Modernization of Pressure Vessel Design Codes

ASME Section VIII, Division 2, 2007 Edition & Fitness-For-Service Codes, API 579-1/ASME FFS-1, 2007 Edition with Applications

EUROJOIN 7
Venezia Lido, Italy
21-22 May, 2009

David R. Thornton
Principal Engineer
The Equity Engineering Group, Inc.
Shaker Heights, Ohio USA
Presentation Overview

- Whole-Life Equipment Management
- Damage Mechanisms
- ASME Section VIII, Division 2, 2007 Edition
- ASME Section VIII, Division 2, 2007 Edition, Code Case 2605 (2.25Cr-1Mo-0.25V)
- In-Service Inspection Codes
- API 579-1/ASME FFS-1, 2007 Edition
- ASME Post Construction Publications
- Examples
  - Section VIII, Division 2 Code Case 2606
  - Application of API 579-1/ASME FFS-1
Whole-Life Equipment Management

- Whole-life management cycle for pressurized fixed equipment involves:
  - Damage Mechanism Identification
  - Construction Codes
  - In-Service Inspection Codes, Inspection planning
  - FFS Standard
  - Repair Guidelines

- Technology integration currently exists between construction codes, inspection codes and FFS Standards
Damage Mechanisms

• Understanding of damage mechanisms is a key feature in Whole-life Management Process
  - Required during the design phase, materials selection
  - Required for FFS if un-anticipated damage occurs (i.e. something not accounted for in design phase has occurred)

• Documents covering damage mechanisms
  - WRC Bulletin 488 for Pulp and Paper Industry
  - API 571 for Refining and Petrochemical Industry (Also published as WRC Bulletin 489)
  - WRC Bulletin 490 for Fossil Electric Power Industry
ASME Section VIII, Division 2, 2007 Edition

Overview

• Incorporates New Technology
  – Design margin of 2.4 on Ultimate Tensile Strength
  – Required material toughness based on fracture mechanics
  – Permits Design-By-Rule (DBR) in creep range
  – Conical transition requirements and opening reinforcement rules
  – Load case combinations for elastic, limit load, and elastic-plastic analysis
  – Local strain criteria for Design-By-Analysis (DBA) using elastic-plastic analysis
  – Fatigue design based on master S/N curve and structural stress method
  – Permits ultrasonic examination in place of radiographic examination
Overview

Enhancements Include:

- Alternative provided for certification of user design specification and manufacturers design report
- Consolidation of weld joint details and design
- Use of weld joint efficiencies and partial radiographic and ultrasonic examination
- Maximum Allowable Working Pressure concept adopted from Section VIII, Division 1
- Upgraded DBR and DBA procedures
- Extension of fatigue rules to 454°C for low-chrome alloys and heavy wall vessels (Code Case 2605)
- Adoption of new examination requirements and simplification of examination rules presentation
- Increased use of equations, tables, and figures to define rules and procedures
- ISO-like format: paragraph numbers, single column
New allowable stress basis in the 2007 editions will typically result in higher allowable stresses and lower wall thickness; extent of wall thickness reduction is a function of the YS/TS ratio at ambient temperature and YS at the design temperature.

Increase in allowable stress and resulting Wall Thickness Reduction (WTR) may be significant for many materials, indicator is the MYS/MTS ratio.

Consider the following comparison:
- Design pressure: 1000 psig
- Inside diameter: 60 inches
- Weld joint efficiency: 1.0
### Comparison: 2006 vs. 2007 Editions

<table>
<thead>
<tr>
<th>Material</th>
<th>MTS (MPa)</th>
<th>MYS (MPa)</th>
<th>Temp (°C)</th>
<th>S-2006 (MPa)</th>
<th>t cyl-2006 (mm)</th>
<th>S-2007 (MPa)</th>
<th>t cyl-2007 (mm)</th>
<th>WRT (%)</th>
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<td>262</td>
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<td>454</td>
<td>169</td>
<td>31.75</td>
<td>199</td>
<td>26.82</td>
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</table>
ASME Section VIII, Division 2, 2007 Edition
Code Case 2605

• Permits use of 2.25Cr-1Mo-0.25V for operating temperatures greater than 371°C and less than or equal to 454°C

• Provides requirements for fatigue evaluation

• Material specifications covered:
  – SA-182 F22V
  – SA-336 F22V
  – SA-541 Grade 22V
  – SA-542 Type D, Class 4a
  – SA-832 Grade 22V

• Approved October 17, 2008
ASME Section VIII, Division 2, 2007 Edition
Code Case 2605

- Design of parts, by either Part 4 or Part 5 of Section VIII, Division 2, 2007, is based on vessel **design conditions**
- Requirements for inelastic creep analysis, fatigue and ratcheting assessment are based on **operating conditions**
- For Hydro-processing reactors:
  - Design temperature typically 28°C higher than operating temperature at end of run
  - Design pressure typically 10% higher than operating pressure
• Code case explicitly addresses the following modes of failure
  - Plastic Collapse
  - Creep
  - Creep-Ratcheting
  - Creep-Fatigue Interaction

• Key technology elements of Code Case 2605
  - Adoption of MPC Project Omega as instituted in API 579-1/ASME FFS-1: analysis method and material data
  - Development of fatigue curves that include the effects of creep-fatigue interaction
Inelastic analysis, including the effects of creep, is performed based on time-temperature load history established using *operating* conditions.

Stress-strain curve is elastic-perfectly plastic.

Creep model used is MPC Project Omega from API 579-1/ASME FFS-1.

- Accumulated creep damage, absent fatigue, is limited to 1.0.
- Outer edge of Heat Affected Zone, measured from surface of the weld as deposited, must be located 25 mm from regions where the creep damage exceeds 0.50.
- Limits placed on total accumulated strain; not really required because damage calculation is performed.
Creep-ratcheting check performed numerically for at least two cycles with a minimum hold time of one year per cycle; loading and unloading must remain elastic at each point of component

Fatigue Analysis is required
- Fatigue curves are provided; design cycles are a function of creep life absent fatigue and of stress amplitude
- Fatigue screening using paragraph Section VIII, Division 2, paragraph 5.5.2.4 (Method B)
- Fatigue analysis performed using paragraph Section VIII, Division 2, paragraph 5.5.3

Required NDE
- Category A & B welds: 100% UT or RT
- Category C, D & E welds: 100% MT or PT
In-Service Inspection Codes

- API 510 Pressure Vessel Inspection Code: Maintenance Inspection, Rerating, Repair and Alteration
- API 570 Piping Inspection Code: Inspection, Repair Alteration and Rerating of In-Service Piping Systems
- API 653 Tank Inspection, Repair, Alteration, and Reconstruction
- NB-23 National Board Inspection Code

- Inspection codes use half-life inspection interval and also permit use of Risk-Based Inspection (RBI) planning as provided in API 580 and API 581
- Inspection codes reference API 579-1/ASME FFS-1 2007, Fitness-For-Service
API 579-1/ASME FFS-1, 2007 Edition

- In 2007, ASME and API jointly produced a co-branded Fitness-For-Service document, API 579-1/ASME FFS-1, based on the 2000 edition of API RP 579

- API 579-1/ASME FFS-1 2007 Fitness-For-Service (FFS)
  - Incorporates planned technical enhancements
  - Includes modifications to address needs of fossil electric power, and pulp and paper industries
  - Organized into 13 Parts that address various damage mechanisms; 11 Annexes provide additional information
  - Provides three assessment levels of increasing complexity; Level 3 permits use of alternate FFS procedures
  - Technical basis provided in WRC bulletins

- May be applied to pressure containing equipment constructed to international recognized standards
API 579-1/ASME FFS-1, 2007 Edition

• Broad application since procedures based on:
  - Allowable stress or plastic collapse for non-crack-like flaws
  - Failure Assessment Diagram (FAD) for crack-like flaws

• Enhancements include procedures for assessment of HIC/SOHIC damage, creep damage, dents and gouges, and laminations

• Fitness-For-Service procedures fully aligned with new Section VIII, Division 2 Design-By-Analysis rules
  - Provides unified analysis methods for new and in-service components

• May be used along with RBI methods to alter risk or develop inspection plans
ASME Post Construction Publications

- Fitness-For-Service repair decisions may utilize ASME post construction standards
  - PCC-1 2000 Guidelines for Pressure Boundary Bolted Flanged Joint Assembly
  - PCC-2 2006 Repair of Pressure Equipment and Piping Standard
  - PCC-3 2007 Inspection Planning Using Risk-Based Methods (similar to API RP 580)

- ASME PCC currently working on guide for life-cycle management of pressure equipment
  - Will initially focus on upstream oil and gas production equipment and on nuclear power equipment
Examples

- Creep-fatigue design of reactor nozzle fabricated from 2.25Cr-1Mo-0.25V using Section VIII, Division 2, Code Case 2606
- Fitness-For-Service Assessment of nozzle cracking associated with pressure and thermal cycles using API 579-1/ASME FFS-1
Code Case 2605 Example

Problem Overview

• Example highlights the use of Code Case 2605; use of design and operating conditions will be emphasized
  – Nozzle material is 2-1/4Cr-1Mo-1/4V

• Design conditions
  – Temperature: 454°C
  – Pressure: 22 MPa
  – Consider only 100 full pressure startup/shutdown cycles
  – Head and nozzle design geometry and configuration satisfy Design By Rule of Section VIII, Division 2, 2007

• Operating conditions
  – Temperature: 432°C
  – Pressure: 20 MPa
Code Case 2605 Example

Elastic Stress at 20 MPa and 432°C (time=0)
Code Case 2605 Example

Creep Damage Fraction for 400,000 hrs at 20 MPa and 432°C (Operating Conditions)
Code Case 2605 Example

Creep Damage Fraction for 1,000,000 hrs at 20 MPa and 432°C (Operating Conditions)
Code Case 2605 Example
Creep-Ratcheting Assessment

• Code case permits use of operating conditions in the creep-ratcheting or shakedown assessment
  – For this example, design conditions were used because solution was available from previous work

• Applied three cycles of 22 MPa pressure at 454°C with 20,000 hour hold time followed by shutdown to 0 MPA

• Results
  – Analysis demonstrated that the unloading and reloading portions of the cycle remain elastic at all points
  – Proposed ratcheting criteria is conservative, but ensures that creep-ratcheting will not occur
Code Case 2605 Example

Creep-Ratcheting Assessment
von Mises Stress versus Time
Three 20,000 Hour Cycles at 22 MPa and 454°C
Code Case 2605 Example
Fatigue & Creep-Fatigue Analysis

• Fatigue calculations use new design fatigue curves in Code Case 2605 that are a function of the stress amplitude and of the creep life absent fatigue (i.e. creep damage)
  – Creep-fatigue interaction implicitly incorporated in the new design fatigue curves

• Example calculations performed at operating conditions for a creep life absent fatigue of 1,000,000 hours; creep damage fraction at this time is 0.72
Code Case 2605 Example

Fatigue Analysis Option Summary

![Graph showing stress amplitude versus design cycles for different life spans.](image-url)
# Code Case 2605 Example

## Fatigue Analysis Summary

### Fatigue Analysis

**Full Pressure cycles at 20 MPa (2901 psig) and 432 °C (810 °F)**

**1,000,000 hr Fatigue Curve Used**

<table>
<thead>
<tr>
<th>SCL</th>
<th>Location</th>
<th>P + Q</th>
<th>P + Q + F</th>
<th>Stress Amplitude</th>
<th>Allowable Number of Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nozzle Outside Radius</td>
<td>211 MPa (30.6 ksi)</td>
<td>289 MPa (41.9 ksi)</td>
<td>144.5 MPa (21 ksi)</td>
<td>12,318</td>
</tr>
<tr>
<td>2</td>
<td>Nozzle Inside Radius</td>
<td>337 MPa (48.9 ksi)</td>
<td>343 MPa (49.8 ksi)</td>
<td>171.5 MPa (24.9 ksi)</td>
<td>4,900</td>
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<tr>
<td>3</td>
<td>Nozzle</td>
<td>212 MPa (30.8 ksi)</td>
<td>212 MPa (30.8 ksi)</td>
<td>106 MPa (15.4 ksi)</td>
<td>67,854</td>
</tr>
</tbody>
</table>

**Notes:**

1. Conservatively, stress relaxation due to creep was not considered in the stress used for the fatigue calculation, stresses at t=0 used.

2. Conservatively the 1,000,000 hour design curve was used for allowable fatigue cycles calculation.
Code Case 2605 Example

Summary of Results

• Inelastic creep analysis shows less than 100% creep damage at the outer nozzle blend radius for 1,000,000 hour life at operating conditions
  – Minimal creep damage at the nozzle inner corner
  – Need to locate weld away from region of 50% creep damage

• Application of three loading cycles demonstrate that creep-ratcheting is not a concern since behavior remains elastic

• Fatigue analysis using Code Case fatigue curves gives 4900 cycle fatigue life for full pressure cycles at the limiting creep location

• Fatigue analysis not difficult to perform because the finite element analysis calculations, required for creep and creep-ratcheting assessment, already have required values needed for fatigue evaluation
API 579-1/ASME FFS-1 Example

Problem Overview

- Radial cracks occurred at corner of nozzle in Mole Sieve reactors
- Reactors subjected to cyclic pressure and thermal operations
  - Pressure cycles from 2.21 MPa to 7.79 Mpa
  - Process temperature cycles from 35°C to 276°C
  - Cycle time between 6.17 hours and 7.75 hours, depending on operations
- Level 3 Fitness-For-Service assessment performed to:
  - Establish critical flaw size
  - Estimate permissible number of cycles
  - Determine recommended modifications to reduce probability of future damage
API 579-1/ASME FFS-1 Example

Inspection Results - Radial Cracks in Mole Sieve Reactor Nozzles

Four crack initiation sites were noted at the refractory retaining ring fillet welds at the base of the nozzle neck.
API 579-1/ASME FFS-1 Example

Refractory Retaining Ring
API 579-1/ASME FFS-1 Example

Radial Crack In Nozzle
API 579-1/ASME FFS-1 Example

Finite Element Model

Existing Nozzle with Retaining Ring
API 579-1/ASME FFS-1 Example
Cyclic Operating Conditions (2 Cycles Shown)
API 579-1/ASME FFS-1 Example

Recommended Thermal Sleeve

Existing Thermal Sleeve
(2 mm thick SS with 3 mm Kaowool between)

Retaining Ring 1/4" Tk (CS) Ring to be in 4 equal segments w/ 1/4" gap between segments

R 1.0" min

R 0.55"
API 579-1/ASME FFS-1 Example

Elastic FEA Results – Regeneration (No Thermal Sleeve)

Temperature (no sleeve)  Nozzle hoop stress
API 579-1/ASME FFS-1 Example

Temperature Results (No Sleeve versus Sleeve)

Temperature (no sleeve)  Temperature (with sleeve)
API 579-1/ASME FFS-1 Example
Nozzle Inside Corner Hoop Stress With and Without Thermal Sleeve
API 579-1/ASME FFS-1 Example
Fitness-For-Service Assessments

- Fracture mechanics crack-like flaw assessment
  - Flat plate semi-elliptical flaw assumed; validity verified by modeling three sizes of explicit cracks
  - Stresses obtained from finite element models for existing design and recommended modified design

- Fracture mechanics crack growth assessment using Paris crack growth law

- Limit Load Assessment (per Annex B) using Elastic-Perfectly Plastic material model

- Fatigue Assessment (per Annex B) using Structural Stress method with master S/N curve
API 579-1/ASME FFS-1 Example

Fracture Mechanics Flaw Assessment

• Material properties for fracture assessment from Annex F
  – Assessment temperature of 35°C
  – Yield strength of 241.3 MPa
  – Lower bound material $K_{IC}$ toughness of
    from toughness master curve

• Residual stress per Annex C also considered:
  – 310.3 MPa for as-welded condition
  – 93.1 MPa for post weld heat treated condition
API 579-1/ASME FFS-1 Example

Explicit Flaw Model

52.3 mm Deep x 150.9 mm High Flaw
API 579-1/ASME FFS-1 Example

Failure Assessment Diagram
52.3 mm Deep x 150.9 mm High Flaw
API 579-1/ASME FFS-1 Example

**Acceptable Flaw Sizes**

With Post Weld Heat Treatment

No Post Weld Heat Treatment
API 579-1/ASME FFS-1 Example

Fatigue Assessment Results

<table>
<thead>
<tr>
<th>Location/Description</th>
<th>Membrane Stress Range (ksi)</th>
<th>Membrane+ Bending Stress Range (ksi)</th>
<th>Total Stress Range (ksi)</th>
<th>Allowable Cycles</th>
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<tbody>
<tr>
<td>Nozzle Inside Corner; No thermal sleeve</td>
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<td>60.99</td>
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<td>18.31</td>
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<td>17,170</td>
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</table>

1. Battelle Structural Stress method used for assessment of weld locations per API 579-1/ASME FFS-1. Membrane and membrane plus bending stresses are used for this method, since the notch effect is implicit in the methodology and test data. Fatigue improvement for burr grinding considered for existing outer blend radius; no fatigue improvement considered for chamfered weld.

2. ASME Division 2 smooth bar fatigue method used for base metal locations. The total surface stress intensity at a point is used for this method.

3. Stress range based on time points consisting of end of regeneration heating and adsorption.
API 579-1/ASME FFS-1 Example

Recommended Inspection Interval
For Varying Initial Crack Size
API 579-1/ASME FFS-1 Example

**Summary of Results**

- Existing refractory retaining ring serves as stress concentration and crack initiation site in an already highly stressed region (nozzle corner)
- Minimal thermal gradient predicted in nozzle with thermal sleeve in place
- The fatigue cracking that has taken place historically is likely due to thermal mismatch between refractory lined shell/head and unlined nozzles/manways
- To substantially reduce cyclic stresses, recommend thermal sleeves on the main flow nozzles; removal of refractory and addition of external insulation
- There is no apparent need for the refractory lining from a metallurgical or thermal stress basis
David R. Thornton
email: drthornton@equityeng.com

20600 Chagrin Blvd. • Suite 1200
Shaker Heights, OH 44122  USA
Phone: 216-283-9519 • Fax: 216-283-6022
www.equityeng.com