CERTIFICATION OF APPROVAL

Innovation Of Ultrasonic Testing As An Effective Corrosion Monitoring Tool

By

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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.

(WAN MUHAMMAD FAIZ BIN WAN RUSTAM)

ABSTRACT

Plant inspection is not only to uphold safety in terms equipment integrity but also to optimize the cost of both operation and maintenance. Ultrasonic testing (UT) is a common Non-destructive technique (NDT) to monitor corrosion rates of the equipments. Current practices of UT only based on point thickness gauging technique to obtain corrosion rates. The utilization of this method can be optimized by area based thickness inspection. This innovation can produce accurate corrosion rate and reliable 3-dimension model for Fitness-for-service (FFS) level 3 assessment by using finite element method. The objective of this project is to develop an effective corrosion monitoring tools by innovating conventional A-scan ultrasonic testing (UT) thickness gauging technique. A series of UT experiment with different corrosion profile will be done. Actual corrosion rate (CR_{act}) as a control variable is measured by weighting the mass loss of the sample. UT thickness measurement is applied by using the specified method to get the corrosion rate (CR_{area}) derived from area based inspection and compared with current application (CR_{point}). The corrosion profile also can be produced and will be analyzed further by finite element analysis in FFS assessment. The result shows that UT innovation can produce high accuracy of corrosion rate as high as intrusive mass loss coupon method compared with current practice. A precise 3-dimension corrosion profile that resembles the actual condition as well can be developed that is practical to produce an accurate FFS level 3 assessments. The conclusion is the innovation of UT in monitoring corrosion has high potential to produce the reliable result in cost effective operation.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Corrosion is the deterioration of materials by the interaction with a specific environment. It is a major problem in petroleum refineries and chemical process plants. Key equipment, such as piping, condensers, vessels, boilers and heat exchangers can be degraded by corrosion attack. Such attack can reduce equipment performance and reliability and in extreme cases, lead to unexpected failures and shutdowns.

Corrosion causes millions dollars spend each year that gives significant influence to global Gross Domestic Product (GDP) values. It is not only about the cost of failure but also the preventive measures taken by the plant owner. Expenditures from plant owner in maintaining corrosion are considered as direct cost, a major part from the total corrosion.

Knowing that corrosion cannot be stopped, reliable corrosion management and maintenance should be implemented in operating the process plant.

One of the major components of plant corrosion management is corrosion monitoring of equipment. The main objective of corrosion monitoring is to assure the integrity of the asset. Corrosion monitoring during operations can help minimize such damage by indicating when corrosion initiated and by measuring the rate of corrosion damage. This information can be used to alter operating conditions to reduce corrosion or to plan maintenance and repair work.

In the last two decades, an extensive range of corrosion monitoring techniques and systems has evolved for detecting, measuring, and predicting corrosion damage. The expansion of oil and gas production under extremely challenging operational conditions, cost pressures brought about by worldwide competitions and public demand for higher safety standard expedite the corrosion monitoring market.

Corrosion monitoring techniques can be divided into two major divisions, direct measurement and indirect measurement. Direct measurement is one that measures parameters directly affected by the corrosion process.

Table 1.1: *Direct Corrosion Measurement Techniques* [1]

INTRUSIVE TECHNIQUES	
Physical Techniques	• Mass loss coupons • Electrical resistance • Visual inspection
Electrochemical DC Techniques	• Linear polarization resistance (LPR) • Zero resistance ammeter (ZRA) • Potentiodynamic-galvanodynamic polarization • Electrochemical noise (ECN)
Electrochemical AC Techniques	• Electrochemical impedance spectroscopy (EIS) • Harmonic distortion analysis
NONINTRUSIVE TECHNIQUES	
Physical Techniques for Metal Loss	• Non destructive testing (NDT) • Magnetic flux leakage (MFL) • Surface activation and gamma radiometry • Electrical field mapping
Physical Techniques for Crack Detection and propagation	• Acoustic emission • Ultrasonic (flaw detection) • Ultrasonic (flaw sizing)

Indirect measurement is to measure the indirect changes, either in the environment or in the metallic component.

Table 1.2: *Indirect Corrosion Measurement Techniques* [1]

ON-LINE TECHNIQUES	
Corrosion products	• Hydrogen monitoring
Electrochemical techniques	• Corrosion potential (Ecorr)
Water chemistry	• pH • Conductivity • Dissolved oxygen • Oxidation reduction (redox) potential
Fluid detection	• Flow regime • Flow velocity
Process parameters	• Pressure • Temperature • Dewpoint
Deposition monitoring	• Fouling
External monitoring	• Thermography
OFF-LINE TECHNIQUES	
Water chemistry parameters	• Alkalinity • Metal ion analysis • Concentration of dissolved solids • Gas analysis • Residual oxidant • Microbiological analysis
Residual inhibitor	• Filming corrosion inhibitors • Reactant corrosion inhibitors
Chemical analysis of process sample	• Total acid number • Sulfur content • Nitrogen content • Salt content in crude oil

Many of the techniques established are reliable in monitoring corrosion, but due to challenging market condition influenced the management to choose cost effective yet reliable technique. Cost effectives can be from reliability, continuous, nonintrusive, instantaneous result and in-situ factors.

Current practice of UT is as thickness gauging at pipeline thickness measurement locations (TML) to calculate corrosion rate. This point based thickness measurement method as shown in ***Figure 1.1*** will produce corrosion rates that not accurately represent the actual condition of the piping or equipment guiding to conservative decisions.

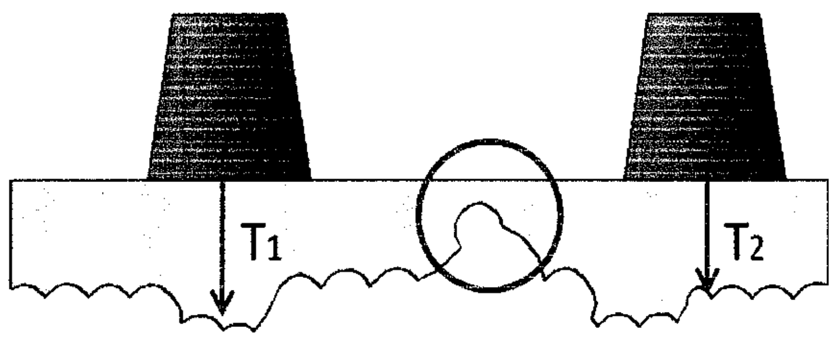


Figure 1.1: *Point Based Thickness Measurement*

Furthermore, current practices in plant inspection require accurate corrosion profile to produce accurate corrosion rate measurement and corrosion profile for fitness-for-service (FFS) assessment.

1.2 PROBLEM STATEMENT

There is a need to innovate and optimize the ultrasonic testing (UT) for corrosion inspection to produce an accurate corrosion measurement for monitoring purpose and also for fitness-for-service (FFS) assessment.

1.3 OBJECTIVE AND SCOPE OF STUDY

The objective of this project is to develop cost effective corrosion monitoring technique by using conventional A-scan ultrasonic thickness gauging. To achieve this objective, several scopes of study will be executed as listed below:

1. UT A-scan innovation technique for measuring corrosion rate of several samples.
2. Analyzing the UT A-scan result (thickness) for corrosion rate determination.
3. Develop the corrosion profile based on UT result for Fitness for Service (FFS) analysis.
4. Develop the detail procedure of implementing the innovated UT A-scan technique for corrosion rate measurement and corrosion profile build up of the sample.

CHAPTER 2

LITERATURE REVIEW

2.1 CORROSION COST

Many studies have been done by governmental or non-governmental bodies about cost of corrosion in various fields of industries. Total cost of corrosion typically estimated by determining the percentage of the Gross Domestic Product (GDP) of those industry.

The total cost of corrosion is divided into two main categories of direct and indirect cost. Direct costs are defined as the costs that incurred by the owner or operator of the facility, plant or structure. Indirect cost indirect costs are defined as those cost that are incurred by others, such as the public, and are not directly felt by the owner or operator. In order to determine accurate corrosion cost, both of the costs should be included in the calculation [2].

This study of UT innovation is related reduce the direct cost. There are several major elements that contribute to direct costs of corrosion [2]. The elements are:

- Cost of additional and more expensive material used to prevent corrosion damage.
- Cost of labor attributed to corrosion management activities.
- Cost of the equipment required because of corrosion-related activities.
- Loss of revenue due to disruption in supply of product.
- Cost of loss reliability.
- Cost of lost capital due to corrosion deterioration.

Latest analytical studies of corrosion cost in 2001 shows that the total direct cost by analyzing 26 industrial sectors in United States (*refer* **APPENDIX A**) is about US$276 billion per year, which is 3.1 percent of the U.S. GDP. Indirect cost to the society was conservatively estimated to be equal to the direct costs. Thus, the total cost to the society could be as much as 6 percent of the GDP.

Focusing into oil and gas business, it is reported that the total annual cost of corrosion in the oil and gas production is estimated to be $1.372 billion, broken down into $589 million in surface pipeline and facility costs, $463 million annually in downhole tubing expenses, and another $320 million in capital expenditures related to corrosion. The total cost of corrosion control in refineries is estimated at $3.692 billion. Of this total, maintenance-related expenses are estimated at $1.767 billion annually, vessel turnaround expenses account for $1.425 billion annually, and fouling costs are approximately $0.500 billion annually. The costs associated with corrosion control in refineries include both processing and water handling [2].

Malaysia also not excluded from this problem, around 4 percent of GDP would mean a loss of around RM 30 billion every year due to corrosion problems. That is also equal or more than RM 1200 annually for every man, woman and child in the country and works out to just about the entire Malaysian healthcare budget for 2008 [3].

2.2 CORROSION MONITORING TECHNIQUES

Referring to NACE standards, there are many techniques that have been implemented in corrosion monitoring. Current corrosion inspection and monitoring typically requires planned periodic shutdowns to inspect the equipments. NACE Standards and Roberge (2007) explain in detail about the techniques that currently used in plant as listed in ***Table 1.1*** and ***Table 1.2*** above.

Not all inspection and monitoring system are applicable for any particular facility and their use will be dependent on the type of corrosion process or material damage that is expected or being looked for. Corrosion monitoring systems vary significantly in complexity. From simple coupon exposures or hand held data loggers to fully integrated plant process surveillance units with remote data access and data management capabilities.

Corrosion monitoring coupon is the simplest and longest-establishment method of estimating corrosion losses in plant and equipment by weight loss analysis. The coupon is introduced to the process and later removed after a reasonable time interval. The coupon is then cleaned from corrosion product and reweighted. From the weight loss, the corrosion rate is obtained by using proper conversion equations. Cleaning of specimen is critical to remove any contaminants that can affect test result. For further detail practice of corrosion monitoring coupon can be referred in NACE Recommended Practice RP-0775 and ASTM G01 and G04. The formula for calculating corrosion rate is:

$$mm/y = \frac{mass\ loss \times 87.6}{(area)(time)(metal\ density)}$$

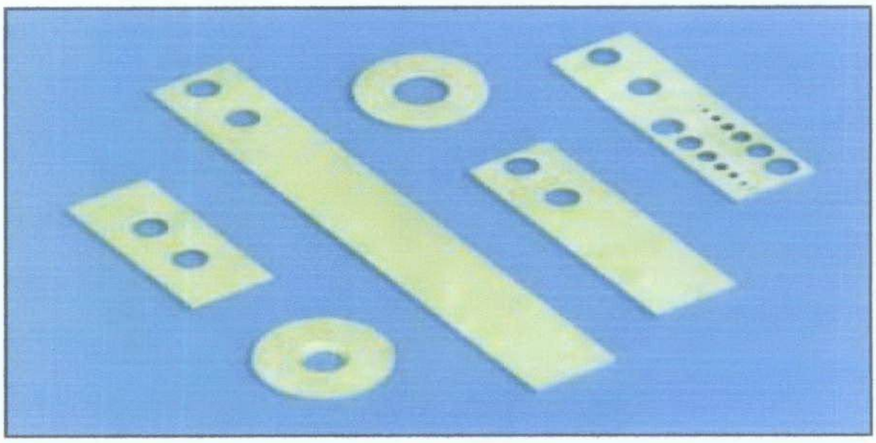


***Figure 2.1:** Mass Loss Corrosion Coupons* [15]

Electrical resistance (ER) probe is one of the most widely used methods for measuring material loss occurring in the interior of plant and pipelines. This technique operates by measuring the changes of electrical resistance of metallic elements immerse in a product. The net change in resistance ratio attributes the metal loss of the equipment to calculate the corrosion rate.

Figure 2.2: *ER Probes* [13]

Inductive resistance probe is a technique that almost similar with ER probe but offer significantly improved sensitivity. Mass changes in the sensor element are detected by measuring changes in inductive resistance of coil, located inside the elements.

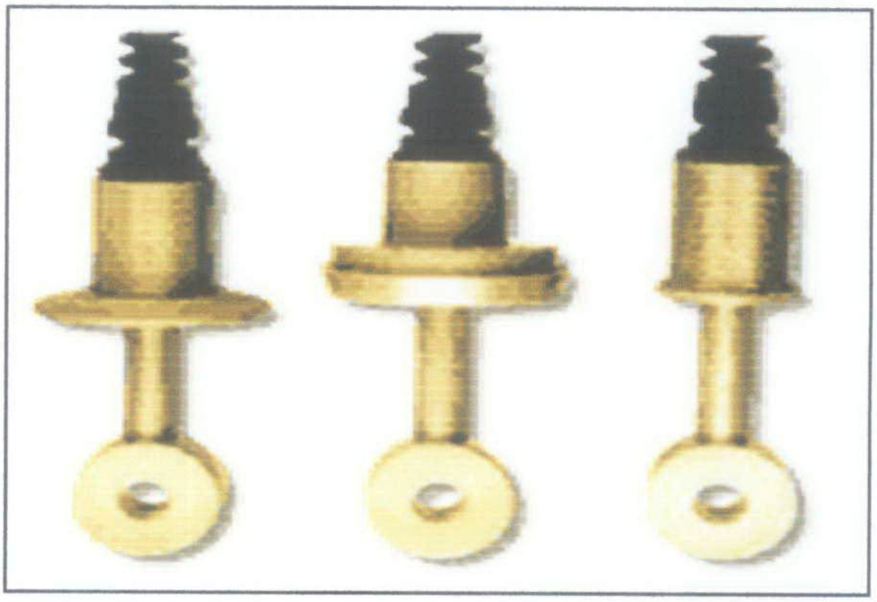


Figure 2.3: *Inductive Resistance Probes* [14]

Linear Polarization Resistance (LPR) is useful as a method to rapidly identify corrosion upsets and initiate remedial action, thereby prolonging plant life and minimizing unscheduled downtime. This technique has been used for over 30 years.

Electrochemical Impedance Spectroscopy (EIS) has been successfully applied to the study of corrosion systems for over 30 years and been proven to be a powerful and accurate method for measuring corrosion rates. In order to access the charge transfer resistance or polarization resistance that is proportional to the corrosion rate, EIS result have to be interpreted with the help of a model interface.

Harmonic Analysis is an on-line analysis that very promising in the field of corrosion monitoring in industrial condition. This technique is related to electrochemical impedance spectroscopy, in that an alternating potential perturbation is applied to one sensor in the three elements probe, with a resultant current probe. Analysis of the harmonic or intermodulation response gives the possibility to obtain the polarization resistance and both Tafel parameters within one measurement. This feature will be further developed to create a corrosion monitoring tool for system under chatodic protection.

Electrochemical Noise (EN) is non-intrusive technique that applies fluctuations of potential or current of a corroding metallic specimen. No other technique, electrochemical or otherwise is even remotely as sensitive as EN to system changes and upsets. ASTM G199 specifies the detail guide for EN measurements.

Potentiodynamic Polarization Method is one of polarization methods that also consist of potentiostaircase and cyclic voltammetry. These three methods are often used for laboratory corrosion testing to produce useful information regarding the corrosion mechanism, corrosion rate and susceptibility of specific material to corrosion in designated environment. Polarization methods involve changing the potential of the working electrodes and monitoring the current which is produced as a function time or potential. Standard test method for this test can be referred in ASTM G59.

Acoustic Emission (AE) is based on measuring the acoustic sound waves that are emitted during the growth of microscopic defect such as stress corrosion cracking (SCC). The sensors can thus essentially be viewed as microphones, which are strategically positioned on structures. Background noise effects have to be taken into consideration for on-line measurement limitation. ASTM E569 and E2374 provide the standard procedure of conducting this technique.

Hydrogen flux monitoring is highly applicable to the oil refining and petrochemical industries with hydrocarbon process stream as indirect corrosion monitoring. One of the common corrosion products of iron or steel in neutral or acidic medium is hydrogen. The generation of atomic hydrogen can be used for corrosion monitoring purpose in either intrusive or non-intrusive forms. Hydrogen monitoring sensors usually attached to the outside walls of piping or vessels.

Chemical analysis is another indirect technique that applies different type of chemical analyses to produce valuable information in corrosion monitoring programs. The measurement of pH, conductivity, dissolved oxygen, metallic and another ion concentrations, water alkalinity, concentration of suspended solid, inhibitor concentrations and scaling indices all fall within this domain. Several of these measurements can be done on-line with help of appropriate probe. Most of the measurements are done by chemical methods in laboratory.

2.3 ULTRASONIC TESTING (UT)

UT is widely used to measure wall thickness and to detect and characterize the failures of piping and equipments. UT is applicable to all structure metals and alloys. With appropriate calibrations standard, proper transducer, and modern, computerized instrumentations, this method becomes more reliable to inspect the reliability of the plants.

As a non destructive method, UT offers obvious advantages over cutting out the pipe or equipment for metallurgical inspection. It is non-intrusive, accurate, reliable, safe to both building and inspection personnel, provides immediate result, require no system shutdown, and it is extremely cost effective. Depending upon the measurement technique, degree of testing, and data analysis method used, UT can produce a general assessment of piping or equipments condition. It also provides direction for capital projects or focus in on a specific area of concern.

The working principles of UT are using the pulse and echo method (reflection method). It uses the high frequency sound waves (0.5 to 25 MHz) are introduced into the material being inspected by piezo-electric transducer. In pulse and echo method, the sound waves travel through the material with some attendant loss of energy (attenuation) due to material characteristics. The pulse will be measured after reflection at interfaces or flaws [6].

Ultrasonic measurement system involves the generation, propagation and reception of short transient signals. It uses straight beam for corrosion detection in the initial investigation. The usage of UT in corrosion monitoring acquires a reading from the same locations at a specified frequency and places great emphasis on its repeatability.

The common types of UT graphical methods are called A-scan, B-scan and C-scan presentations. These three methods will provide a different way of visualizing the region of material being inspected [6]:

- A-scan: result appears in signal amplitude versus distance (material thickness) of y-x axis.
- B-scan: result appears in depth range (material thickness) versus linear movement of transducer (y-x axis).
- C-scan: result appears like topography mapping (planned view of scanned surface of defect disposition).

Until now, ultrasonic testing (UT) still becomes one of the most popular techniques that have been used in various fields of industries for thickness gauging and internal flaw detecting.

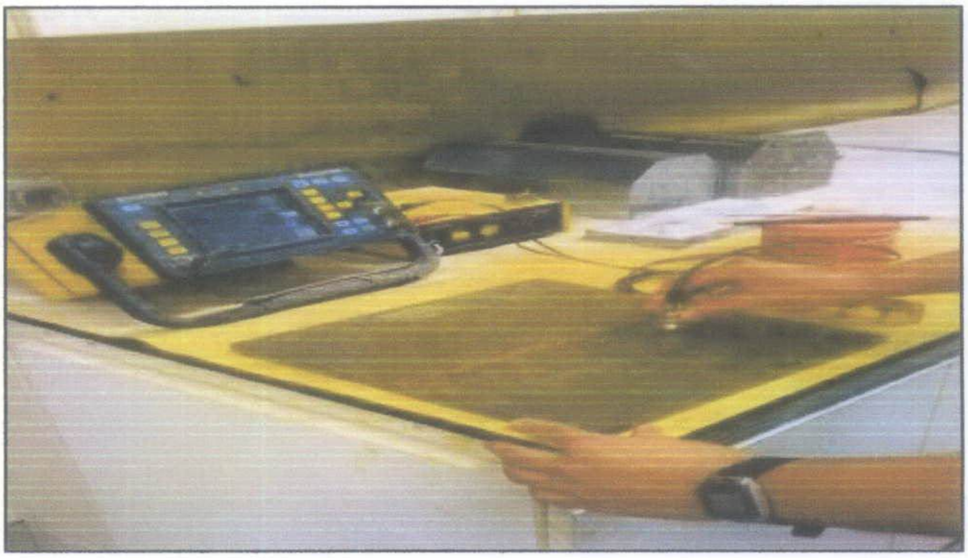


Figure 2.4: *UT A-Scan Thickness Gauging*

2.4 ULTRASONIC TESTING CURRENT PRACTICE IN CORROSION MONITORING

Ultrasonic testing (UT) also has been used as corrosion monitoring tools beside the applications of corrosion monitoring techniques as stated above. American Petroleum Institute (API) Standard API 574, Inspection of Piping System (2003) specifies recommended practice for UT applications in monitoring corrosion by identifying and establishing thickness monitoring locations (TML). TMLs are designated areas in the piping systems where thickness measurements are periodically taken *(refer to* **APPENDIX B***)*. By taking repeated measurements and recording at the same point over extended period, corrosion rate can be calculated by using the specific formula as listed below.

Long term corrosion rate (LT): (mm/year)

$$corrosion\,rate\,(LT) = \frac{T_{initial} - T_{actual}}{t}$$

Short term corrosion rate (ST): (mm/year)

$$corosion\ rate\ (ST) = \frac{T_{previous} - T_{actual}}{t}$$

Remaining life: (years)

$$remaining\ life = \frac{T_{actual} - T_{required}}{corrosion\ rate}$$

$T_{initial}$: Initial Thickness in inches or mm.

$T_{previous}$: Previous Thickness in inches or mm.

T_{actual}: Actual Thickness in inches or mm (measured during inspection).

$T_{required}$: Required Thickness in inches or mm (based on design).

t: time

2.5 FITNESS FOR SERVICE (FFS)

Fitness-for-Service (FFS) assessments are quantitative engineering evaluations which are performed to demonstrate the structural integrity of an in-service component containing a flaw or damage. This assessment is widely used to evaluate the equipments in refining and petrochemical industries. Based on API RP 579, there are several procedures need to be followed to achieve its objective [11]:

- Flaw and damage mechanism identification.
- Consideration of the applicability and limitations of FFS procedure.
- Data requirements for analysis.
- Assessments technique and acceptance criteria.
- Remaining life evaluation.
- Remediation.
- In service monitoring.
- Documentation.

API RP 579 provides three levels of assessment for each type of damage mechanism (*refer* **APPENDIX C**) which is level 1, level 2 and level 3. Each level provides a balance between conservatism, the amount of information required for the evaluation, the skills of the personnel performing the assessment and the complexity of the analysis being performed. Level 1 is the easiest level that produces the most conservative result compared with level 2 and level 3.

Level 3 FFS assessment provide the most detailed evaluation that produces results that are more precise than level 1 and level 2. This level need most detail inspection and component information required. The analysis is based on numerical techniques such as the finite element analysis.

Data gathering also includes the corrosion profile development for detail analysis of the flaw or damage. Any suitable non-destructive technique (NDT) can be used for data collection such as ultrasonic testing or radiography testing. By developing an accurate corrosion profile, the result of assessments will be more reliable to evaluate the equipments.

CHAPTER 3

METHODOLOGY

3.1 THEORY OF EXPERIMENT

New innovation of UT will be based on area thickness measurement in measuring corrosion rate. Based on this innovation, the more accurate thickness difference can be obtained compared with current practice. This method also will give the corrosion profile of the tested area that can be used to estimate type of corrosion and fitness for service (FFS) analysis. An accurate profile is very important to represent the real condition of the equipment for analysis. The load that the flawed area can sustain the operational environment can be measured directly from the profile to decide whether the equipment or piping can continue to operate, service, maintenance or replace. This assessment also can prevent any conservative decision in maintaining the equipment.

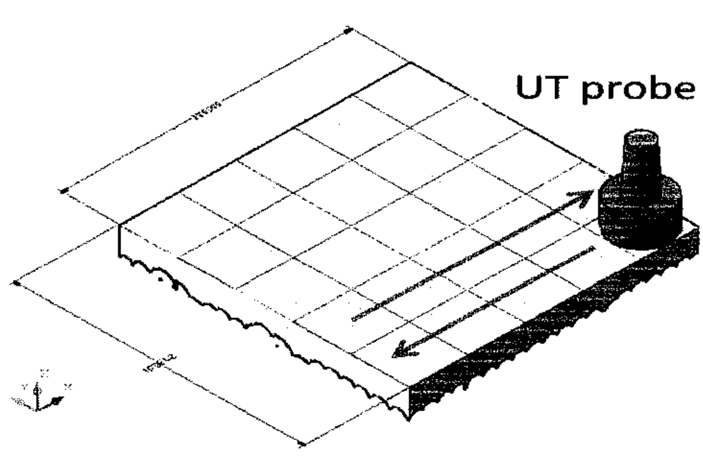


Figure 3.1: *Area Based Thickness Measurement*

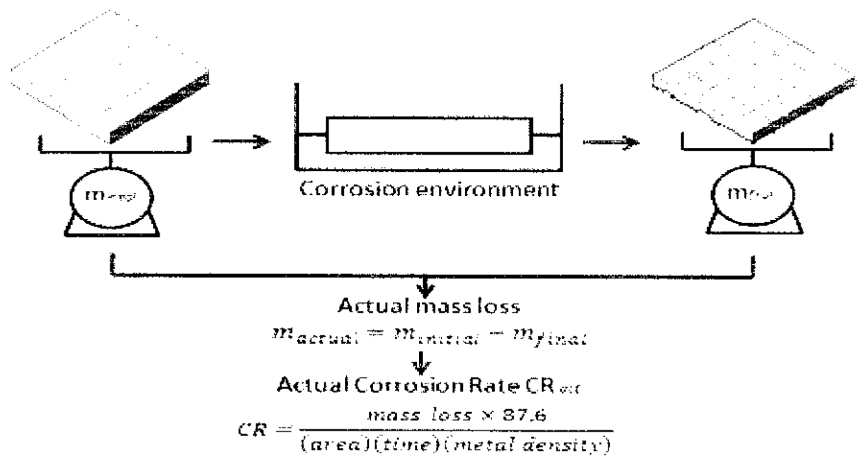


Figure 3.2: *Actual Corrosion Rate Calculation*

UT result analysis to compare the innovation (CR_1) and the current practice (CR_2) with actual (CR_{act}) corrosion rate:

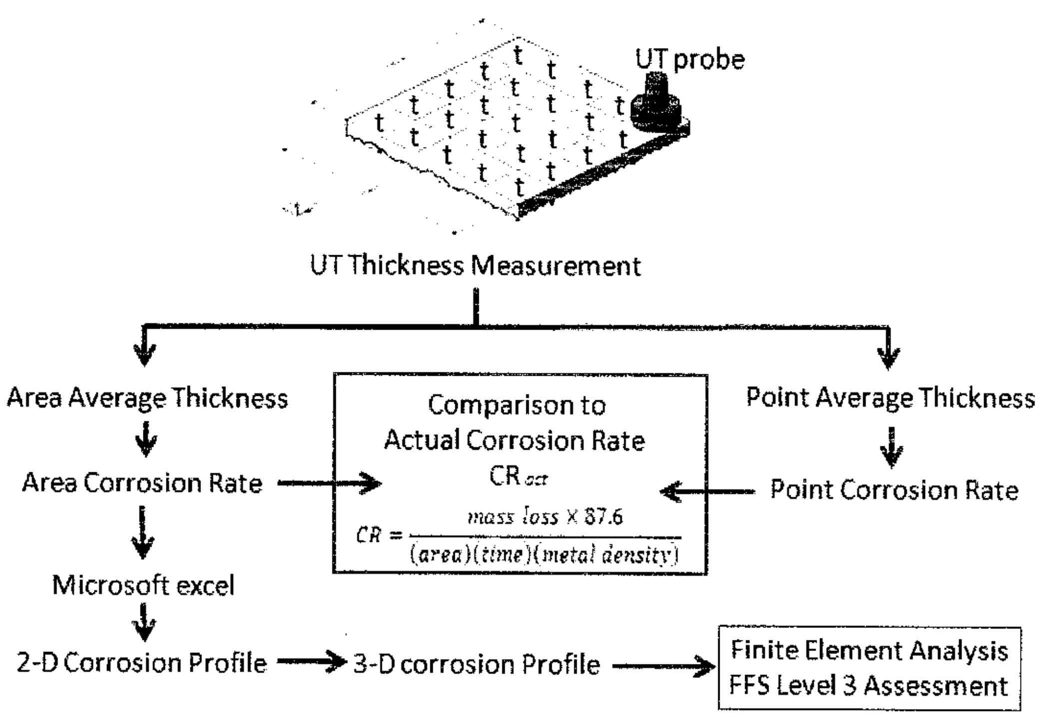
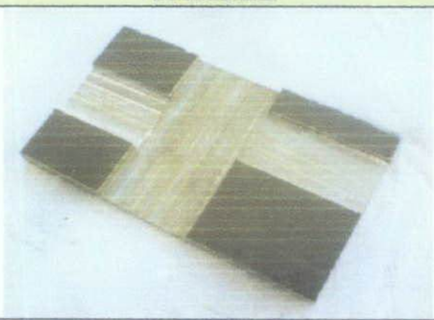
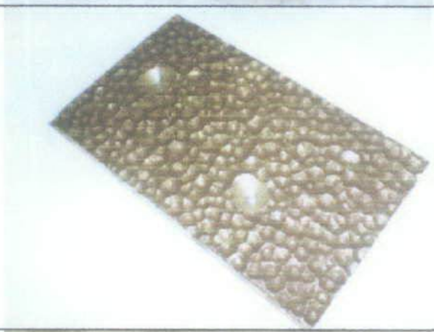
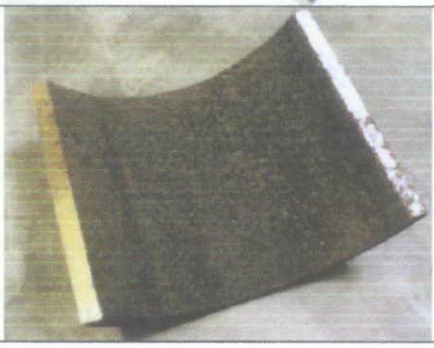


Figure 3.3: *Experimental Flow Chart*

3.2 SAMPLE DEVELOPMENT

The sample is developed with the corrosion profile through machining to create the actual condition of corrosion damage of equipment. Ultrasonic testing will be done on the other side of the sample to measure corrosion rate and developing 3-dimension model for FFS assessment.

Table 3.1: *Sample Development for Inspection*

EXPERIMENT	SAMPLE	DESCRIPTIONS
UT1		• Carbon steel plate. • Simple corrosion profile. • Produce by machining flat surface in different thickness. • Used for corrosion rate measurement.
UT2		• Carbon steel plate. • More complex profile. • General corrosion on one side of the sample. • Used for corrosion rate measurement.
UT3		• Carbon steel X 52 pipes. • Internally general corrosion. • Used for corrosion profile development for FFS analysis.

3.3 CORROSION RATE MEASUREMENTS

3.3.1UT1 AND UT2 EXPERIMENT PROCEDURES

1. Perfect sample will be weighted and recorded.
2. Sample is profiled then will be weighted and recorded.
3. The sample for UT2 is made more complex compared with UT1 sample.
4. Actual corrosion rate (***CR*** $_{act}$) is calculated based on mass loss from the sample.

$$actual\ corrosion\ rate\ (mm/year) = \frac{mass\ loss \times 87.6}{(area)(time)(metal\ density)}$$

5. Thickness of the sample will be measured by UT A-Scan and recorded.
6. Point based inspection corrosion rate (***CR*** $_{point}$) will be calculated by the difference of average of several specified thickness with initial thickness over years of operation.

$$point\ corosion\ rate\ (mm/year) = \frac{T_{previous\ (avg)} - T_{actual}}{t}$$

7. Area based inspection corrosion rate (***CR*** $_{area}$) will be done by the difference of average of overall thickness with initial thickness over years of operation.

$$area\ corosion\ rate\ (mm/year) = \frac{T_{previous\ (avg)} - T_{actual}}{t}$$

8. All the result is analyzed and compared with the ***CR*** $_{act}$ and recorded.
9. Discussion and conclusion should be produced from result.

3.4 FFS STRESS ANALYSIS PROFILE DEVELOPMENT

3.4.1 UT3 EXPERIMENT PROCEDURES

1. Severe corroded pipeline is chosen for the experiment.
2. General thickness measurement should be done by using bigger probe size (Ø 24 mm) to the whole sample.
3. All the thicknesses will be recorded and corrosion profile is created to identify the area that contains critical thickness profile (CTP). Corrosion rate also will be calculated from the average thickness difference from 100% inspection.
4. Thickness measurement will be done to CTP using smaller probe size (Ø 10 mm) and should produce more specific corrosion profile. Corrosion rate will be measured for the critical area.
5. Fitness-For-Service (FFS) assessment will be done based on the CTP following the API RP 579 standards.
6. 3-dimension corrosion profile will be developed from the thickness measurement and will be analyzed for stress analysis.
7. The result from stress analysis and FFS assessment will be compared and analyzed.
8. Discussion and Conclusion will be produced from the result obtained.

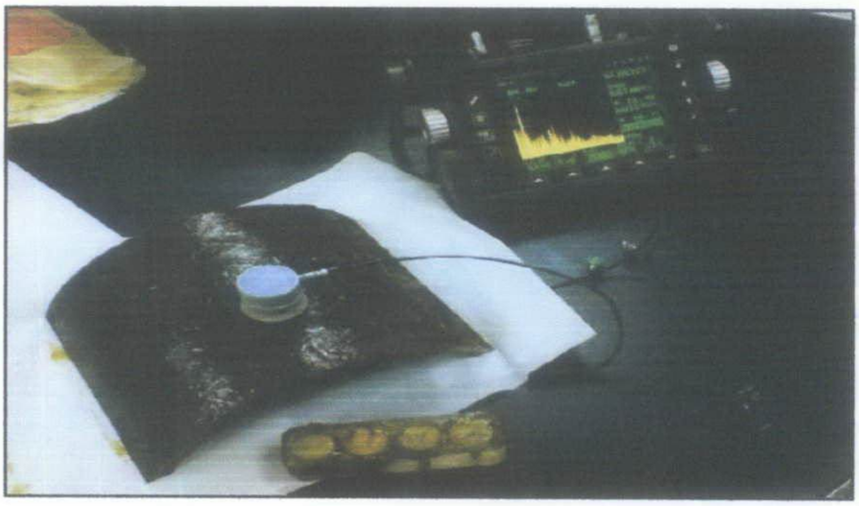


Figure 3.4: *Ultrasonic Testing on the Sample*

3.5 MILESTONES OF THE PROJECT'S MAIN ACTIVITIES

Table 3.2: *Project Milestones*

NO	PROJECT	START	END	REMARK
1	UT familiarization	20/09/2010	24/09/2010	DONE
2	Specified the best method for the experiment.	27/09/2010	01/10/2010	DONE
3	Experiment on machined sample (UT1): Corrosion rate measurement	04/10/2010	22/10/2010	DONE
4	Experiment on corroded sample (UT2): Corrosion rate measurement.	25/05/2011	23/06/2011	DONE
5	Experiment on internally corroded pipe (UT3): Corrosion rate measurement and FFS analysis.	25/07/2011	5/08/2011	DONE

3.6 PROJECT PLANNING

All the details on project plans are in the Gantt chart (*refer* **APPENDIX D**).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 CORROSION RATE MEASUREMENTS

4.1.1 Experiment UT1 Corrosion Rate Measurement

By using sample UT1 (simple corrosion profile), the comparison was done between current monitoring practice based on point gauging (***CR** point*) and area based inspection with 10 MHz (***CR area** 10 MHz*) and 5 MHz (***CR area** 5 MHz*) probe. The result obtained as below:

Table 4.1: *UT1 Corrosion Rates of Each Conducted Test*

Actual corrosion rates based on weight measurement	Point based inspection	Area based inspection	
***CR** actual*	***CR** point*	***CR area** 10 MHz*	***CR area** exp5 MHz*
1.6 mm/year	2.1 mm/year	1.63 mm/year	1.64 mm/year

From the result of corrosion rates above, the experimental values are compared with the actual value to find the error percentage as shown in ***Table 4.2***.

__Table 4.2:__ UT1 Error Percentage of Experimental Corrosion Rates

Percentage of error		
Point Gauging	$error\, point\ (\%) = \frac{\lvert 2.1 - 1.6 \rvert}{1.6} \times 100$	31.3%
Area 10 kHz	$error\, area\ 10\ kHz\ (\%) = \frac{\lvert 1.63 - 1.6 \rvert}{1.6} \times 100$	1.9 %
Area 5 kHz	$error\, area\ 5\ kHz\ (\%) = \frac{\lvert 1.64 - 1.6 \rvert}{1.6} \times 100$	2.5 %

The percentage of error from point gauging is 31% than the actual CR (from weight loss). However, the error by area based measurement is low from 1.9 to 2.5%.

4.1.2 Experiment UT2 Corrosion Rate Measurement

The result is obtained by using complex corrosion profile by using point based inspection and area based inspection to find the corrosion rate. The UT probe used is 10 MHz and the result as below:

Table 4.3: *UT2 Corrosion Rates of Each Conducted Test*

Actual corrosion rates based on weight measurement	**Point based inspection**	**Area based inspection**
CR_{actual}	CR_{point}	CR_{area}
0.72 mm/year	1.31 mm/year	0.53 mm/year

From the result of corrosion rates above, the experimental values are compared with the actual value to find the error percentage as shown in ***Table 4.4***.

Table 4.4: *UT2 Error Percentage of Experimental Corrosion Rate*

Percentage of error		
Point Gauging	$error\,point\,(\%) = \frac{\lvert 1.31 - 0.7 \rvert}{0.7} \times 100$	87.1%
Area	$error\,area\,(\%) = \frac{\lvert 0.53 - 0.7 \rvert}{0.7} \times 100$	24.3%

The error from point based gauging is very high, 87.1% as compared to area based inspection of only 24.3%. Thus, the area based inspection is more accurate and should be used as corrosion monitoring method.

4.2 FFS STRESS ANALYSIS PROFILE DEVELOPMENT

This experiment is conducted on the corroded carbon steel X-52 pipelines (UT3 sample) to develop the corrosion profile by using area based inspection.

4.2.1 General Thickness Profile (GTP)

By using 24 mm (4MHz) UT probe, the general thickness inspection is done to develop the general view of thickness profile to estimate the pipe actual condition as shown in ***Table 4.5*** and ***Figure 4.1***.

Table 4.5: *General Thickness Measurement Result*

	L1	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**	**L9**	**L10**
C1	12.4	12.65	12.65	12.64	12.53	12.45	12.52	12.2	12.45	12.4
C2	11.17	9.55	9.91	8.39	9.92	9.9	9.9	10.38	9.9	11.8
C3	12.44	12.41	12.44	12.42	12.23	12.35	12.39	12.33	11.64	11.69
C4	11.2	11.25	12.2	12.15	12.23	12.26	11.95	11.87	11.21	12.23
C5	11.05	11.66	11.78	11.17	11.46	12	11.86	11.18	11.11	11.05
C6	11.05	11.56	11.41	11.14	11.26	11.04	11.2	11.46	11.14	11.2
C7	11.04	10.76	11.49	11.19	11.23	11.22	11.72	11.37	11.76	11.56
C8	11.49	11.66	11.77	11.72	11.71	11.68	11.48	11.87	11.31	10.74
C9	11.4	11.62	11.82	11.66	11.84	11.67	11.3	11.81	11.46	11.04
C10	11.63	11.51	11.66	11.54	11.54	11.66	11.74	11.42	11.85	11.82
C11	11.67	11.76	11.74	11.82	11.78	11.88	11.89	11.84	11.99	11.96

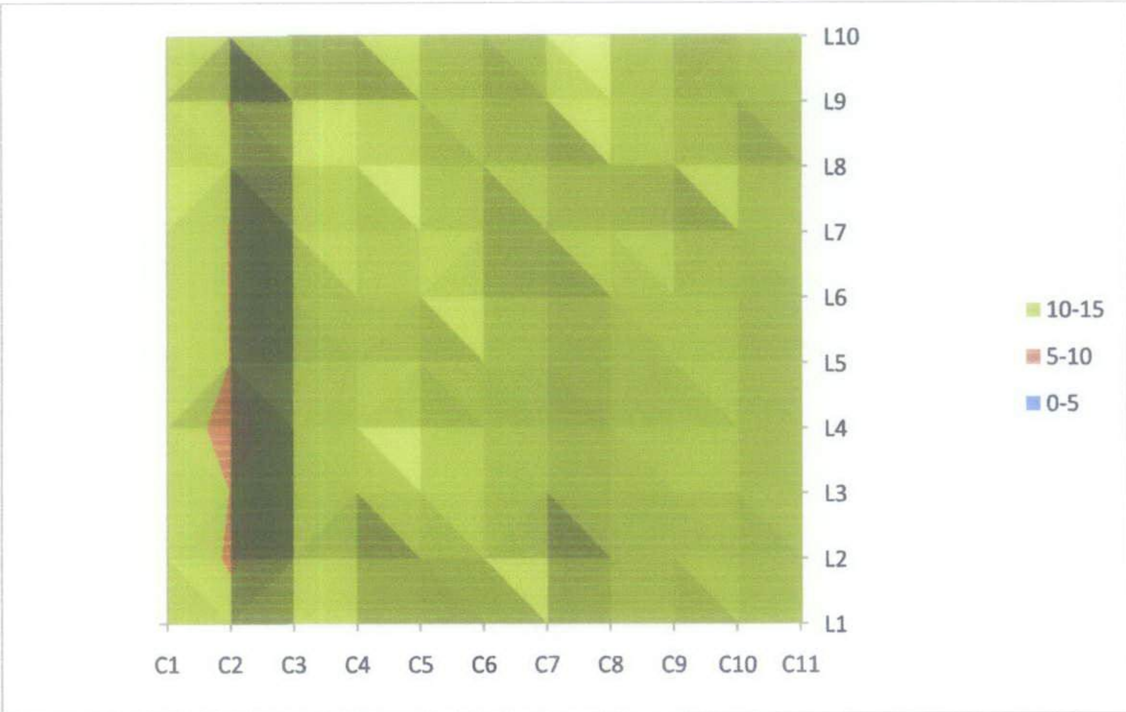


Figure 4.1: *2-dimension General Corrosion Profile*

The critical thinning area can be identified and further investigated by using smaller probes diameter for more detail inspection.

4.2.2 Critical Thickness Profile (CTP)

The detail thickness measurement by using 10 mm (10 MHz) probe on smaller inspection grid produce more accurate corrosion profile as shown below:

Table 4.6: *Critical Thickness Measurement Result*

	C1	C2	C3	C4	C5	C6	CTP	CTP - FCA
L1	12.46	12.32	9.83	10.32	11.58	11.69	9.83	8.83
L2	12.45	12.45	10.12	10.02	11.73	11.69	10.02	9.02
L3	12.47	12.37	9.83	9.92	11.64	11.63	9.83	8.83
L4	12.1	11.93	9.9	9.9	11.6	11.58	9.9	8.9
L5	12.13	11.63	10.2	10.38	12.12	11.98	10.2	9.2
L6	12.1	11.72	9.73	10.11	12.3	12.48	9.73	8.73
L7	12.51	12.37	9.92	9.83	12.3	12.12	9.83	8.83
L8	11.98	12	9.99	9.8	11.8	12.02	9.8	8.8
L9	12.15	12.46	9.9	9.9	12.35	12.37	9.9	8.9
L10	12.45	12.46	9.92	9.89	12.35	12	9.89	8.89
L11	12.45	12.32	9.85	9.78	12.12	12.33	9.78	8.78
L12	12.45	12.22	9.82	9.86	12.2	12.27	9.82	8.82
L13	12.46	12.43	8.63	8.34	12.41	12.38	8.34	7.34
L14	12.48	12.5	8.7	8.52	12.03	11.99	8.52	7.52
L15	12.6	12.57	9.32	9.38	12.4	12.13	9.32	8.32
L16	12.67	12.26	9.63	9.78	10.98	11.72	9.63	8.63
L17	12.39	12.64	9.92	9.9	11.99	12.04	9.9	8.9
L18	12.4	12.54	9.52	9.86	12.33	12.42	9.52	8.52
L19	12.55	12.6	10.12	9.97	12.4	12.3	9.97	8.97
L20	12.56	12.57	10.32	9.82	12.38	12.46	9.82	8.82

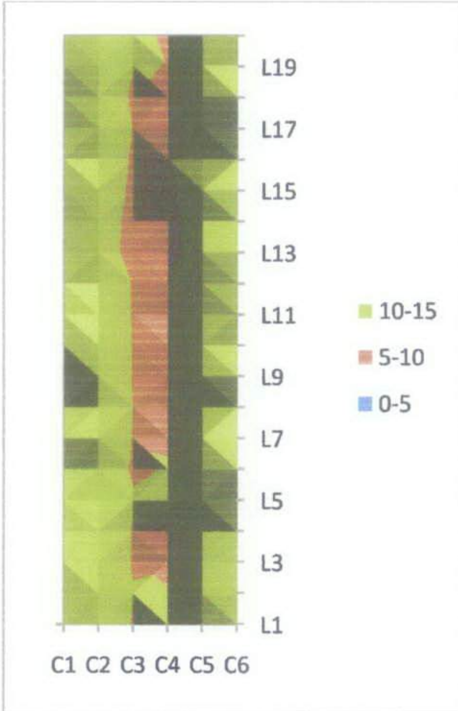
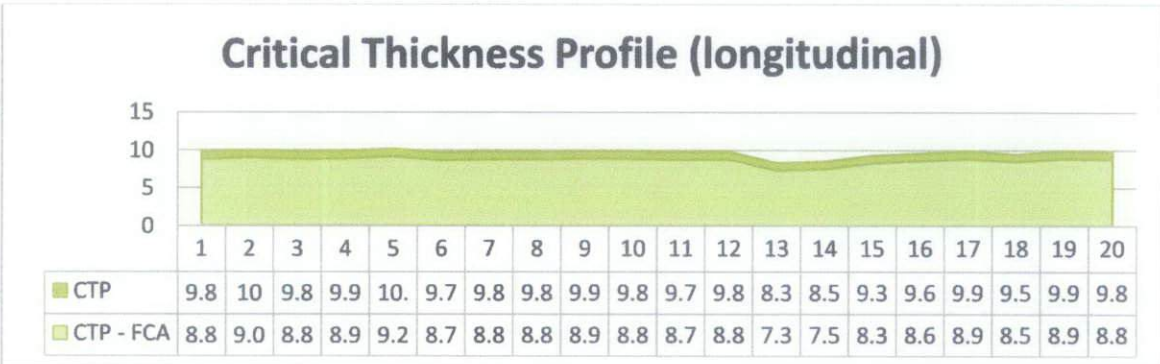


Figure 4.2: 2-dimension Critical Corrosion Profile

From the result, critical thickness profile is obtained to be used in FFS level 1 assessment. The figure below also includes the thickness with future corrosion allowance (FCA) to estimate the future thickness loss.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
CTP	9.8	10	9.8	9.9	10.	9.7	9.8	9.8	9.9	9.8	9.7	9.8	8.3	8.5	9.3	9.6	9.9	9.5	9.9	9.8
CTP - FCA	8.8	9.0	8.8	8.9	9.2	8.7	8.8	8.8	8.9	8.8	8.7	8.8	7.3	7.5	8.3	8.6	8.9	8.5	8.9	8.8

Figure 4.3: Critical Thickness Profile

4.2.3 Corrosion Rate Measurement

By using area based inspection, corrosion rates also measured for general area and critical area.

Table 4.7: *Corrosion Rate Measurement of UT3 Sample*

AREA	INITIAL AVERAGE THICKNESS (mm)	FINAL AVERAGE THICKNESS (mm)	OPERATIONAL TIME (year)	CORROSION RATE (mm/year)
GTP	12.7	11.57	20	0.06
CTP	12.7	11.39	20	0.07

4.2.4 Fitness-For-Service Level 1 Assessment

This level 1 assessment is using analytical method based on API RP 579 standard referring the critical thickness profile (CTP) to determine whether the pipe is acceptable or not for next operation.

a. Minimum required thickness (longitudinal and circumferential):

$$t_{min}^{c} = \frac{PD_0}{2(SE + PY)} + MA = 7.996mm$$

$$t_{min}^{L} = \frac{PD_0}{4(SE + PY)} + t_{sl+}MA = 3.998mm$$

$$t_{min} = max\left(t_{min}^{C}, t_{min}^{L}\right) = max(7.996{,}3.998) = 7.996mm$$

Since:

$$P = maximum\ allowable\ pressure = 11.596\ MPa$$

$$D_0 = outside\ diameter = 254\ mm$$

$$S = allowable\ stress = 137.8\ MPa$$

$$E = quality\ factor = 1.0\ (seamless)$$

$$Y = t_{min} < D_0/6\ coefficient = 4.0$$

$$MA = thread\ or\ groove\ mechanical\ allowance = 0$$

$$t_{sl} = additional\ thickness = 0$$

b. Remaining thickness ratio:

$$R_t = \left(\frac{t_{mm} - FCA}{t_{min}}\right) = 0.918$$

Since:

$$t_{mm} = minimum\ measured\ thickness = 8.34\ mm$$

$$FCA = future\ corrosion\ allowance = 1.0\ mm$$

c. Length for thickness averaging:

$$L = Q\sqrt{Dt_{min}} = 2137.689mm$$

Since:

$$Q = allowable\ remaining\ strength\ factor$$

$$= 50.00\ (refer\ \textbf{APPENDIX E})$$

$$D = inside\ diameter = 228.6\ mm$$

d. Flaw dimension from longitudinal CTP:

$$S = 200mm$$

e. Component determination of continued operation:

Since:

$$(S = 200mm) < (L = 2137.689\ mm)$$

The longitudinal extent of metal loss is acceptable if:

$$R_t(0.918) \geq 0.20 \rightarrow TRUE$$

$$t_{mm} - FCA\ (8.34 - 1.0 = 7.34) \geq 2.5\ mm\ (0.10\ inches) \rightarrow TRUE$$

$$L(2137.689mm) \geq 1.8\sqrt{Dt_{min}} = 76.96 \rightarrow TRUE$$

The metal loss is acceptable for operation.

4.2.5 3-Dimension Corrosion Profile Development

The thickness measured then is used to construct the corrosion profile by using Autodesk Inventor 2010 software. The model style used is rusted carbon steel.

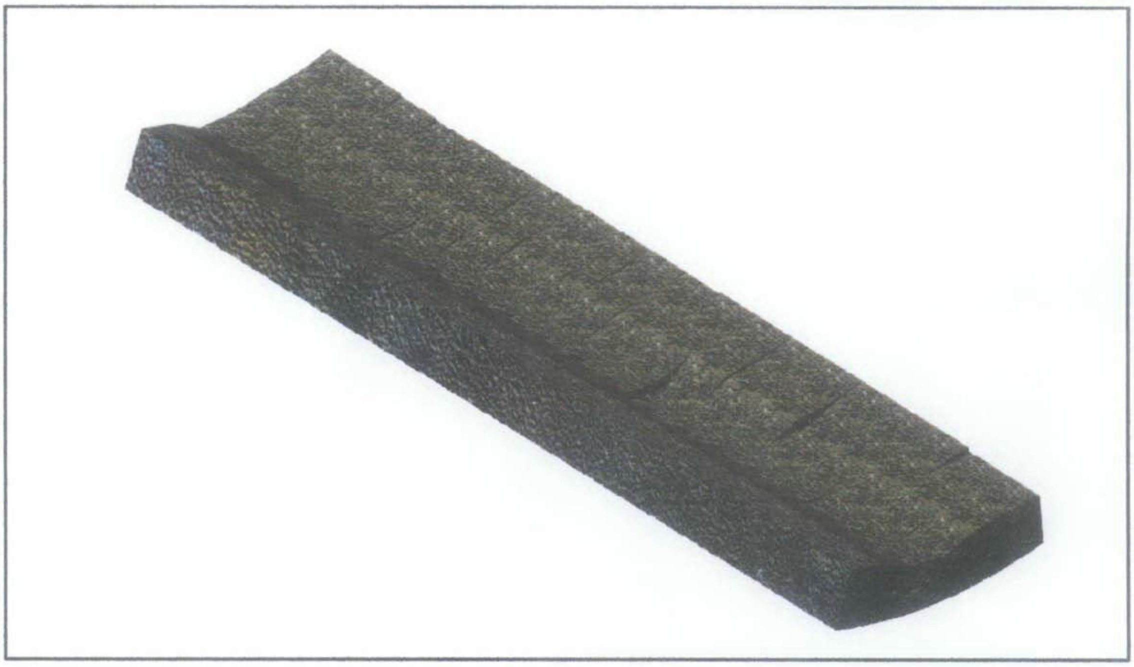


Figure 4.4: *3-dimension Corrosion Profile Model*

The material properties and design conditions as of the inspected pipe as stated below are used for FFS level 3 finite element stress analysis.

Table 4.8: *UT3 Sample Material Properties and Designed Condition*

MATERIAL PROPERTIES	
Material	Carbon steel
Density	7.85 g/cm^3
Yield strength	207 MPa
Ultimate tensile strength	345 MPa
Maximum allowable stress	137.8 MPa
Maximum allowable pressure	11.596 MPa
Nominal pipe size	10 inch/254 mm
Wall thickness (design)	12.7 mm
Pipe schedule	SCH 60
Time of operation	20 years

4.2.6 Finite Element Stress Analysis of Corrosion Profile

From the simulation of finite element stress analysis by using Autodesk Inventor 2010 software, the reactant stress can be measured. The Von Mises stress is the resultant stress of 1st and 3rd Principal Stress. The result in shown below:

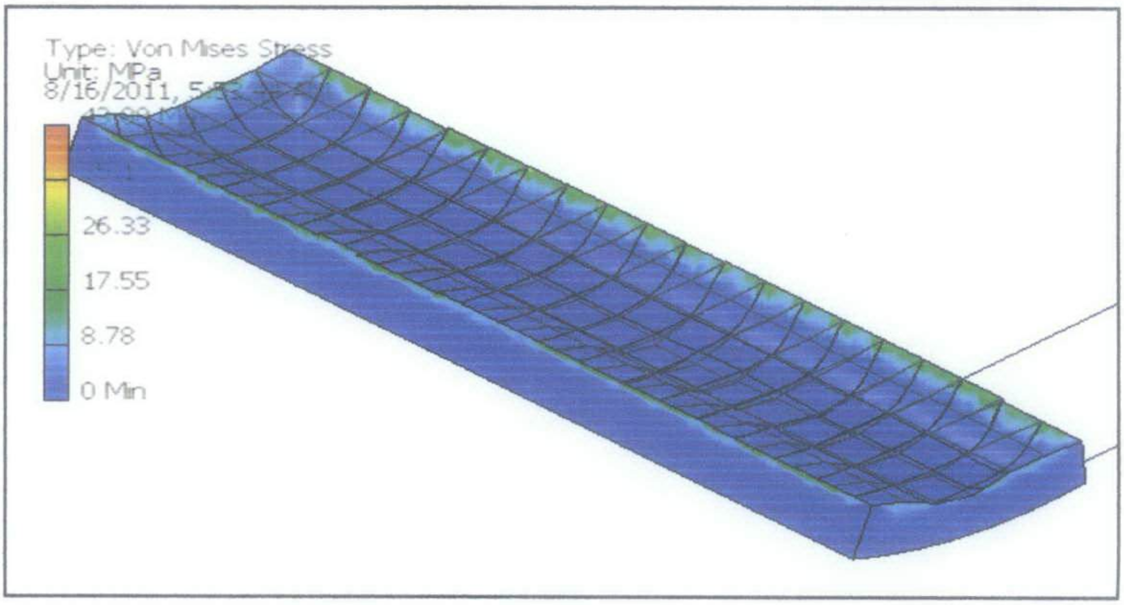


Figure 4.5: *Stress Analysis (Von Mises Stress)*

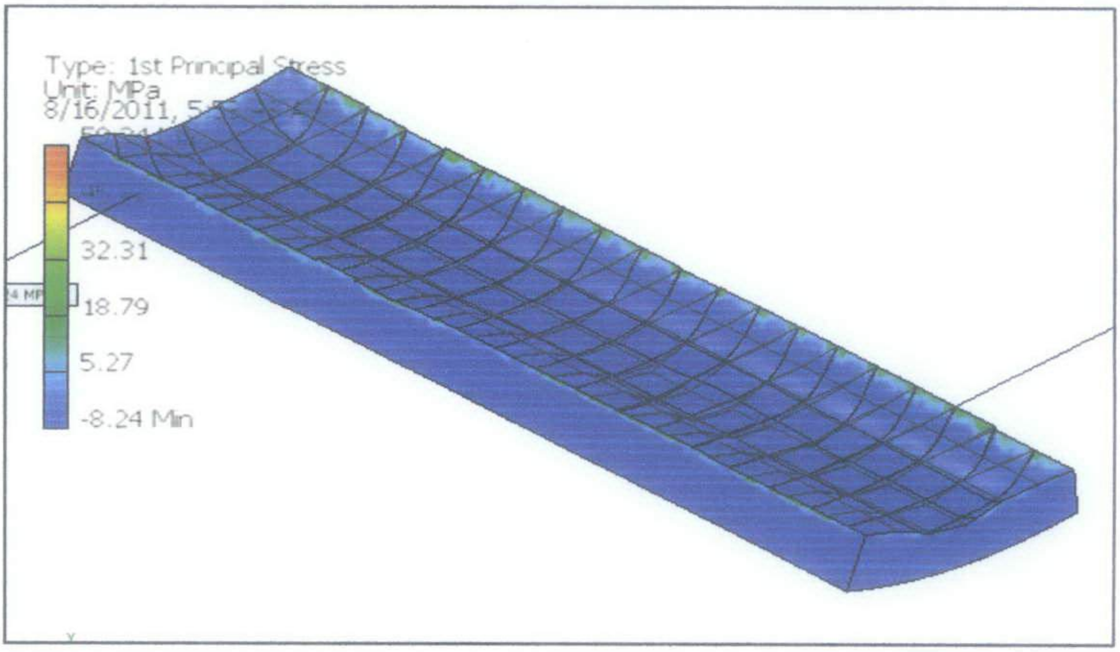


Figure 4.6: *Stress Analysis (1st Principal Stress)*

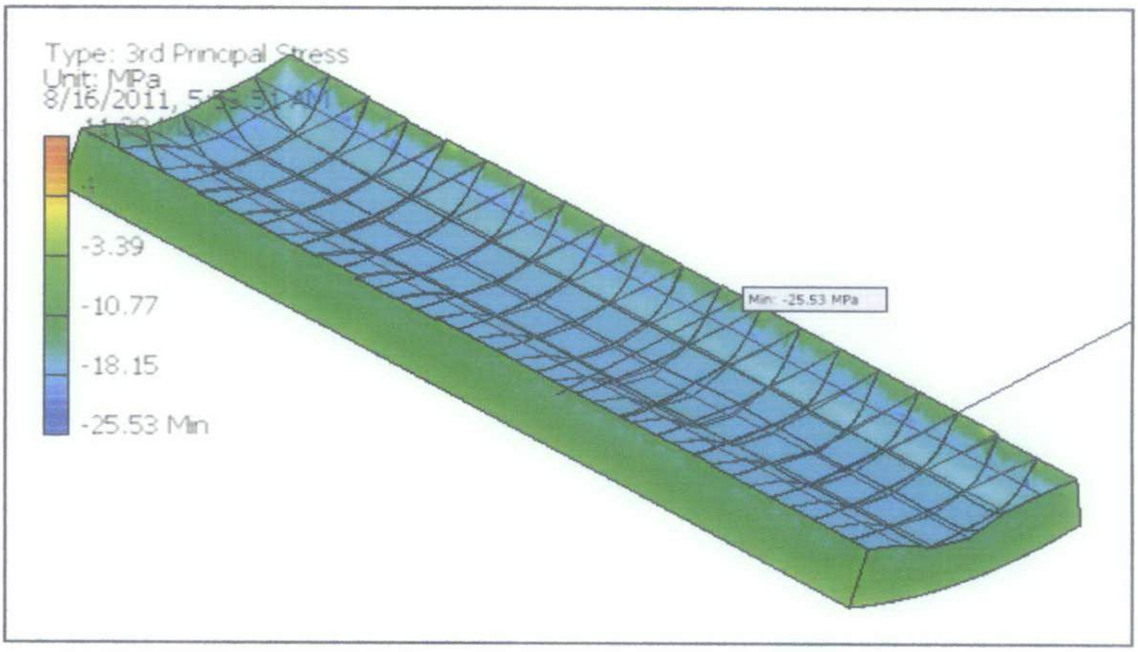


Figure 4.7: *Stress Analysis (3rd Principal Stress)*

The maximum and minimum reactant stress can be achieved from the simulation above:

Table 4.9: *Stress Analysis Summary of 3-dimension Profile*

STRESS ANALYSIS SUMMARY		
STRESS	**MINIMUM (MPa)**	**MAXIMUM (MPa)**
Von Mises Stress	0.0000	43.8772
1st Principal Stress	-8.24447	59.3382
3rd Principal Stress	-25.5309	11.3774

The reaction stress created due to internal pressure did not exceed maximum allowable stress of the pipe. This analysis shows that the pipe still safe for next operation within allowable pressure range.

4.2.7 Evaluation of Maximum Allowable Operating Pressure (MAOP)

After the assessment of the pipe shows that it is safe for next operation, the initial operating pressure is evaluated to determine it is safe to be used or need to be lowered due to corrosion damage. This evaluation is based on ASME B31G standard.

a. Depth percentage of corrosion:

$$\%\, pit\ depth = 100d/t$$

$$d = maximum\ depth\ of\ corroded\ area = 0.17\ inch$$

$$t = nominal\ wall\ thickness\ of\ the\ pipe = 0.5\ inch$$

$$\therefore \%\, pit\ depth = 34\%$$

b. Measured longitudinal extent of corroded area:

$$L_m = 1.12B\sqrt{Dt}$$

$$D = nominal\ outside\ diameter\ of\ pipe = 10\ inch$$

$$B = \sqrt{\left(\frac{d/t}{1.1(d/t) - 0.15}\right)^2 - 1} = 1.142$$

$$\therefore L_m = 2.86\ inch$$

c. Computational of A:

$$A = 0.893\left(\frac{L_m}{\sqrt{Dt}}\right) = 1.142$$

d. Safe maximum pressure for corroded area, P':

$$P' = 1.1P\left[\frac{1 - \frac{2}{3}\left(\frac{d}{t}\right)}{1 - \frac{2}{3}\left(\frac{d}{t\sqrt{A^2+1}}\right)}\right] = 1683.1\ psi = 11.60\ MPa$$

$$P = establish\ MAOP = 11.596\ MPa = 1681.858\ psi$$

e. Acceptance criteria for new MAOP for corroded area:

$$since: \quad P\,(11.596\ MPa) \cong P'(11.60\ MPa)$$

The corroded region can use the established MAOP for operation.

4.2.8 Fitness-For-Service (FFS) result summary

The results of FFS assessment of the corroded pipe are summarized below:

***Table 4.10:** Summary of FFS Assessment Result*

NO	FFS ASSESSMENT	ACCEPTANCE/REJECTION
1	Level 1 Assessment	Acceptable for operation
2	Level 3 Assessment (stress analysis)	Acceptable for operation
3	Maximum Allowable Operating Pressure (MAOP)	Initial operating pressure is acceptable

It is shown that the carbon steel X-52 pipeline is acceptable for every assessment conducted for next operation.

4.3 DISCUSSION

This result of this study shows that the innovation of ultrasonic testing (UT) from point based to area based thickness inspection can produce more accurate corrosion rate measurements and can be further developed a reliable corrosion profile for Fitness-For-Service (FFS) analysis.

Corrosion rates obtained from experiment UT1 clearly shows that the area based inspection produce more accurate result (< 3% of error) compared with point based inspection (32.52% of error). As the corrosion profile becomes more complex in UT2 experiment, the error percentage of the result increasing compared with the actual corrosion. Though, the result yield the same pattern which is by using area based inspection can produce lower error percentage corrosion rate (24.3%) and the higher error value for point based inspection (87.1%).

Results achieved from this experiment also present useful information to the inspector by producing the corrosion profile of the tested sample. Through this information, inspector can predict the type of corrosion and determine the damage mechanisms and further be analyzed in FFS to determine the integrity of the pipeline or equipment in plant based on experiment UT3. Stress analysis shows that the resulting stress from internal pressure applied (11.596 MPa) on the pipeline is acceptable to be used for next service. This result is supported with the FFS level 1 assessment that also approves the pipe acceptability for operation although possibly for other cases, it can be very conservative assessment. The -dimension modeling represents the most accurate condition of the equipment or pipelines for assessment.

Smaller grid and probe used for thickness measurement will produce more accurate 3D corrosion profile although it will be too many readings to be recorded. Therefore, it is preferable that the grid size should be equal with probe size. The justification of the size of area to be inspected also should be based on the size of defects and equipments or pipelines.

CHAPTER 5

CONCLUSION

The purposes of ultrasonic testing (UT) innovation from thickness gauging to area based thickness measurement in monitoring corrosion is achieved. Maximizing the usage of UT technique be able to develop a reliable corrosion management system to be applied in industrial environment especially oil and gas industry.

This innovation can produce a reliable and accurate corrosion rate of equipment or pipelines. The accuracy of UT area based technique doesn't have a significant difference with mass loss coupon method, the most common routine to be used to predict a reliable corrosion rate in industrial applications. Instead of producing only an accurate result, this non-intrusive technique also can give instantaneous result with cost effective compared with mass loss coupon. Finally, the plant owner can acquire a reliable corrosion rate in easier approach that helps to decide the best procedure for the equipment and piping corrosion management.

The thickness measured over the area specified of the equipment can produce a precise 3-dimension corrosion profile for stress analysis in Fitness-For-Service (FFS) assessment. The profile represents the actual condition instead of rough estimation of the inspected equipment for analysis. The result of stress analysis of profile also become more accurate and not too conservative based on the detail attention of complex corrosion damages. The proper action can be done from the accurate analysis without compromising the safety and integrity of the equipment.

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APPENDIX A1: CORROSION COST IN VARIOUS FIELD OF INDUSTRIES

BEA Categories	BEA Subcategories	Appendix	Sector Name	Detailed GDP	Covered GDP	Non-Covered GDP	Cost of Corrosion per Sector	Cost of Corrosion for Covered Sectors	Corrosion Fraction of GDP	Extrapolated Cost of Corrosion
				$ x billion	$ x billion	$ x billion	$ x billion	$ x billion	%	$ x billion
Agricultural, Forestry, and Fishing	Farms, agricultural services	X	Agricultural	127.3	127.3		1.1	1.1	0.86%	1.1
Mining	Metal, coal, and non-metallic minerals	T	Mining	28.2	105.6		0.1	1.5	1.42%	1.5
	Oil and gas extraction	S	Oil and Gas Exploration and Production	77.4			1.4			
Manufacturing	Motor vehicles and equipment	72% of N (*)	Motor Vehicles	107.2	663.2		16.9	38.9	5.87%	38.9
	Miscellaneous manufacturing industries	AA	Home Appliances	25.7			1.5			
	Food and kindred products	Y	Food Processing	124.8			2.1			
	Paper and allied products	W	Pulp and Paper	55.3			6.0			
	Printing and publishing			94.0						
	Chemicals and allied products	G	Hazardous Materials Storage	168.4			7.0			
		87.5% of V (**)	Chemical, Petrochemical, Pharmaceutical				1.5			
	Rubber and miscellaneous plastics products	12.5% of V (**)	Chemical, Petrochemical, Pharmaceutical	55.3			0.2			
	Petroleum and coal products	U	Petroleum Refining	32.9			3.7			
	Electronics and other electric equipment	Z (****)	Electronics	172.8		772.7	No estimate made	-	Same as in analyzed sectors: 5.87%	45.3
	Lumber wood products	-	-	41.4			-			
	Furniture and fixtures	-	-	24.1						
	Stone, clay, and glass products	-	-	58.2						
	Primary metals industry	-	-	54.1						
	Fabricated metals products	-	-	102.2						
	Industrial machining and equipment	-	-	150.8						
	Other transportation equipment	-	-	59.2						
	Instruments and related products	-	-	57.7						
	Tobacco products	-	-	16.8						
	Textile mill products	-	-	25.4						
	Apparel and other textile products	-	-	25.8						
	Leather and leather goods	-	-	4.2						

APPENDIX A2: CORROSION COST IN VARIOUS FIELD OF INDUSTRIES

BEA Categories	BEA Subcategories	Appendix	Sector Name	Detailed GDP	Covered GDP	Non-Covered GDP	Cost of Corrosion per Sector	Cost of Corrosion for Covered Sectors	Corrosion Fraction of GDP	Extrapolated Cost of Corrosion
				$ x billion	$ x billion	$ x billion	$ x billion	$ x billion	%	$ x billion
Transportation and Utilities	Trucking and warehousing	R	Hazardous Materials Transport	109.3	465.3		0.9	61.5	13.22%	61.5
	Railroad transportation	Q	Railroad Cars	41.6			0.5			
	Local and interurban passenger transit	I	Railroads				No estimate made			
	Water transportation	O	Ships	14.1			2.7			
		F	Waterways and Ports				0.3			
	Transportation by air	P	Aircraft	88.2			2.2			
		H	Airports				No estimate made			
	Pipelines, except natural gas	68% of E (***)	Gas and Liquid Transmission Pipelines	6.1			4.8			
	Electric, Gas, and Sanitary Services	32% of E (***)	Gas and Liquid Transmission Pipelines	206.0			2.2			
		J	Gas Distribution				5.0			
		K	Drinking Water and Sewer Systems				36.0			
		L	Electrical Utilities				6.9			
	Communications, inc. telephone, radio, TV	M (****)	Telecommunications	234.1		262.6	No estimate made	-	Same as in analyzed sectors: 13.22%	34.7
	Transportation services	-	-	28.5			-			
Services	Auto repair services and parking	28% of N (*)	Motor Vehicles	80.9	80.9		6.5	6.5	8.03%	6.5
	Miscellaneous repair services	-	-	24.5		24.5	-	-	Same as in analyzed sector: 8.03%	2.0
	Amusement and recreation	-	-	72.2		72.2	-	-		5.8
	Hotels and other lodging places	-	-	76.0		1,659.4	-	-	0.0%	0
	Personal services	-	-	55.4						
	Business services	-	-	447.1						
	Motion pictures	-	-	28.8						
	Health services	-	-	492.6						
	Legal services	-	-	116.4						
	Educational services	-	-	66.7						
	Social services	-	-	57.1						
	Membership organizations	-	-	54.0						
	Other services	-	-	251.5						
	Private households	-	-	14.0						

APPENDIX A3: CORROSION COST IN VARIOUS FIELD OF INDUSTRIES

BEA Categories	BEA Subcategories	Appendix	Sector Name	Detailed GDP	Covered GDP	Non-Covered GDP	Cost of Corrosion per Sector	Cost of Corrosion for Covered Sectors	Corrosion Fraction of GDP	Extrapolated Cost of Corrosion
				$ x billion	$ x billion	$ x billion	$ x billion	$ x billion	%	$ x billion
Construction	Construction	-	-	378.1		378.1	-	-	Same as in Utilities Category: 13.22%	50.0
Wholesale Trade	Wholesale trade	-	-	610.9		610.9	-	-	0.0%	0
Retail Trade	Retail trade	-	-	796.8		796.8	-	-	0.0%	0
Finance, Insurance, and Real Estate	Finance, insurance, and real estate	-	-	1,689.4		1,689.4	-	-	0.0%	0
Statistical Discrepancy	Statistical discrepancy	-	-	-24.8		-24.8	-	-	0.0%	0
Federal	Federal general government	BB	Defense	398.6	398.6	-	20.0	20.0	6.70%	20.1
		CC	Nuclear Waste Storage				0.1	0.1		
	Federal government enterprises	-	-	62.1		62.1	-	-	0.0%	0
State and Local	State and local general government	DD	Highway Bridges	680.7	680.7		8.3	8.3	1.22%	8.3
	State and local government enterprises	-	-	64.4		64.4	-	-	0.0%	0
				TOTAL GDP	Covered GDP	Non-Covered GDP	TOTAL	TOTAL in Sectors That Were Analyzed		TOTAL in U.S. Economy
				$8,790.1	$2,421.6	$6,368.5	$137.9	$137.9		$275.57
					27.55%	72.45%				3.1% of GDP

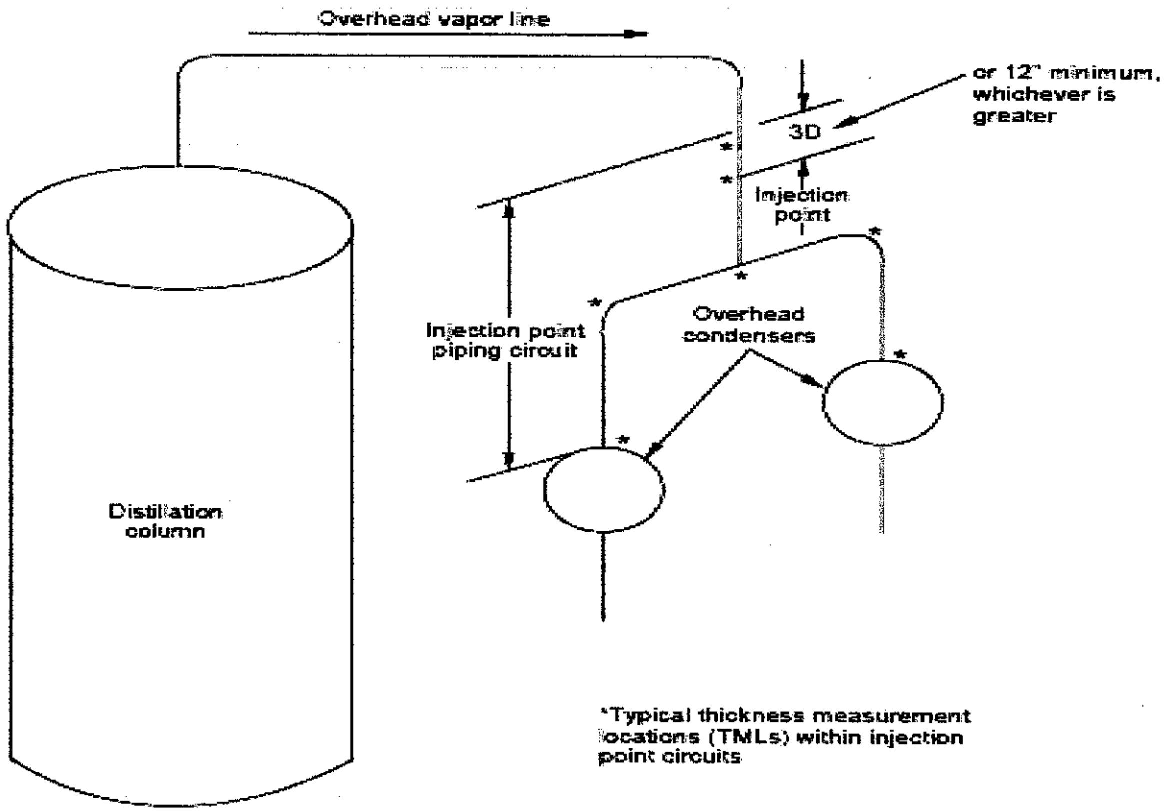
*Based on the estimated cost of corrosion of motor vehicles found in the sector analysis, 72% is assigned to Manufacturing Motor Vehicles and Equipment, while 28% is assigned to Auto Repair Services and Parking.

**12.5% of the total value of shipments in the Chemical, Petrochemical, and Pharmaceutical industry is for Plastics Material and Resin Manufacturing (11.0%) and Synthetic Rubber Manufacturing (1.5%).

***Based on the mileage of transmission and gathering pipelines (328,000 km for gas and 154,000 km for oil), 32% of the corrosion costs of transmission pipelines is assigned to liquid lines, and 68% to gas lines.

****Placed in non-covered GDP, because the sector analysis for Electronics and for Telecommunications resulted in "no estimate made."

APPENDIX B: THICKNESS MEASUREMENT LOCATIONS (TML)

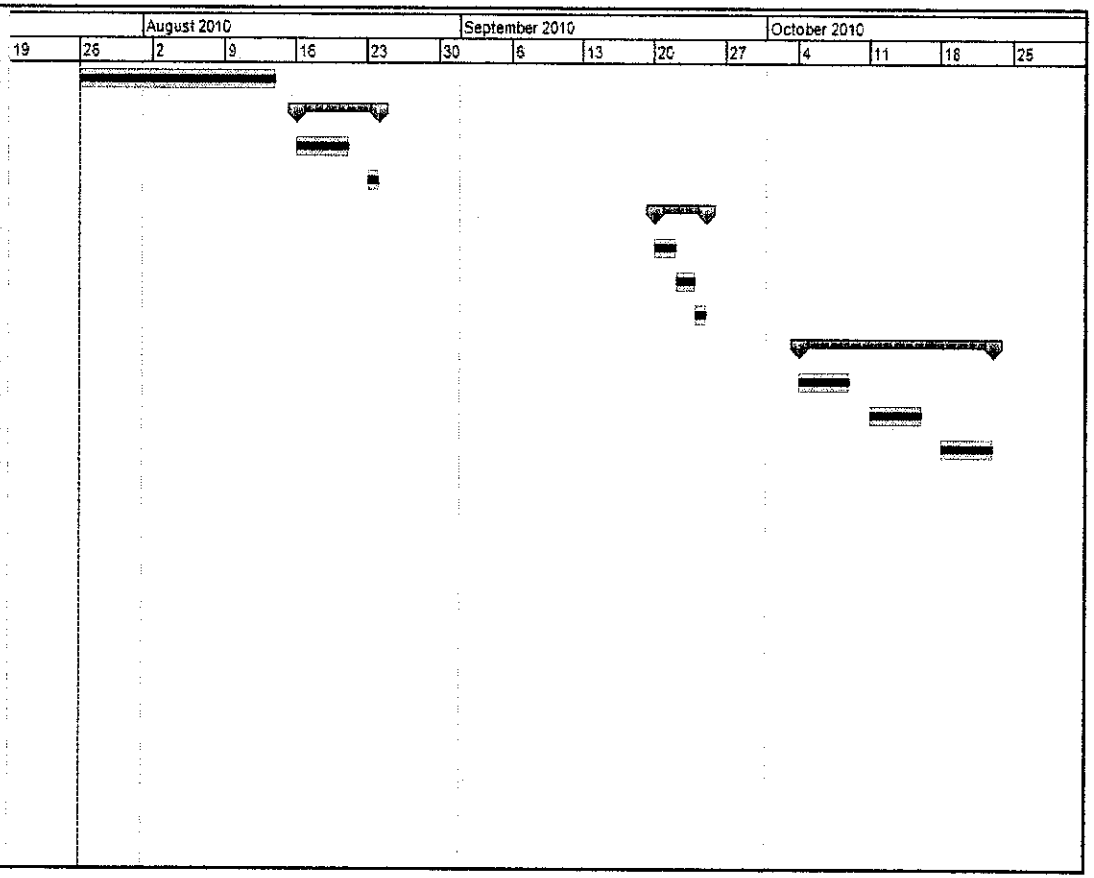


APPENDIX C: OVERVIEW OF FLAW AND DAMAGE ASSESSMENT PROCEDURES

Flaw or Damage Mechanism	Section	Overview
Brittle Fracture	3	Assessment procedures are provided for evaluating the resistance to brittle fracture of existing carbon and low alloy steel pressure vessels, piping, and storage tanks. Criteria are provided to evaluate normal operating, start-up, upset, and shut-down conditions.
General Metal Loss	4	Assessment procedures are provided to evaluate general corrosion. Thickness data used for the assessment can be either point thickness readings or detailed thickness profiles. A methodology is provided to utilize the assessment procedures of Section 5 when the thickness data indicates that the metal loss can be treated as localized.
Local Metal Loss	5	Assessment techniques are provided to evaluate single and networks of Local Thin Areas and groove-like flaws in pressurized components. Detailed thickness profiles are required for the assessment. The assessment procedures can also be utilized to evaluate blisters as provided for in Section 7.
Pitting Corrosion	6	Assessment procedures are provided to evaluate widely scattered pitting, localized pitting, pitting which occurs within a region of local metal loss, and a region of localized metal loss located within a region of widely scattered pitting. The assessment procedures can also be utilized to evaluate a network of closely spaced blisters as provided for in Section 7.
Blisters and Laminations	7	Assessment procedures are provided to evaluate isolated and networks of blisters and laminations. The assessment guidelines include provisions for blisters located at weld joints and structural discontinuities such as shell transitions, stiffening rings, and nozzles.
Weld Misalignment and Shell Distortions	8	Assessment procedures are provided to evaluate stresses resulting from geometric discontinuities in shell type structures including weld misalignment and shell distortions (e.g. out-of-roundness, bulges, and dents).
Crack-Like Flaws	9	Assessment procedures are provided to evaluate crack-like flaws. Solutions for stress intensity factors and reference stress (limit load) are included in Appendices C and D, respectively. Methods to evaluate residual stress as required by the assessment procedure are described in Appendix E. Material properties required for the assessment are provided in Appendix F. Recommendations for evaluating crack growth including environmental concerns are also covered.
High Temperature Operation and Creep	10	Assessment procedures are provided to determine the remaining life of a component operating in the creep regime. Material properties required for the assessment are provided in Appendix F. Recommendations for evaluating crack growth including environmental concerns are also covered.
Fire Damage	11	Assessment procedures are provided to evaluate equipment subject to fire damage. A methodology is provided to rank and screen components for evaluation based on the heat exposure experienced during the fire. The assessment procedures of the other sections of this publication are utilized to evaluate component damage.

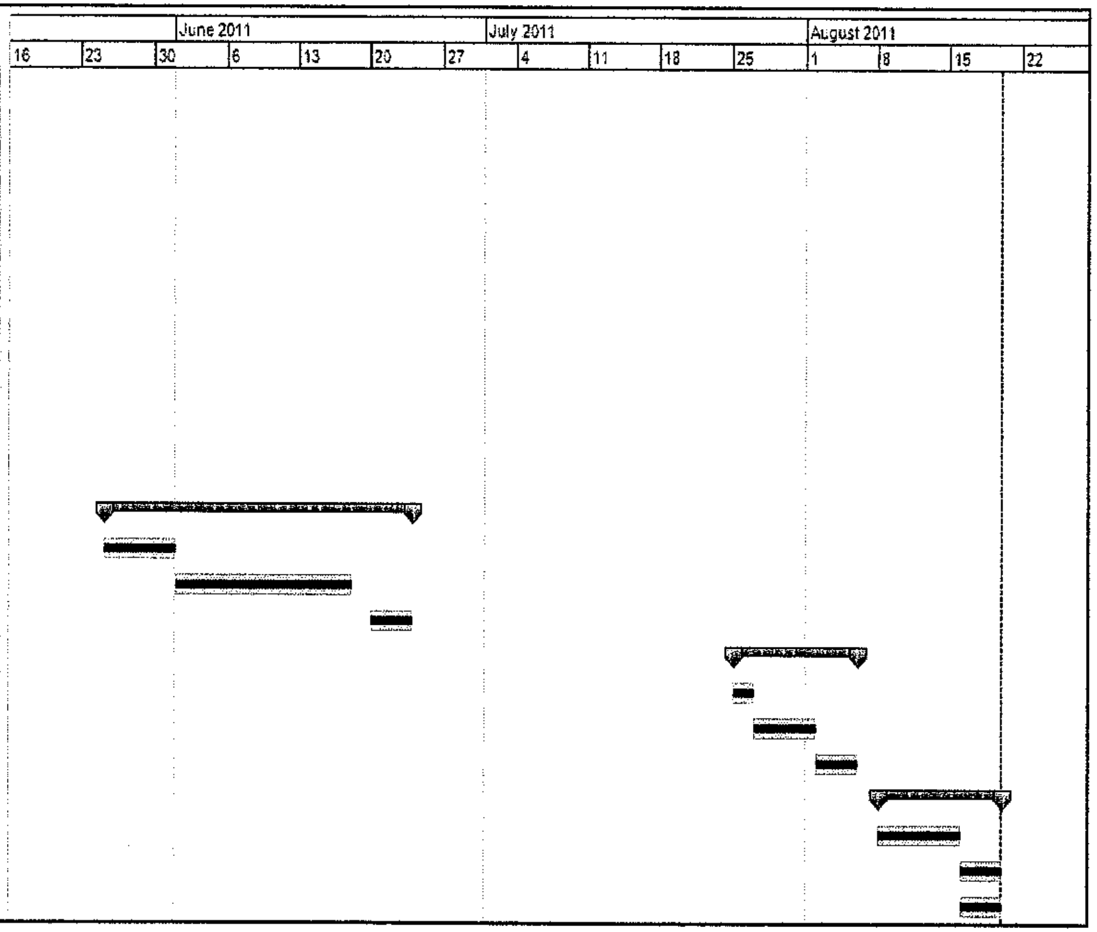
APPENDIX D1: FYP I PROJECT PLANNING

		Task name	Length	Start	Finish
1		Selection of Project Title	15 days	7/26/2010	8/13/2010
2	✓	**Preliminary Resear...**	**6 days**	**8/16/2010**	**8/23/2010**
3	✓	Literature Review	5 days	8/16/2010	8/20/2010
4	✓	Preliminary Report ...	1 day	8/23/2010	8/23/2010
5	✓	**UT Equipment Fami...**	**5 days**	**9/20/2010**	**9/24/2010**
6	✓	Calibration Method	2 days	9/20/2010	9/21/2010
7	✓	Thickness Measure...	2 days	9/22/2010	9/23/2010
8	✓	Flaw Sizing	1 day	9/24/2010	9/24/2010
9	✓	**UT1 Experiment :**	**15 d...**	**10/4/2010**	**10/22/2...**
10	✓	Sample Preparation...	5 days	10/4/2010	10/8/2010
11	✓	UT Thickness Mea...	5 days	10/11/2010	10/15/2010
12	✓	Result Analysis and...	5 days	10/18/2010	10/22/2010
13	✓	**UT2 Experiment :**	**22 d...**	**5/25/2011**	**6/23/2011**
14	✓	Sample Preparation...	5 days	5/25/2011	5/31/2011
15	✓	UT Thickness Mea...	13 days	6/1/2011	6/17/2011
16	✓	Result Analysis and...	4 days	6/20/2011	6/23/2011
17	✓	**UT3 Experiment :**	**10 d...**	**7/25/2011**	**8/5/2011**
18	✓	Sample Selection (...	2 days	7/25/2011	7/26/2011
19	✓	UT Thickness Mea...	4 days	7/27/2011	8/1/2011
20	✓	Result Analysis and...	4 days	8/2/2011	8/5/2011
21	✓	**Documentation**	**10 d...**	**8/8/2011**	**8/19/2011**
22	✓	Final Report	6 days	8/8/2011	8/15/2011
23	✓	technical report	4 days	8/16/2011	8/19/2011
24	✓	slide presentation	4 days	8/16/2011	8/19/2011



APPENDIX D1: FYP II PROJECT PLANNING

		Task name	Length	Start	Finish
1		Selection of Project Title	15 days	7/26/2010	8/13/2010
2	✓	**Preliminary Resear...**	**6 days**	**8/16/2010**	**8/23/2010**
3	✓	Literature Review	5 days	8/16/2010	8/20/2010
4	✓	Preliminary Report ...	1 day	8/23/2010	8/23/2010
5	✓	**UT Equipment Fami...**	**5 days**	**9/20/2010**	**9/24/2010**
6	✓	Calibration Method	2 days	9/20/2010	9/21/2010
7	✓	Thickness Measure...	2 days	9/22/2010	9/23/2010
8	✓	Flaw Sizing	1 day	9/24/2010	9/24/2010
9	✓	**UT1 Experiment:**	**15 d...**	**10/4/2010**	**10/22/2...**
10	✓	Sample Preparation...	5 days	10/4/2010	10/8/2010
11	✓	UT Thickness Mea...	5 days	10/11/2010	10/15/2010
12	✓	Result Analysis and...	5 days	10/18/2010	10/22/2010
13	✓	**UT2 Experiment:**	**22 d...**	**5/25/2011**	**6/23/2011**
14	✓	Sample Preparation...	5 days	5/25/2011	5/31/2011
15	✓	UT Thickness Mea...	13 days	6/1/2011	6/17/2011
16	✓	Result Analysis and...	4 days	6/20/2011	6/23/2011
17	✓	**UT3 Experiment:**	**10 d...**	**7/25/2011**	**8/5/2011**
18	✓	Sample Selection (...	2 days	7/25/2011	7/26/2011
19	✓	UT Thickness Mea...	4 days	7/27/2011	8/1/2011
20	✓	Result Analysis and...	4 days	8/2/2011	8/5/2011
21	✓	**Documentation**	**10 d...**	**8/8/2011**	**8/19/2011**
22	✓	Final Report	6 days	8/8/2011	8/15/2011
23	✓	technical report	4 days	8/16/2011	8/19/2011
24	✓	slide presentation	4 days	8/16/2011	8/19/2011



APPENDIX E: PARAMETERS TO COMPUTE THE LENGTH FOR THICKNESS AVERAGING

RSF_a	0.90	0.85	0.80	0.75	0.70
R_t	Q	Q	Q	Q	Q
0.900	50.00	50.00	50.00	50.00	50.00
0.895	21.19	50.00	50.00	50.00	50.00
0.875	4.93	50.00	50.00	50.00	50.00
0.850	2.82	50.00	50.00	50.00	50.00
0.845	2.62	29.57	50.00	50.00	50.00
0.825	2.07	5.59	50.00	50.00	50.00
0.800	1.68	3.65	50.00	50.00	50.00
0.795	1.62	3.36	36.82	50.00	50.00
0.775	1.43	2.63	8.01	50.00	50.00
0.750	1.26	2.11	4.35	50.00	50.00
0.745	1.23	2.03	4.01	42.94	50.00
0.725	1.12	1.77	3.10	9.20	50.00
0.700	1.02	1.54	2.45	4.93	50.00
0.695	1.00	1.51	2.36	4.53	47.94
0.675	0.93	1.37	2.05	3.47	10.16
0.650	0.86	1.24	1.77	2.73	5.39
0.625	0.80	1.13	1.56	2.26	3.77
0.600	0.74	1.04	1.40	1.95	2.94
0.575	0.70	0.96	1.27	1.71	2.43
0.550	0.65	0.89	1.16	1.53	2.07
0.525	0.61	0.83	1.07	1.38	1.81
0.500	0.58	0.77	0.99	1.25	1.61
0.475	0.55	0.72	0.92	1.15	1.45
0.450	0.51	0.68	0.86	1.05	1.32
0.425	0.49	0.64	0.80	0.98	1.20
0.400	0.45	0.60	0.74	0.91	1.10
0.375	0.43	0.56	0.70	0.84	1.01
0.350	0.41	0.53	0.65	0.78	0.93
0.325	0.38	0.50	0.61	0.73	0.86
0.300	0.36	0.46	0.57	0.67	0.79
0.275	0.34	0.43	0.53	0.63	0.73
0.250	0.31	0.40	0.49	0.58	0.67
0.200	0.27	0.35	0.42	0.49	0.57

Notes:

1. The equation for Q is:

$$Q = 1.123\left[\left(\frac{1-R_t}{1-R_t/RSF_a}\right)^2 - 1\right]^{0.5} \quad for \quad R_t < RSF_a \qquad (4.15)$$

$$Q = 50.0 \quad for \quad R_t \geq RSF_a \qquad (4.16)$$

2. The length for thickness averaging is given by Equation (4.3)