Corrosion Characterization of Salvaged Subsea Pipeline

By

MOHAMAD FAIZAL AZRI BIN AZAHARI

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
In partial fulfillment of requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

MAY 2012

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CERTIFICATION OF APPROVAL

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Approved by,

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AP IR DR MOKHTAR BIN CHE ISMAIL
UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
MAY 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(MOHAMAD FAIZAL AZRI BIN AZAHARI)

ABSTRACT

The condition of subsea pipeline is monitored by intelligent pigging and FFS analysis is done based on metal loss data. The understanding of the distribution of metal loss in the form of uniform corrosion and deep penetrating pitting is not well understood. The objective of this project is to conduct visual inspection on the salvaged subsea pipeline, investigate the occurrence of corrosion in the pipeline with relation to the operation and inspection data, and analyse the contributing factor of the corrosion corresponding to the location of uniform and localize pitting corrosion. This study started with gathering data on the operation condition and doing visual inspection on the corrosion pipeline. The metallographic preparation was done in order to reveal the microstructure and material composition by using Scanning Electron Microscope (SEM) and Energy-dispersive X-ray spectroscopy (EDX). Corrosion rates of both pitting and general corrosion samples were examined using Linear Polarization method for 48 hours immersion at 50°C, 3% NaCl solution and 1 bar CO_2.The visual inspection shows that the actual pipeline condition is parallel with the IP data where it was indicated that the pipelines undergo metal loss and pitting corrosion. The EDX result shows very small difference in elemental composition between pitting and general corrosion sample and it does not affect the corrosion rate between the samples in the long run. Besides that, the difference in corrosion rates of LPR is small where 4.4 mm/yr for pitting corrosion and 4.0 mm/yr for general corrosion, thus can be considered same. This suggests that the inclusions or deposit might be facilitating the pit initiation. However further study can be done to find suitable prevention method in order to reduce corrosion rate and pitting in the pipeline.

ACKNOWLEDGEMENTS

I want to thank God for all His blessing; most of all, I want to give thanks for His amazing love that knows no boundaries and endures forever. Through the experience of life, I have learnt and am still learning that I am strong when I am on his shoulders. I want to thank Him for all his wonderful thoughts of me and for raising me up to so much more than I can be.

I want to express my greatest gratitude to my supervisor, AP Ir Dr Mokhtar Bin Che Ismail for his generosity, kindness and guidance throughout the project. It is not just the guidance that he gave, but he ensured that I got proper understanding and exercising to carry out my responsibilities. I can honestly say that I have benefited lots under his supervision.

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CHAPTER 1

INTRODUCTION

1.1 Background Study

Pipelines are very important assets in oil and gas operation used to transport petroleum to onshore for further processing. The integrity of pipeline is closely monitored through thickness measurement by intelligence pigging (IP) inspection and further analysis by fitness for service (FFS). The decisions to replace the pipeline are strongly dependent on the thickness measurement and the analysis from the intelligent pigging. An opportunity to correlate the accuracy of the measurement and analysis can only be done on the pipeline cut and salvaged from field.

One such opportunity is from the salvaged pipeline from Kepong A (KEA) to Tiong A (TIA) under PMO. The subsea pipelines in the PMO from KEA to TIA have been taken out from offshore based on the FFS report where it shows the pipelines did not fit to continue the service because of corrosion. These pipes have been in service from 1982-2009 and were used to transport the oil crude. The pipes were made of API 5L X 52 steel grades.

Several inspections by intelligent pigging have been done in 1994, 1997, 2003, and lastly at 2006. The analysis showed an intensive increase of defects on the pipeline from year to year. An inline inspection using intelligent pigging tool conducted in November 2006 reported 10,804 metal loss defects and 92 manufacturing defects in the pipeline. 10,803 internal defects distributed along the pipeline and 88% of the defects were concentrated at the first 700m from the KE-A platform. There was only 1 external defect reported at KE-A riser. Based on the visual inspection, the corrosion that happened in the pipelines is not consistent and there are several deep pitting at different area.

1.2 Problem Statement

The IP metal loss data provides a means for engineers to conduct fitness for service assessment and the reliability of FFS assessment depends on the accuracy of the IP data. Overestimation of metal loss by IP means premature retirement of the pipe. Thus, there is a need to establish the understanding of the accuracy of the IP data by referring to the actual pipeline condition. Besides that, the corrosion mechanisms that happen on the real pipe salvage from the offshore showed an intensive corrosion phenomenon. From preliminary inspection of the salvage pipeline, it was shown that the corrosion occurred in the pipeline was not uniform and there are several deep penetrating pitting at different area. The reasons of the different corrosion rates are still not clear and no study has been done to investigate this problem.

1.3 Objectives and Scope of Study

The objective of this project is to characterize corrosion phenomenon in the salvage pipeline, focusing more on general corrosion and deep penetrating pitting.

- To conduct visual inspection on the salvaged subsea pipeline.
- Investigate the occurrence of corrosion in the pipeline with relation to the operation and inspection data.
- Analyse the contributing factor of the corrosion corresponding to the location of uniform and localized pitting corrosion.

CHAPTER 2

LITERATURE REVIEW

PETRONAS Carigali Sdn Bhd (PCSB) is divided into three (3) regions; Peninsular Malaysia Operations (PMO), Sarawak Operations (SKO) and Sabah Operations (SBO).Peninsular Malaysia Operations as known as PMO is the largest production division in PCSB and the general job scope is as exploration and production of oil in peninsular. The transportation of crude oil and gas from offshore to the onshore are by pipeline and the first operation started in 1984. Since then, PMO had been growth and many new pipelines are constructed to transferred oil and gas. Several inspection techniques had been implementing in order to monitor the corrosion rates of the pipelines.

PMO started its operation in April 1984 (the first production division in PCSB) with the commencement of gas production from the Duyong field. The first step taken by PMO in developing the first gas field at Duyong has in fact sparked and fuel led the growth of the petrochemical industry throughout Peninsular Malaysia. After Duyong's success, PMO marked another milestone with its first oil production from Dulang Field in 1991.

Now, PMO is currently operating 17 producing fields, 36 platforms, 2 Floating Production Storage and Offloading Facilities (FPSO), 2 Floating Storage and Offloading Facilities (FSO), 1 Crude Oil Terminal (TCOT), 2 Onshore Gas Terminal (OGT and OSC) and 1 supply base (KSB).

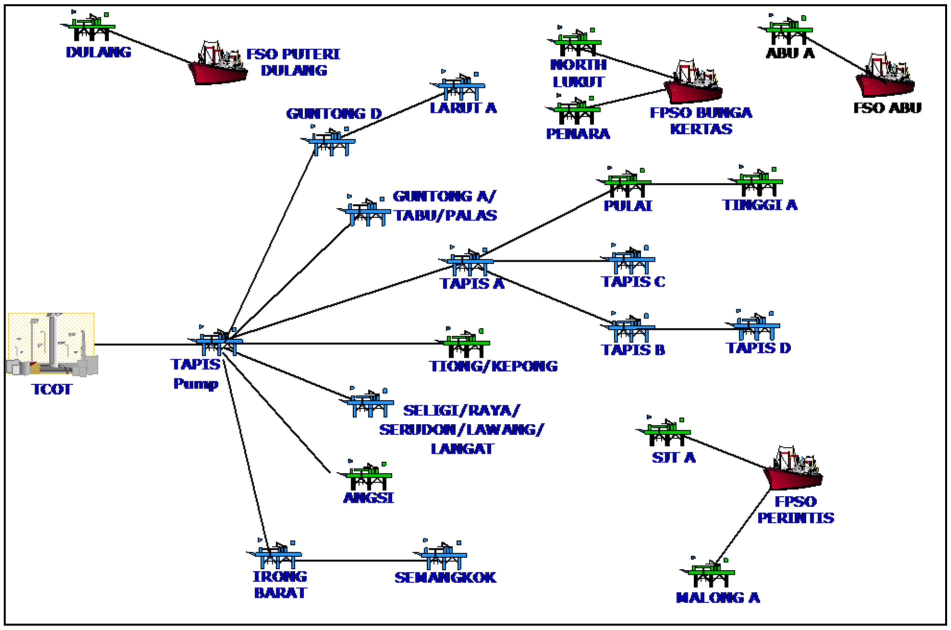


Figure 1: Production–Peninsular Malaysia Upstream Crude Production Network

Based on the FFS and intelligent pigging data, the pipelines from KEA to TIA had to be replace due to the extensive corrosion happen in the pipeline.

2.1 Intelligent Pigging

Intelligent pigs are highly sophisticated instruments that vary in technology and complexity by the intended use and by manufacturer. Intelligent pigs have electronics and sensors that collect various forms of data during the trip through the pipeline. Many pigs use specific materials according to the product in the pipeline. Power for the electronics is provided by onboard batteries which are also sealed.

During the pigging run the pig is unable to directly communicate with the outside pipe due to the distance underwater or materials that the pipe is made of. For example, steel pipelines effectively prevent any reliable radio communications outside the pipe. The pig will record this positional data so that the distance it moves along with any bends can be interpreted later to determine the exact path taken.

After the pigging run has been completed, the positional data from the external sensors is combined with the pipeline evaluation data (corrosion, cracks, etc.) from the pig to provide a location-specific defect map and characterization. The combined data will tell the operator the location and type and size of each pipe defect. This is used to judge the severity of the defect and help repair crews locate and repair the defect quickly without having to dig up excessive amounts of pipeline.

However, several points should be considered when using intelligent pig data to aid a fitness-for-purpose assessment because pigs cannot detect all defects, all of the time, pigs measurements have associated errors and pigs cannot discriminate between all defects. [1] Although continuous improvements are being made to the accuracy of intelligent pigs the defects are sometimes under or over reported in size.

By referring to the IP record done at PMO pipeline 24 10” from KE-A to TI-A, the number of defects increase each time the IP were conducted. In year 1994, 1997, 2003, and 2006, the number of defects that were reported was 9, 44, 2 186 and 10 804 defects.

Table 1: IP 2006 Defects Distribution

Type of defects	Number of defects				Defect Sizing Accuracy	
	INTERNAL		EXTERNAL			
	ZONE 1	ZONE 2	ZONE 1	ZONE 2	Depth sizing accuracy at 80% confidence in ± fractions of t	Length sizing accuracy at 80% confidence in ± X mm
AXIAL GROOVING	40	520	0	0	±0.20	±20
AXIAL SLOTTING	27	176	0	0	±0.20	±20
CIRCUMFERENTIAL GROOVING	14	100	0	0	±0.15	±20
CIRCUMFERENTIAL SLOTTING	7	66	0	0	±0.20	±20
GENERAL	83	1160	0	0	±0.15	±15
PINHOLE	934	1066	0	0	±0.20	±20
PITTING	946	5664	0	1	±0.15	±10

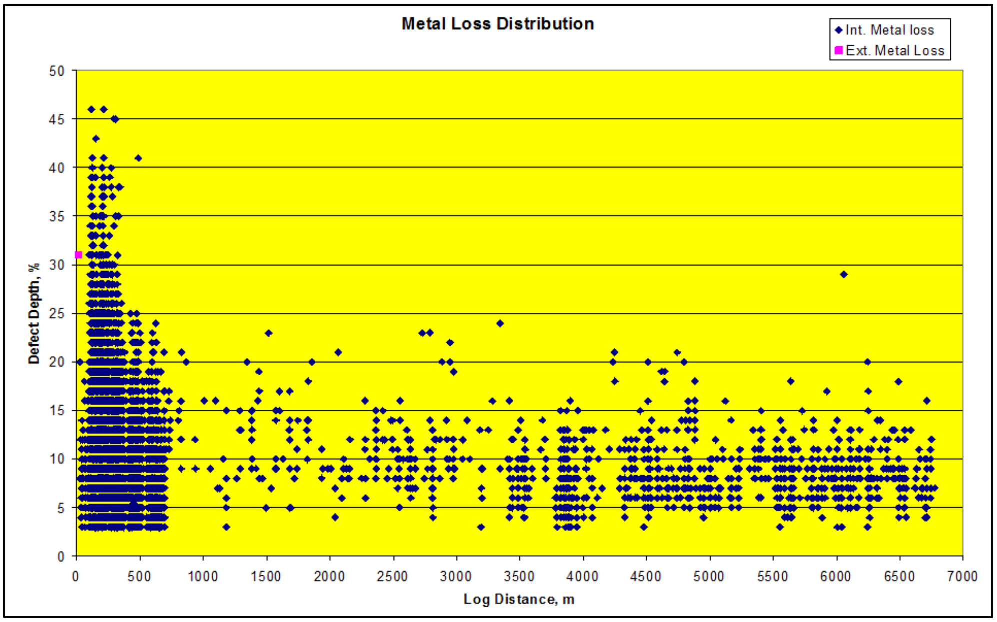


Figure 2: Metal Loss Distribution

2.2 Fitness for Service (FFS)

Fitness-for-service assessment is a multi-disciplinary approach to evaluate structural components to determine if they are fit for continued service. Pipelines may contain flaws or other damage, or may be subject to more severe operating conditions than the original design anticipated. [2] Fitness-for-service methodology is to deliver an assessment of the pipeline for continued operation at defined maximum allowable operating pressure. An evaluation of remaining life and inspection intervals may also be part of FFS assessment.

For any fitness for service assessment, information is required on the input parameters. The parameters is original equipment design data, operational and maintenance history, expected future service and information specific to the assessment such as defect sizes, stress state, location of flaws, and material properties such as tensile strength and fracture toughness. Fitness for Service can then be demonstrated using methods such as stress analysis, defect assessment and fracture mechanics approaches.

The FFS scope of works for PMO pipeline 24 10” is

1) Assessment of the current and future integrity conditions of the pipeline system.
2) Identification of damage causes to quantify the rate of degradation.
3) Recommendations to maintain and improve future pipeline integrity.
4) Recommendations to mitigate control and manage corrosion.

2.3 CO_2 Corrosion

CO_2 corrosion, which is also called "sweet corrosion" in the industry, is by far the most common scenario associated with the internal pipeline corrosion in the oil and gas industry. The mechanism of CO_2 corrosion has been intensively studied over the past few decades, especially with reference to pipeline failures in oil and gas industry. The researchers have already identified the key influencing factors like CO_2 partial pressure, pH, flow, inhibitors, and surface deposits. [3]

The overall reaction is an electrochemical reaction and it can be described asfollows:

$$Fe\ (s) + CO_2\ (g) + H_2O\ (l) \rightarrow FeCO_3\ (s) + H_2\ (g)$$

The overall reaction can be separated into anodic and cathodic half reactions, with both reactions happening simultaneously at the metal surface. Anodic reaction, iron dissolution being:

$$Fe\ (s) \rightarrow Fe^{2+}\ (aq) + 2e^-$$

In the CO_2 saturated system, six homogenous chemical equilibria are possible. Gaseous carbon dioxide dissolves in water:

$$CO_2\ (g) \leftrightarrow CO_2\ (aq)$$

Dissolved carbon dioxide CO_2 (aq) will hydrate to form carbonic acid:

$$CO_2\ (aq) + H_2O\ (l) \leftrightarrow H_2CO_3\ (aq)$$

The carbonic acid H_2CO_3 (aq) will dissociate and give off a proton and a bicarbonate ion:

$$H_2CO_3 (aq) \leftrightarrow H^+ (aq) HCO_3^- (aq)$$

The bicarbonate ion will also dissociate to release another proton and a carbonate ion:

$$HCO_3^- (aq) \leftrightarrow H (aq) + CO_3^{2-} (aq)$$

The water also dissociates to give off a proton and a hydroxide ion:

$$H_2O(l) \leftrightarrow H^+ (aq) + OH^- (aq)$$

Based on the reactions and equilibrium equations provided above, water chemistry can be calculated as a function of temperature, the partial pressure of CO_2 and pH.

There is several type of corrosion happen in the pipeline which is:

1) Pitting corrosion.

   Pitting is noticeable first as a white or gray powdery deposit, similar to dust, which blotches the surface. When the deposit is cleaned away, tiny pits or holes can be seen in the surface. Passive metals such as stainless steel resist corrosive media and can perform well over long periods of time. However, if corrosion does occur, it forms at random in pits. Pitting may be a serious type of corrosion because it tends to penetrate rapidly into the metal section. Pits begin by a breakdown of passivity at nuclei on the metal surface. Pitting is most likely to occur in the presence of chloride ions, combined with such depolarizers as oxygen or oxidizing salts.

2) Uniform corrosion

   The surface effect produced by most direct chemical attacks is a uniform etching of the metal. On a polished surface, this type of corrosion is first seen as a general dulling of the surface and, if allowed to continue, the surface becomes rough and possibly frosted in appearance. The use of chemical-resistant protective coatings or more resistant materials will control these problems. [4]

CHAPTER 3

METHODOLOGY/PROJECT WORK

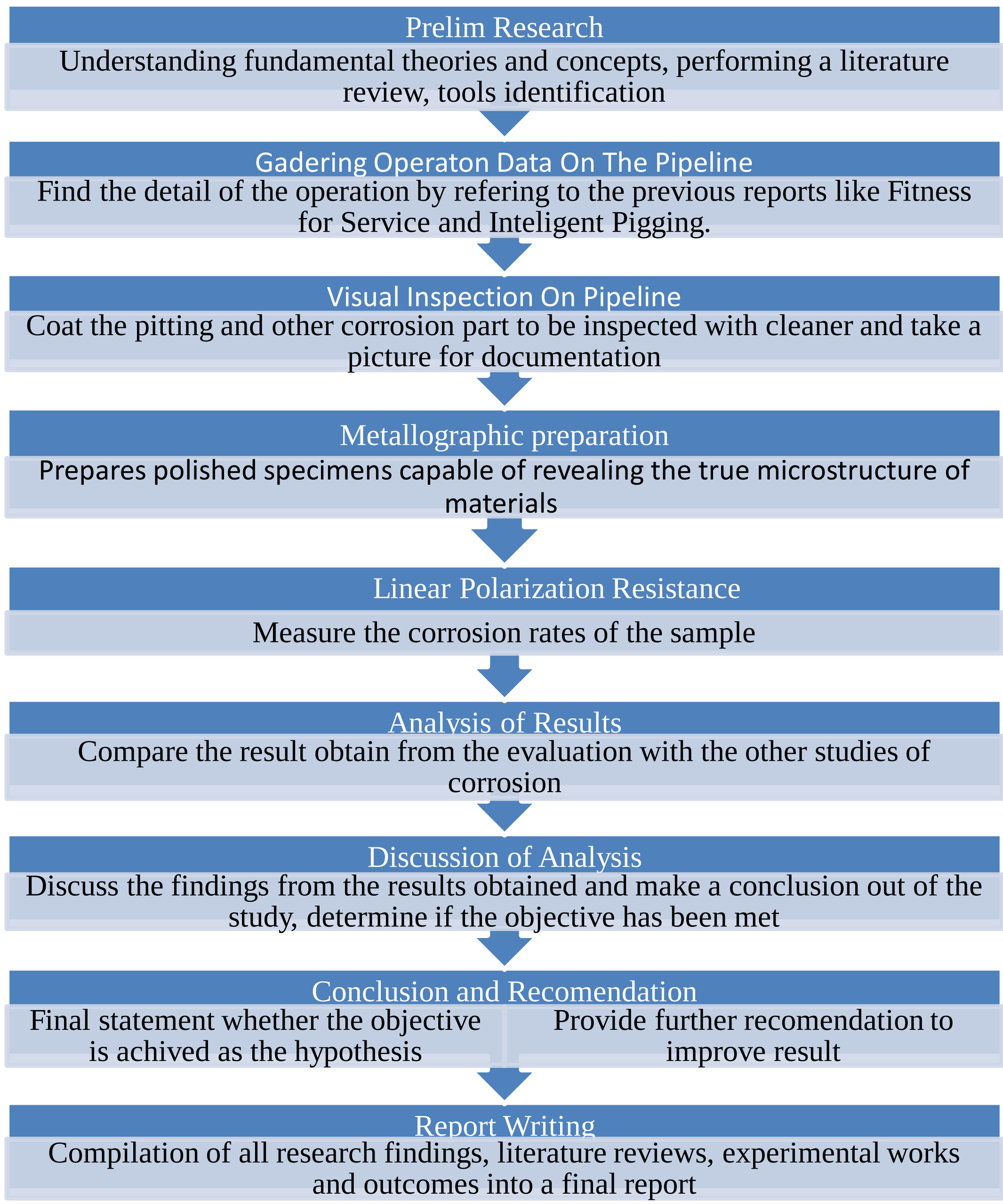


Figure 3: Flow Chart

This project is a study based project. Specifically, it is a study of corrosion inspection of salvaged subsea pipeline. The project began with the research on several issues which has been mention in the research methodology below.

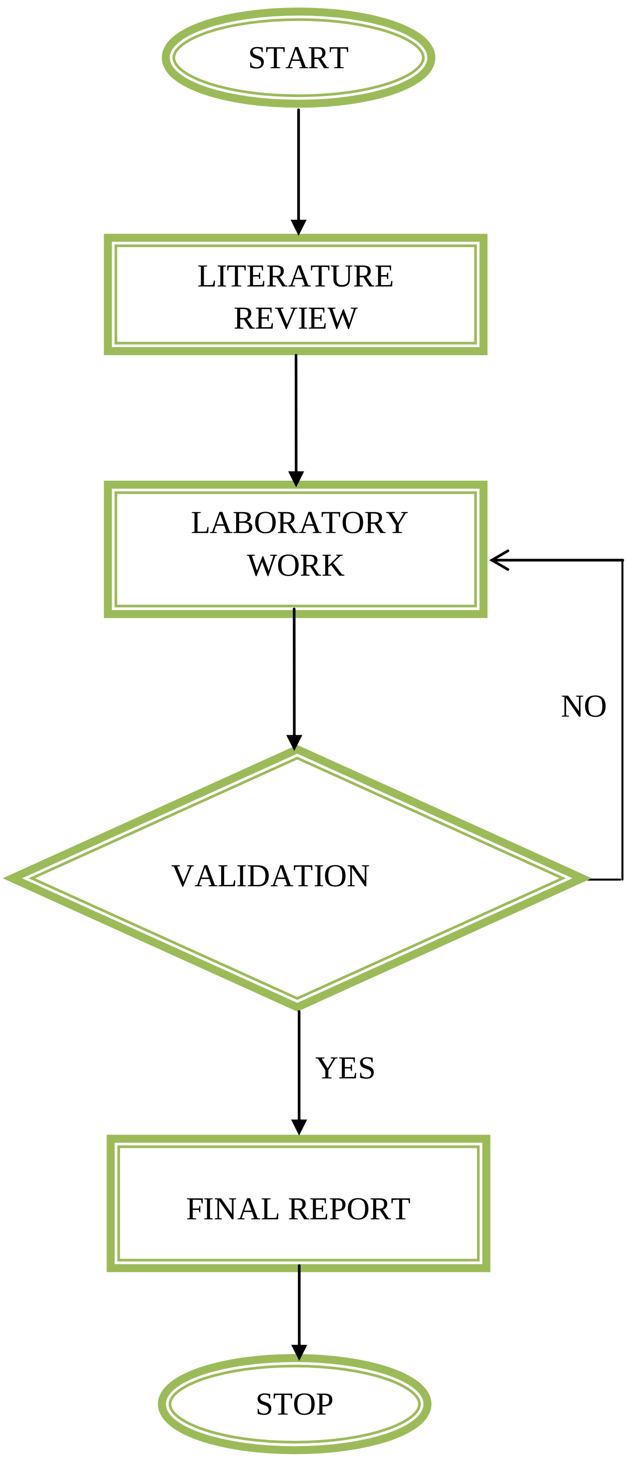
With the collected information, the project proceeded with the literature review on the corrosion study in the subsea pipeline about the type and major factor effect the corrosion rate. After that, the author collected information on the operating condition of the salvage pipeline.

After completing the literature review, the project moved on to the visual inspection on the pipeline which is PMO PL24 10'. During this process, the ultrasonic testing data was compared to the intelligent pigging data in order to make sure the position of the defect same at the actual material. All major defects in the pipeline were labeled with the appropriate type of corrosion and factor of the corrosion happen.

Two types of material testing were employed: metallographic and linear polarization resistance, as to get the characteristic of the pipeline material and corrosion performance between pipeline and product like crude oil. This involved chemical experiment and software to calculate the reaction. From the test, the factor for the corrosion was justified and other prevention method can be proposed.

Lastly, the studies and discussion were compiled in a final report. Apart from that, the details and factors of the corrosion were explained and justified. The fitness for service can be revised and has potential to increase the design life of the pipeline.

3.1 Process Flow



- Preview / Analysis problem
- Identify the usual corrosion type happen on pipeline
- Identify the test methods to examine corrosion
- Fundamental studies from references and journals

- Do the lab work
- Identify microstructure of materials by using metallographic technique.
- Identify particle characterization and elemental composition using SEM and EDX
- Identify the corrosion rates using Linear Polarization Resistance method
- Identify any errors occur during the lab work
- Analysis the result from metallographic and LPR
- Identify whether the result is valid or not

- Report on the cause of difference corrosion rates.
- Recommendation on other corrosion experiment for better result.

Figure 4: Project Process Flow

3.2 Research Methodology

Research is a method taken in order to gain information regarding the major scope of the project. The sources of the research cover the report from fitness of service reassessment done during 2007, e-journal, e-thesis and several trusted link.

3.2.1 The steps of research:

1. Gathering data on the operation condition of the salvage pipeline.
2. Doing visual inspection on the corrosion pipeline.
3. Define all the corrosion type happen in the pipeline and simple background study at all type of corrosion.
4. Testing of material characteristic and corrosion performance.
5. Justify the causes of the pitting corrosion.

3.2.2 Study case

Table 2: Pipeline design specifications

Pipeline ID	PMOPL24
Pipeline Name	10" Crude KEA-TIA
Length	6.9 km
Location	Offshore
Nom Diameter	10.75 in (273.05 mm)
Nom Wall Thick	11.1 mm
Material Type	Carbon Steel
Material Grade	API 5L X52
Predominant Pipe Type	Seamless
Design Pressure	103.5 bar (1501 psi)
Test Pressure	145 bar (2103 psi)
Maximum Allowable Operating Pressure	40 bar (de-rated)
OP	28 bar (average)
Product	Wet, semi processed crude oil
Installation Year	1982
Design Life	20 yrs (2002)
Design Code	ASME B31.8
Operating Temp	55 ºC @ inlet, 30 ºC @ outlet
Min Water Depth	65.5 m @ KEA & 67.2 m @ TIA Inspections

Table 3: Pipeline operating parameters

Inlet Temp (°C)	27 (min)/ 65 (max)
Outlet Temp (°C)	30
Inlet Pressure (bar)	28
Outlet Pressure (bar)	25
CO_2 (mole %)	0.532
H_2S (mole %)	0
CI availability (%)	40 (min)/ 70 (max)
Total flow rate (m^3/d)	488 (min)/ 511 (max)
Crude oil flow rate (m^3/d)	168
API gravity	27.5
Water flow rate (m^3/d)	320 (min)/ 343 (max)
Water cut (%)	67
Inlet Fe count (ppm)	0.02 (min)/ 0.5 (max)
Inlet SRB count (cfu/ml)	1 – 100
Outlet SRB count (cfu/ml)	1

3.3 Detail Procedure

3.3.1 Metallographic preparation

1. Sectioning

   The selection of samples is very important to the outcome of metallographic analysis. The component of the samples is very large which is pipeline, where it required sectioning to provide manageable metallographic samples. Samples of corroded area were taken, however samples of unaffected areas also are very important because it can reveal contrasting structures, thus distinguishing damage as shown in Figure 5.

Figure 5: Samples of corroded area

When the samples were cut using a torch as shown in Figure 6, large areas were removed to leave enough unaffected area for later saw cuts. The oxy-acetylene cutting process was achieved by blowing away the molten material, which was melted by the combustion heat of acetylene gas and oxygen. Generally, only steel material is cut using this process and material of remarkable thickness can be cut.

Figure 6: Cutting of sample by using oxy-acetylene torch

2. Microscopic Examination

Initial microscopic viewing was done by utilizing a stereomicroscope, which revealed a three-dimensional scanning of the specimen surface. The specimen was placed on the stage of the microscope so that its surface is perpendicular to the optical axis. A metallurgical microscope has a system of lenses that can achieve (25X to 1000X) magnifications. The important characteristics of the microscope are: (1) magnification, (2) resolution and (3) flatness of field. When examining a metallographic specimen, the objective of lowest magnifying power should first be used. [5] Initial microscopic viewing will be on the surface of pitting and general corrosion before start on the Scanning Electron Microscopy (SEM) and Energy-dispersive X-ray spectroscopy (EDX).

3. Abrasive sectioning

Abrasive cutting offers the best solution to get the manageable size from larger parts of the samples because the resultant surface is smooth, the sectioning task is quickly accomplished and can withstand the stresses imposed by clamping vises and the action of the abrasive wheel. Low-speed cut-off wheels are utilized in cases where the heat created by standard abrasive cutters must be avoided. Ample coolant and proper speed control are essential in all sectioning operations. Figure 7 shows a localize corrosion and area of the sample taken by using EDM wire cut.

Figure 7: Localize corrosion sample and area of sample taken

4. Sample mounting

Sample should be mounted to provide additional support to the sample. In most corrosion applications, cold molding (room temperature) is often used with epoxy to mount samples by simply mixing the epoxy and pouring it over a sample that is positioned face down in a cold-mounting ring.

5. Fine grinding

Fine grinding as shown in Figure 8 was designed to produce a scratch free surface by employing a series of successively finer abrasives. Failure to be careful in any stage will result in an unsatisfactory sample. Movement from one stage to the next should only proceed when all of the scratches from the preceding stage are completely removed.

Figure 8: Sample grinding and polishing

6. Rough polishing

The purpose of the rough polishing step is to remove the damage produced during cutting and planar grinding. Proper rough polishing will maintain specimen flatness and retain all inclusions or secondary phases. By eliminating the previous damage and maintaining the microstructural integrity of the specimen at this step, a minimal amount of time should be required to remove the cosmetic damage at the final polishing step. Rough polishing is accomplished primarily with diamond abrasives ranging from 9 micron down to 1-microndiamond.

7. Final polishing

The purpose of final polishing is to remove only surface damage. It should not be used to remove any damage remaining from cutting and planar grinding. This step is performed on napped cloths which have been charged with fine alumina of about 0.05 micron size. All scratches will be removed in less than one minute if the previous steps have been performed correctly. Longer polishing times will only result in producing polishing defects like relief, pull-out, residual scratches and unclear microstructures.

8. Scanning Electron Microscopy (SEM)

The scanning electron microscope (SEM) equipment as shown in Figure 9 uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. The signals that derive from electron-sample interactions reveal information about the sample elemental micro analysis and particle characterization. Sample preparation can be minimal depending on the nature of the samples and the data required. Minimal preparation includes acquisition of a sample that will fit into the SEM chamber and some accommodation to prevent charge build-up on electrically insulating samples.

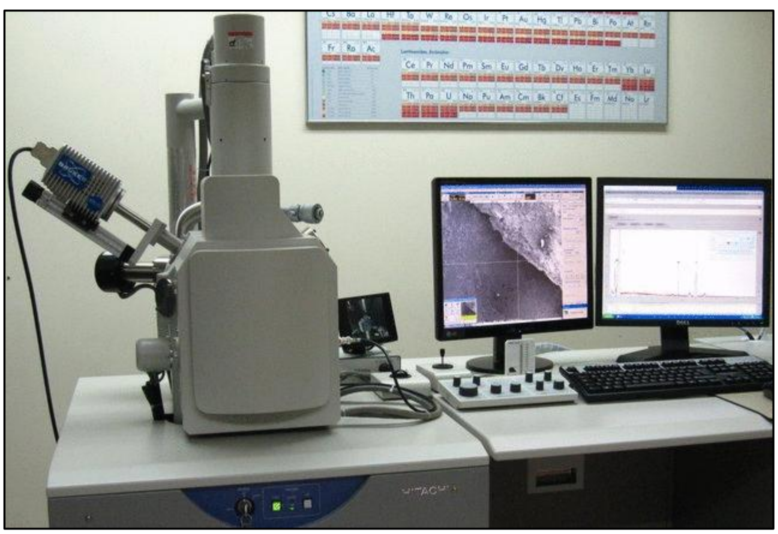


Figure 9: Scanning Electron Microscopy (SEM) equipment

3.3.2 Linear Polarization Resistance

Linear Polarization Resistance monitoring is an effective electrochemical method of measuring corrosion. Monitoring the relationship between electrochemical potential and current generated between electrically charged electrodes in a process stream allows the calculation of the corrosion rate. LPR is most effective in aqueous solutions, and has proven to be a rapid response technique. This measurement of the actual corrosion rate allows almost instant feedback to operators. LPR monitoring has seen wide industry use for nearly 50 years.

When a metal/alloy electrode is immersed in an electrolytically conducting liquid of sufficient oxidizing power, it will corrode by an electrochemical mechanism. This process involves two simultaneous complementary reactions. [6] The polarization resistance is the ratio of the applied potential and the resulting current level. The measured resistance is inversely related to the corrosion rate.

The electrical resistance of any conductor is given by: [7]

$$\boldsymbol{R = \frac{V}{I}}$$

Where

R = Effective instantaneous resistance

V = Applied voltage

I = Instantaneous current between electrodes

The major advantage to LPR monitoring is the speed in which it can provide a measurement of the corrosion rate. Besides, LPR monitoring can provide a qualitative pitting tendency measurement and metal behavior.

Figure 10: Abrasive cutter used to section the material

Figure 11: Hardener and resin used

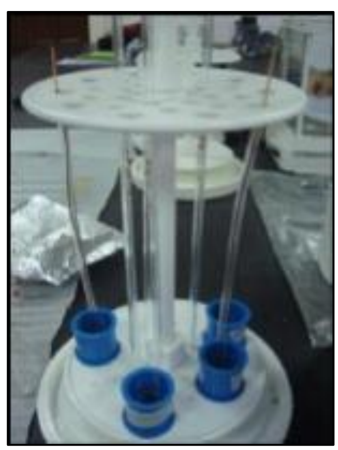


Figure 12: API 5L X-52 samples during mounting

Figure 13: API 5L X-52 samples after mounting

General Procedure:

1. Samples were sectioned into small area using abrasive cutter as shown in Figure 10.
2. After that, measurement of samples width and length were measured using digital vernier caliper in order to calculate the precise area of the samples for electrochemical testing use in the later part.
3. Samples from each heat treatment were soldered to connect the conductor (Copper wire) to the surface of the sample.
4. Mounting cups were greased with lubricant to ease the removal mounted part.
5. Soldered metals placed into the mounting cups along with the transparent tube covering the copper wire.
6. Mounting mixture consist of 5:1 ratio (5 parts of epoxy and 1 part of hardener) as shown in Figure 11 was weighted and this mixture was stirred until clear mixture color achieved.
7. Epoxy mixture then was poured into the mounting cups. Mixture must cover above the tube level.
8. Samples were left for 1 day for curing time of the mixture as shown in Figure 12.
9. Samples were removed from the mounting cups when it is already hardened by pushing it outwards. The samples were degreased and rinsed with deionizer

water and ethanol as shown in Figure 13 and were labeled for ease of identification.

Electrochemical testing was done to study the corrosion rates between general corrosion and pitting area samples. Figure 14 shows the experimental setups for electrochemical testing which was done at Corrosion Research Centre Blok I.

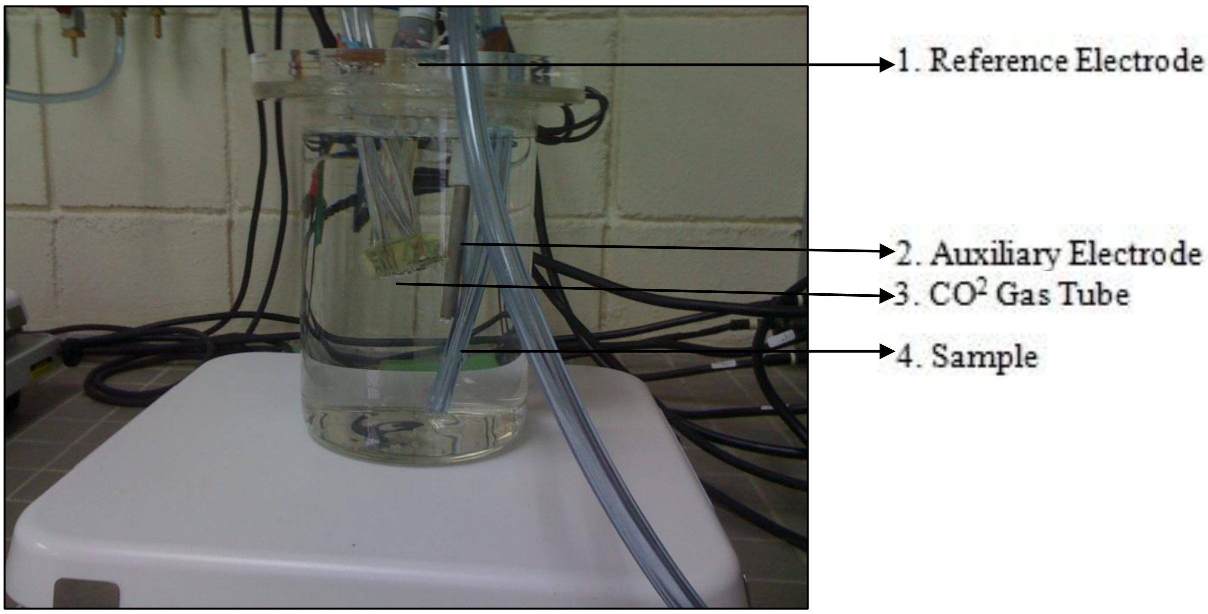


Figure 14: LPR experimental setups

General Procedure:

1. 30 g NaCl weighted and mixed with 1L of de-ionized water to get 3% NaCl solution. This mixture was then stirred using StableTemp Cole-Palmer and left for approximately 2 minutes to make sure all the NaCl powder has already dissolved.
2. Solution is purged by providing CO_2 gas into the solution for 1 hour. Temperature was set to 120°C using hot plate to achieve solution temperature of 50°C at the end of purging process.
3. Sample is grinded with 240 grit, 320 grit, 400 grit, and 600 grit silicon carbide grinding paper.
4. After 1 hour purging, sample and other electrodes were placed in the glass cell and left for 48 hours. Temperature was lowered down to 80°C.
5. LPR and EIS data were taken after 48 hours of experiment.

3.4 Activities/Gantt Chart and Milestone

NO	DETAIL/ WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of project topic								MID SEMESTER BREAK							
2	Preliminary research															
3	Completion of extended proposal															
4	Submission of extended proposal															
5	Proposal Defence															
6	Completion of gathering operation condition															
7	Completion of visual inspection															
8	Starting of material testing															
9	Submission of interim draft report															
10	Completion of interim report															
11	Submission of interim report															

Figure 15 - Gantt chart for 1st Semester

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Project Work Continue								Mid-Semester Break								
	Sample cutting	■															
	Lab booking and tools and item preparation		■	■													
	Scanning Electron Microscopic			■	■												
	Analysis of result from SEM test				■	■											
2	Submission of Progress Report 1				●												
3	Project Work Continue																
	Linear Polarization resistance					■	■										
	Analysis of result from LPR test							■		■							
4	Submission of Progress Report 2									●							
5	Project work continue																
	Review all result										■	■	■				
6	Submission of draft report													●			
7	Submission of Dissertation (soft bound)														●		
8	Submission of technical paper														●		
9	Oral Presentation															●	
10	Submission of Project Dissertation (Hard Bound)																●

Figure 16 - Gantt chart for 2st Semester

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Intelligent pigging data and actual pigging condition

There are several inspections done on the pipeline using Intelligent Pigging (IP) for maintenance and data collection purposes due to its corrosive environment.

- 1994
- 9 defects reported (reporting threshold = 10%)
- Most severe was 21% due to mill defect
- Remaining were group under pitting

- 1997
- 44 defects reported (reporting threshold = 10%)
- Most severe was 17% due to pitting

- 2003
- 2186 defects; with 2127 due to metal loss, 59 due to mill defects
- 2110 internal, concentrated at the first 500m from KEA
- 76 external
- Reporting threshold = 1%
- Most severe was 45% internal (general corrosion)

- 2006
- Reported 10896 defects
- 10804 are metal loss defects and 92 manufacturing defects

- 10803 internals defects distributed along the pipeline, 88% were concentrated at the first 700m section of KEA.
- 1 external defect at KEA riser/splash zone area
- Maximum reported wall loss is 46% @ LD=211.94m and LD=114.58m

- All defects were distributed throughout the pipeline, interacting at some locations mostly within the first 700m section.

According to the visual inspection records done by GTS, the corrosion data were recorded based on the o'clock orientation and log distance. Corrosion on the pipeline was found to be minimal and distributed between 3 O'clock to 9 O'clock. The summary of the visual inspection is shown in Table 4.

Table 4: Summary of visual inspection

Part	Section	Actual Length (m)	Maximum wall Loss by IP, %	Observation During Visual Inspection
				Internal Surface
1	A	10.14	33	- Smooth (look like original) surface between 3 and 12 O'clock position - Rough surface at any other locations
	B	9.69	40	- Rough surface around 12 O'clock position
2	C	8.32	24	- Smooth scale surface between 3 and 12 O'clock position - Rough surface at any other locations
	D	7.34	28	- Continuous groove like defect between 3 to 12 O'clock position
3	E	9.71	33	- Scale of about 3 mm thick around 6 O'clock position
	F	9.84	33	- Hard deposit of corrosion product at 6 O'clock position
4	G	11.40	25	- Small deposit and thin layer of scale

	H	11.78	41	- Overall rough surface - Thin layer of scale around 6 O'clock position - Uniformly distributed shallow pits
5	I	10.01	16	- Very rough surface - General corrosion distribution all over the surface
	J	10.17	22	- Rough surface around 12 O'clock position - Deep pit of about 20 mm x 15 mm at about 9 O'clock position
6	K	0.63	13	- Shallow corrosion pit distributed over the surface

According to the Table 4, most of the pipelines undergo general corrosion while pitting corrosion spot at section H, J, and K. This shows that the actual pipeline condition is parallel with the IP data where it was indicated that the pipelines undergo metal loss and pitting corrosion. However, visual inspection can only indicate rough idea on the IP data accuracy. Further study can be done in order to evaluate the accuracy of the IP data by compare it with other technique of inspection like Ultrasonic Testing (UT).

4.2 Characterization of corrosion phenomenon

From the microstructure result, it is shown a hole type of surface on the pitting area while smooth surface on the general corrosion area. It became evident that the hole was caused by corrosion and not due to torch during the cutting process. The assumption is the inclusion and difference in elemental composition between these two areas and further analysis should be done by using SEM and EDX.

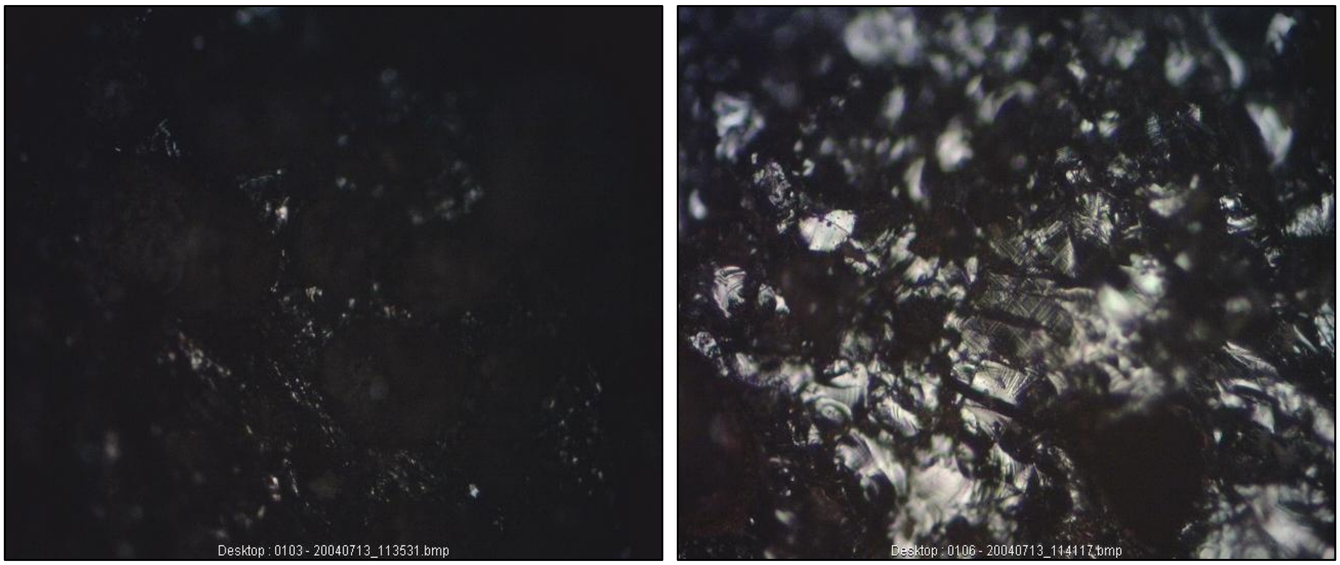


Figure 17.1: API 5L X52 microstructure (50X and 100X) pitting

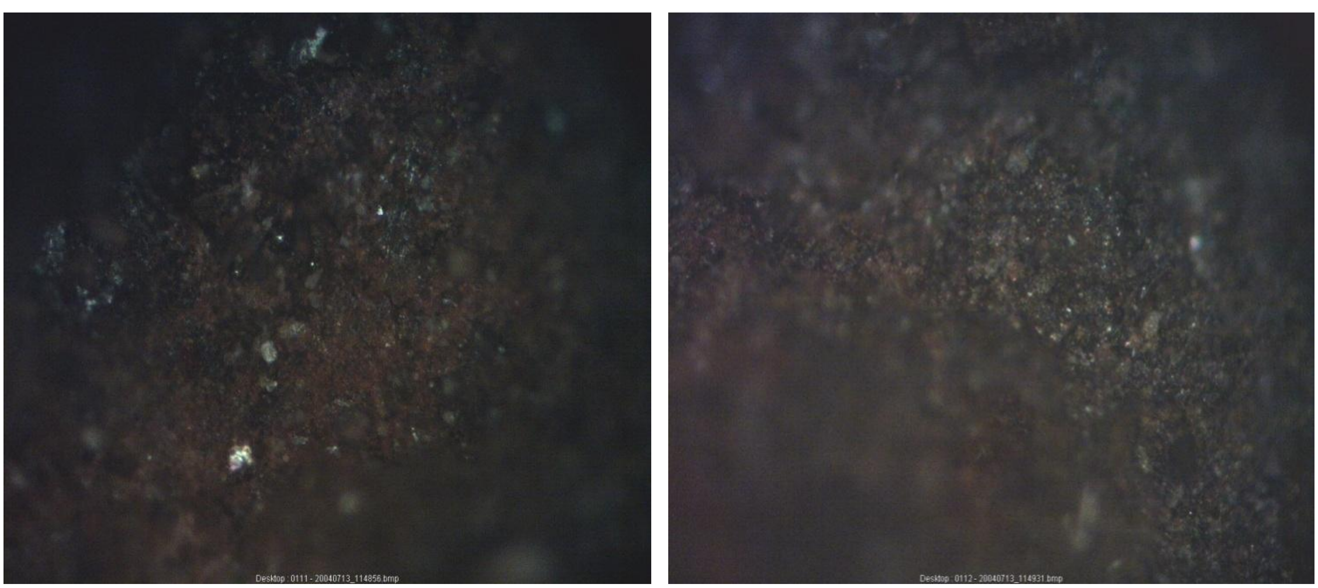


Figure 17.2: API 5L X52 microstructure (50X and 100X) general corrosion

4.3 Scanning Electron Microscopy (SEM)

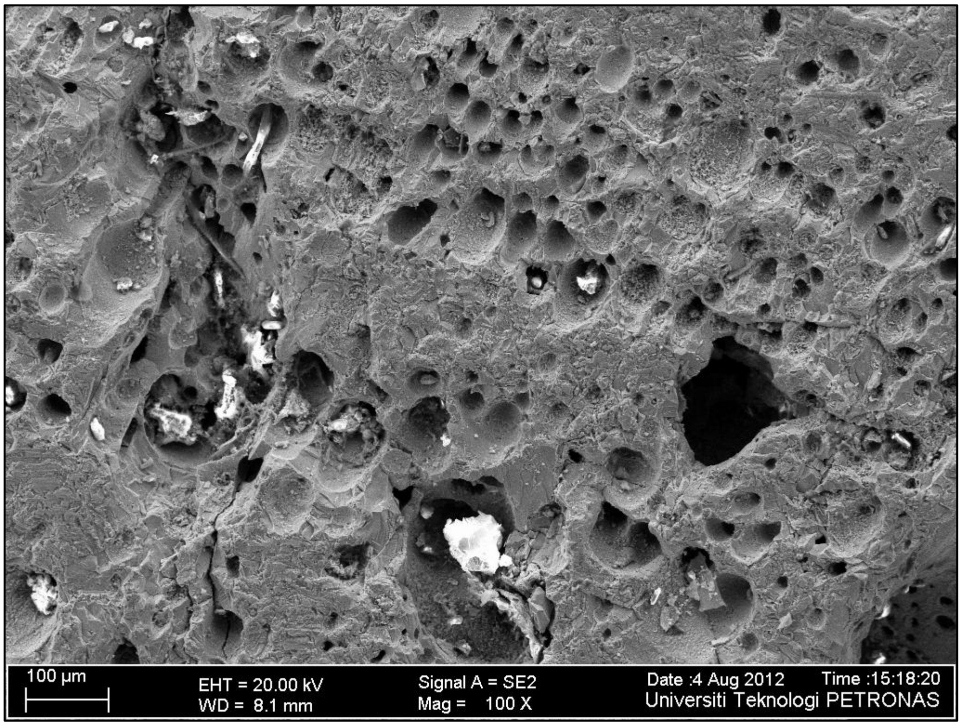


Figure 18.1: SEM image of pitting area (100X)

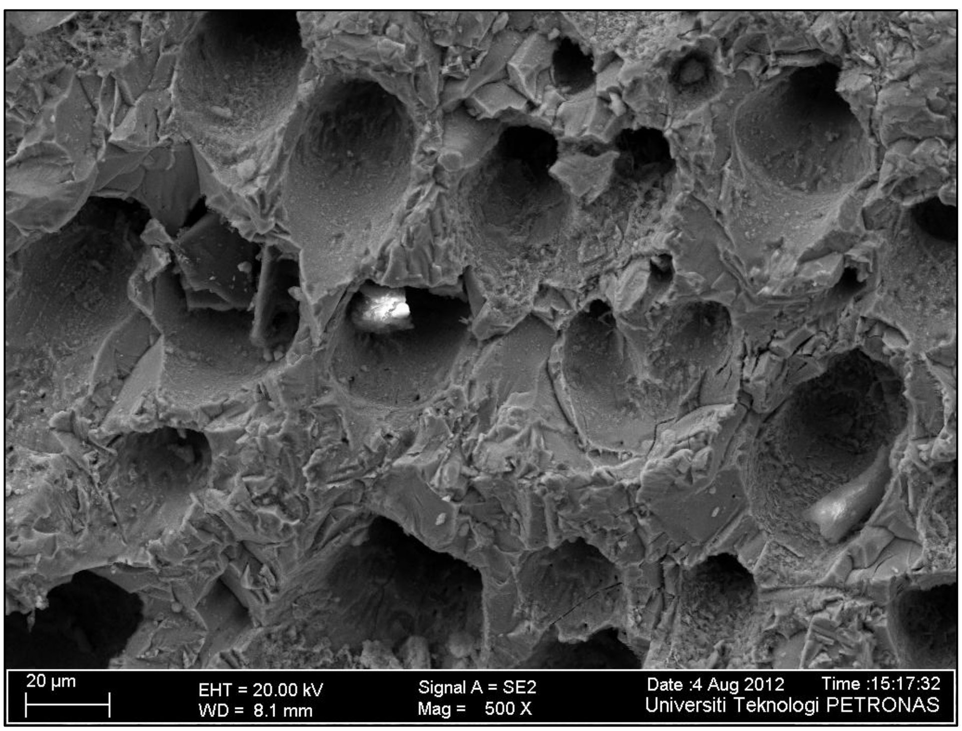


Figure 18.2: SEM image of pitting area (500X)

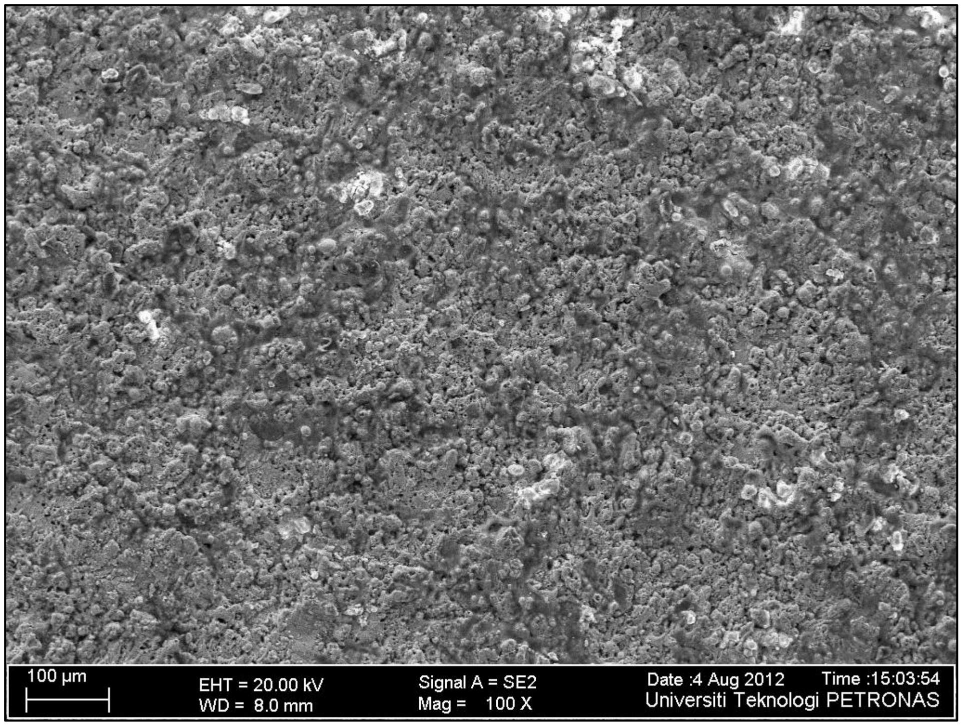


Figure 19.1: SEM image of general corrosion area (100X)

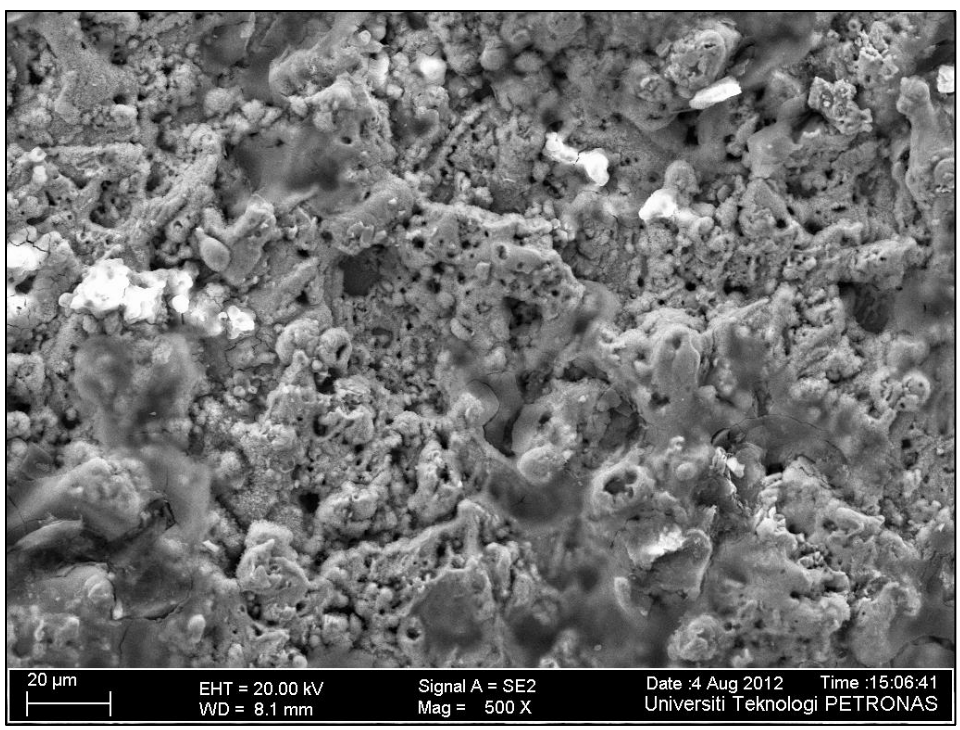


Figure 19.2: SEM image of general corrosion area (500X)

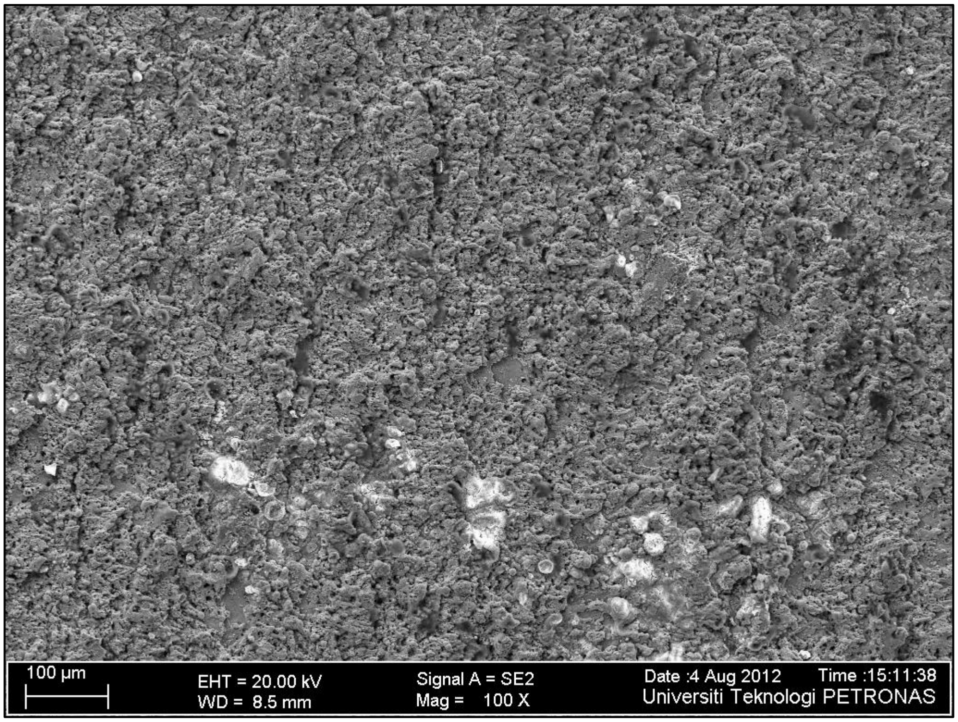


Figure 20.1: SEM image of pitting area surface (100X)

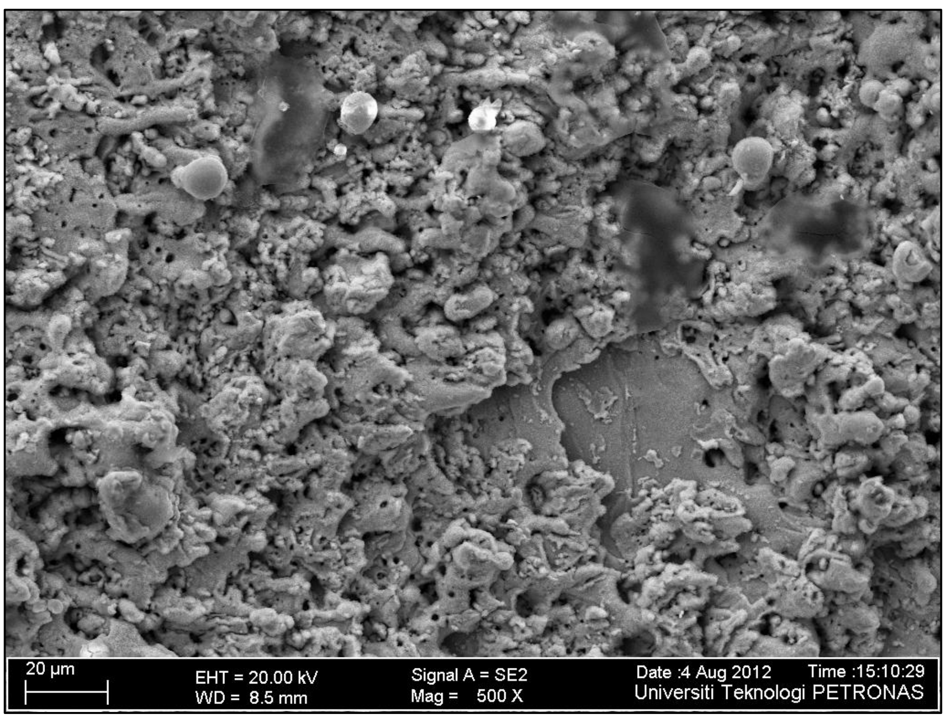
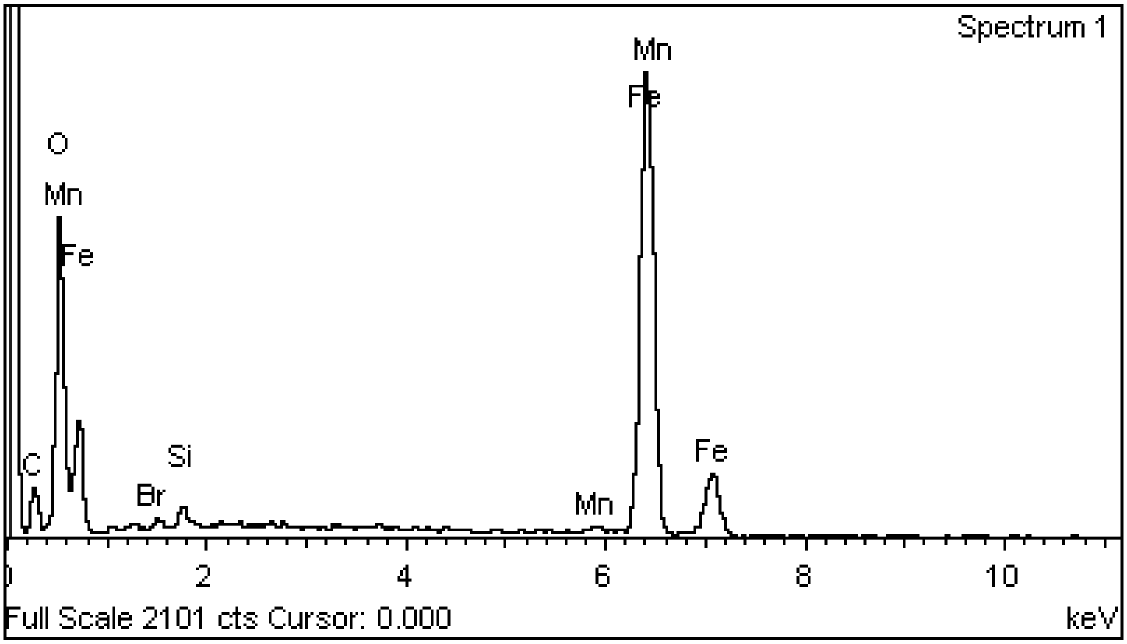


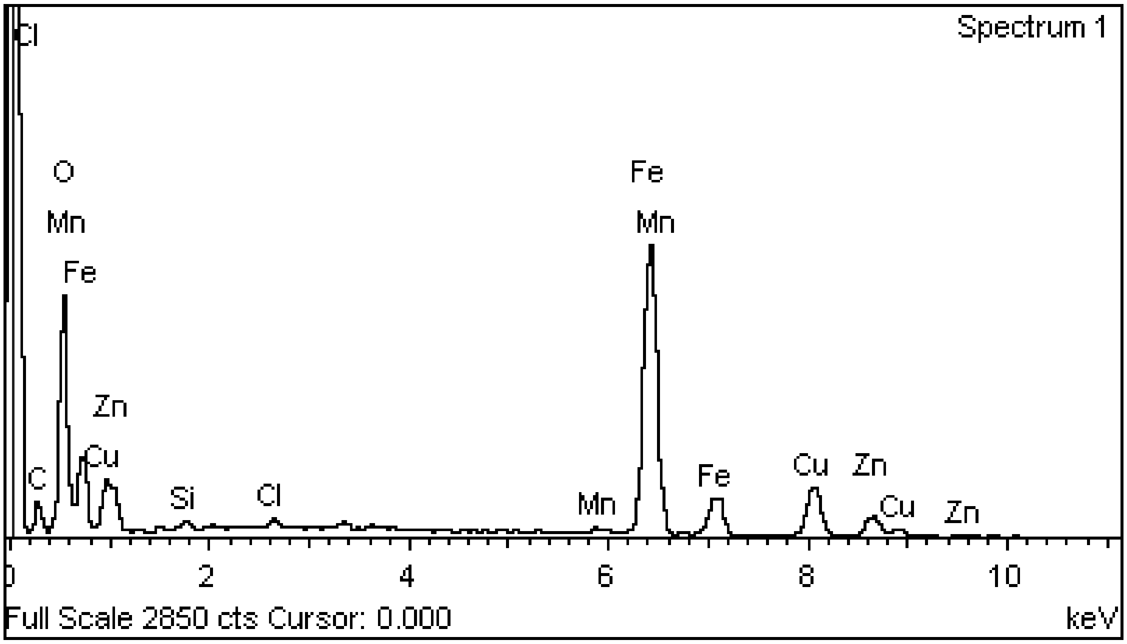
Figure 20.2: SEM image of pitting area surface (500X)

4.4 Energy-dispersive X-ray spectroscopy (EDX)



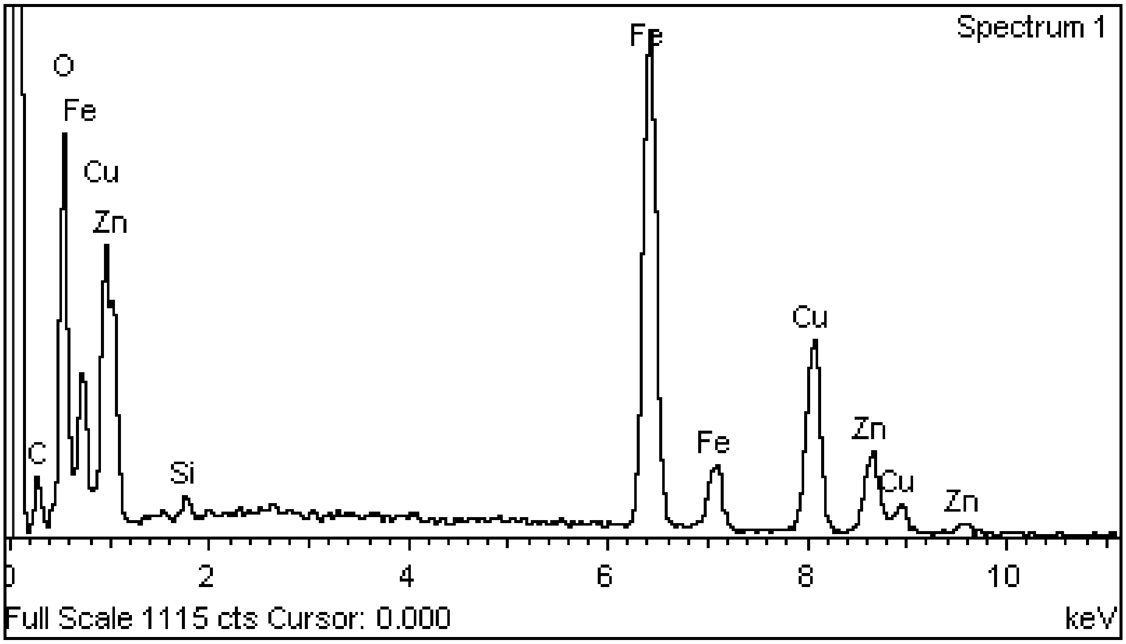
Element	Weight%	Atomic%
C K	14.29	29.97
O K	27.80	43.75
Si K	0.64	0.57
Mn K	0.56	0.26
Fe K	55.85	25.18
Br L	0.85	0.27
Totals	100.00	

Figure 21: EDX image and element composition of pitting area



Element	Weight%	Atomic%
C K	7.14	17.59
O K	26.00	48.10
Si K	0.43	0.46
Cl K	0.44	0.37
Mn K	0.61	0.33
Fe K	43.34	22.97
Cu K	14.59	6.80
Zn K	7.45	3.37
Totals	100.00	

Figure 22: EDX image and element composition of general corrosion area



Element	Weight%	Atomic%
C K	12.78	30.33
O K	21.40	38.13
Si K	0.50	0.50
Fe K	30.26	15.45
Cu K	23.06	10.35
Zn K	12.01	5.24
Totals	100.00	

Figure 23: EDX image and element composition of pitting area surface

4.5 Linear Polarization Resistance (LPR)

The next step was to obtain the results from the experiment. The results obtained from the experiment were collected and analyzed using the linear polarization resistance (LPR). Two different areas which are general corrosion and pitting area were used to study on the corrosion behavior of X52 carbon steel in 3% NaCl solution saturated with CO_2 in this experiment are presented below.

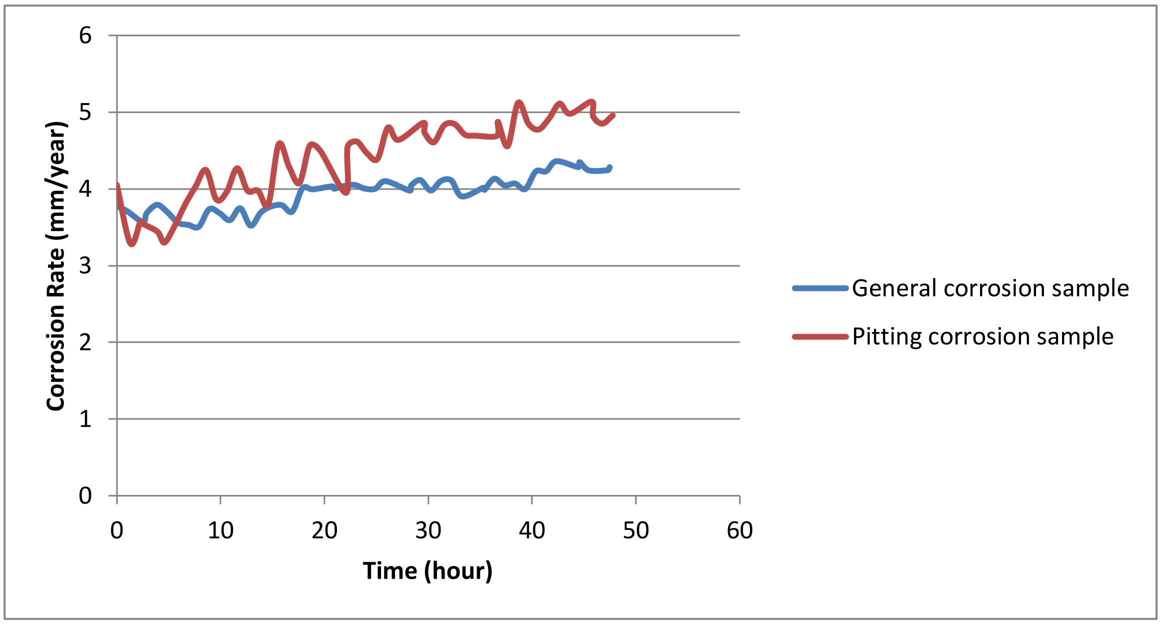


Figure 24: Corrosion rates recorded for general corrosion and pitting corrosion sample API X52 steel after 48 hours immersion at 50°C, 3% NaCl solution, 1 bar CO_2.

The corrosion rate of the two different area that obtained by the LPR test is shown in Figure 24. It can be seen that the pitting corrosion has higher corrosion rate which is 4.4 mm/yr while corrosion rate for general corrosion is 4.0 mm/yr. However, the difference in corrosion rate was relatively small and it was assumed to be the same in the industry.

4.6 Discussions

Operating condition of the pipeline can cause major impact on the corrosion inside the pipeline. Temperature and flow regime are closely linked since CO_2 corrosion is dynamic and very sensitive to electro-chemical and physical imbalances especially in fluctuating pressure (P), temperature (T), and velocity (V). Generally steady state (P, T, V,) conditions tend to promote protective film compaction thus causing passivation and low corrosion rates. Lower temperatures around 50°C tend to promote patchy corrosion with softer multi-layered iron carbonate (siderite) scales and this can been seen along the pipeline because the operating temperature of this pipe is 55^oC for inlet and 30^oC at the outlet.

Other operating condition that can cause pitting in this pipeline is wettability. The competition between oil and water wetting can frequently be the deciding factor. Oil wetting is generally inhibitive whereas water wetting is a root cause of corrosion. The onset of corrosion can be linked to the water cut anywhere in the range ~1-70%. Careful conservatism is vital for deep water assets and water cut is one of the causes that need to be noted: [8]

For <2% water cut - Low Risk corrosion
For 2-10% water cut - Medium Risk Corrosion
For >10-40 % water cut -High Risk Corrosion
For >>40% water cut- Very High Risk Corrosion

High water cut, of which in this project is 67% containing significant level of Cl^- (3,500 ppm max) had led to pitting whenever corrosion inhibitor availability is low (40%). However the pitting in Figure 18.1 and 18.2 is not caused by water cut but it has high probability due to the deposit or inclusion because the pitting is at different area. Below are several possible causes for corrosion in the pipeline:

Possible factors

Factor	General Corrosion	Pitting
Inclusion	Not observed based on the EDX element composition	Not observed based on the EDX element composition
Deposit	No evidence	No evidence
Microbiologically Influenced Corrosion (MIC)	Not observe in the pipeline	Pitting corrosion should be grouped along the pipeline
Process base	Metal loss happen along the pipeline by referring to the visual inspection and IP data.	Pitting corrosion should be grouped along the pipeline

Process base has a high tendency to cause general and pitting corrosion based from what has been discussed above. However, there will be a group of pitting that is near to each other if it is caused by water cut. The pitting area for microbiologically influenced corrosion (MIC) is quite similar with the process base pitting where the pitting happen should be near to each other instead at different areas. MIC is an electrochemical process where microorganisms initiate, facilitate, or accelerate a corrosion reaction on a metal surface. Wagner said that pits associated with MIC often have a small surface opening with a large subsurface cavity but it is differ from Figure 5. [9]

Elemental composition in Figure 21 and 22 shows a very small different in composition and it does not affect the corrosion rate between the sample in a long run. Besides, the difference in corrosion rates shown in Figure 24 is small and it was considered same. This suggests that the inclusions or deposit might be facilitating the pit initiation. However, there is no evidence that deposit might be the factor because the piping sample already is too old.

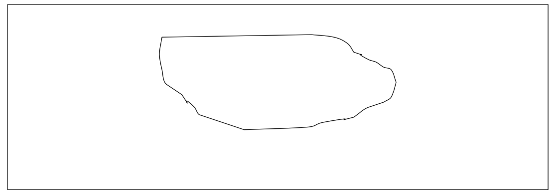


Figure 25–Inclusion

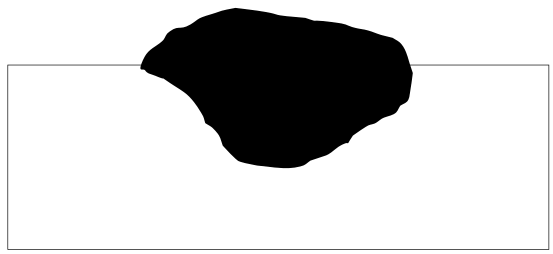


Figure 26–Deposit

Figure 25 illustrates how the pitting happens because of the inclusion. The general corrosion will take place on the metal surface and when the metal losses reach to the inclusion, the pit will be initiated. On the other hand, in Figure 26, the pitting occurrence on a metal surface is due to some environmental difference between one area on that surface and deposit. These differences will create anodic and cathodic areas, setting up a basic corrosion cell. The anode is the area at which the metal is lost. The electrons move by the metal flow to the cathode to be consumed in a reduction reaction. The pitting caused by inclusion and deposit will occur at different area and this parallel with the visual inspection record.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

As a conclusion, the objectives set up for this research has been accomplished which are basically to conduct visual inspection on the actual pipeline condition, investigate the occurrence of corrosion in the pipeline with relation to the operation and inspection data and analyse the contributing factor of the corrosion corresponding to the location of uniform and localize pitting corrosion.

The visual inspection shows that the actual pipeline condition is parallel with the IP data where it is indicated that the pipelines undergo metal loss and pitting corrosion. Overall pipeline condition shows general corrosion symptom while pitting corrosion was spotted at section H, J, and K. Further study can be done in order to evaluate the accuracy of the IP data by comparing it with other technique of inspection like Ultrasonic Testing (UT).

The operation conditions of the pipeline play a major role on the corrosion inside the pipeline. High water cut of 67% contains significant level of Cl^- (3,500 ppm max) that lead to pitting whenever the corrosion inhibitor availability is low (40%). However the pitting in Figure 18.1 and 18.2 is not because of water cut but it has high probability because of the deposit or inclusion. Elemental composition in Figure 21 and 22 shows a very small different in composition. Besides, the difference in corrosion rates shown in Figure 24 is small and it was considered same. The results from visual inspection, EDX, and LPR validate that the possible factor for the pitting is deposit or inclusion. Further study can be done to find suitable prevention method in order to reduce corrosion rate and pitting in the pipeline.

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