Fitness for Service: Using NDT and Inspection

BS 7910, API 579 methodology

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What is Fitness for Service Assessment

Quantitative engineering analysis performed to demonstrate Structural Integrity of an in-service item, due to:

- Presence of a flaw by cracking mechanism or deterioration by thinning mechanism
- Material properties change and / or metallurgical damage
- Concerns on not meeting current design standards or best practices
- Concerns on current operating conditions or fault scenarios
- Changes in operating conditions which are more onerous than current
- Operation under high temperature creep environment
- Operation under mechanical or thermal fatigue environment

FFS is carried out on static equipment

- All types of pressure vessels such as reactors, distillation columns, absorbers, strippers, reformers, fired heaters, heat exchangers, Piping and Storage tanks, Utility plant items: e.g. furnace tubes, boiler drum, de-aerators, headers, economisers
Codes and Standards

FFS assessment involve one or more codes and standards

- BS 7910, API 579
- Design codes such as ASME, British standard BS 5500 or European design codes
- Guidance documents issued by recognized Associations or Authorities
- Good engineering, Root Cause analysis & NDT practices recognized by the industry
Need for Fitness for Service

- ASME, API, BS 5500 & other recognized Design codes provide rules for design and fabrication of new items of plant
  - e.g. pressure vessels, piping & storage tanks
  - These codes do not address the fact that many items deteriorates during operation & that defects due to deterioration or from original fabrication, which are larger than allowed by the “Quality Control levels” found during in-service inspections.
    - The design codes do not address the fact that the mechanical properties and / or metallurgical status of some materials can change over time, under specific operating conditions.
- Acceptance of flaws found during construction is based on “Quality Control levels”.
  - Quality Control levels are usually both arbitrary and conservative, but are of considerable value as they provide a route to achieve reasonable consistency and confidence in the quality of the finished items.
When material deterioration exceeding the Quality Control levels are revealed or when material property changes / metallurgical degradation are suspected, rejection of the item is not necessarily automatic.

The decisions on whether “run as is/ monitor, repair or replace” is based on the derivation of acceptance levels for defects larger than the “Quality Control levels” and / or the demonstration of suitability of materials under specific operating conditions.

- This is the concept of Fitness-For-Service or FFS applications.
- An item is considered to be fit for the intended service, provided it can be demonstrated (with acceptable safety margin) that the conditions to cause failure are not reached within a predetermined time period, giving due regard to the HSE and Business consequence of failure.
Multi-Angle Investigative Approach

- Depending on the complexity of an item & the problems, one or more expertise (multi-discipline) will be used
  - Identify effects of process fluids, applied loads and external environment
  - Identify all damage mechanisms and any interdependency and effects
    - Stress analysis (can range from basic code calculations to Finite Element Analysis)
    - Metallurgical Investigations and Root Cause Analysis
    - Fracture Mechanics assessments
    - Remaining life calculations
    - Assessment of acceptable and optimized Inspection Interval & Inspection Methods based on risk & consequence of failure
Output of Fitness for Service Assessment

Final output will include one or more of the following:

- Tolerable defect sizes and defect growth rates
- Remaining life
- Revised operating limits and/or other risk mitigating measures
- Design improvements
- Suitable NDT inspection methods and acceptable / optimized inspection interval

Management can take important and timely decisions regarding:

- To run item as is and at what inspection interval
- To monitor defect and at what monitoring frequency
- To repair or replace item and when should be carried out
- To revise operating conditions
- To modify design
Overview of API 579

General

- Applicable to pressurized components in pressure vessels, piping, and tankage (principles can also be applied to rotating equipment)
- Highly structured document with a modular system based on flaw type/damage condition to facilitate use and updates
- Multi-level assessment - higher levels are less conservative but require more detailed analysis/data
  - Level 1 - Inspector/Plant Engineer
  - Level 2 - Plant Engineer
  - Level 3 - Expert Engineer
Overview of API 579

General

General FFS assessment procedure used in API 579 for all flaw types is provided in Section 2 that includes the following steps:

- Step 1 - Flaw & damage mechanism identification
- Step 2 - Applicability & limitations of FFS procedures
- Step 3 - Data requirements
- Step 4 - Assessment techniques & acceptance criteria
- Step 5 - Remaining life evaluation
- Step 6 - Remediation
- Step 7 - In-service monitoring
- Step 8 - Documentation

Some of the steps shown above may not be necessary depending on the application and damage mechanism.
Case Study: FFS Assessment

Examples of Fitness-For-Service assessment work successfully carried out by TCR
Isomerization reactor

Location of temperature excursion

- First 4 shells from Top
- Highest temperature recorded at shell 2
- Maximum temperature recorded 710° C

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Thermocouple Location</th>
<th>Temperature (°C)</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>TW2</td>
<td>2ND bed from top</td>
<td>710</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;700</td>
<td>9 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;600</td>
<td>44 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Design limit)</td>
<td>&gt;340</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3h 10 min</td>
</tr>
<tr>
<td>TW3</td>
<td>3RD bed from top</td>
<td>616</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;600</td>
<td>9 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Design limit)</td>
<td>&gt;340</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4h 24 min</td>
</tr>
<tr>
<td>TW4</td>
<td>4TH bed from top</td>
<td>465</td>
<td>1 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;400</td>
<td>5h 26 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Design limit)</td>
<td>&gt;340</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6h 55 min</td>
</tr>
</tbody>
</table>
## Operating and design parameters

<table>
<thead>
<tr>
<th></th>
<th>Normal operating service fluid</th>
<th>C5 / C6 CUT + Hydrogen + Dry Hydrochloric acid</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Normal operating service fluid</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td>165 °C</td>
<td>(End of run) operating parameters (reactor outlet temperature and reactor inlet pressure)</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>35 kg/cm$^2$</td>
<td></td>
</tr>
<tr>
<td><strong>Sulphur stripping operation</strong></td>
<td>Hydrogen + Hydrogen sulphide + Dry Hydrochloric acid</td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td>310 °C</td>
<td></td>
</tr>
<tr>
<td>Operating pressure</td>
<td>23.7 kg/cm$^2$</td>
<td></td>
</tr>
<tr>
<td>Shell plate thickness</td>
<td>36.0 mm</td>
<td></td>
</tr>
<tr>
<td>TL- TL Height</td>
<td>20100 mm</td>
<td></td>
</tr>
<tr>
<td>Inside diameter</td>
<td>1600 mm</td>
<td></td>
</tr>
</tbody>
</table>
Damage mechanisms

• No operation induced damage- as it has run for 2 months.
• Anticipated damages due to accidental temperature rise:
  – High Temperature Hydrogen Attack (HTHA)
  – Metallurgical degradation of microstructure.
  – Mechanical structural distortion
  – Degradation of mechanical strength
  – High temperature corrosion
  – Integrity of weld joints
HTHA (High temperature hydrogen attack)

- Hydrogen can diffuse as nascent form in the steel.
- Hydrogen reacts with cementite of pearlite in steel microstructure.
- Carbides dissociate to form methane gas ($\text{CH}_4$).
- Accumulated $\text{CH}_4$ forms micro voids and fissures at grain boundaries.
HTHA

- Detection of HTHA by Advanced Ultrasonic Backscatter Test
- Attenuation Measurements
**HTHA**

- Probability of HTHA based on nelson curve- API 941

Nelson’s Curve: Guideline API 941

Reactor Pressure during incident $22 – 24 \text{ kg/cm}^2 = 2.35 \text{ MPa}$
HTHA

Theoretical Probability of HTHA

The theoretical incubation period \( t = C \times P^{-3} \times e^{[Q/(R \times T)]} \)

Where,
- \( t \): Incubation time in hours
- \( C \): constant: \( 1.39 \times 10^6 \)
- \( P \): Partial pressure of hydrogen (PSI) = 24 kg/cm\(^2\) or 341.4 PSI
- \( Q \): Activation energy 14.6 kcal / mol
- \( R \): Gas constant
- \( T \): Absolute temperature of exposure (\( ^\circ \)K) = 710\( ^\circ \)C or 983\( ^\circ \)K

Gas constant for hydrogen ‘\( R \)’ = \( R_U / M_{\text{gas}} \)

Where,
- \( R_U \): universal gas constant = 1.9858 x 10\(^{-3}\)
- \( M_{\text{gas}} \): Molecular weight of \( H_2 \) (1.0079),

i.e. \( t = 1.39 \times 10^6 \times 341.4^{-3} \times \exp \left[ \frac{14.6}{(1.9702 \times 10^{-3} \times 983)} \right] \)

\( = 65.6 \) h

Reactor Pressure during incident
22 – 24 kg/cm\(^2\) = 341.4 PSI
Metallurgical degradation

- SA516 Grade 70 in normalized conditions has ferrite and pearlite.
- Reactor shell may undergo transformation of phases if the local temperature excursion exceeds 723°C.
- Pearlite gets spherodized resulting in reduction of strength.
Possible structural distortion

Generally observed as

• Overall or localized bulging of reactor shell
• Leaning / out of verticality of reactor.

Dimensional verification methods:
• Change in outer diameter through circumference measurement
• Plumb measurement at 4 orientations
Other Damage Mechanisms

High temperature corrosion:
• High temperature corrosion in dry hydrochloric acid environment can cause internal damage.
• Can affect effective wall thickness and strength of material in long use
• Can be detected by ultrasonic thickness mapping.

Presence of weld flaws:
• Sudden heat excursion followed by cooling may exert high stresses at the welding joints
• At locations of high stress concentrations, internal defects like crack may occur.
• Presence of internal weld flaws can be detected through
  – Time of Flight Defraction (TOFD) ultrasonic flaw detection
  – ‘A’ scan angle beam ultrasonic method
# On-site NDT

<table>
<thead>
<tr>
<th>Date of inspection</th>
<th>23 to 29 June 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extent of coverage</td>
<td>All shells of reactor, all thermowell and manhole nozzles</td>
</tr>
<tr>
<td>Access for inspection</td>
<td>External only</td>
</tr>
<tr>
<td>Inspection techniques</td>
<td>Visual examination</td>
</tr>
<tr>
<td></td>
<td>Outside diameter measurement</td>
</tr>
<tr>
<td></td>
<td>Dimension profile of verticality</td>
</tr>
<tr>
<td></td>
<td>Ultrasonic thickness measurements</td>
</tr>
<tr>
<td></td>
<td>Wet Fluorescent Magnetic Particle Inspection</td>
</tr>
<tr>
<td></td>
<td>TOFD Flaw Detection</td>
</tr>
<tr>
<td></td>
<td>AUBT and HTHA detection</td>
</tr>
<tr>
<td></td>
<td>‘A’ Scan – angle beaming ultrasonic flaw detection</td>
</tr>
<tr>
<td></td>
<td>In-situ Metallographic Replication</td>
</tr>
<tr>
<td></td>
<td>Hardness Measurements</td>
</tr>
</tbody>
</table>
### Dimension measurement

<table>
<thead>
<tr>
<th></th>
<th>Outer Diameter</th>
<th>Tower Verticality</th>
<th>Shell Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total points of measurement</td>
<td>3 elevations on each shell</td>
<td>4 elevations on each shell (N, E, S, W)</td>
<td>2 elevations on each shell (N, E, S, W)</td>
</tr>
<tr>
<td>Observed minimum value</td>
<td>Circ: 5264 mm</td>
<td>6.4 mm (W)</td>
<td>36.6 mm (CS9)</td>
</tr>
<tr>
<td></td>
<td>OD: 1676 mm (CS1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observed maximum value</td>
<td>Circ: 5275 mm</td>
<td>9.3 mm (N)</td>
<td>38.6 mm (W: CS3-CS4)</td>
</tr>
<tr>
<td></td>
<td>OD: 1680 mm (CS8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum deviation</td>
<td>+4 mm Design: 1600</td>
<td>2.1 mm</td>
<td>+0.6 mm Design: 36.0 mm</td>
</tr>
</tbody>
</table>

- No structural distortion
- No effect of high temperature corrosion
Wfmpi and UT

Wet Fluorescent Magnetic Particle Inspection:
• All weld joints were subjected to 100% inspection, including the nozzles of thermowell and other insulation support clips joints
• Result: No significant linear indication observed anywhere

‘A’ Scan Ultrasonic Flaw Detection:
• Extent of coverage: Weld joint of CS1 and weld joints of top nozzle ‘N1’
• Probe angles: 45°, 60°
• Probe frequency: 4 MHz
• Reference:
  V2 Block,
  Distance Amplitude Correction on Ø4mm SDH of similar material
• Result: No significant defect indication was observed
ToFD

Time of Flight Diffraction (TOFD) Flaw Detection:

Extent of coverage: CS2 – CS5, LS1 – LS3, All Tee Joints
Probes: 2 MHz, Wedge Angle: 60°, Reference: ASME calibration blocks Fig 11.1 - 11.3

Drop in back wall echo with indication of flaw

Defect sizing by angle beam ‘A’ scan UT, size equivalent to Ø4mm (side drilled hole) and 40 mm length
AUBT as per API 941

AUBT: HTHA assessment:

- Extent of coverage: First four shells: 100% scanned with 10% probe overlapping method
- Probes: 10 MHz
- References: (1) Guideline from API 941 (2) Comparison with away region
- No indication of HTHA observed anywhere

Echo pattern at Shell 2

Echo pattern Shell 8
In situ metallography

In-situ metallographic replication:

- Extent of coverage: Total 60 Locations  \textit{(Shell 2 : 16 locations)}
- Method: ASTM E1351 “Practice for production and evaluation of field metallographic replicas”
- Etching technique: Manual swabbing with 2\% nital
- No significant change in microstructure is observed, microstructures show ferrite and pearlite structure. ASTM Grain size 9 to 10. No indication of pearlite degradation.
- \textbf{Heat excursion on external surface of shell is insignificant}

Structure at Shell 2  \hspace{1cm} Structure at Shell 8
Hardness

Hardness Measurements:
- Extent of coverage: 60 locations of metallographic replication
- Instrument used: MIC20-Krautkramer
- Minimum Hardness: Required 147 BHN  
  Measured: 147 BHN

<table>
<thead>
<tr>
<th>Location</th>
<th>Minimum (BHN)</th>
<th>Maximum (BHN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Shell hardness range</td>
<td>147</td>
<td>188</td>
</tr>
<tr>
<td>Shell 1</td>
<td>148</td>
<td>177</td>
</tr>
<tr>
<td>Shell 2</td>
<td>147</td>
<td>170</td>
</tr>
<tr>
<td>Shell 3</td>
<td>150</td>
<td>186</td>
</tr>
<tr>
<td>Shell 4</td>
<td>156</td>
<td>188</td>
</tr>
<tr>
<td>Shell 5</td>
<td>155</td>
<td>172</td>
</tr>
<tr>
<td>Shell 6</td>
<td>148</td>
<td>168</td>
</tr>
<tr>
<td>Shell 7</td>
<td>151</td>
<td>181</td>
</tr>
<tr>
<td>Shell 8</td>
<td>151</td>
<td>169</td>
</tr>
<tr>
<td>Overall weld hardness range</td>
<td>162</td>
<td>218</td>
</tr>
</tbody>
</table>
Laboratory finding

Scanning Electron Microscopy (SEM) Observations:

- Extent of coverage: 15% of replicated structures
- Magnification up to 3500X after Gold coating of replica
- Finding: Fine grained ferrite and pearlite structures
  No significant difference in structures

Structure from Shell 2  Structure from Shell 7
Laboratory simulation experiment

- Two 36mm thick coupon plates were prepared as per WPS given for the equipment.
- Two sets of such welded pieces were fabricated at laboratory.
- Both the coupons were Post weld heat treated soaking for 2h at 610°C.
Heat excursion simulation

Welded coupon placed on heater coil
Covered with 45mm thick hot insulation
Control cooling to simulate actual heat excursion

Simulated Temperature Excursion

- Simulated
- TW2

Temperature °C

Time (Minutes)

Top thermocouple
Bottom thermocouple
# Mechanical tests

## PWHT coupon test result

<table>
<thead>
<tr>
<th></th>
<th>P.M.</th>
<th>Req.</th>
<th>HAZ</th>
<th>Weld</th>
<th>Req.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y.S. (N/mm²)</td>
<td>420</td>
<td>260</td>
<td>-</td>
<td>458</td>
<td>400</td>
</tr>
<tr>
<td>U.T.S. (N/mm²)</td>
<td>530</td>
<td>485</td>
<td>-</td>
<td>535</td>
<td>490</td>
</tr>
<tr>
<td>E (%)</td>
<td>31</td>
<td>21</td>
<td>-</td>
<td>27.6</td>
<td>22</td>
</tr>
<tr>
<td>CVN (Joule)</td>
<td>21</td>
<td>20</td>
<td>23</td>
<td>146</td>
<td>20</td>
</tr>
</tbody>
</table>

## PWHT + Heat Simulated coupon test result

<table>
<thead>
<tr>
<th></th>
<th>P.M.</th>
<th>HAZ</th>
<th>Weld</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y.S. (N/mm²)</td>
<td>441</td>
<td>-</td>
<td>446</td>
</tr>
<tr>
<td>U.T.S. (N/mm²)</td>
<td>551</td>
<td>-</td>
<td>544</td>
</tr>
<tr>
<td>E (%)</td>
<td>35.18</td>
<td>-</td>
<td>26.89</td>
</tr>
<tr>
<td>CVN (Joule)</td>
<td>67</td>
<td>21</td>
<td>113</td>
</tr>
<tr>
<td>Y.S. (N/mm²)</td>
<td>429</td>
<td>-</td>
<td>373</td>
</tr>
<tr>
<td>U.T.S. (N/mm²)</td>
<td>558</td>
<td>-</td>
<td>474</td>
</tr>
<tr>
<td>E (%)</td>
<td>36.06</td>
<td>-</td>
<td>36.54</td>
</tr>
<tr>
<td>CVN (Joule)</td>
<td>179</td>
<td>28</td>
<td>53</td>
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</tbody>
</table>
### Hardness (BHN)

<table>
<thead>
<tr>
<th></th>
<th>PWHT coupon</th>
<th>PWHT + Heat simulated coupon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PM</td>
<td>HAZ</td>
</tr>
<tr>
<td>1</td>
<td>147</td>
<td>148</td>
</tr>
<tr>
<td>2</td>
<td>153</td>
<td>151</td>
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<tr>
<td>3</td>
<td>147</td>
<td>159</td>
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<tr>
<td>4</td>
<td>-</td>
<td>161</td>
</tr>
<tr>
<td>5</td>
<td>158</td>
<td>147</td>
</tr>
<tr>
<td>6</td>
<td>164</td>
<td>153</td>
</tr>
<tr>
<td>7</td>
<td>160</td>
<td>149</td>
</tr>
<tr>
<td>Max. Difference</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>
Microstructure

Between PWHT and PWHT + Heat simulated coupons

- Microstructure are of ferrite and pearlite.
- No significant change in grain size after simulated heat excursion.
- Minor effect of spherodization of pearlite.
- No significant change in microstructural properties after short period temperature excursion up to 710°C
Design calculations

**Elliptical head design:**
- Thickness Due to Internal Pressure [Tr]:
  - \( (P \times (D + 2 \times CA) \times K) / (2 \times S \times E - 0.2 \times P) \) Appendix 1-4(c)
  - \( = (44.600 \times (1600.0 + 2 \times 3.0) \times 1.00) / (2 \times 1406.14 \times 1.00 - 0.2 \times 44.6) \)
  - \( = 25.55 + 3.0 = 28.55 \text{ mm} \)

The available thickness of elliptical head of 50 mm is higher than the minimum required thickness of 28.55 mm.

**Cylindrical shell design:**
- Thickness Due to Internal Pressure [Tr]:
  - \( (P \times (D/2 + Ca)) / (S \times E - 0.6 \times P) \) per UG-27 (c)(1)
  - \( = (44.600 \times (1600.0000 / 2 + 3.0000)) / (1406.14 \times 1.00 - 0.6 \times 44.600) \)
  - \( = 25.9637 + 3.0000 = 28.9637 \text{ mm} \)

The available thickness of shell wall of 36.6 mm is higher than the minimum required thickness of 28.96 mm.
Fracture toughness calculation for assessment of crack like flaw in weld

- Any flaw of less than 11mm x 220mm is Safe
- Flaw existing at CS3 has size of SDH Ø4mm x 40mm
- The existing flaw size is less than critical flaw size
- The defect located at CS3 is innocuous to continued safe operation of the reactor
### Summary

<table>
<thead>
<tr>
<th>All anticipated damage mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Visual abnormality</strong></td>
</tr>
<tr>
<td><strong>Structural distortion</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>HTHA</strong></td>
</tr>
<tr>
<td><strong>High temp. corrosion</strong></td>
</tr>
<tr>
<td><strong>Microstructural properties</strong></td>
</tr>
<tr>
<td></td>
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<tr>
<td><strong>Weld joints</strong></td>
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<td></td>
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<tr>
<td><strong>Simulation study</strong></td>
</tr>
<tr>
<td><strong>FFS calculations</strong></td>
</tr>
</tbody>
</table>
Judgment of FFS

From the accessible inspection and simulation studies it is concluded that the reactor has not been affected due to short term exposure to 710° C temperature to an extent that it is of immediate concern. The condition of reactor vessel is considered fit-for-service, for further operation as per OEM design and operation guidelines. Monitoring of flaw size at CS3 weld joint is to be done within next 2 years of operation.

Considering the limitation of the inspection which excludes internal side of the reactor, regarding distributors, support trays or fittings, no judgment on their internal condition could be provided.
Questions?