MECHANICAL INTEGRITY ASSESSMENT OF A LARGE HORIZONTAL NGL PRESSURE VESSEL: CASE STUDY

Abstract

A methodology for assessing the structural integrity of a large horizontal NGL (Natural Gas Liquid) vessel has been developed. The general analysis procedure, stress analysis and remaining useful life evaluation are described. Recommendations for dealing with anomalies detected during assessment are also presented. The methodology employed can be applied to other, similar, pressurised vessels in the oil and gas, chemical and petrochemical plants.

INTRODUCTION

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 in order to restore a pressure vessel to its original condition. The first question for an engineer, operator or manager is: can we keep operating at this pressure level? Is it safe, or do I have to stop the process to carry out repairs? Structural integrity assessment can be a useful tool for determining the suitability of a vessel for service, and good maintenance management can reduce the inspection cost and extend the equipment life within safety standards.

Pressurised equipment, such as a large horizontal vessel in a typical gas plant can experience in-service damage. The vessel condition deteriorates due to various factors – mechanical, process-related and corrosion-induced. The integrity assessment methodology includes analyses of fitness-for-service and of remaining useful life, based on non-destructive examination results and operating conditions. This case study describes how structural integrity assessment methodology has been developed for application to a large horizontal NGL vessel, and the analysis procedure, stress analysis and remaining useful life evaluation are discussed. Recommendations for dealing with anomalies detected during assessment are also presented.

METHOD

The methodology applied by ABB Service to an NGL gas plant aimed to maximise the pressure vessel’s reliability and availability. The procedure aimed at identifying its mechanical behaviour under different process condition, understanding the potential damage mechanisms and obtaining accurate results from non-destructive inspections. The methodology used in this analysis consisted of five steps, viz.

(A) Creating a qualitative risk matrix and selecting equipment that required a deeper analysis;

Figure 1 The methodology steps
Carrying out the analysis of equipment (stress analysis, potential damage mechanism, failure modes, process condition and maintenance strategy);
Quantification of inspection results;
Fitness-for-Service analysis;
Failure analysis.

Key factors were to complete every step correctly and to respect the sequence A to E (see Figure 1).

Step A: Qualitative Risk Ranking

In this first part a qualitative risk analysis of the pressure equipment needed to be performed. This would result in the deletion from the analysis of much equipment due to the low risk presented – and some equipment would be considered for other types of analysis. The rule of thumb was that 20% of the equipment would account for 80% of the risk, so the idea was to focus on that vital 20%. In this particular study the qualitative risk presented by equipment was calculated following the standard specification from API 580 and API 581 'Risk Based Inspection' [1,2], where the risk is defined as the product of likelihood and consequence, e.g.

Risk = Likelihood x Consequence

For this analysis the large pressure vessel had a low chance of suffering a failure, but the consequences (fire and explosion) were high, so the risk was medium. Figure 2 shows the qualitative risk of the equipment.

Step B: Assessment

Once the risk of equipment had been determined qualitatively a deeper analysis could be required or not, depending on the risk level assessed. A detailed analysis was carried out for this particular pressure vessel. In this part of the procedure three technical aspects were reviewed, i.e.

- Mechanical behaviour of the large horizontal pressure vessel
- Potential damage mechanisms
- Maintenance strategy

Mechanical behaviour analysis of the large horizontal pressure vessel

The aim here was to identify all critical sections of the equipment: where the maximum stress was located; 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 from vertical vessels and require more attention. Zick [3] considers a large horizontal pressure vessel as a beam supported by two-saddle supports resisting the shell plus liquid weight (creating a longitudinal bending stress at mid span) and the internal pressure. There were shear and circumferential stress concentrations at the horn of the saddle (see Figure 3).

To simulate the normal operational condition of the large horizontal NGL pressure vessel a linear finite element analysis was performed. The normal operational pressure, operation temperature, liquid and shell weight were considered for the stress analysis (see Figures 4, 5 & 6).

Pressure vessel data

Material: A516 Gr 70 N
Thickness: 70 mm
Insulated: Yes
Length: 31.000 mm
Diameter: 5.000 mm

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Potential damage mechanisms

A key first step in managing the safety and reliability of equipment is to identify and understand the relevant damage mechanisms. Correct identification is very important when applying the risk-based approach to the maintenance of process equipment. The NDT technique employed needs to be appropriate to the nature of the damage mechanism and its failure mode. Information on this may be found in API Recommended Practice RP 571, which covers situations encountered in the refining and petrochemical industry in pressure vessels, piping, and tanks, and which categorises the failure mechanisms as follows:

- Mechanical and metallurgical failure
- Uniform or localised loss of thickness
- High temperature corrosion
- Environmental assisted cracking

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

For the analysis reported here, i.e. of a large horizontal vessel, the potential damage mechanisms identified were –

- Corrosion under insulation (CUI)
- Mechanical deformation
- Loss of thickness due to internal corrosion

Analysis of the process condition and the operational history indicated that both fatigue and abnormal loading could be discounted as potential damage mechanisms.

Maintenance strategy

Once potential damage mechanisms were identified a maintenance strategy based on in-service and out-of-service (internal) inspection was proposed (see Tables I and II).

Table I: Internal inspection activities

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

Table II: In-service inspection activities

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

Step C: Quantifying the inspection results

The aim of this step was to determine the actual condition of the equipment, quantifying each potential damage mechanism (identified in the previous step) via non-destructive testing. Accuracy of the results was a key factor, so qualified and trained personnel are required on site.

Ultrasonic thickness measurements and UT Scan B

Internal ultrasonic thickness measurements and Scan B were carried out on the large horizontal pressure vessel. Ultrasonic thickness measurements and UT Scan B were carried out on the large horizontal pressure vessel. Ultrasonic thickness measurements and UT Scan B were carried out on the large horizontal pressure vessel.
detecting and examining a variety of surface flaws, such as corrosion, contamination, in the surface finish, and surface discontinuities on joints. Visual inspection is also the most widely used method for detecting and examining those surface cracks which are particularly important because of their relationship to structural failure mechanisms.

Visual inspection

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Liquid penetrant inspection

Liquid penetrant testing is a non-destructive method of revealing discontinuities that are open to the surfaces of solid and essentially non-porous materials. A wide spectrum of flaws is detectable regardless of the configuration of the workpiece and regardless of flaw orientations. For this particular case liquid penetrant inspection was focused on the weld seam located on the shell, between the saddle supports (see Figure 8) and looking for anomalies that can develop in-service or during the erecting phase.

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 at the present time, but its remaining life must be established. This assessment is needed to establish inspection intervals and a basis for reliability-based inspection (RBI) and it will help to determine the risk priorities relative to other plant that needs to be opened during the next turnaround.

For this particular case the remaining life was calculated as recommended in API 510 and pitting corrosion was evaluated as recommended in Chapter 6 of API 579 [5, 6]. Figure 10 shows the anticipated future thickness reduction.
Remaining Life calculation

\[
CR_{\text{long term}} = \frac{T_{\text{initial}} - T_{\text{actual}}}{\text{Time between } T_{\text{initial}} \text{ and } T_{\text{actual}} \text{ (years)}}
\]

\[
RL = \frac{T_{\text{actual}} - T_{\min}}{CR} = \frac{0.04 \text{ mm/year}}{70.8 \text{ mm} - 70.52 \text{ mm}} = 83 \text{ years}
\]

Where –

- \(CR\) = Corrosion Rate
- \(RL\) = Remaining Life
- \(T_{\text{initial}}\) = initial wall thickness (mm) (The as-new thickness at first measurement)
- \(T_{\text{actual}}\) = thickness (mm) measured during most recent inspection
- \(T_{\min}\) = minimum thickness required by pressure or structural load, computed at the design stage

Fitness for service assessment

In this part of the procedure pitting corrosion damage was evaluated applying the Level 1 assessment procedures of Chapter 6 of the API 579 code [6] which can be utilised to evaluate metal loss from pitting corrosion. Pitting is defined as localised metal loss, and can therefore be characterised by a pit diameter and a pit depth. The Level 1 procedure is simplified in that it does not account for the orientation of the pit-couple with respect to the maximum stress direction. Results are conservative and based on pitting charts.

Step 1:

Determining the following parameters –

- \(D\) = inside diameter of equipment, 5000 mm
- \(\text{Loss}\) = thickness loss, 0.38 mm (70.8 – 70.42)
- \(\text{FCA}\) = future corrosion allowance, 1.27 mm
- \(\text{RSF}\) = allowable (non-dimensional) Remaining Strength Factor, 0.9
- \(t_{\text{eq}}\) = wall thickness (mm) measured at the time of assessment

Step 2:

Determining the wall thickness used in the assessment using the equations –

\[
t_{c} = t_{\text{eq}} - \text{FCA}
\]

\[
t_{c} = 70.42 - 1.27 = 69.15 \text{ mm}
\]

Step 3:

Locating area on the component that has the highest density (number of pits) of pitting damage (using photographs including a reference scale).

Step 4:

Determining the maximum pit depth –

\[
W_{\text{max}} = 1 \text{ mm}
\]

Step 5:

Determining the ratio of remaining wall thickness –

\[
R_{\text{wt}} = \frac{t_{c} + \text{FCA} - W_{\text{max}}}{t_{c}} = \frac{69.15 + 1.27 - 1}{69.15} = 1.0039
\]

Step 6:

Determining the Maximum Allowable Working Pressure for the component using the Step 2 thickness –

\[
\text{MAWP (Mpa)} = \frac{2 \times S \times t_{c}}{2 \times R_{\text{c}} + t_{c}} = \frac{2 \times 163 \times 69.15}{2 \times (2500 + 1.27 + 0.38) + 69.15} = 4.4 \text{ Mpa}
\]

Step 7:

Comparing the photograph of the pit damage area with standard pit charts.

Step 8:

Determining the RSF from the table accompanying the pit chart and from \(R_{\text{wt}}\)

\(\text{RSF} = 0.99\)

Level 1 assessment would be accepted only if –

1. \(R_{\text{wt}} > 0.2\) True (see Step 5)
2. \(\text{RSF} > \text{RSF}_{\text{a}}\) True (see Steps 8 and 1)

For the case concerned the pitting damage was acceptable for the actual operating condition, i.e. the MAWP of 4.4 Mpa.

Step E:

Root Cause Analysis (RCA)

The purpose of RCA is to identify and understand the basic root of problems that affect the equipment performance and its integrity. By understanding how anomalies can originate these failures, or re-occurrence of such problems in similar plant, can be avoided in future. For this reason it is very important, during pressure vessel inspection, to analyse every sign or evidence that can be tested in laboratory.

For the analysis reported here a sample of corrosion product was taken from the pressure vessel bottom and subjected to X-Ray diffraction analysis (which explores the sample’s crystal structure). Sample results are shown in Table III and Figure 12.
The diffraction analysis revealed the presence of corrosion products such as goethite (FeO(OH)) and magnetite (Fe₃O₄) with sulphur content (S). Both of these can be created by the CO₂ and/or H₂S that are typically found in NGL. Corrosion by CO₂ was discounted however, because FeCO₃ was not identified during laboratory analysis. The presence of sulphur in the corrosion deposit was a strong indication of Sulphate Reducing Bacteria (SRB) attack. The presence of sand deposits at the bottom of the pressure vessel had contributed to creating an environment for Microbially Influenced Corrosion (MIC).

### Microbially Influenced Corrosion [7]

MIC corrosion is not fundamentally different from other types of aqueous electrochemical corrosion; the difference is that the aggressive environment is produced by micro-organisms as products of their metabolism. The most important group of bacteria associated with corrosion is that of the sulphate-reducing bacteria (SRB). In practice, the great majority of MIC failures are related to the activities of SRB, anaerobic (oxygen-free) bacteria that obtain their required carbon from organic nutrients and their energy from the reduction of sulphate to sulphide. Pitting is created under tubercle deposits (see Figure 13 below).

### Root Cause Analysis for the large horizontal pressure vessel

Water was left in the vessel after hydro-test when the vessel was first put into service. It may be that there was a period between the hydro-test 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 was in the vessel base confirmed the presence, in the base, of water which had drained and remained there. Sulphate in the water would provide the nutrient for the SRB.

Water does not accumulate 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, but SRB bacteria could be generated if even very small vestiges of water were to remain after hydro-testing. Engineers require water specification for such testing and good heating practices to ensure water removal.

### Recommendations

Grinding out the pits to give a smooth surface without going beyond the corrosion allowance was recommended. This would remove local stresses and remove all contamination and traces of the moisture which could allow corrosion if any pitting, or contained deposits, remained.

### CONCLUSIONS

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

When surveying large horizontal pressure vessels special care should be taken when internal and external inspections are carried out on the shell between the saddle supports. Visual inspection should be undertaken very carefully at the horn of the saddle where the effect of circumferential bending stress may be significant.

In the particular case reported here the fitness for service assessment permitted the large NGL pressure vessel to operate at its design performance, i.e. an MAWP of 4.4 Mpa and a Maximum Allowable Operating Pressure (MAOP) of 2.3 Mpa. Even though the degree of pitting corrosion was acceptable, it was suggested that the existing pitting should be removed by grinding.

Water trapping in an NGL pressure vessel is unlikely during service. In this case, however, it was shown that bad water specification and inadequate pre-start-up heating had affected the mechanical integrity of the vessel. An MIC corrosion mechanism had been generated due to the vestiges of water remaining after hydro-testing, creating an environment favouring the growth of sulphate reducing bacteria and then the pitting corrosion induced by the metabolism of such bacteria. 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.

### BIBLIOGRAPHY

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6. API RP 579, Fitness for service (2nd Ed), Washington DC, March 2006