Tee section insulated carbon steel piping before removal of insulation.....	51
Figure 2.36: CUI of Tee section insulated carbon steel piping after removal of insulation.....	52
Figure 3.1: External pitting corrosion of failed stainless-steel pipe.....	55
Figure 3.2: (a) Location of CUI failures of process pipework, (b) Pipework fracture detail, (c) Platform support bracket interaction with pipework insulation, (d) Pipework failures and support bracket. ...	55
Figure 3.3: Fluorescent magnetic particle inspection showing cracks of pipework (Testlabs 2019). ..	58
Figure 3.4: (a) Cracking initiated on both internal external at transverse cross-section and (b) Increase in internal initiated cracks at longitudinal cross section (Roffey & Davies 2014). ..	59
Figure 3.5: (a) Crack's indication of fluorescent liquid under ultraviolet light and (b) close-up view of the failure region (Kumar, Sujata & Bhaumik 2008).....	59

## List of Tables

Table 2.1: Standard potential series of metals (Lamsaki 2007) .....	18
Table 2.2: Industry accepted corrosion rates for metallic materials valid for oil and gas and chemical industries (Pedefferri 2018) .....	24
Table 4. 1: Metallic materials typical application for components in oil and gas (Elayaperumal & Raja 2015) .....	68
Table 4. 2: Cast iron corrosion property with the presence of alloying elements (Papavinasam 2013) .....	70
Table 4. 3: Elevated temperature use in common materials of construction (Elayaperumal & Raja 2015) .....	72
Table 4. 4: Austenitic stainless steel type standard (Elayaperumal & Raja 2015) .....	74
Table 4. 5: Lists of super austenitic stainless steel (Elayaperumal & Raja 2015).....	75
Table 4. 6: Lists of duplex stainless steel (Elayaperumal & Raja 2015).....	76
Table 4. 7: List of nickel base alloys – corrosion and heat resistant (Elayaperumal & Raja 2015). .....	76
Table 4. 8: List of copper and typical copper base alloys (Elayaperumal & Raja 2015).....	78
Table 4. 9: List of wrought aluminium alloys and their mechanical strength range (Elayaperumal & Raja 2015) .....	79
Table 4. 10: Decision matrix justification for material selection .....	81
Table 4. 11: The ranking results of materials based on their weighted scores .....	81
Table D.1: The probability of risk vs the level consequence.....	94
Table D.2: Risk assessment result for the project.....	94

## **List of Acronyms**

**API** – American Petroleum Institute

**CUI** – Corrosion Under Insulation

**GDP** – Gross Domestic Product

**NACE** – National Association Corrosion Engineers

# Chapter 1

## INTRODUCTION

### 1.1 Chapter Overview

With the guidance of selected supervisor, this project is chosen based on University of Southern Queensland provided research projects. The purpose of this chapter is to understand the background, objectives, and outline of the project with regards to industry problems today in which the oil and gas and refining sector are mainly affected. It discusses how corrosion affects different equipment on mentioned industries.

### 1.2 Background

Corrosion accounts for 25% of pipeline incidents in the past years and is the most common damage mechanism of processing facilities, such as in the oil and gas and refining industry. The result of corrosion causes loss of product containment and explosion which is a huge amount of financial loss. Economic Impact (2016) data showed that the cost of corrosion globally is estimated to be equivalent to 3.4% (US\$2.5 trillion) of global GDP (2013). However, the individual safety or environmental impact is not included to the estimated cost. It also influences the transmission failures on pipelines of processing sector due to corrosion control system failures such as ageing coating, unpredicted environment and loss control of rapid corrosion growth which added to corrosion failures (Tsai, Wang, Chien, Wei, Wang & Hsieh 2019).

Ratcliff (2009) stated that everyone was immune from corrosion from household to industry. Almost all engineering materials, such as steel, plastics and concrete are subject to corrosion and degradation. Data shows that corrosion cost Australia up to AU\$32 billion per annum and can result to incidents from train derailments, oil spills, bridges collapsed, shortages of gas and power outages.

One of the severe types of corrosion that challenges worldwide industry today is “corrosion under insulation” (CUI) which refers to the deterioration of the external wall due to corrosion. This is mostly found on piping and vessel fabricated from carbon manganese, low alloy and austenitic stainless steel. The penetration of water underneath external insulations is the primary cause of CUI. This is a major problem because they remain undetected until insulation and cladding is removed to carry out inspection or when leaks to atmosphere occur. CUI is responsible for many leaks that had led to health, safety and environment related incidents, production losses and costly unplanned maintenance budget that are often required to resolve the problem (Winnik

2015). Mohsin, Mokhtar & Tse (2019) stated that CUI is very hard to predict because it occurs in an abrupt and uncertain manner which remain hidden beneath the insulation and continuously grow as a serious problem that causes an industry average of 10% of the maintenance and repair budget.

### 1.3 Project Aim

The aim of this project is to investigate the failure analysis of corrosion under insulation (CUI) of piping components in the oil and gas and refining sector. Part of the investigation is to seek clarity on how the CUI occurred on piping and defined the main factors that contribute to this damage mechanism; identify the industry practices to evaluate the cause of CUI failures; identify the best practice to select suitable material selection process or techniques to maintain the integrity of insulated piping system.

### 1.4 Project Objectives

The objectives of this project are derived from project specification programme in appendix A.

- Provide a brief background on the failure, operations, and operating environment of corrosion under insulation (CUI) of piping components
- Research extensive literature review on analysis of the failure modes and potential causes of failure
- Provide suitable failure analysis of CUI failures of piping components.
- Perform an investigation for appropriate materials to use during design stage of insulated piping components.
- Prepare report for failure analysis and materials selection.

### 1.5 Overview of the Project

Chapter 1 provides the introduction to corrosion, the background and why this is a problem, project aim and project objectives.

Chapter 2 provides more details of literature reviews of the corrosion process on piping components, environment affecting factors, different types of corrosion mechanism and corrosion under insulation mechanism.

Chapter 3 provides the methodology for failure analysis which consists of different procedures to determine the failure.

Chapter 4 provides the material selection in which to determine the best suitable materials for corrosion under insulation failures.

Chapter 5 provides the discussion and recommendation based on the content

Chapter 6 is the conclusion of this document.

## Chapter 2

### LITERATURE REVIEW

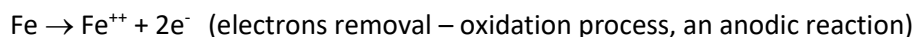
#### 2.1 Chapter Overview

This literature review covers corrosion as a damage mechanism affecting piping equipment. It focuses on principles and types of corrosion on mostly metal materials in the industrial sector. It discusses the flow of corrosion on insulated piping equipment used in oil and gas and refining industries.

#### 2.2 Corrosion Process of piping components

A naturally occurring phenomenon, corrosion is a chemical or electrochemical reaction which results to a deterioration of a material, usually metal, when they are exposed to different environments (Jacobson 2021). As mentioned by Singh (2014), exposure from environment can be atmospheric, exposed in certain liquids, high temperatures or being underground. In every aspect of corrosion, the material could be metallic or non-metallic. Pedferri (2018) stated that corrosion is a breaking down or destruction of material from when iron combines with oxygen and water, commonly called “rust,” which fails when metal atoms are removed from its element. According to Cicek (2017), based on Fontana’s description, corrosion that mostly appear in metal are less stable in their thermodynamically element forms than ores as compound forms. It is not possible to avoid the corrosion process by reversing fundamental laws of thermodynamics.

Singh (2014) stated that most corrosion occur in an aqueous environment by electrochemical reaction for most of engineering materials. Basically, the process is that electron travels from anode to cathode through electrolyte in the corrosion process. The following reaction illustrated below involves the removal of electrons (oxidation) of metal and often indicate that consumption of those electrons is termed reduction reactions from aqueous environment through presence of oxygen or reduction of water.



$\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^{-} \rightarrow 4 \text{OH}^{-}$  (presence of oxygen – reduction and evolution of hydrogen ions, a cathodic reaction)

$2\text{H}_2\text{O} + 2\text{e}^{-} \rightarrow \text{H}_2 + 2\text{OH}^{-}$  (aqueous environment – reduction and evolution of hydrogen ions of water, a cathodic reaction)



The metal loss occurs during oxidation reaction (anodic reaction) while there is a reduction reaction (cathodic reaction) which is electrochemical in nature that is essential for initiation of corrosion. For the corrosion process to continue it needs charge neutrality where the anode must be balanced at the cathodic end with consumption of emitted electrons and the oxidation loss at the anode. Figure 2.1 shows schematically the surface of a corroding metal in an aqueous solution taking place during reactions. Figure 2.2 shows schematically the overall anodic reaction of an atom is shift from the metal (M) into the solution as already described in the form of dissolved ion ( $M^{n+}$ ) from oxidation and reduction reactions in a passive material (Munoz, Espallargas & Mischler 2020).

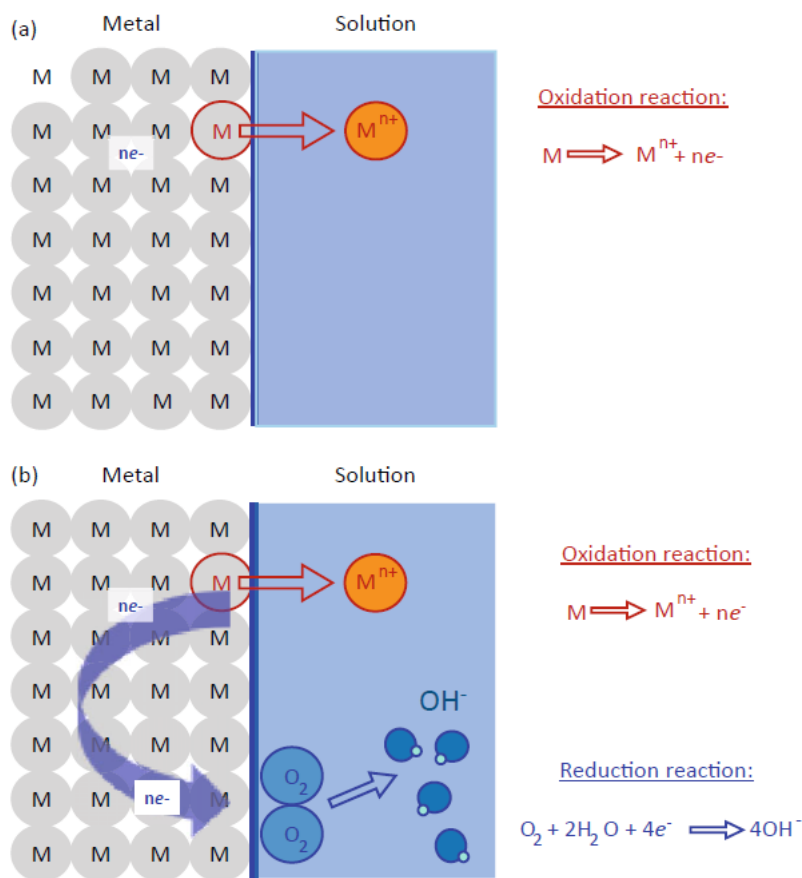


Figure 2.1: Reactions taking place in an actively corroding metal. a.) Oxidation reaction, b.) oxidation and reduction reaction (Munoz, Espallargas & Mischler 2020)

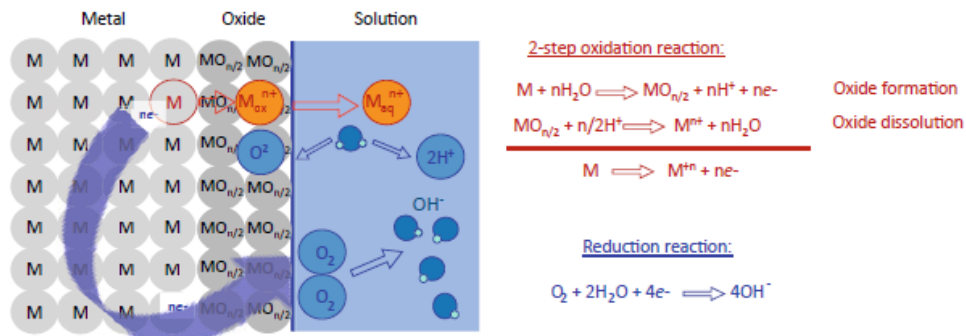


Figure 2.2: Reactions taking place in a passive corroding metal (Munoz, Espallargas & Mischler 2020)

The metal consists of different elements such as anode, cathode, electrical path and electrolyte. Basically, anode and cathode could be the same metal but in different regions. The electrolyte is present from water and electrical path could be on equipment that connects the anode with the cathode. In the absence of any of the four elements, corrosion will not occur. During the corrosion process from the anode region to the cathode region, electrons flow that allow the electrical current energy to accumulate in the metal, which refers to the potential of the metal. Table 2.1 shows that every metal has different corrosion resistant features during processing of the amount of energy, therefore they have different tendencies to deteriorate depending on the type of metal (Lamsaki 2007).

Energy Required for Refining	Metal	Volts	Tendency to Corrode
Most energy required ↑ ↓ Least energy required	Magnesium	-2.37	Greatest tendency ↑ ↓ Least tendency
	Aluminum	-1.66	
	Zinc	-0.76	
	Iron	-0.44	
	Tin	-0.14	
	Lead	-0.13	
	Hydrogen	0.00	
	Copper	0.34 to 0.52	
	Silver	0.80	
	Platinum	1.20	
	Gold	1.50 to 1.68	

Table 2.1: Standard potential series of metals (Lamsaki 2007)

## 2.2.1 Environment affecting factors

There are five factors affecting the corrosion process – temperature, condensation, corrosion products and deposits, flow regime and active-passive related parameters. The process involves the deterioration of a material through the reactions to its environment, which naturally occur in their natural state (Pedefferri 2018).

### 2.2.1.1 Temperature

The temperature affects corrosion even though electrochemical (electrode reactions), chemical (homogeneous reactions) and physical (solubility and diffusion) are the result of elementary series process. The corrosion rate through a complex law depends on temperature, neither exponential, where there is a 10 °C increase in temperature reaction rate as typical for chemical reactions, nor linear as in some physical processes. If the temperature increases when the prevailing elementary process is gas solubility in the solution, the corrosion rate may even decrease (Pedefferri 2018).

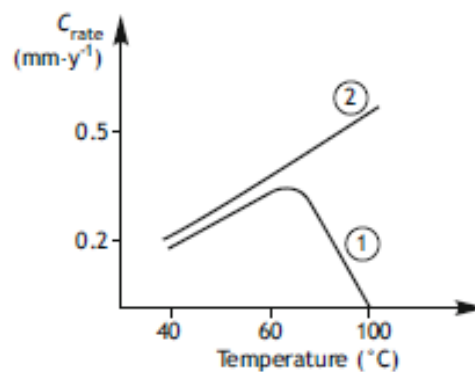


Figure 2.3: Mild steel corrosion rate with temperature: in (1) water equilibrium with atmosphere; (2) constant oxygen content in closed circuit (Pedefferri 2018)

The diffusion coefficient increases as the temperature increases while the water decreases on oxygen solubility then zeroing at boiling temperature. Figure 2.3 shows that curve (1) open circuits where water is exposed to atmosphere and curve 2 for closed circuit where oxygen remains entrapped in the plant and every 25 °C increase, the corrosion rates doubles (Pedefferri 2018).

### 2.2.1.2 Condensation

In a corrosion viewpoint, the physical-chemical condition is important to local variations. Water condensation caused by pressure increase or temperature decrease leads to severe corrosion. An example is in fuel where sulphur is present, the carbonic acid and sulphuric acid form while corrosion rate can be very high where there is water condensation in gas wells containing carbon dioxide. The dew point temperature/ pressure is the critical parameter which determines the water condensation condition. The formation of concentrated sulphuric acid, for instance around 140 °C can be much higher than boiling water temperature compared to dew point temperature at atmospheric pressure (Pedefferri 2018).

### 2.2.1.3 Corrosion Product and deposits

The presence of corrosion products and deposits may be either harmful or beneficial to form a barrier which separates the metal surface from the environment. There are different varieties of protection properties of such barrier depending on characteristics: state (uniform, non-uniform, crystalline or colloidal), solubility, porosity, hygroscopic nature and electrical conductivity. Magnetite and sulphides can cause galvanic like corrosion during electronic conductivity. The ionic conductivity almost neutralises the barrier effect in the case of cuprous oxide of copper. It is always beneficial to the insulating properties where metal surface can scarcely support anodic or cathodic processes. Scale can cause crevice corrosion or erosion during a local turbulence when set up downstream or upstream of the deposit (Pedefferri 2018).

### 2.2.1.4 Flow Regime

Flow regime affects corrosion as the flow rate increases, shown in figure 2.4. From  $v_1$  to  $v_4$  the corrosion rate increases up to a limit by point 4. Figure 2.5 shows how an increase in the flow rate for an active-passive material can facilitate passive film formation. Basically, the corrosion rate increases from point 1 up to 3 as maximum corrosion rate then drops to point 4 when it exceeds  $v_4$  flow rate and metal passivates. Sometimes to avoid stagnant conditions that are prone for pitting, an increase of flow rate is also beneficial and more important. A high flow rate regime is dangerous when leading to corrosion-erosion conditions (Pedefferri 2018).

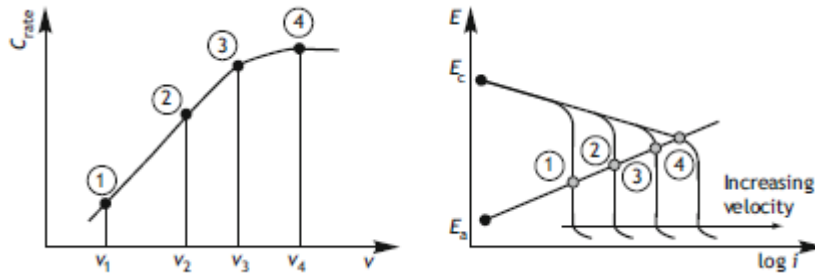


Figure 2.4: The effect of flow rate velocity on the corrosion rate of an active metal (Pedefferri 2018)

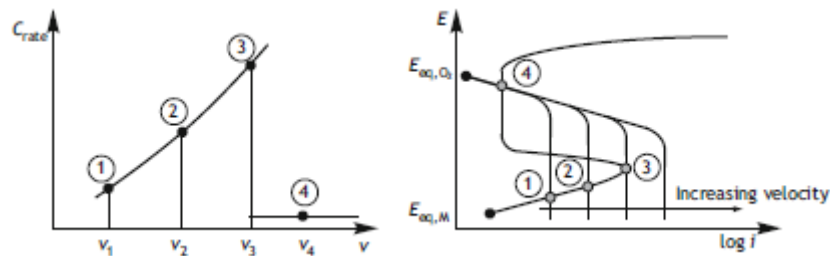


Figure 2.5: The effect of flow rate velocity on the corrosion rate of a passivating metal (Pedefferri 2018)

### 2.2.1.5 Active – Passive Related Parameters

The metal operates in an active or passive condition depending on both the metal itself and the environment. Using Evans diagrams, it can be determined by examining anodic curves. The following are the active-passive corrosion behaviour parameters:

- Passive interval, between passivity ( $E_p$ ) and transpassivity ( $E_{tr}$ )
- Passivity current density,  $i_p$ , passive interval corrosion rate measurement
- Critical passivation current density,  $i_{cp}$ , which defines the ease to passivate

Figure 2.6 & figure 2.7 shows two examples that depict the importance of active-passive corrosion behaviour parameters. The preferred corrosion behaviour is when  $i_p$ , passivity current density is low,  $E_{tr} - E_p$ , passive interval is wide and  $i_{cp}$ , critical passivation current density is low (Pedefferri 2018).

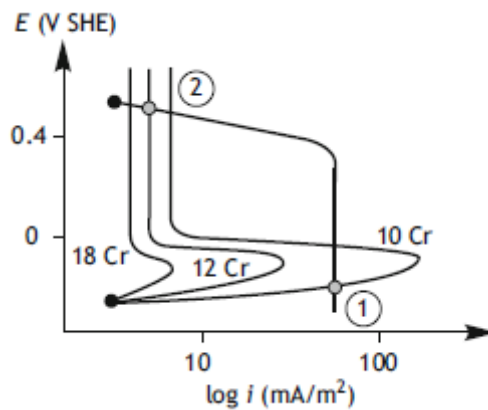


Figure 2.6: Fe-Cr alloys in dilute aerated sulphuric acid solution Evans diagram (Pedferri 2018)

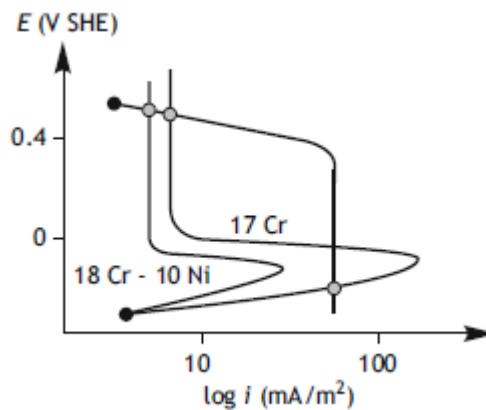


Figure 2.7: A ferritic and an austenitic stainless steel aerated 5% sulphuric acid solution Evans diagram (Pedferri 2018)

Figure 2.6 schematically shows the cathodic curve of the oxygen reduction process in a stagnant condition and the anodic curves of some iron-chromium alloys exposed to air in a dilute acidic solution. This means that from point 1 to point 2, with a corrosion rate reduction of about three orders of magnitude, when the corrosion shifts by increasing the chromium content from 10 to 12% the passivity is achieved. Figure 2.7 shows that in an aerated 5% sulphuric acid solution without or with oxidants added, both stainless steels show a comparable passivity current density. However, it also shows that ferritic stainless steel has a much higher (a big nose) critical passivation current density. Therefore, a robust cathodic process is required that enables the surpassing of the primary passivation potential of the nose to set up passivity. In practice, oxygen alone makes austenitic stainless steel passive in dilute sulphuric acid (Pedferri 2018).

## 2.3 Types of Corrosion Mechanism

Corrosion types can be classified into different modes depending on the environment, location, and atmospheric and temperature ranges (Vachtsevnos, Natarajan, Rajamani & Sandborn 2020). Pedferri (2018) stated that the two main morphologies of corrosion damage that is environmentally exposed are that which is exposed on the whole surface, so called *generalized corrosion*; and that which has only a small surface portion exposed of it, so called *localised corrosion*. The corrosion is classified by the appearances on the attacked materials, and depends on the corrosive environment, type of the metal, content of the components, insulation materials, stress on the metal and other variables. All types of corrosion can be recognized using naked eye and other visual equipment aids in identifying some of them. The eight most common types of corrosion found on insulated components are uniform corrosion, pitting corrosion, crevice corrosion, galvanic corrosion, inter-granular corrosion, erosion or abrasion corrosion, stress corrosion cracking and atmospheric corrosion (Lamsaki 2007).

### 2.3.1 Uniform Corrosion

This type of corrosion is not dangerous because it occurs quite evenly distributed over the surface with uniform thickness reduction. It is responsible for most of the material loss and is the most common form of corrosion which can be predicted by means of simple tests to determine thickness reduction rate (Cicek, 2017). Uniform corrosion (2021) described that breakdown of coating protection on the structures often leads to this type of corrosion and when permitted to continue it may become a more serious damaging corrosion.



Figure 2.8: Result of uniform Corrosion (Uniform corrosion 2021)

Pedefferri (2018) stated that uniform corrosion is a uniformly distributed corrosion that attacks over the metal surface exposed to aggressive environment, which can be measured by the mass loss rate per unit area,  $C_{rate,m}$ , and calculated by the equation:

$$C_{rate,m} = \frac{\Delta m}{S \cdot t}$$

Where  $\Delta m$  is mass,  $t$ , loss in time and  $S$  is exposed surface area

Mg/dm<sup>2</sup>day (mdd) and mg/m<sup>2</sup> hour (mmh) are the most common used units of measurement of mass loss rate. Thinning rate (thickness loss rate or penetration rate) in industrial applications is preferred over mass loss as a corrosion measurement. It is given as  $C_{rate}$  in the equation:

$$C_{rate} = \frac{\Delta m}{\gamma \cdot S \cdot t} = \frac{C_{rate,m}}{\gamma}$$

where  $\gamma$  is metal mass density

The units of measurement of thickness loss rates are mm/yr and mpy (mils per year) (1mpy = 0.025 mm/year or 25.4  $\mu$ m/year). For the most industry-used metal, such as iron, copper and zinc, which have a mass density in the range of 7-8 Mg/m<sup>3</sup> (tons per cubic meter), the relationship between the penetration rate,  $C_{rate}$ , and the mass loss rate,  $C_{rate,m}$ , is:

$$1\text{mdd} = 5\mu\text{m/year} \quad 1\text{mmh} = 1\mu\text{m/year}$$

Corrosion behaviour	Corrosion rate				
	mpy (mils/year)	$\mu$ m/year	nm/h	pm/s	mm/year
Excellent	<1	<25	<2	<1	<0.02
Very good	1–5	25–100	2–10	1–5	0.02–0.01
Good	5–20	100–500	10–50	5–20	0.1–0.5
Average	20–50	500–1000	50–150	20–50	0.5–1
Poor	50–200	1000–5000	150–500	50–200	1–5
Inacceptable	>200	>5000	>500	>200	>5

Units as nm/h and pm/s are reported for comparison purposes only

Table 2.2: Industry accepted corrosion rates for metallic materials valid for oil and gas and chemical industries (Pedefferri 2018)



## 2.3.2 Pitting Corrosion

Pitting corrosion is the most unpredictable observed corrosion type that is mostly found on steel and aluminium due to near neutral pH conditions with corrosive anions such as  $\text{Cl}^-$  or  $\text{SO}_4^{2-}$  present in the content. Pitting corrosion penetrates through the passive film, as characterized by narrow pits with equal radius or magnitude lesser than the depth at irregularities in the oxide structure to the interface of metal oxide. The initiation of pitting is from high local concentrations of aggressive anions with the combination of low solution pH values, in which pits can grow to micrometre from nanometre range (Cicek, 2017). Corrosion types and prevention (2021) described that pits typically penetrate vertical surface downward direction once it has initiated and takes on different shapes as illustrated on figure 2.9.

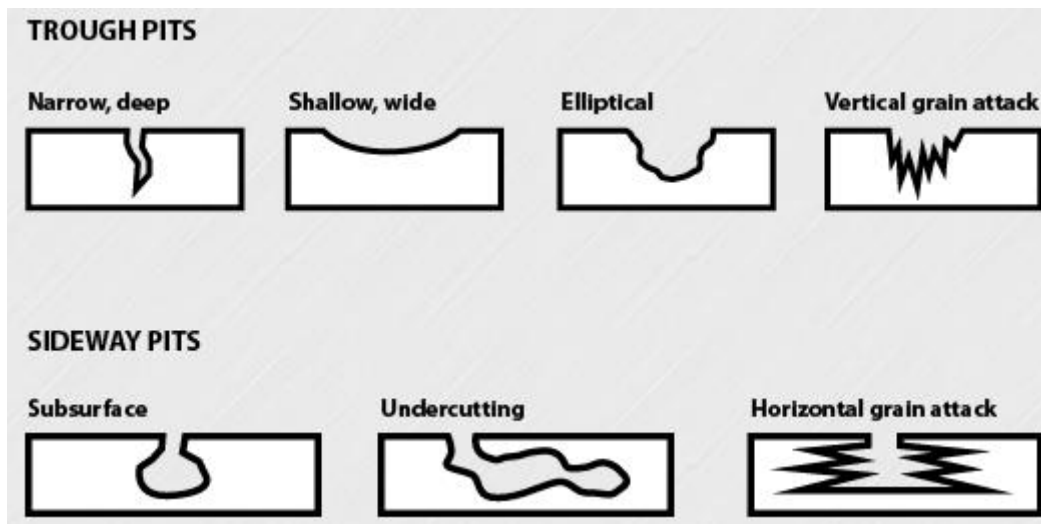


Figure 2.9: Types of pitting corrosion (Corrosion types and prevention 2021)

Pitting produces a deep penetrating attack from severe localized corrosion with less than a few millimetres diameter often isolated in a number varying from few to several hundred per square meter. It occurs on active-passive metals in oxidizing chloride containing environments, which cause a typical localized corrosion attack. The propagation of pitting is a macro cell mechanism where anodic area is inside the pit whilst the external surrounding passive area where oxygen reduction is in cathodic zone. The macro cell circulation gives a current series of reactions and modifications with chloride content increases to further stimulate anodic attack, and inside the pH decreases and surface pH increases on the external passive helping strengthening passivity (Pedefferri 2018).

Pit initiation is an initiation time required of passive film breakdown which is produced by the action of environment, such as chloride ions ( $\text{Cl}^-$ ) and extent halides  $\text{F}^-$ ,  $\text{Br}^-$  and  $\text{I}^-$  to a lesser. Pitting potential depends on both metal and environment properties necessary for electrochemical conditions required to break down the passive film to be more noble than specific operational requirements. Most commonly, pits start on weaker or flawed passive film such as impurities and inclusions present on metal surface. Smooth surfaces are more resistant to influencing pitting initiation than rough surfaces (Pedferri 2018).

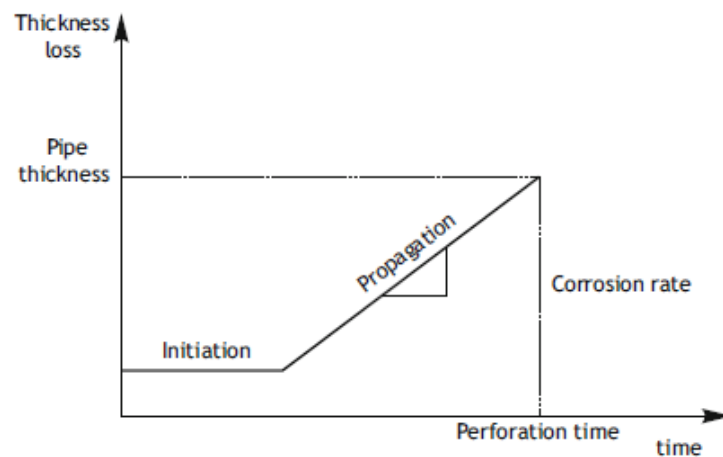


Figure 2.10: Pitting corrosion initiation and propagation stages (Pedferri 2018)

Propagation of pits between the anode and acting as cathode the surrounding passive zones a macro cell current starts flowing. As hydrolysis reaction of metal ions proceeds the solution becomes gradually more aggressive inside pit pH drops to values close to 3 – 4 and acidification increases. Occluded cell is a process where metal cations migrate as shown on figure 2.11 and diffuse towards the pit mouth which react with hydroxyl ions and precipitate as hydroxide (Pedferri 2018).

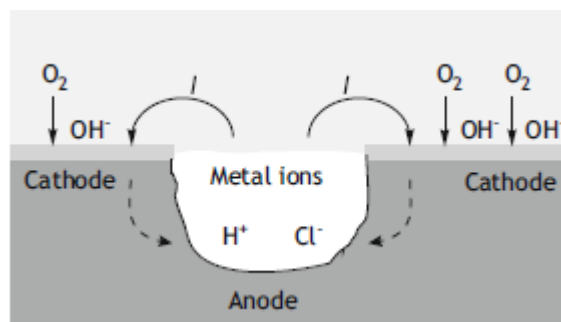


Figure 2.11: Schematic process of an occluded cell (Pedferri 2018)

### 2.3.3 Crevice Corrosion

Crevice corrosion is a localised corrosion that obstructs oxygen supply and occurs underneath deposits and in narrow crevices in which a gap is wide enough for a liquid to penetrate into the crevice but the liquid flow is too narrow. Most steel and aluminium that are exposed to atmosphere beneath a protecting film of metal or phosphate develop a special form of crevice corrosion called filiform corrosion (Cicek, 2017). Crevice corrosion (2021) states that the changes in local chemistry within the crevice initiate crevice corrosion usually from a stagnant solution on micro-environmental level, such as an inhibitor and oxygen depletion in the crevice, thereby shifting acid conditions in the crevice and aggressive ion species build-up in the crevice.

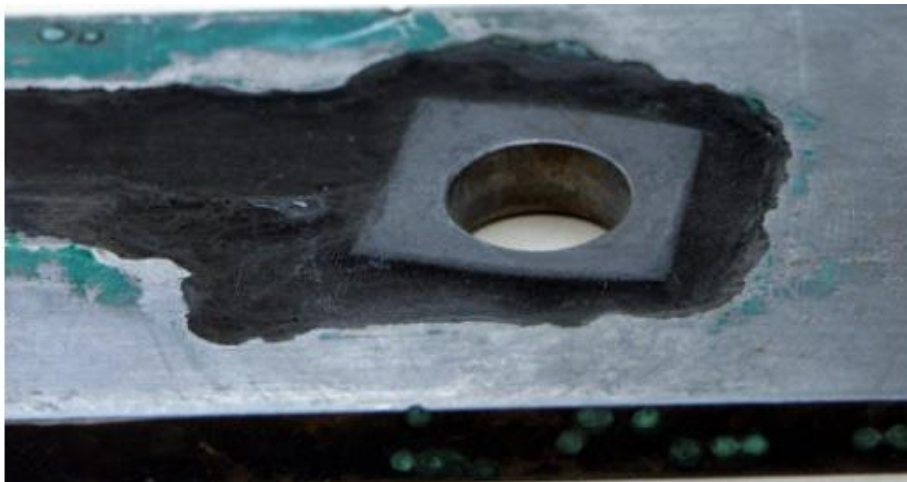


Figure 2.12: Sample of crevice corrosion (Crevice corrosion 2021)

Pedefferri (2018) explained that crevice corrosion is a form of corrosion deterioration that is related to the presence of sub-millimetre interstices such as cracks, gaps, screens or deposits on metal surfaces. It produces perforation and local thinning with a risk of out of service of equipment and environmental pollution. Crevice critical gap size (CCGS) is defined as the minimum critical interstice size that allows the aggressive environment to enter the interstice but obstruct the diffusion of oxygen. The recommended critical gap size depending on the metal composition is between 0.1  $\mu\text{m}$  and 0.1mm. Figure 2.13 shows a typical industry situation where crevice corrosion arise as follows:

- Lack of penetration in welds propagated to cracks
- Joints and threaded connections surface overlapping
- Typically in flanges and sealing gaskets interstices between metal and non-metallic materials

- Presence of scales, deposits, corrosion product and fouling

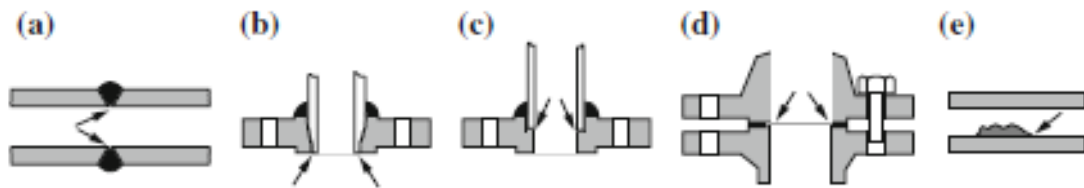


Figure 2.13: Types of crevices (a. Incomplete weld penetration, b. and c. joints, d. seals, e. presence of a probe) (Pedefferri 2018)

### 2.3.4 Galvanic Corrosion

Galvanic corrosion occurs when dissimilar metallic contact is made between a less noble and a more noble metal. A higher reaction rate may lead to a higher metal dis-solution rate or corrosion rate if large cathodic reaction is not balanced correspondingly to a large anodic reaction concentration in a small area where there is a relatively less noble metal (Cicek, 2017). Galvanic corrosion (2021) described galvanic corrosion as a corrosion damage induced in a corrosive electrolyte when two dissimilar materials are coupled. Basically, as the galvanic couple forms, one of the metals becomes anode and corrodes faster as compared to when it would corrode all by itself. Others corrode slower than it would do alone when it becomes the cathode and corrodes. The potential differences between each other are the driving force for corrosion.



Figure 2.14: Sample of galvanic corrosion (Galvanic corrosion 2021)

The main factor influencing galvanic corrosion is the different practical nobility in the same environment where it is electrically connected and immersed with in cathodic overvoltage and ohmic drop in the electrolyte where they possibly dissipate the ratio between cathodic and

anodic areas. There may be a side effect besides an acceleration of less noble metal on a corrosion rate such as a less noble metal prone to possible passivation, possible hydrogen embrittlement of susceptible metals due to hydrogen evolution and cathode surface reduction of oxides, sulphides or other species present (Pedferri 2018).

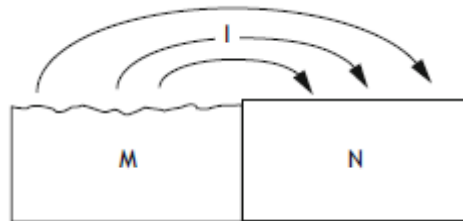


Figure 2.15: Galvanic corrosion of less noble metal M by coupling with more noble metal N (Pedferri 2018)

### 2.3.5 Intergranular Corrosion

Intergranular corrosion is a localised attack with no corrosion on other parts of the surface but propagate into the material structure of which the main cause is the presence of galvanic elements due to differences in alloying elements or concentration of impurities (Cicek, 2017). Intergranular corrosion (2021) stated that the grain boundaries or grain boundaries in immediate adjacent areas are where intergranular corrosion attacks, while the remaining bulk of grains are unaffected. It is usually that the formation of a compound in the boundary or specific elements attack during segregation corrosion then occurs by preferential attack in a zone adjacent to it or on the grain-boundary phase that has lost adequate corrosion resistance, making the grain boundary zone anodic. The entire grains may be dislodged due to a severe case of grain-boundary corrosion along a narrow path along the grain boundaries. This corrosion attack is very severe due to crystallographic structure distortion and impurities and second phase segregation leads to grain detachment then the mechanical resistance is reduced. In some instances, the presence of specific alloying elements or impurities caused intergranular attack. In the past, research show that cast Zn-Al alloy containing impurities of lead exposed to harsh environment showed some intergranular corrosion end up with bulging and cracking (Pedferri 2018).

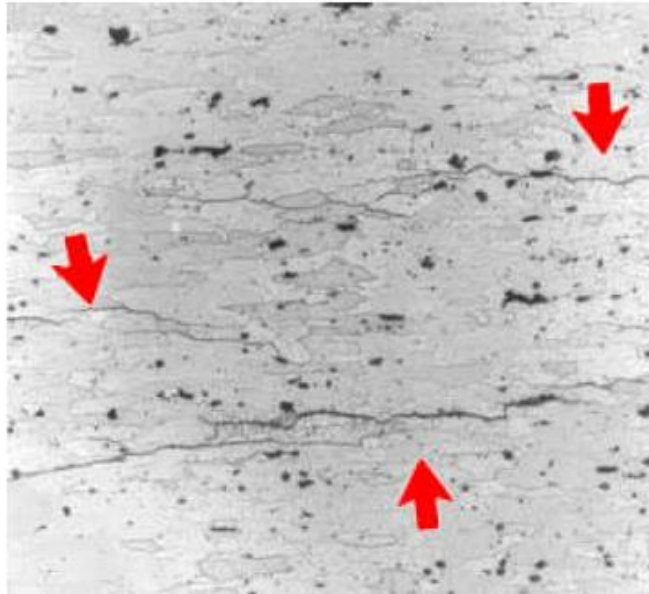


Figure 2.16: Sample of intergranular corrosion (Intergranular corrosion 2021)

### 2.3.6 Erosion or Abrasion Corrosion

Erosion or abrasion corrosion results when the material surface is exposed to mechanical wear due to the movement between corrosive fluid and an immersed metallic material leading to metallically clean surfaces (Cicek, 2017). Erosion or abrasion corrosion (2021) explained that erosion is a relative motion of acceleration in the rate of corrosion attack in metal. High turbulence flow and faulty workmanship can cause increase of erosion rates. Pedferri (2018) defined that erosion-corrosion consists of loss of material progressive from solid surface due to a mechanical interaction and corrosion between the surface and a single or multiple phase fluid. It includes a turbulent fluid, liquid and solid particles impingement corrosion and corrosion cavitation. Increase in corrosion results from increased intensity fluid turbulence and mass transfer because of the fluid over a surface flow, without mechanical interaction.

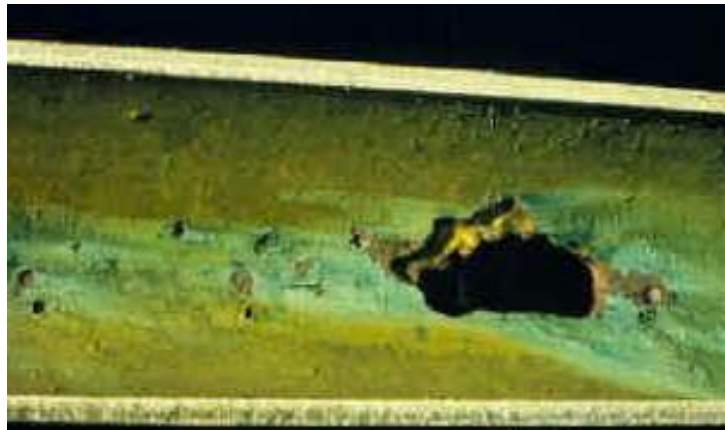


Figure 2.17: Sample of erosion or abrasion corrosion (Erosion or abrasion corrosion 2021)

### 2.3.7 Stress Corrosion Cracking

Stress corrosion cracking (SCC) is the simultaneous effect of corrosion and static tensile strength that develop to a crack formation into the materials. The tensile stress originated from different load and stresses from cold working, heat treatment or welding. Crack propagates intergranularly or transgranularly, generally formed in normal planes to the tensile stress (Cicek, 2017). Stress corrosion cracking (2021) stated that dry cracking and fatigue threshold are the impact of SCC on a material. The stresses from tensile stress may form as residual stresses or direct stresses applied to it. Processing of materials brings residual stresses. Mostly, the importance and magnitude is often disregarded and the result is damaging.

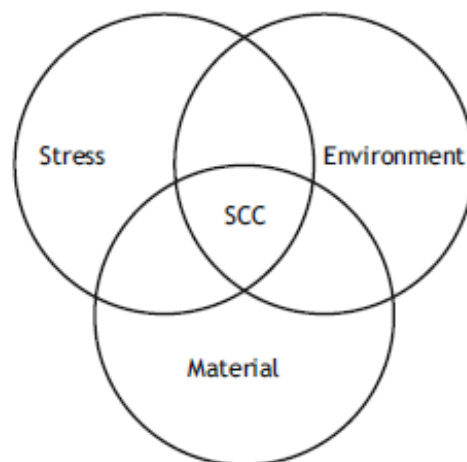


Figure 2.18: Stress corrosion cracking condition representation by means of Venn diagram (Pedefferri 2018)



Figure 2.19: Example of SCC related failure of a carbon steel (Pedefferri 2018)



Figure 2.20: Intergranular SCC on grain boundaries (Stress corrosion cracking 2021)

Stress corrosion cracking results into the formation of cracks with specific combinations of metal-environment-tensile stress as shown on figure 2.18 Venn diagram. They often appear without plastic deformation and could be mistaken as brittle material fracture instead as metal suffering from SCC is normally ductile. SCC do not show visible corrosion products and cracks form in



perpendicular direction to maximum tensile stress. The morphology of cracks depend on stress distribution, environment and metal, are mainly intergranular or transgranular, and are less or more branched as shown on figure SCC1 (Pedefferri 2018).

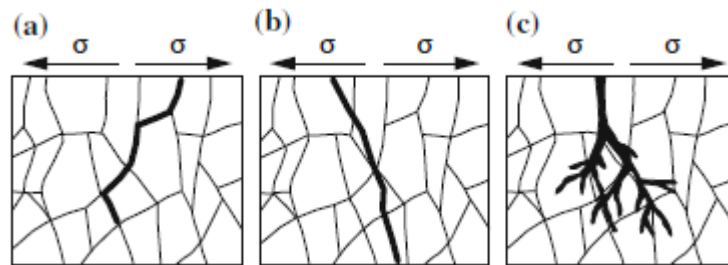


Figure 2.21: Stress corrosion cracking propagation appearance: a) intergranular, b) transgranular, c) delta river transgranular (Pedefferri 2018)

### 2.3.8 Atmospheric Corrosion

Atmospheric corrosion in general is hygroscopic and attracts moisture from air due to solid and dust precipitation. The acidic environment accumulated on the metal surface due to solid precipitates originated from air. An aqueous film of a certain thickness is needed on the metal surface to initiate atmospheric corrosion. However, around  $150\ \mu\text{m}$  is the accepted thickness of the aqueous layer that causes the most corrosion on the metal surface and the surface should be exposed on dry and wet cycles. High relative humidity values such as 80% may accelerate corrosion due to sulfur dioxide to bind the metal surface and aqueous layer containing carbon dioxide and chlorides. Atmospheric condition and geographical directions are important because, as an example, compact structures on east and south sides are less vulnerable to corrosion than north and west sides due to faster drying of the sun (Cicek 2014).

High salt content of the air increases altitude, resulting in a more corrosive environment. In a marine environment, winds from the sea carry chloride ions accumulated on metal surfaces from air that is between  $5$  to  $500\ \text{mg}/\text{m}^2/\text{day}$  and it may exceed to  $1500\ \text{mg}/\text{m}^2/\text{day}$  offshore. Salt can be the origin of carbon particles and high conductivity, which can lead to a large number of small galvanic elements acting as efficient cathodes. Temperature is a source of factors that increase atmospheric corrosion which makes the aqueous layer on the metal surface dry with the highest chance of severe corrosion. When the metal is exposed to air and then it decreases in time, the atmospheric corrosion rate is higher and they influence the formation and protective ability of the corrosion product formed. The corrosion product composition in the aqueous layer depends on participating dissolved metal ions and anions (Cicek 2014).



Figure 2.22: An LPG line suffered atmospheric corrosion (American Petroleum Institute 2011)

## 2.4 Corrosion Under Insulation (CUI)

Corrosion under insulation is an external surface corrosion underneath the insulation layer and is the main failure mechanism for insulated pipe infrastructure. Based on the study by leading oil and gas and chemical industries, CUI is the main cause of leaks and add up to about 10-40% of total maintenance cost. The consequence of this damage mechanism is catastrophic which leads to plant shutdown and environmental impact (Bailey, Long & Hunze 2017). This is particularly challenging because the tendency of water from the environment of when and where they penetrate the insulation cannot be predicted, which cause the underlying steel surfaces to corrode. Undetected CUI may lead to unplanned process shutdowns, and high losses due to damage and operational downtime (Thomas & Hellevang 2020). The root cause is the differential temperature between the insulation interface and the pipe in which the insulation is applied. Basically, condensation occurs when the temperature is below dew point during interface. As the air is cooling down, layer moisture remains trapped, and over a period of time, metal surface can corrode (De Vogelaere 2009). The insulation over pipes where moisture collects and comes in contact with the pipe due to crevices and spaces is where corrosion is expected to occur. Operating insulated systems to monitor degradation is difficult in harsh marine environment, and an increase in corrosion failure is expected if the pipes are not being inspected and maintained on time (Caines, Khan, Shirokoff & Qiu 2015).

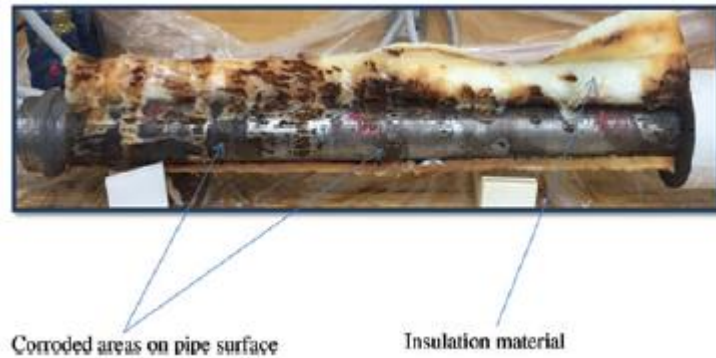


Figure 2.23: Corrosion under insulation uncoated insulated steel pipe (Eltai, Musharavati & Mahdi 2019)

### 2.4.1 CUI Mechanism

Corrosion under insulation is a basic corrosion cell for electrochemical in which the electrically charged ions get transferred by using the insulation's pore fluid between anode and cathode. It requires the same components – anode and cathode should be connected in such a way that basic electrolytic cell allows to flow. There is an oxidation that happens at the anode and reduction at the cathode during electrochemical process as shown on figure 2.24 (Mohsin, Mokhtar & Tse 2019).

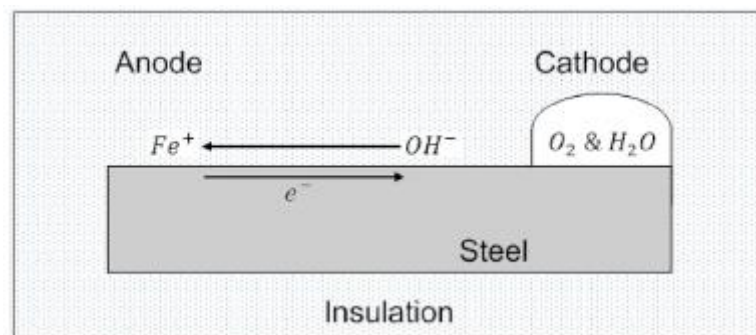
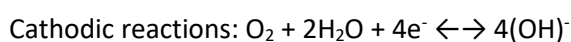
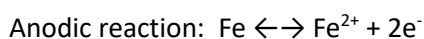
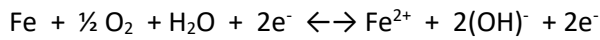


Figure 2.24: Insulated carbon steel CUI mechanism corrosion cell (Mohsin, Mokhtar & Tse 2019)

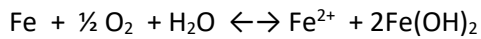
The equation below shows that anode, base metal corrodes while metallic iron (Fe) oxidizes from the steel and with the release of electrons, ferrous ions are produced:



The pore water behaves like an electrolyte accumulated in insulations by rain or moisture condensed from the air. Basically, they convert metallic iron (Fe) into hydroxides, i.e., rust when reaction is taking place as anode and cathode combines as shown on below equation:



Simplifying



They form soluble ferrous hydroxide (Fe(OH)<sub>2</sub>) from the combination of hydroxyl ions ((OH)<sup>-</sup>) and cation (Fe<sup>2+</sup>) with rust white colour appearance, then later on becomes more oxidized and form a reddish brown appearance corrosion (Mohsin, Mokhtar & Tse 2019).

The electrochemical reaction shows on figure 2.25 real applications where water or moisture will either be trapped or absorbed by the thermal insulation when it penetrates. Evaporation will occur when water makes contact with the hot metal surface where condensation takes place, in which the water vapour drives through the insulation towards the cold external barrier. Contaminants can be concentrated during this process as well due to the cyclic or reflux nature during condensation/evaporation cycle and coating degradation if present. The electrochemical corrosion initiates if there is sufficient damage to the coating. The effectiveness/thermal properties of damaged insulation is reduced due to the condensation/evaporation cycle (Winnik 2015).

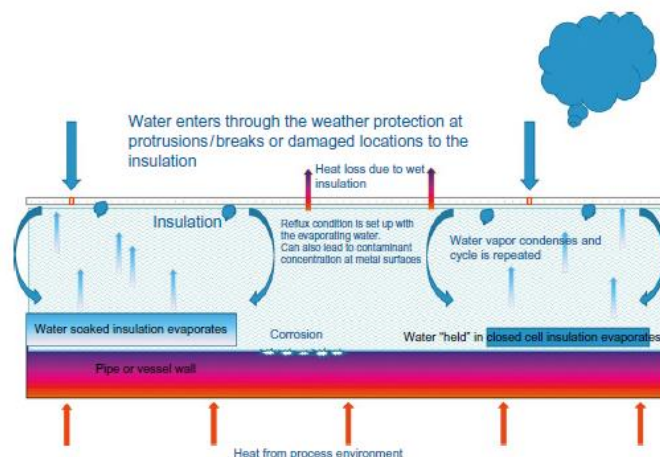


Figure 2.25: Real application of CUI in action (Winnik 2015)

The rate of CUI is dependent on the heat transfer properties of the metal surface and surface wet/dry conditions, contaminants in water, temperature and availability of oxygen. The properties of insulation materials that influence the damage can be localized or general. Service

temperature is an important property to determine the effect on corrosion rate of insulated carbon manganese steel because oxygenated water evaporation is limitedly introduced on the concept of a closed system. The higher temperature resulting in increased corrosion rates are often greater than anticipated as shown on figure 2.26 (Winnik 2015).

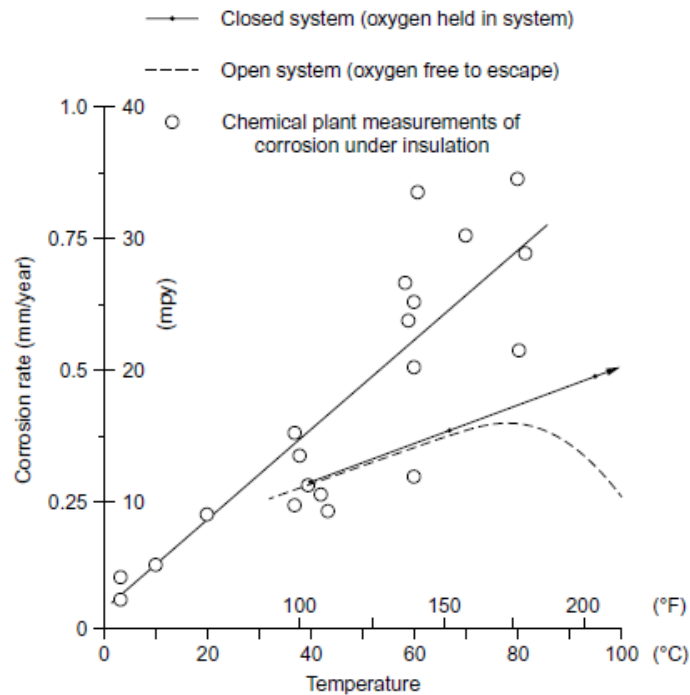


Figure 2.26: Temperature as a function corrosion rate of CUI (Winnik 2015)

## 2.4.2 Factors Contributing to CUI

### 2.4.2.1 Air Pollutants

Air pollutants, such as sulfur dioxide ( $\text{SO}_2$ ), with the combination of atmospheric moisture producing acid rain from converted sulfuric and sulphurous acid contribute to corrosion rates under insulation materials. The principal source of contaminants to the air is industrial activity such as burning fossil fuel from power generation plants which produce acidic compounds. Coal power plants are a source of chloride emissions to the atmosphere. The combustion of these coals that produce hydrogen chloride accelerates corrosion when they combine with water to create an acidic solution then propagate under an insulation system. Hydrogen sulphide or chloride salt ions are less likely to have corrosive effect than hydrogen chloride and gaseous chlorine (Lamsaki 2007).

## 2.4.2.2 Marine Environment

Most oil and gas and refining industries are located near sea water. Marine environment is very aggressive in nature, because sea water and air contain chloride ions and contaminants that are highly soluble in water. The corrosion rate is accelerated when they are deposited on the metal surface, which can produce higher electrical conductivity of the electrolyte. Figure 2.27 shows the comparison of three different corrosive environments relative to rate of metal loss. The CUI's most common type of chloride salt is sodium chloride that is responsible for the sea water salinity. On failed insulation system, the rate of deterioration of steel equipment is influenced when the metal surface is reached by a certain amount of salt particles. They are normally carried by wind and rain over insulation systems where salt particles' hygroscopic characteristic permits the formation of a liquid film and the absorption of water vapour on the metal surface. When moisture, water and the dissolved salts diffuse into the insulation hardware with enough hot temperature, the salts will stay on the metal surface and water will evaporate, which leads to accelerating the corrosion rate (Lamsaki 2007).

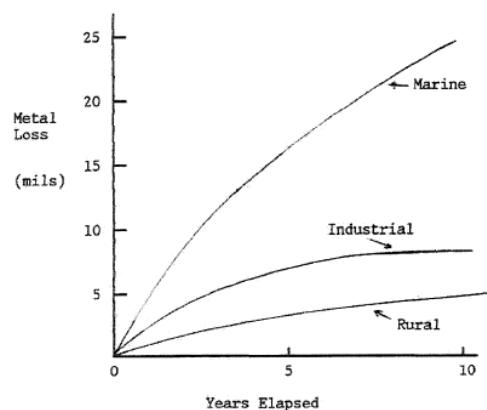


Figure 2.27: Three different environments with relative rate of metal loss (Lamsaki 2007)

## 2.4.2.3 Environmental Conditions

API 571 (2011) identified that insulated system located in areas with high rainfall or warmer, marine locations are more prone to CUI. Corrosion can accelerate on environments with presence of airborne contaminants such as chlorides or sulfur oxide that may leach out of the insulation. The insulation systems to be used are important factors that need to be considered as atmospheric condition is part of natural impact for the corrosion to occur. In areas without air

pollution, the initiation of atmospheric corrosion can happen on 80% relative humidity. However, in polluted environment, corrosion will start on iron at 50% humidity. The presence of sulphate and chloride ions in marine environment is extremely corrosive adding with high level of humidity (Lamsaki 2007).

#### 2.4.2.4 pH Effect

The pH effect of water can cause unanticipated failures of process systems and severe CUI may occur that can result into general and pitting corrosion due to acidic solutions. The atmospheric water of polluted industrial areas can reach levels of pH as low as 3.0 as compared with clean rain water pH level near 5.6. They found that pH of fog moisture to be as low as 2.2 within high degree of air pollution and fog droplets is highly acidic, which become a severe problem and magnify corrosion rates if it diffuses into the insulation. Figure 2.28 shows that when pH falls below 6, the corrosion rate increases considerably, which can be up to 20 times greater than the corrosion of bare metals exposed to atmospheric conditions in wet insulations. The sealants and caulking compounds when wet with water leachable components can produce acidic solution resulting in having pH levels in the range of 1.7 to 10 depending on the type of material insulation.

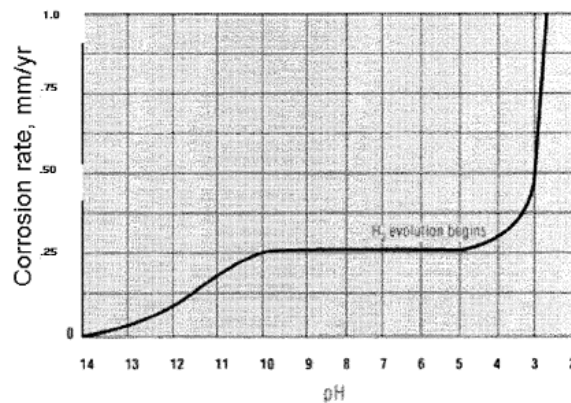


Figure 2.28: The effect of pH at room temperature on corrosion of iron in aerated water (Lamsaki 2007)

#### 2.4.2.5 Service Temperature

API 571 (2011) stated that intermittent service of externally insulated equipment are prone to CUI at temperatures between 10 °F (-12 °C) and 350 °F (175 °C) for carbon and low alloy steels, while it is at 140 °F (60 °C) and 400 °F (205 °C) for austenitic stainless steels and duplex stainless steels. The metal temperatures between boiling point 212 °F (100 °C) and 350 °F (121 °C) likely

become severely corroded for insulated components because water is likely to vaporise and insulation stays wet longer. Increasing metal temperature where water quickly evaporates causes corrosion rates to increase.

## 2.4.2.6 Insulation Materials

Insulation materials play an important role to prevent CUI. It is suggested that water absorbent insulation materials promote CUI than water-repellent insulation materials ([Eltai, Musharavati & Mahdi 2019](#)). Lamsaki (2007) suggests that correct selection of the insulation material can reduce corrosion. Insufficient material specification and applications of insulation may not be economical on a life cycle basis of inexpensive materials. The insulation system that dries most rapidly represents good protection against the corrosion process. Experience has confirmed that sealants and adhesives with chloride and sulphate use for insulation may contribute to corrosion.

### 2.4.2.6.1 Calcium Silicate

Calcium silicate non-asbestos insulation features low thermal conductivity, light weight and high chemical and temperature resistance. They are rigid with high density materials used, ranging from 250° F to 1000° F (121° C to 540° C) high temperature applications. The block and pipe calcium silicate high temperature insulation is manufactured to provide accurate industry standard dimensional tolerances and superior flexural and compressive strength using an industry preferred filter press method. It provides exceptional resistance to mechanical abuse, and attributes that facilitate installation. It complies with ASTM C533, Type I and is asbestos free. They use calcium silicate insulation in piping and equipment at indoor temperatures from ambient to 250° F (121° C) and protected outdoors up to 1200° F (649° C). This is ideal for energy conservation, personal protection, process control and fire protection industries as shown on figure 2.29, the relation between temperature and thermal conductivity (Bahadori 2014).



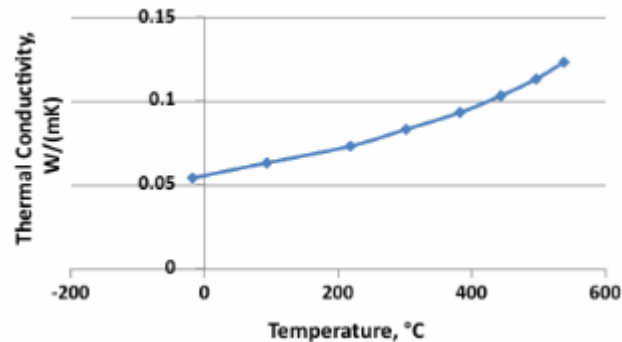


Figure 2.29: Block and pipe thermal insulation relationship between thermal conductivity and temperature (Bahadori 2014)

### 2.4.2.6.2 Expanded Perlite

Expanded perlite is consumed by construction industry for its acoustic insulation, lightness and thermal properties. The perlite expands by heating to 760-1100 °C at which the material expands to 4-20 times its original volume and indigenous water is converted to vapour where they form high-porosity and lightweight aggregates. It has a bulk density of 60-80 kg/m<sup>3</sup> and 712.1-816.4% water absorption making expanded perlites have low thermal conductivity relatively due to low density and fluffy structure. The chemical properties of expanded perlite are mainly composed of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>, which are relatively stable, and at a temperature of 4 °C the thermal conductivity of water is 0.58 W/mK. This means that after absorbing water, its thermal conductivity would have a large degree of growth (Wang, Li, Jing & Liu 2018).

Perlite can be processed into an expanded form of naturally occurring hydrated volcanic glass with a rhyolitic composition for cellular structure formation. They do not react with or leach into ground water which means that it is environmentally friendly and are therefore good composites in general for core material sandwich (Shastri & Kim 2014). Perlite's unique properties have found wide acceptance in low-temperature storage cryogenic for liquefied natural gas insulation applications, cold boxes air separation units, shipping containers, test chambers and food processing. The following are the advantages of perlite:

- Perlite insulation has excellent thermal properties and low thermal conductivity.
- Un-expensive and easy to install and handle.
- Complies with fire regulation requirements, non-combustible.
- They do not swell, shrink, warp or slump.

- It is a vermin and rot resistant inorganic material.
- The material does not retain moisture on closed cell structure (Bahadori 2014).

### 2.4.2.6.3 Glass and Mineral Fibres

Fibres are insulation materials with high resistance to thermal shock which allows rapid firing to save energy and have a number of advantages over the other insulation materials including low cost, ease of installation, flexibility and low thermal mass. However, these are not suitable with very high gas velocities or contact with certain molten metal or glasses application environment. They are usually manufactured and supplied as glass fibres in different forms such as needled blanket or blocks, bulk, vacuum-formed panels and encapsulated fibres. Glass fibre insulation is manufactured using non-continuous methods such as melt blowing, melt spinning or extrusion/spun sol-gel, which have very high throughput and low cost in melt spinning. The melt spinning method occurs in the form of spherical glass particles un-fiberized material which are normally on various sizes called shot particles. The bulk density of glass fibre insulation is usually in the range of 60-350 kg m<sup>-3</sup> that can affect the measurement of thermal conductivity (Modarresifar, Bingham, & Jubb 2016). Lamsaki (2007) stated that fibre glass insulation has a poor compressive strength property, a range 0.22 to 0.26 W/m x °C thermal conduction (k) and a range 3.8 to 4.5 m x °C / W thermal resistance (R) value. The manufacturing process is an important factor to determine the highest temperature at which it can be used but the recommended service temperatures range is from 1.5 °C to 422 °C. There is a capacity that fibrous insulations absorb water and moisture due to their porous structure.

### 2.4.2.6.4 Cellular Glass/Foam Glass

Foam glass thermal insulation is composed of millions of completely sealed glass cells with lightweight and rigid insulating material on each insulating space. This provides an unmatched, all glass, closed cell structure combination of physical properties ideal for industrial equipment above ground, underground, indoors or outdoors at -450 °F to 900 °F (-268 °C to 482 °C) operating temperature. Their advantages include the following:

- Water resistant in both vapour and liquid forms
- Noncorrosive
- Non-combustible/non-absorbent of combustible liquids
- Proof against most industrial reagents

- During a variety of temperature and humidity conditions they are dimensionally stable.
- Higher level of compressive strength (Bahadori 2014)

#### 2.4.2.6.5 Polyurethane and Polyisocyanurate

Polyurethane and polyisocyanurate intended for service temperature between – 100 and 140 °C are used as thermal insulation for pipe work and equipment. The actual temperature limits for specific application may be required in conjunction with the insulant where the service temperatures are to be below ambient with generally suitable vapour-retardant material. To produce preformed rigid cellular polyurethane thermal insulation, it needs chemical reaction of polyisocyanates with polyhydroxyl compounds with the presence of cell stabilizers, catalysts and blowing agents, while the preformed rigid cellular polyisocyanurate thermal insulation is usually in the presence of polyhydroxyl compounds produced by the polymerisation of polymeric polyisocyanates with the addition of catalysts, blowing agents and cell stabilizers (Bahadori 2014).

Polyurethane insulation materials have poor fire resistance characteristics but excellent value of thermal conductivity that ranges from 0.020 W/m °C to 0.042 W/m °C. Polyisocyanurate insulation still does not meet the fire hazard classification even though they improve the fire resistance properties. Polyurethane insulation recommended service temperatures ranges from -73 °C to 82 °C and for polyisocyanurate it is -73 °C to 149 °C with a compressive resistance value of 17 kPa at 5% of deformation. Both contain substances such as fluorides, chlorides and sodium ions when wet. It can produce a low pH solution when it leaches out to the insulation and can accelerate the corrosion process of metal surface (Lamsaki 2007).

#### 2.4.2.6.6 Elastomeric Foams

Elastomeric products use a chemical blowing agent that is commonly based on a blend of nitrile butadiene rubber (NBR) and polyvinylchloride (PVC). They produce primarily nitrogen gas when crosslinked or vulcanized, and the chemical blowing agent decomposes on the heating process. This product was introduced to the market in the 1930's. Sheet materials are similar with what are being used today. Most elastomeric products are based on a PVC/NBR rubber polymeric blend while another is halogen containing ingredients that enhance the flammability characteristics of the product. There are some new classes of introduced materials that eliminate the potential problems associated with halogen, wherein the product burned can produce corrosive smoke,

but this does not meet the requirements of 50 rating on the smoke developed index standard thickness of American Society for Testing and Materials (ASTM) E-84 (Schmidt 1999).

Elastomeric typical service temperature ranges between -70 °F (-57 °C) to 220 °F (105 °C). They offer excellent flexibility, low water vapour transmission (0.1 perm in. or less) and similar thermal conductivity (k) insulation materials (0.30 BTU-in./hr.-sq. ft or 75 °F less mean temperature). They have good oil and ozone resistance and excellent adhesive/coating receptiveness generally derived from this polymeric blend. To enhance the product's physical properties there are some additives applied such as fillers, aging, plasticizers and flame inhibitors to possess similar physical properties to other insulation products. Elastomeric insulation products have few restrictions that prohibit the use of this product but can use on plumbing, burial applications, hot water heating system and duct insulation (Schmidt 1999).

#### 2.4.2.6.7 Aerogels

Aerogels can be used as thermal insulation with their low density ranging from 0.01-0.3 g/cm<sup>3</sup>, high surface area (100-2000 m<sup>2</sup>/g) and low thermal conductivity (<0.02 W/mK). Thermal conductivity can reach as low as 0.012 W/mK due to a few nanometres diameter porosity and small pores affecting the diffusive and convective gas transport and the conduction heat with the solid materials. It is challenging to use aerogels as an insulation material since it complicates the handling due to the brittleness of aerogels and the release of dust is furthermore not desired. The use of granular aerogels is more practical instead of monolithic ones which can be fixed in a more stable matrix (Laskowski, Milow & Ratke 2016). There are several types of aerogel material in terms of the input precursors such as metal oxides, silica and polymers. Silica aerogels are particularly attractive due to the emerging applications of their performance in mechanical strengthening, thermal insulation and noise proofing. The most powerful component of the aerogel based on their properties is thermal insulation which can be used in building materials and protective clothes (Wang, Petit & Ren 2020).

#### 2.4.2.7 Mechanical Design of Equipment and Insulation Installation

In general, the geometry of equipment and related attachments such as brackets, support rings, pressure and temperature gauges devices has an important effect on CUI. During the design, limiting the amount of attachments, protrusions and supports associated with the equipment can be considerably helpful to extend the life of the insulation system. The water can bypass the

insulation when sealants and caulking compounds fail overtime to seal protrusion. In addition, a poorly installed insulation system promotes corrosion of the underlying steel surface. A common installation error has an important influence on the insulations system performance. For example, the lap section of weather barriers should be installed to the sides on horizontal sections, thereby decreasing the water ingress (Lamsaki 2007).

#### 2.4.2.8 Mechanical Damage

Insulation systems suffer mechanical damage from personnel walking over insulated piping system or during routine maintenance climbing over the vessel. The result of this easy entrance of water into the system is that corrosion can start and unexpected failures could happen. This issue often results in production loss, unplanned shutdown and unscheduled replacement or repair of equipment (Lamsaki 2007).

### 2.5 Thermal Insulation System

Hart & Yarbrough (2010) stated that thermal insulation systems play an important purpose on piping and equipment in industrial facilities. They have several functions such as reduction in energy loss, process control, protection to personnel, emissions reduction, condensation, freeze protection and reduction of noise. In oil and gas and chemical process industries, they are often subjected to harsh environment that may include fluctuation of services temperatures, weather exposure, physical abuse, corrosive chemical exposure and accident scenario. The purpose of insulating pipes and equipment varies on different systems and facilities. Based on the experiment, at least 85% heat loss reduces on the first inch and about 95% usually reduces on several inches compared to what it would be from uninsulated surfaces. The following are several goals to achieve the insulation thermal performance:

- To control the temperatures during process, to successfully achieve production and quality goals necessity for the plant.
- To control costs of energy.
- To provide protection to the personnel on the plant from above ambient service temperature systems to retain maximum design value often at 130-140 °F when protected with sheet-metal jacketing.
- To reduce CO<sub>2</sub> greenhouse gas emissions by reducing heat loss significantly compared to uninsulated surfaces.

- To minimise surface condensation of water on below ambient systems from the surrounding ambient air. It can pose a danger to plant personnel on wet walking surfaces located beneath the cold surfaces.
- To prevent either freezing of the liquid in the process pipes or a decrease viscosity of liquid.
- To provide sound control with proper design to absorb emitted noise.
- To provide protection against fire.

The insulation industry has developed to ensure effective energy conservation of insulation materials. The thermal insulation is used for equipment whose working temperature ranges from -75 °C to 815 °C. The mode of installation and proper selection play an important role in energy management of the insulation systems. There are different heat transfer modes: conduction, radiation, convection or a combination of these which can occur during movement of heat (Lamsaki 2007). Thermal insulation materials have different types; both organic such as expanded plastics, wood, wool, cork, straw and technical hemp; and inorganic such as foamed, glass and mineral fibres which differ in shape, flammability, composition and structure. The required thickness of insulation depends on the characteristics of insulating material for any specific application as well as the purpose of the equipment. Reliability is the most important consideration as the deciding factor of heat or power conservation. Insulation is used in different industries to prevent heat loss or heat gain. They have low thermal conductivity and are a poor heat conductor. The main purpose in the market is also to provide more accurate control of process temperatures to prevent condensation on cold surfaces and the resulting corrosion (Bahadori 2014).

## 2.6 CUI Failures in Piping Components

### 2.6.1 Insulated Industrial Piping

Pipelines are used to transport mostly liquids or gases and possess different diameters from point of origin to point of consumption. They are composed of short lines and long trunk lines that may be several kilometres away from the short lines. Most sophisticated pipelines are built to transport hazardous and flammables contents (Menon 2015). The purpose of insulation of the pipelines is to mitigate energy dissipation and for safety manner protection from detrimental impacts of ambience (Cheshideh, Nasirpouri, Mardangahi & Jabbarpour 2021). Insulation on

piping is optimising process efficiency, noise control, fire proofing and protection to personnel (Thomas & Hellevang 2020). The most susceptible areas on piping system to CUI are pipe bends and welds because they are challenging to wrap perfectly. Some standards also include hangers, fittings, platforms, ladders, exposed to mist over spray from cooling towers, exposed form steam vents and spills from products or ingress of acid vapours. Excessive vibration can cause damage to insulation jacketing which could provide a pathway to water ingress (Eltai, Musharavati & Mahdi 2019). Figure 2.30 show the most vulnerable areas where water ingress occurs in a piping system.

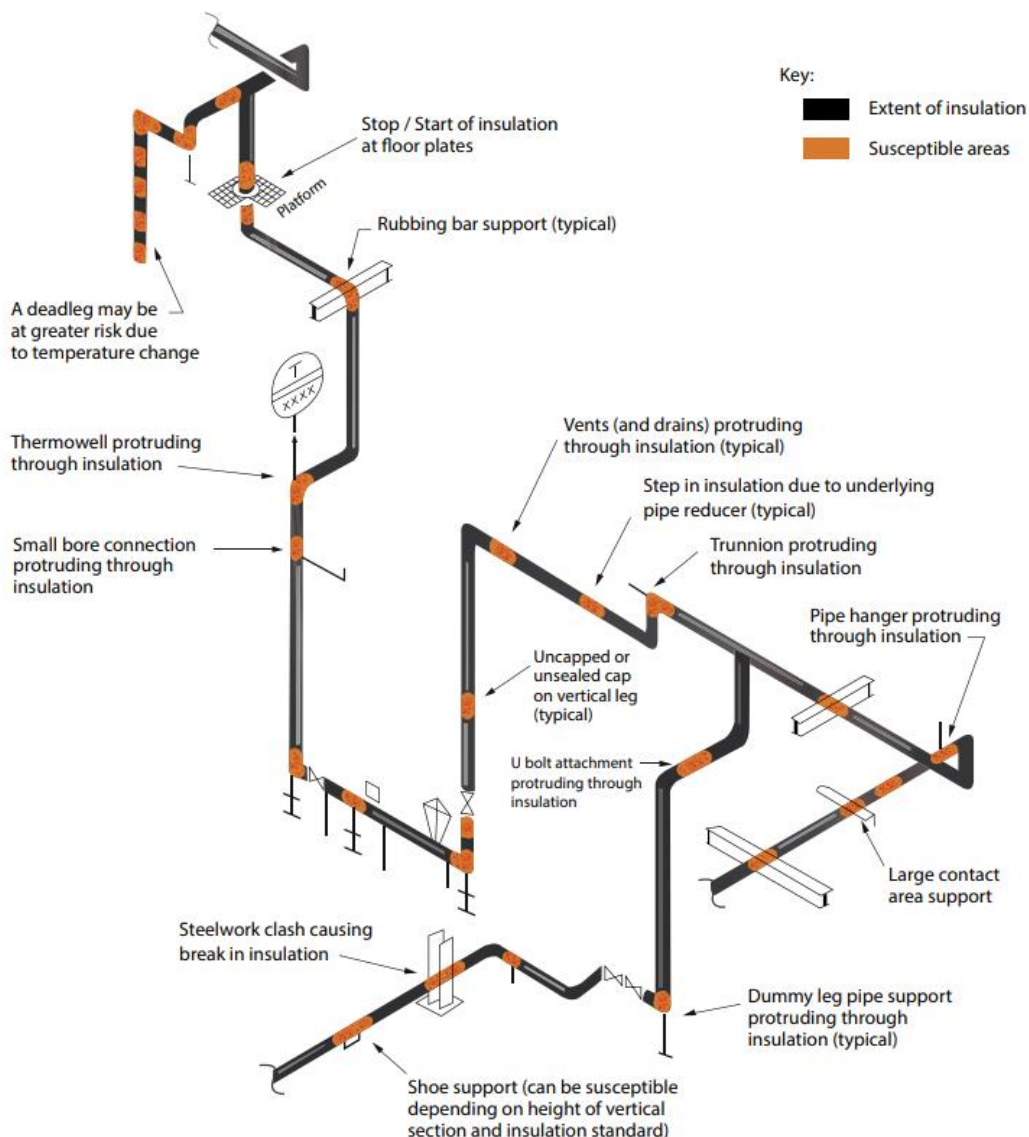


Figure 2.30: Susceptible areas of piping system to water ingress (Swift & Chmielarski 2019)

## 2.6.2 CUI Mechanism on Piping

CUI failures on piping occur when moisture penetrates insulation, which create a corrosion cell that usually form in marine environments, under damage mechanisms such as pitting, uniform corrosion and stress corrosion cracking. It can occur when insulation is poorly installed, has atmospheric wetness, and wicking or damage. Pitting is a common type of localized corrosion to small degradation areas observed on CUI piping, which can lead to catastrophic consequences in marine applications. This type of failure can progress through the wall thickness, which leads to lack of containment of process materials. Pitting is also an initiation site for stress corrosion cracking and brittle fracture, depending on the materials. There are numerous studies to understand the behaviour of pitting on how it affects the life components of the service, but no specific information has been found for pitting under insulation in a marine environment (Caines, Khan & Shirokoff 2013).

During application of insulation over the pipeline, an annular area is formed that act as a crevice, which could be a space for moisture accumulation where CUI typically initiates into insulation then makes direct contact with the pipe afterwards. The result is a localized failure after the reaction of dissolution by creation of a corrosion cell on the pipe surface. One of the failures that occur in this circumstance is crevice corrosion localized attack, which happens inside an existing crevice, as well as conceivable corrosion agents that contribute to attack mechanism, which will leave the piping in terrible circumstance. Crevice corrosion is frequently narrowed, which happens inside the occluded areas of metal/metal groves and metal/non-metal groves for description of the damage in passive metals. Because it takes place by oxygen concentration, cell is more widely occurring on non-passive metals failure. The metal then starts to dissolve severely on crevice environment under several processes, such as prevailing disunion of cathodic and anodic places that resulted from hydrolysis of metallic ions due to decrease of pH levels inside the groove, entry of chlorine anions from the bulk from the enhancement in amount of chloride within the groove and crevice has limited access from constraints on mass diffusion. Oxygen has a substantial contribution on the initiation of crevice corrosion inside the crevice with a potential difference between the bulk metal and occluded regions, which are exposed to enough oxygen. CUI can cause crevice corrosion from oxygen and water and must be mitigated to inhibit catastrophic failure (Cheshideh, Nasirpouri, Mardangahi & Jabbarpour 2021).



### 2.6.3 CUI Failure in Stainless Steel Piping

The piping metals and alloys mostly affected by CUI are carbon steel, austenitic stainless and aluminium. Stress corrosion cracking is the main damage mechanism of 316 and 304 stainless steel, which can easily penetrate through the insulation if chloride ions were present. It can easily severely damage austenitic stainless steel. However, austenitic stainless steel is an excellent anti-corrosion, with desirable mechanical properties and resistance to heat. It is used in chemical, petrochemical, nuclear and other industries (Eltai, Musharavati & Mahdi 2019). A failure of insulated stainless-steel pipeline was caused by chloride stress corrosion cracking. The thermal insulator was found to be the glass wool, which was the source of chlorine that facilitated condensation of chloride ions. Improper choice of insulated materials resulted to chloride induced stress corrosion cracking (Kumar, Sujata, Venkataswamy & Bhaumik 2008). A failure of AISI 304L stainless insulation used to carry hydrocarbon gas is revealed after removal of section of lagging insulation. There is a three-stage mechanism attack that occurs. Both transgranular cracking and intergranular cracking originated from both the external and internal surfaces. Stress corrosion cracking from the internal surface resulted in CUI, where the process of attack occurred, then initiated stress corrosion cracking to the external surface attacked. The combination of water carry-over and corrosive species presence had added to a complex process of corrosion mechanisms that attribute to CUI (Roffey & Davies 2014). Figure 2.32 show failure of CUI resulting from stress corrosion cracking on pipeline supplying hydrogen and figure 2.32 show cracking on instrument tubing under insulation which API (2011) stated is a result of CUI.

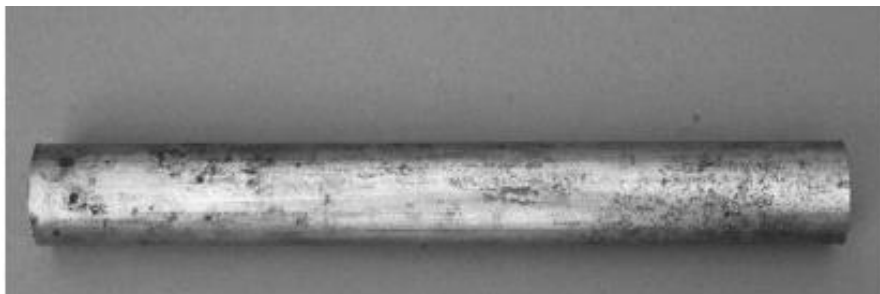


Figure 2.31: Insulated type 321 stainless steel failed region (Kumar, Sujata, Venkataswamy & Bhaumik 2008)



Figure 2.32: Type 304 stainless steel cracking under insulation (American Petroleum Institute 2011)

## 2.6.4 CUI Failure in Carbon Steel Piping

Carbon steel insulated piping systems that operate below 120 °C increase the risk of CUI significantly. Operating above 120 °C will experience intermittent service as is being susceptible to CUI. The direct contact of water ingress and salts in the rainwater yield a concentrated localized pitting on piping. The prolonged downtime at ambient temperature accelerated corrosion during high temperature and was a significant factor for the process of damage mechanism (Ifezue, Tobins & Nettikaden 2014). Localised corrosion from CUI can be severe if undetected or uncontrolled, which results to pipe perforation, or expensive repair. Major factors influencing the rate of CUI in carbon steel piping are waster, contamination, and temperature. Typically, carbon steel is covered by a coating; however, the coating tends to disintegrate once moisture ingress through the insulation and the coated metallic surface reaches steel substrate, thus exposed to corrosive moisture. The low moisture content may lead to localised corrosion driven by more local discontinuity due to distribution of water within the insulation by differential aeration (Cao, Esmaily, Liu, Birbilis and Thomas 2020). Figure 2.33 shows the leak caused by CUI on straight pipe and figure 2.34 shows the pipe support which suffered from CUI. API (2011) demonstrates that the tee section of the piping shown on figure 2.35 suffered from CUI but was not obvious. However, when the insulation was removed as shown on figure 2.36, the CUI was exposed.



Figure 2.33: CUI of carbon steel pipe (Winnik 2015)



Figure 2.34: CUI of carbon steel pipe support (Winnik 2015)



Figure 2.35: Tee section insulated carbon steel piping before removal of insulation (American Petroleum Institute 2011)



Figure 2.36: CUI of Tee section insulated carbon steel piping after removal of insulation  
(American Petroleum Institute 2011)

## Chapter 3

### Failure analysis

#### 3.1 Chapter Overview

This chapter consists of the methodology to identify the failure analysis of corrosion under insulation of piping components. A risk management has been carried out to ensure that this project is aligned with health and safety procedures even though this will focus only on extensive research of literature review to meet the requirements of the objectives of this project. On appendix D a risk assessment was prepared to address the health and safety concerns for this project.

The failure analysis of this chapter is based on the available literature review of the resources found for CUI of piping components. There is a step-by-step methodology available to carry out for this analysis which is discussed on this chapter. Typical CUI failure analysis investigation involves a similar procedure as other failures. However, corrosion related failure needs protection and immediate preservation of all evidence to achieve a meaningful result. CUI failures often directed to environment and material selection details are all useful information resources in resolving corrosion failures (Hossain & Ulcickas 2021).

#### 3.2 Failure Analysis of CUI of Piping Components

A failure analysis of CUI of piping components is a critical process which uses a variety of techniques, such as observation, inspection, and laboratory techniques to determine the physical root causes of the problems of deterioration. Different literatures helped provide knowledge to integrate the analysis of the evidence for better understanding of the stressors and background information of piping components suffered by CUI. Failure analysis is an engineering tool to prevent future failure and enhances product quality through increased accountability and responsibility (Scutti & McBride 2002).

##### 3.2.1 Visual Inspection

Visual inspection is relatively unexpensive, requires no specialized equipment and is easiest to employ (Caines, Khan & Shirokoff 2013). Investigation of failure analysis includes visual observations of features present on corrosion failures to visualise components and

environmental conditions. Observation of the failure analysis is an important step to document the condition of the component and to communicate the findings to others involved on the analysis. Photography is a primary means of recording the conditions and features observed to produce an accurate and meaningful surface failure photograph. The details observed during visual inspection are based on failure surface topography, repeated failure surface features, colour characteristics and reflectivity. Each step of investigation requires careful visual examination and recording of observed features (McSwain 2021).

The aid of hand magnifier or other viewing aid tools suitable for visual inspection can be used to determine the extent of damage, damage zone general appearance and texture, colour, and quantity of surface residues (Davis 2000). Visual inspection using unaided eye can examine large areas rapidly with exceptional depth of focus to detect changes of texture and colours. During inspection, attention should be given on surfaces of failures and paths of corrosion. Any indications of abnormal conditions should be assessed including general design assessment and workmanship. It is also important to include the dimensions of corrosion failures by recording it, either in writing or photographs or by sketches. The observer should be vigilant when performing inspection as carefully as possible because clues to determine the cause of failures may be present but missed (McGarry 2005). Visual inspection requires knowledge of types of materials, forms of corrosion, anticipated and operational/service conditions to consistently grade and evaluate the means of comparison that will provide crucial information for completing and documenting the results of the failure assessment (Akhoondan & Hall 2019). Figure 3.1 shows a sample during visual examination on a stainless steel pipe that revealed corrosion on external surface. Further examination using the aided stereo-binocular microscope revealed severe pitting on most of the pipe external surface (Kumar, Sujata, Venkataswamy & Bhaumik 2008). The important of a systematic approach of visual inspection which is shown on figure 3.2 is to identify the root cause of failures because it is crucial for the failure analysis of components. It would be beneficial to have this methodology first before commencing to other forms of examination.

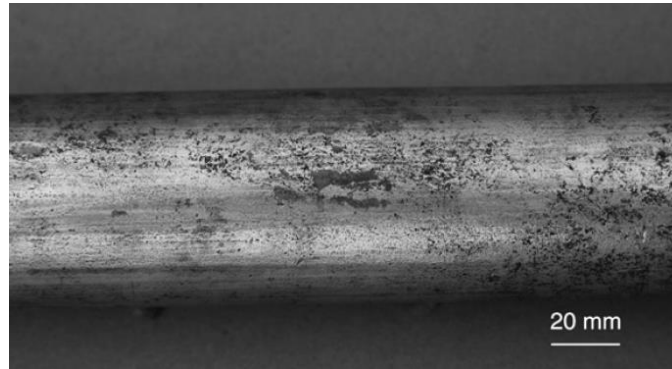


Figure 3.1: External pitting corrosion of failed stainless-steel pipe (Kumar, Sujata, Venkataswamy & Bhaumik 2008)

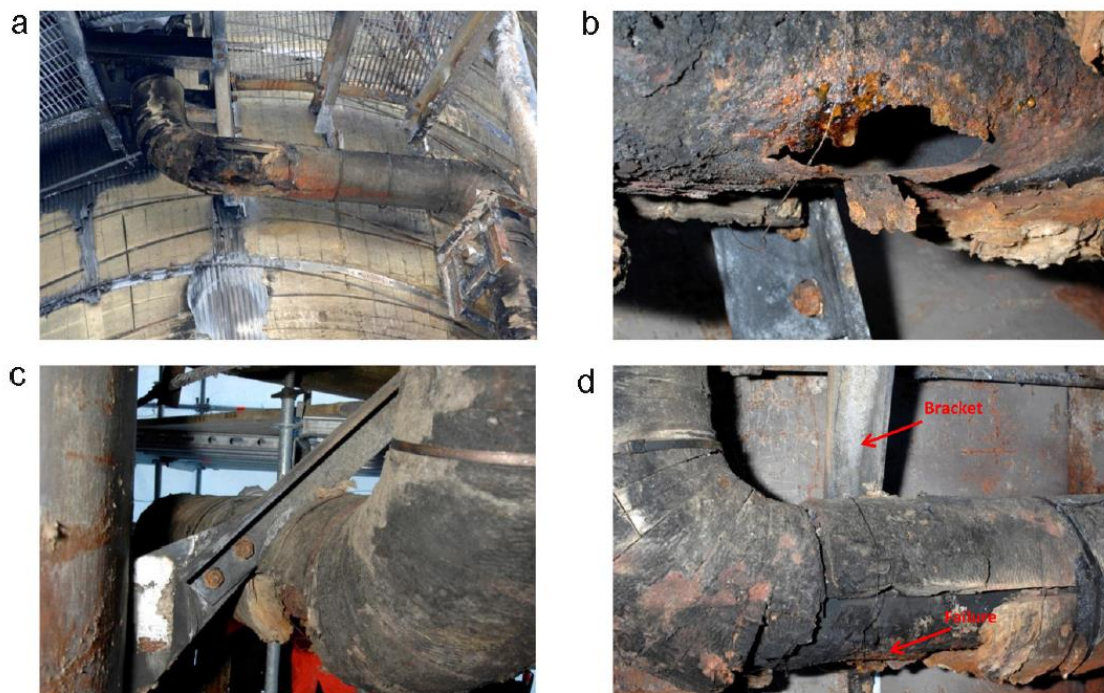


Figure 3.2: (a) Location of CUI failures of process pipework, (b) Pipework fracture detail, (c) Platform support bracket interaction with pipework insulation, (d) Pipework failures and support bracket (Geary 2013)

### 3.2.2 History of Failed Components

Background information is important for failure analysis of CUI to determine the root cause of the problem. Basically, any changes on design parameters and operating environment should be obtained and documented. It is also important that material specifications with engineering drawings need to be obtained and reviewed as part of important documentation (Hossain & Ulcickas 2021). All pertinent details to the failure investigation should be identified by gathering information available regarding the manufacturing, processing, and service histories of the failed

component. The collection of data relating to manufacturing and fabrication history may be grouped into mechanical processing, thermal processing, and chemical processing (Davis 2000).

It is best to obtain and evaluate all available information regarding the circumstances of the failure, failed part history and potential seriousness of the failure when time permits before taking samples and conducting test that might destroy evidence. The engineering drawings and manufacturing and material specification should be examined and act as guide for any part changes that may have been made which might be the cause of failure. Other missing information can be verified from operating and inspection personnel to check the accuracy of any relevant documentary information, such as inspection reports or operations daily log sheets. Sometimes the information obtained may be of questionable accuracy or the information obtained may be impossible to verify (Davis 2000). A complete service record, depending on how detailed and thorough the record keeping was prior to the failure, would simplify information gathering for the failure analyst. When obtaining service histories, it mentioned that special attention should be given to normal and abnormal environmental loading, accidental overloads, cyclic loads, temperature variation and corrosive environment of the operation. The skill and judgement of the analyst is used when working with fragmentary service information when service data are sparse (McGarry 2005).

### 3.2.3 On-site Examination and Sampling

Failure analysis includes on-site examination of the failure area. Photographic documentation should be made to depict the condition after failure. It is also beneficial to look at other similar undamaged operation or assembly area to compare them with the area where the failure occurred. Photographic documentation must capture the true colours of CUI products which include any layering effects in the deposits to guarantee accurate reproduction of surface textures and colour tones of macrographs of corrosion deposit. On-site sampling depends on the type and extent of the components. In most cases removal of corrosion deposits from the surface in field can be performed. However, it may be prudent to carefully retain the corrosion if the sample is undergoing extensive examination for laboratory documentation and removal. Make sure to avoid any contamination if samples are removed on site. Use necessary PPE and kits for sample removal and avoid touching it with bare hands. Physical removal must follow a specific procedure to avoid further damage to the failed component and disturbance of corrosion products (Hossain & Ulcickas 2021). On-site examination is also the same with visual inspection



which entails visually examining the region of failure using hand magnifiers and other suitable viewing equipment available. The possible causative effects on the failure can be determined by examining the immediate adjacent to and near the failure. Colour photographs are particularly useful before samples are removed when coloured corrosion products are present (Davies 2000).

On-site sampling should be guided by the information about the history of failure. The failed area should be sampled and use suitable techniques to obtain the samples. In addition, non-corroded regions from adjacent areas should be obtained to compare it from failed regions. Precaution's consideration is needed for the removal of specimens and sample corrosion product from failed parts to avoid the destruction of evidence that could be of value for investigations and to avoid further damage to the part. Cutting of specimens should be made at a sufficient distance to prevent alteration of the microstructure. Thermal degradation may be present of residues and introduction of contaminants of failure site. The samples should be protected using glass vials and polyethylene film and bags are useful during handling in the laboratory (Davies 2000). McGarry (2005) suggested standard guidelines governing sample collection which include ASTM specifications, E 620, E 678 and especially E 860 and E 1020. All concerned parties should agree about the procedures and the best way to remove the failed samples on-site.

### 3.2.4 Non-Destructive Testing

There are different methods of non-destructive testing that can be performed on the entire sample such as radiography, penetrant inspection, magnetic particle inspection, ultrasonic inspection, eddy current inspection and computed tomography. Depending on the requirements of the failed components some of the common inspection for any surface failure after removing any surface deposits are penetrant inspection and magnetic particle inspection. Radiographic inspection can be used during overall examination to provide information about cracks, pores/voids, pits, sample thickness and other sub-surface defects if surface deposits is present (Hossain & Ulcickas 2021).

#### 3.2.4.1 Magnetic Particle Inspection

Magnetic particle inspection is utilizing magnetic fields in ferromagnetic materials to locate surface and subsurface discontinuities. Basically, the discontinuities lie transverse to the direction of the magnetic field which at and above the surface of the part will cause a leakage field to be formed. This leakage field is detected by means of applied fine ferromagnetic particles over the

surface held and gathered by the leakage field which is called discontinuity. The outline of discontinuity depends on its size, shape and extent. Mostly they use fluorescent material because of higher sensitivity level detecting surface discontinuities, especially cracks. However, ultraviolet light is used to reveal the discontinuities as shown on figure 3.3 in which cracking is present on external surface of pipework. They are not visible to the naked eye (McGarry 2005).

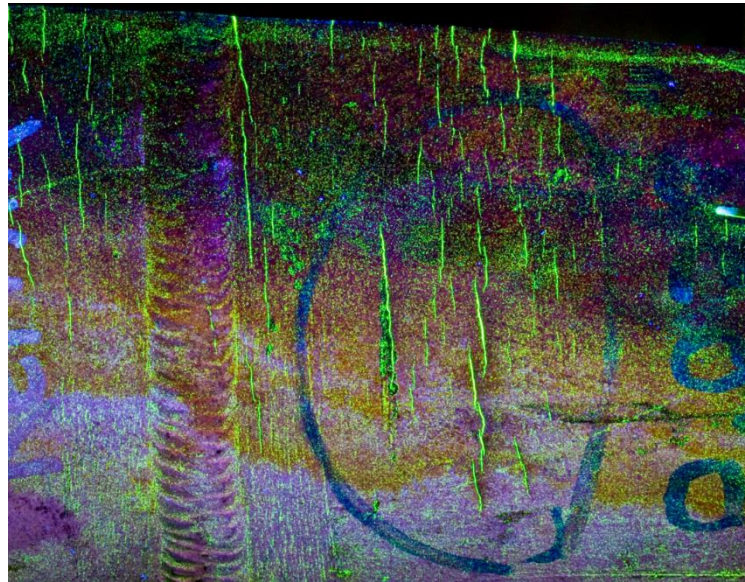


Figure 3.3: Fluorescent magnetic particle inspection showing cracks of pipework (Testlabs 2019)

### 3.2.4.2 Liquid Penetrant Inspection

Liquid penetrant inspection is a technique which involves the spreading of a liquid penetrant to specimen. This liquid will seep into surface discontinuities in the sample because of the ability of wetting characteristics. The excess liquid is wiped after reached the dwell time from the surface and the developer applied to the surface that causes liquid to be withdrawn from surface discontinuities. Depending on what type of liquid, it's usually a very bright colour or contains fluorescent particles. The discontinuities are revealed at the surface of the specimens as shown on figure 3.4 and figure 3.5. Figure 3.4 is a sample visible penetrant inspection using red dye penetrant which can be seen by naked eyes; while the figure 3.5 is a sample of fluorescent dye penetrant which can only be seen using ultraviolet light (McGarry 2005).

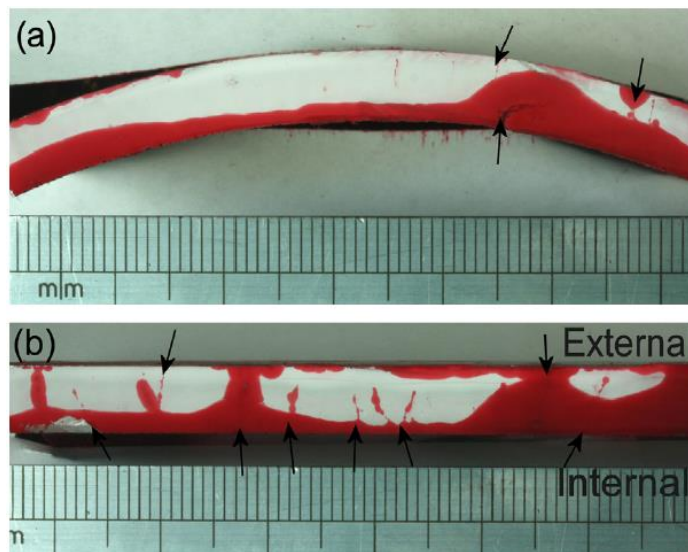


Figure 3.4: (a) Cracking initiated on both internal external at transverse cross-section and (b) Increase in internal initiated cracks at longitudinal cross section (Roffey & Davies 2014)

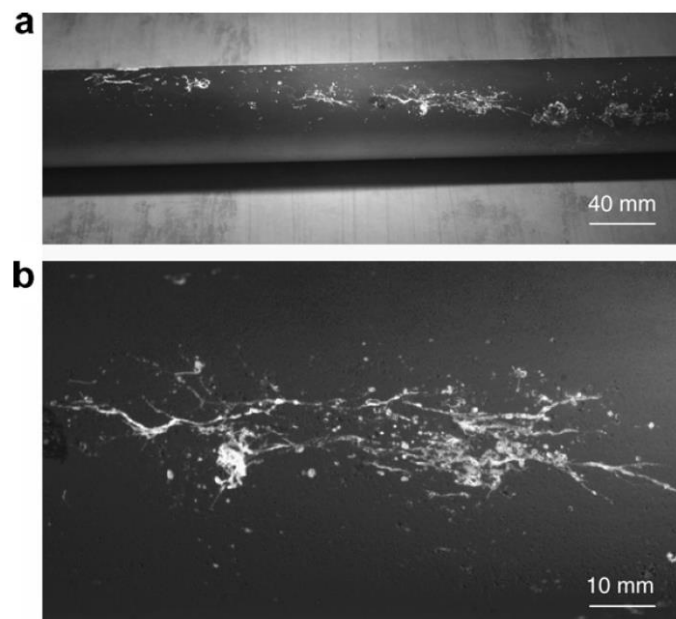


Figure 3.5: (a) Crack's indication of fluorescent liquid under ultraviolet light and (b) close-up view of the failure region (Kumar, Sujata & Bhaumik 2008)

### 3.2.4.3 Ultrasonic Inspection

Ultrasonic inspection's accurate interpretations depend on certain reference standards to isolate the variables. The application of this is limited in failure analysis, however this method is a very

useful tool for investigation of large casting and forging product (McGarry 2005). It is another widely applied set of techniques in which mechanical vibration or waves are used in testing objects. This method is often used to detect internal discontinuities in metals, ceramics and composites. They can also be used to check the material bonding, thickness measurement and extent of corrosion and to determine the properties of materials such as structure, grain size and elastic constants. Ultrasonic techniques refer to sound waves of frequency which is above the limit of 20 kHz human hearing. Most of this method use frequencies between 1 to 10 Mhz which can sometimes be used on either lower or higher from these ranges on special applications (Matzkanin & Yolken 2008). Ultrasonic inspection uses very high frequency sound waves being transmitted through metal and reflected boundary. It can detect small discontinuities using this high frequency sound waves, but the coarse-grained materials easily absorbed during inspection (Lampman, Mulherin & Shipley 2021).

#### 3.2.4.4 Radiography Inspection

Radiography inspection is commonly used for detecting internal defects of components. This is used to captures images via x-rays or gamma rays. The radiation penetrate the object and they are observed based on the defects present in the components. The radiographic image obtained from radiographic film is mainly based on sharpness and contrast (Anouncia & Saravanan 2016). Radiography is based on the differential attenuation of radiation penetration. The part or object is being inspected through transmission by either very short wavelength electromagnetic radiation or particulate radiation. The monitoring of variations in the attenuation of radiation penetration is by detecting un-attenuation radiation that passes through of being tested (Lampman, Mulherin & Shipley 2021)

#### 3.2.5 Chemical Testing

Chemical analysis is used to identify the materials and to compare it on the drawing specification requirements. The quantitative elemental analysis is an analytical technique for metallic components by means of destructive analysis using inductively coupled plasma/atomic or optical spectroscopy. During operation, instrument use atmospheric pressure and radio-frequency electromagnetic field sustained by inductive coupling. The accuracy of the analysis is dependent on this quantitative elemental analysis with a measured value of 0.01 wt% comparing it to a standard solution and used to generate a signal at the analytical wavelength for each element of

argon plasma-excitation source. If these cannot be destructively tested, they use x-ray fluorescence spectroscopy to identify an alloy in a non-destructive way (Hossain & Ulcickas 2021).

There are two useful chemical analysis tools for failure analysis which a failure analyst use such as bulk composition evaluation and microchemical analysis. Bulk composition evaluation is a process which determines whether the subject component has the correct alloy used. There are a few analytical methods today as part of bulk composition verification without knowledge of the intended composition. They use instrumental methods to determine the alloy composition, but it depends on calibration based on alloys similar to the composition. The general idea of any element of the expected amount to the alloys present is rarely linear with respect to the response of the instrument to the composition (Aliya 2002). However, microchemical analysis is used to evaluate the composition on a metallographic specimen microphases composition, evaluate corrosion products and find the evidence of contamination. All chemical analysis methods must not be interpreted as the sole cause of failure because they have their limitations and proper uses (Aliya 2002). Chemical analysis is carried out on surface corrosion products, on deposits and on coating to check the service conditions would indicate any corrosion elements products such as Fe, Cr, Ni, Mo, S, Si, Mn, etc (Elayaperumal & Raja 2015).

### 3.2.6 Mechanical Testing

Mechanical testing is used to provide information about material strength, typically including tensile, charpy impact, microhardness, bend and macrohardness tests. For piping samples, to obtain the modulus of rupture, the ring crush tests are performed if pipe size allows the testing and if not possible, a talbot strip test can be performed (Hossain & Ulcickas 2021). Determination of mechanical behaviour is influenced by their deformation and fracture characteristics. The applied tensile, compressive or multiaxial stresses is influenced by several factors that include material/metallurgical variables, temperature, test methods and nature of stresses applied. Mechanical testing is used in failure analysis as an evaluative tool to collect data of the material being examined regarding macro and micromechanical properties. It helps a failure analyst to understand how the components react to the applied forces. They are also used to verify that the materials meet the design specifications and requirements. In addition, other uses are to confirm the typical mechanical properties, assess how the material has been altered by the environment and temperature of the service conditions (Lane & Dennies 2021).

### 3.2.6.1 Uniaxial Tension Testing

Uniaxial tension testing is the simplest form used for evaluating materials where it is accomplished by gripping the opposite end of a test specimen with a test machine load frame. The tensile force is applied to the test specimen, which results in a gradual elongation and eventual fracture. During the process, results are usually monitored and recorded of how the specimen deforms under the applied tensile force. This tension test provides a failure analyst with data of the actual or typical mechanical properties and exemplar fracture surface failure location and load direction. The tension test determines the following mechanical properties of the specimen, but are not limited to:

- The modulus of elasticity (Young's modulus) and Poisson's ratio
- Proportional limit
- Ultimate tensile strength and yield strength
- The elongation and reduction in area, ductility properties
- Strain-hardening characteristics (Lane & Dennies 2021)

### 3.2.6.2 Uniaxial Compression Testing

Uniaxial compression testing is used to measure the compressive behaviour of the materials under compression loads. Compressive tests and torsion tests are alternative approaches that overcome on limited necking limit to understand the behaviour of materials under large plastic strains during deformation process. The testing are often useful for subscale and for component where tension test specimens would be hard to produce (Lane & Dennies 2021).

### 3.2.6.3 Bend Testing

Bent testing is used to determine the strength or ductility of a material. This is different from other mechanical tests which are designed to give a quantitative result and have an objective endpoint. The result test gives a pass/fail where a test operator judges whether a surface has undergone cracking. There has been minimal standardization despite the value of the test and its long history of use. However, as for the testing strip, sheet, plate and weldments, they use two ASTM International standards – E 190 and E – 290. This is mostly used to understand the ductility of the weld material and heat affected zone. The purpose of assessing the ductility of welds is to validate a weld procedure and the quality of welds of the welders (Lane & Dennies 2021).

### 3.2.6.4 Hardness Testing

Hardness test is the simplest and least expensive method of mechanical characterization because it does not require specimen preparation which involve inexpensive testing equipment. It consists of pressing an indenter into the test material by using a variety of scales which contact pressure involved in deforming the test surface direct or indirect. This also measures the resistance of material to compressive loads when indenter is pressed into the material during testing. The hardness value taken on Brinell, Vickers and Knoop tests is the load supported of the indentation by the unit area. While in the Rockwell tests, the depth of indentation at a prescribed load is determined and converted to a hardness number unitless. They use hardness testing more on failed components or parts of failed components where the specimens are of insufficient size for the standard strength testing. During testing, care should be taken to ensure that the wrong data are not used or draw inappropriate correlations (Lane & Dennies 2021).

### 3.2.6.5 Impact Toughness Testing

Toughness test is used to test the ability of a material to absorb energy and is determined by the presence of a notch under impact loading. They use a variety of specimens to measure notch toughness such as Charpy V-notch impact specimen, Izod impact sample, dynamic -tear specimen, drop weight impact test and plane-strain fracture toughness specimens. The Charpy V-notch is the most widely used specimen to determine the transition behaviour of steels from ductile-to-brittle. Basically, the specimens may be tested on different sets of temperature to determine the energy absorbed during fracture. This normally checks the percent shear (fibrous) (versus cleavage or flat) fracture on the surface fracture or the specimen (lateral expansion) change in width. Impact toughness test is also a useful method to determine the effect on toughness of material by micro structural alteration or the material surface alteration/contamination (Lane & Dennies 2021).

### 3.2.7 Metallography Analysis

Metallography analysis is an essential tool to determine the root cause of failed components. The examination areas included are the location of the failure, an area where corrosion has progressed and an area for direct comparison of the different areas away from the failure location to understand the problem progression. To facilitate the examination the sectioned selected

areas is carefully mounted in a compound resin, ground and polished then examined in the etched and unetched conditions. The microstructure of the materials is examined and revealed during etched examination condition for any microstructural anomalies. However, during unetched condition it evaluates intergranular attack, cracking and surface conditions, depth corrosion, intergranular oxidation, inclusions, and other damage mechanism may be present. Microstructural features provide key evidence about heat treated condition of the material and anomalies that contribute to the cause of failure and extent of damage of corrosion failure (Hossain & Ulcickas 2021).

### 3.2.7.1 Light Microscopy

Metallographic examination is the most important procedure used by failure analyst in failure analysis. The development of powerful electron metallographic instrument has not diminished the importance of light microscopy. This light microscope is used to determine the relationship between the microstructure and the crack path and/or nature of corrosion. Basically, it assesses the nature of the microstructure and its influence on the failure mechanism. The examination also determines whether processing or service conditions have contributed to the failure such that microstructural conditions produced undesirable such as abnormalities due to quality of material, fabrication, heat treatment and service conditions (Vander Voort 2002).

### 3.2.7.2 Scanning Electron Microscope

Scanning electron microscopy may be needed on the sectioned into smaller pieces after stereo and 3D digital microscopy examinations are completed. It is also used to provide information about topography performed at relatively high magnifications to evaluate the initiation of corrosion mechanism or pitting and overall nature of corrosion. Even though stereo and 3D digital microscopy can provide this information, sometimes scanning electron microscopy can add additional information on a corrosion initiation process (Hossain & Ulcickas 2021).



## Chapter 4

### Material Selection

#### 4.1 Chapter Overview

This chapter discusses the material selection process for corrosion resistance materials, especially metallic materials, which are normally used in most piping components in the oil and gas industry. It identifies different types of metallic materials that meet the properties that are suitable for corrosion under insulation failure. The accuracy of the process depends on data given by different resources.

#### 4.2 Material Selection Process

According to Davis (1995), material selection is a combination of processes that require integration of the properties of materials, manufacturing characteristics, design considerations and the product total life cycle. It is appropriate to examine the complex interdependence between design, manufacture, material and life cycle. Design decisions influence the type of material as this may permit different approaches to certain design features. The methods of manufacturing exert a major influence to the properties of a material that may preclude the use of some process methods that are expensive and difficult to process. Material selection can be critical in solving engineering objectives and has a particular set of iterative process. It is also an important part of the overall design process, in which decisions about the past materials are considered after sequential procedure engineering design was performed (Miller 2002).

The objectives of failure analysis and prevention are closely related to material selection and design. In fact, by real time identification of design inadequacies, failure analysis augments the process development, providing optimization opportunities (Miller 2002). From a corrosion standpoint of material selection, the anticipated outcome plays an integral and often critical role to the following factors:

- Specification
- Quality control and fabrication
- Storage and transportation
- Operation
- Maintenance

Unique environmental conditions play an important aspect on the type and extent of corrosion at all stages in a component's lifetime. A lack of consideration of corrosion resulted in corrosion failures. These occur due to poor communication and appreciation of the true service conditions (Elliot 2003).

### 4.3 Corrosion Resistance Material Selection

Corrosion resistance materials are an essential and appropriate choice after ensuring that a thorough analysis of available materials and their corrosion behaviour has been performed. However, solutions to the corrosion problem may not only stem from materials selection but also include mitigation techniques such as inhibitors, cathodic protection, coating, design, monitoring and inspection. It is also important to consider the design and fabrication as the latter does influence the corrosion resistance depending on a large extent on the environment to which it is exposed. Table 4.1 lists the important groups of materials in the oil and gas industry and specifies their most common applications (Elayaperumal & Raja 2015).

Materials selection of corrosion resistance materials depends on different factors, such as composition of chemicals, metal surface structure and condition, composition of the reaction medium, operating conditions and constructive features of the device. It varies with time depending on the conditions of a material dynamic characteristic and it must be taken into consideration for selecting corrosion resistant materials to justify corrosion increment. Materials are chosen by designers keeping in mind the long term and reliable operations of the components under specific operating conditions. The materials must meet the requirements for mechanical properties, technological properties and operational properties (Tarantseva and Korosteleva 2018).

The choice of material must be carried out based on varying conditions of sufficient and insufficient information and tested and untested situations due to the limited information. Decision making and obtaining the necessary information are different in regards with the algorithms in the corrosion resistance of the material. The regression analysis is performed based on the available literature data. Extrapolation is used to determine the depth of possible corrosion damage and predict the life of the structure. The accuracy in this case largely depends on the applied measurement and processing techniques. When the scope of the available data, physical and mathematical modelling is for unproven situations that go beyond the industrial testing date, it should be compared with the simulation results to increase the reliability of predictions. The professionalism of the experts consulted is to ensure the reliability is necessary

to expand the range of materials used. The following steps are the algorithm that is recommended for choosing the right material based on the operational conditions (Tarantseva and Korosteleva 2018).

- Follow reference data and expert recommendation during preliminary selection of materials
- Select the corrosion resistance of materials for testing by correct laboratory and industrial methods.
- Identify the chemical resistance of materials that influence the external and internal factors of the corrosion system. Determine appropriate design for equipment to carry out optimal condition during technological processes and safe operation.
- Predict the full factorial results based on laboratory data as a function of several variables for the corrosion rate of the test material. Random variable must be defined as a function of confidence limits, mathematical expectation, variance and correlation.
- Determine appropriate industrial testing such as corrosion damage on time, process parameters, and environmental factors.
- Compare the result of industrial testing to the brand of the materials according to the regulations.
- Use mathematical modelling if industrial and laboratory testing is not possible to determine the depth of corrosion damage on materials.
- Predict and determine the corrosion damage increment and given lifetime.
- Assess the analysis of technological and manufacturing methods including the project economic efficiency based on recommended structural materials (Tarantseva and Korosteleva 2018).

Material	Usage/Application
Cast Irons	Pumps, compressors, and valves
Carbon steels	General purpose where corrosion resistance is of secondary importance
Alloy steels, including low alloy C–Mo and Cr–Mo steels	Elevated temperature applications, steam service, hydrogen service, high temperature sulfide service
Ferritic and martensitic stainless steels, including 12% Cr and 17% Cr	For resistance to sulfur-related attacks, valve trims. Pumps wear rings and heat exchanger tubings for mild corrosive service
Austenitic Cr–Ni corrosion-resistant stainless steels	All corrosion-resistant duties where corrosion is not very severe
Austenitic Cr–Ni heat-resistant stainless steels	Furnace tubes, fittings, burners, flare tips, liners/shrouds
Duplex Cr-low Ni stainless steels	For corrosive applications where stress corrosion cracking by chloride is of primary importance and for applications where corrosion resistance, erosion resistance, and mechanical strength are of equal importance
Nickel base alloys, Ni–Mo, Ni–Cr–Fe–Mo	For highly corrosive applications in chemical environments and high temperature corrosive applications
Copper	Electrical applications, tubings for steam tracings, instrument tubings
Brass	Tubes and tube sheets for coolers and condensers, instrument fittings and tubes
Bronze	Tube sheets, Valves, and other parts exposed to sea water
Aluminum brass	Tubes for sea water condensers where corrosion resistance and effective cooling are of prime importance
Cupro Nickel (both 90/10 and 70/30)	Tubes for sea water condenser service where resistance to general corrosion, dezincification and erosion corrosion, and also mechanical strength are of equal importance
Aluminum	Insulation sheathing, DM water lines, and for process equipments of oxidizing environments without chlorides
Titanium	Tubes and tube sheets for sea water cooling where lightness and strength are of equal importance along with corrosion resistance and also for certain highly corrosive applications involving acidic chlorides
Tantalum	For ultimate corrosion resistance where normally glass lining is specified

Table 4. 1: Metallic materials typical application for components in oil and gas (Elayaperumal & Raja 2015)

## 4.4 Types of Metallic Materials

### 4.4.1 Cast Iron

Cast iron belongs to a ferrous group of materials which is least expensive and exhibits different mechanical properties and microstructures among all engineering alloys. In order to enhance corrosion resistance of cast iron, other alloys are employed such as nickel, silicon, chromium, copper and molybdenum. Based on research, high silicon cast iron with 12-18 wt.% will exhibit erosion corrosion resistance. Basically, they behave in a manner similar to carbon steel but what distinguishes them from steels is the presence of free carbon, except that of white cast iron which can cause microgalvanic corrosion. The presence of a graphite network in grey cast iron can suffer from graphitic corrosion. However, it resists graphitic corrosion if a network is absent in malleable and ductile cast irons (Elayaperumal & Raja 2015).

The selection and application of cast iron are less forgiving compared to carbon steel, which means it should be performed carefully. Cast iron is a ternary system which is present in three phases (Fe, C and Si). The elements commonly added include phosphorous, nickel, manganese, cerium and magnesium. The most common use of cast iron in oil and gas includes valves, pump, packers and plugs. The corrosion resistance of cast iron depends on the presence of an alloying element equal to that of stainless steel and nickel alloys. Table 4.2 presents the influence of silicon, nickel, chromium, copper and molybdenum to increase corrosion resistance (Elayaperumal & Raja 2015).

### 4.4.2 Carbon Steel

Carbon steel is a commonly used material in oil and gas facilities, and is mainly for process equipment and structural purpose. Structural steel is used in pipe racks, support columns, etc. where these are protected by protective paint coating for corrosion. Carbon steel in process equipment is used for piping, pressure vessels, reactors, columns, etc. where the process is monitored and corrosion is controlled. The mechanical properties of carbon steel such as strength, toughness and weldability, and ductility can be improved by adding alloying elements such as carbon, manganese, silicon, sulphur and phosphorus. The compositional variations within carbon steel do not alter as far as corrosion failures are concerned behaviourally against common corrosion forms such as uniform corrosion, pitting corrosion, crevice corrosion and galvanic

corrosion. These common corrosions are electrochemically controlled which is not composition centred (Elayaperumal & Raja 2015).

The corrosion resistance of carbon steel is very low due to a low value of  $E^\circ$ , its position in the emf and low chemical resistance indicated on galvanic series. Its corrosion product is porous and non-adherent as cathodic reduction can easily take place on its surface. They are used as the most economic materials with or without minor alloying elements of construction under ambient, aggressive conditions and a combination of various protective coatings and abatement methods for corrosion under such conditions with reasonable offer of life expectancy (Chawle 1993).

Alloying Element	Amount	Effect
Silicon	<ul style="list-style-type: none"> <li>Addition of silicon between 3 to 14% drastically increases corrosion resistance.</li> <li>Beyond 14–16% silicon makes the cast iron brittle.</li> </ul>	<ul style="list-style-type: none"> <li>Silicon promotes formation of adherent surface films on cast iron which decreases the corrosion rate.</li> <li>Corrosion rate may be relatively high initially until the surface layer is formed.</li> </ul>
Nickel	<ul style="list-style-type: none"> <li>Nickel up to 4% in combination with chromium increases the corrosion resistance.</li> <li>Addition of nickel alone up to 12% or more is required to increase the corrosion resistance.</li> <li>High nickel cast irons (between 13.5 to 36%) have high resistance to wear, corrosion, and heat.</li> </ul>	<ul style="list-style-type: none"> <li>Nickel facilitates the formation of a protective oxide layer on the surface.</li> </ul>
Chromium	<ul style="list-style-type: none"> <li>Chromium alone or in combination with nickel and/or silicon increases the corrosion resistance.</li> <li>Addition of chromium between 15 to 35% improves the corrosion resistance of cast iron in oxidizing environments.</li> <li>Higher concentration of chromium reduces the ductility of cast iron.</li> </ul>	<ul style="list-style-type: none"> <li>Chromium increases the corrosion resistance of cast iron by refining the microstructure and by forming protective oxide layer.</li> <li>Chromium oxide resists corrosion in the oxidizing environment only, but not in the reducing environment because of the destruction of these oxides.</li> </ul>
Copper	<ul style="list-style-type: none"> <li>Addition of copper between 0.25 and 1% increases the corrosion resistance of cast iron.</li> <li>In some high nickel-chromium cast irons the copper content may be up to 10%.</li> </ul>	<ul style="list-style-type: none"> <li>Exact mechanism by which copper reduces the corrosion rate of cast iron is not known.</li> </ul>
Molybdenum	<ul style="list-style-type: none"> <li>Molybdenum is added mainly to increase the strength and structural uniformity, but 3 to 4% molybdenum also increases the corrosion resistance.</li> <li>In some high-silicon cast irons, 1% molybdenum is enough to decrease the corrosion rate.</li> </ul>	

Table 4. 2: Cast iron corrosion property with the presence of alloying elements (Papavinasam 2013)

### 4.4.3 Low Alloy Steel

Low alloy steel is developed to enhance high temperature creep and temper embrittlement resistance that can attain high strength and hardenability. The alloying element of these steels is between 1-5 wt.%. Cr-Mo steels have been developed as a result of higher content level of Cr and Mo. The driving force for low alloy steels development is to use in the processing industry to improve either the corrosion/oxidation/high temperature resistance or the mechanical properties. During elevated temperatures where hydrogen-related corrosion phenomenon is a potential C-Mo and Cr-Mo steels are employed that depend upon H<sub>2</sub>S partial pressure and temperature. High levels of chromium and molybdenum were used in high temperature applications in addition to strength and resistance to hydrogen embrittlement, which also added resistance to sulphur corrosion (sulfidation). Table 4.3 lists the materials used for high temperature with their typical use in processing industry. The chromium containing alloy steels are extensively used on the steel that would inhibit the breakdown that reduce corrosion rates on the metallic surface. The promotion of hydrogen embrittlement can be a problem under circumstances where there is no caution with regards to selection of low alloy steels for process industries. Their tolerances towards hydrogen content become weak due to the proportionality as strength goes up (Elayaperumal & Raja 2015).

It is very important to consider that fabrication, especially welding of low alloy steels causes unwarranted and residual stresses. Welding can lead to changes that can hamper the useful properties of steel through microscopic variation in microstructures to mechanical properties. The hardness of the heat affected zones can rise and can develop martensitic structures. The residual stresses build-up is a cause for concern to both SCC and hydrogen embrittlement. In order to address this problem stress relief or subcritical annealing needs to be done before components are put into service (Elayaperumal & Raja 2015).

Material	Scaling limit, °C*	Typical use
Carbon steel	540	General purpose
C-0.5Mo	540	Elevated temperature and hydrogen service
1Cr-0.5Mo	565	High pressure steam services and hydrogen services
1.25Cr-0.5Mo	565	
2Cr-1Mo	580	
5Cr-0.5Mo	620	For sulfur corrosion in liquid hydrocarbons or for hydrogen service
7Cr-0.5Mo	635	
9Cr-0.5Mo	650	
18Cr-8Ni austenitic stainless Steel	900	General corrosive service and high temperature sulfur and hydrogen
Incoloy 800 (18Cr-35Ni)	1100	High temperature and reformer furnaces
High carbon centrifugally cast 25Cr-20Ni	1100	

\*Temperature above which scaling in ordinary flue gas, air, CO<sub>2</sub>, or steam would be excessive, may also be limited by corrosion

Table 4. 3: Elevated temperature use in common materials of construction (Elayaperumal & Raja 2015)

#### 4.4.4 Stainless Steel

Stainless steel contain nickel in excess of 6% and molybdenum. They also contain a minimum of 12 % chromium which increase corrosion resistance. Nickel improves mechanical and fabricating properties and molybdenum increases resistance to pitting and strength to high temperature. The formation of a barrier of true oxide separating the metal helps stainless steel to be corrosion resistant to the surrounding environment. This protection depends on the thickness, coherence and adhesion of the oxide layer onto the metal surface. It also includes the diffusion rate of corrosive species and metal irons across it. The corrosion resistance of stainless steel depends on the presence of oxygen. Stainless steel is susceptible to corrosion if the oxygen is depleted thereby weakening the oxide layer (Papavinasam 2013).

Elayaperumal & Raja (2015) added that chromium containing iron base alloys do the trick of imparting corrosion resistance through the formation of passive film. There are others that supplement the corrosion-resistance property of chromium, which includes molybdenum, silicon, nickel and nitrogen whether with respect to localized corrosion to a varying degree. Development



of stainless steel is not only useful for corrosion resistance but also for other properties listed below.

- Corrosion/oxidation resistance
- Mechanical properties
- Fabrication (hot/cold working)
- Welding
- Low cost

#### 4.4.4.1 Austenitic Stainless Steel

Austenitic stainless steel minimum chromium content is 16%. It may also contain ferrite microstructure but in minor amounts that stabilize the austenitic microstructure and ferritic microstructure. However, other elements that also stabilize at room temperature of austenitic microstructure include carbon, nitrogen, nickel and manganese. This type of stainless steel cannot be hardened by heat treatment. By using cold-work their properties can be altered. Austenitic stainless steel has higher corrosion resistance, that is why they are commonly used in the oil and gas industry than ferritic and martensitic stainless steel (Papavinasam 2013).

Elayaperumal & Raja (2015) stated that austenitic stainless steel is more amenable for fabrication techniques and at the same time are a non-magnetic material which has general corrosion resistance corresponding to the level of chromium present. Table 4.4 lists the most common type of austenitic stainless steels used in the process industry and their nominal chemical compositions. Austenitic steel has a rare combination of corrosion resistance in most environments on grades mentioned. The type 304 stainless steel has adequate corrosion resistance having a nominal chemical composition of 18 wt.% CR, 8 wt.% and 0.08 wt.% max C in almost all the environments. However, its limitation is poor resistance to the following corrosion phenomena:

- Reducing acids such as sulphuric, phosphoric, acetic acids which general corrossions may occur
- Pitting, crevice corrosion and SCC by chlorides
- Intergranular corrosion in the sensitized HAZ after welding

AISI Type	UNS Designation	Composition, % Major Alloying Elements (Max. or Otherwise Stated)				
		C	Cr.	Ni.	Mo.	Others
304	S 30400	0.08	18.00–20.00	8.00–10.50	–	–
304L	S 30403	0.03	18.00–20.00	8.00–12.00	–	–
321	S 32100	0.08	17.00–19.00	9.00–12.00	–	Ti: 5 × C min
347	S 34700	0.08	17.00–19.00	9.00–13.00	–	Nb: 10 × C min
316	S 31600	0.08	16.00–18.00	10.00–14.00	2.00–3.00	
316L	S 31603	0.03	16.00–18.00	10.00–14.00	2.00–3.00	
316Ti	F 316Ti	0.08	16.50–18.50	10.50–13.50	2.00–2.50	Ti: 5 × C min.to 0.70
317	S 31700	0.08	18–20	11–15	3.00–4.00	
317L	S 31703	0.03	18–20	11–15	3.00–4.00	
304H	S 30409	0.04–1.00	18–20	8–10.5	–	
310	S 31000	0.25	24–26	19–22	–	

Table 4. 4: Austenitic stainless steel type standard (Elayaperumal & Raja 2015)

Type 304L stainless steel with 0.03 wt. % maximum carbon instead of 0.08 wt. % produce better resistance to intergranular corrosion on a heat affected zone but lower carbon level reduces mechanical strength. Type 321 and Type 347 were developed to overcome this problem as these are stabilized grades and have alloying elements Ti and Nb (Cb). In fact, leaving the latter free of corrosion resistance purpose is through having higher carbide-forming tendencies in preference to that of chromium. Even though these have good resistance to intergranular corrosion in the weld HAZ without losing mechanical strength, they are still prone to knife line attack intergranular corrosion that occurs very close to the weld-fusion zone (Elayaperumal & Raja 2015).

Type 316 stainless steel consist of 2-3 wt. % Mo as an extra alloying element, which makes it more resistant to general corrosion by reducing acids and pitting and crevices corrosion by chlorides. This steel is mechanically marginally stronger than Type 304 stainless steel. Type 316L stainless steel is a low carbon variety which makes it resistant to intergranular corrosion. Type 316Ti is thereby making it resistant to intergranular corrosion without losing the basic strength of 316 stainless steel. Type 317 and 317L are resistant to corrosion by reducing acids and chlorides to make more improvements over 316 and 316L stainless steel with respect to the level of Mo, 3-4% instead of 2-3% (Elayaperumal & Raja 2015).

#### 4.4.4.2 Super Austenitic Stainless Steel

Super Austenitic Stainless Steel is developed for much greater corrosion resistance than the 300 series austenitic stainless steel; also called high alloy austenitic stainless steels. These are also resistant against chloride pitting in solutions of high chloride with or without some acidity including seawater. These have improved resistance to reducing acids such as sulphuric, phosphoric and acetic acids without further modifications. The process consists of increasing Cr,

Ni and Mo contents and adding dissolved high quantities of nitrogen intentionally. By maintaining the austenitic structure and the carbon content fairly low, resistance to intergranular corrosion is maintained. Titanium and niobium are also added as stabilizing agents against heat-affected zone intergranular corrosion. Copper was added for increased corrosion resistance to sulphuric and phosphoric acids. Table 4.5 lists the common types of super austenitic stainless steel and their nominal compositions (Elayaperumal & Raja 2015).

Common Name	UNS Designation	Composition, wt. % Major Alloying Elements (Max. or Otherwise Stated)				
		C	Cr.	Ni.	Mo.	Others
904 L	N08904	0.02	19–23	23–28	4.00–5.00	Cu: 1.00–2.00
Alloy 28	N08028	0.03	26–28	29.50–32.50	3.00–4.00	Cu: 0.60–1.40
Alloy-6XN	N08367	0.03	20–22	23.50–25.50	6.00–7.00	N: 0.18–0.25
316LN	S31653	0.03	16–18	10–14	2.00–3.00	N: 0.10–0.16
20Cb – 3	N08020	0.07	19–21	32–38	2.00–3.00	Cu: 3.00–4.00, Nb: 8 × C
254SMO	S31254	0.02	19.50–20.50	17.50–18.50	6.00–6.50	Cu: 0.50–1.00, N: 0.18–0.22

Table 4. 5: Lists of super austenitic stainless steel (Elayaperumal & Raja 2015)

#### 4.4.4.3 Duplex Stainless Steel

Duplex stainless steel has much lower nickel than standard austenitic steel, with somewhat higher Mo and N. The nickel content becomes either lower or higher than the above range. Microstructure of duplex stainless steel is partly austenite and ferrite as a result of modification. This means that the ferrite phase is resistant to stress corrosion cracking which in spite of the presence of alternate bands of austenite the duplex structure shows full resistance to stress corrosion cracking. Table 4.8 gives the typical DSS and their typical compositions. DSS have almost double yield strength than standard austenitic making it possible to use thinner sections (Elayaperumal & Raja 2015).

Type 329 and 3RE60 were developed with approximately 50/50 of achieving the austenite ferrite phase balance. 2304 and 2205 are giving rise to improved corrosion resistance on higher temperatures and chloride concentrations and to improved phase stabilities particularly at the welds and HAZ. In particular, 2205 is the most common used grade. Based on industry experience, 2507 is prone to crevice conditions when seawater is used as coolant in heat exchanger, coolers and condensers. The last three duplex materials mentioned on the table 4.6 are “super duplexes” with exceptionally high resistance to corrosion seawater phenomena including general and pitting corrosion and SCC (Elayaperumal & Raja 2015).

Common Name	UNS Designation	Composition, wt % Major Alloying Elements (Max. or Otherwise Stated)					Others
		C	Cr.	Ni.	Mo.		
AISI-329		0.10	25.00 – 30.00	3.00 – 6.00	1.00 – 2.00		
3RE60	S31500	0.03	18.00 – 19.00	4.25 – 5.25	2.50 – 3.00		
2304	S32304	0.03	21.5–24.5	3.0–5.55	0.05–0.06		
2205	S31803	0.03	21–23	4.5–6.5	2.5–3.5		N: 0.08–0.20
2507	S32750	0.03	25.00	7.00	4.00		N: 0.30
Ferralium 255	S32550	0.04	24–27	4.5–6.5	2.00–4.00		Cu: 1.50–2.50, N: 0.10–0.25
Zeron 100	S32760	0.03	25.00	7.00	3.00		N: 0.30
3207	S33207	0.03	27.00	6.5	4.8		N: 0.4, Co= 1.0

Table 4. 6: Lists of duplex stainless steel (Elayaperumal & Raja 2015)

#### 4.4.5 Nickel Base Alloy

Pure nickel is used in different industries as it has excellent resistance to corrosion by alkalis and many acids. It can also be electroplated on a number of materials and electrodeposited nickel intermediate layer which is essential in the production of chromium-plated mild steel (Bahadori, 2014). Nickel base alloy offers a wide range of corrosion resistance. It can accommodate larger amounts of alloying elements such as chromium, molybdenum, copper and iron, thus being more corrosion-resistant than stainless steels. The nickel alloys are preferred over stainless steel for high temperature applications in a corrosive environment. Further, these alloys also stabilize precipitates and strengthen in high temperature properties by adding alloy elements such as aluminium, titanium and niobium. Table 4.7 shows the list of certain popular nickel base alloys with their typical chemical compositions. All alloys in this table are highly corrosion resistant in most environments, such as seawater, acidic chloride and caustics. The Incoloy 800/800H and Inconel 625 are used for high temperature gases and corrosives while Monel 400 is used as cladding on the production of fresh water from seawater on carbon steel evaporators (Elayaperumal & Raja 2015).

Common Name	UNS Designation	Composition: wt. % Major Elements (max. or otherwise stated)							
		C	Cr	Cu	Fe	Mo	Ni	Ti	Others
Monel Alloy 400	N04400	0.15		31.5	1.25				Others Si: 0.50
Ally B – 2	N10665	0.01	1.0		2.00	28.0		Bal	Si: 0.10
Inconel 600	N06600	0.08	16.0	0.50	8.00			Bal 0.30	Si: 0.50
Inconel 601	N06601		23.0		14.1			Bal	Al: 1.35
Incoloy 800	N08800	0.1	21.0	0.75	44.0			32.5 0.38	Si: 1.00
Incoloy 800H	N08810	0.08	21.0	0.75	44.0			32.5 0.38	Si: 1.00
Incoloy 825	N08825	0.05	21.5	2.0	29.0	3.0	42.0	1.00	Si: 0.50
Inconel 625	N06625	0.10	21.5		5.00	9.00	62.0		Nb: 4.00 Si: 0.50
Alloy C-276	N10276	0.01	15.5		5.5	16.0	57.0		Si: 0.08 W: 4.00
Alloy C – 22	N06022	0.015	22.0		3.0	13.0	56		Si: 0.08 W: 3.00

Table 4. 7: List of nickel base alloys – corrosion and heat resistant (Elayaperumal & Raja 2015).

#### 4.4.6 Copper Base Alloy

Copper evolved over 5000 years. One of the oldest metals known, bronze, is one of its alloys. These are very expensive, that's why they have been replaced by cheaper material. Copper is used in many applications. Special copper alloys are mostly used on sheet for architectural cladding, tanks and vessels and tubing for heat exchangers (Bahadori 2014). Copper base alloys are used for their noble position in the EMF series as overall good resistance in general. They have superior thermal conductivity values and easy amenability for fabrication techniques. In addition, they are resistant to biofouling by microorganisms. Copper and copper base alloys, as far as corrosion characteristics are concerned, are not free from certain forms of corrosion. These alloys provide superior service in chemical industries' process equipment involving de-aerated highly corrosive acids and organic and inorganic solutions. They are also used for piping and pipe components and plumbing fittings of fresh water and sea water applications. In fact they are mostly used for oil and gas and steam power generation of exchanging heat between hydrocarbon streams in heat exchanger and condenser tubes (Elayaperumal & Raja 2015). Table 4.8 shows a list of copper and its alloying elements. Below are copper's most common applications:

- Pure copper can be used for not demanding high mechanical strength, such as tubing for steam tracing and typical corrosive applications.
- Brass containing Zn is used at various levels of heat exchanger tubes, but mostly on cane juice evaporators sugar plants, adding small quantity of Al as "aluminium brass" for sea water cooler/condenser tubes and adding small quantity of Sn as "admiralty metal for fresh water-cooled condensers tubes.
- Bronze containing Sn, Al and P are used for various levels of certain plates and forging, such as heat exchanger tube sheets with copper base alloys tubes requiring high thickness and galvanic compatibility. Aluminium bronze only containing aluminium as the alloying element in the range 5 to 12% has good corrosion resistance to sulphite solutions with good erosion and impingement resistance as well.
- Cupro-nickels containing main alloying element Ni (10 to 30%) is use in sea water applications for condenser and cooler tubes with or without Fe requiring higher mechanical strength and corrosion and erosion resistance than Aluminium brass tubes.

Sr. No.	Generic Name	UNS Number	Main Elements
1	Coppers	C10100-C15815	>99% Cu
2	Brasses	C21000-C28000	Cu-Zn
3	Tin Brasses	C40400-C48600	Cu-Zn-Sn-Pb
4	Phosphor Bronzes	C50100-C52400	Cu-Sn-P
5	Aluminum Bronzes	C60800-C64210	Cu-Al-Ni-Fe-Si-Sn
6	Copper-nickels	C70100-C72420	Cu-Ni-Fe

Table 4. 8: List of copper and typical copper base alloys (Elayaperumal & Raja 2015)

#### 4.4.7 Titanium

Titanium is relatively high strength, coupled with a low density and excellent corrosion resistance but used sparingly when required. The reason behind this is that it possesses some characteristics that make its processing costly and difficult (Bahadori, 2014). Titanium has a specific gravity, 4.5, which is about 60% of that of steel and stainless steel and 50% of that of copper and nickel. This material is light, strong and corrosion resistant. Pure titanium has greater mechanical strength than that of carbon steel and stainless steels. This results to lower equipment cost from scaling down the thickness of the equipment of the designer. Their corrosion resistance is superior to stainless steels in many ways, particularly on chloride solutions and all aqueous environments with varying degrees of oxidizing power and small amounts of moisture and oxygen in a gaseous environment. However, absence of a source of moisture/oxygen in anhydrous conditions may result in severe corrosion of titanium. Another area of concern is that when they are exposed in low pH high sodium chloride concentration brines with a temperature above 80 °C, they become prone to crevice corrosion. A major disadvantage that can arise is its vulnerability to hydrogen embrittlement. This is the reason they are never used in structures that are cathodically protected and should not be a part of anything cathodically protected (Elayaperumal & Raja 2015).

## 4.4.8 Aluminum Alloys

Aluminium is an extremely useful engineering material with good corrosion resistance, low density and good electrical conductivity. The presence of a thin oxide makes aluminium corrosion resistant with a few atoms in thickness and is improved by anodizing. In fact, it is permeable to oxygen and protects the surface from further attack (Bhadori 2014). Aluminium is a very active standard potential ( $E^\circ = -1.7\text{ V}$ ) that exhibits a driving force for corrosion thermodynamically. In fact, aluminium and its alloys form a passive oxide film that shows very high resistance to uniform corrosion and atmospheric corrosion on exposure to general atmosphere and aqueous solutions. However, presence of chlorides in an environment make them prone to localized corrosion, such as crevice and pitting. The pitting potential as they bring down the process medium such as  $\text{Cu}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Hg}^{2+}$  further accelerates localised corrosion. Aluminium and its alloys cannot be used under acidic as well as alkaline environments due to corrosive conditions. Furthermore, they become anodic to several other metals and alloys if they be joined with them in any structural component and thereby suffer galvanic corrosion (Elayaperumal & Raja 2015). Table 4.9 show the various types of aluminium alloys which can be added to increase specific strength.

Designation	Alloying Elements	Strength Range, MPa
1XXX	Aluminum, $\geq 99.00\%$	70–175 (c)
2XXX	Copper	170–520 (ht) (depends on Cu and Si levels)
3XXX	Manganese	140–280 (c)
4XXX	Silicon	105–350 (c)
5XXX	Magnesium	140–280 (c)
6XXX	Magnesium and silicon	150–380 (ht)
7XXX	Zinc	380–620 (ht) (depends on Cu)
8XXX	Other elements	280–560 (ht) (Li alloyed)

c = cold-worked and ht = heat-treated conditions

Table 4. 9: List of wrought aluminium alloys and their mechanical strength range (Elayaperumal & Raja 2015)

## 4.5 Material Selection Decision Justification

This section maps how to determine a decision to select the appropriate material based on the extensive literature review. The process required to obtain the decision involves comparing the resistance of the materials to the types of corrosion they are susceptible. All the materials mentioned on this chapter were included in the decision justification. The information regarding types of metallic material and resistance to corrosion are based on the literature review. The

following metallic materials are the most common materials that oil and gas industries use in their facilities.

- A Cast iron
- B Carbon steel
- C Low alloy steel
- D Austenitic stainless steel
- E Super austenitic stainless steel
- F Duplex stainless steel
- G Nickel base alloy
- H Copper base alloy
- I Titanium
- J Aluminium alloys

The decision justification for the material selection process is achieved by using relevant criteria based on the possible corrosion failures occurring in corrosion under insulation. The metallic materials are compared to each other by their resistance to different types of corrosion on CUI. The following are the most common types of corrosion visible during CUI failures.

- CUI 1 Uniform Corrosion
- CUI 2 Pitting
- CUI 3 Crevice Corrosion
- CUI 4 Galvanic Corrosion
- CUI 5 Intergranular Corrosion
- CUI 6 Erosion or Abrasion Corrosion
- CUI 7 Atmospheric Corrosion
- CUI 8 Stress Corrosion Cracking

During material selection decision justification, the following steps were undertaken to develop a relevant criterion:

- The one to three scale was used for each material against the criteria
  - 3 – Excellent
  - 2 – Good



1 – Fair

- The weighing factor for each criterion
- Estimate the appropriate score based on the literature review data given from selected materials
- Rank and establish the highest individual score for each material

Table 4.10 presents the results of the material selection justification that scale based on each criterion and includes the sum of weighing score. The scale is based on the data provided in this chapter. On the other hand, Table 4.11 lists the materials ranked from the first to the seventh.

Table 4. 10: Decision matrix justification for material selection

Material	Possible Corrosion Defects								Weighing score
	CUI 1	CUI 2	CUI 3	CUI 4	CUI 5	CUI 6	CUI 7	CUI 8	
A	1	1	1	1	1	3	1	1	10
B	1	1	1	1	1	1	1	3	10
C	2	2	2	1	1	3	3	1	15
D	3	3	3	3	1	3	3	1	20
E	3	3	3	3	3	3	3	2	23
F	3	3	3	3	3	3	3	2	23
G	3	3	3	3	3	3	3	3	24
H	3	3	3	3	2	2	2	3	21
I	3	3	1	2	1	3	3	3	19
J	3	1	1	1	2	1	3	3	15

Table 4. 11: The ranking results of materials based on their weighted scores

Material	Ranking	
A	Cast iron	7
B	Carbon steel	7
C	low alloy steel	6
D	Austenitic Stainless Steel	4
E	Super Austenitic Stainless Steel	2
F	Duplex Stainless Steel	2
G	Nickel Base Alloy	1
H	Copper Base Alloy	3
I	Titanium	5
J	Aluminum Alloys	6

The respective ranking was accomplished by performing the decision justification matrix based on weighted scores. In the next chapter, the results are discussed on why this is the recommended order of selected materials for use on insulated piping components in oil and gas facilities.

## Chapter 5

### Discussion and Recommendation

Through intensive research, it is determined that carbon steel and stainless steel are the main materials used in oil and gas facilities affected by CUI. The carbon steel insulated piping system mostly suffers a generalised corrosion when water ingress to cladding and reach the metal surface. Depending on the exposure area of corrosion, it can be uniform on the metal surface, which can be predicted. However, if there is a high local concentration of aggressive anions with the combination of low solution pH values on water, it can result to a pitting corrosion. This is an unpredictable observed corrosion type that can penetrate as a deep attack which can reduce the integrity of piping. On the other hand, the stainless steel main damage mechanism while insulated is stress corrosion cracking. The presence of chloride by ingress and contaminated insulation is the main cause of this failure.

Poor equipment design influence on the occurrence of CUI. The water and moisture can bypass the insulation system and thereby initiate a corrosion process. The operating temperatures of carbon and low alloy steels are prone to CUI at temperatures between 10°F (-12°C) and 350°F (175°C). For austenitic stainless steels and duplex stainless steels, temperatures between 140°F (60°C) and 400°F (205°C) form the greatest risk of CUI. The rate of corrosion increases as the temperature increases. The environment where the piping system operates is also considered as the root cause of the failures as most oil and gas operate near seawater if onshore and at seawater if offshore.

The CUI failures can be identified during visual inspection. This failure analysis tool is the easiest and doesn't need special equipment to visualise the type of corrosion attack mechanism on CUI. During visual inspection the decision on what type of corrosion is present on CUI is based on the type of material. Corrosion losses on CUI are measured using ultrasonic thickness testing. Magnetic particle testing is carried out to check for any surface and subsurface discontinuities that can be present such as cracks for carbon steel. Penetrant testing is carried out for stainless steel for presence of stress corrosion cracking. Mechanical testing is used to determine if the mechanical behaviour influenced the CUI failure. It also verifies whether the materials meet the

design specification and requirements. In fact, it helps to assess how the materials had been altered by the temperature and environment of the service conditions. The chemical testing is carried out on surface corrosion products to check any indication of corrosion elements which cause the corrosion.

The results of material selection justification show that nickel base alloy ranked first as the preferred material that can be used for insulated piping components. This material offers a wide range of corrosion resistance that can accommodate larger amounts of alloying elements such as chromium, molybdenum, copper, and iron. Furthermore, adding alloy elements such as aluminium, titanium and niobium can stabilize precipitates and strength in high temperature properties. They are also highly corrosion resistant on most environments, such as seawater, acidic chloride, and caustics. It means that they are more resistant than stainless steel, which reduces environmental pitting and chloride-induced pitting and stress corrosion cracking.

The use of nickel base alloy can be the solution to mitigate the CUI, based on material selection justification. However, there are also different factors that need consideration including the cost and market availability of the materials. All these factors should be able to capture to determine which material is viable to use when CUI is the problem. This is the purpose of ranking if the preferred materials are not viable based on the factors required. The remaining materials are the other options which may be suitable for the requirements.

## Chapter 6

### Conclusion

Corrosion under insulation is a topic of interest and one that represents a very common failure in oil and gas piping systems. This document explored the information regarding the background of the CUI failure analysis and material selection. However, the contents are based on intensive research from literature review, which limits the analysis of this document. The CUI failures included different types of corrosion depending on the type of material affected. These can be identified using the failure analysis tools mentioned on this document. The selected materials during material selection can perform their function to prevent CUI based on the data given from literature review.

In fact, there are many studies regarding the CUI failure but there are differences among the researchers on how this CUI phenomenon can be mitigated or prevented. However, CUI failure remains to date as the main corrosion issue in oil and gas industries. With more research, new insights and improvements will mitigate, if not prevent the CUI failure.

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# Appendices

## Appendix A – Project Specification

ENG4111/4112 Research Project

### Project Specification

For: Florentino Cale

Title: A Case Study in Failure Analysis and Materials Selection

Major: Mechanical Engineering

Supervisor: Steven Goh

Enrolment: ENG4111 – S1, Online, 2021

ENG4112 – S2, Online, 2021

Project Aim: The aim of this project is to investigate the failure of corrosion under insulation of piping components at oil and gas and refining industries and select the appropriate materials to help mitigate this problem.

#### **Programme: Version 2, 17<sup>th</sup> March 2021**

1. Provide a brief background on the failure, operations, and operating environment of corrosion under insulation (CUI) of piping components.
2. Research extensive literature review on analysis of the failure modes and potential causes of failure.
3. Provide suitable failure analysis of CUI failures of piping components.
4. Perform an investigation for appropriate materials selection method for insulated piping component.
5. Recommend solution for the best materials to use during design stage of insulated piping components.
6. Prepare report for failure analysis and materials selection.

## Appendix B – Project Resources

The resources needed to complete this project include:

- Risk assessment for the duration of the project
- Personal computer (laptop)
- Internet access at home and mobile devices
- Access to online USQ library, codes and standards, mechanical engineering database and searching websites
- Planned communication with the supervisor every two weeks through a virtual meeting via Google Meeting
- Work desk and comfortable chair
- Quiet room to concentrate on during research and for the write up of dissertation
- Membership with professional/technical societies (e.g., Engineers Australia) to access industry technical papers
- Good time management and project plan in place.

## Appendix C – Project Planning

Milestones	Week																																			
	Semester 1															Exam / Break			Semester 2																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		
Project proposal submission	█	█																																		
Project specification	█	█	█	█																																
Brief background on the failure, operations and operating environment				█	█	█	█	█																												
Identification of failure modes and potential causes of failure literature review							█	█	█	█	█																									
Provide suitable failure analysis of CUI failures of piping components										█	█	█	█	█																						
Investigate for appropriate material selection method for insulated piping components																																				
Recommend solution for the best materials to use during design stage																																				
Dissertation																																				
Write up dissertation and submit to supervisor for review and feedback	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	█	
Present current results, analysis and implications to ENG4903 conference																																				
Final write up for review and feedback of supervisor for submission																																				
Progress Report Submission																																				
Partial Draft Dissertation Submission																																				
Submit dissertation																																				

## Appendix D – Risk Assessment

This project involved different risks even though the focus is comprehensive research of literature review. Risk management is a procedure to mitigate the risks involved on tasks by using a systematic and logical approach to uncertainty and of hazard identification on a workplace. The process is not only used as a mechanism for cultural change in an organization, but also as a source of data and information regarding costs, choices, benefits, decision bases, methods of analysis, assumptions and attention to value of judgments (ENG3003 Engineering Management: Study book module16 2019).

Risk is defined as events that could have harmful consequences if not rectified and the main aim of this is an adoption of a course of action that results with either stopping the risky events or minimizing the impact. There are four steps in the risk management process:

- Step 1 – Hazard identification
- Step2 – Risk assessment
- Step 3 – Risk control
- Step 4 – Monitor and review

Hazard identification process is the step for identifying the potential sources of injury or disease by asking what, why and how things can get wrong. The process will depend on the type of work and hazards available and includes a comprehensive review of hazard inspections, hazard analysis techniques, past records, consultation of everyone involved, information of the product, other parties involved or a combination of these methods.

Risk assessment is a process of evaluating the identified hazards and facilitate judgment of acceptability in terms of level of risk and the degree of existing control over each element. It takes the likelihood or probability consideration to establish risk criteria against which risk levels can be compared by ranking of risk exposures and management action for determining priorities. Table D.1. shows the USQ risk assessment matrix to help assess risk ratings based on probability and consequence. This will identify if hazards present an acceptable risk or need more safety controls to lower the risks (ENG3003 Engineering Management: Study book module16 2019).

		Consequence				
Probability		Insignificant No Injury 0-\$5K	Minor First Aid \$5K-\$50K	Moderate Med Treatment \$50K-\$100K	Major Serious Injuries \$100K-\$250K	Catastrophic Death More than \$250K
Eg 2. Enter Probability	Almost Certain 1 in 2	M	H	E	E	E
	Likely 1 in 100	M	H	H	E	E
	Possible 1 in 1000	L	M	H	H	H
	Unlikely 1 in 10 000	L	L	M	M	M
	Rare 1 in 1 000 000	L	L	L	L	L
<b>Recommended Action Guide</b>						
E=Extreme Risk – Task <b>MUST NOT</b> proceed						
H=High Risk – Special Procedures Required (See USQSafe)						
M=Moderate Risk – Risk Management Plan/Work Method Statement Required						
L=Low Risk – Use Routine Procedures						

Eg 1. Enter Consequence (arrow pointing to the 'Minor' column)

Eg 3. Find Action (arrow pointing to the 'M=Moderate Risk' row)

Table D.1: The probability of risk vs the level consequence (ENG3003 Engineering Management: Study book module 16 2019).

Risk control is a process of dealing with and controlling the risk by identifying a range of options for the treatment and control of the hazard to develop a plan and implement them. There is a range of workplace risk controls and measures for risk reduction such as design, elimination, substitution, redesign, separation, administration, and personal protective equipment. These form a hierarchy of control that is applied in order to reduce exposure, reduce consequence, and reduce the probability of loss, damage and injury (ENG3003 Engineering Management: Study book module 16 2019).

Table D.2: Risk assessment result for the project.

Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Activity	Hazard	Risk	Risk Assessment	Controls	Risk Assessment
Researching literature	Electrical hazard on using laptop, charger, and other accessories	Electrocution	Moderate risk	Check the equipment for any damage. Remove from service if necessary.	Low Risk – no further control required
	Lifting, pulling and pushing	Strain, sprain and back injury	Moderate risk	Use correct techniques. Get assistant if needed and mechanical aid.	Low Risk – no further control required
	Inappropriate and awkward position	Sprain and strain	Moderate risk	Use good posture, stretch if needed and take regular breaks	Low Risk – no further control required

	Dehydration	Unwell and sickness	Low risk	Drink water regularly and have water on the desk ready to drink if needed	Low Risk – no further control required
	Long working hours	Body stress and fatigue	Moderate risk	Good project planning. Regular breaks. Get enough sleep to recover and rest.	Low Risk – no further control required
	Personal issues	Mental health problem	Moderate risk	Any problem contact the supervisor or the examiner for advice.	Low Risk – no further control required
Writing up dissertation	Inappropriate and awkward position	Sprain and strain	Moderate risk	Use good posture, stretch if needed and take regular breaks	Low Risk – no further control required
	Long working hours	Body stress and fatigue	Moderate risk	Good project planning. Regular breaks. Get enough sleep to recover and reset.	Low Risk – no further control required
Use of other facilities for the project research if needed	Driving	Injury to me and others	High risk	Follow road rules. Don't drive tired. If needed use taxi or uber.	Moderate Risk – no further control required
	Close proximity to other workers in the area	Injury to me and others	Medium risk	Positive communication with others.	Low Risk – no further control required
	Trespassing	unauthorised access	Medium risk	Make sure that authorisation access has been approved	Low Risk – no further control required
	Noise from other workers	Cannot concentrate	Low risk	Move to quiet area to concentrate on the project	Low Risk – no further control required

## Appendix E – Assessment of consequential effects and ethics

### Part 1 – Consequential effects

The consequential effects of this project relate to outcomes which are important in any of the engineering and special science technical activities. One of the outcomes of this project is to determine the accuracy of the results based on the investigated findings. This case study of CUI in piping components is an example of a common problem in the processing industries. This project may help but not guarantee the accuracy of findings because this project is only based on extensive research using different studies to determine what needs to be improved in the future to mitigate CUI.

### Part 2 – Ethical responsibility

As engineering practitioners, we have a responsibility to ensure the community should benefit from the engineering solutions we provide for a sustainable future. Our knowledge and skills are generated to serve the community based on the competency as a professional engineer.

The Engineers Australia (2019) Code of Ethics specified in the course of engineering practice mandates that the following regulations shall be abided by:

- Demonstrate integrity by acting on a well-informed conscience, being honest and trustworthy, and being respectful to all persons whatever profession they are.
- Practise competently through maintaining and expanding knowledge and skills, and objectively represent areas of competency based on knowledge gained.
- Exercise leadership through upholding the professional reputation and trustworthiness, maintaining diversity, supporting and encouraging as part of the team, making reasonable efforts to communicate to all stakeholders honestly and effectively, and keeping in mind the reliance of others on engineering practice.
- Promote sustainability by practising engineering responsibly to foster the health, safety and well-being of the community and the environment, taking into consideration the future generations by balancing the needs between present and future.