TANK FITNESS FOR SERVICE

CASE STUDIES

Presented by
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OUTLINE

- FFS, API STDS. & APPLICATION TO TANKS
- FFS CASE 1: Pitting
- FFS CASE 2: Hydrotest Exemption
- FFS CASE 3: Distortion of Upper Courses
- FFS CASE 4: Fabrication Flaws (Weld Defects)
- FFS CASE 5: Settlement
- FFS CASE 6: Banded Tank Thinning
- FFS CASE 7: Stress Corrosion Cracking
- Conclusions
TANK FFS, API 653 & API 579

- Inspection Codes (API 510, 570, 653) recognize API 579
- API 653 Paragraph 1.1.6: recognizes API 579 to fill gaps not specifically covered in API 653, and where FFS is permitted by API 653.
- API 579 covers FFS of API 650 and 620 Tanks
- API 579 uses a Multi-level Assessment Methodology
  - Level 1: Conservative screening criteria
  - Level 2: Analyses are more detailed
  - Level 3: Most detailed. Most applicable to types of Tank Damage not in API 653.
CASE STUDY 1: PITTING

- Tank Geometry:
  - D=35’ x H=32’, A283-C, all shell courses 0.25 inches
    \( t_{\text{min}} = 0.11 \) inches
  - G=1.03, Temp = Ambient

- Damage:
  - Isolated pitting, first course, nearly through-wall.
    Failure sites in coating.
  - \( \approx 1.0 \) inch diameter pits x 0.05 inches min. remaining
    wall (less than 50% \( t_{\text{min}} \))
  - Pits several feet from Bottom
  - Doesn’t meet API 653, Section 4.0.
CASE STUDY 1: PITTING

- First: LEVEL 1 - Pit charts and pit depths
CASE STUDY 1: PITTING

- Level 2 – Determine geometry terms for Pit Couples (pitch, diameters, pit depth, angle to each other) lead to calculation of Remaining Strength Factor (RSF)

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<th>$\theta_k$</th>
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LEVEL 1 and 2 were not met in this case, plus there was the need to look at increasing damage scenarios.

OPTIONS:

- Repair
- Couldn’t Rerate via API 579 because at least one flaw depth criteria was not met
- LEVEL 3
CASE STUDY 1: PITTING

- LEVEL 3
  - Current FFS
  - FFS if Current Pits Enlarge and/or Deepen
  - FFS if Density in same pitting region increases
  - FFS if Region of Pitting Enlarges

- Performed FEA

- Used API 579 Appendix B Criteria (strain, limit load, stress classification per ASME S8D2)
CASE STUDY 1: PITTING

- **CURRENT CONDITION RESULTS:**
  - Current pit groups are FFS

- **FUTURE CONDITION RESULTS:**
  - FFS with 50% growth in diameter and full wall thickness (would leak before collapse)
  - Single isolated pit could grow twice the current size
  - Area of Pitting could become 30% denser
  - Proximity to Bottom was biggest influence on FFS
CASE STUDY 2: HYDROTEST EXEMPTION

- Tank Geometry:
  - D=120’ x H=37.5’, A283-C
  - G=0.70, MDMT = 37°F
  - Two Door-sheets being installed

- Purpose of Analysis:
  - FFS required to Exempt Hydrotest
  - Examine FFS of affected welds / weld NDE requirements
CASE STUDY 2: HYDROTEST EXEMPTION

Plain Door-sheet
Door-sheet with 3 nozzles ↓
CASE STUDY 2: HYDROTEST EXEMPTION

- API 579 Section 9.0
- Focus:
  - Welds to Bottom
  - Nozzle Welds
  - Edges of Door-sheet Welds
- Stresses from FEA models used in LEVEL 2 fracture calculations
- Fill and Settlement Stresses Evaluated
CASE STUDY 2: HYDROTEST EXEMPTION

- FEA Model Stresses at Nozzles:
CASE STUDY 2: HYDROTEST EXEMPTION

- FEA Model Stresses at Bottom Welds / Door-Sheets:
CASE STUDY 2: HYDROTEST EXEMPTION

- Failure Assessment Diagram (FAD) Approach from API 579
  - Judges plastic collapse
  - Judges brittle fracture

- From Stress, Toughness and Residual Stress get Critical Flaw Sizes (CFS) and/or Perform Leak Before Break (LBB) Analysis to get critical through-wall crack length.
  - Use as NDE screening tools
  - OR Evaluate Crack Opening Area (COA), Leak Rates and Consequence (with an RBI type Modeler) for LBB Results
CASE STUDY 2: HYDROTEST EXEMPTION

Figure 1A: Circumferential Surface Crack in Shell
At Toe Fillet Weld Toe Connection with Shell
No Future Tank Settlement Included
CASE STUDY 3: DISTORTED UPPER COURSES

- Section 8.0 of API 579
- Many Bulges & Distortion in Tanks will be outside of limitations of the LEVEL 1 and LEVEL 2 procedures:
  - Proximity to Welds, Discontinuities
  - Inwards profile
  - Sharp profile (Dents, Wrinkles)
  - Multiple Bulges & Distortions
CASE STUDY 3: DISTORTED UPPER COURSES

- Section 8.0 Level 1 and 2: Determine RSF from calculation of local bending due to an isolated bulge

(a) Cylinder with Bulge

(b) Section A-A

(c) Section B-B

Location of Inflection Point (Change in Local Curvature)

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CASE STUDY 3: DISTORTED UPPER COURSES

- **Tank Geometry:**
  - D=134’ x H=48’
  - Vacuum Bottoms, Operates @ 350ºF
  - Fill Level Frequently Cycles (FATIGUE evaluation)

- **Several Bulges & Distortion**
  - Overpressure Events (several!)
  - Shell Settlement
  - Damage crossed welds
  - Buckled Inward & Outward
CASE STUDY 3: DISTORTED UPPER COURSES

Geometry & Photo of Distortion
CASE STUDY 3: DISTORTED UPPER COURSES

- API 579 Section 8.0, 9.0, Appendix B Procedures
  - Section 8.0 LEVEL 3 Bulge Evaluation
  - Section 9.0 LEVEL 2 NDE Screening Curves for cracks in welds
  - Appendix B analysis procedures to determine MFH
  - Fatigue Evaluation

- API 653 Appendix B Settlement evaluation
CASE STUDY 3: DISTORTED UPPER COURSES

- Distortion mapped on FEA
- Portion of Model and FEA Stresses
CASE STUDY 3: DISTORTED UPPER COURSES

RESULTS:
- NDE Screening Curves provided for Welds
- Reduced One Time Fill Limitation (43 feet) for an Upset
- Fatigue Life less than 30 Cycles: Limit on excursions from low fill to a maximum of 38 feet (for Normal Operation)
- Shell Settlement Close to API 653 Permissible value: Increased monitoring needed (later shell settlement became a concern when coupled with other distortion)
CASE STUDY 4: FABRICATION FLAWS

- Poor initial construction or Poor relocation reconstruction
- Several occurrences at sites E²G examined
- Small, non–petroleum industries (agriculture/fertilizer tanks)
CASE STUDY 4: FABRICATION FLAWS

- **Tank Geometry:**
  - One site had several problem Tanks (reconstructed not in accordance with API 653)
  - Basic size: D=40' x H=40'
  - Agricultural Products

- **Damage**
  - Seams with partial penetration of as little as 50% depth
  - Tee joint spacing
  - Other welds quality issues
CASE STUDY 4: FABRICATION FLAWS

- Assessment Focus was Incomplete Weld Penetration
- Treated as Crack–like flaws (API 579 Section 9.0)

- Circumferential Weld Flaw

- Longitudinal Weld Flaw
CASE STUDY 4: FABRICATION FLAWS

- Determined Tank Stresses for different fill heights (FEA would have been used if bottom weld was involved)
- Bending stress from wind also considered
- Used a FAD approach to determine FFS with crack-like weld flaws
  - If a given weld was not under the FAD (not FFS) with the fill assumptions, lowered fill height until the analysis point was under the FAD
- Used lower bound toughness, API residual stress models, API partial safety factors
  - Materials not well documented
  - Account for other uncertainties given general poor weld quality
CASE STUDY 4: FABRICATION FLAWS

- One Tank: FAD at Full Fill

Failure Assessment Diagram (FAD): 1 DPHE = 90.0000 (Degrees)
CASE STUDY 4: FABRICATION

FLAWS

- RESULTS: Same Case: FAD about 35% Full = FFS
CASE STUDY 5: TANK SETTLEMENT

- **Tank Geometry:**
  - D=40’ x H=35’
  - Fixed Roof, Single Column
  - #2 Fuel Oil

- **Damage:**
  - Edge Settlement over the API 653 Permissible Value at 3 or 4 profiles (of 12 profiles)
  - Foundation material and compaction questionable
  - Some lower shell corrosion
  - No other damage
CASE STUDY 5: TANK SETTLEMENT

- Performed more Rigorous Analyses Per API 653 based on Appendix B = FEA Stress Analysis
- Applied all 12 measured profiles
- Used Corroded Thickness, were applicable
- Examined Results based on STRAIN criteria in API 653 Appendix B (3% generally used)
- Estimated and Examined FUTURE edge settlement at worst locations – because of foundation concerns
CASE STUDY 5: TANK SETTLEMENT

- Portion of Model & Typical Displacement
CASE STUDY 5: TANK SETTLEMENT

- Typical Strain Results
CASE STUDY 5: TANK SETTLEMENT

■ RESULTS:
  – Three CURRENT Profiles were at or exceeding 3% Strain (not FFS)
  – Up to 5.8% strain predicted for one estimated future settlement profile

■ REPAIRS needed
  – Concern with foundation material – edge settlement occurring on such a light (small) tank, fairly “young” tank
  – Replace all plastically deformed sketch plate
  – Renew Foundation
CASE STUDY 5: TANK SETTLEMENT

- Shell Settlement Evaluations can also require Rigorous Analysis
- 2004 API Research Work: Revision of Appendix B
  - Difference in Open and Fixed Roof
  - Remove “Penalty” for close-spaced measurements
  - Tank Size Dependent
  - Differences in Settlement Patterns
CASE STUDY 6: BANDED TANK FFS

- Tank Geometry:
  - D=70’ x H=28’
  - Shell supports Fabric / Aluminum Geodesic Roof
  - G=1.5 (residue tank), 200 to 250°F
  - Monel: courses made thinner than required, but reinforced with numerous stiffeners and steel bands

- Damage: Thinning in upper courses
  - Needed $t_{\text{min}}$ for each course for Inspection Plan
  - Concern for buckling: Roof weight increasing due to Product build up on roof
CASE STUDY 5: BANDED TANK FFS

- Assessment was LEVEL 3 because Geometry does not lend itself to API 653 Shell thickness calculations
- Performed FEA modeling
- Determined Corroded Thickness at Full Fill meeting an API allowable stress basis for hoop stress
  - Used API 579 Appendix B (ASME Classification Method) for Local Stresses at bands
- Calculated Elastic Shell Buckling Load (maximum roof load) in corroded condition
  - API 579 Appendix B Procedure
  - Service Margin of 3.0
CASE STUDY 6: BANDED TANK FFS

- FEA Model
CASE STUDY 6: BANDED TANK FFS

- Shell and Nozzle Stresses for $t_{\text{min}}$ Case:
CASE STUDY 6: BANDED TANK FFS

- Buckled Shape with Roof Loads:
CASE STUDY 6: BANDED TANK FFS

- SHELL RESULTS – Inspection Screening Values:
  - $t_{\text{min}}$ provided for all courses

<table>
<thead>
<tr>
<th>Tank Shell Course</th>
<th>Required Tmin (inches)</th>
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<tr>
<td>R1</td>
<td>0.260</td>
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<tr>
<td>R2</td>
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<tr>
<td>R3</td>
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<tr>
<td>R4</td>
<td>0.130</td>
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<td>R5</td>
<td>0.098</td>
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<tr>
<td>R6</td>
<td>0.060</td>
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- Provided safe roof load – 1/3 Load when buckling would occur in thinned shell (when to clean, replace fabric)
CASE STUDY 7: STRESS CORROSION CRACKING

- Industry concern with Ethanol. Other SCC in Tanks & Spheres
- Case Study is Ammonia: Shows basic process
- Tank Geometry:
  - D=110’ x H=78’
  - API 620 R Tank (refrigerated)
  - Ammonia, G=0.68, Temp= –28°F
  - A537 Class 1, Impact Tested
- Evaluated critical flaw sizes for inspection, and remaining life
- Performed LBB, COA, Leak Rate & Consequence Modeling (RBI study often done concurrently)
CASE STUDY 7: STRESS CORROSION CRACKING

- Examined crack growth due to SCC and due to Fatigue (if an issue):

\[
\frac{da}{dt} = B(K)^n (q \times t^{q-1}) \times F(t), \quad \text{and} \quad \frac{da}{dN} = C(\Delta K)^n
\]

- Crack Growth Problem has a Load History Dependency—Need an Operating History

- FEA Stress analysis
  - Stresses at critical weld location like the bottom to shell, roof to shell, nozzles
  - A piping flexibility analysis to get loads can be crucial
CASE STUDY 7: STRESS CORROSION CRACKING

- FEA of various regions of concern
CASE STUDY 7: STRESS CORROSION CRACKING

- Performed FEA of welds to get Residual Stresses
  - More accurate than API 579 Appendix E for larger tank welds
  - Uses actual weld procedures to do Thermal Stress FEA
CASE STUDY 7: STRESS CORROSION CRACKING

- From stress history and crack growth law predicted – performed a FAD calculation for each point in time in the operating history
- Determined current crack size and critical size
- Predicted Remaining Life (time until cracks grows to CFS)
- RESULTS: Inspection recommendations
  - Interval, Critical Locations, Methods
CONCLUSIONS

- Most API 579 Methodologies are applicable to TANKS and damage to TANKS
- Specific Reference to API 579 is now made in API 653
  - Tank should be a API 620 or 650 Design
- Other FFS Issues
  - API 653 Appendix B Shell Settlement Procedure Study is Ongoing
  - NEW AREA OF CONCERN: Security – Impacts and Detonations can and are being evaluated with FFS type techniques