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

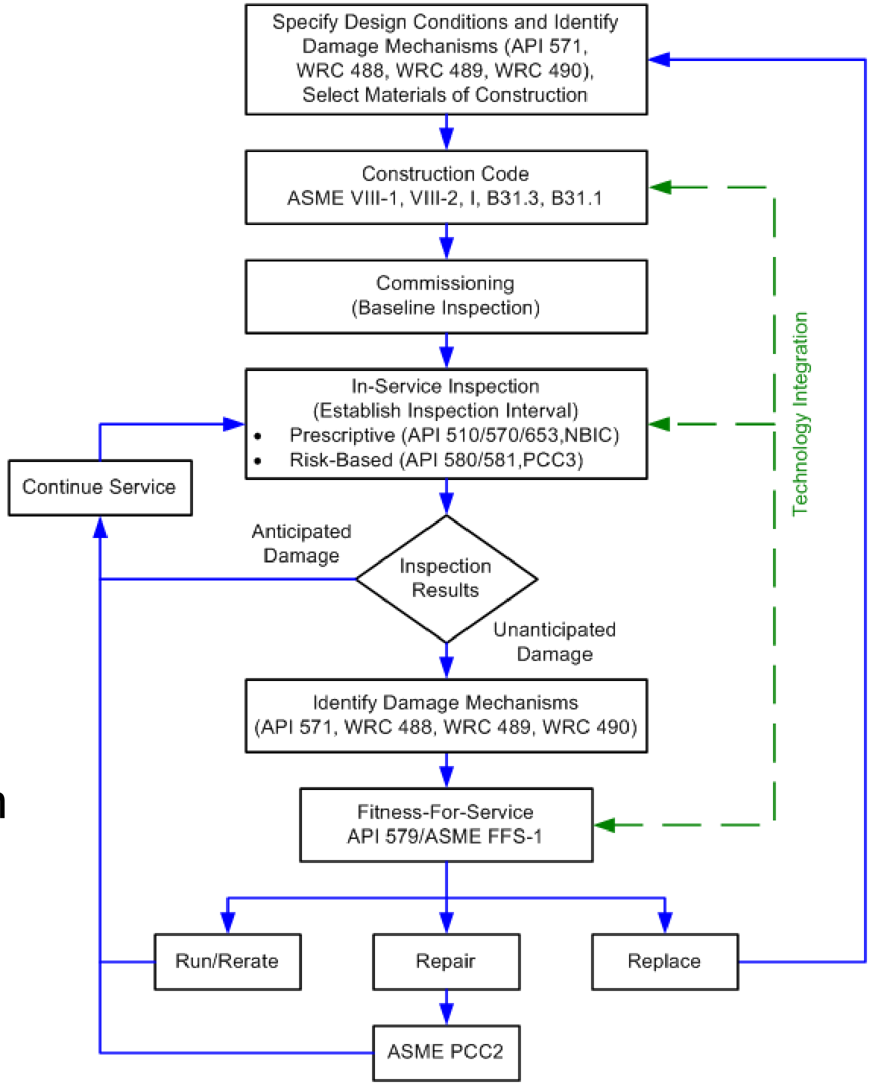
The Equity Engineering Group, Inc.

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 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

ASME Section VIII, Division 2, 2007 Edition
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^{o}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

ASME Section VIII, Division 2, 2007 Edition

Comparison: 2006 vs. 2007 Editions

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

ASME Section VIII, Division 2, 2007 Edition

Comparison: 2006 vs. 2007 Editions

Material	MTS (MPa)	MYS (MPa)	Temp (C)	S-2006 (MPa)	tcyl-2006 (mm)	S-2007 (MPa)	tcyl-2007 (mm)	WRT (%)
SA516 Gr. 70	483	262	38	161	33.43	174	30.73	8
			149	154	34.80	154	34.80	0
SA537 CL1, <= 63 mm	483	345	38	161	33.43	201	26.54	21
			149	151	35.61	200	26.75	25
SA537 CL2, <= 63 mm	552	414	38	184	29.08	230	23.24	20
			149	179	29.87	230	23.24	22
SA737 GR. B	483	345	38	161	33.43	201	26.54	21
			149	161	33.43	190	28.12	16
SA737 GR. C	552	414	38	184	29.08	230	23.24	20
			149	184	29.08	228	23.37	20
SA387 GR. 22 CL1	414	207	38	138	39.07	138	39.07	0
			454	118	45.90	118	45.90	0
SA387 GR. 22 CL2	517	310	38	172	31.09	207	25.83	17
			454	151	35.61	151	35.61	0
SA832 GR. 22V	586	414	38	195	27.41	244	21.84	20
			454	169	31.75	199	26.82	16

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

ASME Section VIII, Division 2, 2007 Edition Code Case 2605

- 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

ASME Section VIII, Division 2, 2007 Edition Code Case 2605

- 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

ASME Section VIII, Division 2, 2007 Edition Code Case 2605

- 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

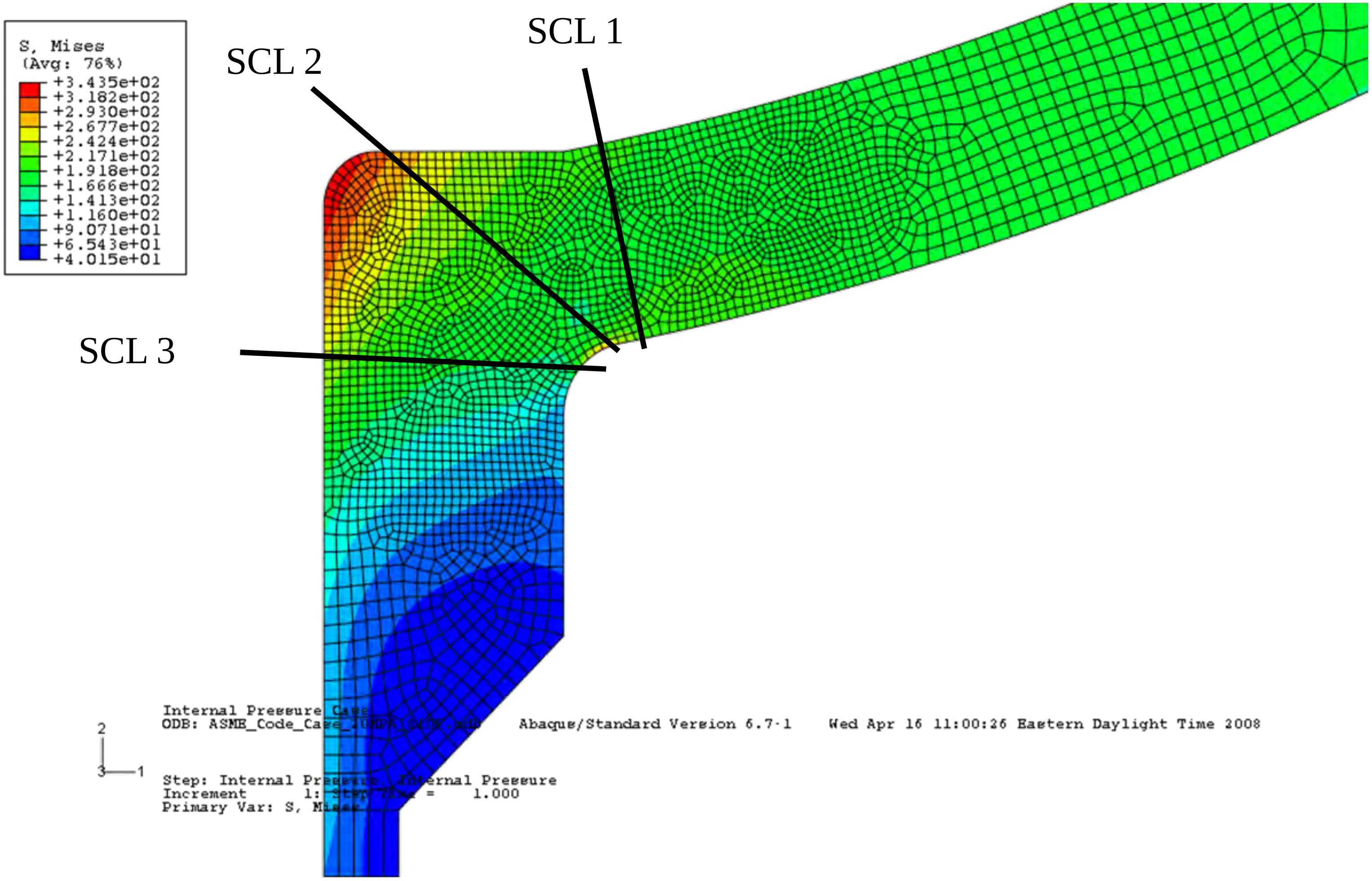
Code Case 2605 Example

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

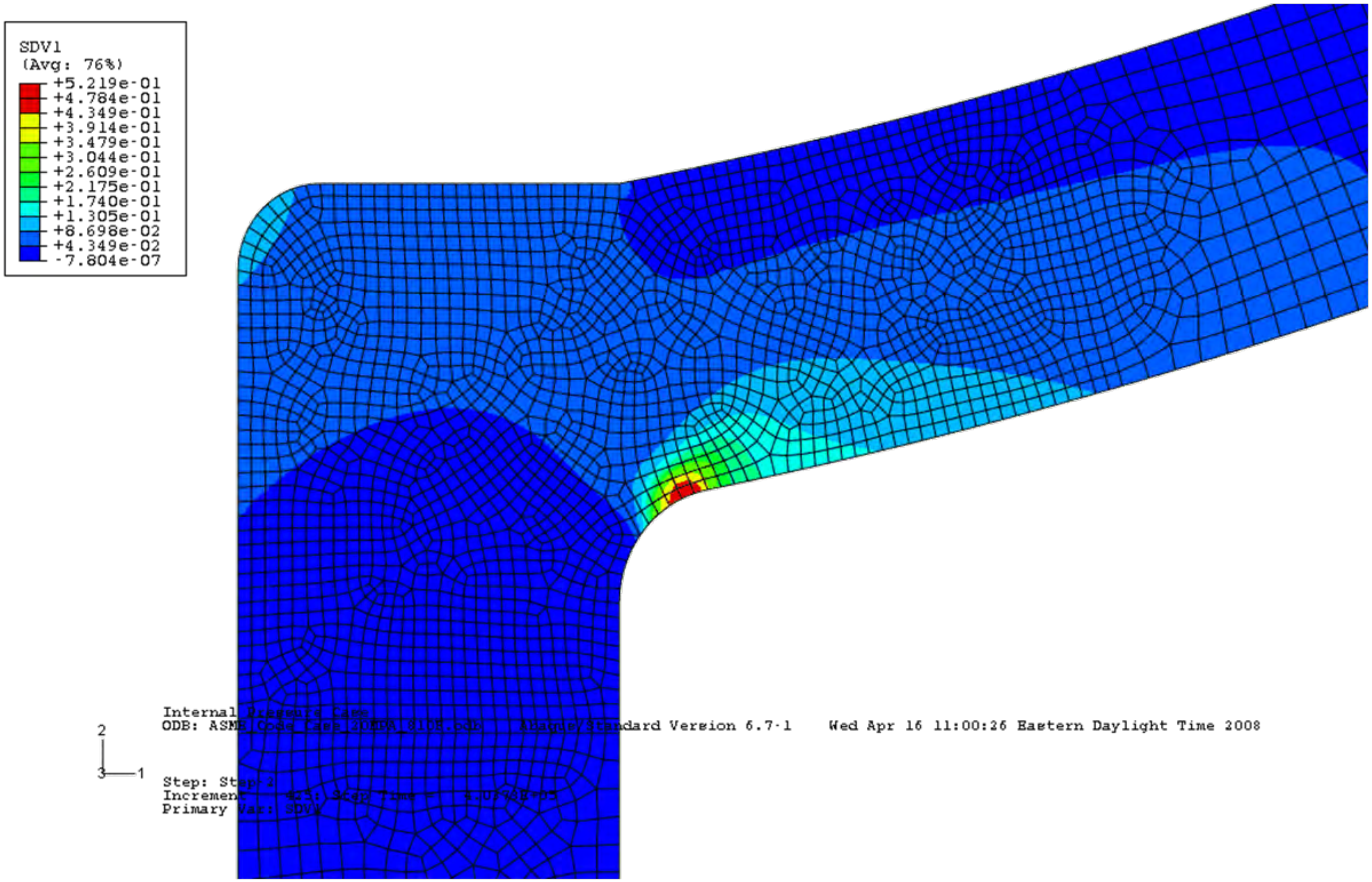
Code Case 2605 Example

Elastic Stress at 20 MPa and 432°C (time=0)



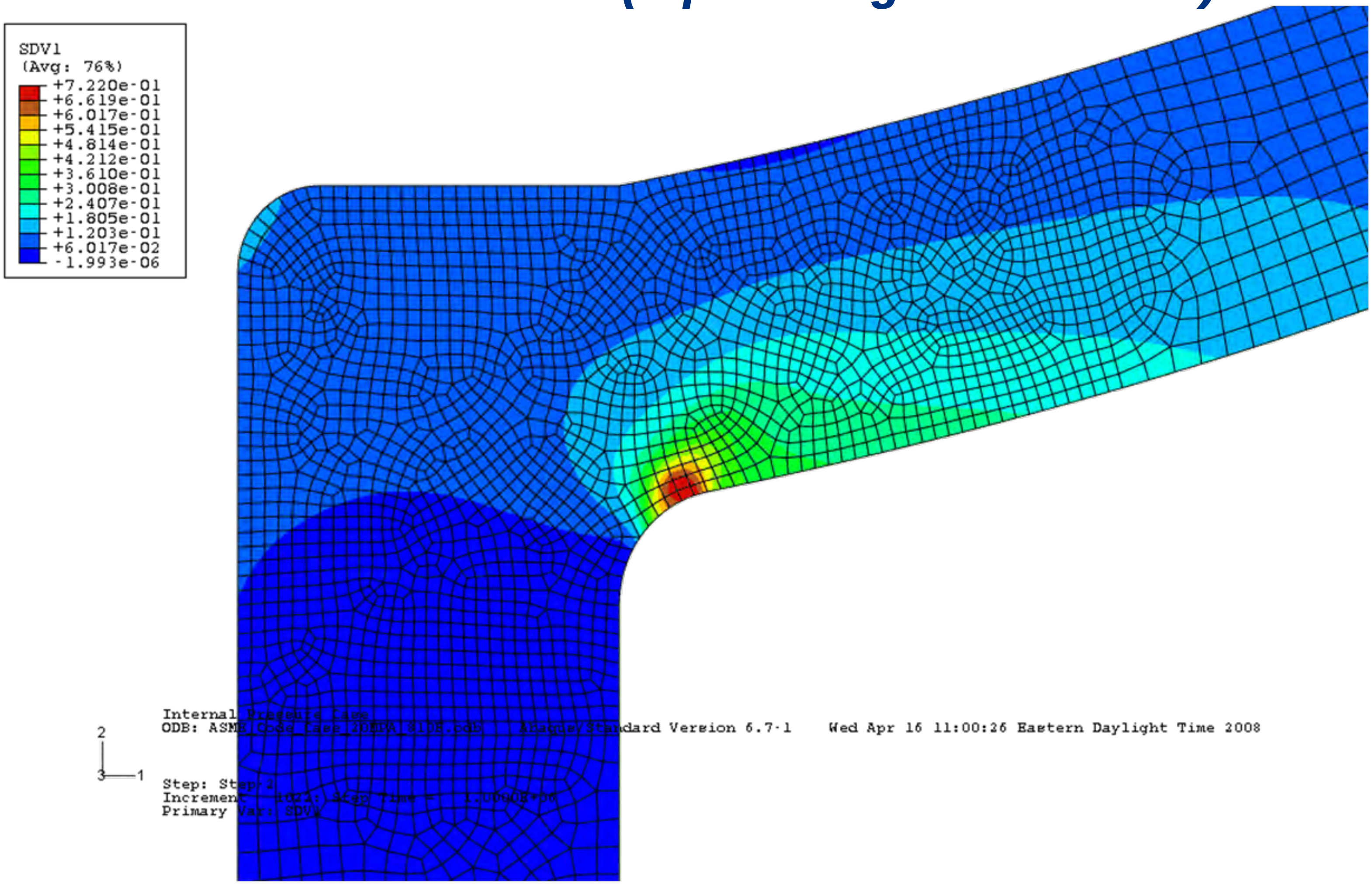
Code Case 2605 Example

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)



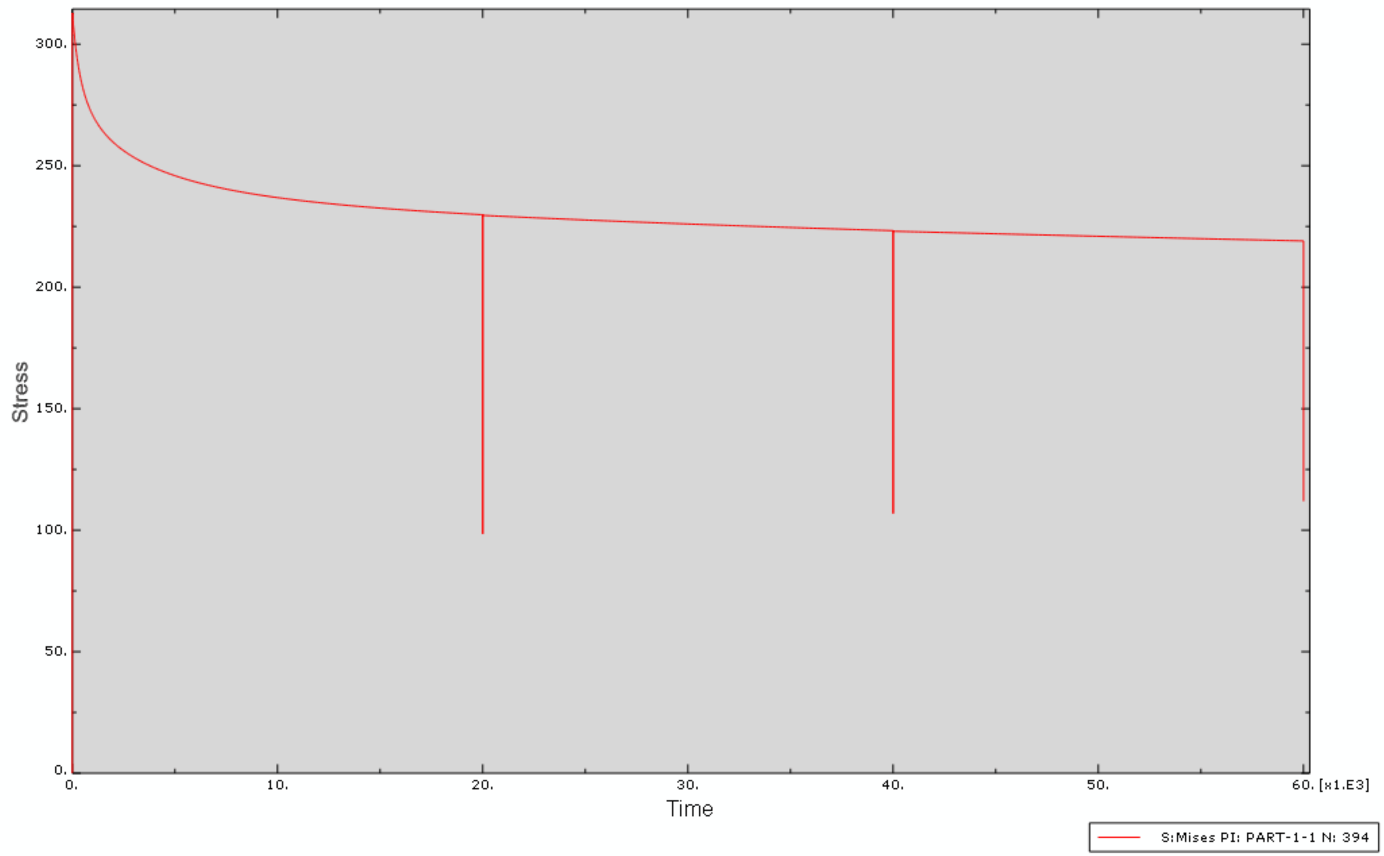
Code Case 2605 Example

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^{o}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



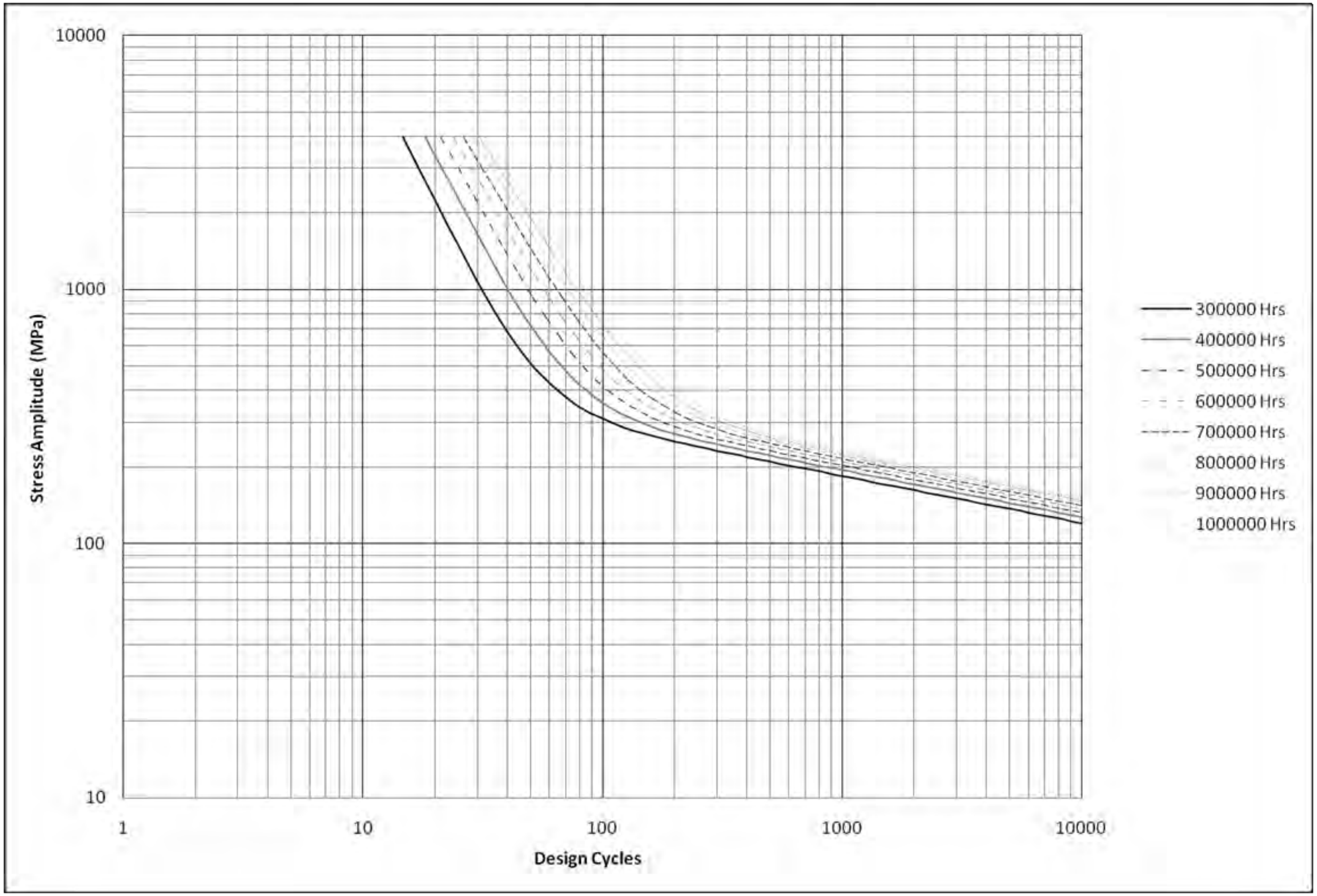
Code Case 2605 Example

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



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

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

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

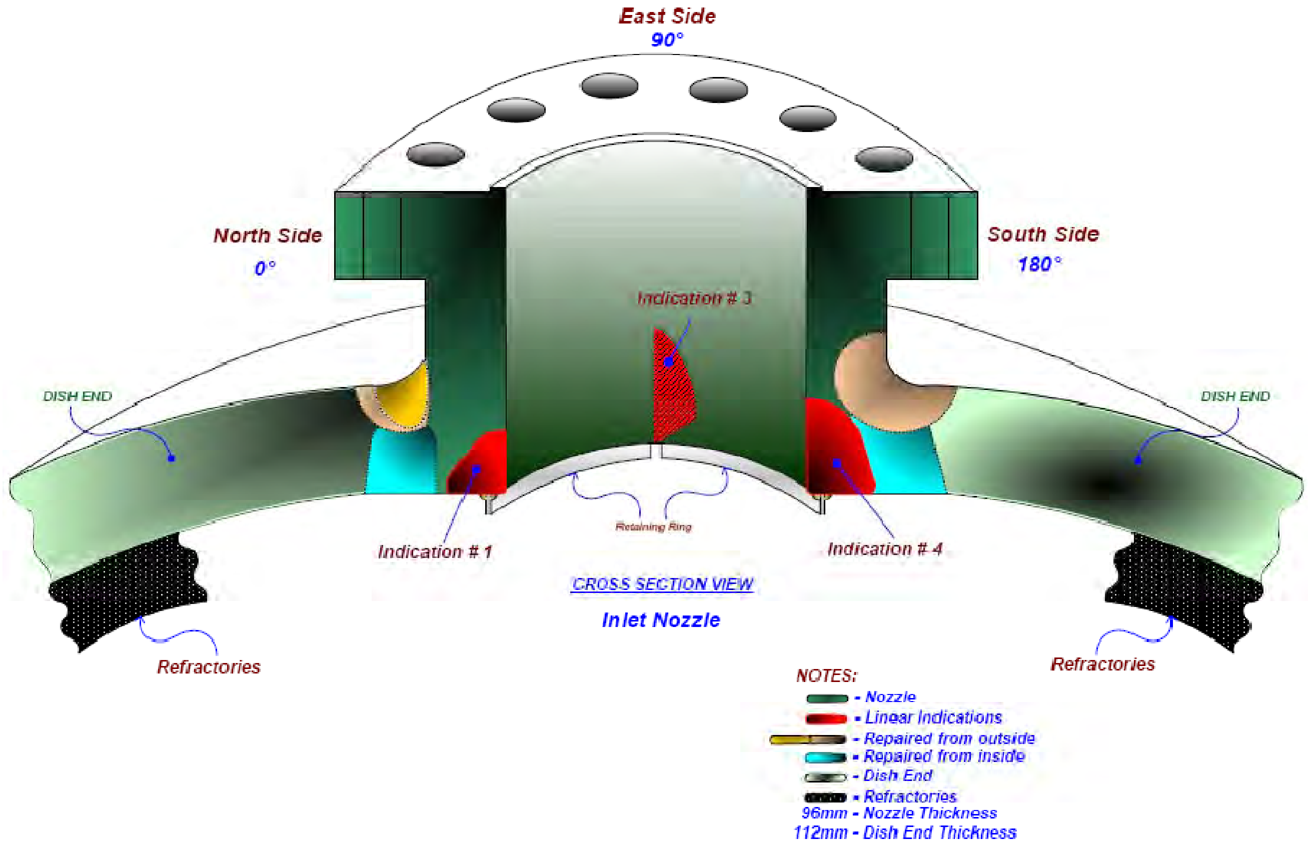
Problem Overview

- 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

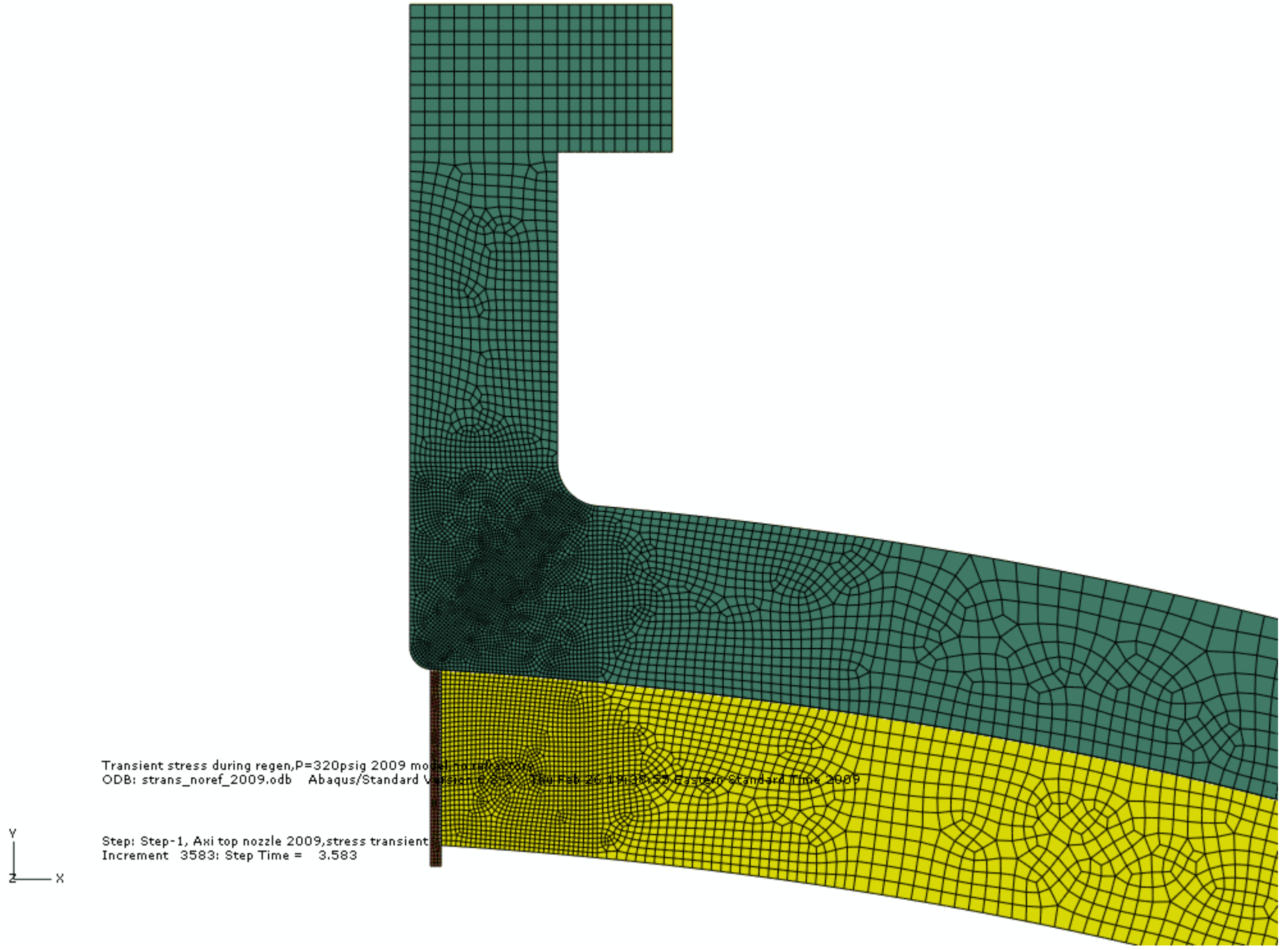
Refractory Retaining Ring

API 579-1/ASME FFS-1 Example

Radial Crack In Nozzle

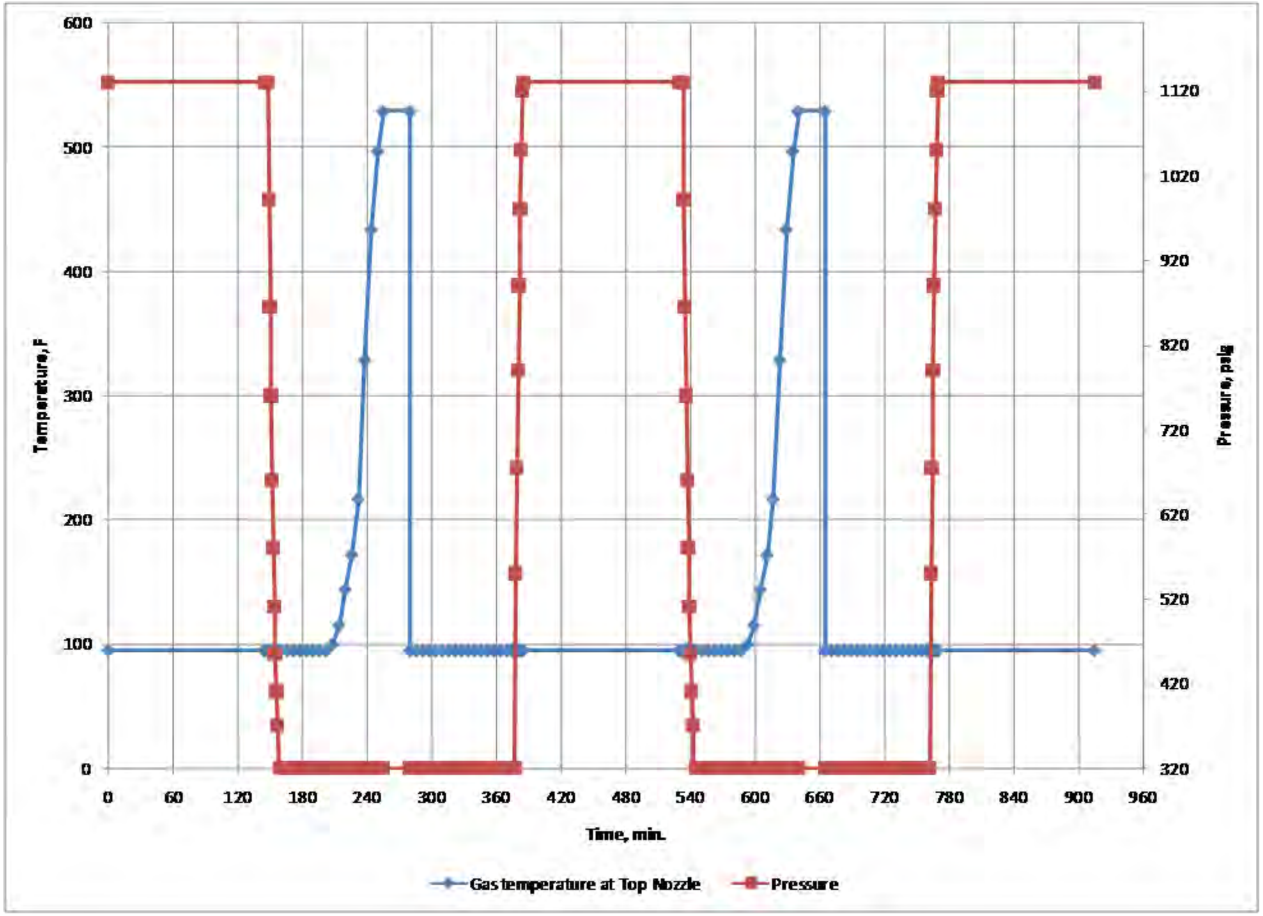
API 579-1/ASME FFS-1 Example

Finite Element Model
Existing Nozzle with Retaining Ring



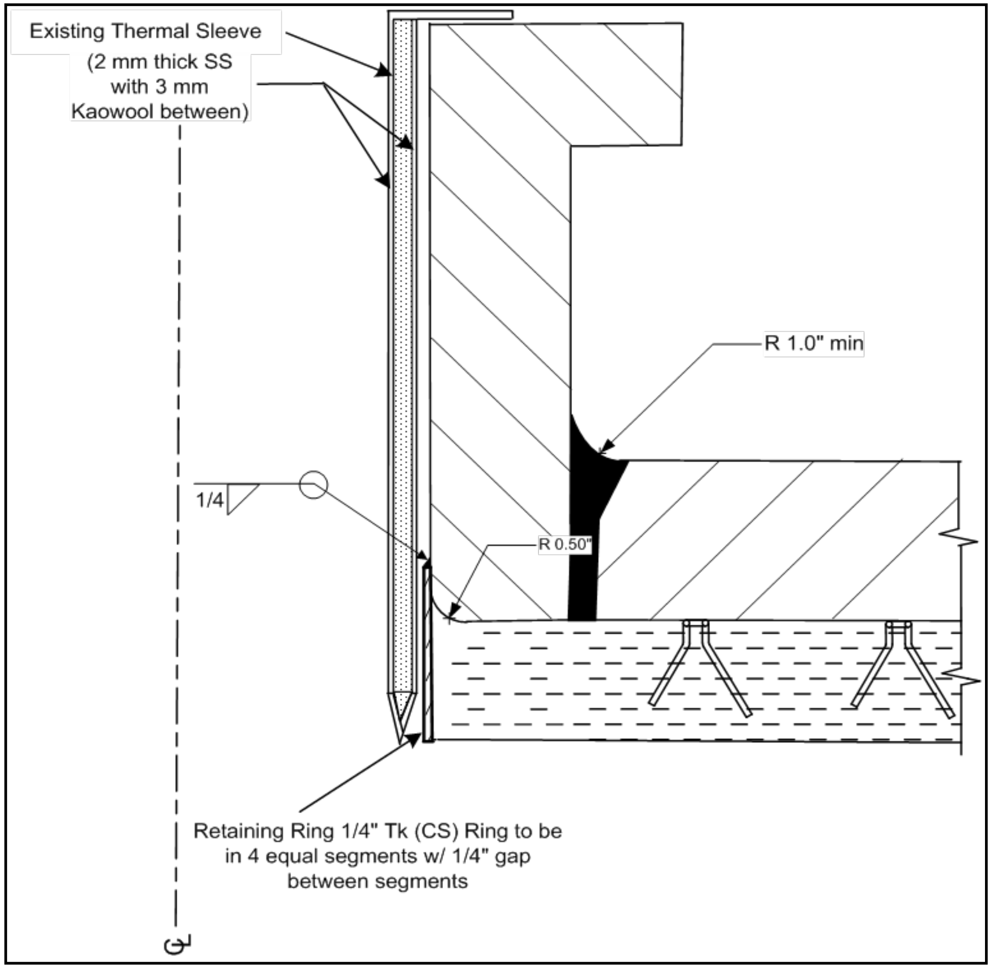
API 579-1/ASME FFS-1 Example

Cyclic Operating Conditions (2 Cycles Shown)



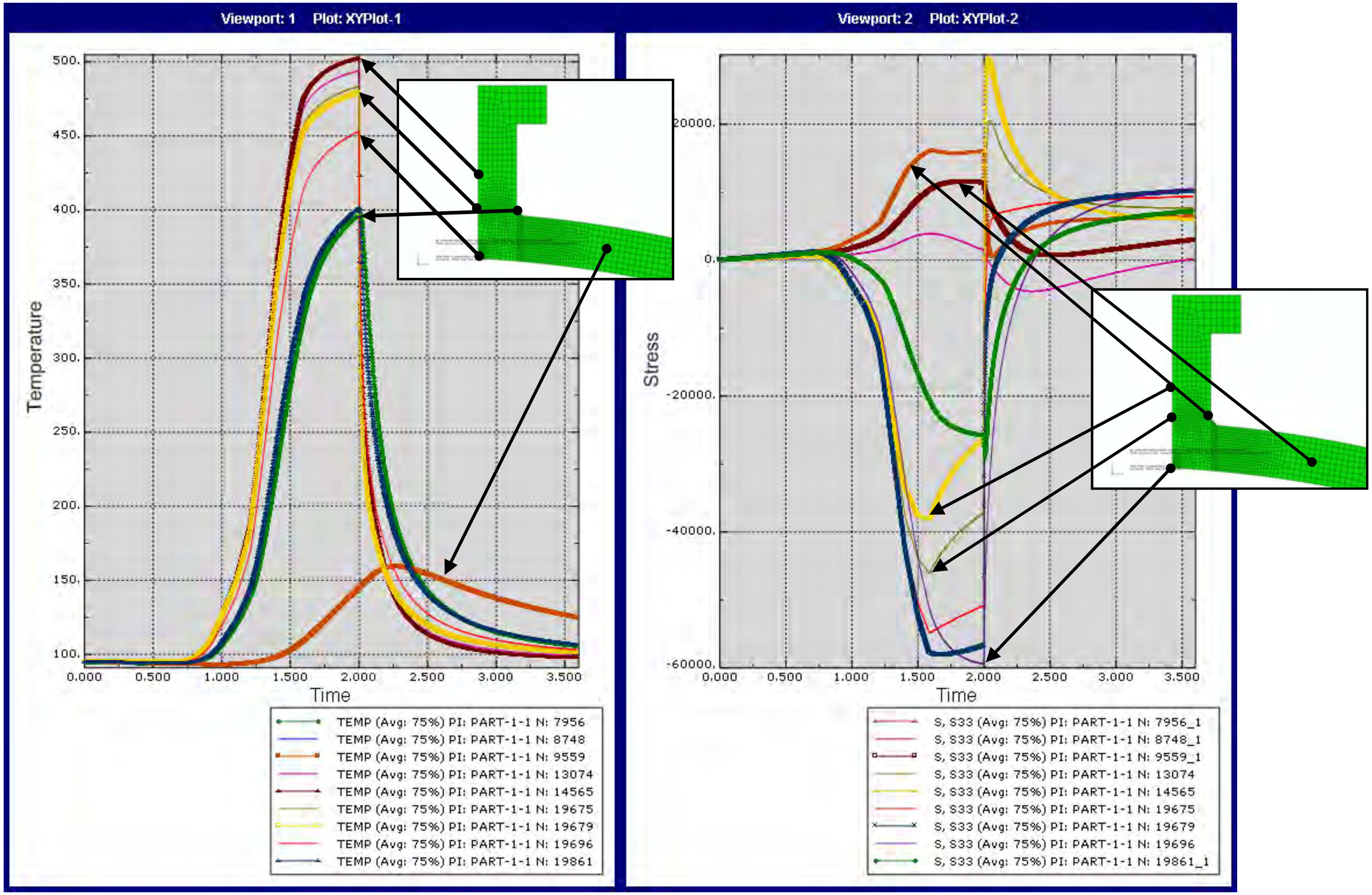
API 579-1/ASME FFS-1 Example

Recommended Thermal Sleeve



API 579-1/ASME FFS-1 Example

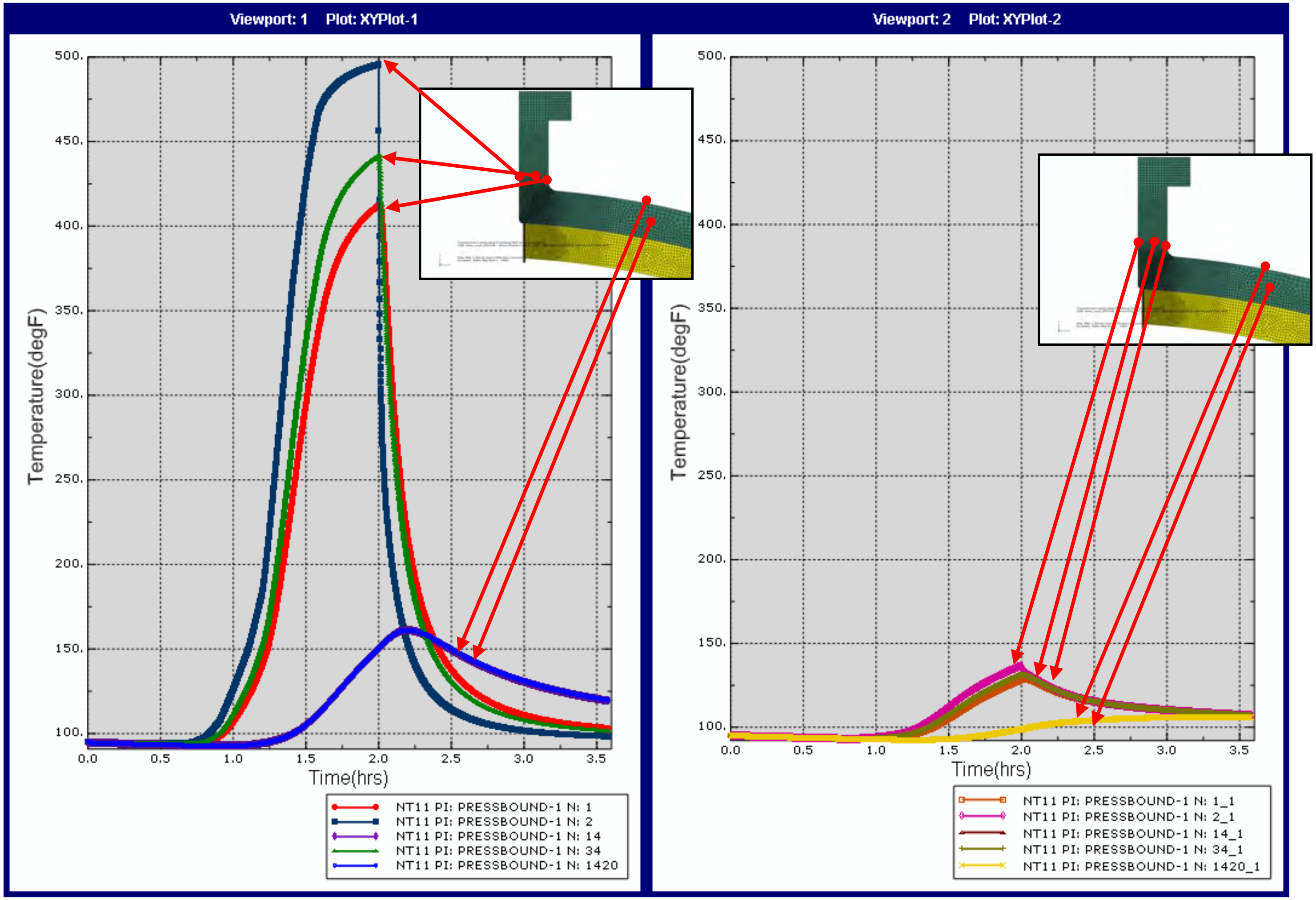
Elastic FEA Results – Regeneration (No Thermal Sleeve)



<u>Temperature (no sleeve)</u> <u>Nozzle hoop stress</u>

API 579-1/ASME FFS-1 Example

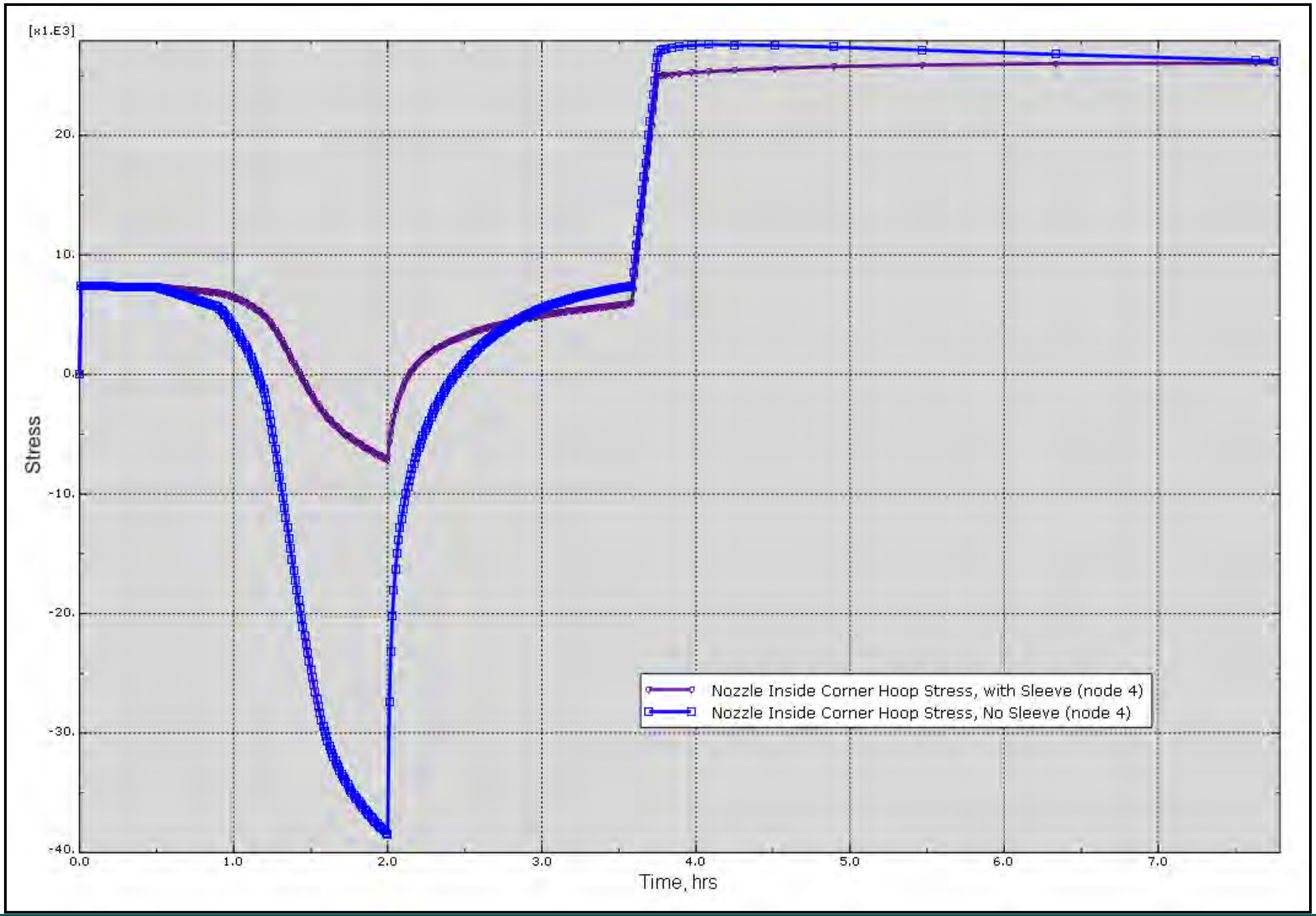
Temperature Results (No Sleeve versus Sleeve)



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

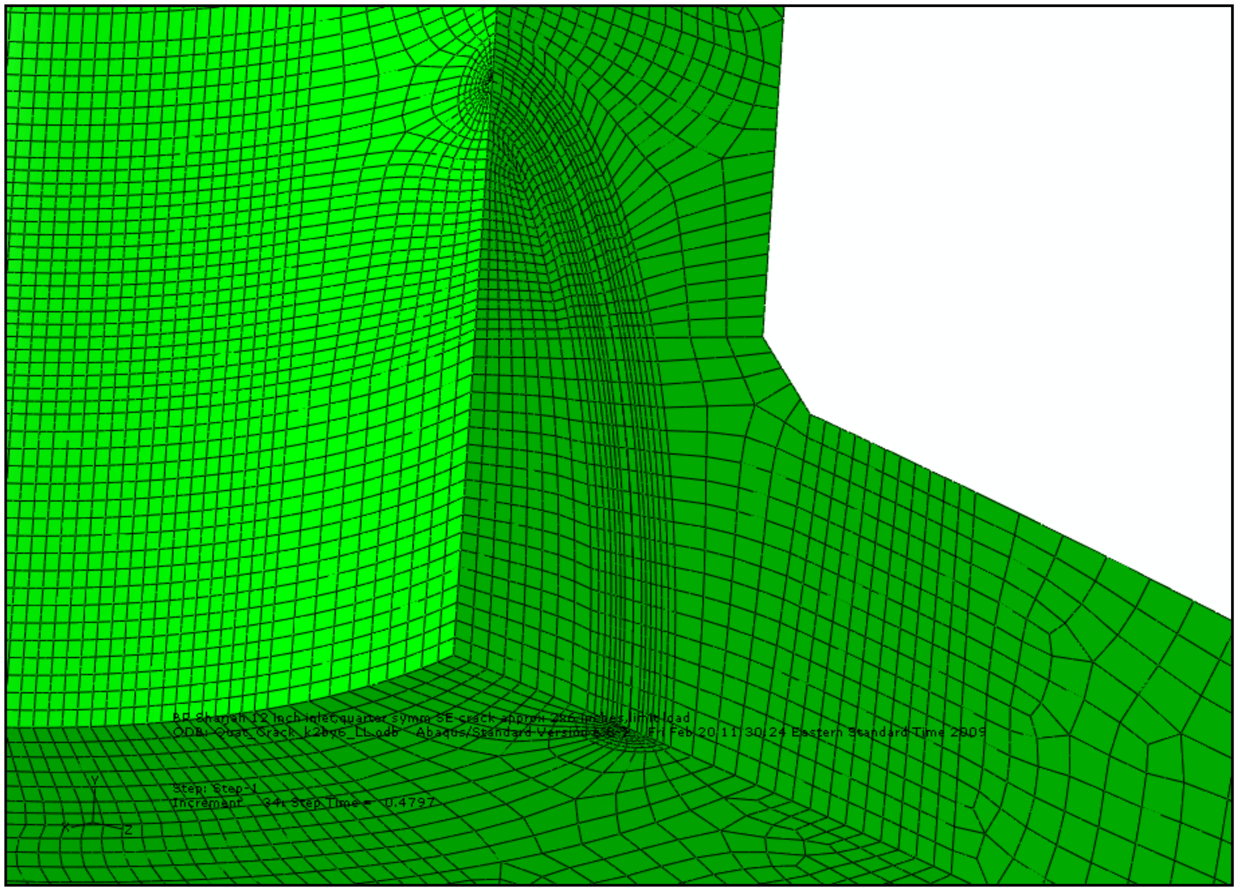
API 579-1/ASME FFS-1 Example

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 $94.5\ MPa\sqrt{m}$ 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

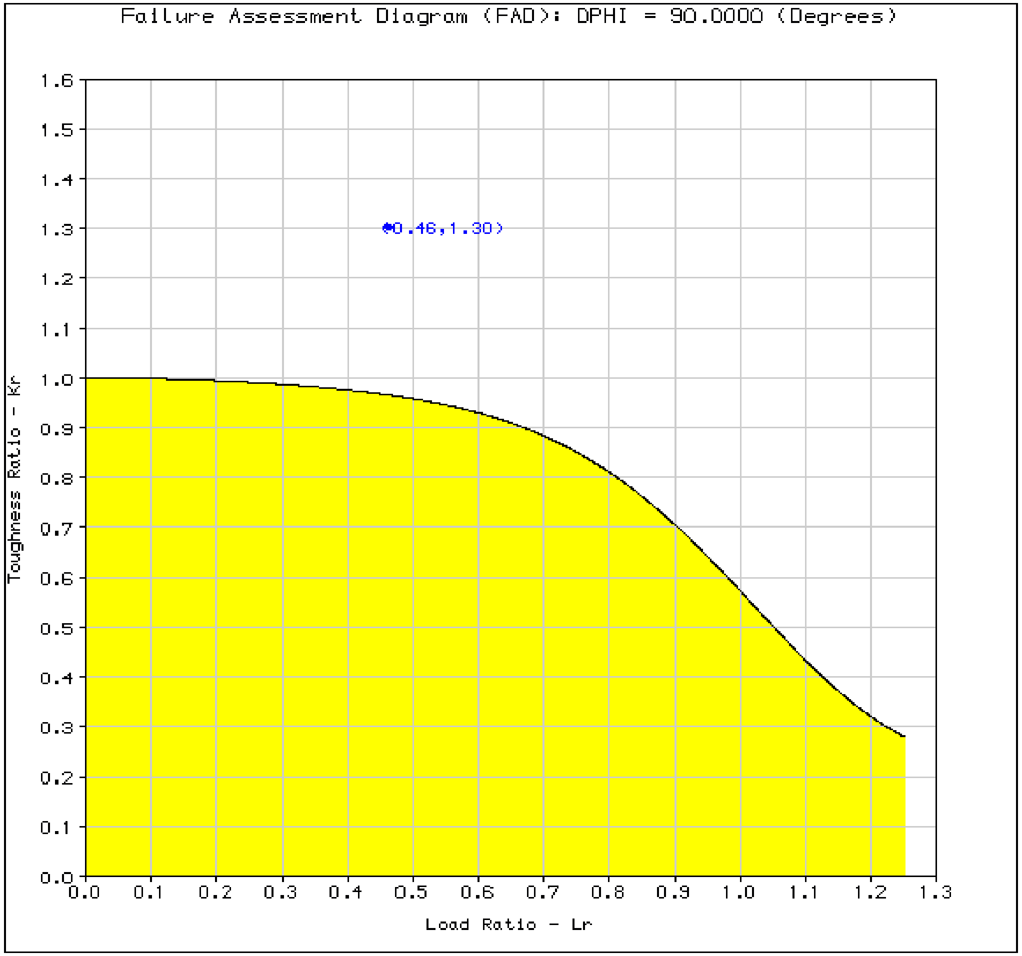
Explicit Flaw Model
52.3 mm Deep x 150.9 mm High Flaw



API 579-1/ASME FFS-1 Example

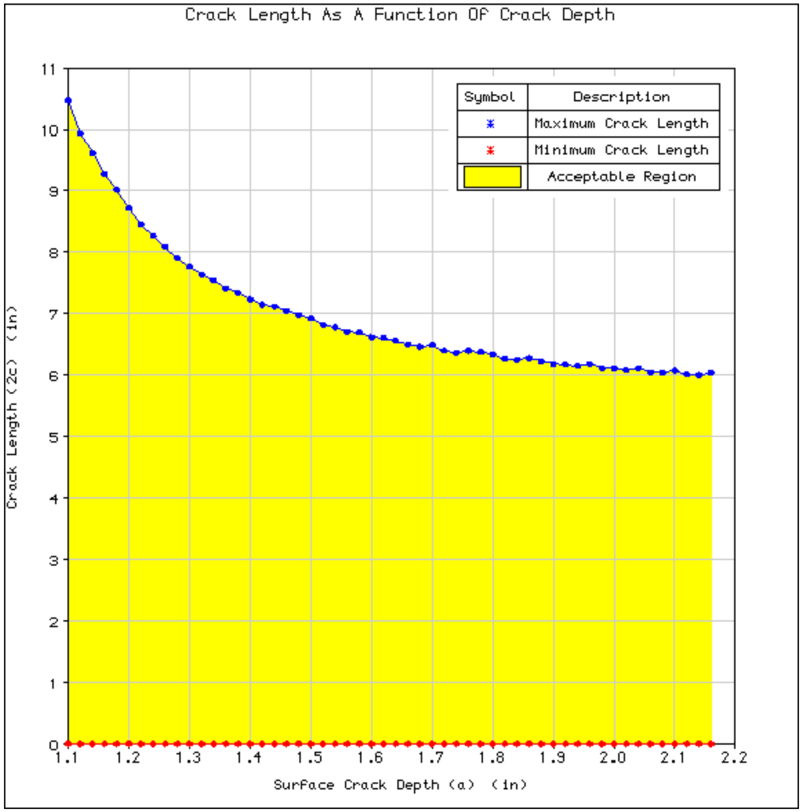
Failure Assessment Diagram

52.3 mm Deep x 150.9 mm High Flaw

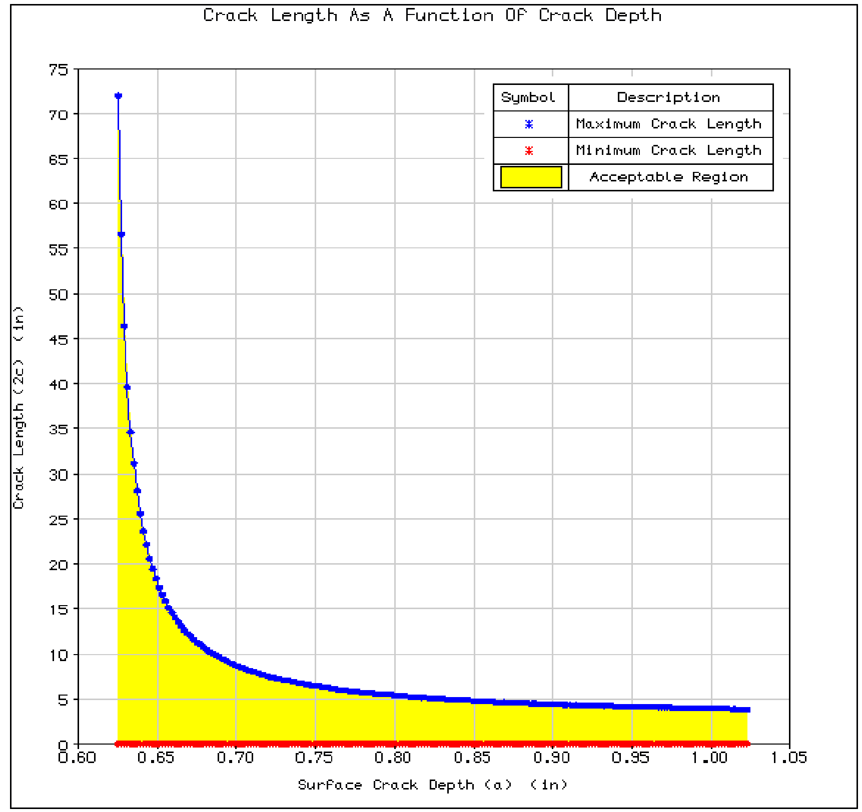


API 579-1/ASME FFS-1 Example

Acceptable Flaw Sizes



With Post Weld Heat Treatment



No Post Weld Heat Treatment

API 579-1/ASME FFS-1 Example

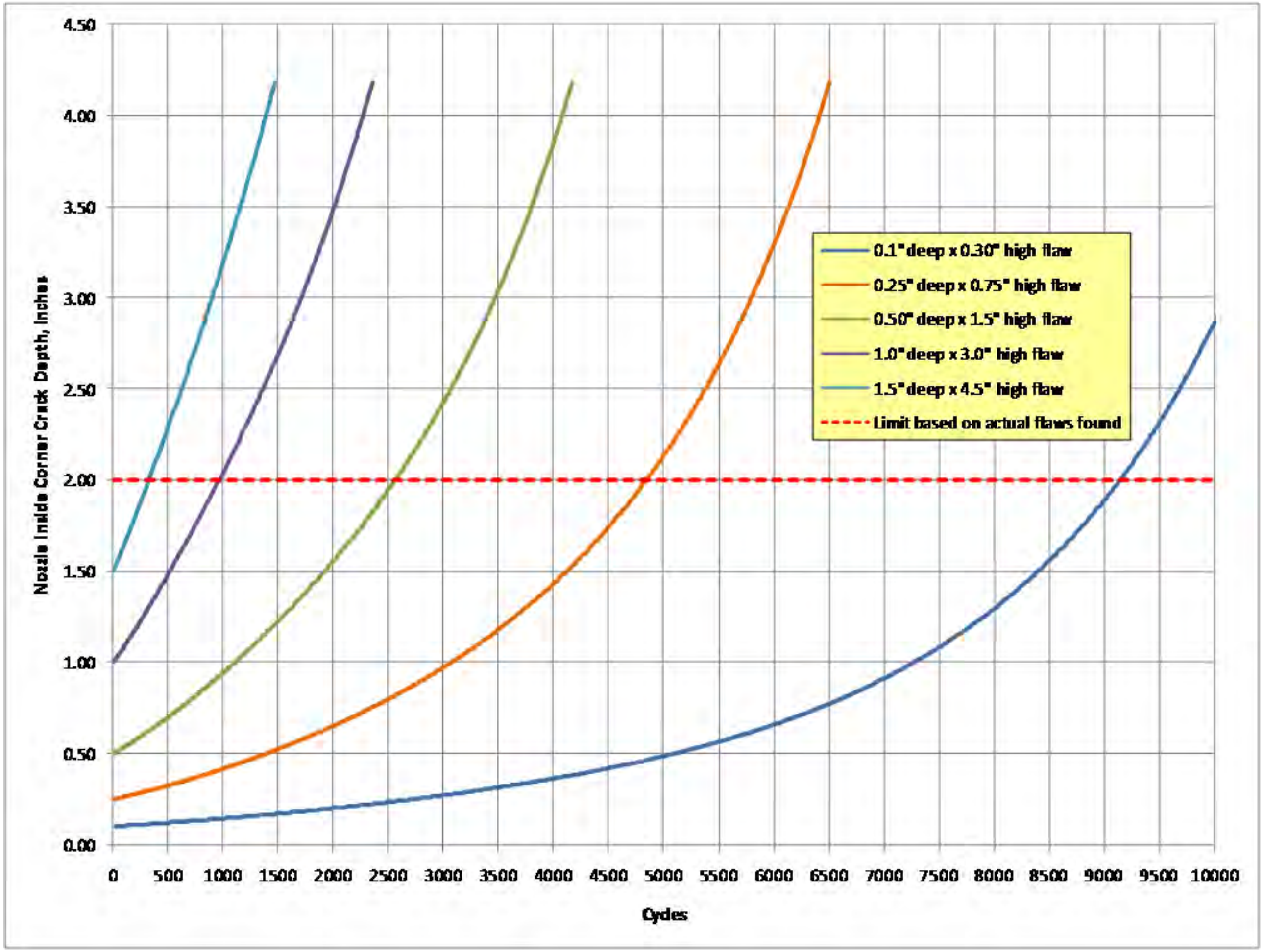
Fatigue Assessment Results

Location/Description	Membrane Stress Range (ksi)	Membrane+ Bending Stress Range (ksi)	Total Stress Range (ksi)	Allowable Cycles
Nozzle Inside Corner; No thermal sleeve	N/A	60.99	67.95	11,389
Nozzle Inside Corner; Includes thermal sleeve	N/A	33.77	35.40	119,099
Nozzle to head weld; No thermal sleeve	17.01	20.37	N/A	27,637
Nozzle to head weld; Includes thermal sleeve	10.51	18.35	N/A	42,049
Nozzle to head weld O.D. weld chamfered for UT readings; Includes thermal sleeve	10.02	18.31	N/A	17,170

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

The Equity Engineering Group, Inc.

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