

**Fitness for Service of Corroded Pressure Vessel**

by

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the requirements for the  
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# **CERTIFICATION OF APPROVAL**

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

Approved by,

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TRONOH, PERAK

June 2009

## **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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MAZREEN BT MOHD RAZALI

## **ABSTRACT**

Fitness for service assessment is performed to ensure that damaged process plant equipment, such as corroded pressure vessels are fit to operate safely and reliably. API RP 579 provides a general procedure for assessing fitness for service of corroded and damaged pressure vessel. The assessment procedure evaluates the remaining strength of the equipment in its current condition and recommends necessary action for repair or replacement. This project will analyze the accuracy of API 579 Fitness for Service (FFS) analysis on corroded pressure vessel. There are three levels of assessment covered in API 579 which are Level 1, 2 and 3. Typically, FFS Assessment is done by using Level 1 and Level 2 since they utilize minimum amount of inspection and known to be conservative. Level 3 Assessment requires most detailed inspection and uses Finite Element Analysis method to give in-depth analysis of the stress involved and projects the remaining life of the corroded pressure vessel. The objective of the project is to conduct and compare Level 3 analysis of the corroded pressure vessel with Level 1 and 2 analyses. Results from these assessments shows that FEA method can verify the calculation done in Level 1 and 2 Assessments. Level 1 and 2 assessments produce conservative results while Level 3 is more accurate. Level 3 Assessment with added capability to visualize stresses involved proven to be useful for critical engineering decision. This capability will assist engineer to confidently decide critical cases in engineering problems. The utilization of Level 3 of FFS provides an accurate assessment of the corroded pressure vessel compared to Level 1 and 2 and also provide added advantage to simulate the operating condition for future planning.

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## **LIST OF ABBREVIATIONS**

ASME – American Society of Mechanical Engineer  
BS – British Standard Institute  
NACE - National Association of Corrosion Engineers  
API – American Petroleum Institute  
FEA – Finite Element Analysis  
FFS – Fitness for Service  
MAWP – Maximum Allowable Working Pressure  
MFH – Maximum Fill Height  
COV – Coefficient of Variation  
FCA – Future Corrosion Allowance  
CTP – Critical Thickness Profile  
LTA – Locally Thin Area  
RSF – Remaining Strength Factor  
FEM – Finite Element Method  
HSE – Health, Safety and Environment

# CHAPTER 1

## INTRODUCTION

### 1.1 Background of Study

Pressure vessel is one of the important equipment used in various industries. There are different types of pressure vessel used based on its sizes and shapes. Most are cylindrical shape with 2:1 semi elliptical heads or end caps on each end and usually designed according to American Society of Mechanical Engineers (ASME) Code, Section VIII and British Standard Institute (BS) 5500. Pressure vessels can be placed in two orientations which are vertical and horizontal. Shell, head, attachments, and piping are some of the components that commonly fail. Corrosion is one of the common types of failures. Degradation of pressure vessel may occur due to internal or external corrosion which can attack the main part of the equipment or the attachments. Corrosion fatigue appears to be the predominant mechanism of crack formation and growth. If vessel rupture occurs, the pressurized fluids will cause blast effects due to sudden expansion and will cause fire and explosion.

Due to these failures, the pressure vessel is susceptible to damage and must be analyze in order to know whether the vessel can be operated as usual for some desired future period. Analysis is done using Finite Element Analysis as per API 579 Fitness for Service to demonstrate the structural integrity of an in-service component containing a flaw or damage which is identified through inspection. FFS covers both the present integrity of the component given a current state of damage and the projected remaining life. In FFS approach, corrosion is assessed using three levels of assessments which are Level 1, 2 and 3. The implementation of Level 3 assessment will give more in depth analysis of the stress involved and projecting the remaining life of the corroded pressure vessel.

## **1.2 Problem Statement**

Pressure vessels are exposed to the internal and external corrosion. The effect of corrosion may be pitting or grooving over either localized or large areas. Corrosion over large areas can bring general reduction of plate thickness. This project is concerned on the corrosion problem that has been encountered on the internal side, on the weld seam of pressure vessel.

Process plant equipment is often exposed to corrosive environments and/or elevated temperatures. Under these conditions, the material used in this equipment can degrade or age with time in service. As important equipment such as pressure vessels become older, the plant operator must decide if they can continue to operate safely and reliably to avoid injuries to personnel and the public, environmental damage, and unexpected shutdowns. FFS assessment procedures provide a means for helping the plant operator make these decisions established engineering principles.

The accuracy of FFS assessment over a corroded pressure vessel that will be analyzed is critical to the decision of which equipment comply with HSE standard and reliable for some desired future period. There is a need to conduct three levels of FFS Assessment which covered under Level 1, 2 and 3. Detailed analysis can minimize costs by avoiding unnecessary over-design or reinforcement.

## **1.3 Objective of Study and Scope of Work**

Objective of the project is to assess and check FFS of the corroded pressure vessel to demonstrate structural integrity of the equipment for continuous operation. Assessments are based on API 579 where three levels of assessment will be covered which cover FFS assessments procedure. These assessments will be compared to the stress analysis result using finite element method software, ANSYS.

Scopes of the study are:

- i. Rate the pressure vessel using Level 1 Assessment
  - Utilized using minimum inspection and component information that provide conservative screening criteria.
  - If Level 1 Assessment is satisfied, pressure vessel can be returned into service but if it is not satisfied, Level 2 Assessment needs to be performed.
  
- ii. Rate the pressure vessel using Level 2 Assessment
  - Involve a more detailed evaluation of components and usually require an accurate measurement of flaws or damage
  - If Level 2 Assessment is satisfied, the pressure vessel can be returned into service but if it is not satisfied, Level 3 needs to be performed.
  
- iii. Rate the pressure vessel using Level 3 Assessment
  - Required more detailed inspection and component information, and analysis is based on numerical techniques such finite element method.
  - Analysis will be done on the finite element analysis software, ANSYS.
  - Provide deformed shape result, nodal stress result and Von Misses stress result.
  - If Level 3 is satisfied, pressure vessel can be returned into service but if it is not satisfied, the pressure vessel needs repair, rerate or replace for continuous operation

All of these scopes of study will be done based on similar geometry model that represent non-corroded model and general corrosion model.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Integration of corroded equipment

The assessment of equipment using FFS is important to determine the equipment is fit for to operate safely and reliably for some desired future period. On 23 July 1984, the Union Oil refinery near Lemont, Illinois, suffered an explosion and a fire. Seventeen people working at the refinery were killed and the damage was estimated to be over \$100 million. The explosion was caused by the ignition of a propane and butane cloud that had leaked from a ruptured amine-absorber vessel.

Prior to the explosion an operator at the column noticed gas escaping from a horizontal crack near the bottom of the vessel. The crack grew and he initiated evacuation of the area. As the company fire fighters arrived, the column cracked further and a large amount of gas was released. The gas ignited and the explosion sent the upper part of the tower into the air, landing over a mile away, Figure 1. This shows the importance of FFS Analysis to avoid this type of incident.

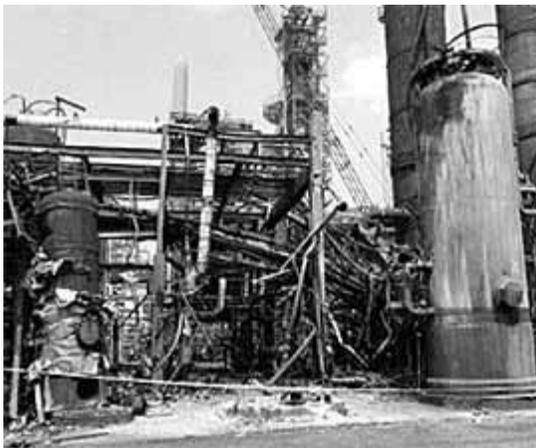


Figure 1 The amine unit after the fire

## **2.2 Assessment of Corroded Shell Plate using API 579 (Fitness for Service Evaluation)**

### **2.2.1 Assessment of General Metal Loss**

The assessment procedures in this section can be used to evaluate all forms of general metal loss (uniform or local) which exceeds or is predicted to exceed the corrosion allowance before the next scheduled inspection. The general metal loss may occur on the inside or outside of the component. Assessment procedures based on thickness profiles and point thickness readings are provided. The assessment procedure to be used in an evaluation is dependent on the type of thickness data available (point thickness readings or detailed thickness profiles), the characteristics of the metal loss (such uniform or local), the minimum required wall thickness, and the degree of conservatism acceptable for the assessment.

Calculation methods are provided to rerate the component if the acceptance criteria in this section are not satisfied. For pressurized components (pressure vessels and piping), the calculation methods can be used to find a reduced maximum allowable working pressure (*MAWP*) and/or coincident temperature. For tank components (shell courses), the calculation methods can be used to determine a reduced maximum fill height (*MFH*).

#### **Level 1 Assessment**

The following assessment procedure can be used to evaluate components subject to the loads. If the flaw is found to be unacceptable, the procedure can be used to establish a new *MAWP* or *MFH*. If the component does not meet Level 1 Assessment, the equipment need to be rerate, repair or need Level 2 and Level 3 Assessment.

- a. Step 1 – Determine the minimum required thickness,  $t_{\min}$ .
- b. Step 2 – Locate regions of metal loss on the component and determine the type of thickness data that will be recorded; point thickness readings or thickness profile data. Based on these data, determine the minimum measured thickness,  $t_{\min}$ . If thickness profile

data are used, then proceed to Step 3. If point thickness readings are used, determine the Coefficient of Variation (*COV*) based on the thickness readings and Future Corrosion Allowance. If the *COV* is less than or equal to 10%, then proceed to Step 6 to complete the assessment using the average thickness,  $t_{am}$ . If the *COV* is greater than 10%, then the use of thickness profiles should be considered for the assessment or a Level 3 Assessment can be performed.

c. Step 3 – Determine the length for thickness averaging,  $L$ .

Step 3.1 – Compute the remaining thickness ratio,  $R_t$ .

$$R_t = \left( \frac{t_{mm} - FCA}{t_{min}} \right) \quad [\text{Eq.1}]$$

Where,

$FCA$  = Future corrosion allowance (mm:in),

$t_{min}$  = Minimum required thickness (mm:in), and

$t_{mm}$  = Minimum measured thickness (mm:in).

Step 3.2 – Compute the length for thickness averaging,  $L$ :

$$L = Q \sqrt{Dt_{min}} \quad [\text{Eq.2}]$$

Where,  $t_{min}$  is defined above, and

$D$  = Inside diameter of the cylinder, cone (at the location of the flaw), sphere, or formed head; for the center section of an elliptical head an equivalent inside diameter of  $K D c c$  is used where  $Dc$  is the inside diameter of the head straight flange and  $Kc$  is a factor; for the center section of torispherical head two times the crown radius of the spherical section is used (mm:in), and

$Q$  = Factor based on an allowable Remaining Strength Factor and the remaining thickness ratio,  $R_t$ .

d. Step 4 – Establish the Critical Thickness Profiles (*CTP*'s) from the thickness profile data, and determine  $s$  and  $c$ , the dimensions which define the region of metal loss in the longitudinal and circumferential directions, respectively. The dimensions  $s$  and  $c$  are determined from their respective *CTP* and  $t_{\min}$

e. Step 5 – Based on the parameters  $L$  and  $s$  from Steps 3 and 4, respectively, perform the *FFS* assessment of the region of metal loss using one of the following methods:

1. For  $s \leq L$  – The meridional or longitudinal extent of metal loss is acceptable if the limiting flaw size criteria d are satisfied. For spherical shells, formed heads and atmospheric storage tanks the assessment is complete.

2. For  $s \geq L$  – One of the following assessment methods may be used:

a) A simple approach is to set the average thickness equal to the measured minimum thickness, or ( $t_{am} = t_{mm}$ ) and proceed to Step 6 (Level 1 or Level 2, as applicable). This approach facilitates the *FFS* assessment; however, the results may be conservative if the remaining thickness ratio is small.

b) Determine the average and minimum measured thickness for the meridional and circumferential *CTP*'s as described below, then proceed to Step 6 (Level 1 or Level 2, as applicable) to complete the assessment.

c) The region of metal loss can be evaluated using a Level 3 Assessment.

d) The region of metal loss can be evaluated using the Assessment procedures for local metal loss.

f. Step 6 – The acceptability for continued operation can be established using the following criteria. The average measured wall thickness should satisfy the following thickness criteria. Alternatively, the *MAWP* or *MFH* calculated based on the thickness ( $t_{am} - FCA$ ) should be equal to or greater than the current *MAWP* or maximum design liquid level, respectively.

$$t_{am} - FCA \geq t_{\min} \quad [\text{Eq.3}]$$

### 2.2.2 Assessment of Local Metal Loss

The procedures in this section can be used to evaluate components subject to local metal loss from corrosion/erosion, mechanical damage, or blend grinding which exceeds, or is predicted to exceed, the corrosion allowance before the next scheduled inspection.

The local metal loss may occur on the inside or outside of the component.

The types of flaws characterized as local metal loss are defined as follows:

- a. *Locally Thin Area (LTA)* – local metal loss on the surface of the component; the length of a region of metal loss is the same order of magnitude as the width,
- b. *Groove-like flaw* – the following flaws are included in this category; a sharp radius may be present at the base of a groove-like flaw.

1. Groove – local elongated thin spot caused by directional erosion or corrosion; the length of the metal loss is significantly greater than the width.
2. Gouge – elongated local mechanical removal and/or relocation of material from the surface of a component, causing a reduction in wall thickness at the defect; the length of a gouge is much greater than the width and the material may have been cold worked in the formation of the flaw.

#### **Level 1 Assessment**

The Level 1 Assessment procedures can be used to evaluate a component with local metal loss subject to internal pressure. The procedures can be used to determine acceptability and/or to rerate a component with a flaw. If there are significant thickness variations over the length of the flaw or if a network of flaws is closely spaced, this procedure may produce conservative results, and a Level 2 assessment is recommended.

- a. Step 1 – Determine the Critical Thickness Profiles and the following parameters:

$D$  = Inside diameter of the cylinder, cone (at the location of the flaw), sphere, or formed head; for the center section of an elliptical head an equivalent inside diameter of  $K_c D_c$  is used where  $D_c$  is the inside diameter of the head straight flange and  $K_c$  is a factor; for the center section of a torispherical head two times the crown radius of the spherical section is used (mm:in),

$FCA$  = Future Corrosion Allowance (mm:in),

$gr$  = Radius at the base of a groove-like flaw (mm:in),

$Lmsd$  = Distance from the edge of the region of local metal loss under investigation to the nearest major structural discontinuity (mm:in),

$MAWP$  = Maximum Allowable Working Pressure (MPa: psig),

$MFH$  = Maximum fill height of the tank, may be calculated, (m: ft), and

$RSFa$  = Allowable remaining strength factor.

b. Step 2 – Determine the minimum required thickness.

c. Step 3 – Determine the minimum measured thickness,  $t_{mm}$ , the remaining thickness ratio,  $R_t$ , the flaw dimension,  $s$  and the shell parameter,  $\lambda$ .

$$R_t = \frac{t_{mm} - FCA}{t_{min}} \quad [Eq.4]$$

$$\lambda = \frac{1.285s}{\sqrt{Dt_{min}}} \quad [Eq.5]$$

d. Step 4 – Check the limiting flaw size criteria; if the following requirements are satisfied, proceed to Step 5; otherwise, the flaw is not acceptable per the Level 1 Assessment procedure.

$$\begin{aligned} R_t &\geq 0.20 \\ t_{mm} - FCA &\geq 2.5mm(0.10") \\ L_{msd} &\geq 1.8\sqrt{Dt_{min}} \end{aligned}$$

e. Step 5 – If the region of metal loss is categorized as an  $LTA$  (a groove or gouge is not present in the  $LTA$ ), then proceed to Step 6; otherwise, check the criteria for a groove-like flaw.

f. Step 6 – Enter the formula for RSF and  $M_t$  with the calculated values of  $\lambda$  and  $R_t$ . If the point defined by the intersection of these values is on or above and to the left of the curve, then the longitudinal extent (circumferential or meridional extent for spherical

shells and formed heads) of the flaw is acceptable per Level 1. If the point is unacceptable, then the component can be rerated with the remaining strength factor computed as shown below. If the component is a cylindrical, conical shell or elbow, then proceed to Step 7 to evaluate the circumferential extent of the flaw. Otherwise, the assessment is complete.

$$RSF = \frac{R_t}{1 - \frac{1}{M_t}(1 - R_t)} \quad [\text{Eq.6}]$$

Where,

$$M_t = (1 + 0.48\lambda^2)^{0.5} \quad [\text{Eq.7}]$$

If the component does not meet the Level 1 Assessment requirements, then the following, or combinations thereof, can be considered:

- Rerate, repair, replace, or retire the component.
- Adjust the *FCA* by applying remediation techniques
- Adjust the weld joint efficiency factor, *E*, by conducting additional examination and repeat the assessment.
- Conduct a Level 2 or Level 3 Assessment.

### 2.3 Assessment of Corroded Shell Plate using ANSYS Software

To start the simulation models of the corroded pressure vessel, the models need to be modeled first in 3D modeling using CATIA / AUTO CAD software. Then, the model will be transferred into ANSYS software for stress analysis.

Figure 2 shows how to set the preferences in ANSYS Software. Setting the preferences allows one to choose the desired engineering discipline (structural, thermal, electromagnetic etc.) for context filtering of menu choices. Analyzing a corroded skirt of pressure vessel performs a static structural analysis, so the structural discipline will be chosen.

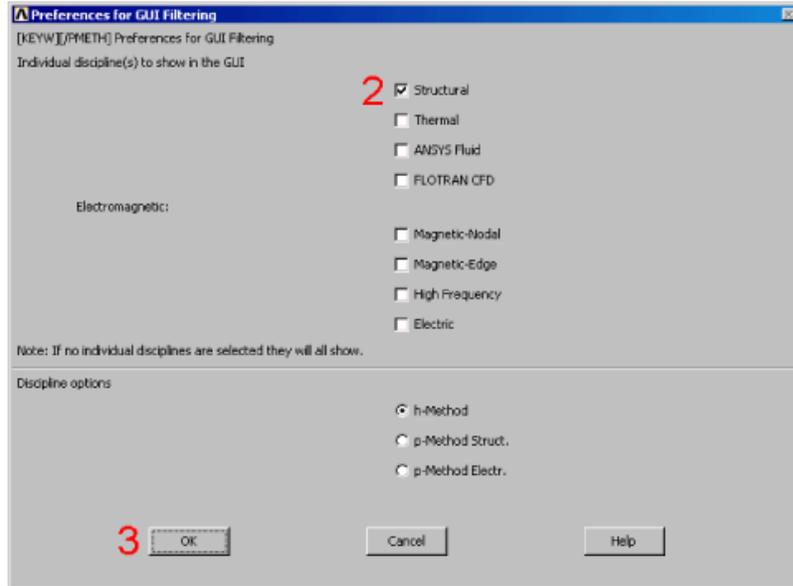


Figure 2 Preferences for GUI Filtering

After that, in any analysis one needs to select from a library of element types and define the appropriate one for the analysis. The element type determines many things such as the degree-of-freedom set (displacement, rotations, temperature etc.), the characteristic shape of the element (line, quadrilateral, brick etc.), and whether the element is 2-D or 3-D.

After that, the material used should be defined by entering the value for its Young modulus of elasticity and Poisson ratio. Any real constant also should be added to these analyses. Next, meshing can be done to the model as different results can be obtained based on different sizes of meshing. The right size of meshing must be entered to get the high accuracy of results obtained. After choosing the right meshing size, the load can be applied to the model. Displacement and pressure load at certain lines, areas or volumes of the model can be applied based on the analysis model.

Finally, the general postprocessor phase will be displayed. Postprocessing is where one reviews the results of the analysis through graphic displays and tabular listings. The general postprocessor (POST1) is used to review results at one sub-step

(time step) over the entire model. Figure 3 shows the example of deformed shape result in ANSYS Software. Deformed shape of the model can be plotted in order to know how the model deformed after the loads has been applied to the model. Figure 4 shows the example of Von Mises equivalent stress contour plot result in ANSYS Software. Equivalent Von Mises stress also can be displayed in the nodal list result or contour plot result.

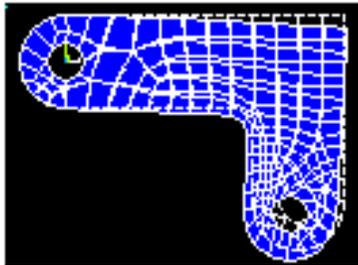


Figure 3 Example of deformed shape result in ANSYS Software

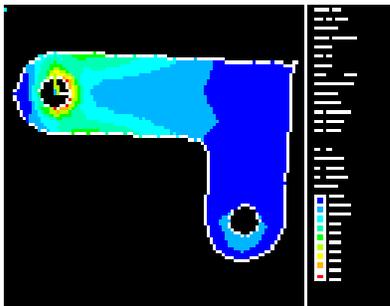


Figure 4 Example of Von Mises equivalent stress contour plot result in ANSYS Software

## **CHAPTER 3**

### **METHODOLOGY AND PROJECT WORK**

Based on Figure 5, first we need to obtain the corroded pressure vessel data. After that, Level 1 is performed based on the data obtained. If Level 1 Assessment is satisfied, the pressure vessel can be returned into service but if it is not satisfied, Level 2 Assessment needs to be performed. Same goes to this level of assessment, if Level 2 Assessment is satisfied, the pressure vessel can be returned into service but if it is not satisfied, we need to proceed to Level 3 Assessment as well. Level 3 is the final stage of the assessment and provides most detailed evaluation which produced more precise result rather than Level 1 and Level 2 Assessment. Using same methodology as in Level 1 and 2, if Level 3 Assessment is satisfied, the pressure vessel can be returned into service but if it is not satisfied, the pressure vessel needs repair, rerate or replace for continuous operation.

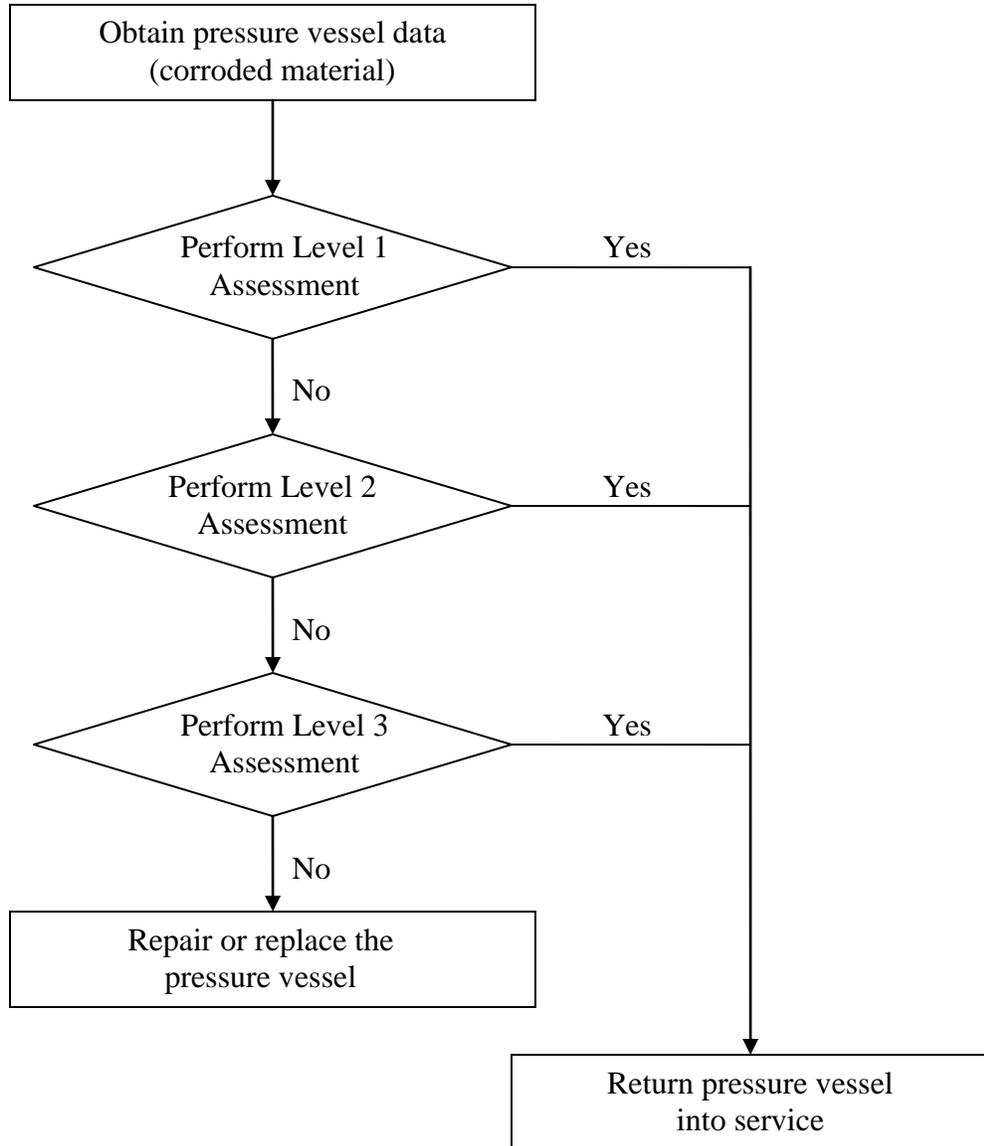


Figure 5 Flow chart of project methodology

### **3.1 Data requirement**

There are 3 different data classifications needed to perform the analysis. The required data that needed for the analysis depends on the type of assessment that needs to be done on the pressure vessel.

#### **Requirement Data for Assessment by Level 1 Assessment**

- i. Thickness profile on the inspected pressure vessel.
- ii. Minimum required thickness and minimum remaining thickness among the thickness profile.
- iii. Flaw Dimensions such  $s$  and  $c$  (longitudinal and circumferential dimension of locally thin area (LTA))
- iv. Materials Property Data.

#### **Requirement data for Level 2 Assessment**

For Level 2 Assessment, the data that are required are similar to the data that required for the Level 1 Assessment. Only in the part of calculation steps will differentiate the both types of assessment.

#### **Requirement data for Level 3 Assessment (Finite Element Analysis Method)**

The 3-D models are being constructed based on real pressure vessel dimensions (thickness and its corrosion condition).

Procedure for construct a model for analysis:

- i. Obtain the dimension of the real inspection pressure vessel.
- ii. Find the value of good plate thickness, lowest thickness measured, average thickness measured.
- iii. Calculated the critical length,  $L$ .
- iv. Construct the model using CAD software by using the given dimension, lowest thickness measured and critical length.
- v. The Level 3 Assessment (Finite Element Analysis) can be done based on the model.

### **3.2 Tools required**

Based on the following procedure, required tools for these projects are:

- i. Sample of inspections report – The inspection reports included summarized corrosion data, summarized shell thickness evaluation and proposed modification.
- ii. ANSYS 9.0 – Tool for complex modeling analysis is use for structural stress analysis of the model especially for Level 3 Assessment.

### **Case Study**

Details regarding the pressure vessel and inspection data have been obtained form the standard API 579. According to the standard, corrosion at a longitudinal weld seam in a pressure vessel has been found during an inspection. The vessel was designed and fabricated to the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1. Below are the details regarding the pressure vessel data:

#### **Pressure Vessel Information**

Design Conditions = 300 psig @ 350°F = 176.7°C

Inside Diameter = 48 inches = 1219.2 mm

Nominal Thickness = 0.75 inches = 19.1 mm

Uniform metal loss = 0.0 inches = 0.0 mm

Future Corrosion Allowance = 0.10 inches = 2.54 mm

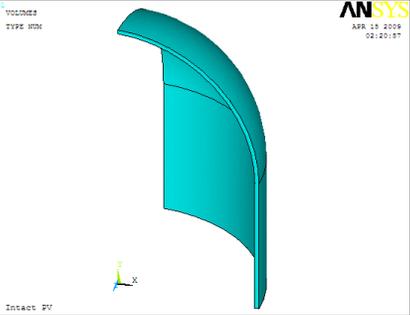
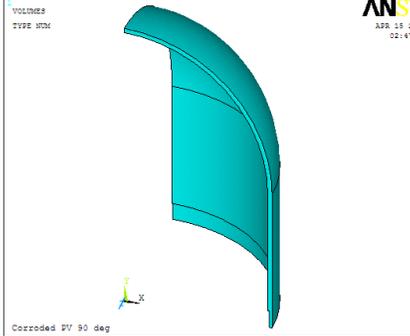
Material = SA 516 Grade 70

Weld Joint Efficiency = 0.85

### 3.3 Models that being used

In the finite element method (FEM) analysis, there are some models that being used in determine the result of FEM analysis. Below are the models that have been used.

Table 1 Model used in the analysis

Model	Drawing	Geometry of model
Intact Pressure Vessel		<p>Internal Pressure : 2.0684 MPa</p> <p>Inner Diameter : 1219.2 mm</p> <p>Plate Thickness : 19.05 mm</p> <p>Length : 2477.2 mm</p> <p>Material : SA516 Grade 70</p>
Corroded Pressure Vessel		<p>Internal Pressure : 2.0684 MPa</p> <p>Inner Diameter : 1219.2 mm</p> <p>Plate Thickness : 19.05 mm</p> <p>Length : 2477.2 mm</p> <p>Material : SA516 Grade 70</p> <p>Corrosion Thickness : 9.1 mm</p> <p>Length of corrosion : 76.2 mm</p>

## **CHAPTER 4**

### **RESULTS AND DISCUSSION**

Details regarding the pressure vessel and inspection data have been obtained from the standard API 579. According to the standard, corrosion at a longitudinal weld seam in a pressure vessel has been found during an inspection. The vessel was designed and fabricated to the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1. Below are the details regarding the pressure vessel data:

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Nominal Thickness = 0.75 inches = 19.1 mm

Uniform metal loss = 0.0 inches = 0.0 mm

Future Corrosion Allowance = 0.10 inches = 2.54 mm

Material = SA 516 Grade 70

Weld Joint Efficiency = 0.85

**Inspection Data**

The grid and data used for the inspection are shown below. The grid spacing set by the Inspector in the circumferential and longitudinal directions is 38.1 mm based on the corrosion profile.

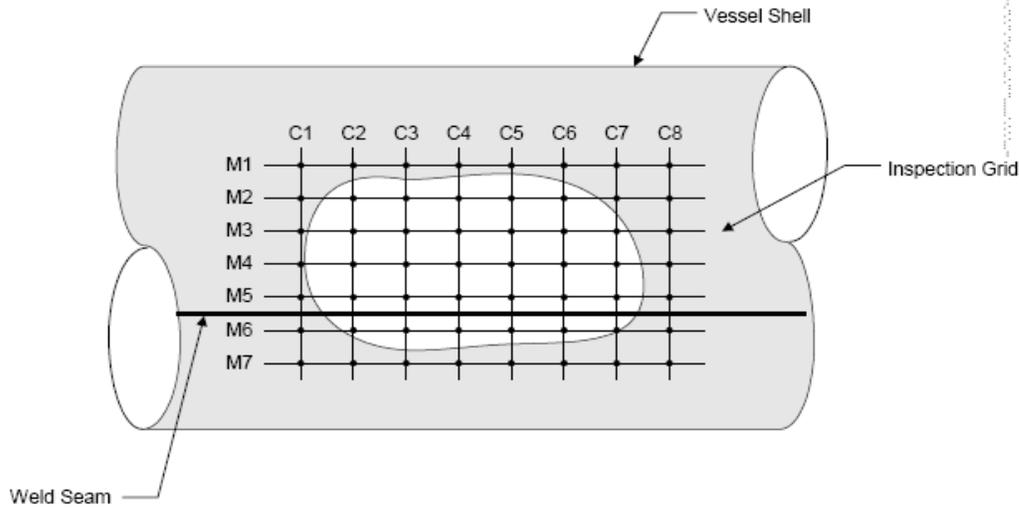


Figure 6 Inspection grid of corrosion thickness profile

Table 2 Data obtained from corrosion thickness profile

LONGITUDINAL INSPECTION PLANES	CIRCUMFERENTIAL INSPECTION PLANES								CIRCUMFERENTIAL CTP
	C1	C2	C3	C4	C5	C6	C7	C8	
M1	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
M2	0.75	0.48	0.52	0.57	0.56	0.58	0.60	0.75	0.48
M3	0.75	0.57	0.59	0.55	0.59	0.60	0.66	0.75	0.55
M4	0.75	0.61	0.47	0.58	0.36	0.58	0.64	0.75	0.36
M5	0.75	0.62	0.59	0.58	0.57	0.48	0.62	0.75	0.48
M6	0.75	0.57	0.59	0.61	0.57	0.56	0.49	0.75	0.49
M7	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
LONGITUDINAL CTP	0.75	0.48	0.47	0.55	0.36	0.48	0.49	0.75	

#### 4.1 Level 1 Assessment

**Step 1** : Calculate the minimum required thickness

$$t_{\min}^c = \frac{300 \text{ psig}(609.6 \text{ mm} + 2.54 \text{ mm})}{17500 \text{ psi}(0.85) - 0.6(300 \text{ psi})} = 12.50 \text{ mm}$$

$$t_{\min}^L = \frac{300 \text{ psig}(609.6 \text{ mm} + 2.54 \text{ mm})}{(2)17500 \text{ psi}(0.85) + 0.4(300 \text{ psi})} = 6.15 \text{ mm}$$

$$t_{\min} = \max[12.5, 6.15] = 12.5$$

**Step 2** - Thickness profiles are provided, the data for thickness readings is in the above table.

**Step 3** – Determine the length for thickness averaging.

Step 3.1 – Determine the minimum thickness and remaining thickness ratio

$$t_{\min} = 9.14 \text{ mm}$$

$$R_t = \frac{9.14 - 2.54}{12.5} = 0.528$$

Step 3.2 – Determine the length for thickness averaging.

From Table 1 with  $R_t = 0.528$  with  $\text{RSF}_a = 0.9$   $Q = 0.62$  or by equation.

$$Q = 1.123 \left[ \left( \frac{1 - 0.528}{1 - \frac{0.528}{0.90}} \right)^2 - 1.0 \right]^{0.5} = 0.616$$

$$L = 0.616 \sqrt{1219.2 \text{ mm}(12.50 \text{ mm})} = 76.05 \text{ mm}$$

**Step 4** – Thickness profiles where taken; therefore, determine the longitudinal and circumferential *CTP*'s, (the thickness readings for the critical inspection planes are indicated in the above table and shown in the following figure) and determine the flaw dimensions.

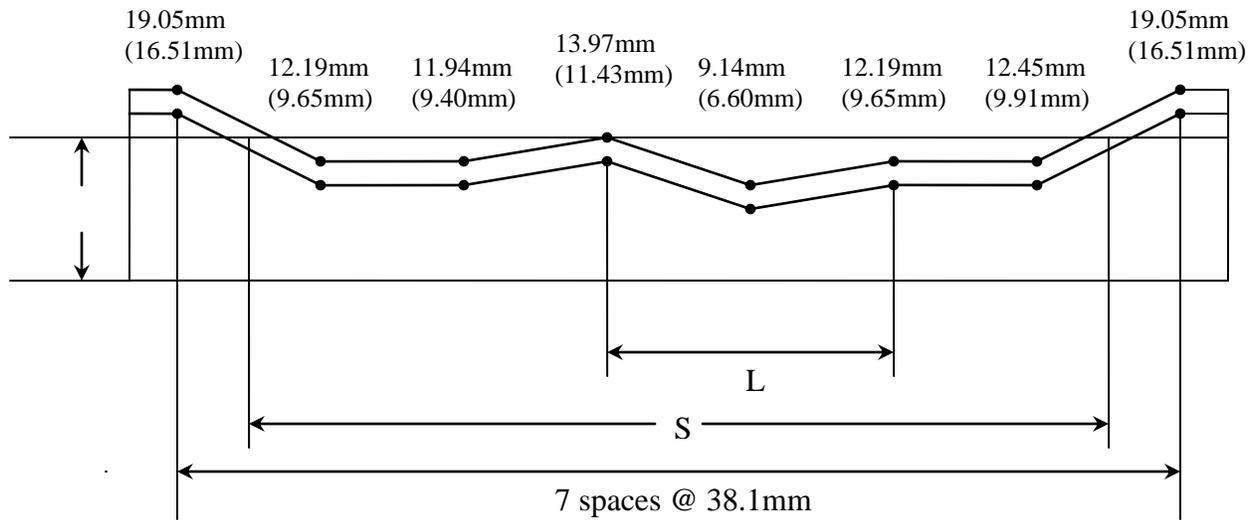


Figure 7 Corrosion Thickness Profile

Note: In this figure, the top number is the wall thickness at the time of the inspection and the number in the parentheses is this wall thickness minus the future corrosion allowance.

$$Flaw\ dimension, s = 5(38.1mm) + \left( \frac{12.5mm - 9.65mm}{16.51mm - 9.65mm} \right) (38.1mm) + \left( \frac{12.5mm - 9.91mm}{16.51mm - 9.91mm} \right) (38.1mm) = 221.23mm$$

**Step 5** – Since this evaluation can be performed by direct averaging the thickness readings that reside within length  $L$ .

$$t_{am} = t^s_{am} = \frac{13.97mm + 9.14mm + 12.19mm}{3} = 11.8mm$$

Alternatively, the average thickness can be established more accurately using areas.

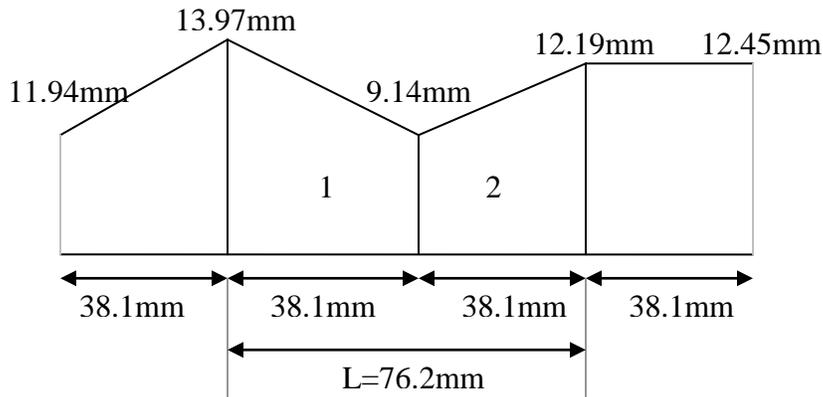


Figure 8 Areas in corrosion thickness profile to be used in the calculation

$$A_1 = \frac{(13.97mm + 9.14mm)}{2} (38.1mm) = 440.25mm^2$$

$$A_2 = \frac{(12.19mm + 9.14mm)}{2} (38.1mm) = 406.34mm^2$$

$$A_1 + A_2 = 440.25mm^2 + 406.34mm^2$$

$$= 846.59mm^2$$

$$t_{am} = t^s_{am} = \frac{A_1 + A_2}{76.2mm}$$

$$= 11.13mm$$

**Step 6** – Determine if the component is acceptable for continued operation.

$$(t_{am} - FCA = 11.13mm - 2.54mm = 8.59mm) \geq (t_{min}^c = 12.5mm) \text{ False}$$

$$(t_{min} - FCA = 9.14mm - 2.54mm = 6.6mm) \geq (\max[0.5t_{min}, 0.254] = 6.25mm) \text{ True}$$

**The Level 1 Assessment criteria are not satisfied.**

From the result, we can observe that Level 1 Assessment is not satisfied. The Level 1 Assessment procedures can be used to evaluate a component with local metal loss subject to internal pressure. There might be significant thickness variations over the length of the flaw or if a network of flaws are closely spaced. This result may be conservative and a Level 2 Assessment is recommended.

## 4.2 Level 2 Assessment

**Step 1** - Calculate the minimum required thickness

$$t_{min}^c = \frac{300 \text{ psig}(609.6mm + 2.54mm)}{17500 \text{ psi}(0.85) - 0.6(300 \text{ psi})} = 12.50mm$$

$$t_{min}^L = \frac{300 \text{ psig}(609.6mm + 2.54mm)}{(2)17500 \text{ psi}(0.85) + 0.4(300 \text{ psi})} = 6.15mm$$

$$t_{min} = \max[12.5, 6.15] = 12.5$$

**Step 2** - Thickness profiles are provided, the data for thickness readings is in the above table.

**Step 3** – Determine the length for thickness averaging.

Step 3.1 – Determine the minimum thickness and remaining thickness ratio

$$t_{min} = 9.14mm$$

$$R_t = \frac{9.14 - 2.54}{12.5} = 13.41\text{mm} = 0.528''$$

Step 3.2 – Determine the length for thickness averaging.

From Table 1 with  $R_t = 0.528$  with  $RSF_a = 0.9$   $Q=0.62$  or by equation.

$$Q = 1.123 \left[ \left( \frac{1 - 0.528}{1 - \frac{0.528}{0.90}} \right)^2 - 1.0 \right]^{0.5} = 0.616$$

$$L = 0.616 \sqrt{1219.2\text{mm}(12.50\text{mm})} = 76.05\text{mm}$$

**Step 4** – Thickness profiles where taken; therefore, determine the longitudinal and circumferential *CTP*'s, (the thickness readings for the critical inspection planes are indicated in the above table and shown in the following figure) and determine the flaw dimensions.

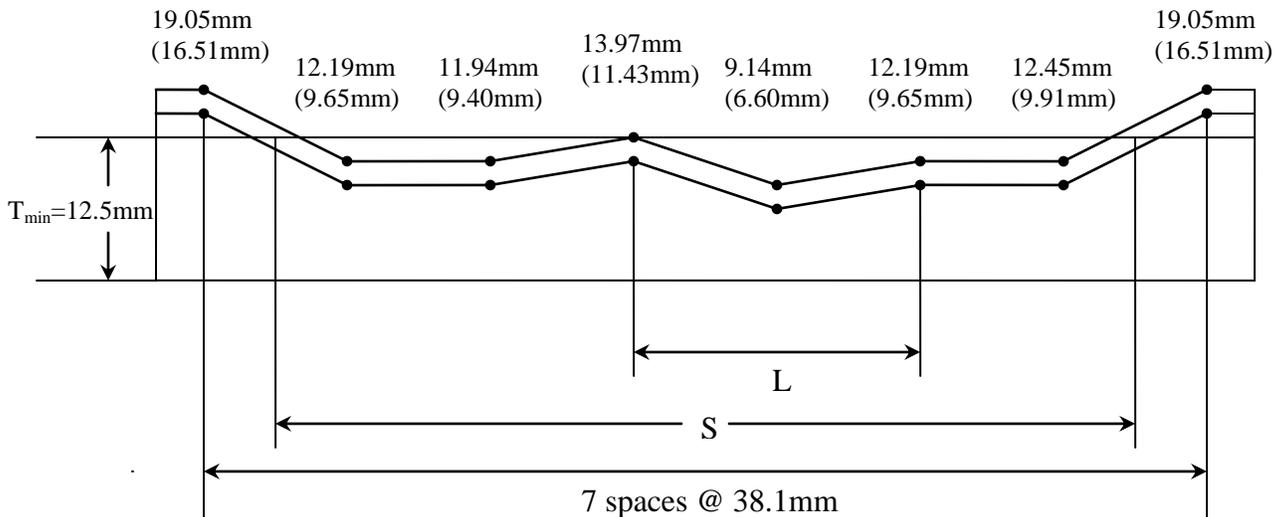


Figure 9 Corrosion thickness profile

Note: In this figure, the top number is the wall thickness at the time of the inspection and the number in the parentheses is this wall thickness minus the future corrosion allowance.

$$\text{Flaw dimension, } s = 5(38.1\text{mm}) + \left(\frac{12.5\text{mm} - 9.65\text{mm}}{16.51\text{mm} - 9.65\text{mm}}\right)(38.1\text{mm}) + \left(\frac{12.5\text{mm} - 9.91\text{mm}}{16.51\text{mm} - 9.91\text{mm}}\right)(38.1\text{mm}) = 221.23\text{mm}$$

**Step 5** – Since this evaluation can be performed by direct averaging the thickness readings that reside within length  $L$ .

$$t_{am} = t^s_{am} = \frac{13.97\text{mm} + 9.14\text{mm} + 12.19\text{mm}}{3} = 11.8\text{mm}$$

Alternatively, the average thickness can be established more accurately using areas.

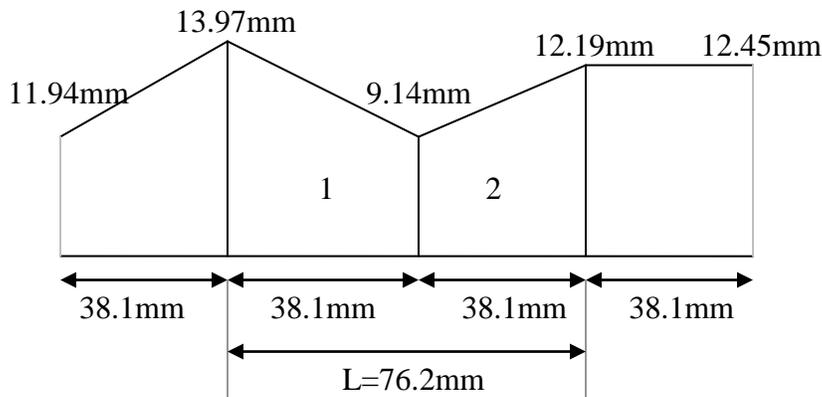


Figure 10 Areas in corrosion thickness profile to be used in the calculation

$$A_1 = \frac{(13.97\text{mm} + 11.94\text{mm})}{2} (38.1\text{mm}) = 440.25\text{mm}^2$$

$$A_2 = \frac{(12.19\text{mm} + 9.14\text{mm})}{2} (38.1\text{mm}) = 406.34\text{mm}^2$$

$$A_1 + A_2 = 440.25\text{mm}^2 + 406.34\text{mm}^2$$

$$= 846.59\text{mm}^2$$

$$t_{am} = t^s_{am} = \frac{A_1 + A_2}{76.2\text{mm}}$$

$$= 11.13 \text{ mm}$$

**The results and procedure in Level 2 are basically the same as in Level 1 Assessment.**

**Step 6** – Determine if the component is acceptable for continued operation.

The acceptability for continued operation can be established using the following criteria.

The average measured wall thickness for the *CTP(s)* should satisfy the following thickness criteria. Alternatively, the *MAWP* calculated based on the thicknesses  $(t_{am} - FCA) / RSF_a$  and  $(t_{am} - FCA - t_{sl}) / RSF_a$  should be equal to or exceed the design *MAWP*

1) Cylindrical and Conical Shells:

$$t^s_{am} - FCA \geq RSF_a \cdot t^C_{\min}$$

$$11.13\text{mm} - 2.54\text{mm} \geq (0.90)12.5\text{mm}$$

$$8.59\text{mm} \geq 11.25\text{mm} \quad \text{False}$$

The minimum measured wall thickness  $t_{mm}$ , for the *CTP(s)* should satisfy the following thickness criterion. For pressure vessels and piping systems;

$$t_{mm} - FCA \geq \max[0.5t_{\min}, (2.54\text{mm})]$$

$$(9.14\text{mm} - 2.54\text{mm}) \geq 6.25\text{mm}$$

$$6.6\text{mm} \geq 6.25\text{mm} \quad \text{True}$$

**The Level 2 Assessment criteria are not satisfied.**

From the result, we can observe that Level 2 Assessment is not satisfied. The Level 2 Assessment rules provide for a better estimate of the structural integrity of a component when significant variations in the thickness profile occur within the region of metal loss. The assessment procedures in Level 2 provide a better estimate of the Remaining Strength Factor than computed in Level 1 for local metal loss in a component subject to internal pressure loading. There might be significant variations in the thickness profile thus produce conservative result. Level 2 Assessment is recommended as it does not meet the requirement.

### **4.3 Level 3 Assessment**

#### **Modeling of Intact Pressure Vessel**

Intact pressure vessel is modeled to prove that FEA can produce more accurate result. Analysis are done analytically and using Finite Element Method. When analyzing analytically, several calculations were made in order to come out with the stress solution.

Below are the specifications of the pressure vessel:

Length = 1220 mm

Inside diameter,  $D_i = 1219$  mm

Thickness = 19.1 mm

Internal Pressure = 2.0684 MPa

The equation for longitudinal/axial stress created by an internal pressure on a cylindrical pressure vessel is:

$$\sigma_L = \frac{P_i D}{4t} \quad [\text{Eq.8}]$$

where;

$P_i$  = Internal pressure (MPa)

D = Diameter (mm)

t = thickness (mm)

The equation for hoop stress created by an internal pressure on a cylindrical pressure vessel is:

$$\sigma_H = \frac{P_i D}{2t} \quad [\text{Eq.9}]$$

where ;

$P_i$  = Internal pressure (MPa)

D = Diameter (mm)

t = thickness (mm)

**Stress involved in longitudinal direction;**

$$\begin{aligned} \sigma_L &= \frac{P_i D}{4t} \\ &= \frac{2.0684 \text{MPa}(1219 \text{mm})}{4(19.1 \text{mm})} \\ &= \frac{2521.3796}{76.4} \\ &= 33.0024 \text{MPa} \end{aligned}$$

**Stress involved in hoop direction;**

$$\begin{aligned} \sigma_H &= \frac{P_i D}{2t} \\ &= \frac{2.0684 \text{MPa}(1219 \text{mm})}{2(19.1 \text{mm})} \end{aligned}$$

$$\begin{aligned}
&= \frac{2521.3796}{38.2} \\
&= 66.0047\text{MPa}
\end{aligned}$$

These two calculations will be compared with the results from Finite Element Analysis (FEA). After obtaining the results from FEA, analysis will be done to relate between the analytical calculations and FEA.

Figure 11 shows the sketch of cross section of the pressure vessel using the real dimension. The pressure vessel has a longitudinal axis of rotational symmetry and is also symmetric with respect to an axis that can be solved with an axisymmetric finite element model. Since this pressure vessel is axisymmetric, Figure 12 shows a slicing plane that contains the symmetry axis exposes the interior configuration of the geometry. Since any slice created by such a plane looks like any other slice, the pressure vessel can be conveniently analyzed by considering any one planar sections.

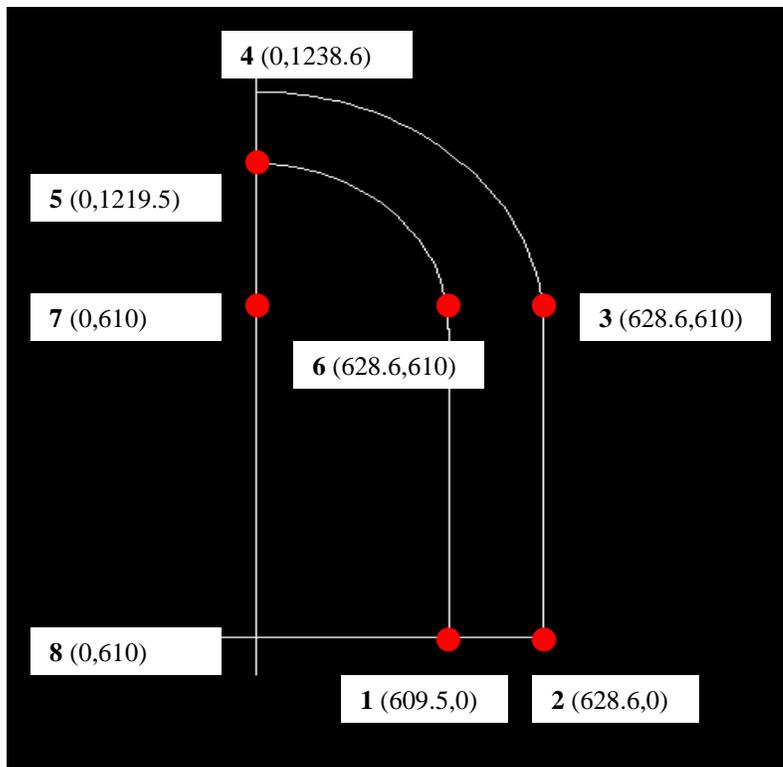


Figure 11 Cross section area of pressure vessel

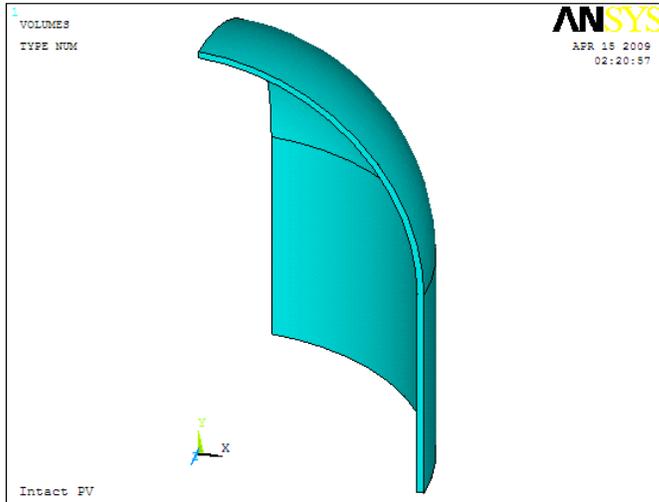


Figure 12 A 180-degree slice of top half of the pressure vessel

For this FEA, some assumptions have been made for some value to be entered during the analysis. The material properties for the pressure vessel are elastic modulus  $E=207 \text{ GPa}$  ( $207 \times 10^3 \text{ N/mm}^2$ ), Poisson's ratio=0.3 and Yield Strength=330MPa ( $330 \times 10^6 \text{ N/m}^2$ ). The geometric modeling was performed using mm as units of length, so a consistent set of units is used. Results calculated with these inputs will have displacements in mm and stresses in  $\text{N/mm}^2$ . Pressure vessel also is assumed using the element types of Brick 8 node 185.

Figure 13 shows the pressure vessel in oblique view and has been meshed. After meshing, all the edges off the pressure vessel were applied with boundary condition. Make sure there are no stresses involved in x and y direction. After applying boundary condition, we must apply the internal pressure to the inside of the pressure vessel. A value of 2.0684 MPa is applied to the inside of pressure vessel.

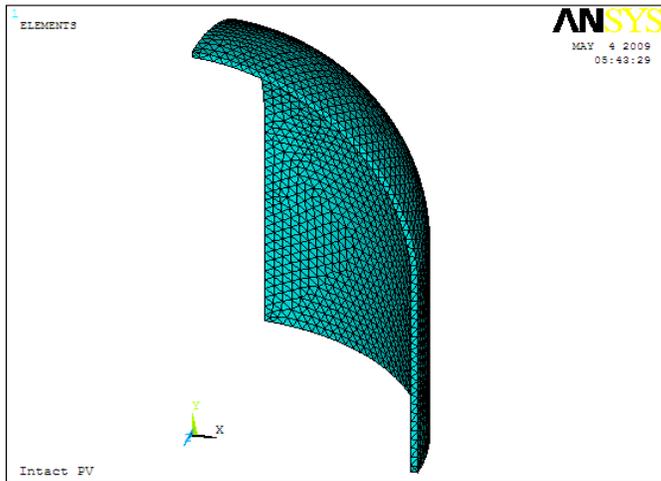


Figure 13 Initial meshed

Figure 14 shows the Von Mises equivalent stress result of the intact pressure vessel. The intermediate von Mises stress area (value of 29.761MPa to 33.236MPa) can be identified at the top of the pressure vessel. High stresses area (value of 57.563MPa to 61.038MPa) are located at the bottom of the edge of pressure vessel.

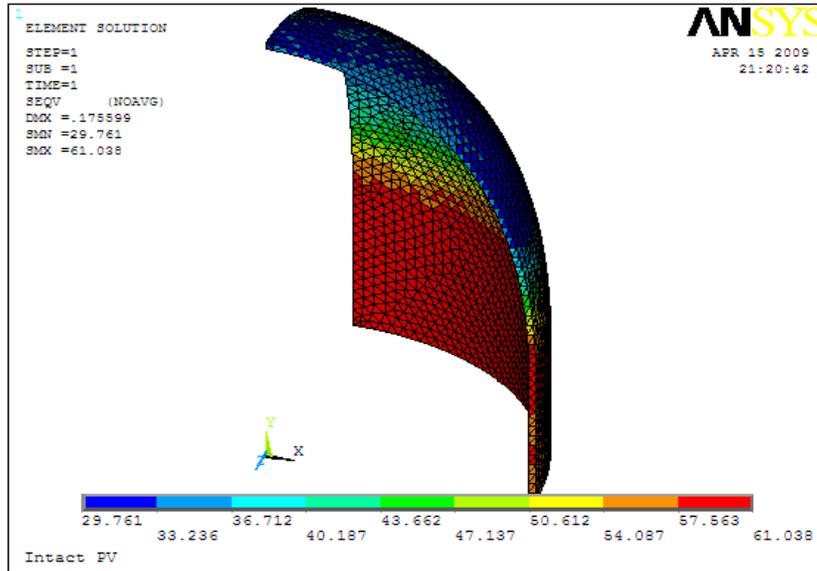


Figure 14 Von Mises equivalent stress result of intact pressure vessel

The element solution plot of the von Mises stress in Figure 14 shows smooth contours indicating a reasonably accurate solution, so we can safely use nodal solution stress values. Zoom in on the edge of the bottom area, we can see the node is numbered as “1” and we can see the list of stress components as in Figure 15. At node 1:

Radial stress (SX) = -1.0319 MPa

Axial stress (SY) = 32.737 MPa

Hoop Stress (SZ) = 66.894 MPa

```

PRNSOL Command
File

PRINT S      NODAL SOLUTION PER NODE

***** POST1 NODAL STRESS LISTING *****
PowerGraphics Is Currently Enabled

LOAD STEP=    1  SUBSTEP=    1
TIME=    1.0000  LOAD CASE=    0
NODAL RESULTS ARE FOR MATERIAL    1

THE FOLLOWING X,Y,Z VALUES ARE IN GLOBAL COORDINATES

NODE    SX          SY          SZ          SXY          SYZ          SZX
1    -1.0319      32.737      66.894      -0.20868      0.31124E-01  0.84782
2    -0.75087     32.131     64.702     -0.61853E-01 -0.30383E-01  0.75423
3    -0.59633     32.186     48.701     -1.3009       -0.20253      0.55896
4     31.818     -0.72639     31.982     -0.56738      0.52520     -0.48105E-01
5     33.290     -0.95074     33.320     -0.43384      0.49286      0.34461E-01
6    -0.76937E-01  32.382     49.150     -1.6665       0.35852E-01  0.87518
7     67.123     32.786     -1.0507     -0.88355E-02  0.21512      0.76282
8     64.686     32.108     -0.71502     -0.23748E-01  0.10522      0.75974
9     48.059     31.909     -0.50108      0.15491       1.4295       0.56668
10    48.832     32.306      0.20006E-01  0.19049E-01  1.6360       1.0780
11    -0.42120     32.019     64.398      0.11379     -0.56525E-01  0.56081
12    -0.56649     32.075     64.468      0.20215E-01 -0.23871E-01  0.68254
13    -0.58452     32.041     64.425     -0.27995E-02  0.66384E-02  0.74336
14    -1.1873     31.919     64.599     -0.36232E-01  0.30609E-01  1.1549
15    -1.1007     32.028     65.434      0.84281E-02 -0.10637E-01  1.2111
16    -0.82579     31.944     65.029      0.12632     -0.49769E-01  1.0280
17    -0.78868     31.945     64.899      0.19291     -0.23539E-01  0.84360
18    -0.81446     31.977     65.281      0.32267E-01  0.12360E-01  0.86575
19    -1.0056     31.887     64.972     -0.14174      0.58927E-01  0.84205

```

Figure 15 Nodal solution at X component

Table 3 Data tabulation of results obtained

Stress	Analytical solution	Finite Element Analysis	% of difference
Axial stress (SY)	33.002 MPa	32.737 MPa	0.8%
Hoop stress (SZ)	66.005 MPa	66.894 MPa	1.33%

From Table 3, the computed values for SY and SZ are at small percent of difference compared to analytical solution. This correlation gives confidence that Finite Element Analysis is proven to be used for Level 3 Assessment. The finite element solution actually gives a better picture of the true stress distribution.

## **Modeling of Corroded Pressure Vessel**

Fitness-For-Service (*FFS*) assessment procedures for corroded pressure vessel subject to general metal loss resulting from corrosion are being modeled. Level 3 Assessment can be performed when the Level 1 and 2 Assessment procedures are not satisfied, or when these assessment levels produce conservative results.

Below are the specifications of the corroded pressure vessel:

Length = 1220 mm

Inside diameter,  $D_i$  = 1219 mm

Plate Thickness = 19.05 mm

Internal Pressure = 2.0684 MPa

Corrosion Thickness = 9.1 mm

Critical Length = 76.2 mm

Material = SA516 Grade 70

Figure 16 shows the Von Mises equivalent stress result of the corroded pressure vessel. The intermediate von Mises stress area (value of 27.618MPa to 33.209MPa) can be identified at the top of the pressure vessel. High stresses area (value of 73.047MPa to 78.739MPa) are located at the ligament part of the corroded area. From the figure, we can observe that the critical part in red spread only at the ligament compared to intact pressure vessel, the critical part spread until half of the pressure vessel. This shows that, due to the corrosion, failure may occur starting at the ligament of the corroded area.

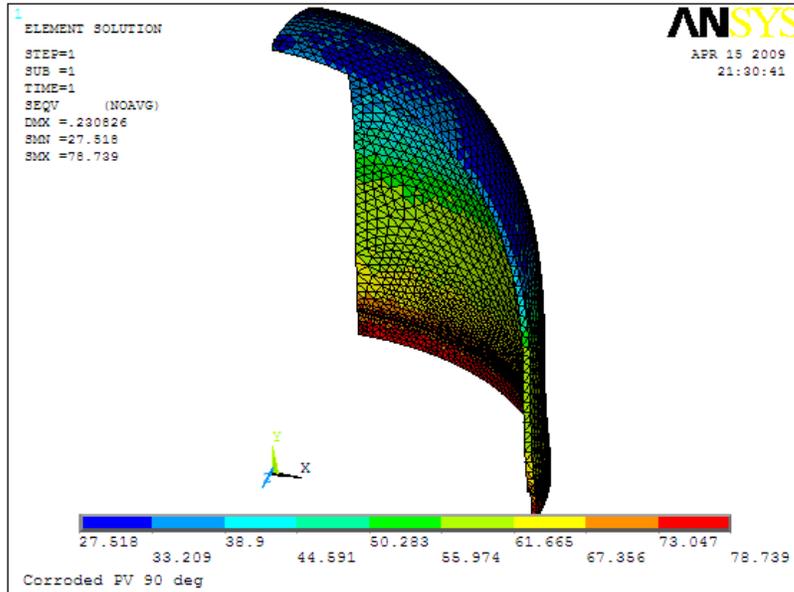


Figure 16 Von Mises equivalent stress of corroded pressure vessel

To determine whether the pressure is safe for service or not, we need to calculate maximum allowable stress for the pressure vessel to uphold the internal pressure applied.

Below is the calculation of maximum allowable stress:

Data required

Material : SA516 Grade 70

Yield Stress : 485 MPa

Safety Factor : 4

$$\begin{aligned} \sigma_{allow} &= \frac{\sigma_y}{SF} \\ &= \frac{485MPa}{4} \\ &= 121.25 MPa \end{aligned}$$

\* Max Stress <  $\sigma_{allow}$

At the current situation where the pressure vessel is corroded, the maximum stress developed through the pressure vessel is 78.739 MPa. The pressure is lower than the maximum allowable stress that the pressure vessel can uphold. We can conclude that the pressure vessel is safe for continuous operation as the pressure is still lower than the maximum allowable stress.

However, due to the corrosion growth, the induced stress in the pressure vessel is increasing through time. Annually, the corrosion growth is assumed to be 2mm per year. After one year since the last inspection, Figure 17 shows that the pressure vessel still can operate safely as the FEA results shows that the maximum stress value is 85.944 MPa which is still below the maximum allowable stress.

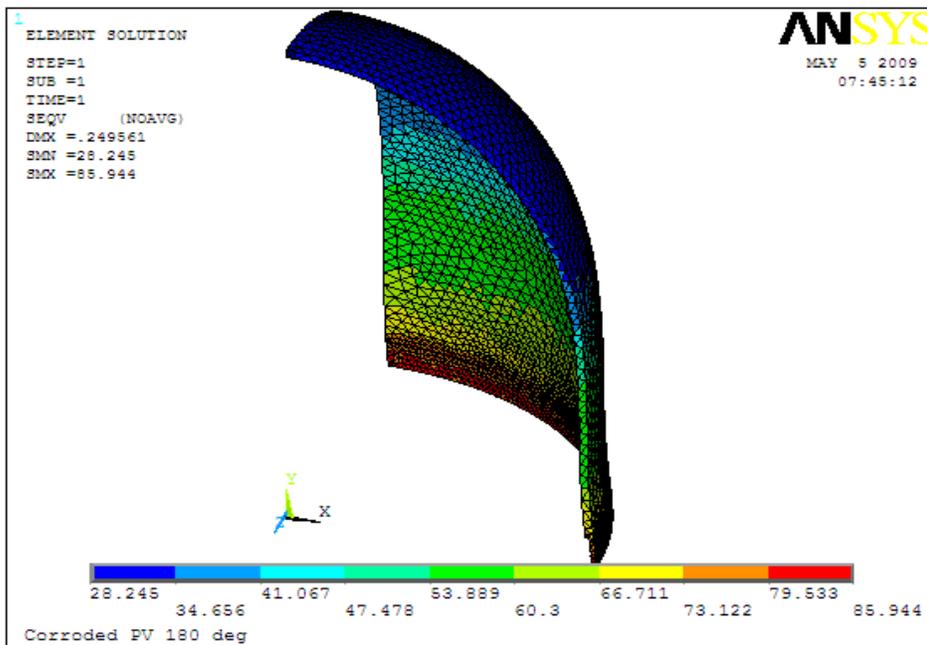


Figure 17 Von Mises equivalent stress of corroded pressure vessel after one year since last inspection

At the second year after inspection, Figure 18 shows the maximum stress is recorded at 98.307 MPa, still below the maximum allowable stress.

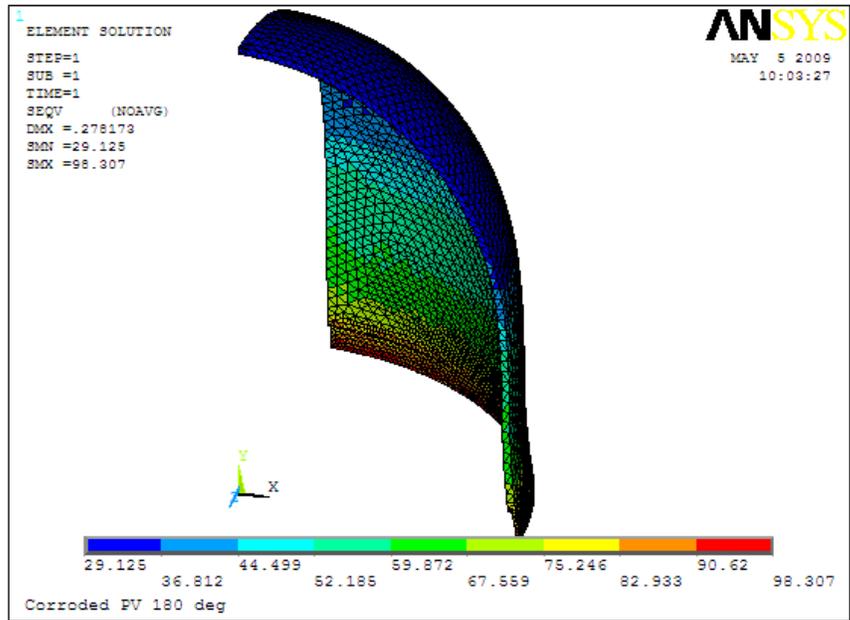


Figure 18 Von Mises equivalent stress of corroded pressure vessel at second year after inspection

Figure 19 shows that at the third year, a FEA result shows the maximum value is 131.442 MPa which have exceeded the maximum allowable stress. At this time, the pressure vessel is unsafe for operation or might have burst and cause explosion. Thus, we can conclude that this pressure vessel can only operate up to two years after first inspection.

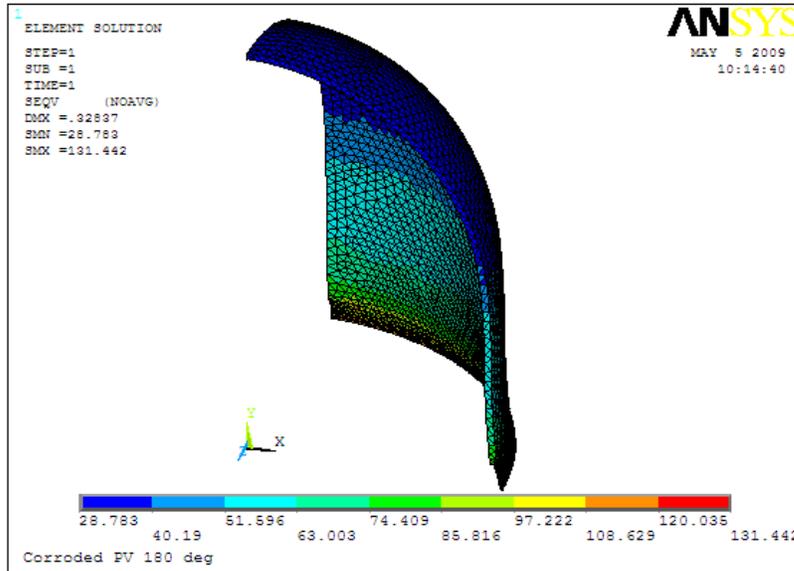


Figure 19 Von Mises equivalent stress of corroded pressure vessel at third year after inspection

#### 4.4 Summary of Result for each model

From the three levels of assessments, the results can be simplified in the table below:

Table 4 Conclusion of result obtained

Level of Assessment	Result
Level 1	Not acceptable
Level 2	Not acceptable
Level 3	Acceptable but need to be replaced after 2 years of operation since last inspection

Table 5 Table of life years of pressure vessel based on Maximum Stress based on FEA

Year	Results of Maximum Stress based on FEA	Remarks
1	85.944 MPa	$\sigma_{\max} < \sigma_{\text{allow}}$ : OK
2	98.307 MPa	$\sigma_{\max} < \sigma_{\text{allow}}$ : OK
3	131.442 MPa	$\sigma_{\max} > \sigma_{\text{allow}}$ : Not OK

## **CHAPTER 5**

### **DISCUSSION**

#### **5.1 Discussion of results obtained**

After obtaining the results from the three levels of assessments, analysis must be done to interpret the results in order to show the accuracy and importance of the assessments. Below is the interpretation that has been done based on the results obtained:

i) Region of low stress increases/extends with the increasing area of corrosion.

From the Von Mises equivalent stress result, it can be observed that the low stress region (minimum Von Mises stress area) is increasing with the increasing area of corrosion or the reducing of plate thickness due to corrosion. High stress area can give potential to shell plate failure and will reduce the capability of the pressure vessel to withstand internal pressure applied. If vessel rupture occurs, the pressurized fluids will cause blast effects due to sudden expansion and will cause fire and explosion.

ii) Region of intermediate stress that surrounds high stress region is decreased with increasing area of corrosion. Figure 20 shows the comparison of low intermediate stress region of Von Mises Stress equivalent stress result

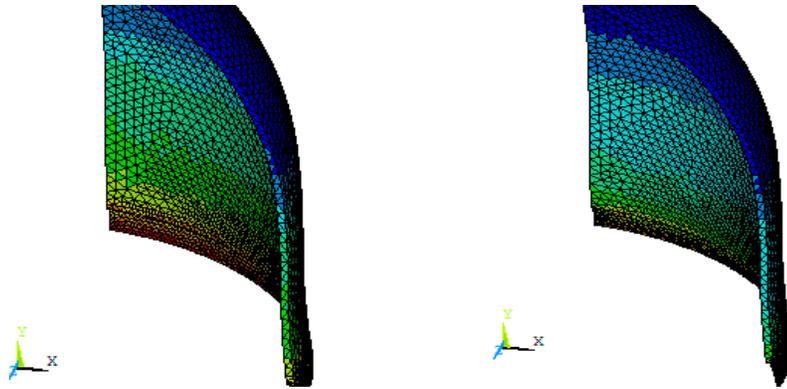


Figure 20 Comparison of low intermediate stress region of Von Mises Stress equivalent stress result

Based on the two models above, it can be observed that region of intermediate stress (green colored area) reduced as the corrosion area increased. Whereas, the high stress region (red colored area) increased as the corrosion increased. Intermediate stress region acts as the resistance to high stress region.

iii) Region of high stress located at corroded area

Based on Figure 21, it can be observed that potential of fracture or leaking is more probable at the corroded area which is at the centre of the pressure vessel.

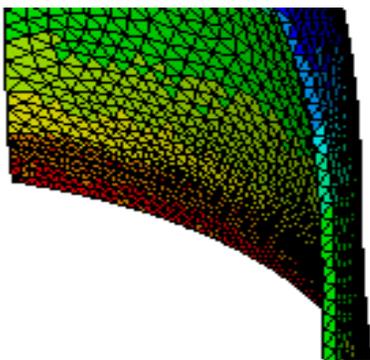


Figure 21 Location of high stress region on corroded pressure vessel

## CONCLUSION

The utilization of Level 3 of Fitness for Service provides an accurate assessment of the corroded pressure vessel compared to Level 1 and 2 and also provide added advantage to simulate stresses of the operating condition for future planning. Thus, in conclusion;

1. Level 1 and 2 produce conservative result as it utilizes with the minimum amount of inspection.
2. Level 3 Assessment can predict the location of failure to occur while Level 1 and 2 assessments can only determine whether the pressure vessel is fit for service or not.
3. Level 3 Assessment can visualize the stress distribution and deformation of plate as a tool for assessment for engineer or high skilled person.
4. Different level of assessment gives more accuracy in determining the right time to do some modification work on corroded plate.
5. Overall, assessments that were made are proven that Fitness for Service is an important tool for decision making to ensure that any corroded pressure vessel can operate in safe condition.

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