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Mechanical Integrity Assessment of NGL Pressure Vessel p. 4

2009 Mary Kay O'Connor Safety Symposium p. 13

API RP 581 RBI Technology - Worked Example Part 3 of 3 p. 14

2nd Annual Pipeline Leak Detection Conference p. 26

2009 ASME Pressure Vessel and Piping Conference p. 26

NDT Canada Conference p. 26

Mechanical Integrity Assessment of a Large NGL Pressure Vessel Case Study

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In the oil and gas industry, pressure vessel integrity is a major concern. After internal and external inspections various anomalies or defects can be reported and repairs could be required for pressure vessels in order to restore its original condition. The first question for engineers, operators and managers is, can we keep operating at this pressure level? Is it safe? Or do I have to take it out of service to repair? Structural integrity assessment methodologies can be used to determine the suitability of a vessel for service as well as a good maintenance management can reduce the inspection cost and extend the equipment life within safe, reliable limits.

Pressurized equipment such as this large horizontal vessel in a typical gas plant can experience in-service damage. The vessel condition can deteriorate due to various factors including mechanical problems, process related problems and corrosion problems. This strategy includes fitness-for-service and remaining useful life analyses of a large vessel based on the non-destructive examination results, mechanical properties and operating conditions. The analysis procedure, stress analysis and remaining useful life evaluation for the vessel are discussed. Recommendations for consideration of anomalies detected during the assessment are also presented. The assessment methodology employed in this paper can be applied to other similar pressurized vessels in Oil & Gas, chemical and petrochemical plants.

The methodology applied by ABB Service in a NGL gas plant aims to maximize the pressure vessel reliability and availability. The procedure intends to determine its mechanical behavior under different process conditions, to identifythe potential damage mechanisms and get accurate results from non destructive inspections for the analyses. The methodology used in this analysis consists of five steps, **Step "A":** Perform a qualitative risk analysis using an output risk matrix to select equipment that requires a more detailed analysis; **Step "B":** Perform the analysis of equipment (stress analysis, potential damage mechanism, failure mode, process condition and maintenance strategy); **Step "C":** Quantification of inspection results; **Step"D":** Fitness for Service Analysis; **Step "E":** Failure Analysis. A key factor of the analysis is to complete every step in sequence from A to E (see figure 1).

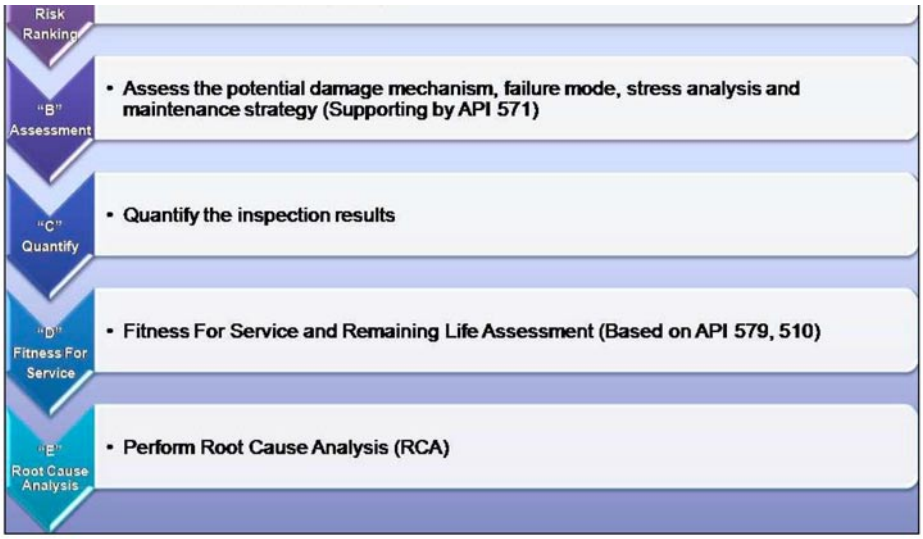

Figure 1.Methodology steps

Step "A"- Qualitative Risk Ranking

In this first part a qualitative risk analysis of pressure equipment needs to be performed. Through this step much of the the equipment will be disqualified from further analysis due to low risk. The remaining percentage will be considered for other types of analysis. The rule thumb from Pareto charts is that 20% of equipment represents 80% of the risk, so the idea is focus on that 20% of equipment. For this particular case the qualitative risk of equipment was calculated following the standard specification from API 581 "Risk Based Inspection", where the risk is the result from combining the likelihood and consequence.

$$Risk = Likelihood * Consequence$$

For this analysis the large pressure vessel has a low chance to suffer a failure, but the consequences (fire and explosion) are high for this reason the risk of the equipment is medium. The next figure 2 shows the qualitative risk of the equipment.

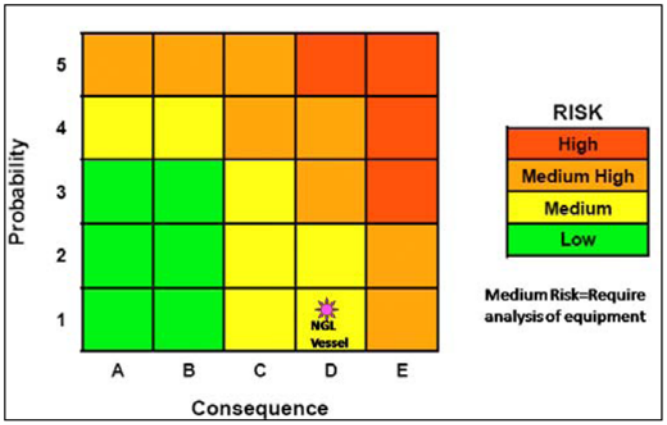

Figure 2.Qualitative Risk Analysis of large horizontal vessel

During the qualitative assessment phase some technical and maintenance management aspects are reviewed. To calculate the probability of failure category the damage mechanisms, failure modes, process conditions, types of inspections and equipment design are assessed. To calculate the consequence of a failure category, basic safety aspects are reviewed like volume enclosed, toxicity, risk of fire and explosion. In this case the large horizontal NGL pressure vessel requires a deeper analysis.

Step "B"- Assessment

Once the qualitative risks of equipment have been determined a deeper analysis could be required or not, depending on the risk level calculated and risk criteria. A detailed analysis was carried out for this particular pressure vessel. In this part of procedure three technical aspects were reviewed:

- Mechanical behaviour of large horizontal pressure vessel (stress analysis)
- Potential damage mechanisms
- Maintenance strategy

Mechanical behavior analysis of large horizontal pressure vessel

The purpose of this section is to identify all critical sections of equipment. For example where are the maximum stresses, what types of stress could be developed during normal operation. From the structural point of view, large horizontal pressure vessels (Length/ Diameter > 3) are different than vertical vessels and require more attention. Zick considers a large horizontal pressure vessel as a beam supported by two-saddle supports resisting the shell plus liquid weight (creating the longitudinal bending stress at mid span) and the internal pressure. There are shear and circumferential stress concentration at the horn of the saddle. (See figure 3)

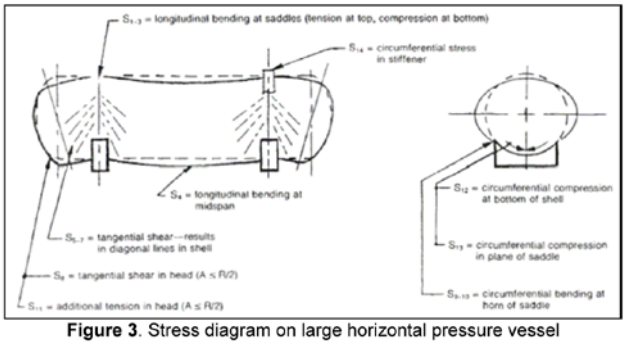

Figure 3. Stress diagram on large horizontal pressure vessel

To simulate the normal operation condition of the large horizontal NGL pressure vessel, a linear finite element analysis was performed. The normal operating pressure, operating temperature, liquid and shell weight were considered for the stress analysis. (See figure 4).

Pressure vessel data:

Material: A516 Gr 70 N
Thickness: 70 mm
Insulated: yes
Large: 31.000 mm
Diameter: 5.000 mm

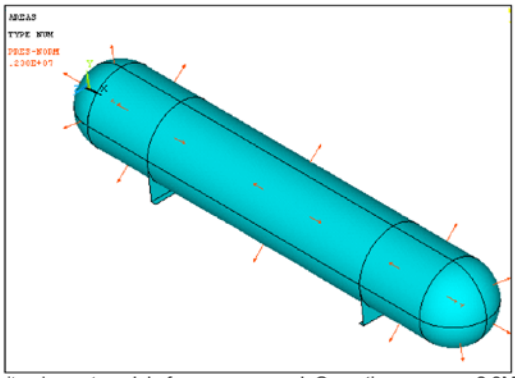

Figure 3.Finite element model of pressure vessel. Operation pressure 2,3Mpa (23bars)

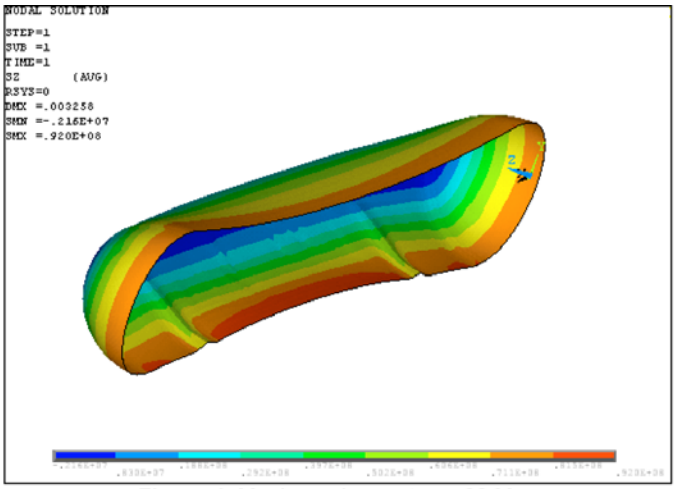

Figure 4. Maximum hoop stress 83 Mpa

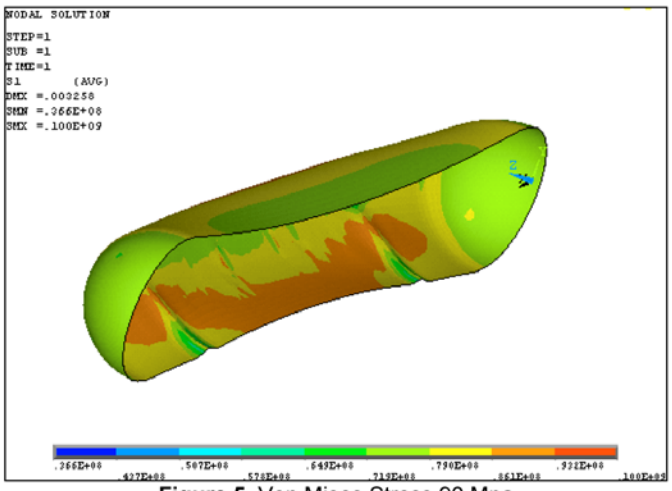

Figure 5. Von Mises Stress 90 Mpa

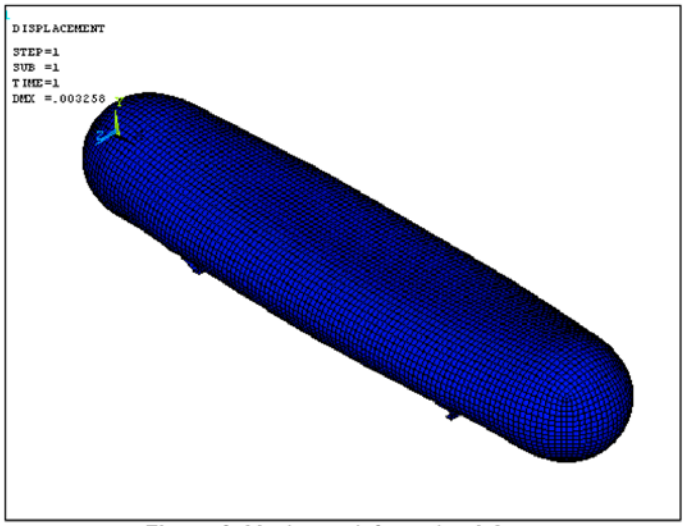

Figure 6. Maximum deformation 3,2mm

From figure 4 and 5 maximum stress is located between supports (90 Mpa), high stress concentration on saddle support was found and the hoop stress acting on the shell was 80 Mpa. Based on this results careful attention will be focused on these critical points during internal and external inspection.

Potential damage mechanism

A key first step in safely and reliably managing equipment is to identify and understand the relevant damage mechanisms. Proper identification of damage mechanisms is very important when risk based maintenance is applied on process equipment. Non-destructive testing is selected based on the damage mechanism and its failure mode. Information related to potential damage mechanisms is supported by API RP 571 "Damage Mechanisms Affecting Fixed Equipment in the Refining Industry". The damage mechanisms in this recommended practice cover situations encountered in the refining and petrochemical industry in pressure vessel, piping, and tanks. The mechanisms are divided into the following groups:

a) Mechanical and metallurgical failure/ degradation
b) Uniform or localized loss of thickness/corrosion
c) High temperature corrosion
d) Environmentally assisted cracking

In this part of the procedure, material of construction, type of process fluid, design construction practices (welding process, non-destructive manufacturing report, codes) and operation condition are considered in the analysis.

For this particular analysis the potential damage mechanisms indentified were:

- Corrosion Under Insulation (CUI)
- Mechanical deformation
- Loss of thickness due to internal corrosion

Maintenance Strategy

Once the potential damage mechanisms were identified a maintenance strategy was proposed for in-service inspection and out of service inspection. In table I and II inspection the strategy is shown.

Table I- Internal inspection activities

Type of damage	Damage mechanism	Behaviour	Non destructive technique	Inspection effectivity
• Loss Thickness	• CUI • Internal corrosion	• General, localized, pitting	• Spot thickness measurement and UT scan B • Full visual inspection	• Highly effective (90%)
• Surface-breaking flaw	• Mechanical failure due to overload. Visible deformation on saddle support.	• Visible deformation	• Liquid penetrant applied on seam weld located between saddle support	• Highly effective (80%-100%)

Table II- In-service inspection activities

Type of damage	Damage mechanism	Behaviour	Non destructive technique	Inspection effectivity
• External Loss Thickness	• CUI • Internal corrosion	• General, localized, pitting	• UT spot thicness measurements • Insulation visual inspection + thermography inspection if water entrance is suspected	• Fairly effective (50%)
Surface-breaking flaw and deformation	• Overload due to process condition	• Visible deformation	• Visual inspection and liquid penetrant on saddle support (high stress concentrations location)	• Highly effective (90%)

Step "C"- Quantify the inspection results

The aim of this section is to determine the real condition of equipment, quantifying each potential damage mechanism (identified in previous step) through non-destructive testing. Accuracy of results is a key factor. For this reason qualified and trained personnel on site are required.

Ultrasonic thickness measurements and UT B Scan

Internal ultrasonic thickness measurements and B Scan were carried out for this large horizontal pressure vessel. Ultrasonic B Scan is a technique where results are presented in a screen type B, where the thickness cross section can be visualized. Using this type of ultrasound technique, performed from inside of equipment, corrosion under insulation (CUI) can be detected without removal of insulation.

From ultrasonic thickness spot measurements the corrosion rate was determined to be 0,04mm/year (1.6 mils per year) and there are no signs of corrosion under insulation (See figure 7).

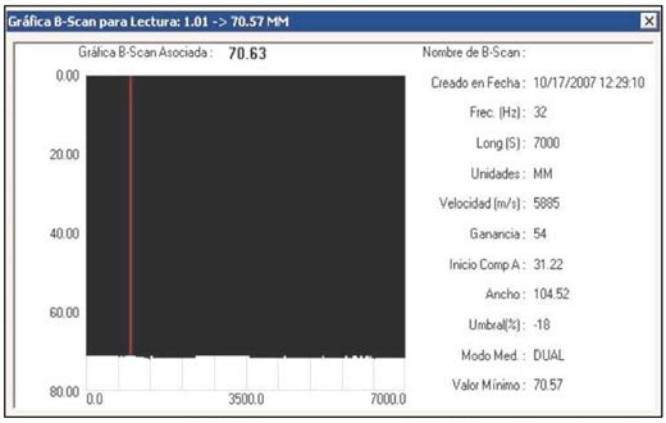

Figure 7. UT Scan B for pressure vessel. Thickness measured 70,63mm, there is no loss material (black side)

Liquid penetrant inspection

Liquid penetrant testing is a nondestructive method of revealing discontinuities that are open to the surfaces of a solid and essentially nonporous material. A wide spectrum of flaws can be found regardless of the configuration of the workpiece and flaw orientation.

For this particular case liquid penetrant inspection was focused on weld seams located on the shell, between saddle supports (See figure 8). Surface breaking fabrication and in-service anomalies would be detected.

Figure 8. Weld seam inspection. No discontinuities were detected

Visual inspection

Visual inspection is a nondestructive testing technique that provides a means of detecting and examining a variety of surface flaws, such as corrosion, contamination, surface finish, and surface discontinuities on joints.

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Visual inspection is also the most widely used method for detecting and examining large surface cracks which are particularly important because of their relationship to structural failure mechanisms.

In this case an internal visual inspection was carried out. During the internal inspection "Pitting corrosion" in the bottom of pressure vessel was detected (see figure 9a, b, c and d).

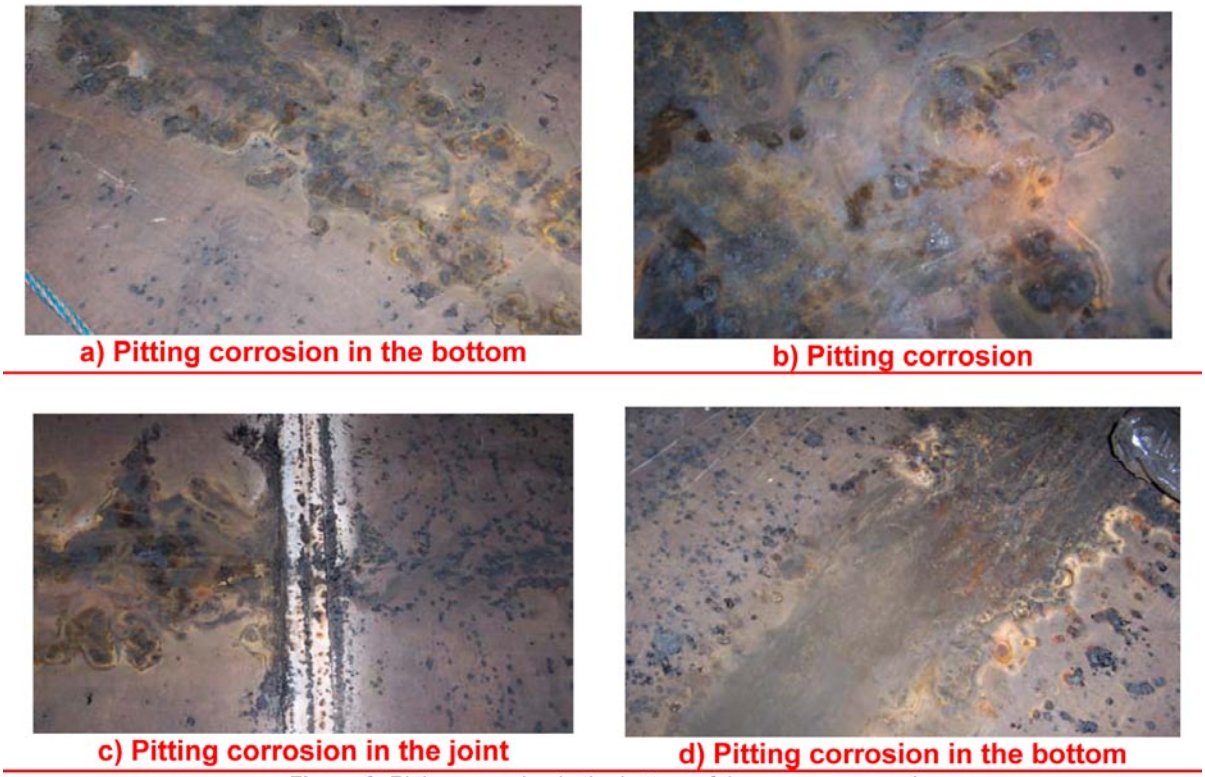

Figure 9. Pitting corrosion in the bottom of the pressure vessel

The limiting pitting size was determinated to be 2 mm (0.080") diameter and the pit depth equal to 1 mm (0.040"). A remaining life and fitness for service assessment were required.

Step "D"- Fitness for Service and Remaining Life Assessment

Fitness for service assessment (FFSA) may be defined as the quantitative analysis of the adequacy of a component to perform its function in the presence of a defect. FFSA must include an evaluation of the remaining life of a component. A damaged component may be acceptable in the present, but the remaining useful life must be determined. This assessment is necessary to establish inspection intervals and a basis for reliability-based inspection (RBI). This assessment will help to determine the risk priorities against other equipment needing opening in the next turnaround.

For this particular case the remaining life calculation was performed based on API 510 and pitting corrosion was evaluated based on chapter six from API RP 579. Figure 10 shows the thickness reduction through the years.

Remaining Life calculation

$$Corrosion\ \ Rate_{LongTerm} = \frac{T_{initial} - T_{actual}}{time\ \ between\ \ Tinitial\ \ and\ Tactual(years)} = \frac{70{,}8mm - 70{,}52mm}{7\,year} = 0{,}04mm/\,year$$

$$Remaining\ \ Life = \frac{T_{actual} - T_{minimum}}{CR} = \frac{70{,}52mm - 67{,}2mm}{0{,}04mm/\,year} = 83\,years$$

Where:

Tinitial= the initial wall thickness (mm). The new thickness at the first measurement
Tactual= the thickness measured during most recent inspection (mm)
Trequired= minimum thickness required by pressure or structural load, computed by design formula

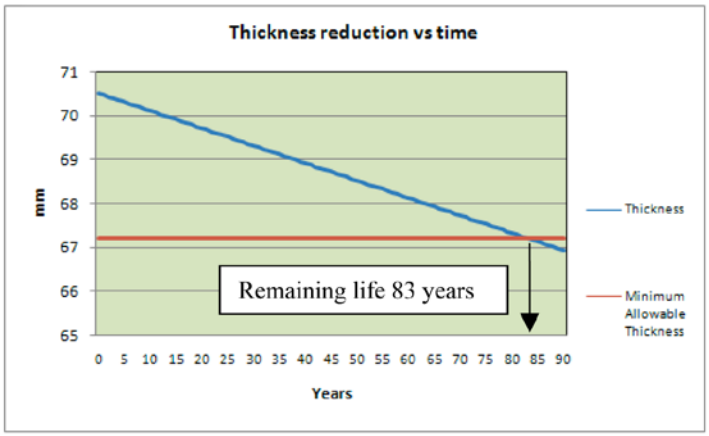

Figure 10. Wall thickness reduction of large pressure vessel

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Fitness for service assessment

In this part of the procedure pitting corrosion damage was evaluated applying the level 1 analysis from chapter six of the API 579 recommended practice. The assessment procedures in this section can be utilized to evaluate metal loss from pitting corrosion. Pitting is defined as a localized region of metal loss, so can be characterized by a pit diameter and pit depth. The level 1 assessment technique is simplified in that it does not account the orientation of the pit-couple with respect to the maximum stress direction. The results are conservative and based on pitting charts.

Step 1- Determine the following parameters:

D= Inside diameter of equipment (mm), 5000 mm
Loss= Thickness loss (mm), 0,38mm (70,8-70,42)
FCA= Future corrosion allowance (mm), 1,27mm
RSFa= Remaining Strenght Factor allowable (adimensional), 0,9
Trq= Wall Thickness measured at the time of assessment (mm)

Step 2- Determine the wall thickness used in the assessment using the following equation:

$$t_c = t_{rq} - FCA$$

$$t_c = 70{,}42 - 1{,}27 = 69{,}15mm$$

Step 3- Locate the area on the component that has the highest density of pitting damage based on the number of pits. Take photographs including reference scale.

Step 4- Determine the maximum pit depth, $w_{máx}$,:

$$w_{máx} = 1mm$$

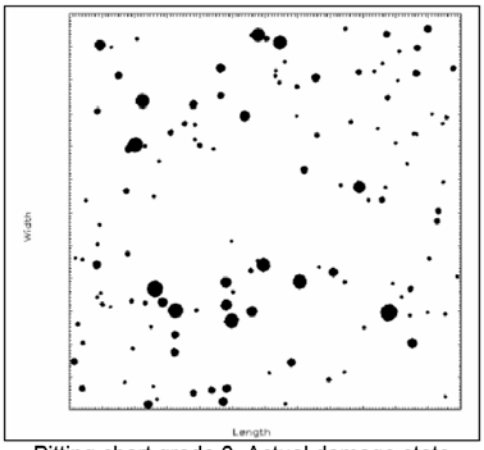
Step 5- Determine the ratio of remaining wall thickness, R_{wt},:

$$R_{wt} = \frac{t_c + FCA - w_{máx}}{t_c} = \frac{69{,}15 + 1{,}27 - 1}{69{,}15} = 1{,}0039$$

Step 6- Determine the MAWP for the component using thickness from step 2:

$$MAWP(Mpa) = \frac{2 * S * t_c}{2 * R_c + t_c} = \frac{2 * 163 * 69{,}15}{2 * (2500 + 1{,}27 + 0{,}38) + 69{,}15} = 4{,}4\,Mpa$$

Step 7- Compare the photograph taken from pit damage area to the standards pit charts.



Pitting chart grade 2. Actual damage state

Step 8- Determine the RSF from table associated with the pit chart and $R_{wt.}$

RSF = 0,99

Level 1 assessment will be accepted if only if:

1. $R_{wt} > 0{,}2$ (1,003>0,2) True
2. RSF > RSFa (0,99 > 0,9) True

The pitting damage is acceptable for the actual operation condition, the MAWP of 4.4 Mpa.

Step "E"- Root Cause Analysis (RCA)

The purpose of RCA is to identify and understand the root of problems that affect the equipment performance and its integrity. Understanding how anomalies can originate help the team to avoid future failures and problems of reoccurrence in this and similar equipment. For this reason it is very important to analyze every sign or evidence found during pressure vessel inspection, some of which can be analyzed in the laboratory.

For this analysis a sample of corrosion product was taken from the pressure vessel bottom. The sample was analyzed with the X-Ray diffraction analysis (EDAX) technique. This techniques is a powerful method by which X-Rays of a known wavelength are passed through a sample to indentify the crystal structure elemental make up with percentages. In table III and figure 11 sample results are shown:

Table III. Corrosion product analysis

Detected element	Atomic %
O	74
Al	0.48
Si	0.37
S	1.54
Fe	24.04

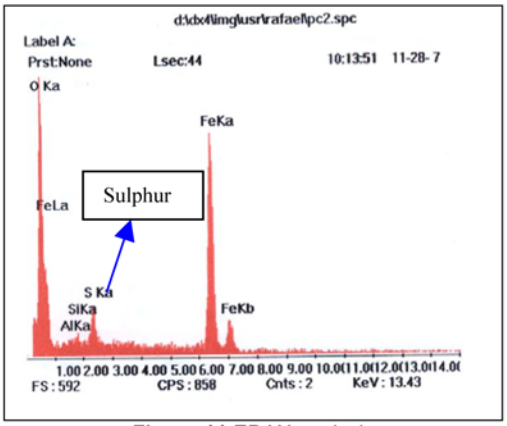


Figure 11.EDAX analysis

From the diffraction analysis some products were detected like goethite (FeO(OH)) and magnetite (Fe_3O_4) with sulphur contents (S). Both Fe_3O_4 and FeO(OH) are corrosion products that can be created by CO_2 and/or H_2S typical components that can be found in NGL. But corrosion by CO_2 was discarded due to $FeCO_3$ was not identified during laboratory analysis. The presence of sulphur in the corrosion deposit is a strong indication of SRB (Sulphate Reducing Bacteria) attack. The presence of the sand deposits at the bottom of pressure vessel has contributed to create the environment for MIC (Microbial Corrosion).

Microbially Influenced Corrosion (MIC)

MIC corrosion is not fundamentally different from other types of aqueous electrochemical corrosion; the difference is that the aggressive environment is produced by microorganisms as products of their metabolism. The most important group of bacteria associated with corrosion is the sulphate-reducing bacteria (SRB). In practice, the great majority of MIC failures are related to activities of SRB. Sulphate-reducing bacteria are anaerobic (oxygen-free) bacteria that obtain their required carbon from organic nutrients and their energy from the reduction of sulphate to sulphide. The pit is created under tubercle deposits (See figure 12).

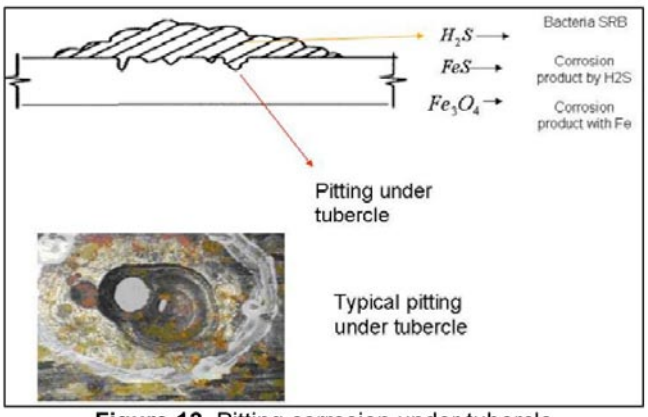


Figure 12. Pitting corrosion under tubercle

The corrosion mechanism created by SRB bacteria is explained in the following equations:

$$2H_2S + O_2 \rightarrow 2H_2O + 2S$$
$$3FeS + 2O_2 \rightarrow Fe_3O_4 + 3S$$

The corrosion process can be explained very easily. The H_2S is created by the bacteria SRB that combined with little water vestiges forming iron sulphide (FeS) that combined with oxygen create magnetite (Fe_3O_4)

Root Cause Analysis for large horizontal pressure vessel

Water was left in the vessel after hydrotest when the vessel was first put into service. It may be that there was a period between the hydrotest and start up when some pitting could have started under deposits, or in the open as normal rusting occurred. The fact that all the damage is in the vessel base supports the presence of water which has drained and remained in the base. Sulphate in the water would provide the nutrient for the SRB. Water is not accumulating in the vessel during normal operation. When the vessel is put back into service there should be no water present and none should be able to enter the system from outside. SRB bacteria could be generated when even little water vestiges remains during hydrotesting. Engineers require water specification for testing and good heating practices for water removal.

Recommendations

Grinding out the pits to give a smooth surface without going beyond the corrosion allowance appears to be a good recommendation. This will remove local stresses and remove all contamination and traces of moisture which could allow corrosion to take place if the pits and the deposits contained in them remained.

CONCLUSIONS

A good mechanical integrity program for pressure vessels is crucial for those plants that need to reduce turnaround time and inspection cost within safety standards.

Large horizontal vessels can be more complicated than common pressure vessels. Special care should be taken while internal and external inspections are carried out on shell between saddle supports. Visual inspection should be performed very carefully at the horns of saddles due to circumferential bending stress.

For this particular case study, the fitness for service assessment permitted the large NGL pressure vessel to operate at the design condition, being MAWP of 4.4 Mpa (638 psi) and MAOP 2.3Mpa (334 psi). Even though the pitting corrosion evaluation was acceptable, it is suggested to remove the pitting corrosion by grinding out the pits.

Water being trapped in this NGL pressure vessel was unlikely during service. In this case evidence supports that a bad water specification and ineffective practices for heating/drying before start up provided an environment for SRB which could have affected the mechanical integrity of this pressure vessel. A MIC corrosion mechanism has been generated due to slight amounts of water remaining from hydrotesting, creating an environment for a bacteria named SRB (sulfate Reducing Bacteria) and then pitting corrosion as final result of this bacteria metabolism. When the vessel is put back into service there should be no water present and none should be able to enter the system from outside.

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